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Superheterodyne Detection of High Frequency Acoustic Waves

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Abstract
A laser ultrasonic system that allows for the excitation and detection of high frequency (GHz range) acoustic waves using low frequency, low cost detection electronics is presented. A continuous wave diode laser source, operating at a wavelength of 1544nm, is amplitude modulated using an integrated electro-absorption modulator and used to excite high frequency, narrow bandwidth acoustic waves. A path-stabilized Michelson interferometer, using a second electro-absorption modulated diode laser operating at 1550nm, is used for detection. Both lasers can be amplitude modulated over a bandwidth of approximately 10 GHz using low power signal generators. In the superheterodyne approach, the detection laser serves as the local oscillator and is modulated at a frequency offset from the excitation laser modulation frequency by a fixed amount. The amplitude and phase information of the acoustic signals are measured at the intermediate frequency using a low-frequency photodetector and lock-in amplifier. The modulation frequencies of the two lasers can be scanned over a broad frequency range while the signals are always measured at the fixed (low) intermediate frequency, obviating the need for high frequency detection electronics. The sensitivity and limitations of the technique are discussed, and results are presented demonstrating surface wave dispersion measurements in aluminum films on a silicon substrate over a 1GHz bandwidth.
Keywords: superheterodyne, continuous wave generation, amplitude modulation, surface wave dispersion, time domain reconstruction

1. Introduction

Laser based ultrasonic systems that use low-power, amplitude modulated continuous wave (CW) laser sources for acoustic wave generation have several potential advantages over conventional pulsed laser systems [1-3]. Pulsed laser sources generate broadband acoustic transients, requiring a frequency matched detection system susceptible to broad-band noise. CW laser sources, on the other hand, can be sinusoidally modulated to generate narrow-bandwidth acoustic waves. The detection system can then be tuned to the generation frequency using a lock-in amplifier, for example, and a majority of the system noise can be eliminated. The CW based approach is particularly attractive for high-frequency or high-spatial resolution applications that require a tightly focused excitation source, such as surface acoustic wave based thin film or coating inspection, or the detection of micro-scale defects in materials. In this case, the amount of energy in a pulsed laser source that can be deposited in a material is severely limited by the ablation threshold, and broadband detection of the high frequency acoustic transient can be challenging. The signal-to-noise (SNR) ratio of CW based systems can be controlled through the lock-in integration time, and can significantly exceed that of pulsed systems in some applications. Distributed feedback diode lasers, originally developed for the telecommunications industry, offer broad-bandwidth (DC-40GHz) modulation using integrated electro-absorption or Mach-

Zehnder modulators, and are attractive options for high-frequency laser ultrasonic applications.
In the detection of high-frequency acoustic signals, the modulated CW excitation approach offers an additional advantage; the signal of interest can be optically down-converted and detected using low-frequency, low-cost detection electronics. In this paper, a superheterodyne approach, similar to that used commonly in radio and television receivers, is presented. In a superheterodyne system, the signal of interest is mixed with a local oscillator in order to down-convert the signal to a low intermediate frequency. The local oscillator is locked, or tuned together with, the signal of interest such that the intermediate frequency is fixed and the downstream electronics are tuned and optimized for detection of this particular frequency. An analogous approach can be used for laser ultrasonic applications. If the laser source used in a stabilized Michelson interferometer is modulated at a fixed offset frequency from the acoustic signal to be detected, the acoustic signal is down-converted to the intermediate frequency and the magnitude and phase of the signal are preserved. The modulation can take the form of either a phase [4] or frequency modulation of the reference beam of the interferometer, or in the case presented here, intensity modulation of the laser source. As with amplitude modulated CW generation, amplitude modulated CW detection can be achieved over a broad bandwidth using compact, fiber coupled sources. The detection of acoustic signals at frequencies up to 1 GHz is demonstrated using low-frequency detection electronics.

