[2]. But we have found that the asymmetric interaction is not sensitive to the change of the magnetic field.

IV. Conclusion

First-order Bragg interaction in a gyromagnetic-dielectric waveguide is analyzed by a singular perturbation procedure. The expression for the dispersion relation in the vicinity of the Bragg frequency is derived. The Bragg reflection characteristics are shown numerically. It is found that the stop bandwidth and maximum decay of waves due to Bragg interaction can be controlled by the magnetic field.

The result given in the present paper may be useful designing millimeter-wave devices such as tunable filters and electrically scannable leaky wave antenna [9].

Acknowledgment

The author would like to thank Prof. Nobuaki Kumagai of Osaka University for his valuable discussions and encouragement.

References

[1] C. Elachi, "Waves in active and passive periodic structures: A review," *Proc. IEEE.*, vol. 64, pp. 1666–1698, Dec. 1976.

[2] S. R. Seshadri, "Asymmetric first-order Bragg interactions in an active dielectric waveguide," *Appl. Phys.*, vol. 17, pp. 141–149, 1978.

[3] M. Tsutsumi, T. Ohira, T. Yamaguchi, and N. Kumagai, "Reflection of millimeter waves by a corrugated dielectric slab waveguide," *Proc. IEEE*, vol. 68, pp. 733–734, June 1980.

[4] M. Tsutsumi and N. Kumagai, "Reflection of millimeter waves by a corrugated ferrite slab," *Proc. IEEE*, vol. 69, pp. 1083–1084, Aug. 1981.

[5] Lax and Button, "Microwave ferrite and ferrimagnetics," New York: McGraw-Hill, 1962.

[6] S. R. Seshadri, Asymptotic theory of mode coupling in a space-time periodic medium-part 1: stable interactions," *Proc. IEEE.*, vol. 65, pp. 996–1004, July 1977.

[7] S. R. Seshadri, "Love wave interaction in a thin film with a periodic surface corrugation," *IEEE. Trans. Sonics Ultrason.*, vol. SU-25, 6, pp. 378–383, Nov. 1978.

[8] R. F. Harrington, *Time-Harmonic Electromagnetic Fields* New York: McGraw-Hill, 1961.

[9] R. E. Horn, H. Jacobs, E. Freibergs, and K. Klohn, "Electronic modulated beam steerable silicon waveguide array antenna," *IEEE. Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 647–653, June 1980.

Microwave Pulse-Induced Acoustic Resonances in Spherical Head Models

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Abstract—**Microwave-induced acoustic pressures in spherical models of human and animal heads are measured using a small hydrophone transducer. The measured acoustic frequencies that correspond to mechanical resonance of the head model agree with those predicted by the thermoelastic theory of interaction. Further, a three-pulse burst applied at appropriate pulse repetition frequencies could effectively drive the model to respond in such a manner that the microwave-induced pressure amplitude would increase by threefold or more.**

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I. Introduction

Auditory responses are evoked in human beings and laboratory animals irradiated with rectangular-pulse, modulated microwave energy [1]–[3]. Most investigators of this phenomena believe that the response stems from microwave-induced thermoelastic expansion [4]–[8], i.e., when microwave radiation impinges on the head, a portion of the absorbed energy is converted into heat which produces a miniscule but rapid rise of temperature in the tissues of the head. This rise of temperature ($\sim 10^{-6}$ °C) occurring in a very short time (10 μs) generates rapid thermoelastic expansion of the brain matter or other tissues in the head which then launches an acoustic wave of pressure that is detected by the hair cells in the cochlea [9].

This thermoelastic theory which covers many experimental observations [8]–[10], suggests among other characteristics that the frequency of the auditory signal is a function of the size and acoustic property of tissues in the head [11]–[12]. Specifically, the fundamental frequency of sound was found to be given by

$$f_s = 3.14\nu/(3\pi a) \tag{1}$$

for stress-free surfaces [11]. Thus, the microwave-induced sound is a function of sound propagation speed (ν), and the radius (a) or circumference ($2\pi a$) of the head. To date, experimental support for this observation comes primarily from measured cochlear microphonics in cats and guinea pigs [10], [13], [14], and the well-documented requirement for human preception of pulsed microwaves; i.e., the ability to hear high-frequency sound [1]–[3]. However, direct experimental confirmation for the mechanical resonances inside the head has yet to appear in the literature. This paper presents direct hydrophone measures of pulsed microwave-induced acoustic signals in variously sized spherical head models filled with brain-equivalent materials.

