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SPOT SIZE DEPENDENT LASER MATERIALS INTERACTIONS DUE TO SURFACE ELECTROMAGNETIC WAVES

R. T. Swimm, M. Bass, L. Fathe, J. Z. Lin, and R. Kurtz

Center for Laser Studies
University of Southern California, Los Angeles, Ca 90089-1112

Measurements of the transient reflectivity change due to heating by a surface electromagnetic wave are reported. Initial results are inconclusive with regard to the existence of surface electromagnetic waves. Implications concerning the effects upon the laser-induced damage threshold are discussed.

Key words: laser induced damage threshold; optical absorption; periodic structure; photothermal; reflectivity; ripples; SEW; surface electromagnetic wave.

1. Introduction

The purpose of our reserach is to directly detect the surface electromagetic wave (SEW) that has been postulated [1] to be responsible for the generation of ripples. These ripples are often seen on the surface of materials that have been irradiated and melted by laser light. The detection scheme is to measure the temperature rise induced by the SEW at a point remote from the laser-irradiated site. The motivation of this work is that the SEW may be important in modelling laser damage, but that to our knowledge, no direct detection of the SEW itself in laser damage events has been reported.

The detection method used is a modification of the technique reported by Swimm in another paper in the proceedings. The method is based on the fact that the reflectivity of a surface depends on the temperature of that surface [2]. Consequently, a transient rise in the surface temperature due to heating by the SEW will result in a transient change in the reflectivity. The effect is quite weak, but as will be discussed, we can presently detect a reflectivity change of a about one tenth of a percent, and we expect to attain some additional sensitivity. This capability will allow direct detection of heating by the SEW, rather than having to rely on the morphological remnant ripples for evidence.

2. Experiment

The pump laser consisted of a Molectron MY-32 10 Hz repetition rate Q-switched Nd:YAG laser running in single axial mode, operating at a wavelength of 1.06 μm. The beam from this laser was focused onto a diamond-turned aluminum sample, within a spot diameter of about 200 μm. The pump-beam pulse energy was about 1 mJ incident on the sample, with the pulse length equal to approximately 20 ns. This energy was selected by trial and error to produce ripples. The probe laser was a Spectra Physics model 106-1 10 mW polarized HeNe laser. The pump beam spot diameter was about 200 μm, and the displacement between the centers of the pump probe spots was about 400 μm. The probe spot was displaced relative to the pump spot in a direction parallel to the pump beam polarization.

The basis for operation of the experiment is that during the pump pulse, the postulated surface electromagnetic wave would be radiated along the surface, illuminating a strip of width equal to the pump beam diameter, with reciprocal absorption length as predicted in the paper by Ursu et. al.[1], and oriented to parallel to the pump beam polarization. This surface electromagnetic wave would result in a change in the surface reflectivity, which would be detected using a probe beam. The probe beam samples a remote point away from the pump spot in order that any heating will be due to the postulated surface electromagnetic wave.

The probe beam was collected using a convergent lens, and then passed through a series of filters which included a rejection filter to remove 1.06 μm wavelength scattered light, a narrow-line bandpass filter of 5 nm linewidth to reduce visible emission from the plasma initiated by the pump beam, and finally through a 100 μm diameter spatial filter to remove the residual light from the plasma that was within the bandwidth of the narrow line bandpass filter. This later filter was crucial to the measurement.

The probe beam was detected by a silicon detector, whose output signal was amplified by a PARC model 115 preamplifier with a gain of 100 before being routed to an oscilloscope and a PARC model 162/165 boxcar averager. The sampling duration on the boxcar was set at 5 ns, and delayed by 70 ns relative to the laser pulse. The signal was averaged for about 20 seconds (a total of 200 pulses), and the baseline was also averaged on alternate pulses, also for 20 seconds, resulting in a measurement duration of 40 seconds.

In the process of experimental development, a large signal was observed, due to the surface acoustic wave generated by the pump pulse. This signal resulted from beam deflection due to sample surface deformation as the surface acoustic wave propagated through the probe site, and was seen whenever the pump beam was partially obstructed or apertured. The signal due to the surface acoustic wave was avoided by setting the boxcar aperture delay such that the signal was sampled after the pump pulse ended, but before the surface acoustic wave arrived.

