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Optimizing Gas Sensors Based on Quantum Cascade Lasers and Photonic Bandgap Hollow Waveguides

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***Abstract*—In the present study, bending losses in conventional hollow waveguides (internally Ag/AgI coated) and in photonic bandgap (PBG) hollow waveguides (HWG) are compared based on studies via FT-IR spectroscopy and quantum cascade lasers (QCL). To date, literature on bending losses in hollow waveguides focuses on conventional HWG structures (e.g., silica structural tube with internal Ag/AgI coating), whereas the results discussed here compare relative bending losses in novel photonic bandgap waveguides, a new type of HWG progressively more integrated in gas sensors, versus conventional HWGs for the first time. Photonic bandgap waveguides are expected to exhibit lower polarization-dependent relative bending losses due to radiation propagation via omnidirectional reflection, in contrast to conventional HWGs. Accordingly, photonic bandgap waveguides offer superior flexibility and robustness against bending losses in coiled configurations rendering them promising structures for next-generation miniaturized QCL-based HWG gas sensors.**

I. INTRODUCTION

Quantum cascade laser (QCL)-based gas-phase spectroscopy inside conventional hollow waveguides has been demonstrated as a viable sensing platform for applications such as environmental monitoring and breath analysis in the low ppm concentration range[1-3]. The use of photonic bandgap waveguides frequency matched to quantum cascade lasers has further reduced this detection limit down to 30 ppb using a 1 meter long PBG HWG segment[4]. It is anticipated that this limit of detection could be further improved by one order of magnitude by increasing the length of the waveguide to 10 or more meters; however, for practical applications as a portable sensing device and for attaining acceptable dimensions, it is required that the waveguide is coiled.

Hollow waveguides efficiently propagate infrared radiation, while simultaneously serving as a small volume gas cell. This concept is especially useful for QCL-based absorption spectroscopy, where hollow waveguides facilitate intimate contact of photons with analyte molecules within the compact hollow core. The hollow waveguides discussed in the present study are conventional hollow waveguides and photonic bandgap waveguides (Figure 1).

Conventional hollow waveguides[5] are internally coated with an Ag layer, and a thin protective layer of AgI to propagate radiation via metallic reflection inside the hollow core from the light source to a detector. PBG HWGs[6] guide radiation via different propagation mechanisms, i.e., radiation is confined and transported only within the optical bandgaps resulting from periodic structures along the radial direction of the PBG HWG. The photonic bandgap material consists of alternating thin layers of glass and polymer generating an appropriate refractive index contrast. The cladding layer of PBG HWGs is made of polymer material, thus offering superior flexibility and robustness; in contrast, conventional HWGs are mainly fabricated from silica tubing. Conventional hollow waveguides fracture and break easily upon bending to small radii of curvature (< 30 cm). Furthermore, PBG HWGs support radiation propagation in a frequency-selective fashion, thereby facilitating sensing with high signal-to-noise ratio in confined spectral regimes.

Bending losses in conventional hollow waveguides[7-11] and in photonic bandgap waveguides[6] have previously been extensively studied during separate investigations; however, a direct comparison study between conventional and photonic bandgap waveguides has not been reported to date for the purpose of optimizing gas sensors based on these devices. The purpose of the work reported here are systematic studies on bending losses for conventional and PBG HWGs leading to optimized configurations for next-generation QCL–based HWG gas sensors.

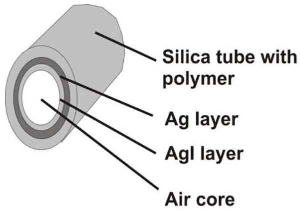

Figure 1. Schematic structure of (a) conventional hollow waveguide, and (b) photonic bandgap hollow waveguide.

II. Experimental

A. Quantum Cascader Laser Equipment

The laser used in these experiments was a pulsed distributed feedback quantum cascade laser operating at 971 cm^{-1} (SPECDILAS® Q-970-GMP-MTE, Laser Components GmbH). The laser was operated at a pulse width of 300 ns, a repetition rate of 1 kHz, and at a temperature of 5 °C. The detector used to evaluate radiation emanating from the distal end of the waveguide was a liquid-nitrogen-cooled mercury-cadmium-telluride (MCT) detector (detector element: 1x1 mm, detectivity D^* = 3 x 10^{10} cm $Hz^{1/2}W^{-1}$, model KMPV 11-1-LJ2, Kolmar Technologies, Newburyport, MA). An oscilloscope was used for resolving the signal and for data acquisition (TDS 3032, Tektronix, Beverton, OR). A total of 512 curves were averaged for each recorded signal.

