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Excitation of high frequency surface acoustic waves by phase velocity scanning of a laser interference fringe

Hideo Nishino[a)] and Yusuke Tsukahara
Technical Research Institute, Toppan Printing Co., Ltd., Takanodai-Minami 4-2-3, Sugito-machi, Kitakatsushika-gun, Saitama 345, Japan

Yoshihiko Nagata, Toshio Koda, and Kazushi Yamanaka
Mechanical Engineering Laboratory, Namiki 1-2, Tsukuba, Ibaraki 305, Japan

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We present a novel method for generating 100 MHz band surface acoustic wave (SAW) by using a scanning interference fringe at the phase velocity of the SAW. The scanning interference fringe is obtained by intersecting two laser beams with different frequencies, and used as a thermoelastic source. The principle of this method is described, and experimentally demonstrated in the 110 MHz Rayleigh waves on an aluminum specimen generated by a long-pulse (140 ns) Q-switched Nd:YAG laser.

The generation of elastic waves by a laser beam in the thermoelastic regime[1] has been widely attempted for noncontact and nondestructive material evaluations. However, the amplitude of the elastic waves generated by the thermoelastic effect[1] is sometimes not sufficient for the measurements. To enhance the amplitude of elastic waves, some methods were proposed, especially in surface acoustic waves (SAWs).[2,3]

Recently, the phase velocity scanning (PVS) method was proposed[4,5] to enhance the amplitude of single mode waves in multimode media, and experimentally verified[4,5] in fundamental symmetric and asymmetric Lamb waves on an aluminum plate by using a scanning laser beam. A theoretical analysis for the PVS method was also investigated.[6] In the previous works, a single laser beam was scanned on the specimen by using a polygon-mirror scanner. Therefore, to increase the frequency of elastic waves for more microscopic measurements, the laser beam must be focused to comparable size as the wavelength of generated elastic waves. However, the focal length of the convex lens for focusing a laser beam should be long enough to achieve high scanning velocity.[4,5] Thus, 100 MHz or higher frequency elastic waves cannot be generated by using a single beam scanning.

In this letter, we propose a novel approach for generating SAWs with 100 MHz or higher frequencies by the PVS method where a scanning interference fringe is employed. In the past, a bulk wave generation in the electrostrictive materials by using the scanning interference fringe was demonstrated.[7] However, the present method of SAWs generation is not based on the electrostrictive effect, but on the thermoelastic effect, being applicable to any kind of materials. After describing the principle of this method, we show an experimental verification by using a long pulse Q-switched Nd:YAG laser to generate a 110 MHz Rayleigh wave on an aluminum specimen.

Figure 1 shows a cross section of a specimen, two laser beams, and the scanning interference fringe. $\mathbf{k}_1$, $\mathbf{k}_2$, ω_1, ω_2, I_1, and I_2 are the wave vectors, frequencies, and amplitudes of each laser beam, respectively. Incident angles of the laser beams are θ and $-\theta$ to the normal of the specimen, respectively. The amplitude I of the laser beams on the surface of the specimen is

$$I = I_1 e^{i[(K\sin\theta)x-\omega_1 t]} + I_2 e^{i[(-K\sin\theta)x-\omega_2 t]}, \quad (1)$$

where $K=|\mathbf{k}_1|\approx|\mathbf{k}_2|$. Consequently, the intensity I^2 becomes

$$I^2 = I_1^2 + I_2^2 + 2I_1I_2\cos[(-2K\sin\theta)x-\omega_a t], \quad (2)$$

where $\omega_a=\omega_2-\omega_1$. Thus, Eq. (2) shows that the interference fringe is scanned at a velocity v_f along the x axis.[8]

$$v_f = -\omega_a/2K\sin\theta. \quad (3)$$

This means that a spatially periodic heat source is scanned on the surface of the specimen, and therefore SAWs are generated by means of the thermoelastic effect[1] and their amplitude is enhanced, when the scanning velocity is equal to the phase velocity of SAWs.[4,5]

