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REAL-TIME DETECTION OF OPTICAL DAMAGE INDUCED BY HIGH-POWER LASER PULSES

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The paper presents the results concerning the development and the implementation of a method and a device to detect in real-time the laser-induced damage of optical surfaces. The damage detection device is integrated in an automated station to measure the laser-induced damage-threshold of optical components according to the appropriate ISO standards, within the Laser Department of the National Institute for Laser, Plasma & Radiation Physics, Bucharest, Magurele.

Keywords: laser-induced damage, real-time damage detection, ISO measurements.

1. Introduction

Recent years witnessed a dramatic growth in the power and the diversity of uses of various lasers. The increase of laser power requires higher quality, advanced optical components, able to withstand high values of laser induced damage threshold (LIDT). For example, the Extreme Light Intensity-Nuclear Physics (ELI-NP) project, to be implemented in Bucharest, Romania within the next couple of years, is intended to achieve (approximately) a peak pulse power of 10 PW, a 20 fs pulse length, and a beam diameter of 500 mm, so the laser components have to work safely at this high levels of pulsed power density (irradiance) and pulsed energy density (fluence) [1].

To improve the manufacturing technology of the optical components for high power lasers, the LIDT has to be determined as accurate as it could be. The damage threshold of an optical component subjected to repeated laser pulses can be affected by a variety of different degradation mechanisms including thermal heating, contamination, migration or generation of internal defects, and structural changes, to name only a few. To account for the influence of different factors on the LIDT value, the ISO standard 21254-2 [2] recommends to measure LIDT by

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using a multiple-pulse test, referred to as the S-on-1 test. This test is based on a protocol that applies a series of up to S laser pulses with constant energy density at each unexposed test site, and stops the delivery of the remaining pulses immediately after a permanent damage occurs at that site, generally after N pulses ($N \leq S$). Therefore, a real-time damage detection system is necessary. Its function is to determine in real-time the appearance of a permanent damage on the irradiated site. This information is further used to determine the exact number of pulses, N, at which that particular site was permanently damaged and to stop the subsequent laser pulses to hit the site after the damage occurred. The damage threshold of a site is defined as the minimum fluence or irradiance level at which any permanent laser radiation-induced change of the surface characteristics of the specimen which can be observed by an incident-light microscope having Nomarski-type differential-interference contrast with a total magnification of at least 100x - 150x [3].

ISO 21254-4 [4] recommends several methods for online damage detection of the surface under test: scatter detection techniques, plasma and thermal radiation, monitoring changes in reflectance - transmittance, online microscopy, fluorescence. Of all these, the scatter detection technique has a series of convenient characteristics: fast response time (in the nanosecond range), clear correlation to morphological damage, suitability for automatic sequences, high sensibility and reliability, relatively low cost. The technique to monitor reflectance – transmittance changes has similar characteristics, but, once implemented, it is less flexible to be used to a broad variety of optics (i.e., high reflecting, partial reflecting, and high transmitting). Consequently, we selected to use the scatter detection technique because of its advantages specified above.

In Section 2 the scatter detection techniques for real-time detection of the optical damage are analyzed, and the specific scatter detection technique to be implemented is established. Section 3 describes the experimental results concerning the implementation of this detection technique on the automated test station for ISO measurements of LIDT, currently in development within the Laser Department of the National Institute for Laser, Plasma & Radiation Physics (INFLPR), Bucharest, Magurele. The performance parameters of the implemented scatter-based detection device are measured and discussed. Section 4 concludes the paper.

2. Scatter detection techniques

The most used real-time damage detection is the collection of laser radiation scattered by the component under test [4]. The sudden increase in optical scattering of the test site is interpreted as a direct consequence of the sudden altering of the surface properties by the contributing damage mechanisms. The damage detection can be performed either directly, by the detection of the scattered radiation from the laser beam inducing the damage (here called the test laser beam), or by detecting the scattering of another beam from a separate laser hitting the test site coincidently with the test laser.

In devices based on scattering of the test laser radiation, the technique is implemented with an additional optical system collecting the scattered radiation on a detector, as it is shown in Fig. 1.

