## Frequency control in laser ultrasound with computer generated holography

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(Received 10 November 1997; accepted for publication 23 February 1998)

In laser ultrasonics a laser is used to excite ultrasonic waves. The intensity profile of the laser on the sample can be used to control the frequency of the ultrasound generated. In this letter we show how the frequency content of Rayleigh (surface acoustic) waves generated with an 82 MHz mode-locked laser can be controlled using computer generated holograms (CGHs). To demonstrate the effectiveness of the frequency control the CGHs used were *defocused* to generate new illumination profiles. The agreement between the actual and predicted amplitudes for these profiles is striking. Using this technique, the intensity output from the CGHs may be considered as a tunable Rayleigh wave source. © *1998 American Institute of Physics*. [S0003-6951(98)04116-3]

Laser Ultrasonics<sup>1</sup> offers a powerful method for characterization of materials offering many advantages over other ultrasonic techniques because it is noncontact, nonintrusive and nondestructive when used in the thermoelastic regime. In order to exploit all the advantages of this technique it is important to control the laser intensity distribution on the sample. Computer generated holography<sup>2–4</sup> has many advantages over conventional techniques since it is possible to generate near arbitrary intensity distributions including ones which will focus over complex surfaces. This gives control over the initial wavefront and frequency content of the generated ultrasound.

Several papers have addressed the issue of frequency control of Rayleigh or surface acoustic waves (SAWs) using grating excitation.<sup>5,6</sup> Achenbach *et al.*<sup>6</sup> used a diffraction grating to ensure that certain frequencies out of a broad input spectrum are selected. An alternative method involves excitation from a moving grating by interfering two coherent beams with different optical frequencies.<sup>5</sup> Computer generated holography can be used in a way similar to these methods to produce a series of lines on the sample surface whose spacing can determine the frequency content of the generated ultrasonic waves.

Computer generated holograms (CGHs) which produce concentric arcs have also been fabricated. These achieve simultaneous focusing and frequency selection of the generated ultrasound. Since the CGHs are made accurately to a specific design the resulting intensity distributions can be accurately modeled either at the design focal length or away from it. This allows the modeling of the ultrasonic frequency spectrum generated for a particular CGH at and away from the CGHs focus. This letter shows how defocusing the CGH may be used to tune the frequency content of the generated SAWs. It is important to note that the modeling used in this letter applies only to the thermoelastic regime and that no damage was observed on any of the samples. In addition the samples were used uncoated with no treatment to enhance ultrasonic generation. Figure 1 shows the experimental setup used. A modelocked Q-switched Nd-YAG laser ( $\lambda$ =1064 nm) is used as the excitation source, which generates approximately 30 short pulses separated by 12.1 ns (82 MHz). The very short duration of the individual pulses ensures that the frequency content of the excitation beam is rich in harmonics, with a flat frequency spectrum, to well above a gigahertz. The CGHs used are self-focusing and require no additional optics to work. Detection of the SAWs was performed using a specialized knife edge detector.

For this study CGHs were designed using the direct search procedure described in Ref. 4. All devices were binary phase and etched in quartz. CGHs were designed and fabricated to produce one, two and four line foci with a focal length of 5 cm. The line spacing of the multi-line elements was 35  $\mu$ m corresponding to the wavelength of 164 MHz SAWs on silicon nitride.

Figure 2 shows the calculated lateral variation in the optical field intensity on the sample as a function of defocus for the two line CGH. The linewidth and depth of focus agrees well with the numerical aperture of the CGH [numerical aperture (NA) $\approx$ 0.04]. The two lines remain well in focus for the expected depth of focus. For more extreme defocuses the lines break up. The intensity distributions are not symmetric either side of focus, because the CGHs were designed only to optimize the intensity at the focus.

Working from Refs. 7 and 8, the amplitude of the SAW,  $a_r \propto 1/\omega_r F_s(k_r) F_t(\omega_r)$ , where  $F_s(k_r)$  is the component of



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FIG. 1. Schematic diagram of experiment.



FIG. 2. Intensity distribution of a two line CGH through its focus. The box marks the expected size of the foci and the arrow represents a length of 35  $\mu$ m, the separation of the two lines.

the Fourier transform of the spatial distribution of the source intensity at the SAW wave number  $k_r$  and  $F_t(\omega_r)$  is the corresponding temporal frequency component of the source at the SAW frequency  $\omega_r$ . This model is valid provided the thermal diffusion length (at the SAW frequency) and the optical absorption length are small compared with the SAW wavelength.

Figure 3 shows the frequency content of the intensity distribution shown in Fig. 2. When the CGH is in focus it can be seen that there is a minimum in the SAW amplitude at 82 MHz and there is a maximum at 164 MHz. The width of the peak at 164 MHz with respect to defocus is limited by the depth of focus of the CGH. At 82 MHz peaks in the amplitude are apparent approximately 2 mm either side of the focus of the CGH.

Figures 2 and 3 have been obtained purely by calculation from the CGH design. In order to verify the validity of the predictions defocus experiments were carried out using the one, two and four line CGHs. The relative SAW amplitude on silicon nitride at 82 and 164 MHz was measured as the defocus was varied from -5 to +5 mm. Knife-edge detectors were used to recover the SAW signal from the samples; these measure the surface gradient of the SAW as it travels under the optical probe. The detectors response is consequently proportional to the measured frequency and the relative amplitude is determined by removing this frequency dependence. The crosses in Fig. 4 show the measured SAW amplitudes and the solid curves show the predicted signal for



FIG. 3. Frequency content of two line CGH image vs defocus. Spatial frequency has been converted to temporal frequency for a SAW velocity of 5700 m/s (silicon nitride).



FIG. 4. Graphs of predicted and measured SAW amplitude at 82 and 164 MHz vs CGH defocus for one, two and four line CGHs.

the three CGHs. For each CGH the theoretical and measured amplitudes were normalized once keeping the amplitude ratio between the 82 and 164 MHz signals fixed.

Comparison of experimental results and theoretical predictions, given in Fig. 4, shows excellent agreement. The results for the one line CGH show that the maximum for fundamental and harmonic amplitude peaks at the focus as expected. It also can be observed that the surface wave amplitude is much more sensitive to defocus for the higher frequency than the fundamental; this is expected as higher frequencies require more tightly focused beams for efficient generation. The results for the two line CGH show a more interesting structure; at the focus there is good suppression of the fundamental and enhancement of harmonic signal. As the sample is defocused by just over 2 mm in either direction there is a peak in the fundamental excitation. The peak amplitude of the 82 MHz signal for the two line CGH is over two thirds of the peak amplitude for the one line CGH at the focus. The four line CGH exhibits even more complex behavior with defocus, again showing an increase in fundamental signal with defocus. These results demonstrate that, by simple defocusing, multi-line CGHs may be used to select a particular SAW frequency.

This letter has shown how the output frequency of generated surface waves can be controlled using CGHs, which produce diffraction limited lines patterns on the surface. The predicted and experimental variation of frequency content with defocus show excellent agreement. The method offers a simple and convenient way of controlling the frequency content of the generated SAWs. A CGH zoom system has been developed to allow the CGHs to be "tuned" to match particular material velocities.

The authors wish to acknowledge the Engineering and Physical Sciences Research Council (EPSRC) and Rolls Royce PLC who have supported this work.

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