

Wideband Protection Filter – Single Filter for Laser Damage Preventing at Wide Wavelength Range

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ABSTRACT

We present a passive, solid-state threshold-triggered Wideband Protection Filter (WPF) that blocks the transmission only if the power exceeds a certain threshold. We demonstrate the protection ability of the WPF against laser threats including protection behavior for single and series of pulses. The WPF can be readily used for protection of detectors, cameras, or eye safety.

Keywords: Wideband filter, threshold filter, nonlinear filter, laser damage prevention, sensor protection, sensor hardening, optical power limiting

1. INTRODUCTION

High power laser radiation when impinging on imaging or detection systems can seriously interrupt the signal. Interruption may start from transient saturation and can lead to permanent damage. The problem exists in imaging sensors comprising of CCDs and other matrix detectors, human eyes or other imaging and non-imaging sensors. Protection from high power laser radiation employed already in the field is performed using fixed absorptive spectral filters used to block specific laser wavelengths. These types of filters block power at a specific wavelength regardless of the power level. The major drawbacks of this solution are that the color impression may be affected and that the protection is limited to specific wavelengths only, whereas the threats can exist in any other laser wavelengths.

Another type of protective mechanism, which is not yet widely employed in field application, is based on non-linear optical limiter performed with particles suspensions. This mechanism type is based on power dependent transmission. When power exceeds a certain level, the filter limits the output power to a certain level, whereas, at low power level the filter is ideally transparent. Various mechanisms have been extensively explored, among which we can consider nonlinear absorptive optical limiting [1,2] and nonlinear scattering mechanism [3,4,5,6]. Most of the above mechanisms are wavelength sensitive and are most suitable for the green wavelength range. Some mechanisms, such as scattering, are wideband but are lacking important properties such as: environmental low temperature resistance, high repetition rate response and short pulses response. The protection mechanism based on suspension suffers from slow recovery from high repetition rate laser threats. Also, the response time is slower than nanoseconds and therefore cannot be applied for shorter pulse durations. Another drawback of these is the integration difficulty within various optical systems due to special holders and mechanics required for holding liquid unit.

We propose another mechanism, which we define as “blocking” [7] and is based on solid-state layer sandwiched in between two substrates. We demonstrate a passive, solid-state threshold-triggered Wideband Protection Filter (WPF) that blocks the transmission only if the power exceeds a certain threshold [8]. As opposed to fixed spectral filters, which permanently block only specific wavelengths, the wideband filter is clear at all wavelengths until it is hit by damaging light. At input power below threshold, the filter has high transmission over the whole spectral band. However, when the

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input power exceeds the threshold power, transmission is decreased dramatically. This decreased transmission is limited to the hitting point. As opposed to the suspensions mechanism, the spot becomes permanently opaque and remains so even after a long exposure to high power. The filter response time is faster than the nanoseconds time scale and can withstand high repetition rates such as kHz without any degradation of blocking efficiency. The WPF can be readily used for protection of detectors, cameras, or eye safety. Within this paper we demonstrate the protection ability of the WPF at several laser wavelengths including protection behavior for single and series of pulses.

2. WPF BLOCKING MECHANISM

The WPF is a totally passive component, designed to protect from excessive optical power transmission. The WPF is a free space device suited for imaging and detection applications such as sensors, cameras and the human eye protection. The WPF is solid-state, and is composed of an active layer sandwiched between two parallel optical windows. Figure 1 presents a photo of a WPF sample; this samples are 1” in diameter, and its optical quality is similar to that of typical 1” optical windows.



Figure 1: Wideband Protection Filter component

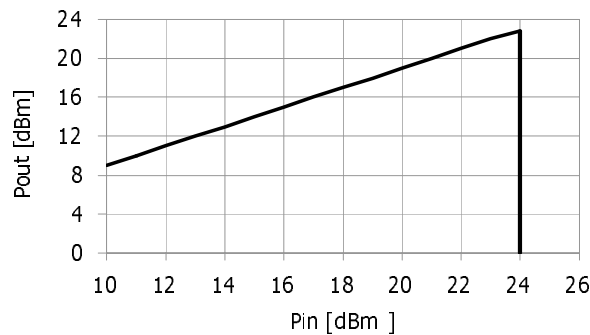


Figure 2: Optical power blocking effect – interruption of optical transmittance by catastrophic breakdown. Based on nano-structures that are used as threshold triggered switches