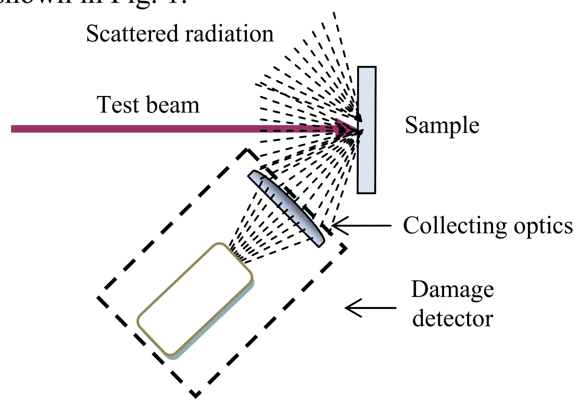


Fig. 1. Schematic of damage detection by monitoring the test beam laser radiation scattered by the sample under test.

For setups with a separate laser source, a laser with excellent pointing and optical power stability is used as a radiation source (see Fig. 2). By using beam-forming and focusing optics, the laser beam is concentrated onto the actual site under test. The scattered radiation is collected by a lens and detected by a photodetector. The fraction of the laser beam reflected by the specimen surface is cut out by a stop aperture. To achieve high sensitivity and low interference with other light sources in the environment of the setup, phase sensitive detection techniques and an interference filter for the laser wavelength are recommended.

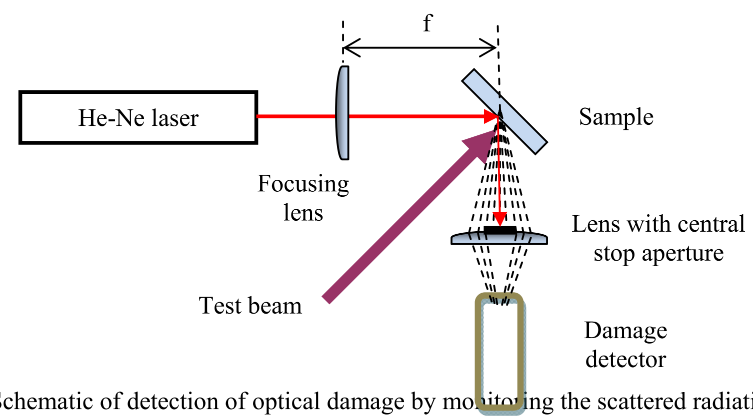


Fig. 2. Schematic of detection of optical damage by monitoring the scattered radiation of a separate laser beam.

In all setups, the temporal resolution of the photodetector output has to be fast enough to identify the onset of damage instantly in correlation to the individual pulses of the test laser [4].

A silicon photodiode of large active aperture, to collect as much scattered light as possible, is normally used as a damage detector. To analyze the photodiode response to an ideally rectangular pulse of scattered light, we use the simplified equivalent circuit shown in Fig. 3.

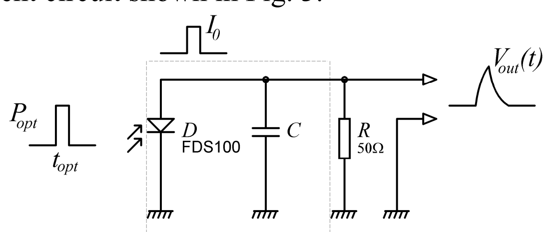


Fig. 3. Equivalent circuit of the photodiode from the detection circuit.

Here *D* represents the photodiode, P_{opt}, t_{opt} are the optical power and the duration of the scattered laser pulse collected by the photodiode aperture, respectively, I_0 is the amplitude of the photocurrent pulse generated by the photodiode, *C* is the equivalent terminal capacitance of the photodiode, *R* is the load resistance. The photodiode is used in zero DC bias (photovoltaic) mode, and its shunt resistance (ideally infinite) and series resistance (ideally zero) are neglected in this analysis. The photodiode response to the input rectangular light pulse, i.e., the output voltage $V_{out}(t)$, is modeled by the equation

$$V_{out}(t) = RI_0(1 - e^{-\frac{t}{RC}}) \quad (1)$$

from which we can see that the maximum level of the output signal, $V_{out} = RI_0$, is achieved for relatively long laser pulses, with durations $t_{opt} \geq 3RC$.

