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GENERATION AND DETECTION OF ULTRASONIC WAVES BEYOND 100 GHz

E. H. JACOBSEN

Department of Physics and Astronomy, University of Rochester, Rochester, New York, U. S. A.

1. Introduction. — The piezoelectric effect should permit the generation and detection of elastic waves in matter over virtually the entire vibrational spectrum, i. e., from zero to about 10^{13} Hz. An attractive feature of the piezoelectric transducer lies in its insensitivity to temperature, and ambient electric and magnetic fields. Moreover, it can be deposited as a thin film directly on a sample [1], and electrically coupled in a simple manner to the driving and receiving circuit. Aside from signal loss due to attenuation, which can be reduced by subjecting the sample to liquid helium temperatures [2], a major problem arises, however, in detecting sound at high frequencies. The difficulty centers on the short sonic wave length; e. g., the wave length will be thousands of Angstroms at 10^{10} Hz, and hundreds of Angstroms or less at 10^{12} Hz. These numbers refer to a solid; in a liquid the wave length will be some five to ten times less...
for the same frequency because of the reduced interatomic forces.

For maximum detection sensitivity, the piezoelectric surface should be flat and parallel to the wave front (assuming a plane wave) to within an angle of approximately $\lambda/D$, where $\lambda$ is the sound wave length and $D$ the average cross sectional dimension (typically millimeters) of the surface. This condition insures that the entire surface is driven at the same phase so that the piezoelectric polarization field is coupled maximally to the external circuit, e.g., resonant cavity. (Transformation from electric to sonic energy, and vice versa, takes place over a surface depth of one half the sonic wave length [3]). At the higher frequencies this condition becomes increasingly difficult to meet because imperfections in the medium will scatter the wave and so produce an irregular wave front, and because even small misalignments between the wave front and piezoelectric surface will easily exceed $\lambda/D$. It is to be noted that these geometrical conditions need not be satisfied in the generation of high frequency sound: complex and misaligned wave fronts will be generated readily by irregular piezoelectric surfaces and will propagate accordingly. Conventional piezoelectric detection of such waves, however, will prove difficult if not impossible at high frequencies.

In recent years, spin systems [4] and superconducting tunnel junctions [5] have been used to detect (and also generate) elastic waves above 100 GHz. These systems respond to elastic waves over atomic volumes and therefore can detect wave fronts which lack phase coherence over macroscopic dimensions. Detection sensitivity is further enhanced by operating these systems in conjunction with synchronous amplifiers.

2. Conventional piezoelectric generation and detection of sound up to 100 GHz. — The piezoelectric generation and detection of sound up to perhaps 25 GHz is quite straightforward: a re-entrant cavity, see figure 1, provides a convenient method of applying a microwave electric field to the surface of a piezoelectric crystal during sound generation. The same cavity also serves to couple the piezoelectric surface polarization, produced by an incident sound wave, to the receiver. For simplicity we assume that the sound field is a pulse which propagates as a plane wave normal to the crystal surface. (This assumption is usually valid if the cross-sectional dimensions of the sample are much larger than the sonic wave length.) Maximum detection sensitivity will obtain when the sound wave front is parallel to the piezoelectric surface. As departure from parallelism occurs, part of the surface will produce a polarization field of opposite phase so that the average polarization field seen by the cavity is accordingly reduced. As the angle between wave front and surface increases further, the average polarization oscillates through a series of nulls and decreasing maxima. The limits in angle are set, of course, by the sound intensity and receiver sensitivity. Typical pulse, superheterodyne microwave receivers in this frequency range routinely provide sensitivities of some 90 dbm (decibels below milliwatt). Using such a receiver we have been able to detect a 1 milliwatt sound pulse in quartz at 24 GHz with a misorientation angle exceeding $100 \lambda/D$.