II. Methods and Materials

A. Models

The spherical models were composed of hemispherical voids carefully machined in 20.3×20.3×7.6-cm blocks of foamed polystyrene and filled with brain-equivalent materials. The foamed polystyrene provided a stress-free boundary to the brain model. The electromagnetic, mechanical, and thermal properties of the brain-equivalent material are similar to brain tissues. It is made from gelling agent, finely granulated polyethylene powder, sodium chloride and water [15]. It has a sonic propagation speed of 1600 m/s at room temperature [16]. Typically, two-kilogram batches of the brain-equivalent material were prepared and then evacuated for approximately 30 min to remove included air.

B. Hydrophone Transducer

A spherical hydrophone, 1 cm in diameter, was used in all experiments (Edo Western Inc., Model 6600). The barium titanate piezoelectric element had a response of 50.1 pA/mV for the range of frequencies encountered in this study. The hydrophone was placed in the center of the model. Its output signal was displayed on an oscilloscope and photographed on Polaroid film.

C. Microwave Irradiation Procedure

Pulsed microwave energy at 1.10 GHz and 4-kW peak power was obtained from an Epsco PG5KB generator. The microwave

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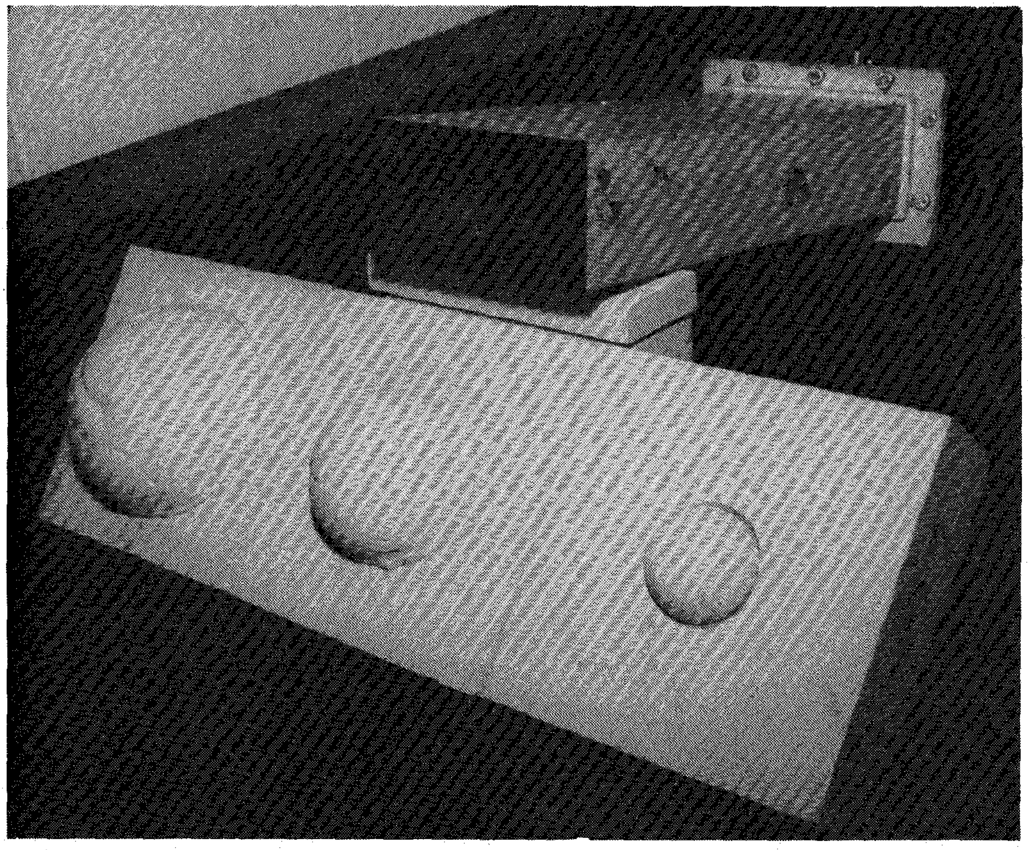

Fig. 1. Spherical models of brain-equivalent material are shown with the front mold halves removed. Also shown is the WR-650 waveguide section that was used to irradiate the models at 1.10 GHz.

pulses were applied to the spherical models using a 46-cm-length of open-ended WR-650 waveguide. Fig. 1 shows the spherical models in the foam molds along with the waveguide. The waveguide was placed in contact with the foam molds of the 10- and 14-cm diameter models; however, the smallness of the 6-cm diameter model required a different configuration. In using the smallest model, one of the foam sides was removed, and the model was allowed to rest partially in the opening of the waveguide and partially in the other foam member. In this way, higher acoustic amplitudes could be obtained than were seen when the waveguide was brought no closer than the mold would allow.

