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Theory and Applications of Frequency Domain Laser Ultrasonics

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Abstract
In frequency domain laser ultrasonics, the pulsed laser source used for ultrasound excitation in conventional laser ultrasonics is replaced by a low power, amplitude modulated laser source. The acoustic signals are detected using an interferometer or contact transducer, coupled to a RF lock-in amplifier or vector network analyzer. The detection bandwidth reduction afforded by this technique allows for a significant improvement in signal-to-noise ratio over systems using pulsed laser excitation. In this paper, the method of frequency domain laser ultrasonics is reviewed and compared to the pulsed-laser based approach. Methods for processing the frequency domain data to extract the information of interest are discussed, along with the effects of measurement bandwidth and frequency resolution. A technique to optically downshift acoustic signals detected using an optical interferometer to a fixed intermediate frequency is presented, which allows for the detection of high frequency (100's of MHz- GHz) acoustic signals using low frequency, low cost detection electronics. Several applications of frequency domain laser ultrasonics are presented including the inspection of thin films, environmental barrier coatings, membranes, and plates.
Keywords: laser ultrasonics, laser generation of acoustic waves, interferometry, materials characterization, frequency domain, time domain reconstruction

1. Introduction

A wide variety of laser-based ultrasonic systems have been developed for the non-contact and nondestructive characterization of materials. The majority of these systems used pulsed laser sources for acoustic wave generation followed by time domain detection of the transient material response using, for example, diffraction or deflection based optical probes or interferometers. Recently, several groups have also developed laser ultrasonic systems that use amplitude modulated continuous wave (CW) lasers for acoustic wave generation [1-3]. While the acoustic signals generated by CW lasers are generally quite small, the signal-to-noise ratio (SNR) of systems using CW sources can be improved through amplitude modulating the source using, for example, a linear chirp or pulse code sequence followed by a matched filter to achieve pulse compression. In this way, the total energy in the signal (and the system SNR) is increased through exciting over a long period of time, while pulse compression allows for temporal resolution to be maintained [1,3]. An alternative approach is to work directly in the frequency domain, exciting the material with sinusoidal modulation and measuring the response at a given frequency [2]. This approach allows for sensitive lock-in detection of the acoustic response, and the SNR of the system is controlled by the detection bandwidth or lock-in integration time. In this paper, an overview of frequency domain laser ultrasonics is presented with an emphasis on the experimental approach and techniques for processing the frequency domain data.

Frequency domain laser ultrasonics can provide significant improvements in SNR over pulsed laser systems in a number of cases, depending on the laser source parameters and thermal and optical properties of the sample. As an example, consider a comparison of pulsed and modulated CW laser sources illuminating an aluminum sample. The maximum energy in the pulsed laser source and the maximum power in the modulated CW laser source are taken such that each heats the surface to the same peak temperature. The following laser source parameters are used: the spot size at the sample surface is 1μm, the CW laser is modulated at 500 MHz, and the pulsed laser source has a pulse width of 1ns. The bandwidth of the detection system required to detect the pulsed response is taken as 1.2GHz while that of the modulated response is taken as 1Hz. Considering a measurement time of one second and assuming that the pulsed laser operates at 100Hz (allowing for an order of magnitude SNR improvement through signal averaging), the SNR of the modulated CW system is found to be approximately three orders of magnitude larger than that of the pulsed system. It is important to note, however, that the narrow-band source provides only the material response at 500MHz (albeit with exceptional SNR) while the broadband source provides information over the entire 1.2GHz bandwidth. Depending on the measurement application, multiple CW measurements may be required to extract a given piece of information about a material leading to an increase in measurement time and a corresponding reduction in the SNR enhancement stated above. In general, the SNR of frequency domain laser ultrasonics, using modulated CW generation at easily attainable power levels, compares favorably with pulsed laser systems when a small generation spot is required and in materials with relatively high thermal diffusivity.

