ered structure by Raman scattering. The observation was made possible by a digital subtraction technique to eliminate the background due to the bulk phonon scattering. The measured dispersion of the upper-mode frequency for the two external media, the air and benzene, agrees well with the theoretical predictions. In particular, we could see the change in frequency when the air is replaced by benzene.

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Observation and Study of Electromagnetic Wave Generation in Metals Using Nanosecond Pulses of Laser Light: Case of Alfvén Waves in Bismuth

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We have observed the generation of an electric field pulse by a nanosecond laser pulse incident on a bismuth surface in an external magnetic field. The propagation velocity and the de Haas–van Alphen–type oscillations are found to be consistent with those expected for Alfvén-wave propagation. This technique may well be a general way of exciting a variety of electromagnetic waves in a plasma.

The semimetal bismuth[1] has traditionally been a material of widespread interest. This is mainly because it is easiest to observe in bismuth the phenomena which are inherent in all metals. The most important characteristics of bismuth are as follows: (1) There are equal numbers of electrons and holes and their numbers are small compared with other metals. (2) The conducting electrons have an effective mass of the order of 0.1–0.001 of the free-electron mass. (3) The Fermi energy is several hundredths of an electron volt. Because of all these properties and the high degree of chemical and physical perfection, the de Haas–van Alphen effect, cyclotron resonance, and magnetoplasma waves are all relatively easy to observe in bismuth.

During the course of a program of study of heat-pulse propagation in metals, we have discovered the generation of an electric field pulse by a 30-nsec laser-light pulse incident on the surface of a bismuth single crystal in a magnetic field. This electric field is observed to propagate as a well-defined pulse through the medium. Although the phenomenon reported here is in some sense similar to that observed by Buchsbaum and Smith,[2] Carter and Libchaber,[3] and Khaiken and Yakubovskii[4] using dc or slowly amplitude-modulated microwaves, the use of short laser pulses and classic time-of-flight techniques has enabled us to study directly the velocity and attenuation of the generated electromagnetic wave. The propagation characteristics are consistent with those expected for Alfvén-wave propagation.

The experimental setup was quite simple. A

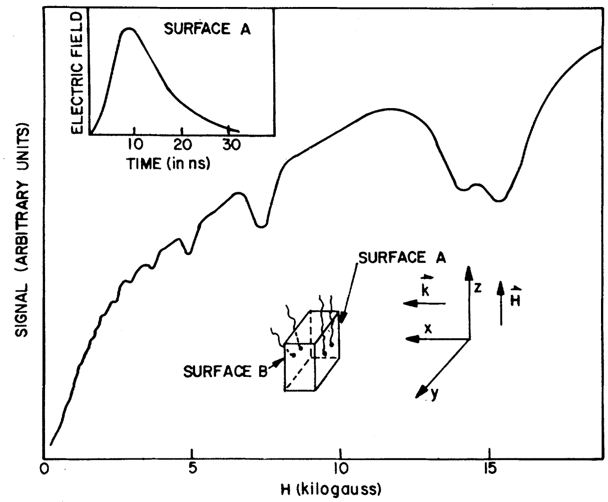

FIG. 1. Signals on surface A as a function of the magnetic field H. The insets show the geometry of our experiment, and a typical voltage pulse observed on surface A. H was parallel to the binary axis and $\vec{k}$ parallel to C_3.

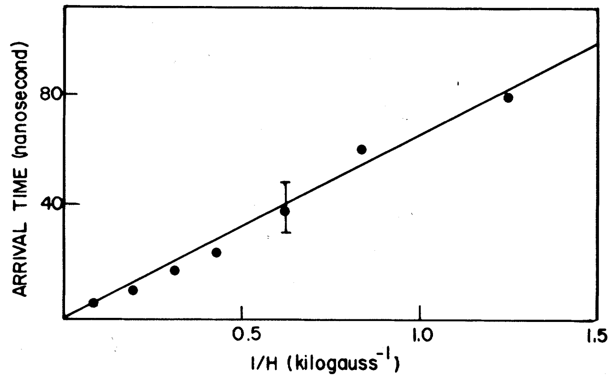

FIG. 2. The arrival time of the electrical signal on surface B as a function of $1/H$.

