Fraunhofer

April 2026

Light Sources for Quantum Key Distribution – Technology Overview and Future Perspectives

Imprint

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Report coordination

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Compiled in the context of the

Umbrella Project for Quantum Communication in Germany
(Schirmprojekt Quantenkommunikation Deutschland – SQuaD),
funded by the Federal Ministry of Research, Technology and Space
(Bundesministerium für Forschung, Technologie und Raumfahrt – BMFTR)

With funding from the:

Federal Ministry
of Research, Technology
and Space

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Cover page: Heyko Stöber, Hohenstein

Published

April 2026

DOI

10.24406/publica-7704

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Notes

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List of Abbreviations

2D materials	two-dimensional materials
BBO	beta-barium borate
BiBO	bismuth borate
CV-QKD	continuous-variable quantum key distribution
CW	continuous wave
DBT	dibenzoterrylene
DFB	distributed feedback
DI-QKD	device-independent quantum key distribution
DV-QKD	discrete-variable quantum key distribution
DW factor	Debye-Waller factor
EEL	edge-emitting laser
EPS	entangled-photon pair source
FWM	four-wave mixing
hBN	hexagonal boron nitride
HOM visibility	Hong-Ou-Mandel visibility
KD*P	potassium dideuterium phosphate
KPI	key performance indicator
KTP	potassium titanyl phosphate
LN	lithium niobate
LO	local oscillator
MDI-QKD	measurement-device-independent quantum key distribution
OIL	optical injection locking
P&M-QKD	prepare-and-measure quantum key distribution
PPKTP	periodically-poled potassium titanyl phosphate
PPLN	periodically-poled lithium niobate
QCom	quantum communication
QD	quantum dot
QKD	quantum key distribution
RT	room temperature
sLT	stoichiometric lithium tantalate

SPDC	spontaneous parametric down-conversion
SPS	single-photon source
TEC	thermoelectric cooling
TFLN	thin-film lithium niobate
TF-QKD	twin-field quantum key distribution
TMDC	transition metal dichalcogenides
TRL	technology readiness level
VCSEL	vertical-cavity surface emitting laser
WPC	weak coherent pulse
ZPL	zero-phonon line

Zusammenfassung und Kernergebnisse (German)

In diesem Bericht werden Technologien von Lichtquellen für die Quantenkommunikation, insbesondere für den Quanten-Schlüsselaustausch (QKD), untersucht sowie ihr Innovationspotenzial und zentrale Herausforderungen für aktuelle und zukünftige Anwendungsfälle bewertet. Da bei QKD Informationen in den Quantenzuständen von Photonen kodiert werden, sind Lichtquellen kritische Komponenten von QKD-Systemen und können deren Spezifikationen beeinflussen. Die Studie umfasst die Betrachtung von kohärenten Quellen für DV-QKD (Discrete-Variable QKD) und CV-QKD (Continuous-Variable QKD), die Erzeugung von Photon-Paaren über spontane parametrische Abwärtskonversion (SPDC) und Four-Wave-Mixing (FWM), Quantenpunktdiodenquellen und andere deterministische Emitter ab.

Während kommerziell erhältliche Prepare-and-Measure-QKD-Systeme überwiegend auf ausgereiften Lasertechnologien beruhen, ist die Photon-Paar-Erzeugung in nichtlinearen Medien eine attraktive Alternative, vor allem kommerzialisiert in Systemen für verschränkungsbasierte QKD. Weitere Optionen, deterministische Quellen wie Quantenpunkte und andere Emitter, können besondere Eigenschaften für QKD-Systeme bieten, insbesondere für QKD mit fortgeschrittenen Protokollen, verschränkungsbasierte QKD und zukünftig auch in potenziellen Quanten-Netzwerken.

Die Studie kombiniert Desk Research und Experteninterviews, um verschiedene Lichtquellentechnologien, ihre wichtigsten Leistungsindikatoren (KPIs), ihre Anwendung in QKD, die jeweiligen Technologie-Reifegrade (TRL) und Wege zur Industrialisierung zu erfassen. Ein Online-Workshop mit Stakeholdern aus Wissenschaft, Forschungsorganisationen und Industrie wurde durchgeführt, um die Ergebnisse zu validieren und Herausforderungen und zukünftige Entwicklungen zu diskutieren.

Leistungsanforderungen an Lichtquellen für den Einsatz in der Quantenkommunikation

In dem Bericht werden zentrale Leistungsindikatoren eingeführt, welche repräsentativ die Leistungsfähigkeit für verschiedene Typen von QKD-Protokollen darstellen. So ist der Betrieb bei Raumtemperatur mit hohen Wiederholraten und hoher Robustheit vorteilhaft für alle Umsetzungen. Die Emissionswellenlänge muss auf das Übertragungsmedium und den Detektor ausgelegt sein. Die Frequenzbereiche im Telekom O- und C-Band sind für die Glasfaser optimal; Freistrahlverbindungen arbeiten üblicherweise im sichtbaren/nahen Infrarot oder bei Telekommunikationswellenlängen. Niedrige Kosten und hohe technologische Reife sind entscheidend für eine breite Kommerzialisierung. In DV-QKD-Protokollen ist eine gute Photonenreinheit wichtig, um die Sicherheit des Protokolls sicherzustellen, wobei für laserbasierte Prepare-and-Measure-QKD bereits gut etablierte Gegenmaßnahmen erprobt sind. Je nach Protokolltypen sind zusätzliche Anforderungen zu berücksichtigen (z. B. Ununterscheidbarkeit für MDI-QKD, Verschränkungsfidelität für verschränkungsbasierte Protokolle).

Die effektive Schlüsselrate hängt von der Quelle und den entsprechenden Kopplungs- und Extraktionseffizienzen, Kanalverlusten, Detektorleistung und erforderlicher Nachbearbeitung (Post-Processing) ab. Deterministische Photonen-Erzeugung bietet hier vielversprechende Vorteile gegenüber probabilistischen Prozessen. Anwendungsaspekte wie die Anzahl der kommunizierenden Parteien, Entfernung, Auslastung der Kommunikationsverbindung und Medium (Glasfaser, Freistrahl, Satellit) beeinflussen die optimale Quellenauswahl und Systemauslegung, einschließlich der Freiheitsgrade, die zur Kodierung verwendet werden.

Überblick über verschiedene Lichtquellen-Technologien

Schwache kohärente Laser für DV-QKD werden weithin verwendet und sind ausgereift. Implementationen beruhen auf Distributed Feedback (DFB) Laser, Vertical-Cavity Surface-Emitting Laser

(VCSEL) und edge-emitting Laser mit Gain Switching, optischem „Injection Locking“ und externen Modulations-/Abtastfunktionen, die Protokolle wie BB84, MDI-QKD und TF-QKD mit Decoy-Zuständen ermöglichen, um Schlüsselraten bei Vorhandensein von Mehrfach-Photonen-Pulses zu erhöhen. Diese Sendereinheiten arbeiten bei Raumtemperatur und können zu Preisen von wenigen tausend Euro implementiert werden. Verbleibende Herausforderungen sind die Entwicklung von kostengünstigeren Quellen mit Wellenlängen-Regelbarkeit in Telekommunikationsbändern, Restphasen-/Intensitätskorrelationen bei hohen Geschwindigkeiten, Reproduzierbarkeit von VCSELs mit identischen Eigenschaften, fehlende Komponentenzertifizierung und dem Bedarf an integrierter Photonik zur Zusammenführung von Funktionen.

Kohärente Laser für CV-QKD erfordern niedriges relatives Intensitätsrauschen (RIN), arbeiten typischerweise im C-Band bei Raumtemperatur und befinden sich auf hohem TRL. Obwohl Modulationsbandbreiten hoch sein können, wird die Leistungsfähigkeit in der Praxis oft durch Detektorbandbreiten und Nachbearbeitungsgeschwindigkeit begrenzt. Die photonische Integration von On-Chip-Lasern schreitet voran, aber es besteht weiter Bedarf an Linienbreiten- und Frequenzstabilität, Wellenlängen-Regelbarkeit und integrierten Lösungen; typische Gerätekosten liegen im Bereich weniger Tausend Euro.

Photonen-Paar-Quellen auf Basis von nichtlinearen Medien liefern Verschränkung für entsprechende QKD-Protokolle und weitere Anwendungen. SPDC funktioniert bei Raumtemperatur, ermöglicht Emissionen im Bereich von 780–1550 nm und erreicht hohe Verschränkungsfidelitäten sowie Ununterscheidbarkeit mit typischen Linienbreiten von einigen Nanometern. Die Reinheit von der „heraldierten“ Einzelphotonenerzeugung und die Generationsrate sind intrinsisch in dem stochastischen Prozess gekoppelt. Aktuelle Systeme befinden sich auf hohem TRL, mit weiteren Entwicklungen rund um die Extraktions-/Kopplungseffizienz, Multiplexing und photonischer Integration. FWM baut auf eine breite Materialbasis auf und hat hohes Potenzial für photonische Integration (Glasfaser, siliziumbasierte Plattformen, Lithiumniobat, Aluminiumnitride), sieht sich jedoch mit einer geringeren Nichtlinearität und auftretendem Raman-/Kerr-Rauschen konfrontiert, das eine Unterdrückung durch Operation bei tiefkalten Temperaturen erfordern könnte. Für FWM werden längere Interaktionslängen benötigt und die Technologie weist einen geringeren Reifegrad als SPDC auf.

Quantenpunkte ermöglichen deterministische Emissionen von Einzelphotonen. Dieser Ansatz für Einzelphotonenquellen weisen eine hohe Reinheit und Ununterscheidbarkeit bei tiefkalten Temperaturen über ein breites Wellenlängenband auf. Einige Systeme können sogar in Telekommunikationsbändern emittieren, obwohl solche Quantenpunkte oft bei anderen KPIs eingeschränkte Performanz zeigen. Typische Erzeugungsraten liegen im Bereich einiger zehn bis hunderte Megahertz. Kommerzielle Systeme existieren bereits, bleiben aber teuer und der TRL für gut implementierbare Technologien liegt unter dem von Laser- und SPDC-basierten Lösungen. Zentrale Herausforderungen sind reproduzierbare Fertigung und Ausbeute, Betriebstemperatur, gute Photonenqualität bei Telekommunikationswellenlängen, Ununterscheidbarkeit bei der Kombination von einzelnen Emittern und Kosten. Selbst mit den vielversprechenden optischen Eigenschaften bleiben die Wettbewerbsvorteile von Quantenpunkt-Einzelphotonen-Quellen für einfache Prepare-and-Measure-Protokolle unklar, da erwartet wird, dass ausgereiftere kohärente Quellen weiterhin starke Vorteile in der Kommerzialisierung haben. Dennoch können Quantenpunkte auch als verschränkte Photonquellen, basierend auf Bi-Exciton–Exciton-Kaskaden, und zur Erzeugung von Cluster-Zuständen dienen. Die Fähigkeit, Photonen-Clusterzustände zu erzeugen, birgt das Potenzial für den Einsatz in vollphotonischen Quantenrepeatern.

Andere deterministische Emitter basieren auf organischen Molekülen, Defekte in zweidimensionalen (2D) Materialien, Farbzentren in Diamant und einzelnen Atome/Ionen. Jede Klasse weist ein individuelles Profil auf, aber im Allgemeinen bleiben ihre TRLs sehr niedrig (1-4) und weitere F&E-Aktivitäten sind erforderlich, um die realisierbaren Vorteile gegenüber ausgereifteren Technologien zu ermitteln. Molekülbasierte Quellen können hohe Reinheit und Effizienz erreichen und wurden in einem Proof-of-Concept für QKD demonstriert; leiden derzeit jedoch unter begrenzter Leistungsfähigkeit bei Raumtemperatur, Lichtbeständigkeit und der fehlenden Fähigkeit im Telekommunikationsband zu emittieren. 2D-Materialien, einschließlich hBN (hexagonales Bornitrid) und TMDCs (Übergangsmetall-Dichalkogenide), bieten hohe Ein- bzw. Auskopplungseffizienzen und in manchen Fällen den Betrieb bei Raumtemperatur. QKD-Demonstrationen existieren, doch Ununterscheidbarkeit, Lichtbeständigkeit, Wellenlängen im Telekommunikationsspektrum und Reproduzierbarkeit bleiben offene Herausforderungen. Farbzentren im Diamant bieten lange Spin-Kohärenz und starke mechanische/chemische Stabilität, stehen jedoch vor Herausforderungen bei der Photonenauskopplungseffizienz, Emissionswellenlänge und Reproduzierbarkeit; sie können vielversprechend für Quantenspeicher für Quantenrepeater sein. Gefangene Atome und Ionen liefern hoch-ununterscheidbare Photonen und lange Kohärenz, allerdings werden komplexe Fallen benötigt, sowie die Notwendigkeit von Wellenlängen-Konvertierung. Sie sind möglicherweise relevant für Anwendungen jenseits von QKD wie für Quantenrepeater und Quantenspeicher.

Zukünftige Perspektiven

Laserbasierte Quellen werden voraussichtlich für viele DV- und CV-QKD-Protokolle die Grundlage bilden, aufgrund ihrer hohen Reife, der praktischen Verwendbarkeit und den vergleichsweise niedrigen Kosten. SPDC-Quellen bilden aktuell – und in absehbarer Zukunft – die Grundlage für QKD-Systeme, die Protokolle auf Basis von Verschränkung nutzen, mit künftigen Performanzentwicklungen durch Integration und Multiplexing. Das Hauptversprechen von FWM liegt in der photonischen Integration, falls Rausch- und Effizienzprobleme aufgelöst werden können. Quantenpunkte könnten für fortgeschrittene DV-Protokolle wettbewerbsfähig werden und attraktiv für Quantenrepeater sein – Verbesserungspotenzial findet sich bei Fertigung, Betriebstemperatur, Ununterscheidbarkeit und Kosten. Andere deterministische Quellen befinden sich in früheren Entwicklungsphasen, mit Potenzial für Nischen oder auf langfristigen Zeitskalen, insbesondere als Komponenten für Quanten-Netzwerke (z. B. Quantenspeicher). Die Gewährleistung der Kommunikationssicherheit unter Berücksichtigung der praktischen Implementierung mit Blick auf Seitenkanal-Angriffe ist eine zentrale Herausforderung für Prepare-and-Measure-Protokolle. Weitere zentrale Herausforderungen über alle Ansätze hinweg sind die Spezifikation von Komponenten und Systemen, photonisch-integrierte Lösungen für kompakte und robuste Geräte, das Ausbalancieren der Trade-Offs von probabilistischen Quellen und die Optimierung des Gesamtsystems mit Blick auf die Spezifikationen der Detektoren.

Schlussfolgerungen

Lichtquellen beeinflussen zentral die Leistungsfähigkeit des Quantenschlüsselaustausches, die Protokollwahl und das Level der erreichbaren Kommunikationssicherheit. Etablierte Lasertechnologien bilden die Grundlage für aktuelle Prepare-and-Measure DV- und CV-Systeme, während SPDC den Stand der Technik für kommerziell verfügbare QKD-Systeme auf Basis von Verschränkungsprotokollen bildet. FWM weist eine geringere technologische Reife als SPDC auf, dürfte aber zu Entwicklungspfaden von verschränkungsbasierter QKD und Integrationsperspektiven beitragen und profitiert dabei von der breiteren Materialbasis. Quantenpunkte bieten deterministische Emission und versprechen die Generation von Cluster-Zuständen für künftige Anwendungen, benötigen jedoch weitere Fortschritte in der Leistungsfähigkeit im Telekommunikationsspektrum, bei der Betriebstemperatur, in der Fertigungsausbeute und den Kosten, bevor eine breite Einführung erfolgen kann.

Andere deterministische Quellen zeigen vielversprechende Eigenschaften für spezielle Anwendungen, insbesondere in Quantenrepeatern. Insgesamt hängt der Fortschritt davon ab, das Leistungsprofil der Quellen mit Detektor-Leistungen abzustimmen, Implementierungs-Schwachstellen zu identifizieren und zu adressieren sowie Zertifizierung und Integration voranzutreiben, um skalierbare, zuverlässige Anwendungen zu ermöglichen.

Executive Summary

This report surveys light-source technologies for quantum communication, in particular, for quantum key distribution (QKD), assessing their innovation potential and key challenges for current and future use cases. Since information in QKD is encoded in the quantum states of photons, light sources are critical components of QKD systems and can influence their specifications. The study covers coherent sources for discrete-variable QKD (DV-QKD) and continuous-variable QKD (CV-QKD), photon-pair generation via spontaneous parametric down-conversion (SPDC) and four-wave mixing (FWM), quantum dot sources, and other deterministic emitters.

While commercially available prepare-and-measure QKD systems largely rely on mature laser technologies, photon-pair generation in nonlinear media is an attractive alternative, mostly commercialized in entanglement-based QKD systems. Additional options, deterministic sources such as quantum dots and other emitters, could offer distinct capabilities for QKD systems, in particular for QKD with advanced protocols, entanglement-based QKD and quantum networks in the future.

Our study combines desk research and expert interviews to explore different light source technologies, their key performance indicators (KPIs), applications in QKD, technology readiness level (TRL), and pathways towards industrialization. An online workshop with stakeholders from academia, research organizations, and industry was held to validate our findings and discuss KPIs, challenges, and prospective developments.

Performance requirements for light sources intended for use in quantum communication

The report introduces key performance indicators that shape QKD performance for different types of QKD protocols. Operation at room temperature with high repetition rates and robustness are beneficial for all approaches. The emission wavelength must be suitable for the transmission medium and the detector. Telecom O- and C-bands are preferred in fiber; free-space links commonly operate around the visible/near-infrared or at telecom wavelengths. Low cost and high technical maturity are crucial for enabling a broad commercialization. In DV-QKD protocols good photon purity is important to ensure the security of the protocol, even though mitigation strategies are well-established in laser-based prepare-and-measure QKD. According to the types of protocols, additional requirements should be considered, (e.g., indistinguishability for measurement-device-independent QKD (MDI-QKD), entanglement fidelity for entanglement-based protocols).

The effective key rate depends on the source and its coupling and extraction efficiency, channel loss, detector performance, and required post-processing. Deterministic photon generation offers promising advantages not achievable with probabilistic processes. The parameters related to use cases such as number of parties, distance, traffic volume, and medium (fiber, free-space, satellite) can influence source selection and system design, including the degrees of freedom used to encode quantum information.

Overview of different light source technologies

Weak coherent lasers for DV-QKD are widely used and mature. Implementations employ distributed feedback (DFB) lasers, vertical-cavity surface emitting laser (VCSEL), and edge-emitting lasers with gain switching, optical injection locking and external modulation/attenuation, enabling protocols such as BB84, MDI-QKD, and TF-QKD with decoy states to increase key rates in the presence of multiphoton pulses. Such senders operate at room temperature and can be implemented for prices of a few thousand euros. Key challenges that remain include lowering costs while enabling wave-

length tunability in telecom bands, residual phase/intensity correlations at high speeds, reproducibility of VCSEL properties, lack of component certification, and the need for integrated photonics to combine functions.