Large-area photodiodes in the zero bias regime are relatively slow devices having equivalent terminal capacitances of few nanofarads, corresponding to time constants *RC* of hundreds nanoseconds on a 50 Ω load resistance [5]. The equivalent terminal capacitance is the sum of the package capacitance and of the photodiode junction capacitance. The latter decreases with an applied DC reverse voltage on the photodiode (when used in photoconductive mode, for real-time detection of short light pulses), due to the proportional increase of the depletion layer's width with increasing reverse voltage. In our case, the opposite is true, the photodiode operates in zero DC bias and its junction capacitance has a maximum value [6]. Consequently, *RC* is large, as mentioned above, and for short laser pulses, with t_{opt} in the nanosecond range or less, the condition $t_{opt} \ll RC$ is fulfilled, and Eq. (1) can be approximated by

$$V_{out}(t_{opt}) \approx RI_0 \cdot \frac{t_{opt}}{RC} = \frac{I_0 t_{opt}}{C} \qquad (2)$$

From Eq. (2) we can see that, within this temporal ranges, the amplitude of the photodiode output is independent of the load resistance value.

The shape of the photodiode output signal for a short (i.e., $t_{opt} << RC$) input light pulse has a short leading edge and a much longer trailing edge (see Fig. 6, below, for a typical shape in our case; neglect the high frequency noise on the leading edge, which is induced by electric parasites, discussed at Section 3). Two factors contribute to the duration of the leading edge of the output signal: the rise time of the optical pulse and the small time constant given by the small series resistance of the photodiode and the equivalent terminal capacitance. These two factors were neglected in Eq. (1). The duration of the trailing edge of the output signal is determined by the RC time constant corresponding to the discharge of the equivalent terminal capacitance through the load resistor.

The technique based on scattering of test laser radiation provides a high sensitivity to damage occurrence, due to the high optical power of the nanosecond or femtosecond pulses applied on the specimen under test. For example, a nanosecond-range test pulse of 5 mJ energy and effective duration of 6 ns has a corresponding optical peak power $P_{opt} \approx 0.8$ MW. If only a 10^{-5} - 10^{-3} fraction of this power is collected by the damage detector, it means that peak-power levels of tens-hundreds watts are incident to the photodiode aperture, and that power can saturate and even destroy the photodetector. Therefore, an optical attenuator has to be interposed between the collecting optics and the photodiode aperture to limit the photocurrent at a reasonable value in the milliamps range.

By appropriate adjustment of the optical attenuation (i.e., of the I_0 value), this technique can discriminate small, incipient damages of the optical surface under test. It is preferable to use a 50 Ω load resistance to improve the temporal resolution of the detector and to reduce the environmental light noise contribution to the output signal. Besides the pulsed light noise (induced by the laser light being scattered from any other surfaces except the site under test, and by potentially other pulsed light sources), the electrical noise is also of concern. The most important sources of electrical noise are the power supplies of the pulsed laser sources used for LIDT measurements and other related devices, as, for example, the fast switching power supplies of the measurement setup.

The detection technique based on a separate laser source is optically less sensitive than the one described above, because the monitoring laser is a low-power continuous wave (CW) laser (usually, a He-Ne laser or a visible red diode laser). To compensate for this, it is necessary to significantly increase the load resistance over the recommended 50 Ω value. Also, to maximize the detector response V_{out}, the modulation period of the CW monitoring beam (i.e., the t_{opt} duration) have to be higher than the time constant RC of the circuit, according to

Eq. (1). This means a lower temporal resolution, which can limit the use of this technique with femtosecond test lasers that operate in the kHz range of pulse repetition rates.

As a conclusion, we consider the damage detection technique based on scattering of the test laser radiation as the most suitable one for our application, due to its higher sensitivity, its faster temporal resolution, and the structural simplicity.

3. Experimental results

The schematic of the test station for multiple-pulse damage tests of optical surfaces according to the S-on-1 ISO procedure is illustrated in Fig. 4. The nanosecond laser source is an electrooptically Q-switched Nd:YAG laser (Brilliant B SLM, Quantel) operating in a single longitudinal mode at 1064 nm wavelength, 10 Hz pulse repetition rate, 0.7 J maximum pulse energy, 6 ns effective pulse duration (the effective duration definition is given in [3]) .

The laser pulse energy is set to the desired level with a variable attenuator consisting of a half-wave plate and a linear thin-film polarizer. As focusing system, a lens with a focal length of 1000 mm is employed. The sample is positioned with a motor-driven transverse XY translation stage. For beam diagnostic purposes, a small fraction of the beam is redirected by a wedge plate in the diagnosis system, where the temporal, spatial and energetic characteristics of the test laser beam are real-time monitored.