multiple-color cavity-dumped argon laser was used to produce the 30-nsec light pulse which had a rise time of 10 nsec and a maximum peak power of almost 50 W. However, most experiments were performed with much lower power, typically of the order of a few watts. Only a fraction of this power was absorbed by the surface. The bismuth crystals themselves were Bell Laboratories zone-refined samples which had been used in the past.[5] The typical resistance ratio, $R_{300\,\mathrm{K}}/R_{4.2\,\mathrm{K}}$, was between 100 and 400. The experiments were performed at 1.8 K with the sample immersed in liquid helium. The light with wave vector $\vec{k}$ (x axis) was incident normal to the sample surface, A, as shown in the inset of Fig. 1. The magnetic field, which was produced by means of a superconducting split solenoid, was parallel to the surface A and therefore normal to $\vec{k}$. Pulsed voltages could be observed both on surface A and at the back surface B, some 6 mm away, by means of two attached pairs of indium wires which were in turn connected to two standard 50-Ω coaxial cables. The signals were then amplified and fed into a PAR 160 boxcar integrator with 10-nsec gate. Great care was taken to eliminate scattered light reaching the back surface B. A typical voltage pulse observed on surface A is shown in the inset of Fig. 1. This voltage pulse was about 30 nsec wide and independent of field on surface A but was wider on surface B at very low fields ($\lesssim 0.5$ kG). The generated electric field was insensitive to the polarization of the laser light. It was predominantly along the y axis and reversed sign when the direction of the magnetic field was reversed.

In Fig. 1, we also show the peak of the voltage signal on surface A as a function of the magnetic field. The magnetic field was along the binary axis and $\vec{k}$ along the C_3 trigonal axis. The 10-nsec gate of the boxcar was fixed at the peak of the signal. The output of the boxcar was fed to the y input of an x-y recorder, whose x coordinate monitored the current in the superconducting coil and was therefore proportional to the magnetic field.

The observed electric field oscillates with an amplitude that increases with the field. It is periodic in $1/H$ and has a period of 7.4×10^{-5} G^{-1}, which is in agreement with previous measurements of the period of the de Haas–van Alphen quantum oscillation along the binary axis.[6] Similar oscillations were observed in the voltage signals on surface B but with more pronounced dips.

The advantage of using light pulses is evident. Since we can observe electrical signals on both surfaces A and B, we can measure the velocity of propagation of the electric field in the crystal by a direct time-of-flight method. Furthermore, by studying the ratio of the signals on surface B to those on surface A, we are able to measure the attenuation as a function of the magnetic field. In Fig. 2, we show the arrival time of the electrical signal on surface B as a function of $1/H$. The propagation velocity is found to be proportional to H and is given by $v \simeq 1.0\times10^4 H$ cm/sec,

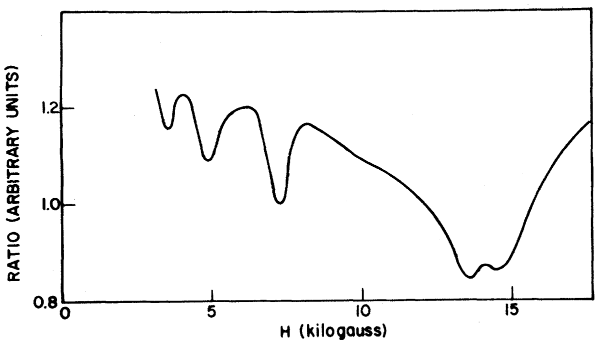

FIG. 3. The ratio of signals at surface B to those on surface A as a function of the magnetic field. Sample thickness was 6 mm. Same geometry as in Fig. 1.

with H in gauss. The accuracy of our measurement is limited by the time resolution of our boxcar at high field, and by the size of the signal at low field. In Fig. 3, we have plotted the attenuation (the ratio of signals at surface B to those on surface A) as a function of the magnetic field. The oscillation of the attenuation is quite drastic and again is periodic in $1/H$ as before.

It is evident from the discussion of experimental results that there are two interesting aspects. The first is the mechanism for generating the electric field, and the second is the propagation and attenuation of the resulting electromagnetic wave in the bismuth.

The generation of the electric field can be understood qualitatively as a "transient" electron or hole Nernst effect (transverse Nernst-Ettinghausen effect).[4] Both electrons and holes are "heated" by the light pulse and their effects are additive. The electric field is induced because electrons and holes moved in opposite direction in the external magnetic field. It is interesting to note that it probably takes very little time for the electrons and holes either to be heated up or to cool down in the "hot" spot (about 2 mm in diameter but only a few hundred angstroms in depth) excited by the laser. This raises the interesting possibility of exciting much faster electric pulses by picosecond light pulses. Since every thermodynamic quantity involving electrons (or holes) should show quantum oscillations, in analogy with the well known de Haas–van Alphen effect, it is certainly not surprising to see that the oscillation with a measured $1/H$ period is in agreement with the previous results.

