Nonlinear cyclotron resonance in bismuth

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A nonlinear cyclotron resonance was observed during irradiation of a bismuth plate by a 3-cm-wide electromagnetic wave in a reflected wave at doubled frequency.

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A well-known resonance in metals in a magnetic field parallel to the surface occurs in experiments as a peculiarity in the impedance in the fields H_n which satisfy the condition:

$$n\Omega_n = \omega, \qquad n = 1, 2, 3 \ldots, \tag{1}$$

where $\Omega_n = eH_n/mc$ are the Larmor frequencies and ω is the frequency of the electromagnetic wave incident on the metal. The resonance is produced by the electrons which periodically return to the skin layer and are in phase with the rf field.

As a result of increasing the amplitude of the incident wave, the linear coupling between the rf field and the current is disturbed principally because of the magnetic field of the wave, which distorts the shape of the electron trajectories in the skin layer. The amplitudes of the higher harmonics in the nonlinear current depend on the ratio of the harmonic frequency to the frequency of the orbital motion of the electrons. Specifically, the resonance conditions such as (1) for the second harmonic have the form

$$\frac{n}{2}\Omega_{n/2} = \omega \qquad n = 1, 2, 3 \ldots, \tag{2}$$

i.e., the resonance occurs at integers and half-integers of the index $n/2$. The theory of nonlinear cyclotron resonance was recently developed by Kopasov.[1] The experiments described below were stimulated by his work.

The disk-shaped, 18-mm-diam, 2-mm-thick Bi sample with an axis C_3 along the axis of the disk was placed at the bottom of a two-mode, cylindrical cavity tuned to the frequencies ω and 2ω. The cavity operated in the E_{010} mode at 9.2 GHz frequency and in the H_{111} mode at 18.4 GHz frequency. The sample and the magnetic field could be turned in the horizontal plane independently of each other. By turning the sample we could vary the contribution of the different ellipsoids to the signal emitted at the frequency 2ω. The cavity was coupled to the receiving waveguide through a narrow slit S, so that only the signal from that oscillation component of the frequency 2ω in the cavity whose current was perpendicular to the axis of the slit could reach the waveguide. The electromagnetic wave was produced by a magnetron operating in the pulsed mode with a pulse duration of 2 and 4 μsec. The repetition frequency was chosen in such a way that there would be no average heating of the sample. The power

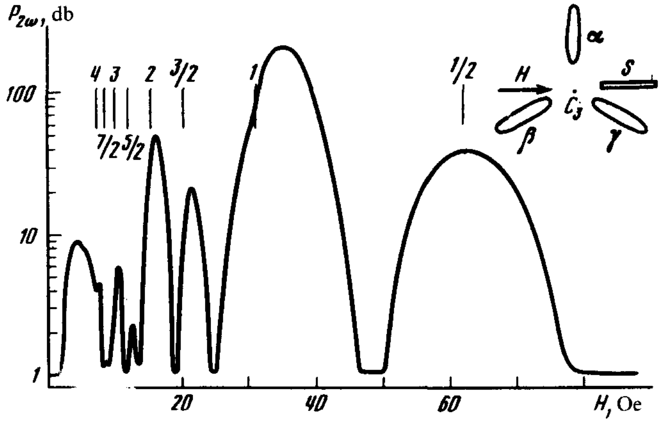

FIG. 1. Dependence of the radiated power at the frequency 2ω on the magnetic field. The temperature is 1.8 K and the amplitude of the incident wave is 12 Oe. The location of the electron ellipsoids relative to the field H and the slit S is shown in the inset.

of the cavity was varied from 1 kW to 10 W, which, for a Q of the cavity equal to 1400, corresponded to an amplitude of the rf field of 4 to 40 Oe. As a rule, the temperature during the experiment was maintained at 1.8 K, but the resonances were also clearly visible at 4.2 K. The emission at the doubled frequency was received by a heterodyne receiver with a sensitivity of 10^{-11} W. This signal was transmitted from the receiver to a pulse voltmeter and then to a logarithmic X-Y recorder.

