then in the solution of the one-dimensional scattering problem the polarization potential $U_p(z)$ can be omitted.

Finally, the conditions for the applicability of the single-center approximation (5) is usually well satisfied in semiconductors. Thus, at $H=6\times10^4$ G and $T=1$ K the estimate (5) yields $n_0 \ll 10^{18}$ cm^{-3} in Ge.

The author is deeply grateful to Yu. A. Gurevich, M. A. Kozhushner, I. B. Levinson, and V. G. Skobov for a discussion of the present work. I also wish to express my gratitude to the participants of O. V. Konstantinov's seminar for a discussion of the results.

[1)]The substitution $m \to -m$ has been made below everywhere.

[1]L. S. Dubinskaya, Zh. Eksp. Teor. Fiz. **56**, 801 (1969) [Sov. Phys. JETP **29**, 436 (1969)].
[2]M. M. Aksel'rod, V. I. Sokolov, I. M. Tsidil'kovskiĭ, and G. I. Kharus, Phys. Status Solidi **9**, k91 (1965).
[3]L. D. Landau and E. M. Lifshitz, Kvantovaya mekhanika (Quantum Mechanics), Fitzmatgiz, 1974, pp. 196 and 525 [Pergamon].
[4]S. P. Andreev, Zh. Eksp. Teor. Fiz. **75**, 1056 (1978) [Sov. Phys. JETP **48**, 532 (1978)].
[5]V. L. Gurevich and Yu. A. Firsov, Zh. Eksp. Teor. Fiz. **40**, 199 (1961) [Sov. Phys. JETP **13**, 137 (1961)].
[6]I. B. Levinson, Zh. Eksp. Teor. Fiz. **57**, 660 (1968) [Sov. Phys. JETP **30**, 362 (1969)].
[7]V. G. Skobov, Zh. Eksp. Teor. Fiz. **37**, 1467 (1959) [Sov. Phys. JETP **10**, 1039 (1960)].
[8]I. I. Gol'dman and V. D. Krivchenkov, Sbornik zadach po kvantovoi mekhanike (Collected Problems in Quantum Mechanics), 1957, str. 29.
[9]B. Davydov and I. Ya. Pomeranchuk, Zh. Eksp. Teor. Fiz. **9**, 1294 (1939).
[10]S. Titeica, Ann. Phys. (Leipzig) **22**, 129 (1935).
[11]V. G. Skobov, Zh. Eksp. Teor. Fiz. **38**, 1304 (1960) [Sov. Phys. JETP **11**, 941 (1960)].
[12]I. S. Gradshteĭn and I. M. Ryzhik, Tablitsy integralov, summ, ryadov i proizvedeniĭ (Tables of Integrals, Sums, Series, and Products), Fizmatgiz, 1963, p. 965 [Academic].
[13]C. Kittel, Quantum Theory of Solids, Wiley, 1963 (Russ. Transl. Fizmatgiz, 1967 p. 254).
[14]H. Brooks, Advances Electron. Electron Phys. **7**, 87 (1955).
[15]F. J. Blatt, Physics of Electronic Conduction in Solids, McGraw, 1968 (Russ. Transl. Fizmatgiz, 1963, 175).
[16]P. S. Zyryanov and M. I. Klinger, Kvantovaya teoriya yavlenii élektronnogo perenosa v kristallicheskikh poluprovodnikakh (Quantum Theory of Electron Transport Phenomena in Crystalline Semiconductors), Fizmatgiz, 1976, p. 413.
[17]K. Seeger, Semiconductor Physics, Springer, 1974.
[18]A. G. Milnes, Deep Impurities in Semiconductors, Wiley, 1973.
[19]G. F. Drukarev, Teoriya stolknoveniĭ élektronov s atomami (Theory of Collisions of Electrons with Atoms), Fizmatgiz, 1963, p. 110.

