

Laser modulated scattering as a nondestructive evaluation tool for defect inspection in optical materials for high power laser applications

Z. L. Wu, L. Sheehan, and M. R. Kozlowski

Lawrence Livermore National Laboratory, Livermore, CA 94550, USA

Wu13@llnl.gov

Abstract: Laser modulated scattering (LMS) is introduced as a tool for defect inspection and characterization of optical materials for high power laser applications. LMS is a scatter sensitive version of the well-known photothermal microscopy techniques. Because only the defects of a super-polished optic generate a scattering signal, the technique is essentially a method for dark-field photothermal microscopy. Experimental results show that the technique (1) measures the local absorption properties of defects, contamination, and laser damage sites; (2) when used in conjunction with DC scattering, can differentiate between absorbing and non-absorbing defects; and (3) detects thermal transport inhomogeneities.

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References and links

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1. Introduction

Laser-induced damage in optical materials, whether these materials consist of optical coatings or bare substrates, is a localized phenomenon associated with the presence of micron and sub-micron scale defects [1-3]. These defects can be absorbers or non-absorbers. In the latter case the defects may cause field enhancement and/or reduction in heat conduction. Each, ultimately, can lead to materials damage.

A number of techniques have been introduced to investigate localized defects in optical materials. Among these techniques are scanning tools such as atomic force microscopy (AFM) [4, 5] and near field scanning optical microscope (NSOM) [6], and imaging tools including optical microscope and total internal reflection microscopy [7-8]. These tools, while having the capability of detecting many kinds of defects in optical materials, do not directly address absorption and thermo-mechanical response issues relevant to laser damage. In contrast, photothermal microscopy (PTM), based on optical beam deflection / diffraction [9] effect, has been developed as a tool for detecting optical absorption and thermal in-homogeneity at the surface and inside the bulk of optical materials [10-13]. Using a low-power CW pump laser, PTM looks predominantly at linear absorbers [10-12]. Using a high-power pulsed UV pump laser source it can probe multi-photon absorption [13]. With an automated scanning system PTM has the ability to generate reproducible 2D photothermal images for both multilayer coatings and super-polished fused silica surfaces [10-12]. For defects in bulk materials, PTM has been used to have the ability to generate reproducible 3D absorption maps for KDP crystals [13].

The traditional PTM, while being useful for detecting micron-size and larger defects, has limited ability to detect sub-micron absorbers. For some optical materials the laser damage precursors are sub-100 nm in size [5,8,14,15]. The contribution of such a small absorber to the overall photothermal signal can be overwhelmed by the background contribution from the host material. Furthermore, PTM as described above uses a time consuming scanning procedure to obtain photothermal images. The practicality of PTM as an inspection tool for large aperture optics is therefore limited.

To complement the existing defect inspection/characterization techniques and overcome some of their limitations, a microscopic instrument has been developed that employs the principle of laser-modulated scattering (LMS). The technique allows simultaneous measurement of the DC and AC scattering signal of a probe laser beam from an optical surface. Since no other parts of a super-polished optics but the defect sites generate scattering signal, the technique is a dark-field tool for defect detection on optical surfaces. By comparison between the DC and AC scattering signals, one can differentiate absorptive defects from non-absorptive ones. Other advantages of the LMS technique include its potential adaptability to lock-in imaging with focal array detectors and its high sensitivity to small defects even with large pump / probe beam sizes.

This paper briefly describes the LMS technique, summarizes the preliminary results that serve as a feasibility study, and discusses future applications of LMS to surface and subsurface defect inspection in optical materials.

2. Principle of the experimental method

The principle of laser modulated scattering from a defect is illustrated in Figure 1. For a typical microscopic tool (such as optical microscopy), it is the DC scattering from the defect

that is measured, as shown in Figure 1 (a). If a pump laser is used to irradiate the defect, absorption at the defect and/or the host material will cause a localized temperature rise and hence a number of photothermal effects, including a change in the scattering field of the probe beam. By amplitude-modulating the pump beam, a modulated scattering field can be generated, as illustrated in Figure 1(b).