B. FT-IR Equipment

A Bruker Equinox 55 Fourier-transform infrared spectrometer (Bruker Optics, Inc., Billerica, MA) was used. Spectra were recorded at 2 cm^{-1} spectral resolution averaging 100 scans per measurement in a spectral range of 400-4000 cm^{-1} using the Blackman-Harris 3-term apodization function. The detector applied to collect transmitted broadband radiation was a liquid-nitrogen-cooled mercury-cadmium-telluride (MCT) detector (detector element: 1x1 mm, detectivity D^* = 3 x 10^{10} cm $Hz^{1/2}W^{-1}$, model FTIR-16-1.0, InfraRed Associates, Inc. Stuart, FL).

C. Hollow Waveguides

The conventional hollow waveguide (Ag/AgI internally coated) was cut to a length of 213 cm using a ceramic cutting blade, and had an internal diameter of 750 µm (Polymicro Technologies, LLC.). The photonic bandgap hollow waveguide (Omniguide Communications Inc.) with an internal diameter of 700 µm was cut to the same length as the conventional HWG. During loss studies, the waveguides were fixed at both ends with male FC termination connectors, which were coupled to mechanical mounting fixtures.

D. Measurement Procedure

The overall experimental setup is shown in Figure 2.

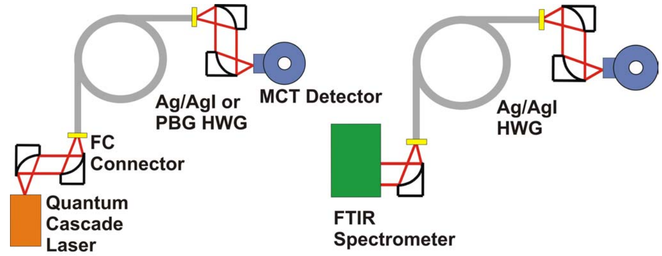

Figure 2. Evaluation of hollow waveguides using (a) a quantum cascade laser, and (b) a FT-IR spectrometer.

Hollow waveguides were first aligned in a straight configuration for providing maximum signal throughput without saturating the detector. Off-axis parabolic mirrors (OAPMs) with a focal length of 2.54 cm were applied to focus the laser radiation into the hollow waveguide (conventional HWG or PBG HWG). One off-axis parabolic mirror with a focal length of 12.5 cm was used to focus collimated broadband radiation from the external port of the FT-IR spectrometer into the input side of the conventional HWG.

Radiation was focused onto the detector after transmission through the waveguide using two OAPMs. The optical alignment was not changed throughout the entire experiment to ensure that the only variable parameter was the bending radius of curvature of the waveguide. The detector signal was recorded first in the bent waveguide configuration followed by the straight waveguide position. This procedure was performed for both the conventional and the photonic bandgap waveguides with the quantum cascade laser light source, and with the conventional HWG in addition using the FT-IR spectrometer. Waveguides were coiled around diameters of 13.5, 16, 21, 26.8, and 36.7 cm, and the experiments were repeated 3 times each keeping the bent section of the waveguide constant at a length of 152 cm, and the straight section of the waveguide constant at 30 cm before and after the bended section. In the case of QCL measurements, the laser was rotated by 90 degrees clockwise to change the polarization status of the emitted radiation.

III. Results and Discussion

A. Bending Losses of Hollow Waveguides using a Quantum Cascade Laser

The total relative waveguide loss is considered as the logarithmic ratio of optical throughput signal in the straight waveguide position versus the bent waveguide position. Figure 4 depicts this relationship as a function of coil diameter.

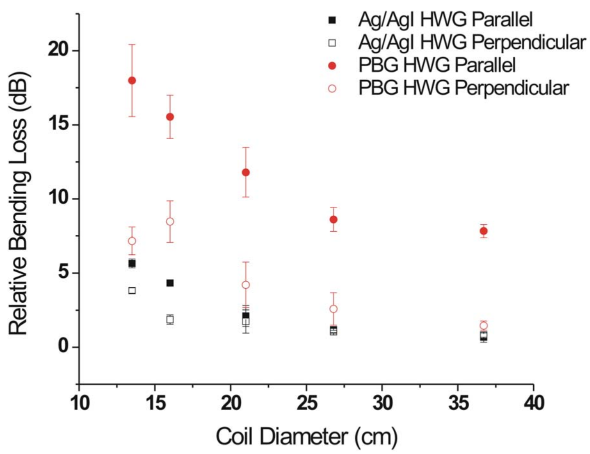

Figure 4. Experimentally determined total loss in conventional and photonic bandgap waveguides using a quantum cascade laser. The nomenclatures "parallel" and "perpendicular" indicate relative relationship between the polarization direction of the laser radiation and the plane of bending. The plane of bending is defined as the plane where the coiled waveguide exists.