At higher frequencies, e.g., beyond 100 GHz, the ratio $\lambda/D$ becomes smaller and harder to satisfy. Moreover, anharmonic attenuation becomes more serious: the attenuation is typically proportional to $fT^4$ at microwave frequencies and low temperatures, where $f$ is the frequency and $T$ is the sample temperature [6]. Finally geometrical scattering of the wave by small imperfections will increase and tend to produce a nonplanar front. Consequently the net piezoelectric polarization presented to the microwave cavity for coupling to the receiver is substantially reduced. Nonetheless, it is possible to piezoelectrically generate and detect sound waves in the 100 GHz range by paying careful attention to transducer alignment and receiver design. Such experiments have been carried out at 114 GHz [2], and are described below.

At frequencies beyond about 25 GHz the re-entrant cavity becomes impractical as a means of coupling the external microwave circuit to a piezoelectric crystal because the cavity dimensions and $Q$ become very small [7]. A way around this limitation is to replace the re-entrant cavity by an enclosed cylindrical or rectangular cavity operating in a higher-order mode. Such an arrangement is shown in figure 2. If the quartz crystal is made to fill the cavity such that the $x$-axis of the crystal coincides with the long dimension, a corrugated wave front will be generated at each end as indicated. The corrugation results from the fact that the phase of the electric driving field $E_x$ oscillates with distance along the transverse direction of the cavity. The resulting sound wave is mainly compressional but contains a small shear component. Such a wave will propagate in fact over several centimeters before the phase of the shear wave changes enough, relative to that of the compressional
wave, to alter significantly the shape of the wave front [8]. It is likely, however, that other sources of wave front distortion, e.g., misalignment and scattering, are much more effective in diminishing the average surface polarization available to the cavity for "reading out" the signal. A rectangular TM_{3,4,8} cavity filled with quartz and bathed in liquid helium will have dimensions of \(0.328 \times 0.425 \times 0.85\) cm\(^3\), a \(Q \approx 1000\) (assuming the use of copper), and be resonant at 114 GHz [2].

The pulses are selected and averaged by a delayable gate and box car integrator, the output of which is fed to a synchronous amplifier, and hence to a recorder. In this way the effective receiver band pass is greatly reduced and the noise averaged out. The delay of the pulse sampling gate is slowly and continuously increased so that the output of synchronous amplifier gradually sweeps through the various phonon echo pulses. This procedure will yield a receiver sensitivity of about 100 dbm, and will permit detecting phonon echoes generated by a microwave drive power of some tens of milliwatts. Non-piezoelectric samples can be studied in the same system by evaporating a piezoelectric film on one surface [1]. Since geometric alignment is critical at these frequencies, it will often prove rewarding to test the propagation of phonon signals in the sample first at 10 GHz. The samples which yield the best signals at 10 GHz usually also yield the best signals at 100 GHz.

It is clear that successful experiments in elastic wave propagation in the 100 GHz range depend on the combination of sample perfection, attenuation, available microwave source power, and receiver sensitivity. Of these items, increases in microwave source power and detection sensitivity appear to be the only practical route for improved research at 100 GHz frequencies and beyond by means of the piezoelectric effect. At this writing carcinotron are available which produce a watt of power between 100 and 300 GHz. At 900 GHz, the HCN laser can produce about the same power. At frequencies above 100 GHz the attenuation of electromagnetic waves in metal wave guides increases rapidly so that dielectric guides, mirrors, or hybrid systems will be required for energy transmission to (and possibly from) the sample. For the same reason it will be necessary to replace the enclosed resonant cavity by structures such as the Fabry-Perot and zone plate systems shown in figures 4 and 5.

It seems likely that more powerful high frequency microwave sources will be developed, a more immediate prospect of improvement appears to lie in the direction of greater detection sensitivity.

Fundamentally, detection of sound can proceed by incoherent or coherent processes. Quantum detection by means of paramagnetic ions in crystals [4],...
and Cooper pairs in superconductors [5] are examples of the former. In this process only the intensity and not the phase of the wave is detected, the obvious advantage being that detection is unaffected by wave shape and sample geometry. Piezoelectric detection, by contrast, is a coherent process; the phase is preserved and the instantaneous amplitude is amplified at the signal frequency. So long as wave shape and sample geometry are not limiting factors, coherent detection offers the advantage of relatively high gain through the property of the superheterodyne principle wherein the intensity at the difference frequency (I. F.) is proportional to the square root of the product of signal and local oscillator intensities.