The modulated scatter, or LMS, signal can be detected using lock-in techniques. Mapping of an optic can be achieved by either scanning the sample or using a detector array. For the scanning case, the resolution is determined by the size of the pump and/or the probe laser beam. When imaging using a focal array detector, the pixel size of the image is the limiting factor for the spatial resolution.

Note that the spatial resolution should not be confused with the sensitivity of the technique for defect detection. The latter depends on the magnitude of the signal relative to the background, not the physical size of the defect. For microscopy based on LMS, the signal from a perfect surface is zero therefore its sensitivity to local defects on or underneath a super-polished surface can be extremely high.

3. Results and discussion

3.1 LMS signal as a function of the pump laser power

Optical scattering from a small defect / particle in general is a complicated phenomenon. The scattering signal measured by a detector is dependent not only on the size, shape, and properties of the scatter, but also the properties of the incident laser (wavelength, polarization, and incidence angle) and the position and size of the detector. Therefore optimistically one says that scattering is a useful tool for defect characterization, and pessimistically one says that scattering is too complicated to be meaningful. As a result of its complexity and potential, scattering has been intensively and extensively studied and has been widely used for defect characterization and particle sizing [16].

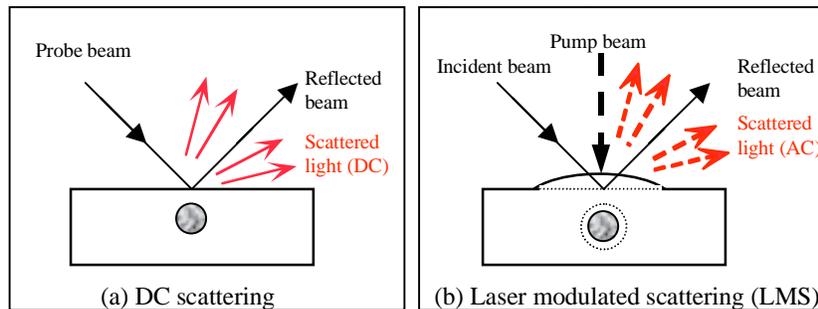


Fig. 1. Illustration of the principle of laser modulated scattering (LMS): (a). DC scattering from a defect; (b). An amplitude-modulated pump laser beam is used to generate laser LMS.

The understanding of LMS is further complicated by the transient nature of photothermal response of an unknown defect and the resulting modification to the scattering field. While a detailed modeling of LMS is under way, experimentally it is found that the amplitude of the LMS signal is proportional to the pump laser energy absorbed by the sample when the pump laser power is at appropriate levels. When the pump power goes to high levels, nonlinear response may dominate the LMS signal.

The proportionality of LMS signal to absorbed energy at low power levels is independent of the specific size and/or shape of the scatter. It is observed for a variety of samples, including contamination particles on optical coatings and defect sites on the surface of polished laser glass. Figure 2 shows the relationship between LMS signal and pump laser power from a defect on the surface of polished laser glass. The fact that LMS signal has a linear dependence on the pump power shows that it is proportional to the level of energy

absorbed. Therefore, scanning an optical surface by using the same laser power maps absorption of the surface, provided that the LMS signal is normalized to the DC scatter signal.

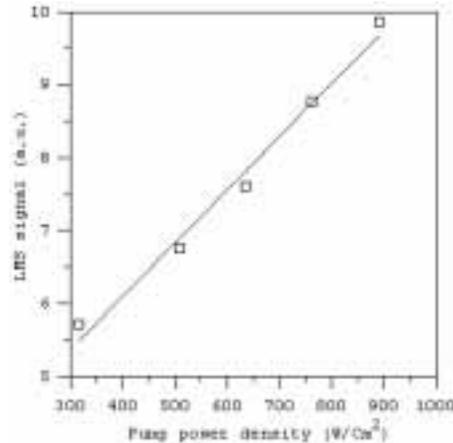


Fig. 2. LMS signal as a function of the pump laser power. The sample used is a defect on the surface of laser glass. Experimental parameters: pump laser - wavelength 488 nm, beam size $\sim 100\mu\text{m}$, normal incidence, chopping frequency 70 Hz; Probe beam - wavelength 633 nm, beam size $\sim 100\mu\text{m}$, 45° incident angle; Detector - pinhole size $\phi 1.0\text{ mm}$, 7.5 cm from the heating spot and 60° from the normal of the sample, detecting forward scattering of the probe beam from the reflection mode as shown in Figure 1(b).