We now turn our attention to the propagation and attenuation of the electromagnetic wave in bismuth. The problem of electromagnetic waves in metals in a magnetic field has been a subject of great interest for many years.[7] For bismuth, which is "compensated," i.e., with equal numbers of electrons and holes, it can be readily shown that the dispersion relation for the magnetoplasma wave is given by the following expressions:

$$k^2 = \omega^2(M/\mu_0 H^2)(1 + i\nu_{\mathrm{eff}}/\omega),$$

provided

$$\omega_{ce} \gg \nu_e,\ \omega,$$

$$\omega_{ch} \gg \nu_h,\ \omega,$$

where $\vec{H} \perp \vec{k}$ and

$$\nu_{\mathrm{eff}} = \frac{\nu_e(\omega, \omega_{ce}) m_e + \nu_h(\omega, \omega_{ch}) m_h}{m_e + m_h}.$$

These expressions are written in rationalized mks units, where ω is the angular frequency of the wave, μ_0 is the permeability of free space, M is the mass density function which for an isotropic band is given simply by $n(m_e + m_h)$, and H is the external magnetic field. m_e and m_h are the effective masses of the electrons and the holes, respectively. ω_{ce} and ω_{ch}, the cyclotron angular frequencies of the electrons and the holes, respectively, are understood to be much smaller than their respective plasma frequencies. n is the number of the conduction electrons (holes) per unit volume. ν_e and ν_h are the inverses of the collision times of the electrons and the holes, respectively, and could depend on the values of ω and ω_c.

In the case where $\omega \gg \nu_{\mathrm{eff}}$ (undamped case) we have the usual Alfvén-wave limit, and the Alfvén-wave velocity v_{A} is given by[8]

$$v_{\mathrm{A}}^2 = \mu_0^{-1} H^2/M.$$

The velocity is therefore independent of frequency, but directly proportional to external magnetic field. Previously, with use of microwaves, the phase velocity of the magnetoplasma wave has been determined through the observation of Fabry-Perot–type interference fringes.[9,10] For $\vec{k} \parallel C_3$ and $H \parallel C_2$, the binary direction, v_{A} was found to be[1,11]

$$v_{\mathrm{A}} = (1.8 \pm 0.4) \times 10^4 H \text{ cm/sec},$$

with H in gauss.

In our case, the frequency distribution is presumably the Fourier transform of the time evolution of the electric pulse. For a pulse rise time of 10 nsec and a total width of about 30 nsec the spread in the frequencies is of the order of 100 MHz. It is therefore important to know ν_{eff} to determine whether the majority of the frequency components are in the Alfvén-wave limit. In a highly anisotropic material, such as bismuth, it is difficult to estimate the precise value of ν_{eff}. For a typical carrier free path of a few millimeters and a Fermi velocity of 5×10^7 cm/sec one obtains a value of $\nu_{\text{eff}}\simeq10^{-8}$ sec^{-1}. Thus for our pulses we expect $\omega\simeq\nu_{\text{eff}}$ and hence some dispersion in the wave velocity. The fact that our measured velocity is somewhat smaller than that obtained at microwave frequencies suggests that we may be in a region of some dispersion in the velocity. This is also consistent with the observed broadening of the signal on surface B at low magnetic fields due to the lower propagation velocity.

The oscillation in the attenuation shown in Fig. 3 can now be attributed to the oscillations of ν_{eff}. It is known from previous analysis that the attenuation should display maxima whenever the condition[7,12]

$$\zeta_{\text{F}}=(l+\tfrac{1}{2})\hbar\omega_c+\tfrac{1}{2}S|g|\mu_{\text{B}}H$$

is satisfied as a consequence of singularities in the density of states. Here l is an integer, $|g|$ is the magnitude of the free-electron g factor, μ_{B} is the Bohr magneton, S takes the values of 1 and -1 for the two spin orientations, and ζ_{F} is the Fermi energy. Maxima in ν_{eff} lead to transmission minima, consistent with our experimental results. Furthermore, experiments were also performed on another thin sample (thickness ~1.5 mm). The results indicate that the oscillations on surface B are much weaker. This thickness dependence confirms our interpretation that we are observing a bulk attenuation.[12]

In conclusion, we have observed the generation of nanosecond electric pulses in bismuth in a magnetic field induced by light. By studying the peak of the signal as a function of the magnetic field, we have observed de Haas–van Alphen-type oscillations. From the time-of-flight measurement, we report the direct measurement of the propagation velocity and the observation of the oscillation in the attenuation. The technique is quite useful in studying de Haas–van Alphen oscillations and may well be a general way of exciting a variety of electromagnetic waves in a plasma. With light focused to a very tiny spot and with a coil around a sample, we can easily observe the oscillations in a sample of very small dimensions. On the other hand, by extending the experiments to subnanosecond light pulses and using higher-frequency electronics, we can then be sure that we are in the Alfvén-wave limit. It is then straightforward to measure the group velocity as a function of the direction and magnitude of the external magnetic field. Another example is with low-frequency amplitude-modulated light; one can then generate and study helicon waves in other metals.

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