2. Theory

Here the basic concept of superheterodyne detection using amplitude modulated laser sources for both the generation and detection of acoustic waves is presented. An amplitude modulated laser source is used to excite acoustic waves in a material and the resulting surface displacement is measured using a path-stabilized Michelson interferometer. If the surface displacement δ is of the form: $\delta = \delta_0 \sin(\Omega_{RF} t + \phi)$, where δ_0 is the magnitude of the displacement at an angular frequency Ω_{RF}, and ϕ is the corresponding phase, then linear detection of the displacement gives an interferometer response of $P_S = C\delta_0 \sin(\Omega_{RF} t + \phi)$, where C is a constant for a given system. Modulation of the detection laser at a frequency Ω_{LO}, with a modulation function (f) of the form: $f = (0.5)[1+\cos(\Omega_{LO} t)]$, gives a resulting interferometer signal of: $P_S = \{C\delta_0 \sin(\Omega_{RF} t + \phi)\}\{(0.5)[1+\cos(\Omega_{LO} t)]\}$. Multiplying the two terms in brackets, it is seen that the intensity modulation results in signals at three different frequencies: Ω_{RF}, $\Omega_{RF} + \Omega_{LO}$, and $\Omega_{RF} - \Omega_{LO}$. Assuming that a low frequency photodetector is used (sensitive only to the signal at the difference frequency), the output of the interferometer is given by: $P = (0.25C)\delta_0 \sin((\Omega_{RF} - \Omega_{LO})t + \phi)$. The signal is thus optically down-converted prior to detection. The modulation frequency of the detection laser Ω_{LO} is selected at each excitation frequency Ω_{RF} such that the difference frequency is a fixed value. A high-sensitivity photodetector and simple single frequency lock-in circuit can then be designed and optimized to work at this particular frequency.

In this down-conversion approach, the signal is split into three frequency components, with half of the original signal power remaining at the acoustic modulation frequency

(Ω_{RF}), and the other half being split between both the sum and difference frequencies. This leads to a demodulated signal that is a factor of four lower than the original signal. Since demodulation is achieved by amplitude modulating the detection laser, the average background intensity, and therefore the shot noise of the system, is also reduced by a factor of two. Assuming shot noise limited detection, this results in a power SNR reduction of 8 (or amplitude SNR reduction of $2\sqrt{2}$) for intensity modulation based superheterodyne detection compared to direct homodyne detection limit [5]. In practice, this may be compensated for by the fact that low frequency photodetectors can handle higher optical power and typically have better noise characteristics than their high frequency counterparts.

3. Experimental Setup

A schematic of the superheterodyne laser ultrasonic inspection system is given in Fig.1. The system has two optical paths leading to the sample surface through a single long working distance microscope objective with a numerical aperture of 0.4. The generation laser is operated at 1544 nm and is initially passed through an erbium doped fiber amplifier (EDFA) where it is amplified to 3.5 W. The collimated generation beam is sent to a gimbal scanning mirror. The light reflected by the scanning mirror is sent through a relay lens system to the long working distance objective where it is focused to the sample surface. The relay lenses are arranged in a so-called *4-f* configuration such that a rotation of the gimbal scanning mirror changes the angle at which the beam enters the objective and hence the position of the excitation laser source within the field of view of the microscope. The detection laser is operated at 1550 nm and is sent through a second EDFA where it is amplified to 1 W. The output of the amplifier is collimated and sent to a beamsplitter where it is split into signal and reference beams in a stabilized Michelson interferometer. The reference beam is sent to a mirror mounted on a piezoelectric actuator, which allows for control of the reference beam path length, and the reflected reference beam is sent to the detection photodiode. The signal beam is directed by a beamsplitter to the microscope objective and focused to the sample surface. The light reflected from the sample surface is collected and returned to the photodetector (7 MHz bandwidth) where it interferes with the reference beam. Approximately 14.5 mW is incident on the photodetector. The output of the photodetector is then sent to a lock-in amplifier. Beam samplers are used to extract a small fraction of the generation and detection beams, which are sent to two reference photodiodes. The outputs from the photodiodes are sent to a mixer and a low pass filter. The output of the low-pass filter, which contains only a modulated signal at the difference frequency, is used as the reference for the lock-in measurements. For this configuration, deriving the reference from optically coupled signals was found to significantly reduce the RF pick-up in the detection system below that achieved when using direct mixing of the electrical signals from the RF signal generators using a power splitter/mixer/low pass filter combination. The two RF signal generators are locked to a single 10MHz clock frequency and computer controlled such that the amplitude modulation of the detection laser is always selected to give a difference frequency at a fixed value between 1MHz and 5MHz.