A typical series of experiments began by applying a single microwave pulse to elicit an acoustic response. The "ringing" of the model following microwave irradiation gave the approximate fundamental mode frequency. Also, during the single-pulse irradiations an optimal pulsewidth was determined that produced the highest amplitude response. Brief pulsetrains, or bursts, consisting of three microwave pulses were then applied to the spherical model. The pulse repetition frequency was equal to the fundamental mode frequency. For each pulsetrain combination, the maximum post-artifact hydrophone output voltage was recorded and graphed as a function of pulse repetition frequency.

III. Experimental Results

A typical hydrophone response, inside a 6-cm diameter spherical brain model, to a three-pulse burst at a 24-kHz rate and a pulsewidth of 10 μs is shown in Fig. 2. It is seen that following an initial period which coincided with the duration of the burst, the response signal was easily separated from the transient microwave artifact. The ringing frequency is associated with acoustic resonances of the model. Moreover, the acoustic signal produced

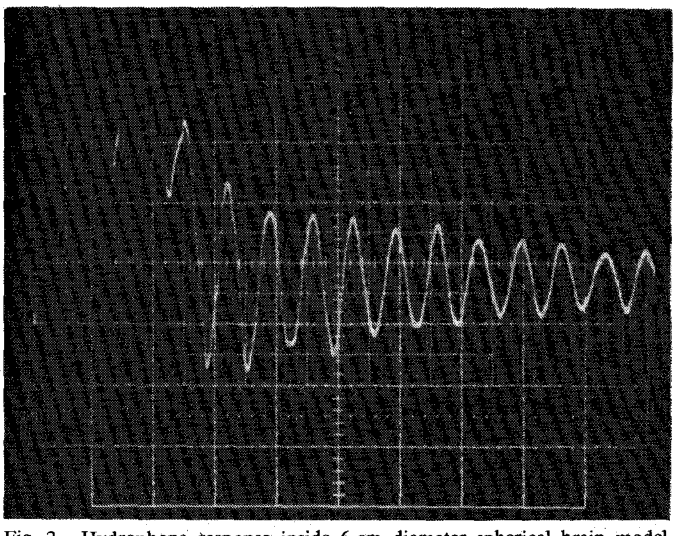

Fig. 2. Hydrophone response inside 6-cm diameter spherical brain model which was irradiated with a burst of three microwave pulses (10 μs) at a 24-kHz rate. Vertical scale was 100 μV/div; horizontal scale was 50 μs/div.

by the three-pulse burst was increased by threefold over the response to a single pulse.

Fig. 3 gives the output voltage of the hydrophone as a function of pulse repetition frequency for the 6-cm diameter model. A pulse repetition frequency of 25.5 kHz gave the highest acoustic pressure amplitude indicating a resonant frequency about 25.5 kHz.

In the 10-cm diameter sphere, a single pulse produced a 16-kHz ringing signal with maximal acoustic pressure occuring at a microwave pulse width of 14 μs, thus, indicating a resonant

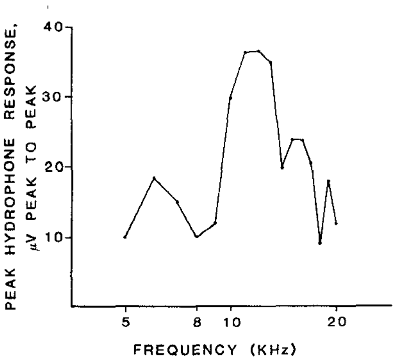

Fig. 3. Hydrophone response in the 14-cm diameter model to a three-pulse burst of 35-μs wide pulses at 1.10 GHz.

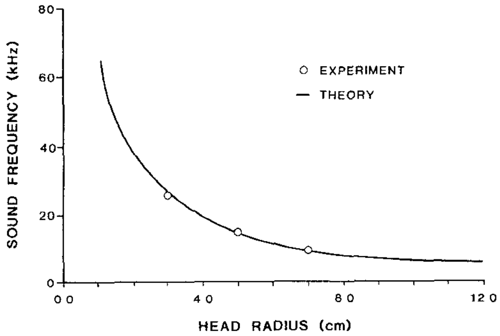

Fig. 6. Comparison of measured and predicted frequency of pressure waves in spherical head models as a function of head radius.