The above principle was experimentally verified by generating 110 MHz Rayleigh wave on a 20-mm-thick aluminum specimen. The experimental setup is illustrated in Fig. 2. Second harmonic waves, $\lambda=532$ nm, of a Q-switched Nd:YAG laser (beam diameter=2 mm) were

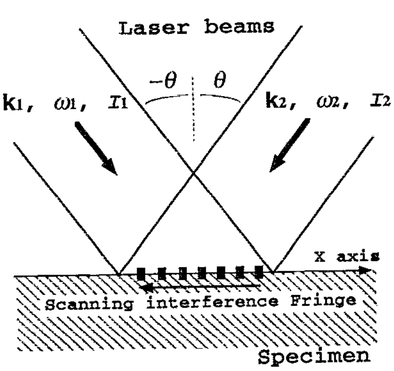

FIG. 1. Cross-sectional view of laser beams, a specimen, and an interference fringe scanning in one direction from right to left when $\omega_1<\omega_2$.

[a)]Correspondence address: Advanced Technology Division, Mechanical Engineering Laboratory, Namiki 1-2, Tsukuba, Ibaraki 305, Japan.

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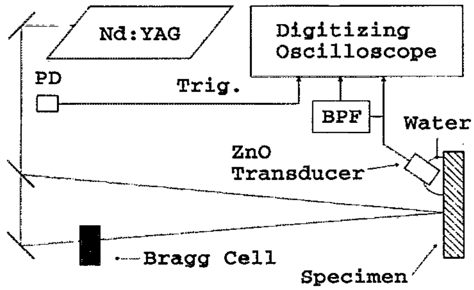

FIG. 2. Schematic diagram of experimental setup for Rayleigh wave generation. PD: photodiode, BPF: bandpass filter.

employed in the experiment. The pulse width of this laser is variable from 20 ns to 200 ns. Such a long pulse is not possible with a standard Q-switched Nd:YAG laser, but it was realized by using a relatively long cavity length of 2 m and by Q-switch triggering earlier than the optimum timing (Continuum K. K. custom laser YG2672-10). The laser beam was split into two beams by a beam splitter. A TeO_2 Bragg cell was driven at 110 MHz and was applied to one beam in order to shift the laser frequency from the other beam. Finally, the two beams were intersected on the surface of the aluminum specimen. The energies of frequency-shifted and nonshifted laser beams were 0.9 and 1.0 mJ/pulse, respectively, on the surface of the aluminum specimen. The Rayleigh waves were detected with a 2 mm×2 mm ZnO piezoelectric transducer, with the center frequency of 120 MHz, fixed at the Rayleigh critical angle with water as a coupler. The transducer was located 5 mm away from the intersection of two laser beams. Scattered light from the laser, which was received by the photodiode (PD), was employed as a trigger signal of a digitizing oscilloscope. The incident angle θ was decided to be 565 mdeg by Eq. (3) with $v_f=2960$ m/s, which equals the Rayleigh wave velocity v_R of the aluminum specimen, an angular frequency $\omega_a=2\pi(110)$ MHz, and a wavelength $\lambda=532$ nm of the laser.

Figure 3 shows digitized waveforms. Ch. 1 is the laser

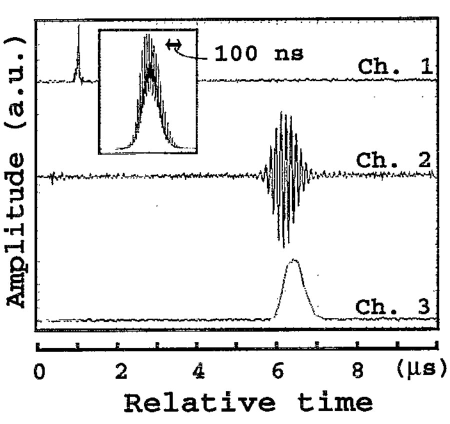

FIG. 3. Results of the experiment for 110 MHz Rayleigh wave generation. Ch. 1: laser pulse signal, Ch. 2: direct waveform, Ch. 3: bandpass (center freq.=110 MHz, band width=3 MHz) filtered and envelope detected waveform.

