EFFECT OF MAGNETIC FIELD ON THE FARADAY EFFECT IN ERBIUM, TERBIUM, AND HOLMIUM IRON GARNETS

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The influence of a magnetic field on the Faraday effect is studied in three rare-earth iron garnets. Two mechanisms of the influence of paramagnetic magnetization of the rare earth lattice on the gyromagnetic and gyroelectric Faraday effects and on the spin-orbit mechanism of variation of the gyroelectric Faraday effect for iron sublattices are considered.

AN investigation of the influence of the magnetic field on the Faraday effect α_F in iron garnets in the saturation region, carried out in[1-3], has shown that there exist at least three types of changes of $\alpha_F(H)$:
1) change of the gyroelectric part of α_F of the iron sublattices of yttrium garnets, not connected with the change of the magnetization[1,2]; 2) change of the gyromagnetic part of α_F in the infrared region of the spectrum, connected with the paraprocess susceptibility $\kappa_p(R^{3+})$ of the rare-earth sublattice[2]; 3) change of the gyroelectric part of α_F in $Tb_3Fe_5O_{12}$ at $\lambda = 1.15\ \mu$, due to $\kappa_p(R^{3+})$ and corresponding quantitatively to the paramagnetic Verdet constant of the Tb^{3+} ions[3]. However, only the first type of $\alpha_F(H)$ dependence in the yttrium garnet was investigated in sufficient detail in the visible and the infrared regions of the spectrum. The purpose of the present investigation was to study, in the infrared region, the second and third mechanisms in iron garnets of erbium, terbium, and holmium, in which an appreciable contribution is made to α_F by the rare-earth sublattice.

The measurements were carried out at room temperature using the setup described in[2], at the same wavelengths: 1.0 ± 0.2, 1.5 ± 0.2, and 2.1 ± 0.4, and $4.5 \pm 0.8\ \mu$. The $Er_3Fe_5O_{12}$ sample was cut in the (110) plane in the form of a plate of thickness $d = 90\ \mu$, the $Tb_3Fe_5O_{12}$ sample ($d = 100\ \mu$) was cut in the (112) plane, the $Tb_3Al_5O_{12}$ sample, on which comparative measurements of the paramagnetic Faraday effect were made, was cut in the (110) plane ($d = 1.5$ mm), and the $HO_3Fe_5O_{12}$ sample, cut in the (110) plane, was polished to a thickness of $90\ \mu$, making it possible to perform measurements at $\lambda = 1\ \mu$, in addition to the measurements made in[2]. Measurements were also made on two gallate single crystals, $Y_3Ga_{1.3}Fe_{3.7}O_{12}$ and $Er_3Ga_{1.3}Fe_{3.7}O_{12}$ ($d = 90\ \mu$).

Figure 1 shows the experimental $\alpha_F(H)$ curves for erbium and holmium iron garnets and for yttrium and erbium gallates at certain wavelengths. The summary results on $\alpha_F(H)$ in the region $H > 10$ kOe from the present investigation and from[2] are listed in Table I.

The results obtained at $\lambda = 4.5\ \mu$ differ in that for all the iron garnets α_F is of gyromagnetic origin at the indicated wavelength[4]. In this case a quantitative estimate of $\Delta\alpha_F/\Delta H$ can be obtained from the formula for the gyromagnetic Faraday effect

$$\alpha_F = \frac{2\pi\sqrt{\varepsilon}}{c}(\gamma_1 I_1 - \gamma_2 I_2),$$

where I_1 and I_2 are the magnetizations and γ_1 and γ_2 are the gyromagnetic ratios for the iron and rare-earth sublattices of the iron garnet. In the yttrium

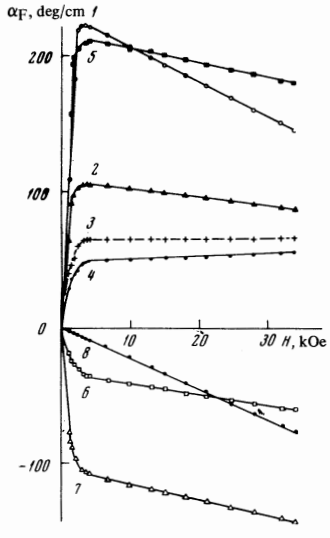

FIG. 1. Influence of external magnetic field on the Faraday effect in iron garnets of erbium (the curves correspond to different wavelengths: 1 – $1.0 \pm 0.2\ \mu$; 2 – $1.5 \pm 0.2\ \mu$; 3 – $2.1 \pm 0.4\ \mu$; 4 – $4.5 \pm 0.8\ \mu$) and holmium (5 – $1.0 \pm 0.2\ \mu$), gallates of yttrium (6 – $1.0 \pm 0.2\ \mu$) and erbium (7 – $1.0 \pm 0.2\ \mu$), and aluminate of terbium (8 – $1.0 \pm 0.2\ \mu$).