The WPF mechanism is based on the “blocking” mechanism, which is similar to the “optical fuse” [7] and is illustrated in Figure 2. At power levels below the threshold level, transmission is high and output power follows input power linearly. When input power level increases above the threshold level, transmission decreases dramatically and filter becomes permanently opaque within the illuminated spot. The basic non-linear phenomenon that occurs when the WPF is hit by high power laser light is catastrophic breakdown. The active layer of the WPF consists of nanostructures that enhance the effect of high electro-magnetic fields, leading to a strong breakdown effect under high optical power density. The catastrophic breakdown results in enhanced scattering from the active layer, leading to significant decrease

in transmission. That spot of decreased transmission in the WPF becomes permanently opaque and remain as so for long exposures to high power laser light. In order to obtain the optical power density required for the breakdown effect, the WPF should generally be placed at or near the focus of the system (see Figure 3).

The WPF reacts to both continuous and pulsed damaging lasers. The reaction of the WPF is fast, so the switch-off is fast enough to intercept damaging optical power before damage occurs, as it can easily operate in the nanosecond range and less. Protection is both wavelength- and impingement angle independent, so the same WPF can block various lasers from various directions. Also, as the WPF is generally placed at or near the focus, most of the field of view remains transparent even after operation of the WPF; the opaque spots are local and limited to the spots exposed to the high power. These spots remain opaque for all wavelengths for long exposures to high power light.

Blocking efficiency is more than two to three orders of magnitude. Also, the opaque spot generally scatters the light of impinging beams, so the small residual transmitted beam through this spot is quality-degraded.

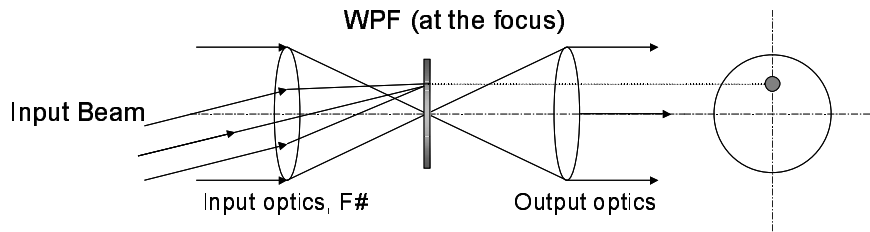


Figure 3: Schematic, cross-sectional view of a WPF within an optical system

3. WPF BLOCKING RESPONSE TESTS

In order to evaluate the filter in terms of laser protection response we define the blocking efficiency (BE) as follows

$$BE = 10 \log \left(\frac{E_{in}}{E_{out}} \right) \quad (1)$$

Where E_{in} and E_{out} are the laser pulse energies at the filter input and output, respectively.

The BE corresponds to the filter's protection capability, e.g. the ability to block a high power laser pulse aiming to the optical system and may cause damage to the system or human eye. High-energy laser pulse entering the filter through the optical system and is blocked by the filter response. As a consequence, the energy arriving to the protected end, detector, sensor or the human eye is reduced and can no longer cause any damage. The BE therefore defines the portion of the energy arriving to the protected end. The BE depends on the laser input energy level. Below a certain level, the filter's BE is equal to its linear transmission value of 1-2dB. Above a predetermined threshold level, the BE can reach 20 to 30dB. This threshold level can be designed and tuned according to pre-defined requirements, by variation of filter layer parameters.

We have to emphasize that even though the BE is a measurement of the energy portion passes the filter, it does not take into account the laser beam quality, shape and size at the exit of the filter. It is known [9] that laser induced damage depends on the laser beam profile, shape and size. In general we can say that small spot size will cause greater damage to most of the components to be protected within the optical systems. Since the WPF scatters the propagating light for high-energy laser pulses, the residual laser beam diameter reaching the sensor or eye will be enlarged in such a way to decrease even more its ability to perform damage.

In this section we will present the blocking response setup, the experimental procedure, example for filter protection results and we will end by discussion.

3.1 Setup description

The limiting behaviour of the WPF-protection filters (i.e. attenuation or transmission) was studied in dependence of the input laser pulse energy on the filter. As laser source we used a Q-switched and frequency doubled Nd:YAG-laser (Coherent, Infinity) working at the wavelength of 532 nm with a pulse repetition rate from single shot up to 100 Hz. The pulse width was less than 3 ns and the maximum pulse energy at the laser output 350 mJ. A sketch of the test set-up is shown in Figure 4. The laser power was measured using the Ophir power meter (Mod. LaserStar) equipped with an 3A-P-CAL detector head. Beam attenuation was achieved using a $\lambda/2$ -plate in combination with a thin film polarizer and with a set of neutral density filters. To work under far field conditions the 5 mm laser beam was expanded to a diameter of 33 mm with a 6.7x – Galileian telescope and then sent to the optical test-unit which contained the protection filter.

