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MAGNETIC PHASE TRANSITIONS IN YbIG[1]

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The existing theoretical magnetic phase diagram of YbIG is improved by use of the two-level model of Yb ion in the molecular field approximation. In contrast to the previous theories our approach reveals the first-order transition for temperatures between 6 and 14 K and for magnetic fields in [110] direction which are lower than 8 T.

1. Introduction

Ytterbium-iron garnet (YbIG) is a suitable object for the study of magnetic phase transitions induced by the external magnetic field owing to a complexity of its magnetic structure. In spite of earlier detailed study of this system there still persists a contradiction between the theory and the experiment. Magnetic structure of the YbIG is formed by two Fe and six Yb sublattices. Whereas Fe sublattices are mutually tightly bound by strong isotropic exchange interaction, the six Yb sublattices are only weakly bound to the Fe system. Due to the anisotropy originating from both the crystal field and the exchange interaction with Fe ions the Yb sublattices form so called umbrella structure. This complex magnetic structure is relatively easily influenced by the external magnetic field and, also, is highly sensitive to the changes of temperature.

The broad and rich variety of different types of phase transitions were deduced for [100] and [111] directions of the external magnetic field by Alben [1]. For [110] direction Loos [2] used the free energy expansion in the neighbourhood of a tetracritical point. This led to a number of second-order transitions.

The magnetic phase diagrams were studied experimentally by the measurements of specific heat, magnetocaloric effect, and magnetic moments in pulsed magnetic fields. While for the magnetic field along [100] and [111] axes the experimental data qualitatively agree with the theoretical predictions, for [110] direction the experiments with pulse magnetic fields [3] indicate a first-order phase transition in a contradiction to the theory [2].

Our laser based equipment for measuring the dependence of the far infrared transmission on temperature and magnetic field enables us to address the problem anew.

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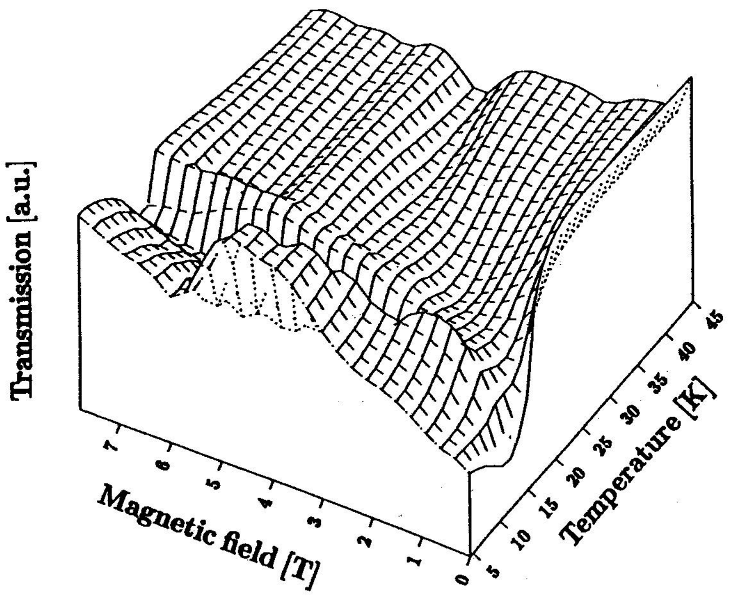

Fig 1. Transmission spectra of YbIG for $\vec{H}\|[110]$

2. Far infrared transmission measurements

In the early far infrared experiments in YbIG by Sievers and Tinkham [4] the exchange resonance absorption and several single ion transitions were observed with no indications of phase transitions. Our preliminary results from the YbIG transmission measurements [5] showed abrupt changes depending on magnetic field and temperature. Fig. 1 displays the transmission spectra of YbIG at 13.4 cm^{-1} in the temperature range between 4 and 45 K for external magnetic field in [110] direction up to 8 T. The pronounced minimum of transmission for temperature region between 5 and 15 K is observed depending on the magnetic field. Magnetic phase transitions seem to be a good candidate for the explanation of these changes. Moreover, observed hysteresis could indicate magnetic phase transition of the first order.

2. Theoretical model and discussion

Magnetic structure of YbIG can be determined by finding the minimum of the thermodynamic potential (Gibbs free energy). As the higher levels are about 500 cm^{-1} apart from the lowest doublet, the two-level model of the Yb ions system in a molecular field approximation is fully justified.