Table I

Garnet		λ, μ: 1.0±0.2	1.5±0.2	2.1±0.4	4.5±0.8
$Y_3Fe_5O_{12}$	α_F^s	195	128	94	69
	$\Delta\alpha_F$	−1.05	−0.35	−0.13	0
$Er_3Fe_5O_{12}$	α_F^s	230	109	65	48
	$\Delta\alpha_F$	−2.5	−0.5	0	+0.206
$Ho_3Fe_5O_{12}$	α_F^s	215	82	52	42.5
	$\Delta\alpha_F$	−1.04	−0.24	0	+0.13
$Tb_3Fe_5O_{12}$	α_F^s	508	348	129	24
	$\Delta\alpha_F$	−3.75	−1	0	+0.097
$Tb_3Al_5O_{12}$	$\Delta\alpha_F$	−2.24	−1.27	−0.2	−0.038
$Y_3Ga_{1.3}Fe_{3.7}O_{12}$	α_F^s	−33	−13	−4	
	$\Delta\alpha_F$	−0.82	−0.29	−0.037	
$Er_3Ga_{1.3}Fe_{3.7}O_{12}$	α_F^s	−104	−37		
	$\Delta\alpha_F$	−1.12	−0.41		

The values of α_F^s are given in deg/cm, and the values of α_F in deg/cm-kOe.

garnet $I_2 = 0$, and the variation of $I_1(H)$ at room temperature is so small ($\kappa_1(Y_3Fe_5O_{12}) \approx 0.12 \times 10^{-4}$ G/Oe-g[5]), so that α_F does not depend on H within the limits of the experimental accuracy. The susceptibility of the rare-earth sublattice, due to the change of $I_2(H)$, is larger by about one order of magnitude, therefore $\alpha_F(H)$ in iron garnets with $I_2 \neq 0$ is determined mainly by the $I_2(H)$ dependence. At temperatures exceeding the compensation temperature, the magnetization of the rare-earth sublattice I_2 is directed opposite to the external magnetic field. An increase of the magnetic field leads to a decrease of I_2, and therefore $\Delta\alpha_F/\Delta H$ in the gyromagnetic region should be positive, in agreement with the experiment. A quantitative estimate of $\Delta\alpha_F/\Delta H$ can be obtained from the formula

$$\frac{\Delta\alpha_F}{\Delta H} = \frac{2\pi\sqrt{\varepsilon}}{c}\left(\gamma_1\frac{\Delta I_1}{\Delta H} - \gamma_2\frac{\Delta I_2}{\Delta H}\right) = \frac{2\pi\sqrt{\varepsilon}}{c}[\gamma_1\varkappa_p(Fe^{3+}) + \gamma_2\varkappa_p(R^{3+})],$$

where $\kappa(Fe^{3+})$ and $\kappa(R^{3+})$ are the susceptibilities of the paraprocess for the iron and rare-earth garnet sublattices.

Using for $\kappa_p(Fe^{3+})$ the value of κ_p of the yttrium garnet, the g-factors of the free ions, and assuming that

$$\varkappa_p(R^{3+}) = [\varkappa_p(R_3Fe_5O_{12}) - \varkappa_p(Y_3Fe_5O_{12})],$$

we obtain for $Er_3Fe_5O_{12}$

$$\Delta\alpha_F/\Delta H = 0.21 \text{ deg/cm-kOe} \quad (\varkappa_p = 8.1\cdot10^{-4} \text{ G/Oe-cm}^3 [6]),$$

for $Ho_3Fe_5O_{12}$

$$\Delta\alpha_F/\Delta H = 0.26 \text{ deg/cm-kOe} \quad (\varkappa_p = 8.8\cdot10^{-4} \text{ G/Oe-cm}^3 [2]),$$

and for $Tb_3Fe_5O_{12}$

$$\Delta\alpha_F/\Delta H = 0.29 \text{ deg/cm-kOe} \quad (\varkappa_p = 7.8\cdot10^{-4} \text{ G/Oe-cm}^3 [6]).$$