2. Experimental Approach

An electroabsorption modulated distributed feedback (DFB) diode laser is used for acoustic wave generation. This type of laser was developed for telecommunications applications and has an integrated intensity modulator that can be driven directly using a standard signal generator. The bandwidth of the electroabsorption modulator is 10GHz (up to 40GHz is commercially available), the wavelength of the laser is 1.54μm, and the output power is approximately 1mW. The DFB laser output is sent to an erbium doped fiber amplifier (EDFA) where it is amplified to 3.5W. The EDFA output is then sent to a computer controlled gimbal scanning mirror, and through a relay lens system to a long working distance objective that focuses the beam to a spot size of approximately 2.7μm. Rotation of the gimbal scanning mirror allows for precise control of the position of the excitation laser spot on the sample surface.

Two experimental approaches have been used for the detection of narrow-band acoustic signals; both of which are based on a path-stabilized Michelson interferometer. In the first approach, which will be referred to as direct detection, the surface displacement is detected using a standard path stabilized Michelson interferometer with a 200mW frequency doubled Nd:YAG laser. The output of the interferometer photodiode is sent to a radio frequency (RF) lock-in amplifier where the complex displacement is measured. The bandwidth of the RF lock-in is 200 MHz. The second experimental approach is superheterodyne detection. The basic concept of superheterodyne detection of high frequency acoustic signals is illustrated in Fig.1. Here, detection of a 1GHz surface vibration is used as an example. The generation laser is amplitude modulated at

f_2=*1GHz*, producing acoustic waves at this frequency which interact with the sample surface causing the surface to vibrate. The Nd:YAG laser used for direct detection is

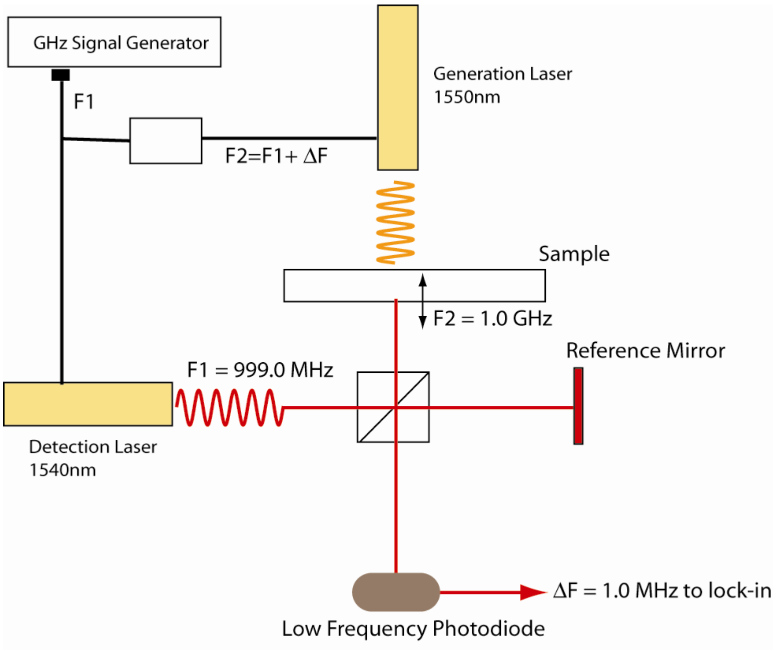

Figure 1. Basic superheterodyne laser based ultrasonic system.