3.2 LMS as a tool for defect characterization

LMS has been applied to a variety of low absorptive optical components. Figure 3 shows a typical result for a low absorptive multilayer optical coating obtained by using (a) LMS and (b) DC scattering mapping. Note that the DC scattering map has a substantial background signal, which is a result of the surface / interface roughness and/or microstructures of the coating component. The images are taken from the same area, with an imaging size of 1 mm^2 and a spatial resolution of about $10\mu\text{m}$. The lines drawn in the images are for eye guidance when comparing the two images. It is found that LMS and DC scattering maps have only a weak correlation. For example, the absorptive defects C, E, I, J found using LMS do not show up at the DC scattering map, and the DC scattering defect K is not observed using LMS. Further, in the DC scattering map defect A has the highest amplitude, but the LMS result shows that defects B, D, G are as absorptive. We might therefore expect that B, D, G are also highly susceptible to laser damage even though they have weak scattering signals.

The difference in the sensitivity of the DC and AC signals is further shown in Figure 4 showing the profile of defect D shown in Figure 3. Compared with the signal from the background material, the DC scattering of the defect is only 2.8% higher but the LMS signal is about 10 times higher, showing that it is a strongly absorptive defect and a highly probable laser damage precursor.

3.3 LMS as a tool for laser damage site characterization

The growth dynamics and mechanisms of a laser damage site under subsequent laser shots are influenced by the optical and thermo-mechanical properties of the damaged site and the host material. Quantitative nondestructive evaluation (NDE) tools for damage sites are largely unavailable, other than topographic techniques such as SEM. Figure 5 shows results from the use of LMS to study laser damage sites on multilayer optical coatings. From the LMS amplitude image it is found that the damage site has an absorption value about 16 times higher than the non-damage area. The enhanced absorption at the damage site can be due to

either a change of coating structures at the damage site or a physical modification of the materials or both. The enhanced absorption properties will lead to increase in absorbed energy from subsequent laser shots, and very possibly, growth of the damage site.

The LMS phase image of the same damage site shows that it has a low thermal conductivity / high thermal resistance near the center, as demonstrated by an almost 180 degree phase change. The size of the thermal inhomogeneity is much smaller than the absorption site shown in the amplitude map. This thermal inhomogeneity can be due to laser-induced delamination, micro-cracks, and/or removal of the coating materials at the center of the damage site.

The above results show that LMS can be a useful tool to non-destructively evaluate (NDE) damage sites and potentially correlate their properties with laser damage growth dynamics. Implementation of the technique into a damage testing system for *in-situ* studies may therefore be useful in the study of damage growth mechanisms.