Translated by J. G. Adashko

High-frequency properties of $ErFeO_3$ in the ordering region of rare-earth systems

N. K. Dasn'shin, N. M. Kovtun, and A. P. Polyanenko

Donetsk Physicotechnical Institute, Ukrainian Academy of Sciences
(Submitted 15 March 1979)
Zh. Eksp. Teor. Fiz. **77**, 1058–1061 (September 1979)

Magnetic resonance at frequencies 10–37 GHz is used to investigate the behavior of the spin-wave frequency in the vicinity of the low-temperature spin flip in a zero magnetic field. A decrease in the frequency of the "soft mode" down to 15 GHz at a temperature 4 K is observed, in correspondence with the ordering of the spin system of Er.

PACS numbers: 75.30.Ds, 76.50.+g

One of the distinguishing features of a definite class of ordered magnets is the presence of an energy gap in the spin-wave spectrum even in a zero external magnetic field H (see, e.g., Ref. 1). This circumstance is connected with the presence of a nonzero anisotropy field H_A. Among these magnets is included, in particular, the rare-earth (RE) orthoferrite $ErFeO_3$, which is a weak ferromagnet with a residual moment m. When no account is taken of the magnetoelastic interaction and of anisotropy of order higher than the fourth, the field H_A vanishes in various kinds of phase transitions (PT), including orientational PT which take place in this crystal. This means that the frequency ν_0 of the "soft mode" of the spin-wave spectrum should also vanish in the PT ($\nu_0 \sim H_A$ at $H=0$).[2] A direct method of determining the spin-wave frequency is the method of homogeneous antiferromagnetic resonance (AFMR).

It is known that in $ErFeO_3$ there take place a number of orientational PT with change of only the temperature ($H=0$), and these were investigated in sufficient detail by various methods.[3–6] Two such PT occur in the temperature region 90–100 K and manifest themselves, with decreasing temperature, in a smooth rotation of the magnetic moment of the iron sublattice by an angle $\pi/2$–from the a axis to the c axis. The change of orien-

 0038-5646/79/090532-03$02.40

tation proceeds here via two second-order phase transitions at temperatures corresponding to the start and end of rotation of the magnetic-moment vector. A study of the magnetic resonance in a number of orthoferrites[3] in this temperature region has shown absorption to take place when the radiation frequency is decreased to 5 MHz. It must be noted, however, that in this temperature range the reorientation is connected only with the iron sublattice. The rare-earth spin system, on the other hand, is still practically in the paramagnetic state, and the contribution of its magnetoelastic energy to the anisotropy energy cannot exert a substantial influence on the spin-wave frequency. In these PT the frequency should therefore decrease to zero.

A different situation can arise when the rare-earth system becomes ordered,[6,7] resulting in an additional rotation of the magnetic-moment vectors of the iron lattice in the *bc* plane (low-temperature reorientation). The considerable magnitude of the magnetostriction connected with the ordering of the RE subsystem can lead in a given PT to the onset of an effective anisotropy field, which in turn limits the decrease of the frequency of the homogeneous AFMR to zero.

We investigate here by the AFMR method frequency dependence, of the "soft mode" of the spin waves in the region of low-temperature spin reorientation, due to the ordering of the RE system.