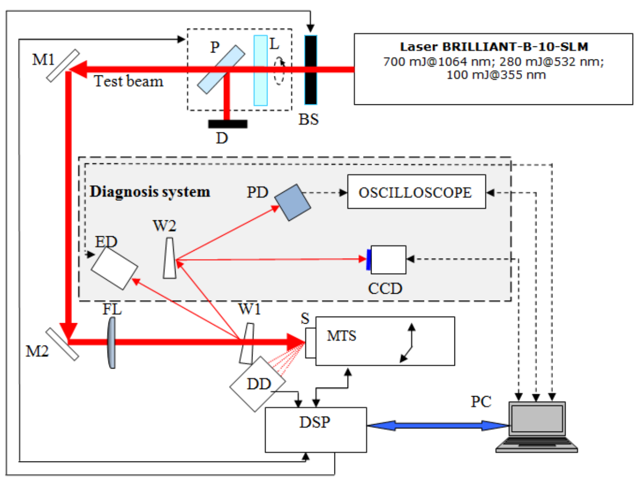


Fig.4. Measuring setup for the S-on-1 ISO procedure.
BS – beam shutter; P – polarizer; L – zero-order half-wave plate; D – beam dump; M1 & M2 – high-reflecting mirrors; FL – focusing lens; W1, W2 – wedges; DSP – digital signal processor; ED – energy detector, CCD – CCD-camera based spatial beam profiler; PD – fast photodiode; DD – damage detector;
S – sample; MTS – motorized translation stages.

In order to control the LIDT measurements, a software operating program was developed. The program is intended to control the sample positioning in the transverse plan of the laser beam, the number and the distribution of the test-sites on the sample, the pulse energy attenuation, the beam shutter, and the number of pulses delivered per site. The damage is detected in real time by monitoring the scattered radiation of the test laser beam. During the damage test, the program evaluates the previously measured dataset and, based on this evaluation, calculates the appropriate energy values for the next test sites. After the completion of the measurement procedure, the program calculates and plots the damage characteristic of the sample and the extrapolated damage threshold for large numbers of pulses. The output of the damage detector (DD) is connected to a fast digital signal processor (DSP). Mainly, the DSP unit performs the fast sequences of the automated procedure: the detection of the optical damage and, therefore, the blocking of the subsequent test pulses on a destroyed site.

The collecting optical system of the damage detector is shown in Fig. 5. The lens L1 collects and collimates the radiation scattered by the sample under test. To gather a significant fraction of the scattered radiation, we use a collecting lens of numerical aperture NA ≈ 0.3. The detector device was designed to allow positioning of the L1 focal plane near the sample site under test. An interferential filter of 10 nm bandwidth centered on 1064 nm laser wavelength is placed after the collecting lens. The lens L2 concentrates the collimated beam on the photodiode aperture. The neutral density filter sets the photodiode photocurrent to an appropriate value.

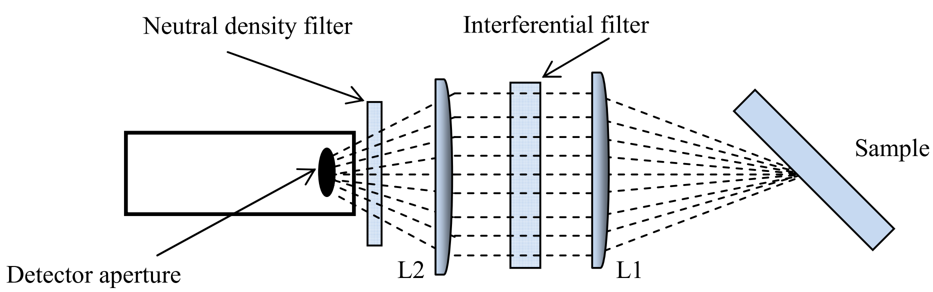


Fig. 5. Schematic of the optical system for damage detection.
L1 – collecting/collimating lens; L2 – focusing lens.

A typical photodiode response at damage occurrence, on 50 Ω load resistance, is shown in Fig. 6, the lower (yellow) trace. The active area of the photodiode is 13 mm^2 and the effective duration of the scattered pulse is 6 ns. Here we can see that the leading edge of the photodiode output is noise contaminated, that can affect the resolution of the damage detector. The noise is mainly generated by the fast high-voltage commutation of the laser Pockels cell (used to Q-switch the laser resonator) shown in the upper (blue) trace, meaning the photodiode noise is synchronously generated with the optical nanosecond pulse.

