Investigation of MW Characteristics of HTS Microstrip and Coplanar Resonators With Ferrite Thin-Film Components

T. Nurgaliev, S. Miteva, Alan P. Jenkins, and D. Dew-Hughes

***Abstract*—Formulas for calculating of the magnetic-field dependence of the resonance frequency and the quality factor of HTS microstrip (MS) and coplanar-waveguide resonators with a tangentially magnetized ferrite film component were obtained within the framework of the perturbation method. The conditions of attaining maximum magnetic tuning effect of the resonance frequency (with reference to the external magnetic-field strength, the field-orientation angle, and the ferrite film position in the resonator) were determined and verified in the example of model resonators, formed from copper MS and ground-plane electrodes, a yttrium–iron–garnet (YIG) ferrite film component, and dielectric spacers. A YBCO MS resonator with a YIG component was also prepared and its characteristics were measured at 77 K.**

***Index Terms*—Ferrite film, High-temperature superconducting (HTS) microstrip (MS) and coplanar resonators, magnetic tuning, perturbation method.**

I. Introduction

HIGH-TEMPERATURE superconducting (HTS) thin-film materials are characterized by extremely low microwave (MW) losses at temperatures below 77 K and are attractive for application in low-loss high-performance circuits and devices [1]. Tunability of HTS devices is important for MW electronics and can be achieved either by variation of the kinetic inductance of the HTS material (by changing the temperature [2] or the applied magnetic-field strength [3]) or by including into the device structure ferroelectric and magnetic materials, the parameters of which are controlled by the electric and magnetic fields, respectively [4]–[6]. Only a narrow tuning range can be achieved by variation of the kinetic inductance. Ferroelectric materials have high MW losses, resulting in devices with low quality factors (Q) [4]. Magnetically tunable yttrium–iron–garnet (YIG) has low MW losses and plays a traditionally important role in MW electronics [6]. HTS YBCO films can be deposited onto buffered single-crystal and polycrystalline YIG substrates [7]. Fukusako and Tsutsumi [8] investigated the tunability of a YBCO microstrip (MS) resonator with a YIG single-crystal component. The resonant frequency was varied from 5.24 to 5.42 GHz by application of a magnetic field of 20–75 mT with Q as high as 1000. Oates and Dionne [9], [10], by applying a field of 0–30 mT, tuned a YBCO MS resonator with a polycrystalline YIG component from 7.25 to 7.7 GHz and maintained a Q value of 2000 at 77 K.

In general, tunable MW devices are formed as layered structures, which can include superconducting electrodes, a tuning ferrite layer, and dielectric substrates. The parameters of such a structure depend on the device geometry, surface resistance, and kinetic inductance of HTS electrodes, the permittivities and loss tangents of the dielectric layers and dynamic permeability, and the MW losses [11], [12] of the ferrite layer. Investigation of the effect of these factors is important for the interpretation of experimental data and for choosing optimal geometries for such tunable MW devices.

Thus, the goal of this paper is an investigation of the magnetic tuning effect in simple basic HTS MW devices, such as MS and coplanar-waveguide (CPW) resonators with ferrite components, using the perturbation method and an experimental verification of the results using example model resonators with YIG–ferrite components.

II. Background

The relation between the wavenumber β and the frequency f of the TEM modes in an MS line waveguide is determined by the capacitance C and inductance L of the line per unit length [13]

$$\beta = 2\pi f (LC)^{1/2}. \tag{1}$$

When an MS line is prepared on a layered substrate, the capacitance can be expressed in terms of the effective dielectric constant ε_e and the effective loss tangent $\mathrm{tg}(\delta_e)$, related to the individual dielectric constants and loss tangents of the dielectric layers

$$C = C_0 \left[1 - j\,\mathrm{tg}(\delta_e)\right] \tag{2}$$

where $j^2 = -1$; $C_0 = C_1 \varepsilon_e$ and C_1 is the capacitance of the MS line of the same geometry when the permittivities of the dielectric layers are assumed to be equal to that of vacuum. The total inductance L of the MS waveguide per unit length can be written as a sum of the external inductance L_e of the structure