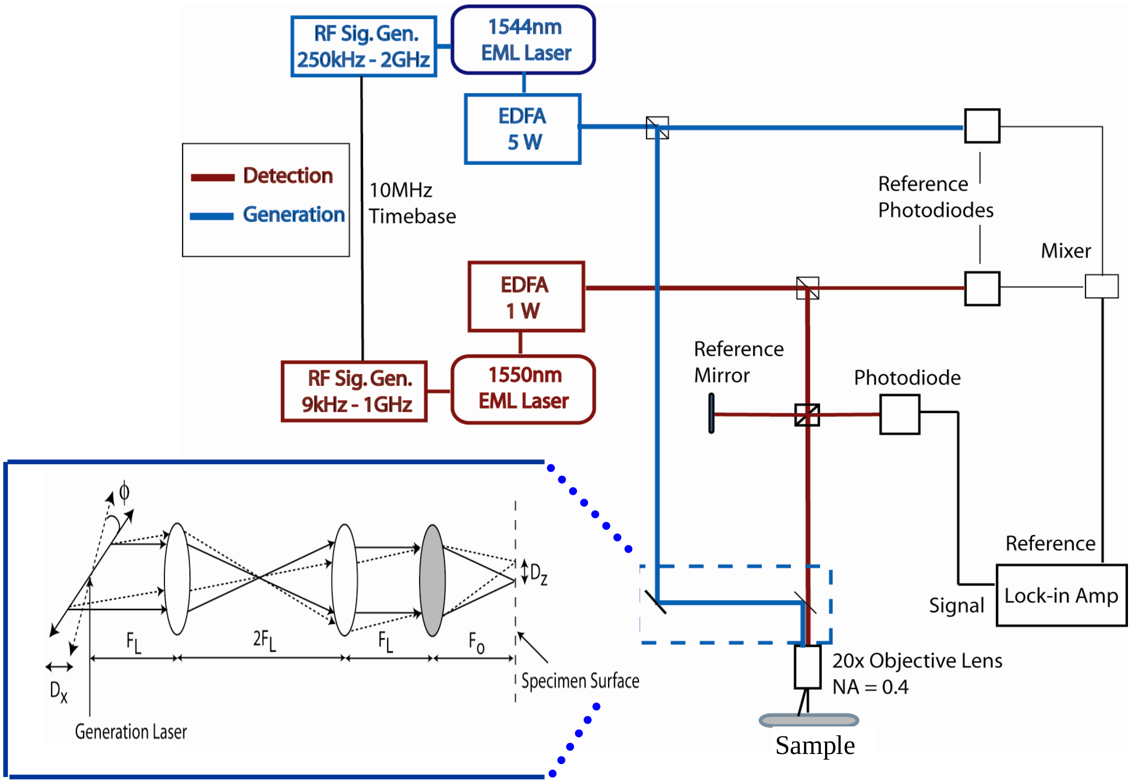

Figure 1. Schematic of experimental setup

4. Experimental Results

Superheterodyne detection of acoustic signals was demonstrated using two methods. First, surface acoustic wave (SAW) velocities were measured at multiple frequencies using a spatial frequency transform approach [6]. In the second technique, a time domain response was synthesized using the collected frequency domain data, and multiple acoustic arrivals were observed.

4.1 SAW Velocity Measurements

Surface wave velocities were measured for thin aluminium coatings on silicon substrates. To make each SAW velocity measurement, the acoustic signal is generated at a fixed modulation frequency, and the generation laser is scanned over the specimen surface in discrete steps with respect to the detection laser. At each source-to-receiver position, the complex amplitude of the normal displacement on the specimen surface is measured. As the source-to-receiver distance is increased, the phase of the SAW is delayed, and the real and imaginary components show periodic behavior. These components exhibit one full cycle of oscillation when the source-to-receiver distance is changed by one acoustic wavelength. In order to measure the SAW phase velocity (V) using this technique, the wavelength (λ) of the SAW is measured for every frequency (f), and the velocity is found through: $V = f\lambda$. A Fourier transform of the complex data reveals distinct peaks corresponding to the spatial frequencies of acoustic waves within a given sample.

