Enhancement of picosecond ultrasonic signals through the use of an optical cavity

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Abstract. We report an experiment in which an optical cavity is employed to enhance picosecond ultrasonic signals. The optical cavity is a Fabry-Perot interferometer formed by a distributed Bragg reflector (DBR) and the sample to be studied. By adjusting the thickness of the air gap between the DBR and the sample, the optical cavity can be tuned to be most sensitive to the sound-induced surface displacement of the sample. It is demonstrated that in the presence of the optical cavity, the efficiency of both the generation and detection of sound is improved. We furthermore show that this technique provides an efficient method of detecting sound in materials in which the piezo-optic coefficients are close to zero.

1. Introduction

The picosecond ultrasonics [1] technique has been used to perform ultrasonic experiments on a wide variety of thin films [2] and other nanostructures [3]. In the picosecond ultrasonic experiments, the magnitude of the stress wave generated by the pump pulse depends on the energy of the pump pulse as well as the optical reflectivity of the sample. The generation of sound becomes inefficient when highly reflective samples are studied and, consequently, an intense pump beam needs to be used in order to achieve a reasonable signal to noise ratio. The detection of the sound pulse is normally through a measurement of the change in optical reflectivity that occurs when the sound pulses return to the surface of the sample. The size of the reflectivity change is proportional to the piezo-optic coefficients of the top layer of the sample and to the amplitude of the returning sound pulse. Unfortunately, for some samples the returning sound can be very weak due to acoustic attenuation, or large differences in the acoustic impedances of the materials forming the sample. In addition, the piezo-optic coefficients of some materials, such as copper [4], are close to zero over a broad range of wavelengths. As a consequence, the reflectivity changes in these cases are too small to be detected with the usual detection scheme.

In the past, interferometric techniques [5] that combine an external interferometer with the picosecond ultrasonics technique have been able to measure changes in both the magnitude and the phase of the change in the reflection coefficient. The change in phase includes a contribution from the displacement of the sample surface, and thus makes a measurement possible even for materials that have zero piezo-optic coefficients. In this paper we describe the use of a planar optical cavity to measure changes in reflectivity. With the use of a resonant optical cavity, the efficiency of sound generation for high reflectivity materials is enhanced, and the detection sensitivity is increased. Planar...
optical microcavities have been used in the past to enhance optical phonon Raman scattering in semiconductors [6].

2. Principle of the method

We show in figure 1 the experimental setup. A DBR is put in the light path between the sample and the light source, instead of having the pump and probe beams directly incident onto the sample as in the normal picosecond ultrasonic setup. The DBR is positioned a fraction of a micron above the sample surface, leaving an air gap. The DRB and the sample form the resonant optical cavity, a planar Fabry-Perot interferometer. Once the light enters the optical cavity, it is reflected multiple times by the DBR and the sample surface before escaping. The reflected light waves within the cavity will be in phase with one another if the thickness of the air gap is such that the phase shift of the light after a round trip in the cavity is an integer multiple of $\pi$. In this condition, a standing light wave within the optical cavity is set up. This resonance of the optical cavity can be tuned by carefully adjusting the air gap thickness.

![Figure 1. Schematic diagram of the experimental setup.](image)

The top layer of the sample is a copper film with a reflectivity about 0.97. The reflectivity of the DBR is about 0.89 for s-polarized (TE) light and 0.63 for p-polarized (TM) light at 45°. We calculated the optical reflectivity of the cavity at 800 nm wavelength and 45° incident angle for s-polarized (TE) light as a function of the air gap thickness. The results are plotted in the left panel of figure 2. The reflectivity remains close to 1 until the air gap thickness satisfies the resonant condition where a steep drop in reflectivity to about 0.45 takes place. When the resonance occurs, the light gets trapped in the optical cavity for much longer, allowing more light energy to be absorbed by the sample. This increases the efficiency of sound generation for highly reflective samples such as copper, since the fraction of the pump light pulse that is absorbed in the sample is increased from 3% to close to 50%. The resonance curve has a periodic structure with air gap thickness since the round trip phase shift of light can be any integer multiple of $2\pi$ to satisfy the resonance condition.