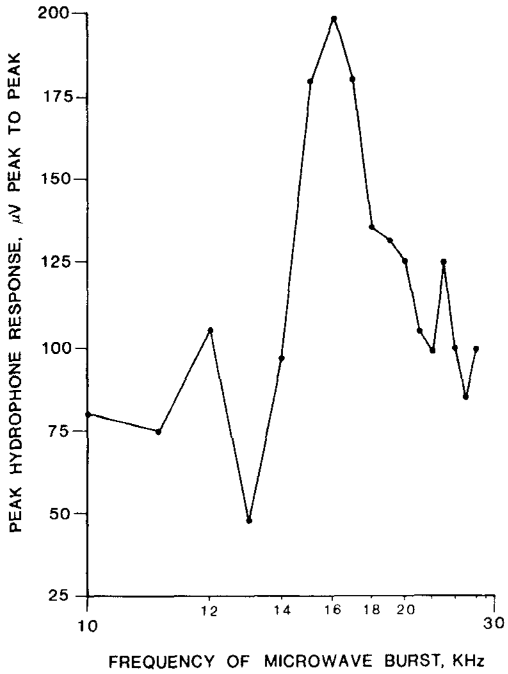

Fig 4. Hydrophone response in the 10-cm diameter model to a three-pulse burst of 14-μs wide pulses at 1.10 GHz.

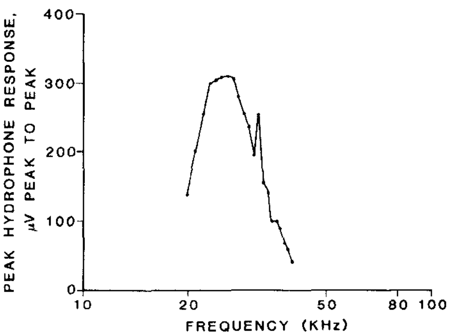

Fig. 5. Hydrophone responses in the 6-cm diameter model to a three-pulse burst of 10-μs wide pulses at 1.10 GHz.

frequency at 16 kHz. This is also revealed in the response "tuning curve" shown in Fig. 4 which peaked at 16 kHz.

In the 14-cm diameter model, single-pulse irradiation yielded a "ringing" frequency of slightly above 10 kHz, and a pulse width of 35 μs produced maximal acoustic response. Fig. 5 shows the results of irradiating the 14-cm model with various combinations of three-pulse bursts. Clearly, a pulse repetition frequency of 11.5 kHz gave the highest pressure amplitude indicating a resonant frequency around 11.5 kHz.

IV. Discussion

The results given in Figs. 3–5 demonstrate that microwave pulses can indeed generate measurable acoustic pressures in spherical models of human and animal heads. Further, they show that appropriately selected pulse repetition frequencies stimulate acoustic resonances that can elevate the microwave-induced acoustic pressure by severalfold. For example, the acoustic signal produced by a three-pulse burst was increased by threefold over the response to a single pulse. In general, the hydrophone response gradually increases from a low value to a peak amplitude at the resonant frequency and then falls off rapidly as the pulse repetition frequency further increases.

It is significant to note that the measured resonant frequencies of pressure waves in the spherical models compared favorably with those predicted by the thermoelastic theory based on a homogeneous brain sphere with stress-free boundaries (see Fig. 6). Specifically, measured resonant frequencies for 6-, 10-, and 14-cm diameter brain spheres were 25.5, 16, and 11.5 kHz, respectively. The corresponding fundamental frequencies of sound pressures calculated from the thermoelastic theory were 26.6, 16, 11.4 kHz, respectively. Except for the 6-cm model, the calculated and measured frequencies were essentially the same. The slight discrepancy at 6-cm (about 4 percent) probably resulted from the fact that the spherical brain had to be disengaged (with consequent changes in shape and dimensions) from the polystyrene foam to increase microwave coupling efficiency.

Thus, the results confirm the existence of microwave-induced acoustic pressures in spherical head models filled with brain-equivalent materials. Also, the agreement between calculated and measured frequencies of acoustic pressure waves lend further support to the thermoelastic mechanism of interaction.

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References

[1] A. H. Frey and R. Messenger, Jr., "Human perception of illumination with pulsed ultra-high frequency electromagnetic energy," *Science*, vol. 181, pp. 356–358, 1973.

[2] A. W Guy, C. K. Chou, J. C. Lin, and D Christensen, "Microwave-induced acoustic effects in mammalian auditory systems and physical materials," *Ann. NY Acad. Sciences*, vol. 247, pp. 194–218, 1975.