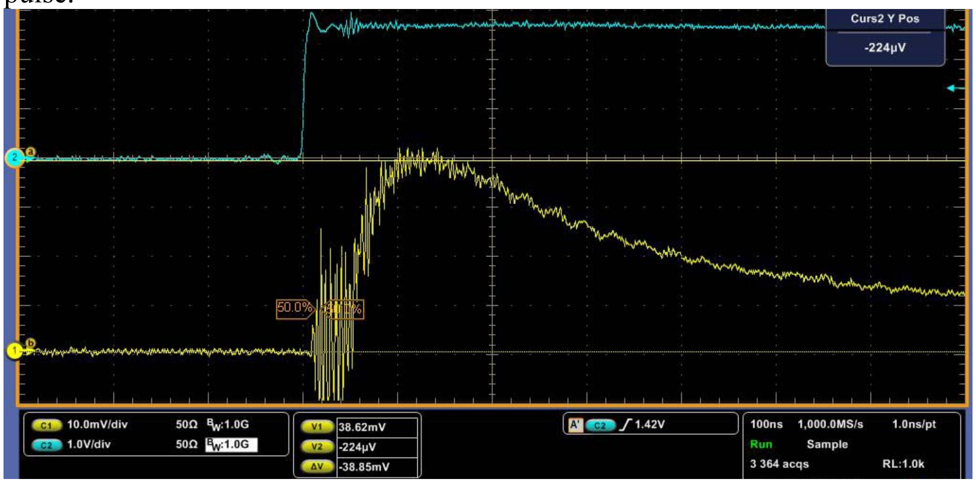


Fig. 6. Photodiode response at damage occurrence. Up (blue trace), the driving pulse of the Pockels cell.
Down (yellow trace), the photodiode response on 50 Ω load. Time scale: 100 ns / major division. Effective duration of the scattered laser pulse 6 ns.

To increase the resolution (or sensitivity) of the damage detector and to cut the high-frequency synchronous noise, the photodiode output is connected to a gain amplifier that operates also as a low-pass filter. The amplifier circuit is realized with a low-power LM224 quad operational amplifier, as shown in Fig. 7, where the electrical circuit of the damage detector is depicted.

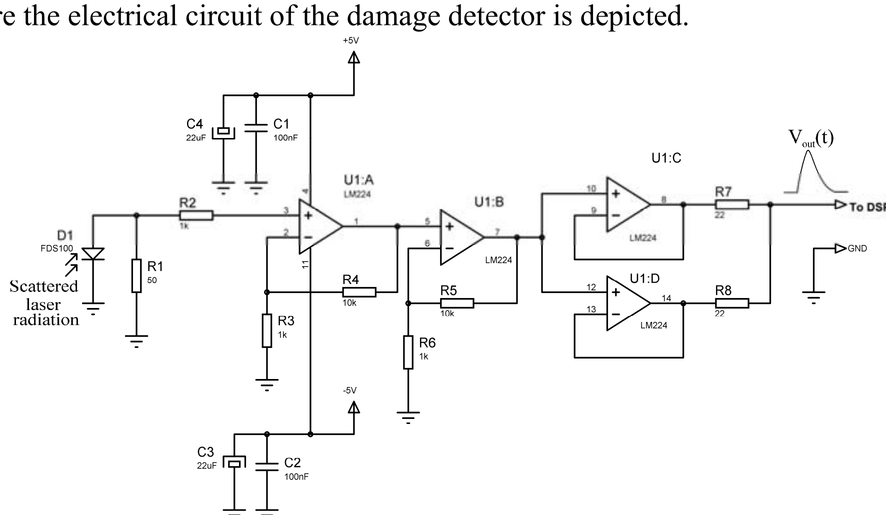
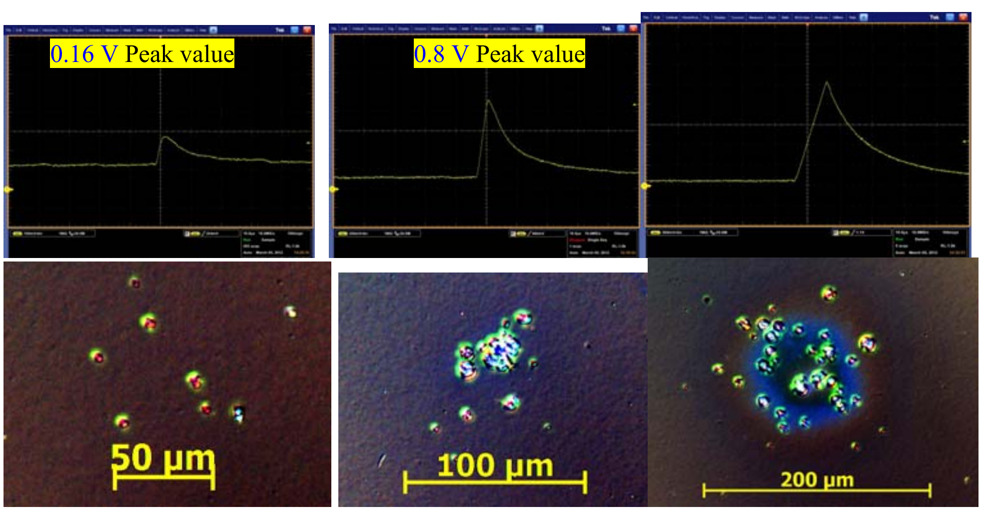