The obtained value of $\Delta\alpha_F/\Delta H$ for $Er_3Fe_5O_{12}$ is in quantitative agreement with experiment (see Table I). For $Ho_3Fe_5O_{12}$ and $Tb_3Fe_5O_{12}$ the discrepancy exceeds the possible experimental errors. The decrease of the experimental values of $\Delta\alpha_F/\Delta H$ compared with the calculated ones is due apparently to the fact that at $\lambda = 4.5 \pm 0.8\ \mu$ the gyromagnetic Faraday effect, for which $\Delta\alpha_F/\Delta H$ is negative, still plays an important role in these garnets. This assumption is in accord with the fact that for the Er^{3+} ions the longest-wave length absorption line is located at $\lambda = 1.5\ \mu$ and for Ho^{3+} at 2.0 μ. For Tb^{3+} there are absorption lines at $\lambda = 3.0$ and $\lambda = 5.0\ \mu$[7].

On going over to the gyroelectric region, $\Delta\alpha_F/\Delta H$ vanishes for all the rare-earth iron garnets in the region of $\lambda = 2.0\ \mu$, and then becomes negative. This is connected with the fact that both the first and the third mechanisms whereby the field influences the gyromagnetic Faraday effect have a negative sign. In the holmium iron garnet, the influence of H on α_F at $\lambda = 1.0$–$1.5\ \mu$ is mainly connected with the first mechanism, i.e., with the effect of the field on the iron sublattices of the garnet, as follows from the numerical agreement between the Faraday effect at saturation, α_F^S, and $\Delta\alpha_F/\Delta H$ for the holmium and yttrium garnets. For $Er_3Fe_5O_{12}$, the contribution of the third mechanism is likewise not very large, although its influence is apparently the reason for the increase of

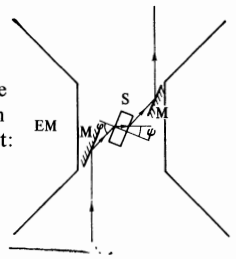

FIG. 2. Placement of the sample and of the mirrors in the gap of the electromagnetic when measuring the anisotropy of the Faraday effect: EM – electromagnetic, S – sample, M – mirrors.

$\Delta\alpha_F/\Delta H$ compared with $\Delta\alpha_F/\Delta H$ of the yttrium garnet. In the terbium iron garnet, the third mechanism plays the main role even at room temperature. The contribution of the rare-earth sublattice to α_F of the terbium garnet is very large, leading to a corresponding increase of $\Delta\alpha_F/\Delta H$.

The experimental results for $Tb_3Fe_5O_{12}$ and $Tb_3Al_5O_{12}$, obtained at $\lambda = 1.0$ and 1.5 μ, confirm the assumption made by Cooper et al.[3] that in the first approximation the Faraday effect of the rare-earth sublattice of Tb^{3+} corresponds to the sum of the paramagnetic rotations of the terbium ions. This assumption can be verified in two independent ways: by determining the absolute value of the Faraday effect and by determining the dependence of $\Delta\alpha_F/\Delta H$. The contribution of the terbium ions to α_F can be determined from Table I, by subtracting from $\alpha_F(Tb_3Fe_5O_{12})$ the gyroelectric Faraday effect of the yttrium garnets and the gyromagnetic Faraday effect of the terbium garnet, i.e., $\alpha_F(Tb^{3+})$ is equal to ~360 and ~250 deg/cm for $\lambda = 1.0$ and 1.5 μ respectively. Using the theoretical value of the paramagnetic susceptibility of $Tb_3Al_5O_{12}$, namely 8.3×10^{-4} G/Oe-cm^3, if the g factor of the Tb^{3+} ion is equal to 1.5 and if T = 300°K, we find from Table I that α_F of the aluminate would amount to 310 and 170 deg/cm, provided its magnetization equals the magnetization of the terbium sublattice of the garnet ($I(Tb^{3+}) = 114$ G/cm^3 [8]). By determining in similar fashion the contribution of the terbium sublattice to $\Delta\alpha_F/\Delta H$, we find that $(\Delta\alpha_F/\Delta H)^{Tb^{3+}}$ is approximately equal to −3.0 and −1.0 deg/cm-kOe for $\lambda = 1.0$ and 1.5 μ. The corresponding values of $(\Delta\alpha_F/\Delta H)^{Tb^{3+}}$, calculated from the values of α_F and $\kappa_p(Tb^{3+})$ in $Tb_3Fe_5O_{12}$, are equal to −2.8 and −1.9 deg/cm-kOe, and those calculated from the values of α_F and $\kappa_p(Tb^{3+})$ for $Tb_3Al_5O_{12}$ are equal to −2.4 and −1.3 deg/cm-kOe.