[3] C. A. Cain and W. J. Rissmann, "Mammalian auditory responses to 3.0-GHz microwave pulses," *IEEE Trans. Bio-med. Eng.*, vol. 25, pp. 288–293, 1978.

[4] K. R. Foster and E. D. Finch, "Microwave hearing: Evidence for thermoacoustical auditory stimulation by pulsed microwaves," *Science*, vol. 185, pp. 256–258, 1974.
[5] C. K. Chou, A. W. Guy, K. R. Foster, R. Galambos, and D. R. Justesen, "Holographic assessment of microwave hearing," *Science*, vol. 209, pp. 1143–1144, 1980.
[6] J. C. Lin, "Microwave auditory effect—a comparison of some possible transduction mechanisms," *J. Microwave Power*, vol. 11, pp. 77–81, 1976.
[7] D. E. Borth and C. A. Cain, "Theoretical analysis of acoustic signal generation in materials irradiated with microwave energy," *IEEE Trans. Microwave Theory Tech.*, vol. 25, pp. 944–954, 1977.
[8] V. V. Tyazhelov, R. E. Tigranian, E. O. Khizhniak, and I. G. Akoev, "Some peculiarity of auditory sensations evoked by pulsed microwave fileds," *Radio Sci.*, vol. 14, pp. 259s–263s, 1979.
[9] J. C. Lin, "The microwave auditory phenomenon," *Proc. IEEE*, vol. 68, pp. 67–73, 1980.
[10] C. K. Chou and A. W. Guy, "Microwave-induced auditory responses in guinea pigs," *Radio Sci.*, vol. 14, pp. 193s–197s, 1979.
[11] J. C. Lin, "On microwave-induced hearing sensation," *IEEE Trans. Microwave Theory Tech.*, vol. 25, pp. 605–613, 1977.
[12] ——, *Microwave Auditory Effects and Applications*, Springfield, IL.: Thomas, 1978.
[13] Chou, C. K., A. W. Guy, and R. Galambos, "Microwave-induced cochlear microphonics in cats," *J. Microwave Power*, vol. 11, pp. 171–173, 1976.
[14] ——, "Characteristics of Microwave-induced Cochlear Microphonics," *Radio Sci.*, vol. 12, pp. 221s–228s, 1977.
[15] A. W. Guy, "Electromagnetic fields and relative heating patterns due to an aperture source in contact with bilayered biological tissues," *IEEE Trans. Microwave Theory Tech.*, vol. 19, pp. 214–223, 1971.
[16] R. G. Olsen and W. C. Hammer, "Microwave-induced pressure waves in a model of muscle tissue," *Bioelectromagnetics*, vol. 1, pp. 45–54, 1980.

Letters

Proposal for an Electrically Tunable Surface Plasmon Light Emitter

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***Abstract*—A new scheme is proposed to generate infrared waves by exciting thin-slab plasmon waves by hot-electron injection via a tunneling thin insulator. These plasmon waves are coupled out by a periodic structure, and, by way of example, this is demonstrated for a Karp structure. The calculated numerical values of the example at a wavelength of 15 μm, show that standard semiconductor technology can be used to fabricate the device.**

A Proposed Infrared Emitter Excited by Surface Plasmons

It has been demonstrated experimentally that planar Metal–Insulator–Metal (MIM) junctions can be used to excite radiative surface plasmon modes [1]. There is convincing evidence that enhancement of light emission takes place [2] from such structures (e.g., Al–Al_2O_3–Ag or Mg–MgO–Ag MIM junctions), when the metal surfaces are roughened. While in early experiments, the light emission was very faint, in a more recent experiment [3] which might also partly be based on radiative plasmon modes, it was visible to the naked eye in a darkened room. In this case the substrate was gallium arsenide and the insulating layer was a native oxide. It has to be stated, however, that the exact origin of the GaAs MOS emission has not yet been established and that several other light-emission effects could here simultaneously be responsible for the observed spectrum.

Better control over radiation based on radiative plasmon modes should be achievable by using slow-wave structures instead of random irregularities in the surfaces. This case represents an interesting analogy with space charge waves of an electron beam coupled to a slow-wave structure. Efficient energy transfer would be facilitated when the frequency and the phase velocity for the electromagnetic field and the space charge waves nearly match with each other.

The purpose of this communication is to present a proposal for such an infrared emitter, with possibly even some tunability.

Various combinations are possible for exciting surface plasmons. Here we propose to use hot carriers to be injected by tunneling through a suitably thin insulating layer into a metal or semiconductor layer, where both normal and tangential modes of

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