Fig. 7. Electrical circuit of the damage detector (for details see text).

The photodiode output is amplified in two amplifier stages U1:A and U1:B, each of them with a voltage gain of 10 V/V or 20 dB. Due to the finite bandwidth, these amplifiers have the frequency response of an integrator with gain. That means that, to first order, the gain of each stage is inversely proportional to the frequency and it is characterized by its gain-bandwidth product (GBWP). For the LM224 circuit the GBWP = 1.3 MHz, that means a frequency bandwidth of 130 kHz for a gain of 20 dB. Consequently, the stages U1:A and U1:B operate as active low-pass filters that cut the high-frequency components of the environmental noise.

The stages U1:C and U1:D are unity-gain buffer circuits that connect the amplifier output to the DSP unit. The detector response to the damage occurrence have to be faster than the repetition period of the laser pulses, in order to allow the blocking of the subsequent pulses on the already damaged site. Typical output signals of the damage detector for progressively higher levels of damaging fluence, corresponding to progressively larger damaged areas, all induced on the same high-reflecting (HR) mirror at 1064 nm laser wavelength are shown in Figs. 8a-8c. Here we can see a clear correlation between the morphology of the damaged sites and the amplitude of the detector output. The effective diameter of the laser spot in the target plane (as defined in [3]) was 200 μm, and the peak fluence of the laser pulses applied on the optical surface under test varied from 9.5 J/cm^2 to 22 J/cm^2.



a) b) c)

Fig. 8. Damage detector response and corresponding damage morphology for different damaging fluence levels, expressed as peak fluence H_{max} in the target plane. (a) H_{max} = 9.5 J/cm^2; (b) H_{max} = 12.5 J/cm^2; (c) H_{max} = 22 J/cm^2. First row - Output signals from the damage detector. Second row - 200x Nomarsky micrographs of the damaged sites.

From Figs. 8a - 8c we can see that the slew rate of the gain amplifier is ≈ 2.5 V/μs, that allows a reliable operation of the damage detector for repetition rates of the test laser pulses up to tens of kilohertz. The efficient cutting of the environmental high-frequency noise improves the detector sensitivity to smaller areas, incipient optical damages, as can be seen from Fig. 8a.

4. Conclusion

A real-time, compact, and easy-to-use device and technique to detect the laser-induced damage of the optical components was developed. The technique is based on obliquely monitoring the scattered light of the test laser beam, the scattering arising from the damage induced by the same test laser beam. The experimental results have demonstrated a high-resolution, or high sensitivity to damage, and a reliable operation of the damage detector. The damage detector is integrated into an automated station for LIDT measurements according to the ISO 21254-2 standard. The station is currently in an advanced developed phase within the Laser Department of the National Institute for Laser, Plasma & Radiation Physics, Bucharest, Magurele.

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REFERENCES

[1] http://www.eli-np.ro/documents/ELI-NP-WhiteBook.pdf
[2] ISO 21254 - 2:2011, "Lasers and laser-related equipment - Test methods for laser-radiation-induced damage threshold - Part 2: Threshold determination".
[3] ISO 21254 – 1:2011, "Lasers and laser-related equipment - Test methods for laser-radiation-induced damage threshold - Part 1: Definitions and general principles".
[4] ISO 21254 – 4:2011, "Lasers and laser-related equipment - Test methods for laser-radiation-induced damage threshold - Part 4: Inspection, detection and measurement".
[5] http://sales.hamamatsu.com/assets/pdf/parts_S/s2387_series_kspd1033e04.pdf
[6] http://sales.hamamatsu.com/assets/applications/SSD/photodiode_technical_information.pdf