Ultrafast nonlinear optical method for generation of planar shocks

Los Alamos National Laboratory, Los Alamos, New Mexico 87545

T. Lippert
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

(Received 20 September 2000; accepted for publication 13 November 2000)

Planar shocks generated by short pulse lasers are useful in studies of shock compression phenomena and may have applications in materials science, biology, and medicine. We have found the fluence profiles of 120–400 fs duration Gaussian spatial mode incident laser pulses are reproducibly flattened via surface optical breakdown and Kerr focusing in thin dielectric substrates at fluences just above the ablation threshold. These flat laser profiles have been used to produce planar shocks that are flat to 0.7 nm root-mean-square over a 75–100 μm diameter. © 2001 American Institute of Physics. [DOI: 10.1063/1.1337629]

To ensure one-dimensional strain in model shock wave systems, extreme tolerances on projectile flatness and tilt, as well as target flatness, are necessary. In the case of laser driven shock waves, this need translates into a requirement of uniform laser fluence distribution over the spatial region of interest. Previous attempts to produce planar laser driven shocks have utilized optical fiber coupling,1,2 Intra- and extra-cavity laser beam shaping methods have been used to produce flat laser fluence profiles, which could be used to drive shocks.3,4 Here, we demonstrate a simple method for producing shocks with very high spatial uniformity by utilizing a combination of ultrafast laser ablation5–8 and Kerr focusing9,10 as a pulse shaping mechanism. To understand the process, we have characterized the transmitted pulse fluence profile in thin borosilicate glass samples and have found it to be flat [i.e., <5% root-mean-square (rms) intensity variation over >75% of the focal diameter] for a significant portion of the parameter space just above the ablation threshold fluence (for 120–400 fs pulses). Slightly different behavior was observed for thin sapphire and LiF samples, which can be related to differences in their ablation threshold fluences and Kerr coefficients. In addition, we have employed this effect to drive planar shocks into thin metal layers vapor deposited onto the dielectric materials and have characterized them using spatially resolved frequency domain interferometry. The short duration shocks thus produced are important for the elucidation of shock induced processes at the molecular scale.

The apparatus used for the generation of planar shocks is fully described in Ref. 11. It utilized 120–400 fs laser pulses at λ = 800 nm from a seeded, chirped pulse amplified (CPA) Ti:Sapphire laser (Spectra Physics). The pulses were focused to a nominal spot diameter of 75 μm at the sample. Samples for the shock wave studies were thin metal films (0.05 to 2 μm thick) vapor plated onto dielectric substrates, usually borosilicate glass microscope slide cover slips (Fisher Scientific). Samples for the transmittance and beam intensity profile studies were the same substrates with no metal coating. The samples were mounted on a computer controlled x-y translation stage and were rastered about 4 laser focus diameters between shots so that each laser pulse would propagate into undisturbed material.

The shock waves were characterized at the metal/air surface using the technique of reflection frequency domain interferometry,12,13 using a small portion of the main CPA laser pulse reflected from a beam splitter (~0.04 mJ). Analysis of the transmitted laser pulse fluence profile was done using a beam profiling charge coupled device (CCD) camera and analysis software (both Spiricon). The back surface of the sample was imaged onto the CCD using an f/3 lens and ×7 magnification. An abraded portion of the sample was used to determine the correct focal plane. The camera and software were also used in conjunction with calibrated neutral density filters to determine the transmittance through the samples.

Figure 1 shows the shock profile at the delay time of peak phase shift11 for a 1 μm thick Al film on a borosilicate cover glass (~150 μm thick) at several incident laser fluences. The development of a planar shock profile is evident at fluences of 2.2 J/cm² (energies of 100 μJ) and above. The phase shift Δφ (in radians) can be translated to surface motion Δx using Δx = Δφλ₀/4π cos θ. Figure 1 shows the shock is flat to 0.01 rad rms phase shift, or 0.7 nm rms, over

FIG. 1. Shock profile at several incident laser energies for a 1 μm Al film deposited on a 150 μm thick borosilicate glass microscope cover slip.
suggested that bulk nonlinear optical effects may play a strong role in the observed flattening process.

The role of bulk nonlinear optical effects was examined using transmitted beam profiles from 1 mm thick borosilicate glass, sapphire, and LiF samples, as well as a 100 μm thick sapphire sample. Some of these images are presented in Fig. 2. In the 1 mm samples, bulk self-phase modulation and self-focusing were evident at incident fluences considerably below the ablation threshold [Figs. 2(e) and 2(f)]. Estimates of the catastrophic self-focusing distance \( z_f \) for each of these substrates using the empirical formula of Marburger\(^6\) are in rough agreement with the onset fluences observed. The 1 mm thick BK-7 sample produced distinct rings in the transmitted profile [Fig. 2(f)] at incident energies above 5.4 \( \mu J \) (where \( z_f = 1 \) mm predicts 5.8 \( \mu J \)).\(^6\) The 1 mm LiF sample produced results similar to the 1 mm thick borosilicate glass. Some flattening was evident above incident energies of 35 \( \mu J \) (where \( z_f = 1 \) mm predicts 32 \( \mu J \)), but it was accompanied by a ring-like intensity distribution. In the 1 mm thick sapphire sample, nonlinear optical effects led to excellent flattening of the transmitted beam [Fig. 2(d)] at incident energies just above \( z_f = 1 \) mm (8 \( \mu J \) both measured and calculated). However, the transmitted intensity was too low to be useful for shock generation. Higher incident fluences led to severe self-focusing and other bulk nonlinear optical effects [e.g., Fig. 2(e)]. Longer pulse lengths (210 and 400 fs) moved the range for flattening to somewhat higher fluences, as was expected because of the dependence of \( z_f \) on pulse length, but still inadequate for shock generation.

The 100 μm thick sapphire sample produced some flattening of the transmitted beam profile at fluences just above the ablation threshold, similar to the borosilicate cover glass. However, the flattening was not very uniform and there was a limited range of useful fluences. Also, the useful fluences were well above the ablation threshold in contrast to the borosilicate cover glass case, suggesting predominance of Kerr focusing similar to the effect seen in the 1 mm sapphire sample.

Future work to optimize the flatness, reproducibility, and transmitted beam fluence (to achieve stronger shocks) will involve varying the substrate material and thickness, as well as the incident laser pulse duration and profile.

This research was performed under the auspices of the U.S. Department of Energy. The authors also acknowledge the generous trust and support of Joe Repa and Judith Snow and the capable technical support provided by Ronald Martinez, Michael Sedillo, Pat Quintana, and Howard Stacy.