replaced by a electroabsorption modulated DFB diode laser, similar to that used for acoustic wave generation but operating at a wavelength of 1.55µm and amplified using a 1W EDFA. The detection laser is amplitude modulated at a frequency of f_1=*999MHz*. The signal detected by the interferometer I contains both the harmonic displacement of the sample surface and the harmonic modulation of the intensity of the detection laser: $I = C\{\delta\cos(2\pi f_2 t + \varphi_2)\}\{1 + \cos(2\pi f_1 t + \varphi_1)\}$, where C is a constant that depends on the interferometer parameters, the first term in brackets is the ultrasonic surface displacement, and the second term in brackets is the modulation of the detection laser. δ and φ_2 are the amplitude and phase delay of the ultrasonic surface displacement, and φ_1 is the phase delay of the detection modulation. Multiplying the two terms in brackets and retaining only terms at the intermediate frequency, one finds: $I = C/2\{\delta\cos(2\pi(f_2 - f_1)t + (\varphi_2 - \varphi_1))\}$. For the case shown in Fig.1, $\Delta f = (f_2 - f_1) = 1MHz$ and both the magnitude and phase of the displacement at 1 GHz have been down-converted to 1 MHz. The main advantage superheterodyne detection over direct detection is that it allows for the detection of high frequency acoustic transients using low-frequency photodetectors and detection electronics.

3. Data Processing and Experimental Results

In frequency domain laser ultrasonics, the magnitude and phase of the surface displacement at a given excitation frequency is measured. This is a steady-state measurement and all acoustic waves that travel from the excitation point to the detection point, along any path, contribute to this complex displacement field. Depending on the inspection needs, there are several techniques available to process the frequency domain data to obtain information about a given material. Three such approaches will be briefly

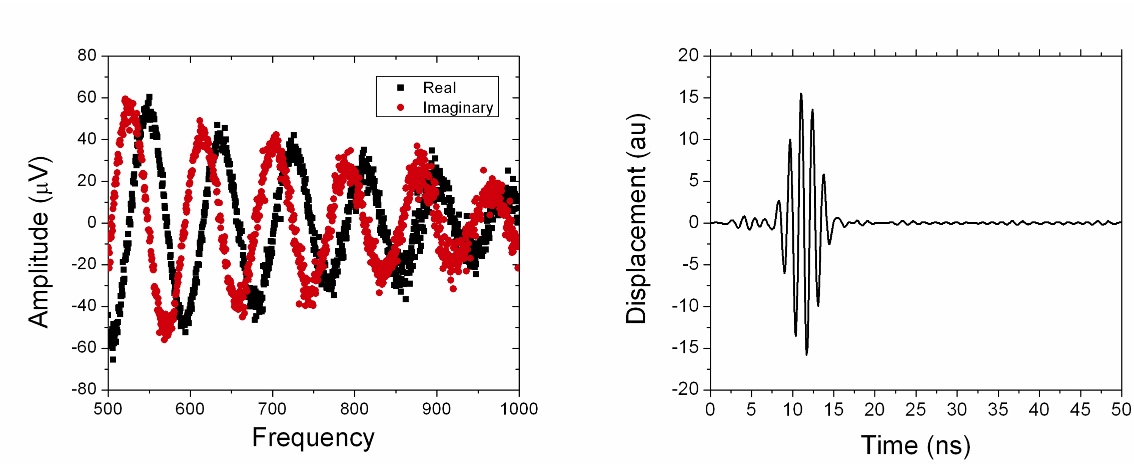

Figure 2. Measured complex displacement (left) and time domain reconstruction (right) detected on an aluminum coated silicon sample with a source to receiver distance of approximately 60µm.

described here: time domain reconstruction, spatial frequency transforms, and direct frequency domain analysis.

3.1 Time Domain Reconstruction

In this measurement approach, the source-to-receiver distance remains fixed and the magnitude and phase of the displacement field are measured as a function of frequency. An inverse Fourier transform is then used to synthesize the transient response of the material. In this "time domain reconstruction" approach individual arrivals of various acoustic modes can be identified and time gated. Several issues related to time domain reconstruction, including the effects of time domain aliasing and selection of frequency resolution, have been discussed in the literature [4]. Fig. 2 shows a time domain reconstruction of a signal measured on silicon wafer coated with a thin film of aluminum, with a source-to-receiver distance of approximately 60µm. Fig. 2 (left) shows the measured complex response from 500MHz-1GHz and Fig. 2(right) shows the time domain reconstruction found by taking an inverse Fourier transform of the measured data. The signals were acquired using the superheterodyne approach and detecting at an intermediate frequency of 5MHz. The main arrival is the surface acoustic waves and the ringing (side-lobes) in the time domain signal is due to the fact the signal is windowed in the frequency domain. There is also evidence of a surface skimming longitudinal wave arrival prior to the surface wave arrival.

