Detection of acoustically induced electromagnetic radiation

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Electromagnetomechanical response of materials is detected through electromagnetic radiation induced by ultrasound waves. Target specimens are placed in the focusing zone of the ultrasound waves at a distance of $\sim 60$ mm from an acoustic generator. The radiation is picked up by a narrow-band loop antenna tuned to the ultrasound frequency. Due to the delay time caused by ultrasound wave propagation in the medium (water), the pulsed electromagnetic radiation from a target is well separated (temporally by $\sim 40 \mu s$) from the apparent signal attributed to the generator, allowing unambiguous and sensitive detection of true signals. Upon stimulation with ultrasounds, emission of electromagnetic radiation is found in bones, woods, plastics, and ferrites as well as a standard piezoelectric material (GaAs). © 2006 American Institute of Physics.

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Ultrasound imaging technique is widely applied as non-invasive probe to human bodies and material structures. One important advantage of the technique is that elastic waves are capable of propagating through opaque substances such as human bodies, metals, and concrete blocks, in which light does not propagate. Owing to the remarkable difference between the sound and the light velocities, elastic waves are featured by remarkably short wavelengths, being by about five digits smaller than those of electromagnetic (EM) waves. It follows that sharp focusing on a millimeter/micrometer scale is achievable in the megahertz/gigahertz range where real-time wave form analysis is performed in commercially available equipments. Despite these advantages, the majority of existing applications are restricted to diagnosing elastic properties of the targets, viz., electromagnetomechanical properties are not probed. Electromechanical imaging techniques are highly developed in scanning probe microscope systems, but only surface analysis is targeted. Here we propose and demonstrate a distinguishing method of probing electromagnetomechanical properties of matters via acoustic-wave excitation.

Electromagnetic and mechanical properties are closely coupled in many materials. A familiar example is the piezoelectricity, which ionic crystals exhibit due to the lack of inversion symmetry. It is known that a variety of crystallized biological molecules such as bones, tendons, muscles, etc., also shows piezoelectricity. A number of studies on medical applications using stress, electromagnetic fields, and ultrasound waves report biological effects of electromechanical response. Since the equation of acoustic waves in piezoelectric materials include electric-field terms, EM waves will be generated when a piezoelectric slab is in resonance with acoustic waves, as theoretically suggested in Ref. 9. Measurements of such EM radiation are performed in wireless operation of acoustic-wave devices, but detection of extremely weak EM radiation from materials to be studied has been untackled. Utilizing a pulsed acoustic technique, we show that EM waves are emitted from a variety of materials when they are acoustically stimulated and that the emission takes place even without the resonance condition.

Figures 1(a) and 1(b) depict the experimental setup. We prepared two schemes, a water-immersion method [Fig. 1(a)] and a nonimmersing probe method with an acoustic transmission tube [Fig. 1(b)]. In both schemes, a target sample is placed in a focused zone at a distance (50–70 mm) from a medical-use polyvinylidene fluoride (PVDF) transducer, in which rectangular 50 ns wide pulses are applied at a repetition rate of 100–500 Hz by a pulser/receiver (Panametrics-NDT, 5077PR). Noting the ultrasound velocity in water (1500 m/s), one expects that EM waves acoustically induced and emitted by the sample are temporally separated by 33–47 $\mu s$ from the generator excitation pulses. EM waves are detected through a loop antenna tuned to the center frequency ($f_0$) of ultrasound waves with a bandwidth of $\sim 200$ kHz. Using a broad-band hydrophone, we confirm that the ultrasound waves are concentrated on a focal spot of less than 2 mm diameter, with a spectrum around $f_0=9.25$ MHz [Fig. 1(c)]. Signals picked up by the antenna are fed to a low-noise preamplifier and averaged over pulses by using a digital oscilloscope. Though not shown here, heterodyne detection of EM waves is also carried out by using a double balanced mixer.

The first target sample is GaAs with piezoelectric component of $d_{14}^{\text{GaAs}}=2.7 \text{ pC/N}$. Longitudinal acoustic waves are expected to generate EM waves when their wave vector $k$ is parallel to the piezoelectric axis of (110). A nondoped 0.35 mm thick GaAs crystal with the [110] axis aligned to $k$ is the incident acoustic waves is studied by the water-immersion method [Fig. 1(a)]. In addition to familiar acoustic echo signal [Fig. 2(a)], EM waves are also detected as shown in Fig. 2(b), where the EM signal is amplified by 82 dB and averaged over 200 pulses (1 s). The prominent two EM signals coincident with the excitation ($t=0 \mu s$) and the echo ($t=88 \mu s$) signals of acoustic waves are attributed to EM waves generated by the PVDF transducer. We find, in addition, a weaker EM signal (68 $\mu V$) occurring at the middle point ($t=44 \mu s$) between the excitation and the echo pulses. This is identified as the EM radiation emitted by the GaAs crystal [Fig. 2(b)]. A secondary EM signal due to GaAs is also visible at $t=132 \mu s$. The envelope of the EM signal clarified by heterodyne detection is shown in Fig. 2(c). When the target is replaced with a (nonpiezoelectric) pure

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silicon crystal of similar geometry, we find no discernible EM signal ascribable to the target, as displayed in Fig. 3. The study of a similar GaAs crystal with the [100] axis aligned to \( k \) confirms that the piezoelectrically active propagation, \( k \parallel [110] \), yields significantly larger EM signals than for \( k \parallel [110] \) as demonstrated in Figs. 3(b) and 3(c). These findings definitely support the interpretation that the observed EM radiation is generated via the piezoelectricity of GaAs crystal.