The question of the anisotropy of α_F and of $\Delta\alpha_F/\Delta H$ in $Tb_3Fe_5O_{12}$ deserves a separate discussion. The anisotropy of the Faraday effect in terbium iron garnet at $\lambda = 4\ \mu$ was first observed by Tyutneva (see[9]). Measurements yield $\alpha_F = 28$ deg/cm along the [111] axis and 33 and 36 deg/cm along the [110] and [100] axes, respectively. Chetkin and Shalygin[10] recently reported the presence of very strong anisotropy of α_F in $Tb_3Fe_5O_{12}$ at $\lambda = 1.15\ \mu$ (the change of α_F exceeds the contribution of the terbium sublattice to α_F) and a strong anisotropy in $\Delta\alpha_F/\Delta H$ (the angle of inclination changes from −6.0 to +7.0 deg/cm-kOe). However, the experimental curve of the anisotropy of α_F in the (112) plane, given in[10], is not convincing, because the mirror symmetry relative to the [110] axis, which is needed for the (112) plane, is missing.

Thus, for example, entirely different results were obtained for the two equivalent axes $[\bar{2}01]$ and $[02\bar{1}]$, which lie in the (112) plane at an angle $\pm 51°$ to the $[1\bar{1}0]$ axis, viz., $\alpha_F \approx 500$ deg/cm and $\Delta\alpha_F/\Delta H \approx -6.0$ deg/cm-kOe for the $[\bar{2}01]$ axis and $\alpha_F \approx 220$ deg/cm and $\Delta\alpha_F/\Delta H \approx +7.0$ deg/cm-kOe for the $[02\bar{1}]$ axis[1)]. We have therefore measured α_F and $\Delta\alpha_F/\Delta H$ for several nonequivalent crystallographic directions in the $Tb_3Fe_5O_{12}$ crystal.

The measurements of the anisotropy of α_F and $\Delta\alpha_F/\Delta H$ were carried out in accordance with the scheme shown in Fig. 2. The sample was placed between the poles of an electromagnet in such a way that the angle between the magnetic field and the normal in the plate was equal to the light-refraction angle ψ. By rotating the sample in its plane, we were able to measure α_F for all the crystallographic directions making an angle ψ with the [112] axis. The advantage of this method lies in the fact that the measurements are carried out using a small volume of the sample, i.e., where the properties are homogeneous and the light path length in the sample is the same for different axes. The angle ψ was chosen equal to 25° ($\varphi = 67°$) and the measurements of α_F were made for axes lying at the intersections of the indicated cone with the planes passing through the axis [112] and the axes [111], [101], [011], [001], [212], [012], [122], and [102]. The axes along which α_F was measured will be denoted, for example, by $[111]_{+6°}$ or $[101]_{-5°}$, where the index denotes the angle between the measurement axis and the corresponding axis [111] or [101].