Figure 1 shows the trace of the variation of the reflected power as a function of the magnetic field H. We can see from the geometry of the experiment shown in the inset that the ellipsoid is not involved at all in the formation of the signal at the frequency 2ω and the ellipsoids β and γ are arranged symmetrically relative to the field H, so that their resonance fields $H_{n/2} = 2mc\omega/en$ coincide. These fields, which were calculated according to Eq. (2) using a well-known value m, are denoted by vertical lines in Fig. 1. It can be seen without doubt that the peaks of the emitted signal are due to the nonlinear cyclotron resonance, although the resonance peaks with the indices 1, 3/2, and 2 are in higher fields than those of condition (2). The reason for this is not yet clear. The nature of the strong signal in the weak fields, which we shall not examine here, is also not clear. As expected, the peaks of the nonlinear cyclotron resonance split as a result of rotating the field, i.e., the signals from the ellipsoids β and γ are seen separately.

The most interesting result of the experiment is the large resonance amplitude—the increase of the radiated power increases by two orders of magnitude. For comparison, we remind that the impedance in the linear resonance varies by $\leqslant 1\%$. Moreover, it was experimentally concluded that the resonances with integer indices have a large amplitude, i.e., resonances in those fields in which a linear resonance also can take place.

Let us examine the characteristics of the metal that determine the observed effect. The nonlinear current at the doubled frequency $j_{2\omega}^{NL}$

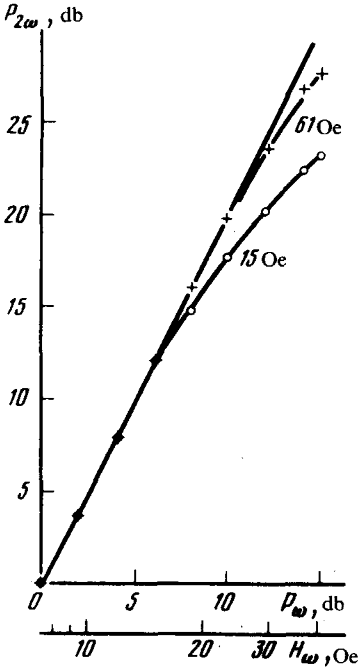

FIG. 2. Dependence of the radiated power $P_{2\omega}$ on the incident power P_ω. The straight line is the quadratic dependence. The constant resonance fields $H_{1/2}$ and H_2 are indicated near the experimental curves.

$$\mathbf{j}_{2\omega}^{NL} = \iint \hat{\sigma}_{2\omega}(r, r', r'') : \mathbf{E}_\omega(r')\mathbf{E}_\omega(r'')\, dr'dr'' \tag{3}$$

is the external source which excites the harmonic oscillations in the cavity. The amplitude of the field $E_{2\omega}$ in the cavity, which is proportional to its Q-factor, is given by

$$E_{2\omega} = \frac{Q}{2\omega}\int \mathbf{e}_{2\omega}(r)\,\mathbf{j}_{2\omega}^{NL}(r)\, dr, \tag{4}$$

where $e_{2\omega}$ is the normalized field of the H_{111} mode in the metal and the integration is carried out over the sample's volume. The distributions of the fields e_ω and $e_{2\omega}$ are determined by the linear characteristics of the metal. On the basis of the experimental fact—the cyclotron resonance changes the impedance only slightly[2]—we can ignore the dependence of the $e_{2\omega}$ and e_ω on H and assume that the observed resonance curves represent the dependence of the nonlinear conductivity $\sigma_{2\omega}$ on the magnetic field. This makes it possible to compare our experimental results with Kopasov's[1] calculations of the nonlinear conductivity tensor, without referring to that part of his paper in which he used the theory of linear cyclotron resonance,[3] which predicts a large variation of the linear characteristics in the resonance. Such a comparison gives a good agreement with the theory, since, according to Ref. 1, for a square dispersion law the nonlinear response increases by a factor of $(\Omega\tau)$ for a resonance with a nonintegral index [odd n in Eq. (2)] and by a factor of $(\Omega\tau)^2$ for a resonance with an integral index (even n). A 100-fold increase of the radiated power indicates that the nonlinear current $j_{2\omega}^{NL}$ increases 10-fold. This apparently shows that the sliding electrons contribute to $j_{2\omega}^{NL}$ relatively little.

Figure 2 shows the dependence of the harmonic power $P_{2\omega}$ radiated during the resonance on the power P_ω incident on the sample. It can be seen that the quadratic dependence is maintained up to relatively large rf fields H_ω, which justifies the use of the perturbation theory. A deviation from the quadratic dependence begins when the amplitude of H_ω becomes approximately equal to the external field H.

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