Coherent lasers for CV-QKD require low relative-intensity noise, typically operate in the telecom C-band at room temperature and are at high TRL. Although modulation bandwidths can be high, practical performance is often limited by detector bandwidths and the speed of post-processing. Photonic integration of on-chip lasers is progressing, but further improvements are required in linewidth and frequency stability, wavelength tunability and integrated solutions; typical device costs are in the low-thousand-euro range.

Photon-pair sources in nonlinear media provide entanglement for respective QKD protocols and beyond. SPDC is room-temperature capable, supports emission in the range of 780–1550 nm, and achieves high entanglement fidelity and indistinguishability with typical linewidths of a few nanometers; heralded single-photon purity and generation rate are intrinsically coupled by the probabilistic process. Current systems are at high TRL, with ongoing developments around extraction/coupling efficiency, multiplexing, and photonic integration. FWM offers a broad material base and photonic integration pathways (fibers, silicon-based platforms, lithium niobate, aluminum nitride) but faces lower nonlinearity, Raman/Kerr noise that may necessitate cryogenic suppression, longer interaction lengths, and a lower maturity level than SPDC.

Quantum dot sources provide deterministic emission. Single-photon sources demonstrate high purity and indistinguishability at cryogenic temperatures across a broad wavelength range. Some systems can emit even at telecom bands, although such quantum dots often exhibit limited performance in other KPIs. Typical generation rates are in the tens to hundreds of mega-hertz. Commercial systems exist but remain expensive, with TRL estimates below laser and SPDC-based solutions. Key challenges include reproducible fabrication and yield, operating temperature, good photon quality at telecom wavelengths, indistinguishability for different sources, and cost. Even with their attractive optical properties, the competitive advantages of quantum dot single-photon sources for simple prepare-and-measure protocols are yet unclear, as it is anticipated that more mature coherent sources will continue to be highly competitive. However, quantum dots can also serve as entangled-photon sources based on biexciton–exciton cascades and cluster-state generation. Their unique capability to generate photonic cluster states highlights the potential for their use in all-photonic repeaters.

Other deterministic emitters include organic molecules, defects in two-dimensional (2D) materials, color centers in diamond, and single atoms/ions. Each class exhibits unique properties, but in general, their TRLs remain very low (1-4) and further R&D activities are required to clarify their advantages over more mature technologies. Molecule-based sources can achieve high purity and efficiency and a proof-of-concept QKD has been demonstrated with this type of source; however, they continue to face constraints in room temperature performance, photostability and telecom-band emission. 2D materials, including hBN (hexagonal boron nitride) and TMDCs (transition metal dichalcogenide monolayers), offer high outcoupling and, in some cases, room-temperature operation. Early QKD demonstrations exist, though indistinguishability, photostability, telecom coverage, and reproducibility are still unresolved. Color centers in diamond provide long spin coherence and strong mechanical/chemical stability, but face challenges in photon-extraction efficiency, emission wavelength and reproducibility; they can be promising for quantum memories for quantum repeaters. Trapped atoms and ions deliver highly indistinguishable photons and long coherence, albeit with complex trapping infrastructure and the need for wavelength conversion, with potential relevance for beyond-QKD applications such as quantum repeaters and quantum memories.

Future perspectives

Laser-based sources are expected to remain foundational for most DV and CV-QKD protocols due to high maturity, practicality and comparatively low costs. SPDC sources are the foundation of current entanglement-based systems and are anticipated to continue doing so, with performance gains from integration and multiplexing. FWM's main promise lies in photonic integration if noise and efficiency challenges are addressed. Quantum dots could become competitive for advanced DV protocols and essential for quantum repeaters with the improvement in fabrication, operating temperature, indistinguishability and costs. Other deterministic sources are at earlier stages, with niche and longer-term potential, particularly in quantum networking components such as memories. Ensuring security against side-channel attacks is a crucial challenge for prepare-and-measure protocols. Further key challenges across all approaches include the specification of components and systems, the development of integrated photonic solutions for compact and robust devices, managing trade-offs in KPIs, and system-level co-optimization with detectors.

Conclusions

Light sources are central to QKD performance, protocol choice and security posture. Mature laser technologies enable current prepare-and-measure-based DV and CV systems, while SPDC is the state of the art of the solutions for commercially available entanglement-based QKD systems. FWM shows lower technological maturity than SPDC but is expected to contribute to entanglement pathways and integration prospects due to its broader material choice. Quantum dots offer deterministic emission and promise unique cluster-state capabilities in the future, but require advances in telecom performance, operating temperature, fabrication yields and cost before broad deployment. Other deterministic sources demonstrate attributes that support their use in specialized roles, especially in quantum repeaters. Overall progress depends on aligning source capabilities with detector performance, mitigating implementation vulnerabilities, and advancing certification and integration to support scalable, reliable deployments.

1 Introduction

The current development of quantum communication technologies is strongly driven by the emerging commercialization of quantum key distribution (QKD) solutions. QKD promises the secure establishment of cryptographic keys by exploiting the quantum nature of single photons (discrete-variable QKD; DV-QKD), i.e., the unclonability of photons, or electromagnetic waves (continuous-variable QKD; CV-QKD) (Schmaltz et al. 2024). In this context, the necessary light source technologies are a crucial component for QKD as a source of these optical quantum states.

QKD has become one of the more mature quantum technologies (QT) of the second generation of QT, with several QKD systems already being offered by industry actors. However, it is facing challenges related to anticipated market penetration in the coming years (Schmaltz et al. 2025). Numerous experiments, prototypes, and testbeds have successfully demonstrated QKD in real-world environments (for example, (Open European Quantum Key Distribution Testbed 2024; Goy et al. 2025)). Large-scale QKD infrastructures have been established in China (including QKD satellites) (Chen et al. 2021; Chen et al. 2025) and in South Korea (ID Quantique 2025), while commercialization efforts are well advanced also in Europe. The main technological and non-technological challenges for QKD solution providers lie in further maturing the technological approaches to demonstrate security against potential implementation attacks and in the subsequent certification and approval of the technologies (Schmaltz et al. 2025).

The generation of quantum states is a crucial process in QKD. The security of the QKD process depends on its performance and implementation of the system, and the achievable key rate can be influenced by the generation rate of the photon source of the QKD system, although the bottleneck for the key rate in commercially available systems mostly lie in detector-side limitations (Shirinzadeh et al. 2026). Moreover, the choice of light source technology and QKD protocol for the key exchange process are interdependent. The characteristics of the light sources are, therefore, critical for the performance of high-quality QKD systems. Furthermore, high-performance light sources are necessary for quantum repeaters, which could enable large-scale quantum networks connecting diverse quantum applications beyond QKD in the future (Sangouard and Zbinden 2012).

Although most commercially available QKD systems currently rely on mature technologies, there remains significant room for improvement and opportunities to adopt diverse emerging light-source technologies, especially for advanced QKD protocols. In this report, we discuss the following light sources that are most relevant for quantum communication technologies and especially QKD:

- Coherent sources (weak coherent lasers for DV-QKD, coherent lasers for CV-QKD)
- Sources based on photon pair generation in nonlinear media (Spontaneous Parametric Down-Conversion and Four-Wave Mixing)
- Quantum dots and other deterministic sources

Our study is based on extensive literature research, numerous interviews with experts from science and industry and an expert workshop (section 2). An overview of the different technological approaches and key performance indicators for QKD light sources are provided in section 3. The various types of light sources are analyzed in terms of their specifications for QKD systems (section 4) and compared based on their future innovation potential (section 5).

2 Methods

The following methods were used to gather information on different light source technologies, their applications in QKD, technology readiness, and paths towards industrialization. The central goal of the study was to combine different perspectives to create a coherent and nuanced discussion of the key aspects of the different approaches.

Desk research

As a first step, preliminary qualitative and quantitative information on various technologies studied in this report was collected from scientific literature. The primary objective of the desk research was to identify promising light-source technologies and to classify their technical characteristics. The selected technologies were then reviewed based on their application scenarios in QKD, technology readiness level (TRL), as well as their advantages and shortcomings. Commercial products of QKD systems and light sources were identified and analyzed to assess the current state of commercialization. The information gathered in this step was validated and further elaborated by the subsequent steps of the adopted methodology. A review of relevant literature and technical reports was continued in parallel to track the latest research and industry developments.

Expert interviews

More than 30 expert interviews were conducted to identify focus technologies and important key performance indicators (KPIs). The interviews gradually focused on the technical characteristics of the selected technologies, their TRL, applications, market and industry barriers, as well as pathways towards industrialization of products. Input for the discussion workshop was gathered during the interviews. This allowed target stakeholders from research and industry to become familiar with the objectives of the study and enabled deeper analyses to be conducted during the workshop. At the same time, the interviews enabled the project team to identify relevant stakeholders for the targeted workshop sessions based on their expertise profiles.

Workshop

A discussion workshop was held with experts from universities, research and technology organizations, and industries. In the online workshop, participants discussed various aspects of current KPIs and challenges and potential future developments for different light-source technologies. By combining different discussion formats, a high involvement of the invited stakeholders was achieved. The results of the workshop verified and complemented the information gathered in the previous steps of this methodology.

Acknowledgement to experts

We would like to sincerely thank all the experts who provided us with valuable insights throughout the process described above. We also wish to thank our colleagues in the SQuaD consortium for their continuous support, in particular the colleagues from the Physikalisch-Technische Bundesanstalt (PTB), especially Prof. Dr. Stefan Kück, Dr. Alí Angulo, and Dr. Sebastian Koke.

3 Light Sources and their Use in Quantum Communication

Many quantum communication (QCom) technologies require light sources with specific requirements. This section introduces the key performance indicators (KPIs) for specifying light sources for quantum communication and in particular QKD and discusses the requirements for different QKD protocols and application scenarios.

3.1 Key Performance Indicators

In the following, definitions of key characteristics of light sources that significantly influence the performance in QKD applications are provided. Extensive discussions of SPS characteristics can be found in publications from the NIST (Bienfang et al. 2023) or the PTB (Kück 2020).

As DV-QKD protocols rely on the non-cloning theorem of quantum particles, the presence of two photons with identical quantum states in the same time bin gives an eavesdropper an opportunity to obtain key information without being detected, if no countermeasures are implemented. The **purity of the photon pulses** is often described by using the second-order correlation function $g^{(2)}$. Perfect purity corresponds to $g^{(2)}(0)=0$, and in general a high photon purity corresponds to a low $g^{(2)}(0)$ value. The experimental confirmation of the photon purity can be realized by using a Hanbury-Brown-Twiss-interferometer (Brown et al. 1957).

The most relevant system-level KPI of QKD systems is the **effective key rate.** This indicator cannot be discussed straightforwardly, isolated from the other components of the QKD system. For DV-QKD protocols, the key rate is strongly connected to the number of single-photon pulses emitted and detected. Therefore, the number of usable single photons the light source can generate per time unit is crucial. However, care is needed on the exact specification of the number of photons per time unit: For example, the number of photons or photon pairs generated in nonlinear crystals or quantum dots is typically greater than the number of photons extracted from the source, collected by the subsequent optics, or coupled into optical fibers. The source type can influence extraction and coupling efficiency, which should always be considered when discussing the **photon generation rate** of the light source. Furthermore, the detection systems can limit the achievable key rate, imposing an upper limit on the beneficial photon generation rate of the source. Finally, the key rate is affected by generally required post-processing and security enhancement procedures, which shorten the length of the usable key. The effective key rate is usually strongly limited by transmission loss, with typical losses of 0.2 dB on a length of one kilometer of fiber (Hiskett et al. 2006). Atmospheric loss is lower, but beam divergence must also be taken into account for free-space QKD.

In pulsed implementations, the number of usable single photons generated per unit time is often specified through the **pulse repetition rate** of the source, together with the **mean photon number per pulse** (Paraïso et al. 2021; Grünenfelder et al. 2020). The **modulation bandwidth** is an important characteristic in laser sources, which are the most practically relevant light sources for QKD, and directly linked to the maximum pulse repetition rate. It describes how quickly the optical output of the source can change when the electrical drive signal is varied (Paraïso et al. 2021). A larger modulation bandwidth means that the source can be switched on and off, or between different output levels, within shorter time intervals. This allows the generation of short optical pulses and fast changes between encoded quantum states in QKD transmitters, with demonstrated operation in the GHz range (Grünenfelder et al. 2020; Paraïso et al. 2021).

For CV-QKD, where quantum information is encoded in coherent states of light, an analogous system-level quantity is the **symbol rate**, which describes how many quantum symbols (modulated coherent states) are prepared and transmitted per second. In typical implementations based on a continuous-wave laser and external modulators, this symbol rate is a key performance indicator for the coherent light-source, because together with the mean photon number or modulation variance per symbol it sets the rate at which quantum states are launched into the channel and thus contributes directly to the raw key rate (Hajomer et al. 2024a). In contrast to DV-QKD, in many CV-QKD implementations, the laser is operated in continuous-wave mode and external modulators are used, so the relevant speed limit is given mainly by the bandwidth of these modulators and the detectors rather than by the modulation bandwidth of the laser itself.

The definition of **transmission frequencies** plays a central role in classical communication networks, as the choice of frequency can offer different advantages and disadvantages. Similarly, the choice of wavelength of the emitted photons influences the capabilities of the photon source and the respective QKD system. For fiber-based QKD links, wavelengths in the telecom O-band or C-band are desired. The telecom C-band corresponds to wavelengths around 1550 nm exhibits the lowest loss in state-of-the-art optical fibers (FL-E-admin 2023). Although free-space links have also been demonstrated within the telecom C-band, they are often implemented with wavelengths at around 780-850 nm, because the atmosphere is mostly transparent in this range and low-cost silicon single-photon avalanche diode detectors can be utilized (Kržič et al. 2023; Shirinzadeh et al. 2026). The ability to provide a broad range of emission frequency with a single-photon source, i.e., a broad bandwidth, is therefore improving the source’s versatility.

The **linewidth** describes the broadness of the emission peak at the target wavelength, i.e., the variation of wavelengths in the emitted signal. A narrow linewidth in the range of few nm is often desired to minimize losses. On the other hand, a broad linewidth could be exploited for multiplexing approaches, when multiple emitted frequencies are being used. However, this is connected to a loss of signal, due to the frequency filters required. In either way, good stability of the emitted frequency with respect to environmental conditions and fluctuations over time is desired. This robustness is generally desirable for all relevant performance parameters, as operating conditions can vary strongly across use cases. While laboratories or controlled spaces in industrial applications can provide dust-free and temperature-stabilized environments, this is not guaranteed in more practical scenarios.

Furthermore, additional features can enhance the capabilities of the photon source. Most discussed devices rely on probabilistic photon emissions, i.e., the likelihood of emission at a point in time is defined, but emission cannot be triggered purposely at an exact moment in time. Deterministic sources, by contrast, promise on-demand single photon emission. In this case, the uncertainty about timing becomes a relevant parameter, i.e., the **timing jitter** of the source.

Indistinguishability of emitted photons is required to achieve two-photon interference and high-fidelity entanglement. It is commonly quantified by the visibility of the Hong-Ou-Mandel (HOM) interference in percent (Wang et al. 2017a). HOM interference is a fundamental quantum phenomenon that occurs when two indistinguishable photons are incident on a beamsplitter. In this interaction, the photons exhibit quantum interference, resulting in a higher probability of exiting together from one output port rather than splitting between the two output ports (Hong et al. 1987; Fedrizzi et al. 2009). As this HOM visibility involves photon interference, it is a relevant parameter for measurement-device-independent-QKD (MDI-QKD; will be explained in the next section) protocols. For photon pair sources, the heralding efficiency describes the ratio of coincidences on the detector to single counts (D N Klyshko 1980), influencing the usable key rate. It depends strongly on the optical set up, transmission losses, and the respective detector efficiencies, and less on the performance of the source itself.

While technical performance is essential for commercialization, the **price** of the final product is central for large-scale market adoption. Cost is therefore another KPI to be discussed in the following. Especially at early stages, costs are expected to be significantly higher than after upscaling and are likely to be highly dynamic. Nevertheless, comparing the costs of different technologies or components offers a valuable insight into the remaining challenges for future developments.

Finally, the **technology readiness** describes the maturity of the technology and will be discussed in the following. In Europe, the Technology Readiness Levels (TRLs) are widely used. Their definition is based on the original concept by NASA, describing the readiness of space technologies. In their more generalized definition, they categorize whether a technology is still in the concept phase (TRL 1-3), development phase (TRL 4-6), or deployment phase (TRL 7-9). For precise definitions in the European contexts (i.e., the European Commission projects), the reader is referred to (EURAXESS 2025). Although TRLs are widely used, the framework has its flaws, as technological development is rarely straightforward or isolated.

To make these KPIs comparable and reliable, it is also emphasized that the development of metrological characterization of single-photon and entangled-photon-pair sources and their traceable measurement is important (Kück 2020; Chunnilall et al. 2014). In particular, a good understanding for all components in large-scale QKD networks is required to enable efficient and reliable implementation. This includes the accurate determination of optical transitions, wavelengths, and temporal precision, as well as the proper calibration of monitoring photodiodes in the sender unit used to estimate the emitted mean photon number per pulse. However, achieving accurate and traceable measurements at the single-photon level remains highly challenging.

To address these challenges, advances in metrological technologies are required. Innovation in this field in particular lies in improving transmission links and enabling high-precision synchronization of time and frequency signals to ensure reliable and low-error communication (Physikalisch-Technische Bundesanstalt 2026). In addition, characterization of emerging light sources to ensure precision and traceability is expected to be in high demand, such as for quantum dots (Georgieva et al. 2024) and color centers in diamond (Christinck et al. 2024). Metrological development can also contribute to performance optimization. For example, recently, BB84 with quantum-dot-based single photon sources and entanglement-based QKD have been demonstrated over a 78 km optical fiber link between Hannover and Braunschweig, in which characterization and optimization of the QKD systems was carried out to improve the synchronization (Yang et al. 2024; Hreibi et al. 2025).

3.2 Requirements for Quantum Key Distribution

The most relevant properties of a QKD system are the security level provided, the key rate achieved as a function of distance, and the associated costs. Additional characteristics, such as robustness and adaptability, should also be considered.

Assessing and comparing the security of QKD systems is not straightforward, as it depends on the protocol executed by the system, the implementation within the network infrastructure and many more aspects. While experts mostly agree that embedding trusted nodes into the network opens additional attack surfaces and thus could decrease the overall security, their estimates of the magnitude of this impact vary significantly. Similarly, views differ regarding the impact of the implemented protocol on systems security, most prominently the comparison of prepare-and-measure protocols with decoy states and entanglement-based protocols, among the consulted experts. In general, many experts working on prepare-and-measure protocols expect that similar or equal security levels can be achieved, while experts focusing on entanglement-based protocols argue that the reduced attack surface along the path between emitter and receiver, present in entanglement-based protocols, provides an overall security advantage that cannot be achieved by other protocols.