The energy level splitting of this doublet depends on the external magnetic field, on the orientation of Fe magnetic sublattices, on the (anisotropic) exchange interaction involving Yb and Fe ions and on the crystal field at the dodecahedral c-sites where Yb

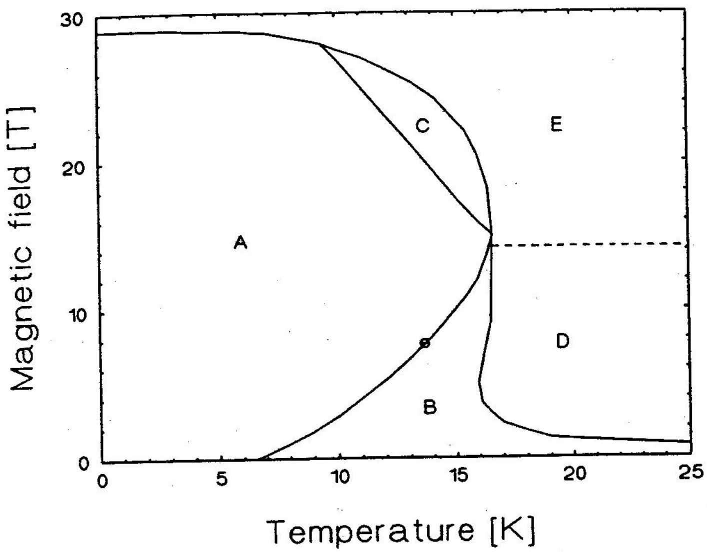

Fig. 2. Phase diagram of YbIG for $\vec{H}\|[110]$

ions are placed. Free energy of the coupled system of Yb and Fe sublattices (related to two formula units) can be expressed by [6]

$$F(\theta_{Fe},\varphi_{Fe};\vec{H},T) = -kT\sum_i \ln[2\cosh\frac{\Delta_i(\theta_{Fe},\varphi_{Fe})}{2kT}] \\ -\vec{M}_{Fe}\vec{H} + A_{Fe}(\theta_{Fe},\varphi_{Fe}) \qquad (1)$$

where

$$\Delta_i(\theta_{Fe},\varphi_{Fe}) = |\mu_B\vec{H}\,\overset{\leftrightarrow}{g}{}^i - \frac{\vec{M}_{Fe}}{M_{Fe}}\,\overset{\leftrightarrow}{G}{}^i\,|$$

Here θ_{Fe} and φ_{Fe} are azimuthal and polar angles of $\vec{M}_{Fe}$ (resulting magnetization of octahedral and tetrahedral Fe sublattices), $\overset{\leftrightarrow}{g}{}^i$ and $\overset{\leftrightarrow}{G}{}^i$ are g- and exchange tensors, respectively. In the local coordinate system of i-th Yb site the tensors are diagonal with the respective values (2.85, 3.60, 3.78) and (11.6, 25.7, 29.9) cm^{-1} [6]. For the constants $K_1 = -24800$ and $K_2 = 2300$ erg/cm^3 for single ion anisotropy A_{Fe} the YIG values [7] were used. The splitting Δ_i is to be calculated for all 6 nonequivalent Yb sites. Magnetic structure will then correspond to the minimum of free energy (1) with the unit vector $\vec{M}_{Fe}/M_{Fe}$ used as the order parameter. ¿From the symmetry behaviour of Yb and Fe magnetizations the phase transitions were identified in (T,H)-plane (see Fig.2.)).

Denoting the resulting magnetic moment of all Yb sites $\vec{M}_{Yb}$, the noncollinear arrangement of $\vec{M}_{Fe}$ and $\vec{M}_{Yb}$ arises in the regions A, B and C, whereas regions D and

E correspond to antiparallel and parallel arrangement, respectively. At the dashed line the umbrella structure is continuously flopped with zero projection of $\vec{M}_{Yb}$. The regions A, B and C differ in symmetry of noncollinear arrangement. The line between A and B is interesting from the point of view of phase transition type. For $T < 13.5$ K and for small $\vec{H}$ both $\vec{M}_{Fe}$ and $\vec{M}_{Yb}$ lay in $(1\bar{1}0)$ plane, for certain critical value of $\vec{H}$ they jump by several tens of degrees towards general direction (first-order transition), and finally with increasing H they continuously pass from phase A (possibly through B) to collinear phase E. At $T = 13.5$ K the jump approaches to zero, and for $T > 13.5$ K the phase transition between B and A becomes continuous. The detailed description of magnetic structure in specific regions will be published elsewhere.

The comparison with experimental data indicates that for proper explanation of far infrared transmission experiments the calculation of dynamic effects (magnetic resonance etc.) will be necessary.

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