HIGH FREQUENCY LASER BASED ACOUSTIC MICROSCOPY USING A CW GENERATION SOURCE

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Abstract: A laser ultrasonic system has been developed which uses a modulated CW laser source for ultrasonic wave generation. The majority of high frequency laser ultrasonic systems use picosecond pulsed laser sources to generate ultrasound in the hundreds of MHz to the low GHz range. High frequency SAW generation and high-resolution acoustic microscopy require that the generation laser spot be tightly focused on the sample surface. This places a severe restriction on the amount of energy that can be deposited in the sample without causing surface ablation and ultimately limits the sensitivity of the system. In this work, we explore the use of an amplified, electro-absorption modulated diode laser source for high frequency ultrasound generation. The laser can be amplitude modulated up to 2 GHz and the peak power is approximately 2 Watts. While LBU systems using modulated CW generation can have extremely high SNR when lock-in detection systems are employed, they have disadvantages when compared to pulsed systems in terms of signal interpretation when multiple acoustic modes are present or when signals are reflected from the boundaries of the target material leading to complex acoustic interference patterns. In order to avoid these difficulties the source frequency is scanned over the bandwidth of interest and the transient response of the specimen reconstructed from the frequency domain data. Experimental results are presented for data obtained on thin films and plates in the 0.1KHz-200MHz range. The acoustic waves are detected using a stabilized Michelson interferometer fed into an RF lock-in amplifier. The reduced bandwidth of the system afforded by lock-in detection allows for a substantial improvement in signal-to-noise ratio over systems using pulsed laser generation for the same surface temperature rise. The experimental results are compared to theory and a detailed analysis of the SNR of the system given.

Introduction: Conventional laser ultrasonic techniques typically use pulsed laser sources for the generation of acoustic waves [1-3]. This is due in part to the fact that modulated laser sources with enough power to generate acoustic waves with sufficient amplitude for detection with an optical probe have not been readily available. Recent developments in laser technology, geared primarily for the telecom sector, have resulted in electro-absorption modulated DFB diode laser sources that can be amplitude modulated at frequencies approaching 40GHz. In addition, erbium doped fiber amplifiers are available to amplify the output of these lasers. It is noted that these components are relatively inexpensive, especially when compared to femtosecond and picosecond solid-state laser systems. High power laser sources that can be modulated at GHz frequencies provide an attractive alternative to pulsed laser sources for laser based acoustic microscopy.

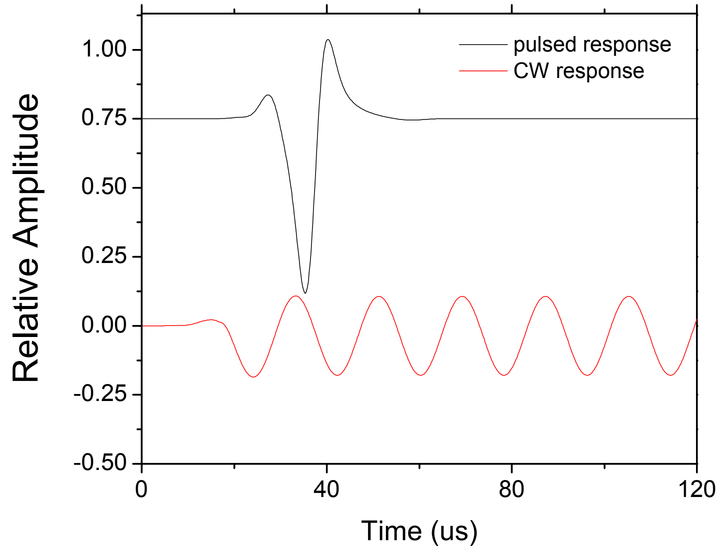

Figure 1. Acoustic response of an aluminum half-space showing SAWs generated using CW and pulsed laser sources. The laser sources produce the same maximum surface temperature in the sample.