As different light source technologies enable different protocols, this ambiguity directly affects the discussion of security comparison among the approaches discussed below. Further aspects, such as the likelihood of multiphoton emission, which can open the door for photon number splitting attacks, will be introduced as well.

3.2.1 Discrete Variable Quantum Key Distribution

The light source requirements for DV-QKD are summarized in Table 1. The emission wavelength depends on the communication channel. For fiber-based communication, C-band or O-band wavelength are typically used, as fiber attenuation is lowest in these ranges. High repetition rates, highly directional emission, and room-temperature operation are additional beneficial parameters for DV-QKD photon sources.

Prepare-and-measure QKD

Prepare-and-measure quantum key distribution (P&M-QKD) are approaches of QKD in which quantum states are prepared on single photons. These prepared photons are sent from a sender (often referred to as Alice) to a receiver (often referred to as Bob), who analyzes the quantum states. Upon exchange of information on the bases used for encoding and decoding, Alice and Bob obtain a secret key that can then be used to encrypt the actual message. Interception by an eavesdropper introduces an increase in errors that Alice and Bob can detect. One of the best known and most widely used protocols in this category is the BB84 protocol, which was proposed by Bennett and Brassard in 1984 (Bennett and Brassard 2014).

Different degrees of freedom, such as polarization, energy, or timing, can be used to establish random key bits. Approaches toward high-dimensional QKD aim to increase the number of key bits established by each photon by exploiting multiple degrees of freedom at the same time or by increasing the number of states (e.g., the number of time bins) utilized in a single degree of freedom.

In contrast to BB84, measurement-device-independent QKD (MDI-QKD) equips Alice and Bob with photon sources that simultaneously send prepared photons to a centrally located detector that performs a Bell-state measurement on the two photons and reports the outcome. Since the Bell-state measurement only reveals information about the correlation between Alice’s and Bob’s encoded bits, without disclosing the bit values themselves, the protocol is inherently robust to detector-side vulnerabilities. Recently, a scheme called twin-field QKD (TF-QKD), which uses a setup similar to MDI-QKD but transmits optical fields instead of single photons, has demonstrated communication distances exceeding 1000 km, however, at very low key rates (Liu et al. 2023).

Attenuated lasers can be used as photon sources for these P&M-QKD protocols. Laser pulses are typically attenuated so that each pulse contains, on average, less than one photon. However, since attenuation is a probabilistic process, each pulse can have zero, one, or multiple photons. The multiphoton fraction enables photon-number-splitting attacks; therefore, state-of-the-art P&M-QKD employs decoy-state protocols to mitigate this risk.

A narrow linewidth is desirable, but not strictly necessary for BB84 protocols. High single photon purity is desired to reduce the risk of side-channel attacks, but mitigation strategies can be implemented to reduce the relevance of this parameter. Indistinguishability of photons is relevant for protocols that rely on two-photon interference. It is therefore not required for common prepare-and-measure protocols, such as BB84, but should be sufficiently high for MDI-QKD (Simon et al. 2018).

Table 1: Selection of light source requirements for DV-QKD

Specification	Requirements on light source
Emission range (nm)	Depending on communication channel. For fiber: ideally telecom C-band (1530-1565nm) or O-band (1260-1360nm) Free-space: 850nm or 1550nm
Linewidth (kHz)	A narrow linewidth is desirable, but not strictly necessary for BB84.
Photon purity $g^{(2)}(0)$	The higher the purity the better; but low purity, i.e., high $g^{(2)}(0)$, can be mitigated with P&M-QKD decoy state protocols.
Operating temperature (K)	Room temperature operation desired.
Repetition rate	Ideally GHz
Indistinguishability (HOM visibility (%))	Not needed for BB84. For MDI-QKD, higher indistinguishability is essential. For entanglement-based protocols well above 90% are desired.
Emission direction	Highly directional, fiber-coupled.
Sensitivity to noise/robustness	Ideally highly stable and robust. Low maintenance in operation is strongly required.
Price	Max. few thousand €.

Entanglement-based QKD

Entanglement-based QKD uses entangled photon pairs, in which the quantum state of one photon and thus the measurement result thereof is correlated with that of the other, to securely exchange secret keys. In the Ekert-91 protocol, an entangled-photon pair source (EPS) sends a photon pair to Alice and Bob, each of whom receives and measures their photon using a randomly selected basis. Due to the properties of entanglement, if Alice and Bob choose the same basis, their measurement outcomes will be correlated. Eavesdropping attempts can be detected by examining the degree of entanglement, as any such interference reduces or disrupts correlations. Thus, to ensure reliable eavesdropping detection, the entanglement quality of photons is critical. To achieve high entanglement fidelities, the emitted photon pairs must exhibit high levels of indistinguishability between different pairs. Fidelities greater than 90% are desired to guarantee high security and reasonable key rates.

3.2.2 Continuous Variable Quantum Key Distribution

Continuous variable QKD (CV-QKD) uses continuous coherent light, onto which the quantum information is encoded via phase and amplitude modulation techniques. The receiver uses a homodyne or heterodyne detector to read out the information from the received signal. This technique can be implemented using largely mature and commercially available telecom components.

Due to the different nature of the protocols between DV-QKD and CV-QKD, the requirements on the light sources are inherently different. CV-QKD typically utilizes bright and coherent laser sources that operate at telecom wavelengths (C-band or O-band). High coherence and spectral purity are essential for ensuring reliable modulation and detection of the quadratures of the electric field, i.e., the amplitude and phase, which are used to encode the key bits. To this end, stable intensity and phase characteristics are required. Operation at room temperature and large modulation frequencies are beneficial for realizing practical QKD implementation. Low-cost components are crucial to maintain competitiveness with DV-QKD setups. An overview of the key performance requirements is given in Table 2.

For CV-QKD, the laser source should ideally have a narrow linewidth below 20 kHz (Zhang et al. 2024), although expert interviews suggest that linewidths below 100 kHz are commonly used in practice. The linewidth is a crucial measure of the spectral purity of the laser output, indicating the range of wavelengths (or frequencies) over which the laser emits light. Additionally, the laser must exhibit low relative intensity noise to ensure optimal performance.

Table 2: Selection of light source requirements for CV-QKD

Specification	Requirements on light sources
Emission range	Telecom wavelengths (C-band, O-band).
Linewidth (kHz)	Narrow linewidth preferred (kHz range), but stability is equally important. Other noise sources dominate beyond a certain point.
Modulation frequency	Modulation in the order of tens of MHz, done by external modulator. Key rate is often limited rather by the speed of post-processing.
Operating temperature (K)	Room temperature.
Sensitivity to noise/robustness	High reliability and robustness required.
Price	It should be less than 3k€ per unit.
Others	European supply chain is a challenge. Photonic integration is attractive for future.

3.3 General Aspects

As outlined above, the choice of QKD system technology and photon source depends strongly on the desired performance specifications for specific applications. The following aspects commonly recur in discussion of which source is best for which system, or which protocol is best for which application.

While quantum communication applications are potentially diverse, the relevant use cases for QKD are all directed toward securing communications. The aspects that the most strongly influence the choice of technology and light sources are the number of parties, the distance between the parties, the volume of data transmitted (to be secured), and the available transmission path, which is again connected to the aforementioned distance between sender(s) and recipient(s).

Currently most QKD activities consider the simplest example of one sender and one recipient —a quantum secured point-to-point link. Network topologies that go beyond, involving multiple parties in different network structures (e.g., star-shaped networks based on a central node), generally require a more complex implementation and integration of the quantum channel in the classical network structure. The ability of QKD systems to be implemented in QKD networks is crucial for the anticipated market penetration.

The most prominent and easy-to-implement transmission medium is optical fiber. Compared to other approaches, it provides reasonably good control over distortions and noise and enables connecting users beyond line of sight. Nevertheless, signal loss is problematic, as low photon numbers are crucial in most protocols. Most DV-QKD schemes are currently limited to distances of up to 100 km. Other approaches are based on optical free-space links from one ground station to another. While these approaches eliminate coupling into fiber, they are exposed to atmospheric distortions and require a free line of sight. Finally, satellite-based QKD links are considered most challenging but highly promising, as they provide the possibility of bridging large distances. Depending on the implementation, the photon source can be located at a ground station or within a satellite. The latter obviously imposes additional requirements on the robustness and operability of the light source. Furthermore, depending on the chosen transmission path, parameters such as the desired emission wavelength, coupling/extraction efficiency, and robustness to certain environmental conditions provided by the light source within the QKD system play different roles.

Finally, the key can be implemented in a different property or degree of freedom of the photons. In many DV-QKD schemes, for example, the key is derived from the (randomly) different polarization of the photons. Similarly, other degrees of freedom can be used, such as the relative time with respect to a local oscillator or shifts in photon frequency. In CV-QKD the quadrature of the electric field is commonly used, corresponding to small changes in amplitude and phase of two continuous waves. The choice of photon sources directly defines what degrees of freedom can be utilized and what protocols can be realized by the QKD system.

The close interrelation between protocols, transmission paths, and network structure and the desired performance of the QKD system—and, therefore, its light source(s) —limits the comparability of different light sources, as discussed in section 5.

4 Light Source Technologies

In this section we provide an overview of the most relevant technological differences among the various types of photon sources for QKD. To this end, we introduce and discuss KPIs that encompass both technical and non-technical metrics, thereby effectively capturing the techno-economic "performance" of each device. As light sources are in this context a component technology, the assessment of their performance is strongly linked to the desired capabilities of the QKD system.

4.1 Coherent Sources

Lasers are a crucial component for all photon generation processes for QKD. Their use as a primary light source in DV- and CV-QKD protocols will be discussed in this section.

4.1.1 Weak Coherent Lasers for DV-QKD

Description of technology

The development of reliable single-photon sources for DV-QKD has been a significant challenge. While ideal single-photon sources provide the highest level of security, their practical implementations often face technological hurdles, including complexity, cost, and efficiency. As a result, researchers have turned to semiconductor lasers as a viable alternative. Among these, weak coherent lasers have emerged as a practical solution widely adopted in most QKD systems.

Laser source preparation

The use of weak coherent lasers in DV-QKD systems requires careful consideration of the laser type and modulation techniques. Weak coherent lasers can operate in either continuous-wave (CW) mode or pulsed mode. In fiber-optic DV-QKD setups, the so-called weak coherent pulses (WCPs) that usually emit at 1550 nm are standard. In DV-QKD, pulsed lasers are often preferred due to their ability to produce discrete quantum states that can be used for encoding information.

WCPs can be generated by attenuating the output of semiconductor lasers, resulting in a probabilistic emission of photons that approximates single-photon behavior. By carefully adjusting the attenuation to achieve a mean photon number (μ) of less than one, typically around 0.1, the likelihood of multiple photons being emitted in a single pulse is minimized, although the probability of emitting multiple photons is not zero. This feature significantly reduces the risk of photon number splitting attacks, which occur when an eavesdropper intercepts and measures photons from multiphoton pulses. In such cases, the attacker could split off a photon to gain information about the key while allowing the remaining photons to continue to the legitimate receiver. By using WCPs with $\mu \ll 1$, the probability of emitting multiple photons can be sufficiently low, making it more challenging for eavesdroppers to exploit this vulnerability. However, the non-zero probability of multiple-photon emissions still poses a risk, necessitating the implementation of additional security measures to safeguard against potential attacks (Jain et al. 2020).

General implementation of WCPs

The implementation of WCPs involves a laser module capable of generating narrow optical pulses at high repetition rates. The laser output is heavily attenuated using neutral-density filters to ensure that the average number of photons per pulse remains below one, thus enhancing the security of the transmitted key (Jain et al. 2020; Grünenfelder et al. 2020).

WCP sources can operate at high repetition rates, often reaching up to a few GHz (Grünenfelder et al. 2020), with pulse widths as narrow as 5 ns. Specialized pulse driver circuits control the operating conditions of the laser diode to ensure precise timing and amplitude of the emitted pulses. Additionally, temperature stabilization mechanisms are implemented to maintain consistent laser performance under varying environmental conditions, further enhancing the reliability of the WCP source (Jain et al. 2020).

Laser types used for WCPs

Common laser types employed in DV-QKD applications include semiconductor laser diodes such as distributed feedback (DFB) lasers (Paraïso et al. 2021), vertical-cavity surface emitting lasers (VCSELs), and conventional edge-emitting lasers (EELs) (Schranz and Udvary 2018).

DFB lasers are commonly used in QKD due to their high pulse performance, single-mode operation, and excellent modulation bandwidth. Their ability to maintain a high pulse repetition rate and extinction ratio makes them advantageous for optical transmission. However, a drawback is their limited wavelength tunability, which often necessitates an external cavity, increasing the size of the laser and reducing confinement and modulation bandwidth (Griffiths et al. 2023b).

VCSELs are usually preferred for free-space QKD (Paraïso et al. 2021) thanks to properties such as their high radiation tolerance (La Cruz et al. 2020). Moreover, VCSELs enable efficient and simplified coupling to optical fibers, making them also well-suited for fiber-based QKD applications (La Cruz et al. 2020; Schranz and Udvary 2018). Additionally, their compact size and energy efficiency, particularly in comparison to EELs (Schranz and Udvary 2018), further contribute to their suitability. However, a notable disadvantage of VCSELs is their susceptibility to polarization switching, which can introduce errors in protocols such as BB84 with polarization encoding (Schranz and Udvary 2018).

Modulation techniques

Amplitude-modulation techniques, such as gain switching, are commonly employed in DV-QKD to achieve pulsed operation. Gain switching involves periodically driving the laser above its lasing threshold to produce short optical pulses while keeping it below the threshold between pulses. This method allows for the generation of pulses with controlled timing and phase characteristics, which are essential for secure quantum communication (Lo et al. 2022).

The choice of additional modulation techniques can impact on the performance of DV-QKD systems. In some setups, additional amplitude and phase modulators may be utilized to create optical pulses tailored to the specific requirements of the QKD protocols that use either phase modulation, amplitude modulation, or a combination of both. The amplitude modulators can also be utilized to control the intensity of the pulses, allowing for precise shaping of the optical signals for encoding quantum information effectively. Phase modulators complement amplitude modulation by introducing specific phase shifts, which are crucial for encoding quantum information in different quantum states. The dual-modulation approach ensures that the generated optical pulses meet the requirements for robust quantum communication (Lopez Grande et al. 2021).

Additionally, variable optical attenuators can be employed to accurately regulate the average number of photons transmitted per signal pulse at the output of the sender (Alice). This feature enhances the system's adaptability to changing channel conditions by enabling dynamic adjustments to the signal intensity, ensuring optimal performance under varying transmission circumstances. (Lopez Grande et al. 2021; Lo et al. 2022)

Optical injection locking (OIL)

In many recent high-speed DV-QKD experiments, weak coherent lasers are implemented using optical injection locking (OIL). In this setup, a master laser provides the initial optical pulse, which is injected into a slave laser that generates the actual quantum states. The master laser is often gain-switched to create a pulse train at high repetition rates, while the slave laser is also modulated to produce shorter pulses. This configuration enables efficient phase encoding, where the quantum information is encoded in the relative phase between the emitted pulses. OIL has been widely applied to various QKD protocols, including BB84, coherent one-way QKD, MDI-QKD, and TF-QKD (Lo et al. 2022).

The experimental realization of gain-switched lasers in OIL configurations has demonstrated improvements in pulse timing jitter and modulation bandwidth, making them suitable for high-speed QKD applications. However, these setups often require extensive calibration and optimization to achieve performances comparable to state-of-the-art systems. The need for specialized knowledge and equipment to set up and maintain these systems poses a barrier to widespread commercialization.

Further optimization of laser performance

Recent advancements, such as the development of self-tuning transmitters utilizing machine-learning techniques like genetic algorithms, showcase the potential for optimizing laser parameters in real time. While these methods demonstrate promise for achieving optimal performance, they are still largely in the research phase and are not yet commonly available in commercial products. The complexity of the underlying laser dynamics necessitates careful tuning of parameters such as injection power, frequency detuning, and pulse timing, which remains a challenging task in practical QKD systems (Lo et al. 2022).

Protocol implementation

At the final transmitting stage, the QKD protocol needs to be implemented. For example, in a decoy-state BB84 DV-QKD implementation using the time-bin method, the transmitted optical signals consist of quantum signals, decoy-state signals, and reference signals. The quantum signals are created by two weak coherent light pulses, referred to as "early" and "late" time bins, which encode the secret key. These signals are prepared using two mutually unbiased bases: the Z basis, which includes the early and late states, and the X basis, which combines these states with specific phase differences (Lopez Grande et al. 2021).

Decoy states are interleaved with the quantum signals to help characterize the transmission of the quantum channel and ensure security. Electro-optic modulators generate these time-bin states, while optical attenuation is used to set the mean photon number. The resulting optical pulses must be timed precisely, allowing the receiver to accurately detect and interpret the information encoded in the quantum signals (Lopez Grande et al. 2021).

Composite weak-laser sources in QKD applications

Composite weak-laser sources are employed in QKD to simplify qubit encoding, especially when rapid encoding is challenging. In this setup, individual lasers are designated for each qubit state. For instance, in the polarization-encoded BB84 protocol, four lasers emitting light at -45º, 0º, 45º, and 90º polarizations can be utilized.

These lasers are combined using a beam combiner, and their outputs are attenuated to ensure the desired intensity levels. When an external trigger is received, one laser is activated based on the input signal, enabling precise selection of the emitted qubit state. To maintain indistinguishability among the emitted photons, it is essential that each laser exhibits identical properties, including wavelength, spectral profile, and temporal profile (ETSI GR QKD 003 2018).

KPIs

The KPIs for weak laser sources used in DV-QKD are shown in Table 3. Currently, the emission range can be chosen flexibly, primarily utilizing telecom bands, while some QKD setups may require stable and tunable lasers that are yet more costly. Indistinguishability becomes significant when using composite laser sources or MDI-QKD protocols (Paraïso et al. 2021), although it is not critical for standard BB84 implementations.

The modulation bandwidth has been reported to reach around 10 GHz for some commercial laser diodes (Paraïso et al. 2021). The pulse repetition rate, reported to reach a few GHz (Grünenfelder et al. 2020), reflects the repetition rate at which the laser emits pulses, which is important for maintaining high-speed communication. In practice, the pulse repetition rate is usually lower than the maximum modulation speed of the source. Other components, especially detectors, electronics, and the transmission channel, cannot reliably operate at the highest speeds without introducing errors or distortions. Additionally, sensitivity to noise is a critical factor. While OIL can enhance performance by mitigating relative intensity noise, maintaining a stable temperature through a thermoelectric cooling (TEC) controller is also essential for consistent operation, although it is less critical than temperature control for detectors.