An additional effect that had to be avoided was obstruction of the surface by the buildup of a white powder deposited on the surface in the vicinity of the pump spot during irradiation. The reflected power was compared before and after the 40 second beam exposure to ensure that no significant change in the steady state surface reflectivity occurred.

Following the initial setup work a total of nine sites were irradiated for the reported data. After normalizing the signal to account for pump power variations, the transient relative reflectivity change was determined to be 8×10^{-4}, with a standard deviation of 3×10^{-4}.

3. Discussion

In order to place these results into the proper context, it is necessary to consider the expected signal strength under various experimental conditions. The first step is to assume that the Soviet prediction for the absorption coefficient of the postulated surface electromagnetic wave is correct. Therefore one has [1]

$$\alpha_{diss} = \frac{\pi}{8\lambda} A_0^2 \frac{\kappa}{n}$$

where

$$A_0 = \frac{4n}{n^2 + \kappa^2}$$

where n = refractive index, κ = extinction coefficient, λ = wavelength, and α_{diss} is the dissipative component of the SEW absorption coefficient. Clearly the values of n and κ to be used must be appropriate to the experimental conditions, and in particular they must correspond to the temperature and phase of the irradiated site during the irradiation. Unfortunately, the optical constants of molten metals are not generally available, and so estimates of n and κ are uncertain at best. Scaling room temperature data on the basis of temperature alone is not a reliable method of predicting optical constants for the molten phase. Alternatively, it might be possible to scale according to the electrical conductivity of the room temperature solid, and the molten phase of the same material. This may be accomplished using the following two relations:

$$\alpha_{bulk} = \frac{4\pi}{\lambda} \sqrt{\frac{\mu\sigma}{\nu}}$$

where λ = free space wavelength, μ = relative permeability, ν = frequency of the electromagnetic wave, σ = electrical conductivity, and α_{bulk} = absorption coefficient for an electromagnetic wave propagating through the bulk of the conductor [2]. This expression is subject to the condition

$$\frac{\sigma}{\nu} \gg \varepsilon$$

where ε = relative permitivity.

The other expression needed here is [3]:

$$\alpha_{bulk} = \frac{4\pi\kappa}{\lambda}$$

Eliminating the bulk absorption coefficient from these two relations, it follows that

$$\kappa = \sqrt{\frac{\mu\sigma}{\nu}} \text{ if } \frac{\sigma}{\nu} >> \varepsilon$$

The conductivity and the extinction coefficient are strong functions of temperature [4] e.g.,

$$\sigma_{lattice} \propto \frac{1}{T} \text{ (solid phase only)}$$

but the refractive index is a relatively weak function of temperature by comparison.

A rough estimate of α_{diss} for molten aluminum can be made using the fact that [5]

$$\frac{\rho_{molten\ Al}}{\rho_{solid\ Al(20°C)}} \simeq 7.8$$

where ρ = electrical resistivity = $1/\sigma$. By interpolation of room temperature values of n and κ[6] one finds using the Soviet expression for α_{diss} that for aluminum at a wavelength of 1.06 µm,

$$\alpha_{diss}\Big|_{T = 20°C} \simeq 120 \text{ cm}^{-1} .$$

If this number is scaled using electrical conductivity, then one finds (ignoring temperature dependence of n):

$$\alpha_{diss}\Big|_{\substack{T = 670° \\ \text{Liquid Al}}} \simeq 3 \times 10^3 \text{ cm}^{-1} .$$

From these estimates, one may conclude that the surface electromagnetic wave would propagate only a few microns in the melt region. Thus at wavelengths of m or shorter there will not be significant redistribution of energy outside the laser spot except the for rare case of micron-size spots. It is only at longer wavelengths such as 10µ where energy distribution and resultant spot-size dependence of laser-induced damage threshold can be expected.

Finally, in the context of the present experiment, the surface electromagnetic wave is not expected to have reached the probe site as originally assumed. Therefore the present measurements are inconclusive. However, on the basis of experience gained in this work, we believe that under appropriately chosen operating conditions it should be possible to test the existence of surface electromagnetic waves by their surface heating signature.

4. Summary

The present experiments designed to directly detect the presence of surface electrol-magnetic waves are inconclusive. Surface electromagnetic waves are predicted to propagate only a few microns in molten aluminum at a wavelength of 1 μm, thus precluding significant energy redistribution. Additional experiments to detect surface electromagentic waves by their surface-heating signature are under consideration.

5. References

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