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and the complex kinetic inductance L_k of the HTS electrodes [14]

$$L = L_e + L_k \tag{3}$$

$$L_k = (2\pi f)^{-1}\left[(G_s X_{s1} + G_g X_{s2}) - j(G_s R_{s1} + G_g R_{s2})\right] \tag{4}$$

$$\begin{aligned} G_g &= \frac{1}{2\pi d}\left[1 - \left(\frac{w}{4d}\right)^2\right] \\ G_s &= G_g\left[1 + 2\frac{d}{w} + 2\frac{d}{\pi w}\,\ln\left(\frac{2d}{t}\right)\right] \end{aligned} \tag{5}$$

where R_{s1}, X_{s1} and R_{s2}, X_{s2} are the effective values of the surface resistance and reactance for the HTS thin-film strip and ground-plane electrodes, respectively, related to the characteristic surface resistance R_{sc} and the penetration depth λ of the material [14], [15]; t is the thickness of the HTS electrodes, G_s and G_g are the geometric factors, d is the substrate thickness, and w is the strip width. The external magnetic field H_e affects the surface impedance of HTS material, resulting in an increase [16], [17]

$$R_{sc} = R_{0c} + p_1 H_e \quad \lambda = \lambda_L + p_2 H_e \tag{6}$$

where R_{0c} and λ_L are the characteristic surface resistance and London penetration depth for the case when the external field is absent $H_e = 0$; p_1 and p_2 are the coefficients related to the dynamic parameters of the magnetic fluxons, which depend on the field orientation, temperature, and film quality [16].

The wavenumber β is determined by the resonator length l ($\beta = n\pi/l$, where $n = 1, 2, 3, \ldots$, are the mode numbers) and, therefore, the complex resonance frequency f_n of the MS resonator can be expressed as follows:

$$f_n = \frac{n}{2l(LC)^{1/2}} \approx f_{0n}\left\{1 - \frac{G_s X_{s1} + G_g X_{s2}}{4\pi f_{0n} L_e} + \frac{j}{2}\left[\mathrm{tg}(\delta_e) + \frac{G_s R_{s1} + G_g R_{s2}}{2\pi f_{0n} L_e}\right]\right\} \tag{7}$$

where $f_{0n} = (\pi n/l)(L_e C_o)^{-1/2}$.

A similar method can be used to calculate the resonance frequency of CPW resonators. The complex capacitance C of a CPW line per unit length, prepared on a layered substrate, can also be expressed in terms of the effective values of ε_e and $\mathrm{tg}(\delta_e)$ as in (2) [18], [19]. The inductance of the CPW includes the external and kinetic inductances L_e, L_k of the electrodes [20], [21]

$$\begin{aligned} L &= L_e + N\left(\mu_0\lambda - j\frac{R_{sc}}{2\pi f}\right) \\ N &= \frac{P}{4ADK(k)} \cdot \left(\frac{1.7}{\sin h(t/2\lambda)} + \frac{0.4}{\sqrt{\left[(B/A)^2 - 1\right]\left[1 - (B/D)^2\right]}}\right) \\ A &= -\frac{t}{\pi} + \frac{1}{2}\sqrt{\left(\frac{2t}{\pi}\right)^2 + (w)^2} \\ B &= \frac{w^2}{4A} \\ P &= B - \frac{t}{\pi} + \sqrt{\left(\frac{t}{\pi}\right)^2 + \frac{1}{4}(w_1 - w)^2} \\ D &= \frac{2t}{\pi} + P \end{aligned} \tag{8}$$

where $K(k)$ is the complete elliptic integral of the first kind, $k = w/w_1$, w and w_1 denote the widths of the central electrode and the distance between the ground plane electrodes, respectively, and μ_0 is permeability of vacuum. The complex resonance frequency of the CPW resonator can be calculated using a formula similar to (7), as in the case of an MS resonator

$$f_n = f_{0n}\left\{1 - \frac{N\mu_0\lambda}{2L_e} + \frac{j}{2}\left[\mathrm{tg}(\delta_e) + \frac{NR_{sc}}{2\pi f_{0n} L_e}\right]\right\}. \tag{9}$$

MW properties of the ferrite material are described in terms of the dynamic permeability tensor μ. The components of this tensor in the coordinate system, one of the axes of which coincides with the external field H_e and the magnetization direction, are expressed as [6], [22]

$$\begin{aligned} &\mu_{13} = \mu_{23} = \mu_{31} = \mu_{32} = 0 \\ &\mu_{33} = 1 \\ &\mu_{11} = \mu_{22} = \mu \\ &\mu_{12} = -\mu_{21} = i\mu_a \\ &\mu = \frac{f_{Hc}(f_{Hc} + f_M) - f^2}{f_{Hc}^2 - f^2} \\ &\mu_a = \frac{f_M f}{f_{Hc}^2 - f^2} \end{aligned} \tag{10}$$

where $f_M = \gamma_e H_M/2\pi$, $f_{Hc} = f_H + j\alpha f$, $f_H = \gamma_e H_e/2\pi$, $H_M = M/\mu_0$, α is the Landau–Lifshitz damping parameter, γ_e is the gyromagnetic ratio [2.21 10^5 m/(A s)], and M is the saturation magnetization (T).