EM radiation spectrum studied by the heterodyne detection is shown in the inset of Fig. 3. The distinct peak of the spectrum at 7.60 MHz is suggested to be due to mechanical resonance of the GaAs crystal, the thickness of which (0.35 mm) is comparable to the half-wavelength [the sound velocity of 4730 m/s in GaAs (Ref. 15)]. The enhancement factor due to the resonance is \( \sim 10 \), but we note that EM waves are detectable also in the nonresonant condition.

Owing to the ubiquity of electromechanical coupling in biological materials,3–4 this measurement scheme may find broad application in biological and clinical researches. We have carried out preliminary studies on bone. Principal ingredients of bone are hydroxyapatite crystal (\( \sim 70\% \)) and highly oriented collagen fibers (\( \sim 20\% \)), where the latter is known to contribute to piezoelectricity (\( |d_{\text{bone}}| \approx 0.1 \text{pC/N} \)).3 We take costae of swine as the sample of bone and prepare \( \sim 2 \) mm thick square plates, respectively, out of the outer hard layer and the inner soft tissue, where the fiber axis is parallel to the plate surface. The samples are washed in eth-

*FIG. 1. Schematic representation of measurements for acoustically induced EM radiation: (a) Water-immersion method and (b) nonimmersing probe method with a plastic tube instead of water tank. (c) Spectrum of ultrasound wave produced by a PVDF transducer.*

*FIG. 2. Typical time traces obtained for a GaAs (110) plate: (a) Acoustic echo signals, (b) EM signals, and (c) an envelope of EM waves obtained via heterodyne detection. A scale of the signal intensity for (b) is denoted on the left axis.*

*FIG. 3. Time traces for (a) Si (100) plate, (b) GaAs (100) plate, and (c) GaAs (110) plate. Longitudinal ultrasound wave is normally incident on the plate. The inset shows the spectrum of EM waves emitted from a GaAs (110) plate.*
anal solution for 1 h by ultrasonic cleaner. The acoustic wave vector is perpendicular to the fiber axis for all the samples. The signal is amplified with a gain of 97 dB and averaged for 10 min with 500 Hz repetition. We find acoustically induced EM signal from the outer layer of bone as shown in Fig. 4(a), where result obtained via the water-immersed method is displayed. Similar result is obtained from the samples of inner tissues with no discernible difference in the signal intensity. It is reported that piezoelectricity of bone is considerably reduced by water due to ionic screening. In the present experiments, however, the screening effect might be negligible because the process of screening is usually slower than in the megahertz range. The measurements of immersed bones here make us expect possible application of the present method to noninvasive probing of living bones.

Using the nonimmersing probe method [Fig. 1(b)], we have extended the studies to different materials such as wood and plastic. Acoustically induced EM radiation is found in wood as shown in Fig. 4(b). The mechanism is supposed to be due to the piezoelectricity of crystallized cellulose,5 which is the basic component of wood. Though extremely weak, EM signal is detected in an amorphous polymer compound of commodity plastic (composed of a piezoelectric polypropylene) as shown in Fig. 4(c), suggesting the presence of crystallized grains.

Additional experiments on thicker slabs of bone and wood reveal that the enhancement takes place primarily at the leading edge of each EM wave pulse. This suggests that the EM wave emission occurs predominantly in a region close to the front face of each specimen. This may be reasonable because if a regular sinusoidal distribution of alternating electric polarization is assumed over a region substantially larger than a half-wavelength of acoustic waves, the EM radiation will be canceled out at a distance well larger than the acoustic wavelength.

In addition to piezoelectricity, magnetomechanical coupling is expected to generate acoustically induced EM radiation. Figure 4(d) represents the EM waves emitted from ferrite (SrO/Fe2O3), where a cylindrical ferrite magnet (20 mm diameter × 15 mm height) is studied by the immersion method. The comblike structure in the EM wave form indicates a multiple reflection of acoustic waves at the front and back faces of the specimen.

In summary, we have demonstrated a unique method of exciting a wide variety of materials with acoustic waves and probing induced EM waves. The materials studied include biological tissues, plastics, and ferrites as well as piezoelectric GaAs. It is a distinct advantage of the present method that pulsed EM signals are temporally well separated from the excitation and the echo signals/noises generated by the ultrasound transducer. When combined with ultrasound scanning technique, the method will make it possible to image electromagnetomechanical properties of a wide variety of matters.

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12Studies of EM radiation originated from piezoelectricity of rock are reported in geophysical researches, but the EM signals are generated by rock fracture or high-pressure experiments. For instance, see Ref. 17.
13Although the inverse phenomenon, EM-wave-induced acoustic radiation, is applied to biomedical imaging, the quantity obtained is not piezoelectric response but thermal expansion response generated by absorption of EM waves. See M. Xu and L. V. Wang, Rev. Sci. Instrum. 77, 044101 (2006).
18To avoid apparent EM signal from the plastic tube, the edge of the tube should not touch the specimen stimulated acoustically.
19EM radiation may not be strictly canceled in the present measurements, where pulse waves are focused on the specimen. Hence EM waves emitted from the bulk region will be detectable if the sensitivity is improved.
20Detection time of EM-signal peak in the comblike structure corresponds to a half of arrival time of echo signal reflected on the top or the bottom face of the ferrite. Owing to the large impedance mismatching with water, the long-time response is allowed by ultrasound waves confined in the ferrite.