The reflectivity of the cavity changes rapidly with the air gap thickness near resonance, and so near resonance the reflectivity is very sensitive to the displacement of the surface of the sample. The calculated sensitivity $\frac{dR}{dl}$, where $R$ is the reflectivity and $l$ is the thickness of the air gap, is plotted in the right panel of figure 2. The sensitivity curve is also periodic with air gap thickness. Figure 2 shows just the first resonance. The sensitivity is a maximum at 538 nm and 546 nm with a magnitude of about 0.05 nm$^{-1}$.

The resonance of the optical cavity also shifts when the angle of incidence of the pump and probe light beams are changed. Thus, in our experiment the goal is to adjust the cavity spacing and the angles of incidence so as to minimize the reflection of the pump light and to give a maximum value of $\left| \frac{dR}{dl} \right|$ for the probe light. This optimization process is limited by three main factors. 1) The pump and probe light beams have a finite spectral width and so an optical cavity that has a quality factor $Q$ above a critical value does not provide any further advantage. 2) It is necessary to focus the pump and probe beams onto the sample and so the finite numerical aperture of the focusing lenses means that
each beam contains light with a range of angles of incidence. This again limits the maximum value of \( Q \) that is useful. 3) The width \( l \) of the optical cavity must be precisely adjusted and controlled carefully. In the present experiment, we used a large area DBR and sample with a slightly wedged air gap. To investigate the performance of the cavity, we measured the probe reflectivity as it was swept over a fringe. The probe beam (s-polarized) was focused onto a spot of 25 \( \mu \)m in diameter and had an incident angle of 45\(^o\). The reflectivity as a function of the probe spot position is shown in figure 3. Although the dip is shallower than the theoretical value, the reflectivity still drops to about 0.65. This indicates that the limitations are not serious problems.

3. Results and discussion

The sample examined consists of a silicon substrate with 100 nm of thermally grown silicon dioxide. Then 5 nm of tantalum was deposited as an adhesion layer for the final layer of 150 nm of PVD copper. The light source used for both the pump and the probe is a diode-pumped mode-locked Ti:Sapphire Laser with a pulse width of about 200 fs (FWHM), repetition rate 80 MHz and wavelength 800 nm. The pump beam was chopped at a frequency of 1 MHz with an electro-optic modulator, and lock-in detection was used to measure changes in reflectivity of the probe beam. In figure 4, the change in reflectivity as a function of time delay is shown for three different air gap thicknesses. The data in figures 4a and 4c were taken with the cavity on opposite sides of the resonance curve. When the cavity is slightly off resonance, the structure is sensitive to surface displacements of the copper. The oscillations shown in figures 4a and 4c show the changes in reflectivity caused by the acoustic pulses bouncing between the free surface of Cu and the substrate. Since the piezo-optic coefficients of Cu at 800 nm wavelength is close to zero [4], the oscillations are primarily due to the surface displacement of the Cu film. In figures 4a and 4c, the oscillations have changed sign, since the sign of the sensitivity function changes across the resonance. The data in figure 4b was taken with the cavity very close to resonance. Note that in figure 4b, the oscillations are much smaller, which indicates that the cavity is near resonance where the sensitivity curve in figure 2 is zero.

We note that in figure 4b there is a sharp peak in the reflectivity change near time zero. This occurs even though the sensitivity of the cavity to changes in spacing is zero and so no acoustic signal can be detected. We believe that this signal arises from a change in the magnitude of the reflectivity of the copper film, rather than any change in the phase of the reflectivity or motion of the surface.
Figure 4. Measured reflectivity change as a function of time. The data in figure 4c has been expanded in the vertical scale by a factor of 3.

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