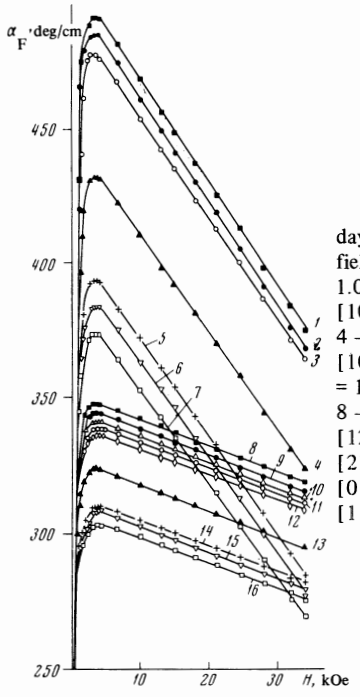

FIG. 3. Dependence of the Faraday effect on the external magnetic field in terbium iron garnet at $\lambda = 1.0 \pm 0.2\,\mu$ (measurement axes: 1 – $[102]_{+1°}$, 2 – [112], 3 – $[012]_{+1°}$, 4 – $[001]_{-10°}$, 5 – $[011]_{-5°}$, 6 – $[101]_{-5°}$, 7 – $[111]_{+6°}$) and for $\lambda = 1.5 \pm 0.2\,\mu$ (measurement axes: 8 – $[102]_{+1°}$, 9 – [112], 10 – $[122]_{+3°}$, 11 – $[012]_{+1°}$, 12 – $[212]_{+3°}$, 13 – $[001]_{-10°}$, 14 – $[011]_{-5°}$, 15 – $[101]_{-5°}$, 16 – $[111]_{+6°}$.

Figure 3 shows plots of α_F for the indicated axes at $\lambda = 1.0$ and $1.5\,\mu$, while Table II gives the numerical values of α_F^S and $\Delta\alpha_F/\Delta H$ for λ equal to 1.0, 1.5, and 2.1 λ. The error in the measurement of the anisotropy of α_F and $\Delta\alpha_F/\Delta H$ is characterized by the difference between the numerical values of these quantities for the equivalent axis, for example, $[012]_{+1°}$ and $[102]_{+1°}$ or $[122]_{+3°}$ and $[212]_{+3°}$. The relative values of α_F^S and $\Delta\alpha_F/\Delta H$ for the [112] axis were established less reliably, since they were obtained not from measurements on the indicated cone, but at the usual orientation of the sample perpendicular to the light beam and to the direction of the magnetic field. It follows from the obtained data that the change of $\Delta\alpha_F/\Delta H$ is always negative for λ equal to 1.0 and $1.5\,\mu$, and is isotropic in the first approximation. The anisotropy of the Faraday effect amounts to $\pm 13\%$ for $\lambda = 1.0\,\mu$, $\pm 7\%$ for $\lambda = 1.5\,\mu$, and $\pm 10\%$ for $\lambda = 2.1\,\mu$.

Our preliminary measurements of the anisotropy of α_F in a $Tb_3Al_5O_{12}$ sample by the method described above have shown that, within the limits of the experimental accuracy, the Faraday effect in terbium aluminate garnet is isotropic and consequently the anisotropy of α_F in the terbium iron garnet is due to the exchange field acting on the Tb^{3+} ions and produced by the iron sublattices of the garnet. Qualitatively, the character of the anisotropy is the same as for the gyromagnetic Faraday effect[9], i.e., α_F is minimal for the easy anisotropy axis [111], and α_F decreases when the axis "becomes more complicated." The "complication" is apparently connected with the fact that when the saturation magnetization I_S is oriented along the [111] axis we have the minimum number (two) of local nonequivalent surroundings for the rare-earth ions, and on moving away from the [111] axis this number increases to six[11]. However, the qualitative agreement between the character of the anisotropy of

Table II

λ, μ		Direction of light beam in sample								
		$[111]_{+6°}$	$[101]_{-5°}$	$[011]_{-5°}$	$[001]_{-10°}$	$[212]_{+3°}$	$[012]_{+1°}$	$[122]_{+3°}$	[112]	$[102]_{+1°}$
1	α_F^S	387	397	406	446		492		498	504
	$\Delta\alpha_F$	−3.5	−3.5	−3.5	−3.65		−3.8		−3.8	−3.8
1,5	α_F^S	308	312	314	327	340	343	345	347	352
	$\Delta\alpha_F$	−0.94	−0.94	−0.91	−0.94	−0.91	−0.94	−0.94	−0.97	−0.97
2,1	α_F^S	105	107	109	116		123		127	130

The values of α_F^S are given in deg/cm, and the values of α_F in deg/cm-kOe.