Table 3: KPIs of weak laser sources used in DV-QKD

KPI	**Value**
TRL	9 (established technology)
Emission range	Tunable, typical telecom C- or O-band for fiber-based QKD[1]; for free-space QKD typically around 780 nm-850 nm.
Modulation bandwidth	Current commercial laser diodes commonly have a gain-switching bandwidth limit of approximately 10 GHz (Paraïso et al. 2021).
Pulse repetition rate	A few GHz (5 GHz reported in (Grünenfelder et al. 2020)).
Sensitivity to noise / robustness	Noise can be mitigated with OIL and use of TEC controller to keep temperature stable.
Indistinguishability (HOM visibility (%))	Not needed for BB84 in general (though indistinguishability is important for MDI-QKD protocols or BB84 with composite laser sources).
Emission direction	Highly directional, fiber-coupled.
Operating Temperature	Room temperature.
Price	Typical lasers cost a few thousand EUR, although additional components (e.g., electronics for modulation, controller) are required.

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[1] C-band (conventional): 1530–1565 nm, O-band (original): 1260–1360 nm (Paschotta 2005b)

State of research and industrialization

The laser technologies used in QKD have existed for a long time and have matured significantly, laying a solid foundation for their application in QKD systems. Ongoing research aims to enhance the performance of these coherent light sources, particularly through the integration of on-chip laser technologies.

Players in R&D and industry

The technology for coherent light sources used in QKD is well established, with numerous providers in the market. Companies and research institutions across North America, Europe, and East Asia are actively developing and supplying these technologies.

Capabilities, limitations and challenges

Key challenges in utilization of laser sources for DV-QKD include the need for cost-effective, wavelength-tunable sources, as well as issues related to phase and intensity correlations that could compromise security. In addition, the reproducibility of VCSELs with consistent properties and the lack of standardized certification for components pose significant challenges to be addressed in the future. Proposed solutions involve scaling technologies to meet market demands, along with the development of integrated photonic platforms that combine essential functionalities, enhancing user experience and cost-efficiency.

Wavelength tunability is important because it allows for the integration of QKD systems with classical communication networks, reducing the risk of noise and disturbances from nearby classical devices operating at similar wavelengths. This flexibility is crucial in large-scale commercial networks where multiple operators may not be able to adjust their wavelengths. However, achieving wavelength tunability is challenging due to the limitations of current single-mode lasers used in DV-QKD, which offer only a narrow range of wavelengths and require significant modifications to hardware for wavelength changes. Moreover, the structures that enable tunability can degrade laser performance in pulse-based communication systems, complicating their practical implementation (Griffiths et al. 2023a).

The linewidth of a laser source, which refers to the spectral width of the laser's emission, is another critical parameter affecting the transmission rate and the spectral stability of the quantum signals. A narrower linewidth corresponds to a longer coherence time[2] and a more stable output. However, achieving a narrow linewidth presents significant challenges due to the complexities involved in laser design. Additionally, while improving linewidth may enhance performance, it often increases the difficulty in maintaining accurate and continuous wavelength tuning, which makes implementing narrow-linewidth tunable lasers challenging (Çirkinoglu et al. 2022). The linewidth of a laser is strongly dependent on its type and can be minimized by optimizing laser design and reducing external noise influences. Additionally, optical feedback from high-finesse reference cavities can further reduce the linewidth of laser diodes (Paschotta 2005a). For DV-QKD, the laser linewidth is comparatively less critical. In contrast, for CV-QKD it becomes a key performance indicator, because a broader linewidth is associated with stronger phase fluctuations and a shorter coherence time, which in turn degrade the quality of the quadrature measurements and thus limit both the achievable key rate and transmission distance.

Frequency stability is another important feature that is closely related to laser linewidth. A stable optical frequency and a narrow linewidth are required to keep the output signal frequency well-

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[2] The coherence time of the laser source is approximately inversely related to its linewidth.

defined. Similar to linewidth reduction, optical feedback is a technique used among other various frequency stabilization methods introduced. Additionally, piezoelectric actuators are commonly employed for frequency adjustments in laser systems, allowing for effective stabilization and compensation of slow frequency drifts.

Application scenarios (now and in the future)

Currently, coherent lasers are widely used in DV-QKD systems to generate quantum signals, as they offer the best and most cost-effective solution currently available. In the near term, they will likely remain the preferred choice due to their established performance. For protocols such as BB84, coherent lasers may continue to be the best option, given their favorable performance-to-price ratio. However, for more advanced schemes such as MDI-QKD and TF-QKD, alternative solutions could emerge as superior in the future.

4.1.2 Coherent Lasers for CV-QKD

Description of technology

Coherent lasers are used as light source technology for CV-QKD. Laser signals used in CV-QKD can be either continuous wave (CW) or pulsed. CW lasers do not require amplitude modulation, which simplifies setup and operation. In contrast, pulsed lasers are advantageous for clearly distinguishing quantum states due to the time separation between pulses, making them particularly useful in the early stages of development (Zhang et al. 2024).

Modulation techniques

The process begins with a CW laser that generates a coherent beam of light, typically operating at a wavelength of typically 1550 nm with a narrow linewidth (Wang et al. 2018; Zhang et al. 2024). After the laser pulse is initiated, it is modulated to encode the quantum information. This modulation can be achieved by varying the amplitude or phase of the light.

In a CV-QKD setup using a pulsed laser, a continuous laser beam is directed into an electro-optic amplitude modulator. This modulator transforms the continuous laser output into discrete pulses, usually around a few ns in width. Pulse modulation is essential, as it serves to create the quantum states that will be sent to the receiver (Bob). The amplitude modulator adjusts the intensity of these pulses, while a phase modulator alters their phase, enabling the encoding of quantum information in both quadratures of phase space, specifically the X and P quadratures.

A typical modulation process uses Gaussian modulation, where the amplitudes of the coherent states follow a Gaussian distribution. This ensures that the encoded quantum information is robust against noise and interference. The mathematical representation of this modulation involves adjusting the amplitudes and phases so that the resulting quantum states maintain their coherent properties while effectively encoding the desired information (Zhang et al. 2024).

Implementation setup

A classical reference pulse is generated simultaneously with the quantum signal and serves as a phase reference for the signal pulse. This reference signal is important for synchronization and for helping to correct errors in the key reconciliation process.

To separate the modulated light into two paths—one for the signal and another for a reference pulse—a 50:50 beamsplitter is commonly used. The signal path carries the data-encoded pulses, while the reference path carries a pulse that serves as a phase reference. Time multiplexing is employed to delay the reference pulse, ensuring that it arrives at the receiver at the correct time relative to the signal pulses, thereby minimizing interference (Wang et al. 2018).

The intensity of the quantum signal is kept low to minimize the risk of eavesdropping and to preserve the quantum properties of the signal. The reference pulse must be strong enough to provide reliable phase information but not so strong as to introduce excess noise that could interfere with the quantum signal. (Wang et al. 2018; Zhang et al. 2024).

In addition to reference-signal intensity, modulation variance can significantly affect the system performance in CV-QKD. It quantifies how much the encoded quantum states can vary around their average value, i.e., the spread of these states, indicating the amount of uncertainty present in the signal. The modulation variance is adjusted to optimize the amount of information that can be encoded in each quantum state: a higher modulation variance allows for more information to be transmitted and can increase the secure key generation rate. However, if the variance is set too high, increased noise makes it more difficult to accurately distinguish between the states, ultimately reducing the security and efficiency of the key generation process. Modulation variance and intensities of light pulses can be adjusted by using variable optical attenuators in both the quantum-signal and reference paths (Wang et al. 2018).

The entire setup can be connected via a standard single-mode fiber, typical for telecommunications applications. This fiber transmits the encoded quantum states from Alice to Bob, where the system's performance is evaluated based on key rates achieved and noise levels measured (Zhang et al. 2024; Wang et al. 2018).

Detection

At the receiver's end, Bob performs homodyne or heterodyne detection to measure one of the quadratures of the signal pulse, which is essential for extracting the encoded quantum information. Heterodyne detection is used for the reference pulse, allowing measurement of both quadratures simultaneously. The dual-detection process is critical for compensating any phase drift that may occur during transmission, ensuring the quantum information remains intact (Wang et al. 2018).

The local oscillator (LO) is a critical component in this detection process, serving as a fixed phase reference for the measurements. However, phase noise is eventually inevitable in a CV-QKD system, as there is always an amount of phase mismatch between quantum signal and the LO (Zhang et al. 2024).

In traditional CV-QKD setups, the LO is sent from sender (Alice) to receiver (Bob). This approach can introduce challenges, such as contamination from scattered photons and potential eavesdropping attacks, including LO-fluctuation attacks. Attenuation of the LO during transmission can also limit detection effectiveness, potentially reducing the system's ability to accurately measure the quantum signal (Wang et al. 2018). A “real LO” or “local LO,” on the other hand, refers to a local oscillator generated by another laser source at the receiver's side rather than being transmitted from the sender. Using a real LO simplifies the setup but might introduce greater phase drift because the quantum signal and LO are generated from different sources (Zhang et al. 2024). Nevertheless, some experimental setups have demonstrated that generating the LO locally at Bob's side under certain setup can effectively mitigate these issues, allowing for high key rate as well as enhanced transmission distances and signal-to-noise ratios (Wang et al. 2018; Hajomer et al. 2024b).

Recent advancements

The integration of laser sources on chip for CV-QKD is essential for advancing the technology toward scalable and cost-effective solutions. According to experts, photonic integration is expected to miniaturize components and reduce costs while enhancing system performance. The development of integrated quantum light sources addresses the challenges of traditional external laser setups, which can introduce complexity and potential security vulnerabilities.

Recent work has demonstrated progress in integrating on-chip quantum light sources, particularly tunable lasers, which are critical for CV-QKD systems that rely on coherent detection (Li et al. 2023). The study by Li et al. (Li et al. 2023) presents the design and fabrication of high-performance on-chip lasers for the first time. These lasers feature narrow linewidths and high output power, marking a pivotal step toward fully integrated CV-QKD systems.

KPIs

Table 4 summarizes the most relevant KPI for coherent light sources for CV-QKD. The laser technologies used in CV-QKD have been commercially available for some time and have achieved a high level of maturity, indicated by a TRL of 9, signifying its established status in the industry. These laser sources typically operate within the tunable telecom C-band, with future implementations aiming for the O-band to facilitate easier integration with existing fiber-optic infrastructure.

A linewidth of less than 100 kHz is essential for optimal performance; however, according to experts, a narrower linewidth of less than 10 kHz is desirable for achieving high performance. While a symbol rate in the GHz range has been used in quantum communication research (Richter et al. 2021), the effective symbol rate is often limited by the bandwidth of the detectors, which typically limited to around 500 MHz according to experts. This means that although the transmitter-side can theoretically support higher modulation rates, actual performance is constrained by the detectors' ability to process those rates. Typically operating at power levels between 10 and 30 mW, these lasers must also maintain low phase and amplitude noise, ideally approaching the quantum limit to enhance the effectiveness of key distribution.

Table 4: KPIs of coherent sources used in CV-QKD

KPI	**Value**
TRL	9 (established technology)
Emission range	Tunable, typical telecom C-band;
Linewidth	< 100 KHz
Symbol rate	Symbol rate in the range of GHz has been shown (Richter et al. 2021), however detectors' bandwidth poses a practical limit around 500 MHz
Power	~ 10 – 30 mW
Sensitivity to noise / robustness	Phase noise and amplitude noise must be low
Operating Temperature	Room temperature
Price	~ EUR 2 to 5 K

State of research and industrialization

The integration of laser sources on photonic chips is seen as a key step toward realizing compact, reliable, and efficient QKD systems that can support future global quantum communication networks. Recent advancements, such as those described in (Li et al. 2023), highlight the development of high-performance on-chip tunable lasers that exhibit high output power, fine tunability, and narrow linewidth, which are critical parameters for effective coherent detection in CV-QKD.

Players in R&D and industry

Similarly to laser sources used in DV-QKD, the market in this sector is well established and features numerous global players.

Capabilities, limitations and challenges

As mentioned for DV-QKD, the lack of integrated solutions fulfilling all system requirements and enhancing usability and cost-efficiency is also relevant for CV-QKD. Similarly, low relative intensity noise in the laser source as well as frequency stability are critical requirements that have to be addressed in the future to enable enhanced performance and affordability.

Another significant challenge for laser sources employed in CV-QKD is achieving small linewidths. In some setups using a CW laser, the linewidth has been even reported to be around 100 Hz to maintain a good performance (Hajomer et al. 2024b). Achieving a low linewidth can be challenging, requiring increased manufacturing complexity and higher costs. In addition to fiber lasers, which can be adjusted for narrow linewidth (Paschotta 2007), external-cavity lasers, a type of semiconductor laser, also enable low linewidth (Paschotta 2005a; Li et al. 2023) and have been used in some CV-QKD setups (Zhang et al. 2024; Li et al. 2023).

Wavelength tunability is also essential for CV-QKD systems, ensuring compatibility with telecom bands for integration with fiber-optic networks. Solutions such as tunable lasers and integrated photonic devices enable precise wavelength adjustments (Paschotta 2006), enhancing operational flexibility and overall system performance.

Application scenarios (now and in the future)

Coherent-state CV-QKD relies on coherent laser sources to exploit the properties of coherent states of light for key generation. Novel approaches such as squeezed-light sources (Mehmet et al. 2011) are being investigated for potential future implementations of CV-QKD. Squeezed-state QKD promise enhanced robustness against channel noise and loss, and improved secret-key rates compared to traditional coherent-state CV-QKD (Oruganti et al. 2025). Despite these advantages, challenges in the practical generation and manipulation of squeezed states must be addressed before they can be widely adopted in real-world applications.

4.2 Photon Pair Generation in Nonlinear Media

One of the most relevant techniques to generate photons for QKD is spontaneous parametric down-conversion (SPDC), in which a nonlinear medium is used to split a pump photon into a signal and an idler photon. A similar method is four-wave mixing (FWM), in which the interaction of two photons in a nonlinear media generates two correlated photons. While only materials with $\chi^{(2)}$ optical nonlinearity[3] can exhibit SPDC, $\chi^{(3)}$ nonlinearity is sufficient for FWM, enabling the use of a broader range of (centrosymmetric) materials, such as glasses (Eisaman et al. 2011). While SPDC-based light sources are being used for QKD by many research groups and start-ups, FWM-based sources remain more niche so far.

4.2.1 Spontaneous Parametric Down-Conversion (SPDC)

The most prominent technology for photon-pair generation in nonlinear media is SPDC, as it can draw on the typically largest nonlinearity found in $\chi^{(2)}$ (Amann and Ortsiefer 2006). The following

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[3] The electric polarization induced in a material by an electric field depends on the material's electric susceptibility χ. Non-linear optical phenomena in materials can be explained by considering higher orders of χ (some of which can be forbidden by symmetry considerations).

introduction of the technology is oriented along review papers (Zhang et al. 2021; Eisaman et al. 2011; Anwar et al. 2021) and complemented by a discussion of the current state of the art and future perspectives for SPDC photon sources, strongly based on the results of expert interviews.

Description of technology

The generation of a correlated photon pair originated by the excitation of nonlinear material by one pump photon is called spontaneous parametric down-conversion or parametric fluorescence. As this is a probabilistic process with a very low conversion probability, a very large number of pump photons are usually needed to obtain a single down-conversion event. Due to energy conversion, the frequencies of the outgoing photons sum to the frequency of the incoming photon. It is therefore the inverse process of the second-harmonic generation, where two photons are combined to generate a photon with a frequency equivalent to the sum of the frequencies of the incoming photons. The quantum nature of SPDC was first experimentally investigated in the 1960s (Klyshko 1967; Burnham and Weinberg 1970) and found its way into applications such as optical brightness standards (Klyshko 1977) and calibration of photodetectors (D N Klyshko 1980) already a decade later. The theoretical description of the effect was developed in 1984 (Hong and Mandel 1985) (See (Zhang et al. 2021)for a more extensive discussion). The first experimental demonstration of a polarization-entangled photon-pair source based on SPDC in a beta-barium borate (BBO) crystal was reported in 1995, after previous demonstrations relied instead on approximating entangled states by post-selection of the detected states (Kwiat et al. 1995).

One main advantage of photon sources exploiting SPDC is their ability to generate entangled photon pairs, which enables the use of QKD protocols beyond BB84 (or other prepare-and-measure protocols), such as E91 (Ekert 1991) and BBM92 (Bennett et al. 1992). Entanglement-based protocols promise a different and, according to some experts, a potentially higher-level security profile. Furthermore, technologies based on entanglement could offer advantages for more complex network architectures or QCom applications beyond QKD or cryptography.

Photon-pair generation can also be used for prepare-and-measure protocols, in which one photon (often called the idler) is measured directly at the emitter to identify (herald) the emission of the other photon (often called the signal), which is then used for the protocol. By measuring the heralded photon, the sender gains information about the exact timing of the (probabilistic) photon-pair generation. Using SPDC for creating single photons for P&M-QKD only plays a minor role in the current discussion of using SPDC photon sources for QKD, as the capability to provide entangled photon pairs is a striking advantage of these sources. The entanglement of the photon pair is only achieved by carefully engineering the indistinguishability of the two potential photon pair generation events. SPDC photon-pair generation offers pathways to entangle the two photons in multiple degrees of freedom, such as frequency, time, polarization, momentum and position.

The experimental realization of SPDC-based photon-pair generation can be achieved by different approaches, based on different materials or material configurations, and is often distinguished by the relative polarization of the incident and outgoing photons. This leads to an engineering of the photon pair correlations taking into account several parameters, in particular the phase matching made available by the material and the pump (excitation field) properties (Graciano et al. 2019; Machado et al. 2019; Boucher et al. 2021). Furthermore, different optical set-ups can be used to exploit and enhance the generation of indistinguishable photons with SPDC (e.g., within a Sagnac loop). In the following, we will highlight the most relevant approaches to provide a concise, though not exhaustive, overview.

Implementation of SPDC crystals

The simplest implementation of an SPDC photon source is based on straightforwardly using a bulk crystal of a suitable material. This approach was the first realization of an SPDC source (Kwiat et al. 1995) and is still commonly used. Its advantage over more complex configurations lies in this simplicity. Preparation of the medium (bulk crystal) is straightforward and it is a comparatively low-cost component with good market availability. Furthermore, the requirements on the accuracy of the alignment of the optical setup are not as stringent as for other approaches. However, the conversion rate in bulk crystals is typically very low, on the order of only one in a million pump photons being converted into a photon pair (Zhang et al. 2021). This approach works with materials with non-zero second-order nonlinear optical susceptibility $\chi^{(2)}$. Typically, materials with a high $\chi^{(2)}$ are selected, i.e., with a strong quadratic dependence of the induced polarization on the applied electric field. Furthermore, the phase-matching constraints[4] must be satisfied for the desired pump and generated wavelengths. Using longer crystals can increase generation rates, while increasing the risk that generated photons are absorbed within the crystal. As some approaches are based on combining two differently oriented crystals, their size directly influences the indistinguishability, as the two possible pair-generation events should occur in proximity.