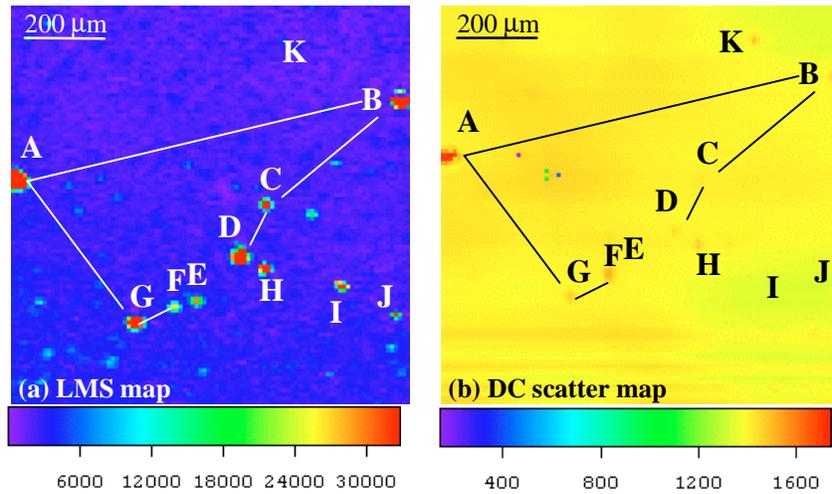


Fig. 3. Defect mapping using (a) LMS and (b) DC scattering of the same area of an optical coating. The color scale is in arbitrary units. The laser parameters are as follows: pump wavelength 1.06 μm ; probe wavelength 0.6328 μm ; pump beam size $\sim 5 \mu\text{m}$; probe beam size $\sim 25 \mu\text{m}$. Other parameters are the same as shown in Figure 2.

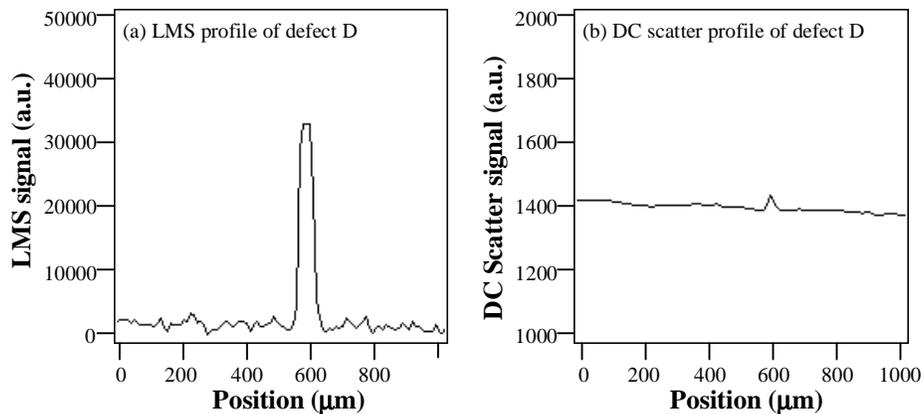


Fig. 4. Profile of defect D shown in Figure 3. Compared with the background material, the DC scattering of the defect is only 2.8% higher but the LMS signal is about 10 times higher.

3.4 LMS as a tool for contamination studies

High power laser optics can be contaminated by improper handling, contaminated use areas, or by debris resulting from laser damage. A diagnosis tool that detects and characterizes contaminants is therefore of interest to laser damage studies. Figure 6 shows an example for such applications, where the laser-induced debris (caused by the damage shown in Figure 5) is scanned with micron spatial resolution. Both the amplitude and phase images indicate that the debris consists of two separated parts, profiles of which are shown in Figure 7.

