A Feasibility Study on Generation of Acoustic Waves Utilizing Evanescent Light

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Abstract. A new approach of generating acoustic waves utilizing evanescent light is presented. The evanescent light is a non-propagating electromagnetic wave that exhibits exponential decay with distance from the surface at which the total internal reflection of light is formed. In this research, the evanescent light during total internal reflection at prism surface is utilized for generating acoustic waves in aluminium and the feasibility for ultrasonic measurements is discussed. Pulsed Nd:YAG laser with 0.36 J/cm\textsuperscript{2} power density is used and the incident angle during the total internal reflection is arranged to be 69.0° for generating the evanescent light. It has been demonstrated that the amplitude of the acoustic waves by means of evanescent light is about 1/14 as large as the one generated by the conventional pulsed laser. This reveals the possibility of using a laser ultrasonic technique with near-field optics.

1. Introduction
Laser ultrasonic measurement is a sophisticated technique which enables the evaluation of the mechanical properties of material, crack detection, identification of temperature distribution and so on [1][2]. In this technique, the measurement resolution is limited by the diameter of the incident light spot. Therefore, the novel method that overcomes the resolution limitation in laser ultrasonic measurement is strongly aspired. To extend this technique smaller than the diffraction limitation of the light wave, utilizing the near-field optics is one of the promising alternatives to the conventional laser ultrasonic system. Ultrasonic near-field optical microscopy (UNOM) has been developed to provide nanoscale spatial resolution for ultrasound detection [3]-[6]. The UNOM technique allows local mapping of ultrasound with deep sub-optical wavelength spatial resolution. However, little attention has been given to the point that the generation of ultrasound utilizing near-field optics at local area which is smaller than the wavelength of the light wave. In this article, the evanescent light during total internal reflection at the prism surface is utilized for generating acoustic waves in aluminium plate and the feasibility for ultrasound measurements is discussed.

2. Evanescent wave
The evanescent light is a non-propagating electromagnetic wave that exhibits exponential decay with distance from the surface at which the total internal reflection of light is formed. Figure 1 shows the evanescent light which penetrates inside the material 2. When the total internal reflection of the light is formed, the electric field of evanescent light at the prism surface is defined as follows.
\[ E(x, z) = T_0 \exp \left( -i\omega t + ik_2 \frac{x}{n} \sin \theta_1 \right) \cdot \exp \left( -k_2 z \sqrt{\frac{1}{n^2} \sin^2 \theta_1 - 1} \right) \]  \hspace{1cm} (1)

\[ k_2 = \frac{2\pi}{\lambda_2}, \quad n = \frac{n_1}{n_h} \]  \hspace{1cm} (2)

where \( T_0 \) is the maximum amplitude of the electric field, \( \omega \) is angular frequency of the incident light, \( k_2 \) is wave number of the light in material 2, \( \lambda_2 \) is wave length of the light in material 2, and \( \theta_1 \) is angle of the incident light. In equation (1), if we assume \( z = 1/k_2 \sqrt{(1/n)^2 \sin^2 \theta_1 - 1} \), the amplitude of the electric field decreases 1/e as small as the electric field at \( z = 0 \). Therefore, the 1/e-penetration depth \( \Lambda \) of evanescent light is defined as shown below [7].

\[ \Lambda = \frac{1}{k_2 \sqrt{\frac{1}{n^2} \sin^2 \theta_1 - 1}} \]  \hspace{1cm} (3)

In this research, refractive index of prism \( n_h \) is 1.51, refractive index of aluminum \( n_{al} \) is 1.37 [8]. According to Snell’s law, the critical angle is determined to be 65.1° where the incident light shows the total internal reflection at the interface between prism and material. The critical angle of prism-air interface is determined to be 41.2° as well. In our experiment, the angle of the incident light is arranged at 69.0° which is larger than the critical angle of prism-aluminum interface to generate the ultrasonic waves only by the evanescent light. Figure 2 shows the electric field of evanescent light according to the position from the prism surface to the air [7]. We used Nd:YAG laser of 1064 nm optical wavelength, so the 1/e-penetration depth \( \Lambda \) of evanescent light is determined to be 170 nm by using equation (3). When the evanescent light reaches the aluminum surface, the conduction electrons at the surface screen the interior of the aluminum from the incident light so that the absorption and reflection take place within the surface layer. This ‘skin depth’ in the aluminum specimen is estimated at 5 nm for the wavelength of ND:YAG laser [9].

\[ \text{Figure 1. Evanescent light during total internal reflection at prism surface.} \]

\[ \text{Figure 2. Electric field of evanescent light from prism surface to air.} \]