An approach to optimize the conversion rate is periodic poling of nonlinear crystals. Periodic poling refers to a way of material preparation in which short pieces of a crystal are combined with an alternating orientation, i.e., an alternating sign of the crystal nonlinearity (Eisaman et al. 2011). As this introduces an additional wavevector, the phase-matching conditions are relaxed. Periodic poling is usually realized in a collinear configuration along the crystal axis to avoid birefringence, i.e., the dispersion of the diffractive index for differently polarized light in the medium (Fedrizzi et al. 2007). Using periodic poling allows the materials that would otherwise not satisfy the phase-matching requirements to be employed, enabling a complete utilization of their nonlinear properties. While periodically poled crystals can achieve higher conversion rates than bulk crystals, their engineering is more challenging. Nonetheless, periodically poled crystals for SPDC light sources are already commercially available. As their periodicity must be engineered exactly according to the desired wavelength configuration, temperature-dependent crystal parameters must be accounted for in system design. While this requires more sensitive temperature control, it could, in principle, also be utilized to realize a frequency tunability.

Finally, approaches that aim for utilizing SPDC in single-mode waveguides that can directly be coupled to fibers should be mentioned. Integrating photon sources in this way promise high extraction rates, as coupling losses can be minimized. However, the full integration of SPDC photon sources is still under development. Photon sources based on bulk or periodically poled crystals are currently more widely available and mature.

Materials for SPDC crystals

The required non-zero $\chi^{(2)}$ can be found in materials that lack certain symmetries[5]. The most important differences between the materials used for SPDC-based photon sources - besides their respective $\chi^{(2)}$ – are their transparency windows (i.e., the range of frequencies not absorbed by the material) and whether the material is suitable to be manufactured into periodically poled photon sources (Nasr et al. 2008). The first fully entangled-photon source (EPS) was realized with a bulk

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[4] The interferences within the crystal can be constructive or destructive, depending on the phase difference of the partial waves being transmitted into and reflected within the crystal. To get a relevant signal, the phases must match to get a constructive interference. The phase matching depends on the optical properties of the crystal, its length and the wavelength of the photons.

[5] Centrosymmetric materials cannot exhibit SPDC. Centrosymmetry is present in crystals that have an inversion center: when every atom in the crystal is mirrored by this point, its structure is maintained.

BBO crystal, by using the birefringent properties of BBO to realize type-II phase matching (see below). Incoming UV photons were converted into two overlapping cones of outgoing photons with a wavelength of 702 nm and opposite polarization (vertical/horizontal). At the two intersecting points of the cones, entangled photon pairs were emitted (Kwiat et al. 1995). The wide transparency window of BBO, especially for short wavelength, might be advantageous for applications in non-fiber media. However, to guarantee long-term operability, measures to mitigate the degradation of BBO under UV light must be implemented.

One of the most common materials that is currently being implemented in nonlinear photon sources, is potassium titanyl phosphate (KTP). One advantage of KTP is its flexibility, not only in its spectral properties: bulk KTP crystals, periodically poled configurations (PPKTP), and periodically poled waveguides have been used to realize EPSs. It provides good stability, and experts report on good commercial availability. Since it is a biaxial crystal, i.e., it has two optical axes with distinct optical properties, its use in complex photonic structures might be limited. PPKTP-based photon-pair sources have been used in many research experiences, and one famous example is the satellite-based entanglement distribution over 1200 km from a Chinese group (Yin et al. 2017).

Another prominent material is lithium niobate (LN), which offers similar flexibility in terms of implementation pathways: it is commonly used in periodically poled configurations (then abbreviated PPLN) or as a thin-film (TFLN) (for example, (Shi et al. 2024)) and has shown promising results when integrated as PPLN into waveguides (U'Ren et al. 2004). With LN, more complex structures, such as micro- and nanostructured photonic guiding structures can potentially be realized, which could enable photonic integration of the light sources. In addition, there are potential synergies with existing telecommunications technologies, as LN is used for integrated optical components in standard high-speed communications (Alibart et al. 2016).

Similarly promising properties are provided by stoichiometric lithium tantalate (sLT), which has also been used to realize waveguided SPDC photon sources and could offer advantages for the generation of photons at short wavelengths (around 800 nm) (Nasr et al. 2008). Finally, the group of III-V semiconductor materials, such as AlGaAs (Baboux et al. 2023; Placke et al. 2024; Marino et al. 2019), for SPDC must be highlighted due to relevant recent improvements, their potential for photonic integration and complementary features, such as potentially enabling electrically pumped photon-pair generation. The list of materials that can be used for SPDC photon-pair generation is longer than what can be discussed here; it includes potassium dideuterium phosphate (KD*P), which was used historically but lost significance thereafter, lithium iodate, bismuth borate (BiBO) and many others. However, the discussion above covers the most prominent materials used in the most recent research activities.

Types of SPDC

Finally, SPDC photon generation is categorized by how the phase-matching conditions are met. Depending on the material and the chosen geometry of the optical setup, three types of phase matching are distinguished by the relative polarization of the incoming and outgoing photons. The process is called Type-0 SPDC if all three photons (pump, signal, and idler) have the same polarization. If the signal and idler have the same polarization but are polarized perpendicular to the pump photon, the process is of Type-I. Type-II SPDC occurs when the signal and idler photons are polarized perpendicular to each other. Which of these types is preferred can depend on various factors, such as the application context (e.g., the QKD protocol used). As all photons have the same polarization in the Type-0 SPDC, phase matching can be achieved by a broad range of different geometries. Therefore, Type-0 usually provides a broader spectrum of outgoing wavelengths (see non-degenerate SPDC below), which might offer advantages for multiplexing approaches. It also exhibits the largest photon conversion rate, as the nonlinear coefficient is the largest for Type-0. While Type-II SPDC emits entangled photon pairs of the same wavelength in the same spatial direction, this is usually not the case for Type-0 SPDC. To enable the separate use or manipulation of the signal and idler photons in Type-0 SPDC, workarounds, such as post-emission routing of the photons into distinct spatial modes or multiple pair-creation approaches, are required (Chen et al. 2018). Type-I has a broad spectral bandwidth similar to Type-0 SPDC, but a smaller nonlinear coefficient, leading to lower spectral brightness, i.e., photon generation rate over the frequency bandwidth. As Type-II directly yields an entangled singlet state (if one photon is measured to be polarized horizontally, the other is polarized vertically), as described above, without the need for post-emission photonic guiding structures, the engineering of indistinguishable photons with high spectral purity is facilitated. As the optical properties of the materials used for SPDC can be quite temperature sensitive, most sources require precise temperature stabilization (on the order of 0.1°C). However, Type-II SPDC processes could, under certain conditions, be significantly less temperature sensitive, which would offer further advantages for specific application cases (Pan et al. 2021).

The literature also distinguishes some additional ways to categorize different approaches to SPDC. One classification is collinear or non-collinear photon generation, describing whether the signal and idler propagate in the same direction as the pump photon or not. While collinear photon generation is desired to prevent signal losses (e.g., when coupling into a fiber), photonic guiding can be used to realize sources based on non-collinear SPDC. Similarly, the wavelengths of the outgoing photons can be equal (degenerate SPDC) or different (non-degenerate). It should be kept in mind, however, that conservation of momentum holds, giving a distinct relation between the wavelengths and propagation direction of the two outgoing photons in respect to each other. Which of these types of sources is preferred depends on the application. The categories into which the photon-pair emission falls depend on the optical setup and the chosen SPDC crystal.

State of research and industrialization

SPDC represents a highly promising photon source technology for quantum communication applications, as it is easily implementable and operates at room temperature with comparatively low noise. It is already being used in various testbeds and prototype or early commercial applications on the ground and on satellites. Commercially available SPDC sources offer a range of different specifications (e.g., brightness, purity, frequency range) to ensure suitability for different applications. While commercially available sources can be used directly in QKD systems, a few QKD system providers prefer to manufacture their own SPDC sources for the sake of value creation and to tailor these components directly to their specific needs. The technical parameters achievable with current sources are considered generally sufficient for QKD applications — the performance for QKD systems is currently rather limited by the performance of single photon detectors (Shirinzadeh et al. 2026) and not predominately by the light sources. In the following, we discuss the state-of-the-art performance across the key indicators that define the performance of SPDC photon sources.

Table 5: Typical performance indicators of SPDC photon sources for QKD systems

KPI	Value
TRL	9 (next technology generations TRL 5-8)
Emission range	Tunable For QKD typically: 780 – 1550 nm The emission wavelength could be different for signal and idler.
Linewidth	Typical for QKD applications: 2-3 nm Depends on system requirements

KPI	Value
Conversion efficiency	Typical: one in a million photons 0.01 – 0.1 photons per pump-pulse
Photon generation rate	Depends on pulse-rate. Typically order of several 100,000 photons / s Coupling efficiency around 90%
Emission Direction	Mostly collinear
Entanglement fidelity	>99%
Sensitivity to noise / robustness	Rather high / stable
Indistinguishability / HOM visibility	> 93% (Wang et al. 2017b)
Single photon purity $\boldsymbol{g_{(2)}(0)}$	Depending on photon rate Typical: 0.001 – 0.1 Can be further improved (e.g., with multiplexing approaches)
Operating temperature	Typically room temperature, but precise temperature control usually required

Source: Cited literature and expert interviews

The emission wavelengths of SPDC photon sources for QKD applications usually lie between 780nm and 1550nm, and are, in principle, tunable. However, periodically poled crystals are optimized for a single wavelength. The chosen wavelength depends strongly on the application specifications, as the optimal wavelength is different for fiber- and free space communication. Linewidths as low as a few nanometers have been achieved, and the emission direction is mostly collinear. The photon purity correlates directly with the generation rate: the lower the input power, the higher (better) the photon purity, i.e., the lower $g^{(2)}(0)$, and the lower (worse) the generation rate. As SPDC is a probabilistic process, this trade-off is intrinsic and cannot be overcome by the choice of material. Hence, reported photon purities should always be put in perspective. Typical photon purities lie at values below 0.1 (Eisaman et al. 2011), whereas typical generation rates are on the order of several 100,000 photons per second, with less than 0.1 down-converted photons per pulse. The resulting key rate also depends on the extraction or collection efficiency of the setup. Coupling losses into fibers, for example, were reduced to values of around 10%. Even though the heralding efficiency of the system is connected to the complete setup and not only the source, it is an important measure that also indicates the performance of the photon source. For example, heralding efficiencies of above 75% with nearly perfect detector efficiencies were reported (Giustina et al. 2015). Entanglement fidelities of around 99% were reported, which is sufficient for QKD applications (Magnitskiy et al. 2015). The degrees of freedom that can be used for entanglement and encoding are broad. While polarization is currently the most common approach, time, energy and angular momentum can also be exploited. An overview of the most relevant KPIs is provided in Table 5.

The current development is best highlighted by the distances achieved for QKD with SPDC sources over long distances (Scheidl et al. 2009), new developments at the material level (such as III-V materials (Baboux et al. 2023)), prototypes deployed in space (Anwar et al. 2022), but most importantly by the range of commercial QKD systems on the market that use SPDC photon sources.

Many scientific and industrial players develop SPDC photon sources or use SPDC photon sources for their QKD systems. A non-exhaustive list of examples for industrial QKD system developers that implement SPDC photon sources include Quantum Optics Jena (DE), Quantum Industries (AT), and Qubitekk (US – acquired by IonQ in 2025) (IonQ | IonQ Completes Acquisition of Qubitekk, Solidifying Leadership in Quantum Networking 2026).

Capabilities, limitations and challenges

Entanglement-based QKD systems promise a unique attack surface that might be potentially smaller than in other approaches due to the entanglement of the photons. Furthermore, SPDC could be additionally used to utilize the quantum randomness of the process for the random choice of bases in the emitting unit.

Current SPDC photon sources achieve satisfactory values in most KPI. Ideal emission wavelengths are realized; room-temperature operation is provided; nearly ideal indistinguishability and entanglement fidelity are provided; and more, as discussed above. However, there is room for improvement. The linewidth could be optimized to values as low as, e.g., 0.4 nm, as long as this does not result in a negative impact on the key rate. Realizing sources that can operate at very low temperatures in a cryogenic environment can be useful for high-performance applications, where the detector must be cooled as well. Some limited room for improvement is still given for the emission direction of the photons, anticipated, for example, in III-V materials. Further miniaturization of SPDC photon sources by photonic integration would improve the attractiveness of SPDC-based QKD systems for future applications (e.g., by using thin-film lithium niobate). Nevertheless, the customized fabrication to realize photonic integration is challenging. Another challenge for photonic integration might be to realize an approach to filter out the incident optical power of the pump laser, which is not converted and, therefore, not desired in the transmission fiber.

The coupling of photon purity and generation rate limits the independent optimization of both parameters, as it results from the probabilistic nature of the process similar to weak coherent pulses. To improve the capabilities of SPDC photon sources, optimization of the fiber coupling efficiency is anticipated, moving towards 99% and beyond. This would mitigate the major limitations of this source type slightly, namely that the generation rate is coupled with the multiphoton emission probability. Other workarounds are also possible, such as using multiplexing to realize efficient heralded single-photon (Kaneda and Kwiat 2019). Multiplexing is expected to play an important role in further improving the performance of SPDC photon sources and the respective QKD systems. These systems could also benefit from the pairwise emission of photons, as this can be an asset for realizing more complex network architectures (star-type). The combination of multiple sources to realize further use cases is possible but challenging due to the required synchronization of the sources and the probabilistic nature of SPDC.

Finally, it should be noted that the main challenges for SPDC sources are not their own technical optimization itself, but rather their commercialization in QKD systems. The optimization of the complementary components (such as detectors) is at least as important.

Table 6: Technical challenges and proposed solutions for SPDC-based light source

Challenges	Potential Solutions	Relevance
Miniaturization via photonic integration	Short / Medium term: Hybrid integration Longer term: Full integration with TFLN (fab-like manufacturing)	Not needed for first adopters. Opens large potential future market.
Photon Purity vs. Emission rate	Short-Term: Applications that do not require large key rates. Medium-Term: Multiplexing, further material innovations, improving extraction efficiency.	Many use cases do not require large key rates.

Application scenarios (now and in the future)

SPDC photon sources are rather versatile and can be used for different DV-QKD approaches in terms of protocol, degrees of freedom available for encoding, infrastructure, network architecture and more. Single (heralded) photon sources based on SPDC play only a minor role in the current commercialization of this technology and are mostly used in academic applications, whereas the generation of entangled photon pairs is the most important asset of these sources. QKD systems using SPDC entangled photon-pair sources are already being commercialized and provide an alternative to more established QKD systems based on attenuated lasers. With continuous improvements in the capabilities of SPDC photon sources, a relevant market share can be expected in the short term; however, it is expected to be not as high as that of weak coherent sources.

In the next years, the implementation of SPDC-based QKD systems will primarily take place in fiber-based (prototype) implementations, as the number of satellite prototype missions will be small due to their high costs, and the added value of earthbound free-space links is limited to only very specific application scenarios. In general, SPDC photon sources might be used specifically for star-shaped networks, i.e., a central node connected to multiple communication partners. The advantage of this approach is that only one entangled-photon source is needed in the central node, and all communication partners require only detection hardware.

So far, the photonic integration of SPDC-based photon generation has lacked compatibility with generic photonic-integrated technologies. However, promising candidates on the material side have been already identified with TFLN, potentially opening up the development of photonic-integrated photon sources and corresponding commercialization potentials.

Implementing SPDC photon sources in "beyond-QKD" applications can be another driver for further innovation and commercialization. Most prominently, entanglement distribution for various applications, such as interlinking distant quantum computers, is highly anticipated. Furthermore, SPDC can be used for certain quantum sensors and imaging techniques.

4.2.2 Four-Wave Mixing in Optical Fibers or Atomic Ensembles

Four-wave mixing (FWM, also called Spontaneous Four-Wave Mixing - SPFM) is, like SPDC, an approach to generate photon pairs in nonlinear media. However, FWM has received less research attention compared to SPDC and currently exhibits lower technological maturity. This section highlights the key differences between the two approaches.

Description of technology

Four-wave mixing describes the conversion of two pump photons into two correlated output photons within a $\chi^{(3)}$ (third-order) nonlinear medium. The third-order susceptibility is generally smaller than the second-order susceptibility utilized in SPDC. Unlike second-order nonlinearity, which requires materials with low symmetries, third-order nonlinearity can occur in a broader range of materials, including centrosymmetric ones. This enables the use of materials that are easier to fabricate into waveguides, such as silicon-based glasses, facilitating the integration of FWM photon sources into QKD systems.

As $\chi^{(3)}$ is weaker than $\chi^{(2)}$, FWM requires less stringent - and therefore less challenging - phase-matching. This makes the alignment and preparation of the nonlinear media less challenging compared to SPDC. Additionally, FWM sources can operate across a wider spectrum, which may benefit niche QKD applications requiring non-standard wavelengths. As with all photon sources discussed, the choice of protocol determines the advantages and limitations of the approach.

The most common FWM process is the conversion of two degenerate photons, i.e., photons with the same frequency, into two non-degenerate photons. However, alternative processes are possible, such as the conversion of two non-degenerate input photons into two degenerate photons or a process involving four photons with distinct frequencies.

Due to its compatibility with a variety of materials, FWM processes are most commonly performed in optical fibers. Photon generation via FWM has been demonstrated with different fiber types. The effect is present in standard birefringent fibers (Smith et al. 2009), which are typically used for classical optical communication. However, their commercial use for FWM-based photon sources is limited due to high noise levels. Dispersion-shifted fibers (Dyer et al. 2008) provide better results for FWM, although relatively long fibers – often hundreds of meters to several kilometers – are required to achieve high photon generation rates. A major challenge in this approach is Raman scattering, which introduces single photon noise. Cryogenic cooling can reduce Raman scattering but comes at the cost of high energy consumption and, therefore, operating cost. Other approaches to mitigate the influence of Raman scattering have been also explored, for example, dual pump scheme (Blay et al. 2016) and changing propagation medium (Afsharnia et al. 2024).

Photonic crystal fibers (Alexander Ling et al. 2009) represent a promising alternative for FWM-based photon pair generation. These fibers exhibit higher nonlinear efficiency than dispersion-shifted fibers, enabling higher generation rates at shorter fiber lengths. However, their current technological maturity is insufficient for widespread commercial use due to their high production cost in comparison to alternative technologies. Nevertheless, the promise of a high nonlinearity enabling high generation rates at low fiber lengths is attractive for anticipating a commercialization in the long-term. Additionally, fiber splicing, which is necessary for connecting different fiber sections, causes significant losses – often exceeding 3 dB.

Beyond fiber-based approaches, recent research has explored micro-ring resonators for FWM, which are particularly promising for on-chip systems (Heuck et al. 2019; Helt et al. 2010). Devices with high quality factors (indicating low energy losses during oscillation) can achieve high-brightness photon sources with minimal input power. However, the high Q factor can degrade the time correlation between photon pairs, reducing their indistinguishability – a critical limitation for QKD applications.

For non-fiber-based FWM, the most common materials include silicon and silicon nitride. More recently, lithium niobate crystals, aluminium nitride and aluminum gallium arsenide on insulator

(Mahmudlu et al. 2021) have been investigated, expanding the range of candidate materials. Thanks to the relaxed symmetry requirements of $\chi^{(3)}$, a wide array of materials could potentially be explored in future research (Elefante et al. 2023).