[1)]According to a private communication from the authors of [10], this asymmetry is due to the fact that the magnetization vector does not coincide with the direction of propagation of the light in the crystal when the rotation of the polarization plane is measured.

the gyromagnetic and gyroelectric Faraday effects at room temperature does not mean that the physical mechanism of the anisotropy of α_F is the same in both cases. The difference between these mechanisms can be verified by measuring the anisotropy of α_F at a temperature ~100°K. It is not very likely that the character of the anisotropy of the gyroelectric Faraday effect will change at this temperature. From the data of Cooper et al.[3] it follows that the increase of α_F at nitrogen temperatures corresponds to an increase in the magnetization of the terbium sublattice and consequently, the specific rotation of the Tb^{3+} ion remains unchanged in first approximation. On the other hand, if the assumption advanced earlier[9] is valid, then the anisotropy of the gyromagnetic Faraday effect should change strongly in this temperature region. The Faraday effect has a positive and maximum value along the [111] axis, and on moving away from this axis the effect should decrease sharply and even reverse sign, owing to the contribution α'_F made to the Faraday effect by the single-ion exchange resonance.

In conclusion, let us stop to discuss certain considerations, supplementing the earlier investigations[1,2], concerning the character of the influence on the magnetic field on the Faraday effect of the iron sublattices of yttrium garnet (the first mechanism). First, plots of $\alpha_F(H)$ for yttrium and erbium gallate-ferrites, shown in Fig. 1, confirm the assumption that the $\alpha_F(H)$ dependence is determined mainly by the influence of the field on the Fe^{3+} ions of the octahedral sublattice. When the tetrahedral iron ions are abundantly replaced by nonmagnetic ions of gallium, the magnetization of the garnet is determined by the octahedral sublattice and the magnetic field begins to enhance the sign-changing Faraday effect rather than decrease it[12]. Second, if we start from the assumption that the magnetic field influences only the contribution made to α_F by the octahedral sublattice of the iron ions, then we can estimate from our data the internal effective field responsible for α_F in $Y_3Fe_5O_{12}$. According to[3], the contribution of the octahedral sublattice to the Faraday effect α_F^{oct} at $\lambda = 1.15\ \mu$ amounts to approximately 800 deg/cm.[2)] Using the value of $\Delta\alpha_F/\Delta H$ from Table I, we find that the magnetic field at which α_F^{oct} vanishes is equal approximately to 750 kOe. Assuming that at $\lambda = 1.5\ \mu$ the ratio of α_F^{oct} to α_F^{tetr} remains the same as at $\lambda = 1.0\ \mu$, i.e., it equals 1.3, we get $\alpha_F^{oct} \approx 270$ deg/cm at $\lambda = 1.5\ \mu$. The corresponding value is $H_{eff} \approx 770$ kOe.

It is significant that the values of H_{eff} obtained above practically coincide with H_{eff} determined from measurements of $\Delta\alpha_F/\Delta H$ in the visible region by Kharchenko et al.[1], who advanced the hypothesis that H_{eff} is due to the spin-orbit splitting (70 cm^{-1}) of the electronic transition with charge transfer at $\nu_0 \sim 9 \times 10^{14}$ sec^{-1} (28 000 cm^{-1})[3)]. Thus, the aggregate of the available experimental data confirms qualitatively our assumption[14] (see also[1,2]) that when the influence of H on α_F does not reduce to a simple change of the magnetization of the ferromagnet, it is due to the influence of the field on the spin-orbit interaction. Quantitative estimates of this effect and an exact identification of the electron transitions responsible for it can be made only after a study and classification of the ultraviolet electronic transitions in the Fe^{3+} ions, in analogy with the study recently made for the rare-earth orthoferrites[15].

We are grateful to N. A. Khatanov and A. B. Ivanov for help during the x-ray diffraction determination of the orientation of the investigated crystals.

[2)]The value of α_F obtained by us for $Y_3Fe_5O_{12}$ at $\lambda = 1.0 \pm 0.2\ \mu$ is somewhat smaller than that obtained in [3] for $\lambda = 1.15\ \mu$. This difference may be connected with the presence of two electronic transitions at λ equal to 0.9 and 0.98 μ [13], or with the influence of the Fe^{2+} ions, which change sufficiently strongly the absolute value of α_F, although they do not influence the value of $\Delta\alpha_F\Delta H$ [1].

[3)]The values of the gyroelectric Faraday effect that follow from Table I for λ equal to 1.0 and 1.5 μ do not contradict the dependence of $\Delta\alpha_F/\Delta H$ on $(\nu_0^2 - \nu^2)$ given in [1].

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