In the light of these remarks it is of interest to consider methods for improving both coherent and incoherent detection of sound at ultra-microwave frequencies and beyond. We propose in the following paragraphs some possible schemes for doing so.

3. New methods of detecting sound above 100 GHz.

3.1 JOSEPHSON JUNCTION PIEZOELECTRICALLY COUPLED TO SOUND. — A novel method of phonon detection arises in the use of a weak-link superconducting Josephson junction. This device is highly sensitive to oscillating electric and magnetic fields [9], and may be deposited on a piezoelectric surface in microgeometry. Such an arrangement is expected to couple to the local piezoelectric polarization field on the scale of the junction dimensions, which means that the sound wave need be phase coherent over a much smaller spacial extent.

The coupling of a Josephson junction to an oscillating field produces a series of steps in the d. c. current-voltage characteristic of the junction. If only one frequency is present, each step occurs at a voltage corresponding to a multiple of the excitation frequency, according to the relation $V = n hf/2 e$. $V$ is the d. c. voltage applied to the junction, $n$ is an integer, $h$ is Planck's constant, $f$ is the excitation frequency, and $e$ is the electron charge. If two frequencies are present, the steps in the I-V curve occur at voltages corresponding to sum and difference frequencies, and multiples and combinations thereof.

Two weak-link geometries suitable for coupling to the piezoelectric polarization field and outlined in figures 6 and 7. Figure 6 shows a point-contact junction affixed to the end of a sample. The junction comprises a sputtered film and point of niobium, separated by a thin (1 000 Å) piezoelectric layer of cadmium sulfide. The point is pressed through the piezoelectric layer by means of a differential spring drive mechanism so as to establish a weak link. Coupling to the local polarization field occurs over a small volume surrounding the point. The piezoelectric properties of the thin transducer determine whether transverse or longitudinal waves will be coupled to the junction. In the arrangement outlined here both a longitudinal and transverse wave can produce a parallel field which will couple to the junction.

Unfortunately the scheme in figure 6 is rather sensitive to mechanical vibration and external a. c. fields. An alternative arrangement which is much less sensitive to external influences is outlined in figure 7. Here the junction comprises a thin film in the shape of an « H » with the central region functioning as the weak-link. The assembly is deposited directly
on a piezoelectric surface, so that the lateral polarization field between the legs of the « H » excite the junction and produce steps in the I-V curve as in figure 6. The central (weak-link) region of the junction must be small, typically 0.5 micron long by 0.25 micron wide. An ingenious method of producing such microgeometry has been reported [10]. Electron beam lithography [11] appears especially attractive as a means of fabrication, since all dimensions of the junction can then be made small, e. g., a cross-sectional width of order ten microns. The orientation of the junction relative to the piezoelectric substrate will determine the polarization of the sound wave to be detected. Figure 7 shows a junction oriented on quartz in such a way that a transverse wave polarized along the c-axis and propagating along the x-axis will generate a polarization field along the c-axis and thereby excite the junction. A different choice of orientation, crystal, and piezoelectric tensor would permit detection of a longitudinal wave by means of the same configuration. An alternative procedure would be to misorient the plane of the junction by a small angle relative to the wave front so that the two halves of the junction would be driven out of phase. The angle would be of order \( \lambda/D \), where \( D \) is the cross sectional dimension of the junction. Our experience with waves at 10 GHz indicates that it is possible to create controlled small angle misorientations by applying a small force at right angles to the sample. Hence, it may be possible to mechanically « tune » such a system so as to achieve maximum phase difference between the two halves of the junction.