State of research and industrialization

Compared to SPDC photon sources or weak coherent sources used in QKD, FWM photon sources exhibit lower technological maturity. Although research has been conducted on a wide variety of materials and experimental setups, widespread commercialization FWM photon sources for QKD remains out of reach. This is primarily due to low photon conversion efficiencies and high noise levels.

FWM photon sources offer a broad range of emission frequencies, spanning both the visible and infrared spectrum. The linewidth is highly dependent on the implementation and can be tailored to meet the specific requirements of the QKD systems and protocols. Linewidth as narrow as sub-nanometer values have been demonstrated in experiments (Eisaman et al. 2011; Rambach et al. 2016). As the conversion of photons depends strongly on the interaction length, improving the conversion efficiency (at shorter fiber lengths) is critical to enabling practical FWM-based photon pair generation.

The indistinguishability of emitted photons depends on the system design priorities. For instance, a recent study reported an indistinguishability of 0.89 alongside a photon purity of $g_{(2)}(0) = 0.09$ (Couteau et al. 2023). Photon purities with $g_{(2)}(0) < 0.01$ are achievable but require significant experimental effort and optimization. While FWM photon sources can operate at room temperature, cryogenic cooling is often employed to suppress Raman scattering, which improves source performance but increases energy consumption and operational cost.

Capabilities, limitations and challenges

The most significant advantage of FWM-based photon sources is the flexibility in material selection. Since FWM is typically realized in fibers, coupling losses are eliminated or reduced to splicing losses. Moreover, FWM can be miniaturized and integrated on photonic chips, offering potential for compact and scalable implementations.

Phase-matching conditions are less stringent for FWM compared to SPDC, enabling the use of a broader spectrum. This flexibility can be advantageous for certain QKD protocols and applications requiring multiplexing or non-standard wavelengths. However, the main challenge facing the commercialization of FWM sources is their low photon conversion rates, which necessitate long interaction lengths. Additionally, Kerr noise and Raman scattering are inherent limitations of the process. While there are several approaches to mitigate these noise sources such as cryogenic cooling, it is unlikely to be feasible for large-scale commercial applications due to high energy costs in the next few years.

Application scenarios (now and in the future)

FWM's potential for integration into photonic chips is its most compelling long-term feature. This capability could enable miniaturized, scalable photon sources in future QKD systems. However, whether this advantage is sufficient to open the path towards a widespread adoption remains uncertain, for now, given the low nonlinearity and unavoidable noise challenges associated with FWM.

The relaxed requirements for material symmetry and phase-matching offer opportunities for innovative material research, which may significantly enhance the performance of FWM-based photon sources. While FWM is currently a niche technology, its future potential to produce entangled-photon sources for specialized applications cannot be overlooked.

4.3 Semiconductor Quantum Dot Photon Sources

The light source technologies discussed so far are all probabilistic sources, i.e., the photons cannot be produced on demand (Lodahl et al. 2022). In contrast, deterministic single-photon sources emit photons at high probability (ideally 100%) in a defined time window after excitation and thus allow on-demand production of photons. The currently most advanced technology of deterministic single-photon sources are semiconductor quantum dot single-photon sources. Beyond the deterministic generation of single photons, quantum dot light sources can also be developed to emit entangled photons. This section discusses quantum dot single-photon sources and entangled-photon sources.

4.3.1 Quantum Dot Single-Photon Sources

Semiconductor quantum dots (QDs), formerly called "artificial atoms," are nanoscopic ensembles of a semiconductor material that, due to their spatial limitation, form discrete electronic energy levels (Bera et al. 2010; Arakawa and Holmes 2020). These discrete levels can be used for individual optical transitions of single electrons and, consequently, to realize single-photon sources (Arakawa and Holmes 2020). The properties of these QDs depend on their material, size, and structure and can be now well controlled. Using well-established III/V semiconductor materials makes these QDs well-suited for optical applications (Heindel et al. 2023).

Description of technology

The nanoscopic confinement leads to discrete electronic levels in QDs. These energy levels can be used for the radiative recombination of electron-hole pairs, leading to the emission of photons with a wavelength defined by the energy difference of the electronic levels in the QD. QDs with a direct bandgap (e.g., In(Ga)As or GaAs QDs) typically exhibit efficient spontaneous emission via the radiative transition from the conduction band to the valence band (Heindel et al. 2023).

Material systems

Various material systems can be used to grow QDs for single photon generation. III-V and II-VI semiconductors are typically chosen due to their favorable optical properties. Different semiconductor materials are used depending on the targeted wavelength: (Heindel et al. 2023; Arakawa and Holmes 2020)

GaN/AlGaN (wurtzite structure), GaN/AlGaN (zinc-blende structure), or InGaN/GaN can be used for the wavelength range of ca. 280 – 450 nm. They typically allow for room-temperature operation but exhibit low efficiency and low rates. InGaN/GaN, CdTe/ZnTe, CdSe/ZnSSe, or CdSe/ZnSe can be used for the wavelength range of ca. 400 – 600 nm. These systems also allow room-temperature operation but also exhibit low efficiency and low rates. InP/AlInGaP can be used for the wavelength range of ca. 640 – 690 nm. GaAs/GaAsP or GaAs/AlGaAs can be used for the wavelength range of ca. 750 – 900 nm, providing very good optical properties; however, they require cryogenic cooling. InGaAs/GaAs or InAs/InP can be used for the wavelength range of ca. 900 – 1550 nm. These material systems achieve decent to good optical properties; however, they must be operated at cryogenic temperatures. This last wavelength range is of particular interest, as it reaches the currently used telecom bands and is most compatible with existing fiber technologies (Heindel et al. 2023; Arakawa and Holmes 2020). InAs, GaAs and InGaAs are currently the most advanced material systems for QD SPS.

Device design and fabrication technology

These materials must be processed into quantum dot structures, i.e., dimensionally confined structures, to create discrete energy levels. Epitaxial growth of QDs via methods such as the Stranski-

Krastanow method, nanohole filling, or droplet epitaxy is an established technology. The fabrication of colloidal QDs is also possible; however, it typically leads to lower photon quality. The integration of QDs into nanophotonic structures is widely used to efficiently outcouple photons from the QDs with high efficiency and directionality. For photon direction perpendicular to the device surface, micropillar cavities, circular Bragg gratings, photonic wires and microlenses can be used. Photonic crystal waveguides can be employed for lateral photon guiding in integrated photonic circuits (Heindel et al. 2023).

For the processing of the QDs as well as the nanophotonic structures, well-established semiconductor micro- and nanofabrication techniques can be utilized. Nonetheless, the fabrication of QS SPS with precisely defined properties is very demanding, as even slight variations in size of the QD and positioning of the QD in the nanophotonic structure can lead to significantly different optical properties. Deterministic fabrication technologies (Rodt et al. 2019), such as pick-and-place techniques, marker-based lithography techniques, or in-situ lithography techniques can be used to optimize QD positioning in the nanophotonic structure and thus increase the fabrication yield (Heindel et al. 2023). Optimizing and scaling of QD SPS fabrication to achieve high reproducibility and yield are thus a significant challenge. At the same time, it has the potential to enable low-cost manufacturing, because of the use of highly established micro- and nanofabrication technologies. For more detailed information on fabrication techniques, we refer to the literature (Heindel et al. 2023; Thapa and Biswas 2025).

State of research and industrialization

The use of QD SPS for quantum communication has also been a topic of R&D activities for several years. Notable achievements include lab experiments of free-space QKD using electrically driven QD SPS, reported in 2012 (Heindel et al. 2012). In 2014, 500 m free-space QKD outside the lab was demonstrated also with electrically driven QD SPS (Rau et al. 2014). In 2024, field trials used a QD SPS and a frequency converter that converted the photons to the telecom wavelength to realize QKD over a distance of 18 km in the metropolitan area of Copenhagen (Zahidy et al. 2024). The latest achievement was the demonstration of intercity QKD over a distance of 79km using a QD SPS and BB84 prepare-and-measure protocol (Yang et al. 2024).

Players in R&D and industry

Various research institutions are working on QD-based single-photon sources. The most active institutions in publishing on this topic can be found in Europe and China, among others. QD-based single-photon sources are already commercially available. In Europe, for example, the companies Aegiq from UK (Aegiq Ltd.), Quandela from France (Quandela) and Sparrow Quantum from Denmark (Sparrow Quantum ApS) offer commercial products.

Capabilities, limitations and challenges

QD SPS are deterministic photon sources with generally good-to-excellent photon properties. In this subsection, some of the most relevant KPIs of QD SPS will be discussed. For more detailed discussions on these parameters, we refer to the literature (Heindel et al. 2023; Thapa and Biswas 2025).

Emission range: A broad wavelength range from 280–1550 nm can be covered with QD SPS, depending on the material system used (Arakawa and Holmes 2020). Current commercial systems (without frequency conversion module) offer wavelengths of around 925nm (Quandela 2024; Aegiq Ltd.) and around 780nm (Quandela 2024). One major challenge for QD SPS is to fabricate SPS that emit high quality single photons in the telecom wavelength bands (e.g., 1310nm or 1550nm), which would be desired for fiber-based QCom networks. These wavelengths are generally possible with

QDs but show limited performance so far (Phillips et al. 2024). Alternatively to using QDs made of materials with the corresponding energy transition, frequency conversion of high-quality near-infrared photons into telecom-band photons could be a promising approach (Morrison et al. 2021).

Linewidth: The linewidth of QD SPS depends on various factors, including excitation energy and temperature. The closer the excitation is to the emission energy, the smaller the linewidth. The linewidth is generally smaller for lower temperatures and thus can be small at cryogenic temperatures at which many QD SPS are operated. A lifetime-limited linewidth (Fourier-limited linewidth) is desirable, challenging, and generally possible. Decreasing the linewidths requires a better understanding of the broadening mechanisms and finding ways to suppress them. Typical values for QD SPS linewidths range from 1 to 20 GHz; values below 1 GHz have also been demonstrated (Zhai et al. 2020). Commercial systems also exhibit values of around 1.2 GHz (Quandela 2024).

Photon generation rate: Typical photon generation rates of QD SPS are in the range of 20–100 MHz. Generation rates in the GHz regime are possible, especially when using electrical excitation. Achieving high photon quality with electrical excitation, however, remains challenging; therefore, optical excitation is currently preferred as it allows higher optical quality of the photons. Furthermore, for many applications in QCom, such high generation rates are not necessary. Beyond the photon generation rate, the extraction rate is of high importance. The extraction efficiency is typically higher than 50% and could, according to experts, approach 80% in the future by using optimized photonic structures. The usable single photon rate in an optical fiber can reach e.g., 40MHz (Tomm et al. 2021).

T1 (radiative lifetime): Typical T1 lifetimes of QDs are in the range of 0.1–1 ns, or even below. Record lifetimes below 50 ps have been reported (Tomm et al. 2021; Liu et al. 2018).

Emission directionality: The emission from the QDs themselves is non-directional. To use the photons for, e.g., QCom applications, high directionality is desired and can be achieved by introducing nanophotonic structures.

Indistinguishability: QD SPS produce highly indistinguishable photons with HOM visibilities typically above 90% (at cryogenic temperatures). Values as high as 97.5% have been reported from the same source (Tomm et al. 2021). The reproducibility of the quantum dots light sources is, however, still limited; for different light sources this value is typically lower. Values of, e.g., 93% have been reported for remote QD SPSs (Zhai et al. 2022). The fabrication of devices on separate chips with identical photon properties, and thus high indistinguishability, represents a major challenge.

Photon purity - $g^{(2)}(0)$: The photon purity of QD SPS is generally high, which can be expressed by a low $g^{(2)}(0)$ value, typically around 1-2%. Significantly lower values can be reached, with reported record values as low as 7.5×10^{-5} (Schweickert et al. 2018). The challenge is to maintain high values even at temperatures above the typical below 10K-regime and in the telecom bands.

Operating temperature: Many QD material systems need to be operated at cryogenic temperatures to exhibit good optical properties. Various parameters, such as linewidth, indistinguishability and photon purity depend (strongly) on the temperature, and only at cryogenic temperatures good photon properties can be achieved. While most systems in research as well as commercial systems are operated at 4 K (Quandela 2024), generally good photon properties can be achieved also with temperatures below 10K. The challenge to improve usability is to increase the operating temperature, so that ideally a cooling via liquid nitrogen (77K), by Stirling coolers, or even Peletier coolers, could be possible, while maintaining the photon properties at sufficiently high levels needed for the respective application.

TRL: Although the first QD SPS products are already commercially available, and thus the TRL could be in the range of 8-9, some experts assessed the TRL to be rather in the range of 7 or even below.

Especially considering that, to the best of our knowledge, no QD SPS is currently used in QCom systems such as QKD, the technological and market maturity is still limited.

Price: Currently available QD SPS are still expensive, with prices above 100,000 €, due to the still small scale of commercial fabrication. Price reductions toward 10,000 € are considered realistic with production scaling.

Table 7: Typical performance indicators of quantum dot photon sources for QKD systems

KPI	Value
Emission range	• Broad wavelength range possible: ≈ 280 nm – 1550 nm (Arakawa and Holmes 2020) • Current commercial systems: 925nm, 780nm • Telecom bands are possible, but so far limited performance
Linewidth	• Typically values: 1 – 20 GHz
Photon generation rate	• Typical values: 20 – 100 MHz • GHz possible
T1 (radiative lifetime)	• Typical value in the range of 0.1 – 1 ns • Record lifetimes below 50ps
Emission directionality	• Non-directional from QD itself • By using nanophotonic structures high directionality can be reached
Indistinguishability (HOM visibility)	• Generally highly indistinguishable photons • HOM visibilities of typically above 90% (at cryogenic temperatures) • Values as high as 97.5% (from the same source) and 93% (for remote sources) have been reported
Single-photon purity: $g^{(2)}(0)$	• Generally high photon purity • Low $g^{(2)}(0)$ value of typically around 1-2% • Record values as low as 7.5×10^{-5}
Operating temperature	Cryogenic temperatures, typically below 10 K are necessary for good photon properties
TRL	Depending on approach still low (<4) or higher (up to 7). Still: first commercial systems are being sold.
Price	>100,000 €

Beyond improving all of these KPI, the biggest challenge for QD SPS lies in the reproducible fabrication of devices with ideally identical properties. As the properties are, however, strongly dependent on the exact size, shape, and alignment of the quantum dot, this represents a significant engineering challenge. Transferring these devices from the lab into the mass market will require controlling the device properties fabricated on different wafers to a sufficiently high degree and achieving sufficiently high fabrication yields to reduce costs of production for QD SPS.

Application scenarios (now and in the future)

QD SPS can, in principle, be used for BB84 P&M-QKD systems (Yang et al. 2024). The advantage compared to established attenuated lasers is the high photon purity, which makes the system resistant to photon number splitting attacks. However, attenuated lasers currently show superior performance in terms of photon rate, are significantly cheaper and less complex (room temperature operation), and the use of decoy protocols allows for sufficient security against photon number splitting attacks. Consequently, there is no justification for using QD SPS for this application at the moment. Improving performance in terms of photon rate (brightness) and significant cost reductions could open a limited window of opportunity for this application, although cryogenic cooling will still be required, increasing system complexity.

Building on their advantages, i.e., high photon purity, high indistinguishability and on-demand photon production, QD SPS could be used for alternative QKD schemes such as MDI-QKD, TF-QKD, or Device-Independent QKD (DI-QKD)[6]. However, even MDI-QKD systems can be realized using attenuated lasers, and time will show whether QD SPS can deliver significant performance enhancements that justify the higher complexity of the system (especially cryogenic cooling) and higher costs. Cost reductions and further technical improvements of QD SPS could lead to opportunities for implementation into QCom systems. However, as of today, the unique selling proposition for using QD SPS in QKD for practical implementations is not obvious.

Another possibility is the use of QD SPS for future applications such as quantum repeaters, leveraging its spin-photon interfaces. In addition, quantum dot entangled-photon sources also show promise for quantum repeaters, as discussed in the following section.

4.3.2 Quantum Dot Entangled-Photon Sources

Quantum dots are not only suited for the fabrication of deterministic single-photon sources but also for entangled-photon sources. Such QD entangled-photon sources (QD EPS) are gaining interest in research but are, so far, at a rather low level of technological maturity.

Description of technology

QD EPS are based on the same general materials systems and device structures as QD SPS. Hence, the materials and fabrication processes are the same as described in section 4.3.1. There are generally two ways to use QDs as entangled-photon sources: first, generating entangled photon pairs via biexciton–exciton cascade; and second, generating cluster states, i.e., sequences of entangled photons.

***Entangled photon pair generation via biexciton–exciton cascade*:**

The first demonstration of generating entangled photons with QDs was carried out using a biexciton–exciton cascade. This process uses fine-structure-splitting in the QD and an emission cascade,

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[6] Device-independent QKD (DI-QKD) is a framework that aims to guarantee security without relying on assumptions about the internal implementation of the devices. Entanglement-based protocols that exploit Bell-inequality violation, such as E91, can in principle enable DI-QKD.

first to the fine-structure level and then to the ground state. In this process, a pair of either horizontally or vertically polarized photons is generated (Heindel et al. 2023). The polarization entanglement of the photon pair can be controlled by the geometry and material composition of the QD. The emission shows a certain time delay between the two photons, depending on the lifetime of the fine-structure-level state.

***Photonic cluster state generation*:**

QD can be also used to produce photonic cluster states, i.e., multi-qubit entangled states (graph states) with a regular lattice such as a 1D chain. The general principle involves a local quantum state in the QD that becomes entangled with the generated photons. Upon generation of multiple photons, they all are entangled with the local spin and thus with each other. (Heindel et al. 2023)

The advantage of such cluster states is the redundancy it provides against photon loss or the probabilistic nature of photonic Bell measurements – repeated trials are possible if the first measurement fails (Cogan et al. 2023). This is particularly interesting for applications in all-photonic quantum repeaters and for quantum computing.

Beyond 1D chains of cluster states, 2D photonic cluster states are of high interest, especially for photonic quantum computing. Such states could also be generated by QD light sources (Heindel et al. 2023).

State of research and industrialization

QD EPS are still under development and in a rather low TRL (estimated at TRL 4 by experts). Today, no commercial QD EPS systems are available yet. Although companies are involved in research on this topic (Guichard et al. 2025), commercialization will still require further R&D efforts and time.

At the research level, several achievements have been reported in recent years. Recently, Guichard et al. reported the production and characterization of up to six entangled photons of a cluster state with a QD EPS (Guichard et al. 2025). This is the highest number of entangled photons in a cluster state that has been realized and measured. In 2023 Cogan et al. reported, in another setup, a characteristic entanglement length of about ten photons (Cogan et al. 2023). They were, however, not individually characterized. These examples show that the field is advancing quickly.