Total bending losses increase as the coiling radii get smaller for both types of HWGs. It was also found that coiling waveguides parallel to the polarization direction of the radiation results in more losses for both types of HWGs as well. Radiation emitted from the QCL is polarized, and the direction of polarization can be selected depending on the mounting position of the laser chip inside the housing; accordingly, the high and low loss plane can be interrogated by rotating the laser chip by 90 degrees. In the case of parallel polarization, the PBG HWG loss value of 1.27 dB for a 21 cm coil diameter compares well with the previously reported literature value of approximately 1.05 dB[6] at the same radius of curvature for a 90 degree bend. This comparison results from dividing the total relative bending loss in the coil diameter by the number of coils for deriving the loss per 90 degree bend.

B. Bending Losses of Hollow Waveguides using a FT-IR Spectrometer

The same procedure was performed for conventional hollow waveguides coupling broadband radiation from a Fourier-transform infrared spectrometer into the waveguide, however, without particular polarization of the emitted radiation. Figure 5 displays transmission spectra through straight and coiled Ag/AgI internally coated hollow waveguides.

It was found that propagation losses in coiled conventional hollow waveguides are similar to, but somewhat less using broadband radiation as opposed to QCL radiation, where the range of QCL bending losses in parallel polarization amounts approximately 0.68-5.65 dB, and the range of FT-IR-determined bending losses approximately 0.56 dB – 1.91 dB. The discrepancy between these two ranges may result from different coupling conditions into the hollow waveguide structure.

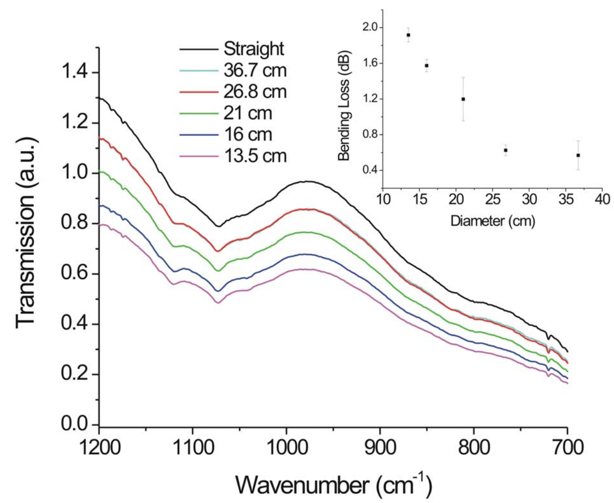

Figure 5. FT-IR-based transmission measurements of Ag/AgI coiled hollow waveguides. The inset shows the bending losses inside conventional hollow waveguides vs. the coil diameter.

The transmission window at a particular wavelength is particularly important for FT-IR-based HWG gas sensing. Conventional hollow waveguides propagate broadband infrared radiation; however, optical transparency is not uniform throughout the mid-infrared spectral regime (typically 4000-400 cm^{-1}). The internal dielectric coating thickness can be altered to optimize transmission for a particular wavelength[5]. The achievable limit of detection for a HWG-based gas sensing device relies on the frequency position of the absorption wavelength of a particular analyte weighed against the signal-to-noise ratio achievable, and given the attenuation of the waveguide within the relevant wavelength band.

Photonic bandgap waveguides are designed to only propagate radiation within the optical bandgap, similar to an optical bandpass filter. FT-IR-based studies at PBG HWGs are currently in progress. However, mid-infrared photonic bandgap waveguides are engineered for applications using monochromatic radiation sources such as e.g., CO_2 lasers or quantum cascade lasers with the laser emission wavelengths matched to the photonic bandgap provided by the waveguide for establishing efficient radiation delivery systems in laser surgical applications, or for sensitive and selective platforms applicable in gas sensing of complex matrices with low limits of detection[6].

IV. Conclusion and Outlook

In this study, bending losses for different radii of curvature for conventional HWGs and PBG HWGs were measured with two different types of radiation sources, i.e., QCLs lasing at 10.3 μm, and broadband mid-infrared radiation provided by a FT-IR spectrometer. Relative bending losses for both waveguides were studied with polarized QCL radiation and broadband FT-IR radiation. The research goal of these studies is taking advantage of an increased interaction path length utilizing coiled HWG configurations without trading-off the compact form factor of HWG-based sensing systems. Studies on the bending losses for a variety of HWG materials will provide the fundamental information for optimizing the bending radius and the ratio between straight sections versus bent sections for future miniaturized gas sensor design.

ACKNOWLEDGEMENT

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