III. Calculation of the Complex Resonance Frequency

The basic configuration of the structure is shown in Fig. 1. An HTS strip (2) of a width w is situated on the top of the dielectric substrate (1) and separated by a dielectric spacer (3) from an epitaxial ferrite film (4) deposited on a substrate (5). The structure may contain either an HTS or metal bottom electrode (0), the MS resonator, or two HTS electrodes (2a), placed at a distance w_1 from each other, the CPW resonator. The length l and width w_f of the structure are considerably greater than the width w of the central strip electrode (2). The thickness of the HTS electrodes (2), ferrite layer (4), bottom electrode (0), and dielectric layers (1), (3), and (5) are t, t_f, t_0 and t_1, t_3, t_5, respectively. The relative permittivities and the loss tangents of media (1) and (3)–(5) are ε_1, ε_3–ε_5, and $\mathrm{tg}(\delta_1)$, $\mathrm{tg}(\delta_3)$–$\mathrm{tg}(\delta_5)$, respectively. The permeabilities of all media, except the ferrite, are $\mu = 1$. An external dc magnetic field H_e is applied parallel to the plane of the structure and makes an angle φ with the central strip-line direction. Primary and secondary coordinate systems x, y, z and x', y', z', the $0z$ and $0z'$ axes of which are oriented parallel to the strip line and the applied field directions, respectively (see Fig. 1), are introduced. The $0y$ and $0y'$ axes of these systems

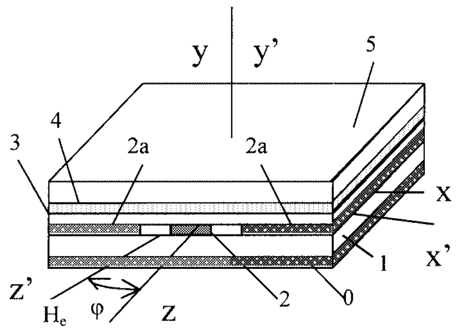

Fig. 1. The geometry of the MS and CPW resonator structures: 0—HTS or metal ground plane (in the case of MS resonator); 1, 3, 5—dielectrics; 2—HTS strip; (2a)—HTS ground plane (in the case of CPW resonator); 4—ferrite layer. Electrodes 0 or (2a) are assumed to be absent in the cases of CPW or MS resonators, respectively.

are assumed to be perpendicular to the plane of the structure, while the $z0x$ plane of the coordinate system coincides with the bottom surfaces of electrodes (2), (2a). The components of the permeability tensor of the ferrite have the simplest form (10) in the secondary coordinate system.

A MS resonator structure, with electrodes (2a) in Fig. 1 absent, is first considered. The MS resonator of the same geometry, where the ferrite film is replaced by the dielectric one, (the permeability and permittivity of which are equal to those of vacuum μ_0 and of the ferrite ε_f, respectively) can be considered as an unperturbed resonator structure. The complex resonance frequency f_n and the spatial distribution of the MW current for the unperturbed resonator structure is known, and it is necessary to deal only with the investigation of the permeability effect of the ferrite film on the HTS MS resonator parameters. The problem is considered in a quasi-static approach and MW radiation losses are neglected.

The formula for the perturbation method [22] for calculating the complex resonance frequency f_{pn} can be represented in the primary coordinate system as follows:

$$f_{pn} = f_n \left\{ 1 - \frac{\mu_0}{4E_0} \int_{-w_f/2}^{w_f/2} dx \int_{t+t_3}^{t+t_3+t_f} dy \int_{-l/2}^{l/2} \cdot \left[(\mu_\perp - 1) h_{x'}^* h_{x'} + \frac{1}{\mu} (\mu - 1) h_{y'}^* h_{y'} + j\frac{\mu_a}{\mu} \left(h_{x'}^* h_{y'} - h_{y'}^* h_{x'} \right) \right] \right\} dz \tag{11}$$