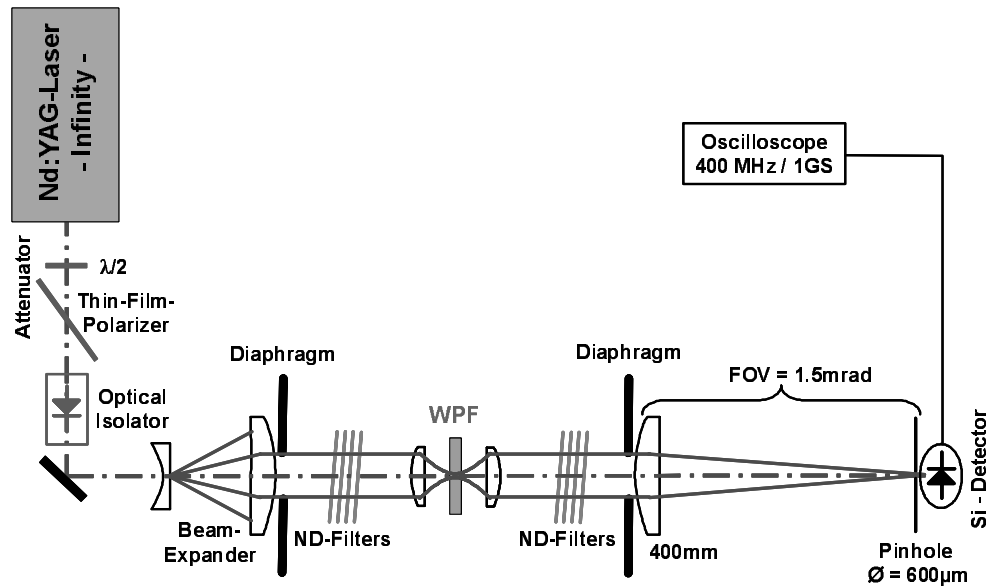


Figure 4: Sketch of the experimental set-up.

Typical field optics like binoculars, telescopic sights or periscopes have f-numbers in the range of $f/3$ to $f/8$. Therefore the protection filters shall be tested with an optical set-up which meets an f-number in that range. As a rule it is common to work with optics close to an f-number of $f/5$.

The optical test-unit had an entrance aperture of 12 mm ($1/3$ of the expanded beam diameter) and consisted of two symmetrically mounted plane-convex lenses with focal lengths of each $f = 70$ mm leading to magnification one (1:1 telescope) and to an f-number of $f/\# = 1/5.8$.

The protection filter was carefully positioned in the intermediate image plane of the test unit via monitoring the strongest attenuation when shifting the filter along the optical axis (see 3.2).

To identify the residual hazardous energy transmitted through the protection filter, a further optical system was used to represent the human eye. A good measure for the energy hazardous to the human eye is the focusable energy, often also referred to as *encircled energy*. This is the amount of energy passing through a small hole in the focal plane of a lens. According to the DIN-EN 60825-1, the aperture and the lens were chosen in that way to define a field of view of 1.5 mrad. That is, since an eye damage usually results in a loss of vision of 1.5 mrad, which is nearly independent of the damaging energy. Thus the transmitted pulse energy was gathered using an $f = 400$ mm lens and an aperture of $600 \mu\text{m}$ in diameter, positioned in the focal plane of that lens. Behind the aperture a calibrated fast Si-detector and an oscilloscope were used to determine the amount of the transmitted energy.

3.2 Experimental procedure

Since the functional layer of the WPF-filter was very thin the filter had to be positioned very keenly in the intermediate image plane of the test unit. This was achieved via monitoring the strongest attenuation (at a constant input energy) when the filter was shifted along the optical axis (z-scan). As the filter would be damaged with each single laser pulse the procedure for this part of the measurement was always to go to a new spot on the filter for each individual step along the z-position.

To study the pulse to pulse degradation of the WPF-filter in dependence of the pulse repetition rate, series of pulses were sent onto the WPF-filter. As like just described, also for the determination of the energy dependence of the WPF-filter's transmission a new spot on the filter had to be chosen for each individual value of the pulse energy and for each pulse-series. With an oscilloscope a series of 20 pulses was recorded for each pulse energy and subsequently analyzed.