The reasons for exploring photoacoustic microscopy using a CW laser source are twofold. First, it is expected that the signal-to-noise ratio of a CW system will be significantly improved over that of a pulsed system in a number of cases. Next, it is possible to resonantly excite small scale structures such as coatings, membranes, beams used in MEMs applications using a CW laser source to evaluate their mechanical properties. For thermoelastic generation of acoustic waves, there exists some temperature T_{max} (typically taken as the melting point) that the sample surface is kept below in order to avoid damage or ablation. For a given laser pulse shape, this limits the maximum allowable absorbed power density at the surface. As an example, we compare laser generation of ultrasound in aluminium with a 5ns pulsed laser source and a 60 MHz CW laser source. The laser spot size is taken as 3μm. It is found that, for the same absorbed power density in each case, the CW laser heats the material to a temperature of approximately 3.0 times higher than the pulsed laser. This is due to the fact that heat builds up in the sample between cycles until the sample reaches steady state. Now, the CW laser power is scaled down by a factor of 3 such that both of the laser sources produce equivalent surface heating. The scaled pulse shapes are then convolved with the impulse response of an aluminum semi-infinite half space (with the source and receiver slightly offset on the sample surface) to find the acoustic response of the sample. The resulting signals are shown in Figure 1. As is evident in the pulsed laser case, the laser source produces a strong surface acoustic wave (SAW). For laser powers that produce equivalent surface heating, the SAW displacement peak-to-peak amplitude is a factor of about 3.0 higher than that of CW generation. However, the bandwidth of the CW signal can be substantially reduced through detection with an RF lock-in amplifier. Using a sufficiently long integration time, the bandwidth can be reduced by more than six orders of magnitude for the narrowband case over the broadband case, resulting in a SNR increase of more than three orders of magnitude for this particular example. SNR is an important issue in laser based systems, which have lower sensitivity than conventional contact transducers [1], and this type of SNR increase could open up the possibility of using these non-contact systems for a much wider range of inspection applications.

Note that the improved SNR is strongly dependent on the spot size and thermal conductivity of the specimen. For laser ultrasonic microscopy, though, small spot sizes are required to produce localized sources and to make measurements over short source to receiver distances. It is also noted that the above analysis assumes that a high power CW laser source, capable of operating just below the ablation threshold of the sample, is available. Using diffraction limited spot sizes in the 0.75-3.0 μm range, peak power densities in the 100's of MW/cm^2 can be achieved with CW lasers operating in the standard 1-20W range.

One of the disadvantages of CW generation is that the signals can be difficult to interpret, especially when multiple acoustic arrivals are present. In addition, there is the possibility of setting up complex interference patterns on the sample surface due to reflections from sample boundaries. In this work, the CW modulation frequency is scanned over the range of interest and a time domain response, similar to that observed when generating with a pulsed laser source, is reconstructed from the measured frequency domain data. This approach allows for individual arrivals or modes to be easily identified in the data and for time domain gating of signals for data analysis. We demonstrate non-contact detection of acoustic waves generated with a modulated diode laser source at frequencies up to 200 MHz. Several researchers have demonstrated the feasibility of using modulated CW sources for acoustic wave generation in the kHz to low MHz frequency range. Pierce et al.[4], for example, demonstrated that it was possible to detect the acoustic signals generated using a diode laser source modulated using a pseudorandom binary sequence. The signals were detected using a surface bonded optical fiber and the output was correlated with the sequence to obtain the time domain displacement.

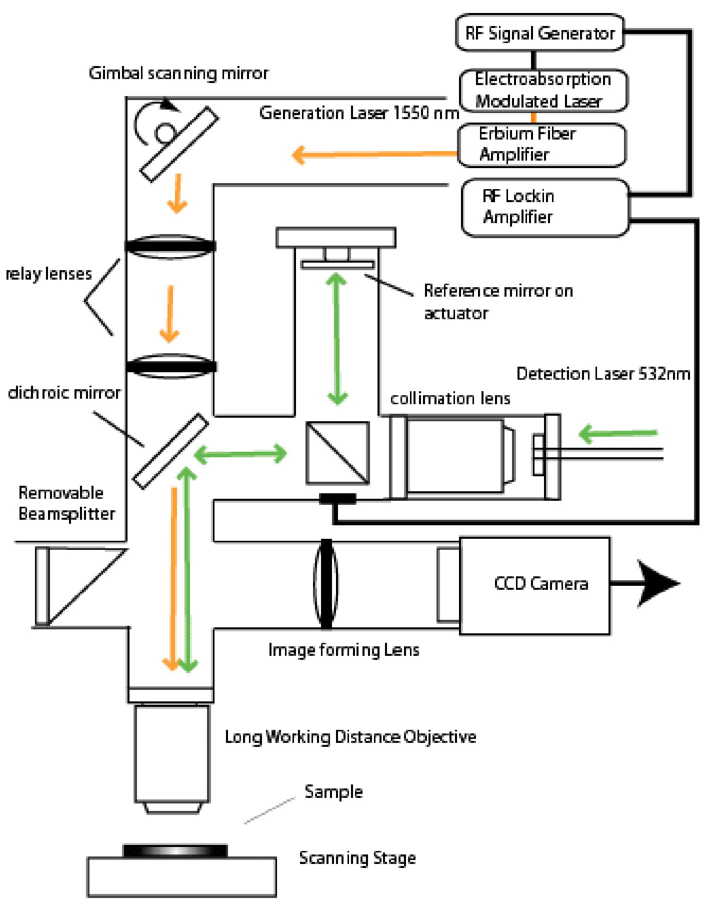

Figure 2. Schematic of experimental setup.