EXPERIMENTAL PROCEDURE

The AFMR was investigated with a direct-amplification spectrometer operating in the frequency band 10–37 GHz, in the frequency range 1.65–4.2 K, and at magnetic fields $H=0$–14 kOe. The diagram of the measurement cell is shown in Fig. 1. The $ErFeO_3$ sample 1–2 mm^3 in volume was placed on a rotating table *2* placed at the center of a plunger *3*, which short-circuited a rectangular waveguide *4*. The sample was cleaved from a bulky single crystal and was secured with epoxy adhesive to table *2* in such a way that the crystal plane *ac* lied in the plane of rotation of the electromagnet *5*. Such an experimental geometry made it possible to establish any angle between the direction of the constant magnetic field **H**, the magnetic component of the microwave field **h**, and the *a* axis of the crystal along which the weak ferromagnetic moment **m** was directed. In another modification of the measuring cell, the rotating table was placed in the center of the broad wall of the waveguide. In the latter case, it was possible to study resonance only in the polarization $\mathbf{H}\|\mathbf{h}$, but on the other hand it was possible to orient with sufficient accuracy the sample in two planes (by rotating the magnet and by rotating the table). The aggregate of these experimental possibilities made it possible, in final analysis, to obtain a sufficiently accurate $\mathbf{H}\|\mathbf{m}$ orientation and to perform the measurements at arbitrary polarization of **H** relative to **h**. The accuracy of the orientation ($\mathbf{H}\|\mathbf{m}\|a$) was monitored against the symmetry of the trace of the absorption signal on the recorder chart. The spectrometer operated in all the experiments "in reflection." The sufficient intensity of the signal made it possible to dispense with a resonator, making it quite simple to tune the spectrometer frequency and to operate in the necessary frequency band. The external magnetic field was modulated at a frequency 18 Hz, so that the quantity registered in the experiments was the derivative of the absorption signal with respect to the magnetic field.

EXPERIMENTAL RESULTS

A direct measurement of the frequencies of the homogeneous AFMR at $H=0$ (of the initial splitting) entails great difficulties, since the resonance lines broaden greatly when a procedure with scanning of the magnetic field is used, and their amplitude decreases. Therefore the temperature dependence of the energy gap ν_0 at $H=0$ was determined in the present study from the temperature dependences of the gap in the magnetic field. To this end, the temperature dependences of the resonant field $H_\parallel$ was measured at a large number of frequencies from the indicated band and extrapolation of each of the dependences to zero magnetic field yielded in fact, at a certain accuracy, the value of $\nu_0(T)$ at the given radiation frequency ν. By way of example, Fig. 2 shows the temperature dependences of the resonant fields $H_\parallel$ for two frequencies: 25 and 16 GHz. As seen from this figure, each of the frequencies corresponds to two resonant fields. Extrapolation of the temperature dependences to a zero field yields at all frequencies at which resonance is observed certain values of the temperatures T_1 and T_2, which are so arranged relative to the ordering temperature of the rare-earth system $T_{N2}\approx 40$ whose K, that $T_1 < T_{N2} < T_2$. Lowering the frequency ν brings these characteristic temperature closer together until at a certain frequency ν_c the resonance lines merge to form one. The lines then broaden considerably and decrease in amplitude. No resonance is observed at lower frequencies. The plot of the frequency of the homogeneous AFMR at $H=0$, constructed from these data, is shown in Fig. 3. As seen from this figure, the temperature dependence of $\nu_0(T)$ has a rather clearly pronounced

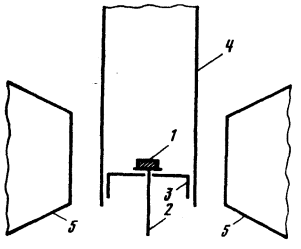

FIG. 1. Diagram of measuring cell: 1—sample, 2—rotating table, 3—short-circuiting plunger, 4—receiving-transmitting wave guide, 5—poles of permanent magnet.

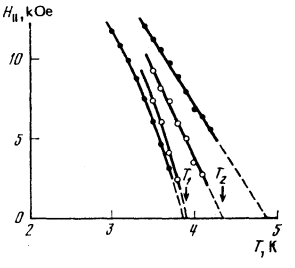

FIG. 2. Temperature dependences of the resonant field $H_\parallel$ for two frequencies ν: ●—25 GHz, O—16 GHz.

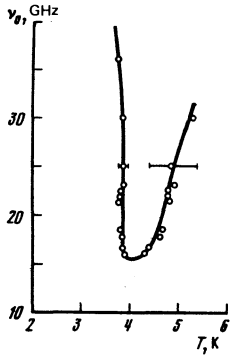

FIG. 3. Temperature dependence of the frequency of homogeneous AFMR at $H = 0$ (of initial splitting). The experimental points were obtained from the temperature dependences of the resonant field at various frequencies. The horizontal bars show the maximum temperature width of the absorption lines at the corresponding frequency.