3.2 Spatial Frequency Transform

The spatial frequency transform technique allows for measurement of the velocity of acoustic waves excited at a single frequency and it is particularly useful in mapping the dispersion characteristic of single or multiple modes excited in films, coatings, and thin plates [5]. In this technique, the excitation laser source and receiver (interferometer probe) are displaced on the sample surface and the real and imaginary components of the displacement field are measured. The source is then displaced further and the

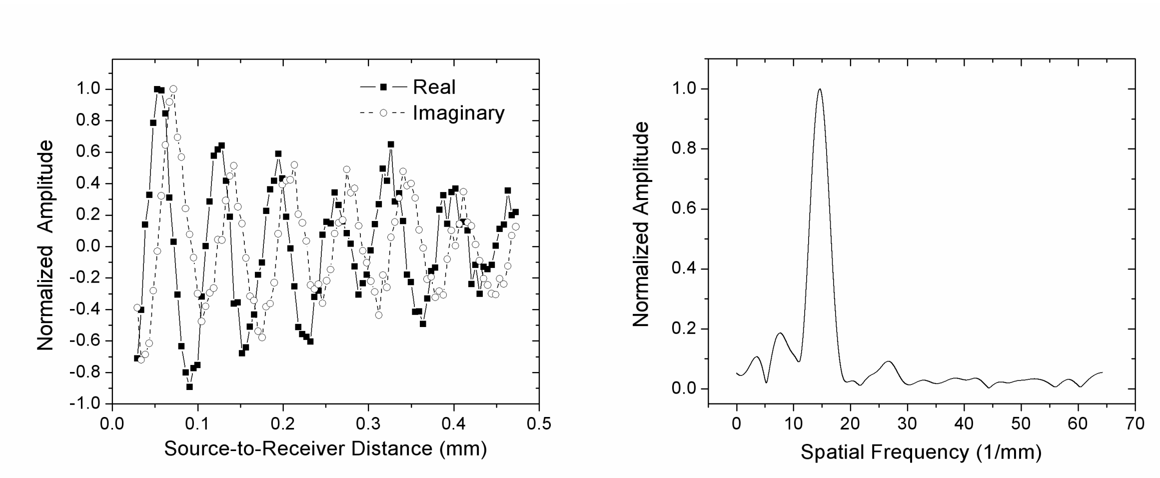

Figure 3. Complex displacement as a function of source to receiver distance (left) and Fourier Transform (right) at a frequency of 100MHz in a mullite coating on a silicon carbide substrate.

measurement is repeated at several source-to-receiver distances. As the source is displaced with respect to the receiver, the phase of the SAW is delayed. The phase (and real and imaginary parts of the signal) is periodic, going through a 2π phase shift when the source is moved by one wavelength with respect to the receiver. By tracking the periodicity in the complex displacement signal, one can find the wavelength λ of the generated acoustic waves. The excitation frequency f is known and hence the velocity v is determined through: $v = f\lambda$.

Fig. 3 shows an example of a surface acoustic wave velocity measurement on a mullite environmental barrier coating with a thickness of approximately 12μm on a silicon carbide substrate at an excitation frequency of 100MHz. Fig. 3(left) shows the measured complex displacement as a function of source to receiver distance. The periodicity in the signal is evident. Fig. 3 (right) gives the Fourier transform of the measured data, which shows a spatial frequency peak at 14.62mm^{-1} giving a wavelength of 68.38μm. At a frequency of 100 MHz this corresponds to a surface wave velocity of 6838m/s. In order to determine the dispersion characteristics of a given sample, the measurement is repeated at each required excitation frequency.