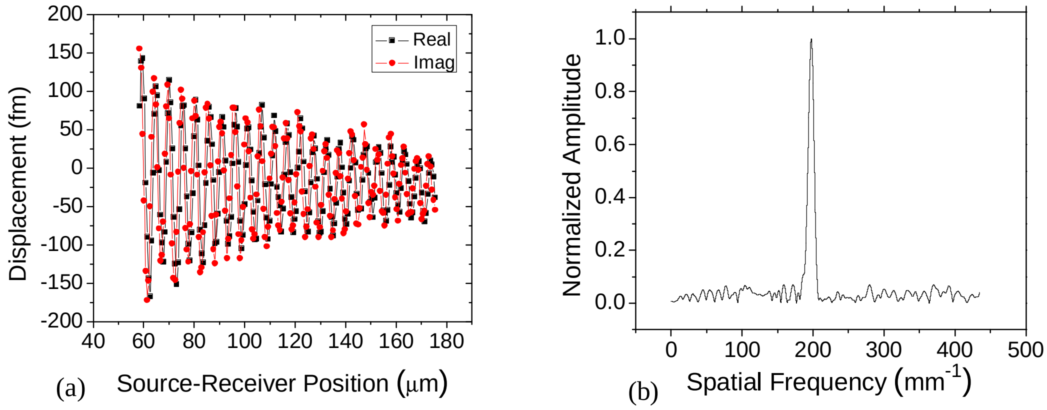

Figure 2. (a) Example of raw data collected at 1GHz and (b) Fourier transform of raw data.

An example of one velocity measurement is shown in Fig. 2, where a 25 nm aluminum coating was inspected. For this scan, the generation laser was amplitude modulated at 1 GHz while the detection laser was amplitude modulated at 995 MHz, yielding an intermediate frequency of 5 MHz at which the signal was measured. The source-to-receiver distance was scanned from 58 μm to 175 μm in steps of 0.58 μm. A distinct peak in the Fourier space is evident at a spatial frequency of 197.5 mm^{-1}, corresponding to a velocity of 5063 m/s. Dispersion curves were measured by repeating the previously described experiment at multiple frequencies from 200 MHz – 1 GHz. For all measurements, the intermediate frequency was held fixed at 5 MHz. In order to evaluate the precision of the velocity measurements, 10 measurements were taken at each frequency. The standard deviation of the velocity measurements over this frequency band ranged from 1.1-3.4 m/s.

4.2 Time Domain Reconstruction

In addition to surface wave dispersion analysis, time domain material responses can be studied by collectively summing the frequency domain data over a broad range of frequencies. In these experiments, the source-to-receiver position is held fixed, and the magnitude and phase of the acoustic signal is measured at each frequency. The time domain output can then be reconstructed using an inverse Fourier transform [7]. One example of a reconstructed waveform is shown in Fig. 3, where a 90 μm thick aluminum plate was examined. In this experiment, the source laser was held 60 μm away from the receiver, and measurements were taken from 100 MHz – 1 GHz in steps of 1 MHz. Again, all signals were measured at the 5 MHz intermediate frequency. It is clear from the reconstructed response in Fig. 3 that this technique can be used to identify and time gate individual acoustic arrivals within a particular specimen. Additionally, the ability to detect bulk waves allows for subsurface inspection of material systems.

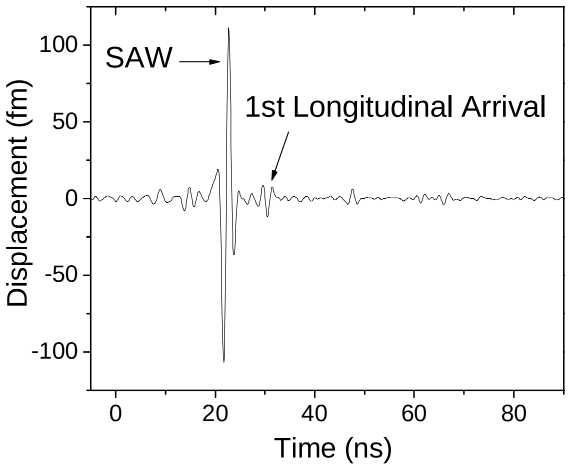

Figure 3. Time domain reconstruction on a 90 μm thick Al plate

5. Conclusions

In certain situations, CW modulated ultrasound has proven to be beneficial, offering improvements in SNR due to a reduced detection bandwidth and avoiding the limitations placed on conventional pulsed ultrasonic generation due to surface heating of the sample. The superheterodyne technique further improves upon this technology by eliminating the need for high frequency photodetectors and lock-in amplifiers while still allowing for high frequency analysis of material systems. Surface acoustic wave and bulk wave signals were measured at frequencies up to 1 GHz using the superheterodyne approach and detected at an intermediate frequency of 5 MHz. This technique opens up the possibility of using CW sources for a wide variety of laser ultrasonic applications.

Acknowledgements

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