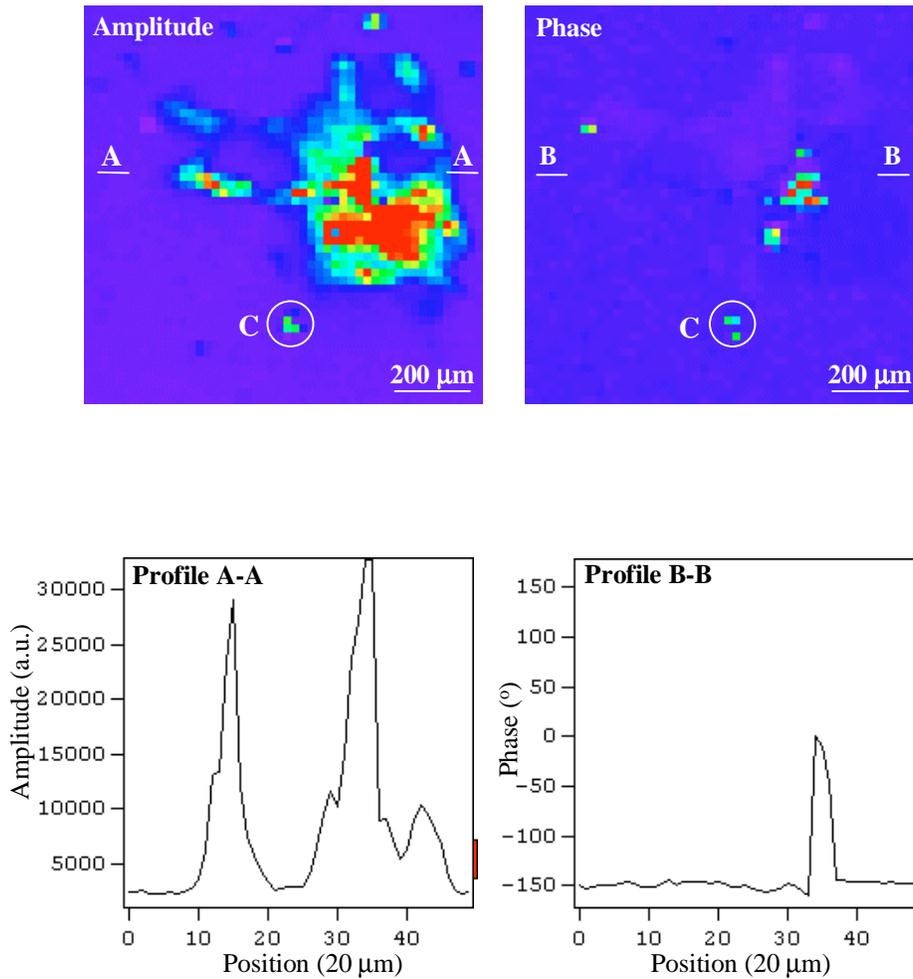


Fig. 5. LMS image (top) and profile (bottom) for a laser damage site of an optical coating sample. The defect labeled as C is laser-induced debris. The experimental parameters are the same as shown in Figure 3.

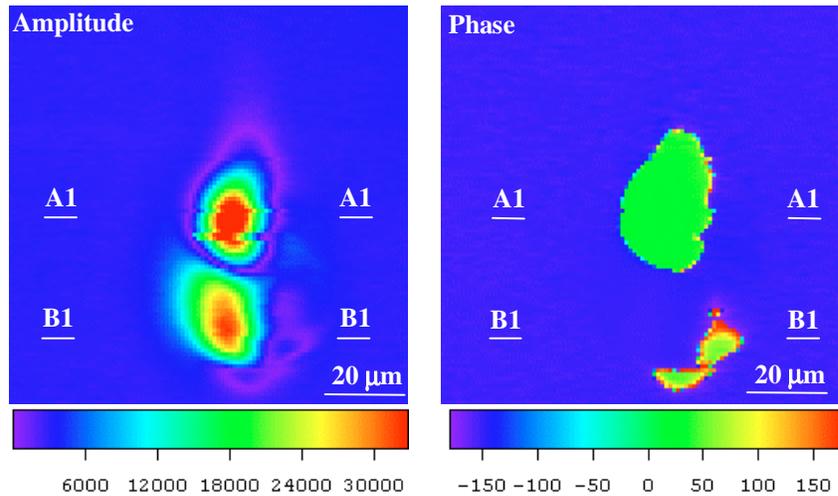


Fig. 6. High resolution DPTM image of the laser induced debris as labeled as C in Figure 5. Both the amplitude and the phase image indicate that the debris consists of two separate parts, i.e. A and B; profiles of them are shown in Figure 7.

From the image as well as the profiles, a few comments can be made about contaminants A and B. First, both are absorptive, with absorption more than 7 times higher than the background host materials.

Second, both of them are not well contacted to the background material, as can be seen from the phase image. The phase at the center of contaminant A is about 180 degrees different from that of the background. The phase jump happens at the edge (Profile A2-A2), spatially corresponding to the dip in the amplitude signal (Profile A1-A1). The combination of the amplitude and phase signals suggests a thermal-wave interference phenomenon caused by the poor thermal contact between contaminant A and the host material.