Capabilities, limitations and challenges

QD EPS are deterministic photon sources that are currently still at the R&D stage. The achievable KPIs are generally similar to what can be achieved with QD SPS (see the previous section). An additional important parameter for QD entangled light sources is entanglement fidelity. With QD EPS, the entanglement fidelity up to 98% has been reported, albeit with limited brightness (Ding 2024; Huber et al. 2018). Other publications have reported high entanglement fidelities of 88% (Liu et al. 2019; Heindel et al. 2023), 96% with high brightness (Rota et al. 2024; Ding 2024), and even 99% (Schimpf et al. 2021). Consequently, high entanglement fidelities can be achieved with QD EPS; however, achieving these at high brightness and in different materials systems (and thus wavelengths), including the telecom bands, remains a challenge (Ding 2024).

QD EPS are generally operated at cryogenic temperatures (the same as with QD SPS; see the previous section). This is necessary to achieve good photon properties with most materials systems and, thus, wavelengths. The challenge is to increase the operating temperature to values at which cooling systems can be more compact and cheaper. This limitation currently represents a clear disadvantage compared with other sources of entangled photon pairs, such as SPDC sources. On the other hand, QD EPS offers the potential of cluster-state generation, which is not possible with approaches such as SPDC.

For cluster state generation, entanglement fidelity is also a crucial parameter. It is, however, strongly limited by spin-coherence time and the optical losses of the resonator in these systems (Heindel et al. 2023). Fidelity values of 80% for two photons and 63% for three photons have been reported (Coste et al. 2023) More recently, slightly higher values for entanglement fidelities of 86.5% for two photons, 77.6% for three photons, and 63.8% for four photons have been reported (Guichard et al. 2025).

Hence, the main challenges for quantum dot cluster state sources are to achieve a long spin-coherence time of the local spin and to keep the optical losses of the resonator low, in order to realize high entanglement fidelities and, ideally, a high number of photons in the cluster state (Heindel et al. 2023).

Application scenarios (now and in the future)

The technology is still under development and at a rather low TRL; hence, QD EPS are not yet used in any application. Entanglement-based QKD systems represent a potential application for QD EPS that produce entangled photon pairs via biexciton–exciton cascade. However, currently used SPDC-based entangled-photon sources are cheaper and can be operated at room temperature. Therefore, the advantages of QD EPS in this application are currently not obvious. QD EPS that generate photonic cluster states, on the other hand, show a clear unique selling proposition, as no other light source can currently generate such cluster states in a similar way. Applications for these types of light sources could include photonic quantum repeaters that do not require quantum memories, as the cluster states provide redundancy against photon loss and the probabilistic nature of Bell state measurements. Another potential application is photonic quantum computers. For both applications, however, further R&D efforts are necessary.

4.4 Other Deterministic Single-Photon Sources

The deterministic generation of photons can be realized with a broad variety of technological approaches beyond quantum dots. This includes molecules, two-dimensional materials, color centers in diamond and trapped atoms or ions. These technologies will be introduced and discussed in the following sections.

4.4.1 Organic Molecule-Based Single-Photon Sources

Description of technology

Organic molecules were the first condensed-matter systems in which photon antibunching[7] was demonstrated (Lounis and Orrit 2005). For feasibility reasons, the emitting molecules are often embedded in an optically transparent matrix material. The eigenstates of molecules in such a host matrix are more complex than those of isolated molecules or single atoms and ions, as they involve not only electronic states but also vibrational states and phonons. However, due to the rapid nonradiative relaxation from highly excited singlet states to the lowest excited states (Kasha's rule), spontaneous emissions mostly occur from the lowest excited states. At very low temperatures the vibrational states are frozen, and the emission spectrum becomes very narrow at the zero-phonon line (ZPL) with a lifetime-limited linewidth (Lounis and Orrit 2005).

As single molecular photon emitters, planar and rigid polycyclic aromatic hydrocarbons have been actively explored, because of their narrow linewidths below 2K (Toninelli et al. 2021). For example, pentacene, perylene and dibenzo-anthanthrene were used in previous studies (Gaither-Ganim et al. 2023). In particular, dibenzoterrylene (DBT) exhibits high efficiency due to its low intersystem crossing. To fabricate solid-state emitters, such molecular chromophores are often embedded in a host matrix, such as organic crystals, polymers, Shpolskii matrices, which can isolate and protect the molecule from environmental noise. However, the interaction with a host matrix can also influence some properties, including the quantum yield and decoherence (Gaither-Ganim et al. 2023). Recently, a new type of system was reported, consisting of single terrylene molecules absorbed on the surface of hexagonal boron nitride (hBN; two-dimensional material) substrates. This system demonstrates high spectral stability at the ZPL after annealing, and the study indicates the compatibility of single molecules and hBN, which could enable the encapsulation of single molecules between hBN layers to improve the spectral stability (Smit et al. 2023).

State of research and industrialization

In 2023, Murtaza et al. demonstrated the first proof-of-concept QKD system exploiting a molecule--based single-photon source. The system employed DBT molecules embedded in anthracene nanocrystals and exhibited a high purity ($g^{(2)}(0)=0.02\pm0.01$) and efficiency of 8% at room temperature (Murtaza et al. 2023). However, most current R&D activities in this field have focused on basic research. Some experts expressed skepticism regarding the short-term commercialization of molecular-based technologies for QKD systems.

There are a number of researchers working in this field, in universities and RTOs, particularly in Europe (e.g., Germany, Netherland, Italy, and the UK). However, to the best of our knowledge, no companies have yet worked on molecule-based single-photon sources. Some experts view that, unlike quantum dots, which are backed by a long history of semiconductor development, the material fabrication techniques for molecular materials could have still room for further advancement.

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[7] Represents a non-classical nature of lights. Antibunched light has photons equally spaced rather than bunched and is characterized with g(2)(0) < 1.

Capabilities, limitations and challenges

Brightness is a significant advantage of molecular systems, due to their large transition-dipole moments. On the other hand, with respect to the emission wavelength, there is a lack of molecular infrared emitters. To enable their use in fiber-based communication, further development of new molecules or efficient wavelength conversion will be necessary.

Photon purity was already demonstrated to some extent in the proof-of-concept experiment by Murtaza et al. However, maintaining photon purity under strong excitation remains a challenge for improved key-generation performance. To address this problem, further research should explore, for example, novel matrix materials.

It is important to note that the properties of molecular single photon sources differ between room temperature and cryogenic temperatures. Even at room temperature, these systems can exhibit high photon purity but low indistinguishability, as the emission spectrum is broad. In addition, molecules are typically susceptible to photobleaching under ambient conditions. At liquid-helium temperatures, molecular emission demonstrates high indistinguishability from the ZPL with a narrow linewidth close to the lifetime-limit and high spectral stability. On the other hand, as the collection efficiency is often the limiting factor in the overall loss budget (Toninelli et al. 2021), applying nano-optical structures, such as immersion microscope lenses, is a feasible option at room temperature to improve efficiency. However, implementing such a strategy at cryogenic temperature is technically challenging, resulting in lower efficiency. Thus, there are two directions for future technological development: 1) achieving higher brightness at cryogenic temperatures; 2) achieving higher indistinguishability and photostability at room temperature.

Furthermore, entanglement generation based on the cascade mechanism has not been yet demonstrated and may be a future challenge for R&D. In the short term, molecular-based systems would be realistically expected to focus on their use as SPS, not EPS.

Application scenarios (now and in the future)

The room-temperature operation while maintaining high photon purity is a significant advantage of these systems. However, achieving high indistinguishability for some QKD protocols, such as MDI-QKD, requires cryogenic operation.

Some literature highlights the potential advantages of molecular-based materials for applications, including mechanical flexibility, ease of synthesis and fabrication (Gaither-Ganim et al. 2023), and the possibility of on-chip integration (Toninelli et al. 2021).

4.4.2 Two-Dimensional (2D) Materials

Description of technology

Recently, defects on two-dimensional (2D) materials have garnered attention as atomic defect-based single-photon sources. Two major groups of material systems whose defects display distinct physical properties as photon emitters are:

1) *Transition metal dichalcogenides (TMDCs):* TMDCs are semiconductors with chemical composition of MX2, where M represents a transition metal and X denotes a chalcogen.
2) *Hexagonal Boron Nitride (hBN):* hBN possesses a hexagonal structure similar to graphene. Since hBN is an insulator, photon emitters based on hBN are regarded as a variation of color centers in a wide gap material (Becher et al. 2023).

Despite the intriguing optical properties of defects in 2D materials, the origin of single-photon emission has not been fully characterized[8], which presents challenges for achieving reproducibility.

State of research and industrialization

Research on 2D materials as single-photon sources is a relatively new topic and applying them to QKD system has only recently begun. Since 2022, several research papers have demonstrated QKD using 2D materials-based single-photon sources (e.g., the BB84 protocol with WSe_2 (Gao et al. 2023); the B92 protocol in free-space with hBN (Samaner et al. 2022); and the BB84 protocol with hBN (Al-Juboori et al. 2023)).

Most of the R&D efforts in this technology are currently being carried out in academia - particularly in Australia, Europe (e.g., Germany, France and the UK), China and the US - but application-oriented research activities are beginning. For example, in 2024, a research group at the University of Technology Sydney started a spin-off company to commercialize 2D-material-based single-photon source for QKD. In Germany, a research project funded by the German Aerospace Center aims to demonstrate free-space QKD with hBN-based photon sources in a real space environment (Ahmadi et al. 2024).

Capabilities, limitations and challenges

2D materials offer several advantages as single-photon sources compared to other deterministic sources. Firstly, they exhibit good photon outcoupling because the emitters are not surrounded by high-refractive-index materials unlike diamond-based systems or quantum dots. Additionally, 2D systems can utilize full polarization visibility due to the orientation of the dipole to in-plain bond, unlike random orientations in 3D systems. As a common drawback, an indistinguishable single photon emitter based on the material system has not yet been demonstrated (Azzam et al. 2021). Moreover, monolayer-based system tends to suffer from bleaching and blinking[9], depending on the substrates.

Furthermore, two different material systems, TMDCs and hBN, have their own unique properties:

1) *TMDCs:* Photon emission can be quenched at room temperature, as its relatively low exciton binding energy allows excited states to relax thermally. Therefore, they mostly operate as photon sources at cryogenic temperature, typically cooled with liquid helium. TMDCs also face challenges in achieving high photon generation rates (in the tens to hundreds of kHz range (Azzam et al. 2021)) without cavity enhancement. In terms of advantages, their semiconducting nature allows electrical excitation, and some TMDC-based sources cover the telecom bands (1300nm and 1550nm) (Zhao et al. 2021).
2) *hBN:* Defects in hBN are insulated from the band edges, resulting in high quantum efficiency even at room temperature. As a result, hBN exhibits a high photon generation rate, typically in the MHz range. The emission wavelength of hBN defects can be engineered with different fabrication methods. Although theoretical simulations suggest that the defects could emit photons in the telecom range (Shaik and Palla 2022; Cholsuk et al. 2022), it has not yet been demonstrated experimentally and needs to be further explored.

TMDC and hBN are also attractive because of the ease in fabricating single-photon sources. However, a significant challenge for commercialization would be ensuring scalability and reproducibility

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[8] For example, in 2023, a study claims that the single-photon emission of 2D hBN in the vicinity of 2eV originate from the impurity of organic molecules on hBN. Ref: Neumann et al. 2023.

[9] Photobleaching refers to the irreversible photochemical change in materials that makes them unable to fluoresce. Blinking is also known as "fluorescence intermittency" and refers to the phenomenon of random switching between light off and light on. The fundamental mechanisms of such unwanted photophysical properties remain unclear

of the material. Compared with 3D crystals, 2D materials are sensitive to external pressure, such as pushing and stretching, as well as residual strain, which can affect the emitted wavelength. As possible solutions to establish reliable material fabrication, nanoimprint, ion-implantation and electron-irradiation technologies can be considered. Another issue is the difficulty of the fabrication process of optical cavities.

According to interviewees, while it is possible to generate entanglement based on 2D materials through SPDC, it is challenging to identify fundamental advantages of using them in nonlinear processes. Direct entanglement generation has not yet been demonstrated (Azzam et al. 2021). Therefore, the utilization of 2D materials as a single-photon source is more promising than as an entangled-photon source with the current technology.

Application scenarios (now and in the future)

One interesting application scenario involves the use of hBN for satellite-based QKD, leveraging its robustness under severe conditions (Vogl et al. 2019). The ability to operate at room temperature can eliminate cryogenic equipment, which can facilitate meeting the requirements for satellite. In addition, a daylight QKD scheme has been proposed to enable free-space QKD during daytime. In this scheme, information is encoded in the Fraunhofer lines to suppress sunlight noise. Here, the broad spectral coverage of hBN would not be a significant concern, unlike in fiber-based QKD (Abasifard et al. 2024).

4.4.3 Color Centers in Diamond

Description of technology

"Color centers" are crystal defects at which electrons or holes are trapped at point defects within a crystal. These defects can absorb and emit light at specific wavelengths, making them useful as single photon emitters. One particularly interesting material system is color centers in diamond, specifically:

1) Negatively charged nitrogen vacancy color centers (NV-centers) in diamond exhibit long coherence time even at room temperature. However, they have low Debye-Waller (DW) factors[10] (3-5% (Bathen and Vines 2021)), which makes it challenging to apply this technology to conventional QKD, which in general requires high emission rate.
2) Group VI vacancy centers (SiV-, GeV-, SnV-, PbV-centers) in diamond, on the other hand, can provide higher DW factors (70% for SiV (Aharonovich et al. 2011)). However, their spin-coherence time is strongly temperature dependent and degrades at higher temperatures due to the hyperfine structure.

Both of these material systems demonstrate high chemical and mechanical stability, leading to smaller blinking and photobleaching, for example, compared with molecular systems.

As a similar material system to color centers in diamond, defects in SiC have also recently received attention due to their similar spin properties to NV-centers and its commercial availability in the field of high-power electronics. Additionally, rare earth impurities in yttrium aluminum garnet (YAG)/ yttrium orthosilicate (YOS) have become of interest in the past few years due to their extremely narrow linewidth and long coherence time, despite their faint emission.

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[10] In this context, the factor represents the ratio of the emission into the zero-phonon line to the total emission intensity.

State of research and industrialization

In 2014, Leifgen et al. demonstrated a BB84 QKD testbed using NV- and SiV-centers as single-photon sources (Leifgen et al. 2014). Recently, however, the research focus in this field has shifted from applying this material system to simple point-to-point QKD, to other applications. One area of significant effort is the development of quantum memory as a component of quantum networks, leveraging their long coherence time.

Similar to other deterministic sources, the majority of players working on this technology are academic researchers. In 2005, a venture company was founded in Australia with the goal of producing a diamond-based single-photon source for fiber-based quantum communication (The University of Melbourne > 2005), but the company ceased its activities. Currently, Amazon Web Services is at the forefront of the application of color centers in diamond to quantum communications. They are working on scalable fabrication of SiV-centers on diamond nanophotonic devices and demonstrating quantum networking protocols using their SiV platforms. In 2024, the research team successfully demonstrated entanglement of two spin memories based on SiV-centers through a 35km fiber loop (Knaut et al. 2024). In general, however, industrial actors often focus on exploring other applications of color centers, such as quantum computing (e.g., Quantum Brilliance in Australia) and sensing (e.g., NVision in Germany).

Capabilities, limitations and challenges

Becher et al. have pointed out that low extraction efficiency is a common challenge for practical applications of diamond and SiC emitters, limiting entanglement rates and entanglement distribution distance. Furthermore, each emitter mostly exhibits a specific emission wavelength, with the ZPL of NV and group VI vacancy centers only emitting around the visible and infrared wavelengths (Becher et al. 2023).

The key bottlenecks to achieve higher TRLs are material quality and availability for scalable applications, targeted creation of defects with high reproducibility, and nanofabrication techniques to enhance photon-collection efficiency (e.g., integration with optical cavities and waveguides). It is also challenging to address trade-offs between different KPIs, such as photon collection rate, single photon purity, and linewidth. Further research is needed on fabrication techniques, including the application of nanostructures and plasmonic enhancement.

Application scenarios (now and in future)

Some experts believe that color centers in diamond would not offer significant advantages as a single-photon source for QKD compared with other promising technologies, such as attenuated lasers or quantum dots, mainly due to their low emission rate.

Instead, color centers are seen as more suitable as quantum memories in quantum repeaters, which require long spin-coherence time and the ability to emit single photons entangled to a local spin state. Quantum repeaters are a crucial component for quantum networks and are essential for achieving long-distance quantum communication, making this technology valuable in the long term.

4.4.4 Single Atoms and Ions

Description of technology

Sub-Poissonian light statistics were first observed in 1974 using a cascade transition of atoms (Clauser 1974). Since then, atoms and ions have been extensively studied. To manipulate a single atom or ion, it is typically isolated using atom/ion trapping techniques, which confine it with magnetic fields, laser light or electric fields, often in a cavity. Trapping helps suppress the Doppler Effect and collisions with residual gas, resulting in narrow and life-time limited transitions (Lounis and Orrit 2005).

Various species of atoms can be used as single-photon sources. The most extensively researched systems include Rb atoms, Cs atoms, and Sr atoms. Similarly, different ions such as Ca^+, Ba^+ and Sr^+ can also function as photon emitters.

State of research and industrialization

Despite its long history of research, experts assess that the technology is still at the level of demonstration experiments (TRL2) in terms of technological maturity. In addition to academic researchers from universities and public research organizations, trapped atoms and ions are also being explored by startup companies, but often in the context of developing quantum computing[11].

Capabilities, limitations and challenges

The biggest advantage of this technology is that all the sources are identical, meaning that their states are highly reproducible, contributing to very high photon indistinguishability. In addition, single atom systems tend to exhibit longer spin-coherence times than quantum dots.

However, manipulating atoms and ions requires a rigorous trapping setup under ultra-vacuum conditions, which makes it cost-inefficient for normal point-to-point QKD. Another challenge is that many explored systems require wavelength conversion to achieve an optical interface between a memory and an optical system (Arenskötter et al. 2022). Coupling efficiency into an optical fiber is also critical for better performance and can be improved, for example, by developing cavities and multiplexing.

Application scenarios (now and in the future)

Atoms and ions, with their long spin-coherence times and ability to act as quantum emitters, can be used for quantum memories in quantum repeaters, serving as interfaces between light and material. Considering the first quantum processor based on atoms and ions has already been built, this technology has an advantage as a component for quantum networks. In addition, proof-of-concept experiments have already been conducted for memory-based DI-QKD using quantum memories based on single Sr ions or single Rb atoms, leveraging the entanglement between photons and atoms (Zapatero et al. 2023).

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[11] For example, the market players working on trapped ion qubits are Alpine Quantum Technologies, Aquabits, eleQtronGmbH, HonHai / Foxconn, IonQ, neQxt, Oxford ionics, Qudora Technologies, Quantinuum, Quantum Art and Universal Quantum; those on neutral atom qubits are Atom computing, Infleqtion, GDQLABS, NanoQT, PASQAL, Planqc, QuEra and QUANTier.(The Global Market for Quantum Technologies 2024- 2034, (2023), Future Markets, Inc.) To best our knowledge, no actor specifically working on the utilization of such qbits for quantum communication was found.