3.3 Results

Z-scan results are summarized in Figure 5, where the BE in dB as a function of unit distance from the focus in mm is illustrated. The focus is defined as the z point where the BE is maximal for both the 1st and 2nd pulses. There is an additional blocking of more than 10dB for the 2nd pulse over the 1st one. This ratio is kept around 10dB even when sample is placed out of focus and the overall blocking efficiency decreases.

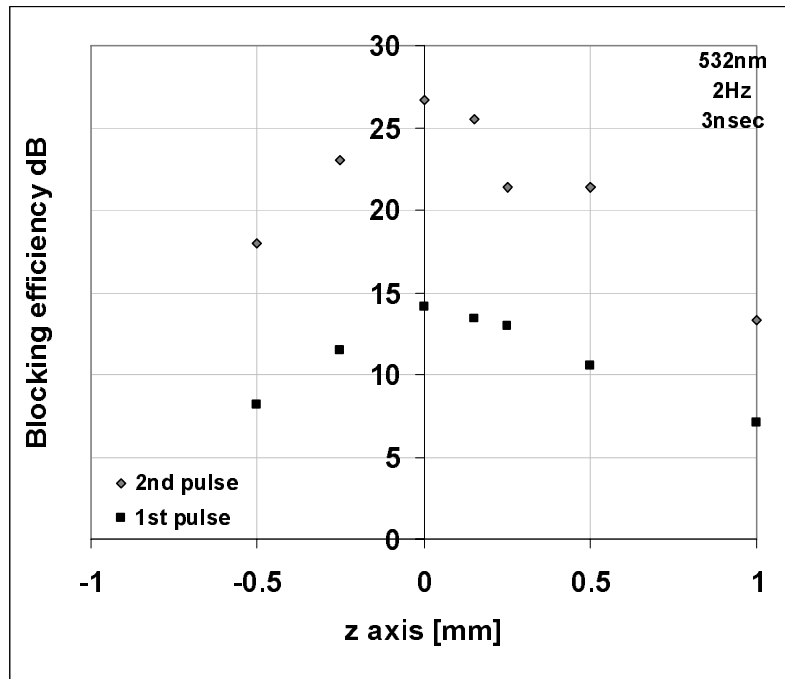


Figure 5: Blocking efficiency in dB as a function of WPF distance from focus for 1st and 2nd pulse with repetition rate of 2Hz

The optimum sample position is determined from the z-scan results according to the maximal BE. Then, the protection ability is measured for series of input energies (refer to Figure 6) for 1st, 2nd and 3rd pulses at 2Hz repetition rate. Below a certain energy level, the blocking is simple the linear transmission which is measured to be 1.5dB, which is equal to 70% transmission. Passing a certain threshold and the blocking efficiency increases with increasing input energy. The blocking efficiency increases even more for every additional input pulse and can get up to 10dB additional blocking between the 1st to 2nd pulse and between the 2nd to 3rd pulses. Testing the WPF for series of pulses reveals the same phenomena of increasing blocking efficiency with increasing number of pulses. After 10 pulses usually the blocking value stabilized on a certain value and stays there even after hundreds of pulses.

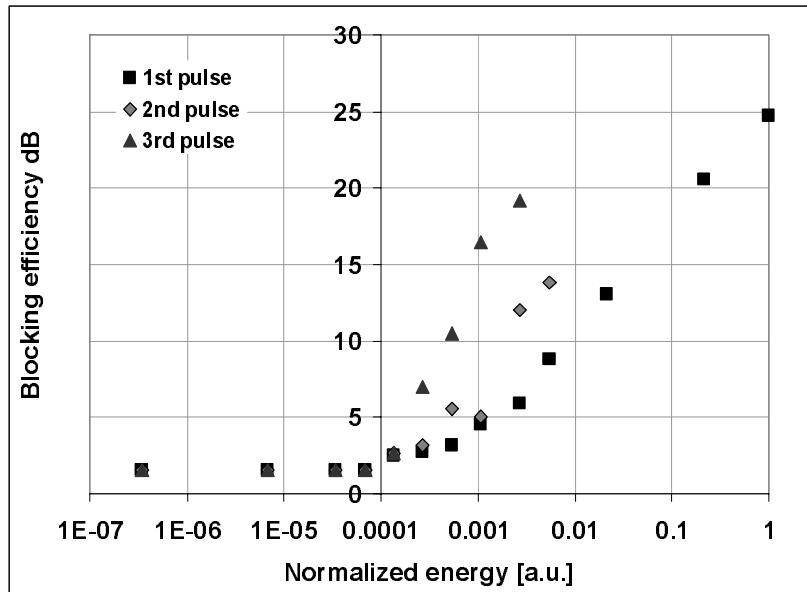


Figure 6: Blocking efficiency as a function of normalized input energy for 1st, 2nd and 3rd pulses for repetition rate of 2Hz