Third, the LMS image for contaminant B is not as symmetric as that for A. This asymmetry is observed more clearly in the profiles shown in Figure 7. The phase difference exists only for the right half of contaminant B (Profile B2-B2), corresponding also to the dip in the amplitude signal (Profile B1-B1). The results indicate that contaminant B is better contacted to the background material, with thermal resistance present only for a small portion of the interface. The contact between the contaminant and the surface is relevant to laser cleaning, conditioning and damage processes.

The above interpretations of the data need to be further verified by laser damage testing as well as a quantitative modeling of the LMS signals. Nevertheless, the results have demonstrated the potential of LMS as a quantitative NDE tool for detection and characterization of contaminants.

4. Summary

LMS is demonstrated to be a sensitive and non-destructive evaluation tool for defect detection and characterization of optics for high power laser applications. Results from optical coating studies show that the technique is also a promising tool for damage growth and contamination studies. Compared with existing techniques for defect characterization, LMS has a few distinguishing features that warrant wide application of the technique. First and foremost, for super polished optical surfaces LMS is a dark-field tool and hence has higher sensitivity for small defect detection than conventional PTM techniques. Second, by

detecting DC scatter and LMS signals simultaneously the technique is sensitive to both absorptive and non-absorptive defects and can separate them from each other. Third, by analyzing LMS phase signals thermal inhomogeneities can be detected. Research towards this direction is currently under way.

Finally, it should be pointed out that the complicated nature of scattering and LMS signals demands careful modeling so as to take full advantage of the LMS technique for nondestructive evaluation. Efforts towards a quantitative understanding of the LMS signals from optical surfaces and thin film coatings are in progress and will be reported in forthcoming papers.

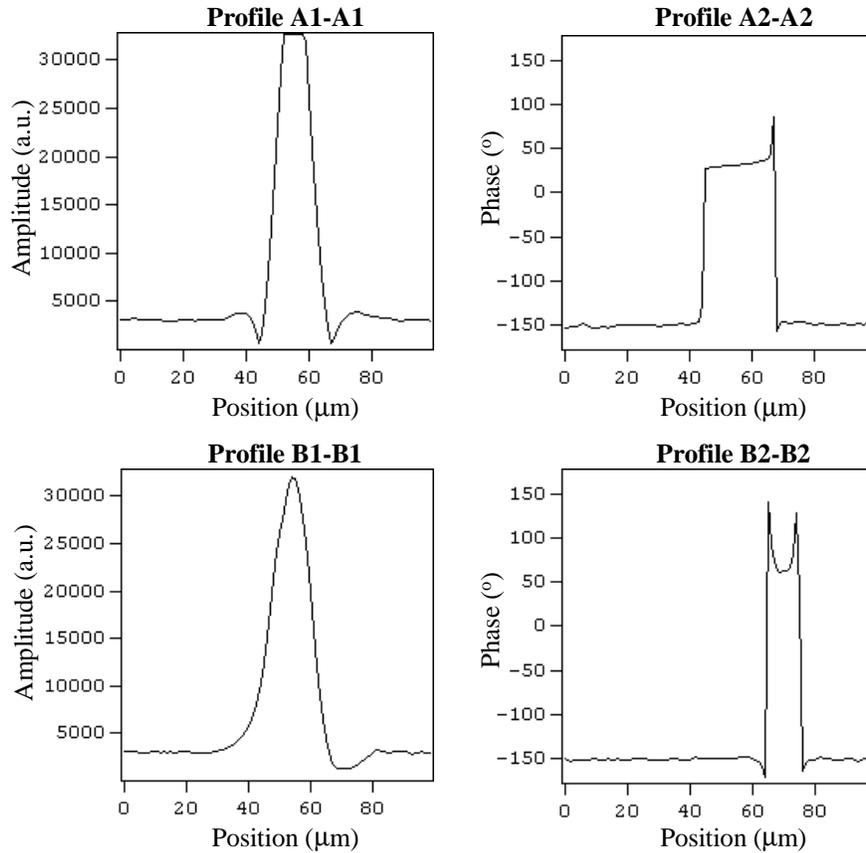


Fig. 7. Profiles of Section A and B of the debris as shown in Figure 6. While for both sections the absorption peaks at the center, part A and B differs in that A is more symmetric than B.

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