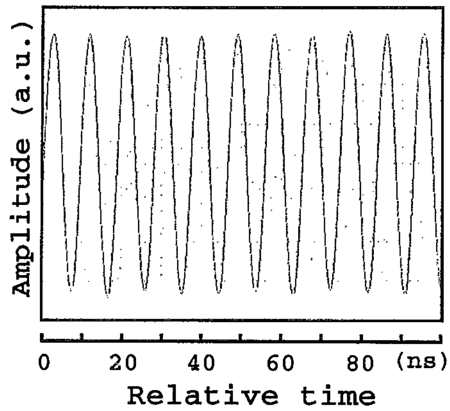

FIG. 4. Expanded direct Rayleigh waveform. The frequency can be observed to be about 110 MHz.

pulse. The laser pulse was expanded in the inset of Fig. 3. It has periodic spikes determined by the characteristic frequency 75 MHz of the laser cavity. The half width at half maximum (HWHM) was estimated to be 140 ns. Ch. 2 is a Rayleigh waveform from a signal of the ZnO piezoelectric transducer. Ch. 3 is a 110 MHz center frequency and 3 MHz bandwidth bandpass filtered and envelope detected signal of the Rayleigh wave. An expanded Rayleigh waveform of Ch. 2 is shown in Fig. 4. These results show that the frequency of the Rayleigh wave was 110 MHz identical with the shift frequency ω_a of the laser.

The Rayleigh waveforms and filtered signals disappeared, when one of two split laser beams was intercepted. This is proof that the scanning interference fringe, rather than a laser beam itself, generated the Rayleigh waves.

Duration of the excited Rayleigh wave was 700 ns (HWHM). By using this value and Rayleigh wave velocity v_R, the beam diameter is calculated to be about 2 mm. This leads to a fairly good agreement with the actual laser beam diameter. A 5.2 μs delay from the laser pulse signal (Ch. 1) to a Rayleigh wave (Ch. 2) was observed in Fig. 2. This is the propagation time delay through the aluminum surface as a Rayleigh wave, and through the water and a fused quartz (buffer rod of the ZnO piezoelectric transducer) as longitudinal waves.

The ablation threshold of aluminum[9] is more than 9.0 MW/cm^2, but the laser power density in our experiment was less than 0.4 MW/cm^2. Consequently, no ablation was caused on the surface of the aluminum specimen.

Based on the above experiment, we discuss advantages of the PVS method. Clear oscillations of Rayleigh waves were obtained without any averaging in Figs. 3 and 4. The signal to noise ratios in the direct Rayleigh waveforms were better than 30 dB and in filtered signals were better than 50 dB in spite of using a relative low power laser. It is a result of an amplitude enhancement effect of the PVS method.[4,5] This effect was obtained by using a 140 ns long pulse laser with a 15 wavelengths long scanning of an interference fringe.

In principle, the frequency of the generated SAWs by the present method could be increased up to gigahertz range, because referring to Eq. (2), the spacing of the fringe ($\pi/K \sin\theta$) is reduced to 3 μm at $\theta \approx 5$ deg. The generation of gigahertz range SAWs were also demonstrated by using a static interference fringe[10] modified to employ a mode-locked picosecond laser,[11] but the PVS method is superior to it, because one can use a much simpler standard *Q*-switched laser. Furthermore, the above feature of the amplitude enhancement effect of generated SAWs is unique to the PVS method.

In conclusion, we have shown a novel method of generating high frequency and high amplitude SAW by using a scanning interference fringe. Since the apparatus and signal processing of the present method are simple and reliable, we believe that a noncontact and nondestructive evaluation of the micromechanical structures could be developed by using the present method together with noncontact optical detectors.[12]

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