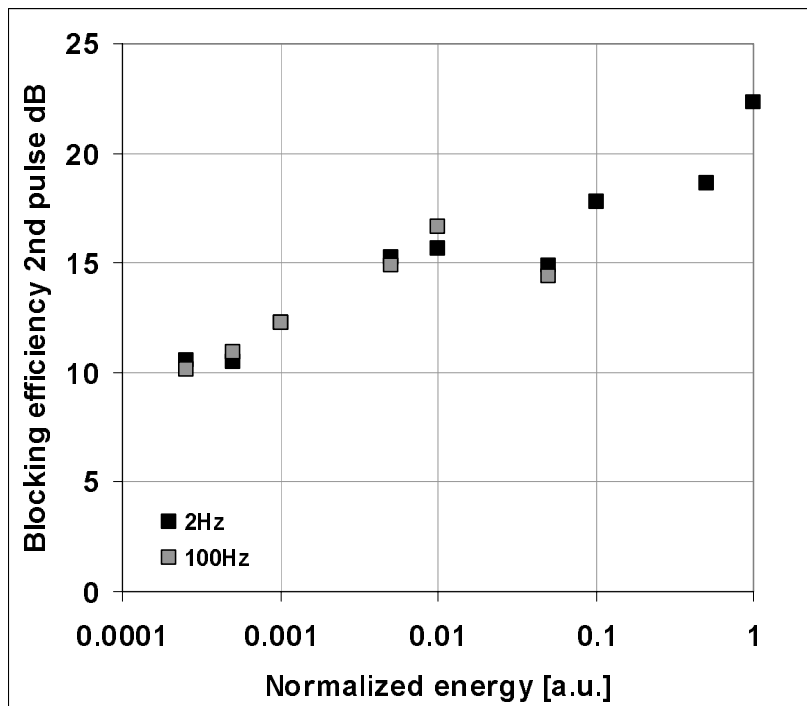


Figure 7: Blocking efficiency of 2nd pulse as a function of normalized input energy for repetition rates of 2Hz (black) and 100Hz (gray)

Protection filter based on particles suspensions do not respond well to high repetition rates, whereas WPF solid-state based protection filter blocking response does not degrade with repetition rate increasing. Figure 7 presents the blocking

efficiency of the 2nd pulse as a function of normalized energy for 2Hz (black) and 100Hz (gray) repetition rates. There is obviously no degradation in blocking efficiency when repetition rate increases.

3.4 Conclusions

We defined the term of blocking efficiency (BE) as the evaluation value for the WPF protection ability. We demonstrated z-scan experimental results utilized for optimum unit placement. We discussed the BE increase with number of pulses and input energy. We also presented 2nd pulse blocking efficiency values similar for low and high repetition rates.

4. APPLICATIONS

We presented a passive, solid-state threshold-triggered Wideband Protection Filter (WPF) that blocks the transmission only if the power exceeds a certain threshold. One of the straightforward applications is the use of this filter as eye protection when implemented within the focus of imaging systems such as sights and binoculars. Due to its high transmission within the linear power region, it has no effect of the image quality, for daily use. However, when a over threshold power pulse laser arrive at the imaging system, the WPF becomes permanently opaque within the laser hitting spot formed in the imaging focal plane. The opaque spots are limited to the exposed areas only – most of the field of view remains transparent after exposure to high power. Which means that system imaging ability sustains even after the laser attack. The opaque spots generally scatter the light of impinging beams, so the small residual transmitted laser beam through this spot is quality-degraded, which lower even more the damage risk to the eye. To summarize, on daily use, there is no degradation of imaging quality with WPF within the system. When a laser hit the system, the WPF blocks the laser beam and letting only a quality degraded fraction of the beam to pass and reach the eye. This residual beam can no longer damage the eye, resulting in eye protected imaging system.

Another possible application is the use of the WPF as cameras protection against possible damage due to high power laser pulses. In this case the WPF should be implemented as nearest as possible to the CCD, so to be placed within the Rayleigh range of the system focus. The WPF protection general mechanism in this case is similar to the one described for the eye protection with the exception of placing the protector near the object to be protected in this specific example. Whereas the protection capabilities remain more or less the same, the integration process might involve additional mechanical issues to be solved. After integration is performed the camera is protected within the visible and near IR wavelength range from any possible laser threat.

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