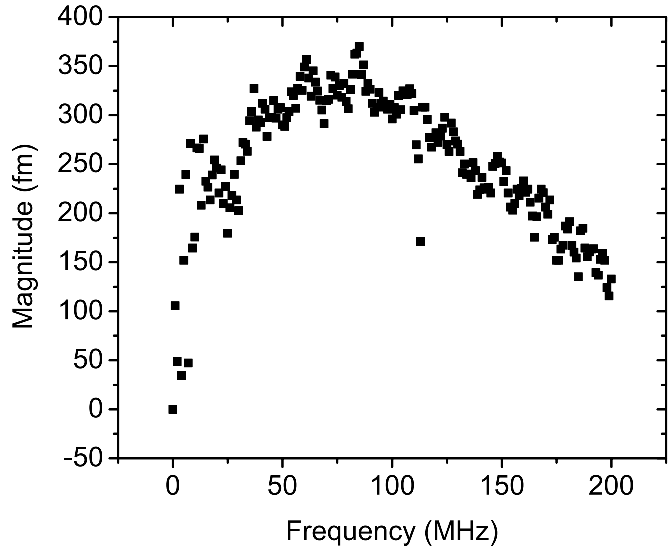

Figure 3. Magnitude of acoustic signals detected as a function of frequency.

Results: The experimental setup is illustrated in Figure 2. The system has three optical paths that lead to the sample surface through the same 20x objective (NA = 0.4). The first path leads to a CCD camera and allows for optical imaging of the sample surface as well as sample alignment. In the second path, the detection laser light enters the microscope though a single mode optical fiber, is collimated, and directed to the sample surface. Upon reflection from the sample the light is returned to a stabilized Michelson interferometer where the acoustic signal of interest is detected. The detection laser is a 200 mW frequency doubled Nd:YAG (λ=532nm). The generation laser is collimated, directed to a mirror on a gimbal mount, sent though a relay lens system, and directed to the specimen. The gimbal mount allows for precise control of the generation point within the field of view of the microscope. The total field of view of the microscope is 320 x 280 µm. An electroabsorption modulated DFB diode laser with a 1W fiber amplifier is used for ultrasound generation. The average generation power incident on the specimen was approximately 400mW. The generation laser is modulated using a signal generator and has a maximum modulation frequency of 5 GHz. The output signal from the photodetector is sent to an RF lock-in amplifier with a maximum detection frequency of 200 MHz. The signal generator and lock-in amplifier are controlled using a Labview program that allows for the modulation frequency to be scanned over the region of interest.

The laser source was scanned over the 1-200 MHz frequency range in 1 MHz steps. At each excitation frequency the magnitude and phase of the detected signal was measured. The bandwidth of each measurement was reduced to 1 Hz using the lock-in amplifier. Figure 3 shows the magnitude of acoustic signals on a 6mm thick aluminium block as a function of frequency, with a source to receiver distance of 256µm. The combination of the Michelson interferometer with lock-in detection allows for excellent sensitivity. The magnitude of the displacement measured over this frequency range is in the 200-300 femtometer range. There is a fall-off in the signals at higher frequency due primarily to a reduced modulation depth in the excitation source. The modulation depth falls from about 85% at 1MHz to 65% at 200MHz. It is unclear what is responsible for the reduced amplitude at low frequencies, but we hypothesize that this may be due to interference effects due to the waves reflecting off of sample boundaries. The data is processed in order to synthesize the time domain response of the system to a pulsed excitation source. The source function is given by:

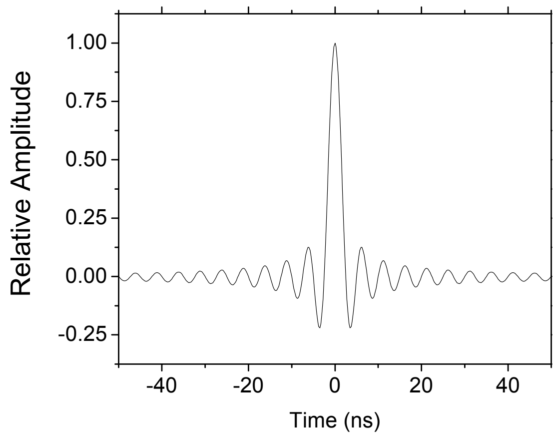

Figure 4. Synthesized input function used to obtain transient response of system.