3. **Experimental setup**

Figure 3 shows the schematic diagram of experimental setup for measuring the generation of acoustic waves. Figure 4 shows the detailed view of the experimental setup. A well-polished aluminum plate with 5 mm thickness is used as a specimen. The right angle prism is in close contact with the specimen. The evanescent light is formed during the total internal reflection at prism surface by using a pulsed laser. The incident angle of the pulsed laser is determined to be 69.0° which is more than the critical angle of 65.1° derived from Snell’s law. Pulsed Nd:YAG laser (maximum power 180 mJ) is operated at 1064 nm optical wavelength, with duration time of 3~5 nsec. A lens with 100 mm focal length is used to focus the pulsed laser onto the specimen. To detect acoustic waves, the ultrasound transducer with coupler is arranged on the other surface of the specimen with proper pressure as shown in figure 4. The ultrasound transducer is longitudinal wave type with 10 MHz band frequency, 9 mm diameter. The power density of pulsed laser is measured by using a power meter to evaluate acoustic waves quantitatively. Laser power is controlled to be 10 mJ, and distance from lens to aluminum is arranged...
130 mm which is longer than the focal length of the lens to enlarge the irradiated area on the specimen. Because a damaged region will be introduced inside the prism due to perfectly focused laser, we intended to control the energy density (laser power / irradiated area) of pulsed laser carefully. Although the spot diameter of the laser is usually estimated by \(1/e^2\) (13.5%) power as compared with the beam center, we utilized the simple method this time. The irradiated area is estimated by drawing an ellipse over the damaged region on the sensitized paper. The irradiated area is estimated to be \(2.75 \times 10^{-2} \text{ cm}^2\), so the energy density is calculated at 0.36 J/cm².

![Figure 3. Schematic diagram of experimental setup.](image)

![Figure 4. Generation and detection of acoustic waves by evanescent light.](image)

**Figure 3.** Schematic diagram of experimental setup.

**Figure 4.** Generation and detection of acoustic waves by evanescent light.

**Figure 5.** Measured acoustic waves generated by direct laser irradiation (left), evanescent light (right).

### 4. Results and Discussion

Figure 5 shows obtained acoustic waves generated by conventional pulsed laser and the evanescent light. A 29 dB gain and a 59 dB gain are applied to the original signals generated by the conventional laser ultrasonic method and the evanescent light, respectively. For fair comparison, this gain is canceled after the data processing. The highest signal of the acoustic waves generated by evanescent light is approximately 1/14 as large as the one generated by the conventional pulsed laser. The starting times of both the first and the second echo are almost the same and the time delay from the first echo to the second echo is estimated at 1.63 μs utilizing cross correlation method. Therefore the velocity of ultrasound was estimated at 6130 m/s. This value agrees well with the reference value of longitudinal wave velocity in aluminum (6260 m/s). These results indicate that it is possible to generate acoustic waves by means of evanescent light.

The condition of contact between the prism and the specimen which affects irradiation degree of evanescent light is examined. The surface roughness of prism and aluminum specimen is investigated by AFM. Figure 6 shows the representative surface of a prism and specimen where both materials contact each other and evanescent light is formed. The maximum distance from the highest to the
The lowest point is 44 nm at the prism surface and 153 nm at the aluminum specimen, respectively. The surface accuracy (surface height differential on whole surface) of the prism is 158 nm according to the vendor specifications. The surface accuracy of the aluminum specimen for the contact area is 1362 nm investigated by laser microscope scanning. The sum of two surface roughnesses (197 nm) is almost the same as the 1/e-penetration depth of evanescent light (Λ = 170 nm) in equation (3). However, the irradiation degree of the evanescent light depends on the surface accuracy of the aluminum specimen because of the existence of the spatial gap between the prism and the aluminum specimen. It is considered that the relatively large gap causes the very weak signal generated by evanescent light in this experiment. Due to the existence of the average gap between the prism and the specimen, the actual penetration depth of the evanescent light in the air is estimated to be reduced by an average of 450 nm when we consider the signal degradation (1/14) and the relationship between the electric field of evanescent light and the distance from the prism as shown in Fig. 2. Note that there are some contact points at the actual prism-specimen interface as with some gaps.

![Figure 6. Surface roughness of aluminum specimen (left), prism (right) measured by AFM.](image)

5. Conclusion

A novel method generating acoustic waves by evanescent light during total internal reflection at prism surface is presented. Nd:YAG laser with 0.36 J/cm² power density is used and the incident angle is determined to be 69.0° which is more than the critical angle of the total internal reflection for generating the evanescent light. It has been demonstrated that the intensity of the acoustic waves by means of evanescent light are about 1/14 as large as the one generated by the conventional pulsed laser. The time delay from the first echo to the second echo is approximately 1.63 μs, which almost agrees with the expected value determined from the longitudinal velocity of the aluminium by conventional pitch-catch method. These results reveal the possibility of using a laser ultrasonic technique with near-field optics.

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