3.3 Direct Frequency Domain Analysis

A third approach to materials characterization using a modulated CW laser excitation source is to excite resonant modes in a given sample and to use the ultrasound spectrum to determine the physical or mechanical properties or sample dimensions. This type of non-contact resonant ultrasound spectroscopy is particularly well suited for the inspection of small-scale materials systems. We have used this technique to detect subsurface features in micron scale membranes [6], for example, and to evaluate and study zero group velocity resonance in thin plates [7]. In addition, this approach has been used to excite resonance modes in doubly clamped nanomechanical beams [8]. The result of one such measurement is given in Fig. 4. A 6μm long, 1 μm wide bi-layer (200nm Si, 50nm Cr) doubly-clamped beam was excited at the center using a modulated laser source and the magnitude of the displacement was measured as a function of frequency. Fig. 4 shows the fundamental resonance of the beam at 18.9 Mhz. The

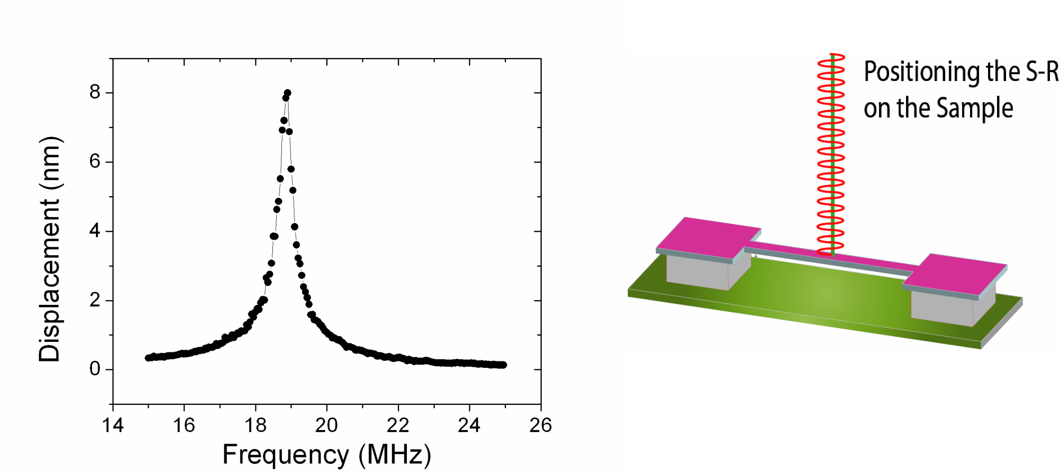

Figure 4. Displacement as a function of frequency measured on a 6μm long doubly clamped silicon beam. The source and receiver are placed at the center of the beam as shown in the figure on the right.

quality factor (Q) of the resonance is approximately 30, which is consistent with atmospheric damping. Measurements on small-scale structures can potentially be used to either to evaluate the mechanical properties of the structures or to detect small shifts in the resonance frequency or Q due to exposure to a biological or chemical species. The latter application may be important in the development of high sensitivity nano-mechanical sensors.

4. Conclusions

Frequency domain laser ultrasonics is well-suited for a variety of applications in nondestructive evaluation. Compact, low cost, fiber coupled, amplitude modulated laser sources are available for narrow bandwidth acoustic wave excitation over the kHz-GHz frequency range. Using a superheterodyne detection approach, we have demonstrated that high frequency acoustic waves can be detected using low frequency photodetectors and detection electronics optimized for operation at a single intermediate frequency. Depending on inspection needs, several options have been reviewed for processing frequency domain measurements and ultimately extracting material property information or assessing material integrity.

Acknowledgements

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