HIGH FREQUENCY ULTRASOUND GENERATION USING A FEMTOSECOND LASER

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ABSTRACT. We present measurements of high frequency ultrasound generated by a femtosecond laser pulse. Focussed on thin aluminum foils (8 - 80 \textmu m), the measured ultrasonic spectrum extends up to a detection limit of 800 MHz. The high frequency ultrasonic echoes allow measurements of foil thickness down to 8 \textmu m, the minimum foil thickness used in this set of experiments.

INTRODUCTION

There is a need in industry to measure the thickness of metallic coatings in the 1-50 \textmu m range. A typical example is the Zn coating on galvanized steel. Presently, such coatings are characterized by removing samples from the production environment and mechanically or chemically etching the coating (destructive test). Because of their ability to penetrate opaque matter, ultrasounds are used extensively for quantitative nondestructive evaluation. However, the wavelength of currently used systems (\geq 0.3 \textmu m in aluminum) corresponding to frequencies \sim 20 MHz do not allow spatial or depth resolution smaller than \sim 0.1 mm.

Laser generated high frequency ultrasound offers the possibility of measuring the thickness of opaque coatings down to 1 \textmu m. For example, the wavelength of compression waves in aluminum at 1 GHz is 6.4 \textmu m with an attenuation of 0.02 dB/\textmu m. At this level of attenuation, several echoes can easily be measured. The coating thickness can then be calculated using the known phase velocity of the compression wave.

There are two regimes for laser generation of ultrasound in a solid: thermo-elastic and ablative [1]. The former uses low-energy laser pulses to heat the surface of the sample. The transient thermal expansion of the near surface volume (where the laser light is absorbed) launches compression waves into the sample. The laser-generated displacements are very small (\sim 10 pm) in metals because of the small energy absorption; in such conditions, pump-probe and lock-in detection techniques must be used. In the ablative regime, a higher energy density laser pulse causes partial ablation of the target surface and ionization of the ablated material. The laser-induced plasma can reach very high pressures,
expanding away from the surface and thus launching a compressive elastic wave into the sample. The amplitude of these waves is much greater (~10 nm) than those generated in the thermo-elastic regime and can easily be measured by single shot interferometric techniques.

Short laser pulses have been used to generate high frequency ultrasound. An acoustic microscope using a transducer tuned to 840 MHz has detected ultrasonic waves generated by a burst of ~40 laser pulses (0.2 nsec duration) focussed onto a 25 μm thick aluminum foil [2]. Ultrasound frequencies up to 500 MHz, generated by 2.5 nsec Excimer laser pulses focussed onto 0.8 mm thick aluminum plates, have been measured using interferometric techniques [3]; the averaging of 400 shots was necessary to achieve a S/N ratio of unity at 500 MHz.

EXPERIMENT

We present measurements of femtosecond laser generated high frequency ultrasound. The laser source is a Ti:Sapphire laser (800 nm) producing pulses in the range 60 - 300 fsec after the compressor or 270 psec (uncompressed) with adjustable energies up to 600 mJ. The laser can operate at 10 Hz but is used in single shot mode for these experiments. Positioning the target out of focus (f = 60 cm), the laser fluence used for these measurements is in the range 0.26 - 1.3 J/cm² at two different pulse widths of 270 fsec and 270 psec. The amplitude of the surface displacements associated with the ultrasonic pulse generated by the laser in this parameter range is sufficient to allow single shot measurements by interferometric techniques. The targets are aluminum foils with thickness between 8 and 80 μm.

The ultrasounds are detected by measuring the displacement of the surface opposite to that of ablation (back side of the sample). To this end, we use a CW Nd:YAG (500 mW) frequency-stabilized laser coupled to a confocal Fabry-Pérot interferometer in reflection mode [4]. In this configuration, the measurement bandwidth is limited only by the detector/amplifier. We use a 50 cm Fabry-Pérot with a measured Finesse of 39, a corresponding bandwidth of 3.8 MHz (FWHM) and an Étendue of 0.13 mm²-sr. Measurements are made with a 350 μm InGaAs detector coupled to a 1.3 GHz amplifier. A high pass filter (> 20 MHz) is used to maximize the high frequency response. Data acquisition is by a 1 GHz bandwidth, 4 GS/s oscilloscope. A 2 msec shutter is placed before the detector to limit the average power and thus improve the S/N ratio. The detection system has a measured 3 dB bandwidth of 450 MHz. The whole measurement system has a maximum dynamic range of 26 dB and a S/N ratio greater than 1 for frequencies up to 800 MHz.