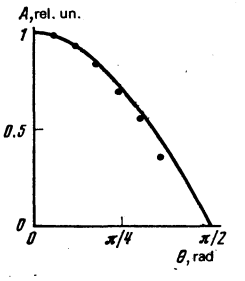

FIG. 4. Dependence of the amplitude of the AFMR signal on the angle θ between H and h. The solid line corresponds to the function $A = \cos\theta$, $\nu = 18.6$ GHz.

minimum, which corresponds to the temperature 4 °K, at which, as is well known,[6] an orientational magnetic phase transition takes place, due to the ordering of the rare-earth system of spins in $ErFeO_3$. It is possible to state definitely that in this phase transition the frequency of the spin wave "softens." However, as follows from Fig. 3, the value of the energy gap decreases not to zero but only to a certain value corresponding to $\nu_e \approx 15$ GHz.

It should be noted that in the present paper we discuss the temperature dependence of only that AFMR spectrum branch which is observed in sufficiently weak magnetic fields, so that it is possible to extrapolate the temperature dependences to a zero field. This branch has a rather definite temperature dependence in the region of the ordering temperature of the RE system. On the whole we are interested only in the dependence of the initial splitting on the temperature. In fact, experiment reveals also other spectrum branches whose resonant fields depend little on the temperature, or which exist only in sufficiently strong magnetic fields. However, their interpretation and detailed discussion are beyond the scope of the present article.

To identify the absorption lines from the soft mode of the spectrum, we plotted the dependence of the amplitude of the AFMR signal against the mutual polarization of H and h, as is shown in Fig. 4. As seen from this figure, the largest amplitude of the absorption lines of interest to us corresponds to the polarization $\mathbf{H} \| \mathbf{h} \| \mathbf{m}$, whereas when the angle between H and h is increased to $\pi/2$ the amplitude decreases to 0, (with the orientation $\mathbf{H} \| \mathbf{m}$ preserved).

Thus, the frequency of the homogeneous AFMR soft mode of the spin-wave spectrum decreases also in the phase transition due to the ordering of the rare-earth spin subsystem, but does not vanish. One of the causes of the appearances of the gap ν_c in low-temperature reorientation may be the magnetoelastic interaction. Then its value should characterize to a certain degree the contribution of the magnetoelastic energy to the anisotropy energy.

[1]E. A. Turov, Fizicheskie svoĭstva magnitouporyadochennykh kristallov (Physical Properties of Magnetically Ordered Crystals), 1963.

[2]J. R. Shane Phys. Rev. Lett. **20**, 728 (1968).

[3]R. C. Lecraw, R. Wolfe, E. M. Gyorgy, F. B. Hagedorn, J. C. Hensel, J. P. Remeika, J. Appl. Phys. **39**, 1019 (1968).

[4]K. P. Belov and A. M. Kadomtseva, Usp. Fiz. Nauk **103**, 577 (1971) [Sov. Phys. Usp. **14**, 154 (1971)].

[5]N. M. Kovtun, Z. S. Karnachev, E. E. Solov'ev, A. Ya. Chervonenkis, and A. A. Shemyakov, Fiz. Tverd. Tela (Leningrad) **14**, 2150 (1972) [Sov. Phys. Solid State **14**, 1856 (1971)]. V. D. Doroshev, N. M. Kovtun, E. E. Solov'ev, A. Ya. Chervonenkis, and A. A. Shemyakov, Phys. Stat. Sol. **51**, K31 (1972).

[6]V. A. Klochan, N. M. Kovtun, and V. M. Khmara, Zh. Eksp. Teor. Fiz. **68**, 74 (1975) [Sov. Phys. JETP **41**, 357 (1975)].

[7]I. M. Vitebskiĭ and D. A. Yablonskiĭ, Proc. 20th All-Union Conf. on Low-Temperature Physics, part II, 1979, p. 125.

Translated by J. G. Adashko