5 Future Perspectives

This section summarizes and compares the previously discussed light source technologies and their KPIs, limitations, and challenges. It further examines the use of these light sources technologies in QCom systems, especially QKD systems.

5.1 Comparison of Light Source Technologies

Weak coherent sources

Benefits of weak coherent sources include practicality (incl. room temperature operation), ease of use, cost-effectiveness, and compatibility with existing technologies. Challenges arise from their susceptibility to certain attacks, low single-photon purity (requiring decoy protocols).

Table 8: Pros and Cons of weak coherent sources for DV-QKD

Pros	**Cons**
Technology is mature, available, and practical compared to single-photon sources	Despite heavy attenuation, there is vulnerability to photon number splitting attacks due to possible emission of more than a single photon (requiring decoy protocols)
Cost-effective	Degraded performance over longer distances due to attenuation and imperfections in wavelength uniformity
Good compatibility with optical communication technologies and scalability for scalable QKD systems	Requires careful calibration and alignment
Room temperature operation	

Coherent sources for CV-QKD

Fiber lasers and semiconductor lasers (laser diodes) are both used in CV-QKD (Zhang et al. 2024). Fiber lasers can be manufactured to provide a very narrow linewidth (even below 1 kHz) as well as high beam quality (Paschotta 2007) and can be operated at room temperature. Furthermore, in CV-QKD, laser sources can exploit high brightness, facilitating reduced signal degradation over longer transmission distances. However, the susceptibility to noise of CV-QKD protocols is significantly larger, limiting the distances that can be achieved.

Coherent sources enable encoding information in continuous variables such as amplitude and phase. This allows more information to be encoded per light pulse in CV-QKD, which can result in higher key generation rates compared with DV-QKD, where the information is limited to discrete states. However, coherent encoding of information relies on maintaining precise phase relationships, making it particularly vulnerable to phase noise. Similarly, higher laser-beam brightness increases sensitivity to noise and environmental fluctuations. Even minor disturbances might impact the phase and amplitude of the coherent light, leading to signal degradation.

Table 9: Pros and Cons of coherent sources for CV-QKD

Pros	Cons
Established high-performance technology with various commercial options	Higher costs for fiber lasers
High brightness and photon generation rate	Sensitive to noise and environmental fluctuations
Good spectral properties for encoding information	Complexity in maintaining phase stability
Room temperature operation	

SPDC

The main advantage of SPDC sources over weak coherent sources for use in QKD is the direct generation of entangled states, which enables not only entanglement-based protocols, but also opens a path toward quantum communication applications beyond QKD. They are also the currently most commercially advanced entangled photon source technology. In addition, the likelihood of multiphoton emission $g_{(2)}(0)$ can be controlled more effectively with SPDC sources (though at cost of photon generation rate), whereas attenuated lasers are intrinsically prone to photon splitting attacks. On the other hand, the commercialization of weak coherent photon sources is further advanced, and they generally achieve higher key rates.

SPDC sources are probabilistic, i.e., down-conversion events cannot be predicted exactly as they occur spontaneously. SPDC sources can be operated at room temperature and therefore have lower energy consumption and lower system complexity as compared with certain deterministic photon sources, such as quantum dots. On the other hand, they need good temperature stabilization, as the photon quality is strongly influenced by temperature changes (esp. for periodically poled systems). Furthermore, the commercialization of SPDC sources is more advanced than any of the technological approaches to realize deterministic photon sources. Significant competition with deterministic photon sources for use in QKD systems in the short- and medium-term is therefore not expected. Other advantages of SPDC sources are the comparatively straightforward implementation of the relevant telecom wavelengths (e.g., 1550nm) and the good indistinguishability of the entangled photons (≫90% (Wang et al. 2017b)). Realizing both with current approaches for deterministic photon sources requires significant effort.

Table 10: Pros and Cons of SPDC sources for their use for QKD

Pros	Cons
Wide range of wavelength availability	Probabilistic photon source
Providing (high-fidelity) entangled photon pairs	Needs high-intensity input laser
Wide range of operating temperatures	Low conversion efficiency
Decent photon purity achievable	Trade-off generation rate / photon purity
Flexibility (multiplexing, frequencies, materials)	Temperature stabilization necessary
The most mature technology offering EPS	

Four-Wave Mixing

Compared with weak coherent sources, FWM-based photon sources provide comparatively low key generation rates. The main advantage is the ability to generate entangled photon pairs, enabling a wider range of protocols and future applications. Therefore, FWM competes with SPDC sources, but is currently still at rather low level of technological maturity. Many (potential) advantages such as a wide range of wavelengths, high-quality entanglement, and wide range of operating temperature are the same as for SPDC sources. Additionally, lower requirements on the material are a plus for FWM. On the other hand, FWM and SPDC share several drawbacks, such as the probabilistic nature of the conversion process, the low conversion efficiency and the need for high input lasers (that then need to be filtered out). FWM suffers from higher noise levels (e.g. Raman) than SPDC, which is, combined with the low level of technological maturity and lack of commercial availability, the biggest challenge of FWM.

Table 11: Pros and Cons of FWM sources for their use for QKD

Pros	Cons
Wide range of wavelength availability	Probabilistic photon source
Providing (high-fidelity) entangled photon pairs	Needs high-intensity input laser
Wide range of operating temperatures	Low conversion efficiency
High materials flexibility compared to SPDC	Not yet commercially available
	Higher levels of noise (Raman)

Quantum dot SPS

Quantum dot-based single-photon sources (QD SPS) are promising light sources for quantum technologies and quantum communication. They have been demonstrated for many years at R&D level, and further research is ongoing to improve optical properties and fabrication techniques. The wide variety of materials systems, nanophotonic structures, fabrication techniques and modes of excitation (optical, electrical) offer a broad range of possibilities for QD SPS, including a broad spectrum of available wavelengths. Other advantages of QD SPS include the deterministic nature of photon generation, allowing on-demand photon production. QD SPS generally offer good-to-excellent photon properties —including high photon purity, high indistinguishability, and high photon generation rates —and are compatible with CMOS technology. This makes photonic integration feasible. On the other hand, QD SPS generally require cryogenic operating temperatures. Recently, the first commercial systems have been introduced to the market, but they are currently still very expensive.

InAs and GaAs-based QD SPS currently achieve the best photon properties, also due to more established material availability and processing experience. InP-based QD SPS are very interesting because of their emission wavelength in the telecom-band. However, material development and processing techniques are not as established as for InAs and GaAs, and the photon properties achieved to date are worse than those of InAs/GaAs-based devices.

Table 12: Pros and Cons of quantum dot as single-photon sources

Pros	Cons
Wide range of wavelengths available	Cryogenic operating temperatures for many wavelengths and thus complex systems
Deterministic single-photon source (on-demand photon production)	Currently high prices
Good photon properties, incl. high photon purity, and high indistinguishability	Lower TRL than laser sources and SPDC
High brightness / photon generation rate possible	
Compatible with CMOS technology -> good for photonic integration	
Electric injection possible (as compared to other deterministic light sources)	

Quantum dot EPS

The advantages of QD entangled photon sources include the deterministic nature of the light sources, the possibility to realize various wavelengths and the ability to generate cluster states. On the downside, cryogenic operating temperatures are necessary for most relevant material systems (and thus wavelengths), and the technology is currently at a low level of development.

Table 13: Pros and Cons of quantum dots as entangle photon sources

Pros	Cons
Deterministic entangled photons	Cryogenic operating temperatures for many wavelengths and thus complex systems
Cluster states possible (not achievable by classical nonlinear sources)	High costs can be expected, when commercialized
Various wavelengths possible	Lower TRL than SPDC, not yet commercially available

Other deterministic sources

Single photon sources based on molecular materials, 2D materials, color centers in diamond, and atoms and ions have different pros and cons as summarized in the following table. One common drawback of these technologies is their lowest technological maturity among the light source technologies mentioned in this report.

Table 14: **Pros and Cons of other deterministic sources for the use for QKD**

Sources	Pros	Cons
Molecular materials	• High brightness • Inexpensive materials • RT operation is possible • Lifetime-limited at low temperatures	• Photobleaching and low stability at RT • fabrication technologies not established • Lack of telecom band emission • Direct entanglement generation has not yet been demonstrated
2D materials	• Broad spectral range • RT operation is possible (hBN) • High outcoupling, resulting in high efficiency • Utilization of full polarization visibility due to in-plain dipole alignment	• Limited photostability depending on substrate • Emission is sensitive to strain • Emission mechanism is still unclear; Limited reproducibility • Lack of telecom band emission • Direct entanglement generation has not yet been demonstrated
Color centers in diamond	• RT operation is possible (NV-Center) • Good mechanical and chemical stability (photobleaching is unlikely) • Long spin-coherence time	• Low stability in the charged state that has a spin property • Low photon collection and DW factor (NV-center) • Reproducible creation of defects difficult • Lack of telecom band emission
Atoms and ions	• Presenting strong antibunching (high photon purity) • Stable under laser excitation • All the sources are identical, enabling multiplexed indistinguishable photons • Long spin-coherence time	• Vacuum condition and atom trapping required (technically complex) • Low coupling efficiency into fiber • Wavelength conversion is necessary for telecom bands

5.2 Key Challenges

Each technological approach towards light sources for QKD faces unique challenges for widespread commercialization in the coming years. In Table 15, key challenges for different light source technologies are presented.

Table 15: Overview of some of most important technical challenges of different light sources

Technology	Identified challenges
Attenuated laser	• Cheaper sources with wavelength tunability • Lack of specification and certification for components • Reproducibility of Vertical-cavity surface-emitting lasers • Remaining phase and intensity correlation in gain-switch laser
Coherent sources for CV-QKD	• Wavelength tunability in telecom bands • Simultaneous improvement in KPIs (linewidth, stability) • Photonic integration (in the medium term)
SPDC/FWM	• Photonic integration • Engineering of larger systems with multiple sources (more complex) • Adapted security proofs etc. for non-deterministic sources • Simultaneous improvement of relevant KPIs (e.g., photon generation rate and photon purity)
Quantum dots	• Improvement in relevant KPIs (brightness and photon purity in telecom bands, distinguishability for different sources, operating temperature) • Cost reduction • R&D on QD EPS for cluster state generation (beyond QKD applications)
Other deterministic sources	• Future exploration on new materials/material systems • Fabrication technology • Improvement in KPIs/Solving trade-offs between KPIs

Attenuated lasers, the most mature of the discussed technologies for DV-QKD, face not only technical, but also non-technical challenges, such as cost reduction, component specification and certification, and manufacturing technology (reproducibility). Although coherent sources for CV-QKD are also laser-based, they require different specifications, such as narrower linewidths, higher stability at high power, and higher frequency stability.

For sources based on SPDC/FWM, one of the most important KPIs is photon purity, which is a general drawback of non-deterministic sources. For sources based on nonlinear media this is tied to the generation rate and therefore offers limited room for improvement. In addition, photonic integration and multiplexing are required for significantly improving the QKD market potential.

To make the sources widely available, challenges are not only found on the hardware side, but also in security proofs, concepts, and coding techniques.

Although quantum dots have recently attracted a lot of attention from QKD system developers, there is still a need for improvement in various KPIs, especially also cost reduction. In addition, if we consider the materials as components of a quantum network, i.e., quantum memory, further research should be done on the coupling between photons and internal spin states.

There are different technical challenges for various other deterministic sources. Overall, there is still room for improvement in various relevant KPIs, development of new materials and fabrication technology, among others.

Challenges concerning metrology, standardization and certification

Towards broader industrial adoption of quantum key distribution (QKD), standardization and certification are essential (Schmaltz et al. 2025). In 2016, the European Telecommunications Standards Institute (ETSI) published a technical specification on the characterization of optical components for QKD systems, providing the definition and procedures of the measurements for relevant optical components (ETSI 2016).

However, comprehensive measurement standards, reproducible reference implementations, and typical uncertainties have not yet been established for most quantum light source technologies, with the exception of conventional laser sources. Therefore, in addition to improving the KPIs of the different source technologies listed above, further metrological work is required to systematically characterize, benchmark, and validate these emerging light sources.

5.3 Perspectives for the Use of Light Source Technologies in QKD Systems and Beyond

In this section, we discuss future perspectives for the use of different light sources in QKD systems and QCom technologies beyond QKD.

Table 16: Potential of light sources in quantum communication

Light Source Technology	Current use in QCom	Future perspective in QCom
Weak coherent pulses	Widely used in P&M QKD systems	Good prospects to be used in P&M QKD systems also in the future
Coherent lasers for CV-QKD	Used in CV-QKD systems	Used in CV-QKD systems
SPDC	Widely used in Entanglement-based QKD systems	Good prospects to be used in Entanglement-based QKD systems also in the future
FWM	Shown in prototypes (Wang et al. 2016)	One potential path towards photonic integration of QKD systems
QD SPS	Not currently used in QCom beyond R&D	Could potentially be used for advanced QKD protocols; but strong competition of weak coherent pulses

Light Source Technology	Current use in QCom	Future perspective in QCom
QD EPS	Not currently used in QCom beyond R&D	Could potentially be used for entanglement-based QKD; but strong competition of SPDC Cluster state QD EPS potentially for quantum repeaters and/or other beyond-QKD applications
Organic molecules	Not currently used in QCom beyond R&D	Skepticism in its early integration in QKD
2D materials	Not currently used in QCom beyond R&D	Could potentially be used as SPS for DV-QKD but needs more R&D
Color centers in diamond	Not currently used in QCom beyond R&D	Potential for quantum repeaters
Single atoms and ions	Not currently used in QCom beyond R&D	Potential for quantum repeaters

Point-to-Point QKD

Coherent sources are currently predominantly used in commercially available QKD systems for BB84 and CV-QKD. According to experts, these current laser-based sources, when combined with decoy states, could also be used for MDI-QKD systems.

SPDC is recognized as the most promising technology for realizing entangled-photon sources in the short-term. Commercial entanglement-based QKD systems already incorporate this technology. Some experts also indicated that SPDC-based technologies can be promising single-photon sources for future MDI-QKD systems. Furthermore, FWM can open a path towards the photonic integration of QKD systems.

Recent R&D activities have begun to explore the use of quantum dots as light sources for QKD. Although quantum dots offer several advantages over attenuated lasers, such as higher single-photon purity and high indistinguishability, many industry experts still consider the technology to be insufficiently mature for industrial-level QKD applications. Further technological improvements and cost reductions are needed (see section 4 for details of challenges). If these challenges can be overcome, quantum dots could potentially be integrated into different QKD systems, providing improved photon number statistics.

Recently, some research articles have reported proof-of-concept demonstrations for using molecular-based systems and 2D materials in QKD systems, primarily with BB84. However, experts express skepticism about their early integration into QKD systems, due to the lack of commercial efforts and investments in this area. Conversely, some experts optimistically anticipate medium-term implementation of 2D materials in P&M QKD, given the recent R&D efforts toward applications. In general, however, the TRLs of these “other deterministic sources” are considered to be lower than that of quantum dots, and they require further R&D efforts for integration into QKD systems.

Beyond QKD

For quantum networks designed to provide functionalities beyond short-range fiber-based QKD, the required specifications of the light sources are more stringent, and weak coherent sources are often not a viable option. The most relevant quantum communication technologies in this regard are entanglement distribution as a resource for various applications, such as connecting quantum computers, and quantum repeaters for extending the direct sender-to-receiver distance in a quantum network without relying on trusted nodes.

For entanglement distribution, the high-quality generation of entangled photons is essential. Some applications even require complex entangled multiphoton states, known as cluster states, which impose demanding requirements on the photon sources. Most technological approaches to realizing quantum repeaters rely on quantum memories, which must store the quantum information of an incoming photon in a stationary quantum system and later release it by emitting a corresponding photon. The quantum systems investigated for this purpose include quantum dots, neutral atoms, ions, and color centers. The development of deterministic photon sources is therefore paving the way for this type of quantum repeaters.

6 Conclusions

The photon sources, or light sources, for QKD are a key component of the sending unit. Current technologies enable the first commercial QKD systems of different types. Laser-based technologies are widely used in DV- and CV-QKD systems. In CV-QKD systems, they generate pulsed or continuous signals, while in DV-QKD systems for prepare-and-measure protocols they are strongly attenuated to achieve pulses with a high likelihood of containing only a single photon. Decoy-states are implemented to mitigate the risk of photon number splitting attacks that exploit multiphoton pulses. Photon sources based on attenuated lasers that are available at reasonably low costs are widely used in corresponding QKD demonstrations and products and the room for further improvement is limited.

Photon sources based on effects occurring in nonlinear media, spontaneous parametric down conversion and four-wave mixing, are commercially available in first QKD systems of several companies. As these types of sources enable the generation of entangled photon pairs, they support the use of entanglement-based protocols that could potentially open the pathway to a future "quantum network", connecting different quantum applications through entanglement distribution. Achieving high key rates while minimizing multiphoton pulses remains challenging. Paths toward photonic integration, and therefore miniaturization of QKD systems, are given and might be advantageous for FWM-based approaches.

Quantum dots have emerged as promising candidates for deterministic SPS and EPS. Commercially available QD-based photon sources already exist, and recent R&D activities have significantly advanced the use of QDs for QKD. QDs demonstrate a range of characteristics across different material systems, offering high photon purity and indistinguishability with deterministic emission processes. At present, their practical application in QKD is limited by significant challenges, such as high costs and the need for low operating temperatures. While the advantages of using QD-based sources in simple prepare-and-measure protocols are not yet clear, they could prove promising in alternative QKD protocols, although more mature coherent sources and SPDC remain strong competitors. The use of QDs for beyond-QKD applications such as quantum repeaters is another interesting possibility for the future.

In addition to QDs, other deterministic photon sources demonstrate interesting optical characteristics. Molecular-based materials can offer high brightness, photon purity, and the possibility of room-temperature operation. 2D materials can exhibit high emission rates due to their efficient out-coupling. Notably, hBN can operate as SPS at room temperature. Color centers in diamonds, as well as atoms and ions, are expected to be applied to future technologies beyond QKD, such as quantum repeaters. However, all of these sources still face numerous technical challenges for their practical use in QCom applications and their TRLs are still very low (1-4). Further R&D activities are needed to clarify their potential advantages over more mature technologies.

Within the next few years, the key research priority for QKD sending units is the mitigation of potential implementation attacks. Strong and viable approaches are required to pave the way toward the certification and approval of QKD systems for high-security applications. The discussion above demonstrates that the potential for improving the overall performance of light sources varies significantly depending on the type of source and the specific challenges each faces. Furthermore, progress toward scalable QKD will depend not only on source performance, but equally on traceable metrology, standardized characterization procedures, and certification-ready measurement infrastructures. Moreover, the added value is strongly tied to the performance of the photon detector. If a low-cost single photon detector is used, improvements to the light source have limited impact.

Therefore, the presented analysis provides only a narrow perspective on the whole picture regarding large-scale commercialization of QKD systems. Many different components and subsystems define the overall performance of the QKD link, including the various interfaces between them. Nevertheless, the light source is of special relevance, as it generates the quantum states, which inherently define the unique attack surface of QKD-based secure communication.

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