$$i(t) = \frac{1}{m}\sum_{n=1}^{m} P_n(nf_0)\cos(2.0\pi n f_o t), \quad (1)$$

where f_0 is the frequency step, P_n is the peak power of the excitation source at frequency nf_0, and m is the total number of measurements taken. Note that Eqn. 1 is simply a mathematical construction and does not represent the actual incident laser intensity, but rather a sum of the excitation sources over all of the incident modulation frequencies. Once the response of the system is known over a given frequency range, the output of the system to any arbitrary input signal can be determined. In the case that P_n is constant over the entire frequency range and the frequency step is infinitely small, Eqn. 1 represents an sinc function centered at t = 0. Figure 4 shows a synthesized source function over the 1- 200 MHz frequency range with a frequency step size of 1MHz. The peak power at each frequency is taken to be constant and the output is normalized.

The time domain output of the system s(t) is found by summing the signals at each of the measured frequencies:

$$s(t) = \frac{1}{m}\sum_{n=1}^{m} M_n(nf_0)\cos[2.0\pi n f_o t + \theta_n(nf_0)], \quad (2)$$

where $M_n(nf_0)$ is the magnitude of the signal measured at frequency nf_0 and $\theta(nf_0)$ is the corresponding phase. The DC component of the signal is not measured, and thus is not reconstructed in either the source or output signals. The data can also be inverted using an inverse FFT algorithm rather than the Fourier series representation given above.

Figure 5 shows the results of reconstructing time domain signals using the frequency domain data acquired over 50, 100, and 200 MHz. The data is taken over 1MHz steps and thus the number of waveforms summed increase for the waveforms reconstructed over the larger bandwidths. As expected, the signals become more localized in time as the bandwidth increases. In the signal reconstructed over 200 Mhz, both the surface skimming longitudinal wave (SSL) and surface acoustic wave (SAW) are observed. The advantage of using time domain reconstruction is evident; individual acoustic arrivals can be identified and time gated. This is particularly useful when multiple acoustic modes are generated in the system or when looking for a reflected or scattered acoustic signal.

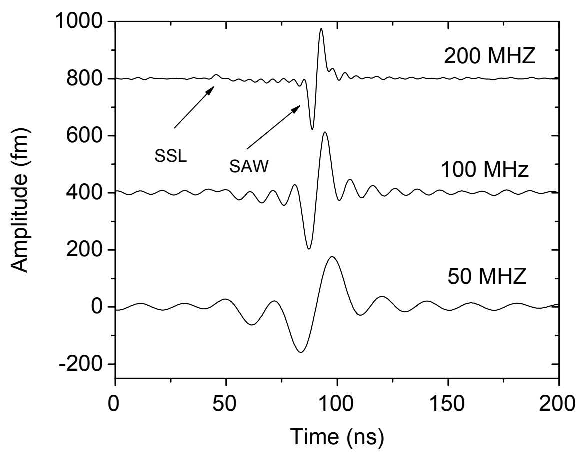

Figure 5. Time domain signals on an aluminium plate reconstructed over bandwidths of 50, 100, and 200 MHz.

Discussion: The use of CW generation, combined with lock-in detection, allows for the detection of displacements in the femtometer range, generated with only moderate surface heating. We estimate that the maximum heating of the aluminium surface used in these experiments was less than 20 degrees. The combination of this approach with time domain reconstruction provides time domain resolution and the ability to time gate for signal processing an analysis. It is noted that the improvement in signal-to-noise ratio does come at the expense of measurement time. For time sensitive applications, a faster integration time may be required. However, it may be possible to compensate for this in the inspection of some materials through the use of a higher power generation source, while still working well away from the material ablation threshold.

We also expect that this technique can be used for the measurement of film thickness or mechanical properties using surface acoustic waves. The frequency of the detection system is currently limited to 200 MHz due to the RF lock-in response. We hope to extend this to the GHz range by either mixing the signal down to a lower frequency or detecting the signal with a vector network analyser.

Conclusions: A laser based acoustic microscopy system has been developed which uses an amplified electroabsorption modulated laser source for generation. The system provides a substantial improvement in sensitivity over systems using pulsed lasers for generation through a reduction in signal bandwith using a lock-in detection scheme. In addition, we demonstrate that it is possible to reconstruct the time domain response of the sample, giving signals similar to those observed using pulsed laser sources. This allows for individual acoustic arrivals to be easily identified and for time gating. Experimental results demonstrate that the displacement sensitivity of our detection system is in the femtometer range. Time domain reconstructions of acoustic signals generated in an aluminium block show the presence of both the surface skimming longitudinal wave and surface acoustic wave. Future work will focus on increasing the maximum detection frequency and on using the system for thin film inspection.

References:

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