To obtain good echo resolution, important for ultrasound thickness measurements, the ablation region must be large enough with respect to the foil thickness so that there is little diffraction of the ultrasound wave to corrupt the measured signal. In such conditions, the ultrasonic wave remains a plane wave for several round trips in the foil [5]. The diffraction regime of the laser generated ultrasound is characterized by the Fresnel parameter for near field condition $S = \lambda \times \frac{z}{a^2}$ where $\lambda$ is the wavelength of the compression wave, $z = (2n-1)d$ is the distance travelled by the ultrasound, $d$ is the foil thickness, $n$ is the number of round trips and $a$ is the radius of the ablation (ultrasound generating) laser. The plane wave condition is achieved when $S < 0.1$. For the measurements presented here, the Ti:Sapphire femtosecond laser spot size is 2.2 mm in diameter while the spot size of the detection laser on the rear surface of the target is ~ 0.1 mm in diameter. For this laser spot size, the $S < 0.1$ criterion is maintained for ultrasound.
FIGURE 1. Interferometer measurement of the rear surface displacement of an 82 μm foil irradiated with a 270 fs, 50 mJ (1.3 J/cm²) laser pulse. The vertical line indicates the time of incidence of the laser pulse on the front surface of the foil.

frequencies greater than 50 MHz in a 50 μm thick foil for 10 roundtrips (10 peaks). Implicit here is the requirement that the ablation laser beam have a uniform fluence distribution.

Figure 1 shows the measured displacement of the rear side of an 82 μm thick aluminum foil irradiated with a 270 fs (FWHM), 50 mJ laser pulse corresponding to a fluence of 1.3 J/cm²; this fluence level is greater than the ablation threshold for a 270 fs pulse [6]. The maximum measured displacement is approximately 40 nm. The time delay for the first echo is half that of the other echoes because of the single transit of the ultrasonic pulse through the foil. Using the compression wave phase velocity of 6374 m/sec, the 25.7 nsec delay between successive peaks corresponds to a foil thickness of 81.9 μm which agrees very well with the measured thickness of 82 μm. The baseline between each peak is close to the zero signal level indicating the absence of plate waves.

The rear surface displacement of an 82 μm thick aluminum foil irradiated with a much longer 270 ps (FWHM), 50 mJ laser pulse is shown in Figure 2. The fluence (1.3 J/cm²) is the same as above but is now below the ablation threshold for this pulse duration [6]. The maximum surface displacement is approximately 50 nm. The peaks are broader

FIGURE 2. Interferometer measurement of the rear surface displacement of an 82 μm foil irradiated with a 270 ps, 50 mJ (1.3 J/cm²) laser pulse. The vertical line indicates the time of incidence of the laser pulse on the front surface of the foil.
than for the 270 fs pulse with the same energy density, indicative of a lower frequency content. The baseline between peaks deviates significantly from the zero signal level indicating the presence of plate waves. The displacement is roughly the same for both pulse durations. Intuitively, the foil displacement for the 270 psec pulse should be less since there is no ablation to provide an added impulse to launch the ultrasound. It is not known why the displacements are similar for both pulse widths.

A spectral analysis using a continuous WAVELET transform [7] with a Morlett wavelet \((k = 3)\) has been performed on the traces of Figures 1 and 2. This analysis reveals that the highest frequency components are centred on the peaks. The spectral distribution of the first peak for the 270 fs and 270 psec traces (Fig. 1, 2) are presented in Figure 3. There is a resonance in the detection circuit at \(~ 220\) MHz which increases the high frequency response. The spectrum associated with the 270 fs laser pulse is broader than that of the 270 psec pulse; this is to be expected since the impulse that launches the ultrasonic waves is much shorter.