In addition to detecting high frequency elastic waves by means of a Josephson junction, it appears possible in principle to generate them according to the relation \( f = 2 eV/h \). This relation states that an a. c. voltage at frequency \( f \) will appear across the junction when the applied d. c. voltage is \( V \). The a. c. voltages and resulting fields will be small under typical conditions. However, it may be possible to develop a resonant geometry which will substantially increase the effective a. c. field. Generation of sound by such a device is attractive in that the frequency can be continuously tuned over a vast range. Further efforts in this direction may prove rewarding.

As noted earlier, superheterodyne detection is attractive because of the possibility of power gain and the convenience of processing the signal at the difference frequency. It is well known that the Josephson junction is a non-linear device which permits the mixing of two microwave signals [9]. This feature offers the possibility of operating the junction configurations of Figures 6 and 7 in the superheterodyne mode, instead of searching for steps in the I-V curve, as a means of detecting the presence of high frequency phonons. While this method appears interesting, there exists an alternative method of perhaps greater potential by which to employ the superheterodyne principle with its consequent enhancement of detection sensitivity. This method, non-piezoelectric in nature, utilizes the relatively strong coupling between Cooper pairs and phonons with energies which exceed the gap energy of a superconductor. Hence the system functions as a square law detector in the same way as a photoelectric cell exposed to light. These ideas are described further below.

3.2 Superheterodyne detector (for \( \hbar \omega > E \) gap). — When a superconductor-insulator-superconductor sandwich is biased as in figure 8, very little quasiparticle tunneling current will flow from side [2] to [1] since there are relatively few particles above the gap at low temperatures. If, however, phonons with \( \hbar \omega > E \) gap are incident on the sandwich the tunnel current from [2] to [1] will increase as a result of breaking Cooper pairs and sending quasiparticles above the gap [5], [11]. The same process should also occur for incident photons provided that \( \hbar \omega > E \) gap [12]. Moreover, the increase in tunnel current will be proportional to the number of phonons or photons present, i. e., proportional to the intensity of the incident sound or light wave. This situation raises the possibility of detecting phonons in a superconducting sandwich by means of the superheterodyne principle (i. e., by using the superconductor as a square law detector). In this arrangement the sandwich would be simultaneously excited by phonons (signal at \( \omega_1 \)) and photons at a slightly different frequency from a klystron (local oscillator at \( \omega_2 \)) through a suitable wave guide assembly. Assuming the sandwich to be excited coherently by the two waves, the tunnel current will be of the form

\[
I = I[A \sin \omega_1 t + bE \sin (\omega_2 t + \phi)]^2
\]

where \( A \) and \( E \) are, respectively, the amplitudes of the sound and electromagnetic waves, and \( a \) and \( b \) are the corresponding coupling constants between wave and Cooper pairs. The current will contain frequency components at \( 2 \omega_1, \omega_2, \omega_1 + \omega_2 \) and \( \omega_1 - \omega_2 \). We are interested in the latter which represents the cross terms in the above expression. Since

![FIG. 8. — Density of states and gap for two identical superconductors biased across an insulating barrier. For excitations exceeding the gap energy, quasiparticles are lifted above the gap resulting in net current flow from film (2) to film (1).](image-url)
the current component which varies at \((\omega_1 - \omega_2)\) is proportional to the product \((AE)^2\), power gain is possible by making the local oscillator amplitude \(E\) large. (Should the cross mixing of phonon and photon amplitudes appear questionable, it should be recalled that the sound wave is really an oscillating electric field on the local scale.) The difference frequency \((\omega_1 - \omega_2)\) could easily be adjusted to fall between 1 and 100 MHz, and it should be quite practical to extract currents at these low frequencies from the junction and amplify them with conventional I. F. amplifiers. Figure 9 outlines such an arrangement.

![Figure 9](image)

**FIG. 9.** — Biased tunnel junction (two superconductors separated by an insulating layer) deposited on sample and used as square law detector. Output is taken at the difference frequency between phonon signal at \(f_1\) and local oscillator at \(f_2\).

4. Piezoelectric generation of sound above 100 GHz.

— Whereas the piezoelectric detection of high frequency sound presents difficulties because of the short wave length, the generation of sound does not. Generation merely requires an electromagnetic source of sufficient intensity and a means of coupling to the piezoelectric transducer. With present technology two approaches to this problem suggest themselves as likely candidates for development in the near future.

One approach is to drive the piezoelectric transducer at the frequency of the source by a coupling scheme similar to that of figures 4 and 5. At the present time molecular lasers produce powers of about a watt at discrete frequencies near 900 GHz. The upper frequency limit of electron tube devices is about 300 GHz so that a gap exists between 300 and 900 GHz for which no monochromatic source exists presently. It seems likely, however, that this part of the spectrum will be filled in due course by some form of laser oscillator. Above 900 GHz molecular gas lasers furnishing milliwatts at discrete frequencies are becoming practical [13]. Future laser development will undoubtedly provide more powerful monochromatic sources in the range between \(10^{12}\) and \(10^{13}\) Hz.

A second approach to sound generation by piezoelectric conversion of electromagnetic energy is to mix two laser beams in a non-linear device and drive the transducer at the difference frequency. Recent experiments in mixing the outputs of two \(\mathrm{CO}_2\) lasers \((f \approx 3 \times 10^{13}\) Hz) in a thin slab of GaAs yielded microwatts of power at a difference frequency of some 900 Hz [14]. The lasers were pulsed and yielded a peak output power of about 2 kW. Calculations indicate that such a system could generate output at a difference frequency over the range of 300 GHz to about 6000 GHz. The low conversion efficiency resulted from the lack of phase matching of the primary waves in the crystal with the result that generation occurred over a coherence length of 0.7 mm. II the conversion efficiency could be improved to the level of yielding watts of power at the difference frequency, very useful sources for generating monochromatic sound at thermal frequencies would become available.
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References


DISCUSSION

B. R. Tittmann. — 1) In what materials do you conduct your experiments ?
2) What is the phonon loss at 100 GHz ?

2) Approx. 0.2 dB/cm at 4 °K. It would be nice to conduct studies in other materials such as ZnO but this for the future.

C. Elbaum. — You propose that the use of tunnel junction detectors would permit detection of waves with frequencies up to, or even in excess of \(10^{12}\) c/s. Would the detection process not be limited, essentially to the superconducting gap frequencies (because of the falling efficiency in breaking Cooper pairs as the frequency increases above \(\omega \sim \Delta/\hbar\) ) ?

E. H. Jacobsen. — It’s a question of how fast the electron phonon interaction decreases as we go up to frequency beyond \(10^{12}\) c/s. It seem to recall that the interaction is still sufficiently strong at these frequencies, but should check this again.

M. Papoular. — Could you give a typical figure for the sensitivity of the Josephson junction device ?

E. H. Jacobsen. — We expect to be able to detect sound power levels of \(10^{-10}\) W/cm² using the weak link Josephson junction.

J. Lewiner. — Could you say a few words on the technique you use to get a Josephson junction thinner than a micron ?

E. H. Jacobsen. — Method # 1: Use a diamond scratch piezoelectric surface, then evaporate thin superconducting film, then make light cut in direction at right angles. (See ref. to Gregers-Hansen of Lenenson in my paper for details.)

Method # 2: Use electron beam lithography technique. (See ref.’s under IEEE in my paper for details.)

H. Levine. — What is the nature of the interaction between an acoustic wave and a Cooper pair ?

E. H. Jacobsen. — The acoustical wave produces an oscillating electric field which modulates the attractive potential between two electrons, comprising the Cooper pair, at the phonon frequency. (The attractive potential is formed by the electron-phonon interaction, which is also electric in nature.) When \(h\omega\) of the phonon > E gap, there is a strong probability of breaking a pair, and thereby permitting one of the resulting quasi-particles to be excited above the gap and subsequently flowing across the junction. The quasi-particle current is proportional to the intensity of the exciting radiation, thus providing square law detection, hence non-linear mixing. (The attractive potential is not simple represent.)