The time evolution of the wave amplitude the successive peak for three different frequency components is plotted in Figure 4 for the spectral analysis of the 270 fs trace (from Fig. 1). The decay is exponential for these frequency components in the first 150 nsec. As would be expected, the attenuation increases with frequency. Using the

![Figure 3: Frequency spectra at the time of the first peak for the traces in figures 1, 2.](image)

![Figure 4: Time evolution of the peak amplitude of three frequency components for the trace in figure 1. The dotted lines are linear fits to the first seven points (~150 nsec).](image)
FIGURE 5. Interferometer measurement of the rear surface displacement of a 15 \( \mu \)m foil irradiated with a 270 fsec or a 270 psec, 20 mJ (0.53 J/cm\(^2\)) laser pulse.

... compression wave phase velocity to establish a time-distance correspondence, the measured attenuation of 3 dB/mm at 260 MHz is the same as the value published in reference 2. However, the measured attenuation of 4.8 dB/mm for the 530 MHz component is less than the 6 dB/mm reported in reference 2. The time evolution of these three frequency components (at the peaks) for the 270 psec trace (shown in Fig. 2) are far from exponential because of the presence of plate waves.

The motion of the backside of a 15 \( \mu \)m thick aluminum foil is presented in Figure 5 for two laser pulse widths. In both cases, the laser pulse energy is 20 mJ corresponding to a fluence of 0.53 J/cm\(^2\). For the 270 fsec pulse, this fluence is near the ablation threshold whereas it is below the ablation threshold for the 270 psec pulse [6]. The observed displacement is much greater for the former pulse, indicating that ablation possibly contributes to the foil acceleration, contrary to the 82 \( \mu \)m foil measurements where the displacement is roughly the same for both pulse durations. Foil acceleration with ensuing plate waves is evident for both pulse width. The average time between echoes is 4.7 nsec which corresponds to the round-trip time of a compression wave in a 15 \( \mu \)m thick aluminum foil.

The thinnest foil measurements were performed on an 8 \( \mu \)m foil. The backside motion of this foil is shown in Figure 6. The pulse duration is 270 fsec with an energy of 10 mJ corresponding to a fluence of 0.26 J/cm\(^2\); this fluence is under the ablation threshold. Foil acceleration is more than evident as are the ensuing plate waves. The Doppler shift produced by this foil acceleration is greater than the bandwidth of the Fabry-Perot interferometer such that the contrast of the ultrasonic peaks decreases significantly as a function of time. The peaks at early times are shown with an expanded time scale. These peaks correspond to a displacement of approximately 2 nm, a factor of 2-3 greater than the detection limit for these measurements. The average time separation between the first 5 peaks is 2.3 nsec, corresponding to a foil thickness of 7.3 \( \mu \)m. The measured thickness agrees well with the mechanically measured foil thickness of 8 \( \pm \) 0.5 \( \mu \)m. It should be
FIGURE 6. Interferometer measurement of the rear surface displacement of an 8 \( \mu \)m foil irradiated with a 270 fsec, 10 mJ (0.26 J/cm\(^2\)) laser pulse.

mentioned that the backside displacement for a 270 psec pulse duration at the same energy density is too small to be measured.

CONCLUSION

We have demonstrated that ultrasound with frequencies greater than 100 MHz can be generated with short pulse lasers and have sufficient amplitude to allow single shot measurements. The ultrasonic pulses are very narrow with a spectral content nearly reaching 1 GHz for a 270 fsec laser pulse, allowing good temporal discrimination and consequently an accurate determination of the foil thickness at least down to 8 \( \mu \)m. For the same fluence, the 270 fsec pulse induces greater peak displacement amplitudes than the 270 psec pulse for foil thicknesses of 15 \( \mu \)m and 8 \( \mu \)m, probably because of the added impulse produced by ablation. It is not known why there is no difference in the amplitude of the peaks for a 82 \( \mu \)m thick foil for these two pulse duration. For this later thickness, the 3 dB/mm measured decay at 260 MHz is consistent with previous measurements whereas the 4.6 dB/mm decay at 530 MHz is smaller than the reported value of 6 dB/mm. These results clearly demonstrate that high frequency ultrasound can be used to measure the thickness of metallic layers in the 5-50 \( \mu \)m range.

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