where $\mu_\perp = (\mu^2 - \mu_a^2)/\mu$; $h_{x'} = h_x \cos\varphi + h_z \sin\varphi$, $h_{z'} = h_z \cos\varphi - h_x \sin\varphi$ and $h_{y'} = h_y$ are the components of the MW magnetic field in the secondary coordinate system; h_x, h_y and h_z are the components of the field in the primary coordinate system; E_0 is the energy stored in the resonator. The asterisk in this expression denotes a conjugate complex quantity. The components of the MW magnetic field can be expressed in terms of the MW current amplitude in the resonator I_0

$$h_x = \frac{I_0}{2w} F_x(x, y) \sin\left[\left(z + \frac{l}{2} \right) \frac{\pi n}{l} \right]$$
$$h_y = \frac{I_0}{2w} F_y(x, y) \sin\left[\left(z + \frac{l}{2} \right) \frac{\pi n}{l} \right]$$
$$h_z = 0$$

$$F_x(x, y) = \frac{1}{\pi} \int_{-w/2}^{w/2} \left[-\frac{y - y_1}{(x - x_1)^2 + (y - y_1)^2} + \frac{y + y_2}{(x - x_1)^2 + (y + y_2)^2} \right] J_1(x_1) dx_1$$
$$F_y(x, y) = \frac{1}{\pi} \int_{-w/2}^{w/2} \left[\frac{x - x_1}{(x - x_1)^2 + (y - y_1)^2} + \frac{x - x_1}{(x - x_1)^2 + (y + y_2)^2} \right] J_1(x_1)\, dx_1 \tag{12}$$

where $y_1 = 0.5t$; $y_2 = 2t_1 + 0.5t$; $J_1(x_1)$ is the function which describes the dimensionless sheet MW current density distribution in the short circuited plane of the MS line, which is related to the current density distribution function $J(x, y)$ in the same plane

$$J_1(x) = \frac{w}{I_0} \int_0^t J(x, y)\, dy \qquad \int_{-w/2}^{w/2} dx \int_0^t J(x, y)\, dy = I_0.$$

The energy stored in the resonator can be expressed in terms of the MW current amplitude I_0 by the following approximate formula:

$$E_0 = L_e I_0^2 l / 4. \tag{13}$$

A substitution of expressions (12), (13) into formula (11) yields

$$f_{pn} = f_n \left\{ 1 - S \left[(\mu_\perp - 1) G_x \cos^2\varphi + \frac{(\mu - 1)}{\mu} G_y \right] \right\}$$
$$G_x = \frac{1}{w_f t_f} \int_{t+t_3}^{t+t_3+t_f} dy \int_{-w_f/2}^{w_f/2} F_x^2(x, y)\, dx$$
$$G_y = \frac{1}{w_f t_f} \int_{t+t_3}^{t+t_3+t_f} dy \int_{-w_f/2}^{w_f/2} F_y^2(x, y)\, dx$$
$$S = \frac{\mu_0 w_f t_f}{8 L_e w^2}. \tag{14}$$

After some manipulations formula (14) can be transformed to the following:

$$f_{pn} = \frac{n}{2l(LC)^{1/2}} \approx f_{0n} \left\{ 1 - \frac{G_s X_{s1} + G_g X_{s2}}{4\pi f_{0n} L_e} - m_1 + \frac{j}{2} \left[\mathrm{tg}(\delta_e) + \frac{G_s R_{s1} + G_g R_{s2}}{2\pi f_{0n} L_e} + 2m_2 \right] \right\} \tag{15}$$

$$m_1 = S \frac{f_s f_M \left(f_{fm}^2 - f_{0n}^2 \right)}{\left(f_{fm}^2 - f_{0n}^2 \right)^2 + \alpha^2 f_{0n}^2 \left(f_M + 2f_H \right)^2} \times \left(G_x \cos^2\varphi + \frac{f_H}{f_s} G_y \right) \tag{16}$$

$$m_2 = S \frac{\alpha f_{0n} f_M \left(f_s^2 + f_{0n}^2 \right)}{\left(f_{fm}^2 - f_{0n}^2 \right)^2 + \alpha^2 f_{0n}^2 (f_M + 2f_H)^2} \times \left(G_x \cos^2\varphi + \frac{f_H^2 + f_{0n}^2}{f_s^2 + f_{0n}^2} G_y \right) \tag{17}$$

$f_s = (f_H + f_M)$; $f_{fm} = [f_H(f_H + f_M)]^{1/2}$ is the ferrimagnetic resonance frequency of the tangentially magnetized film.

The quality factor Q_{pn} can be calculated from the complex resonance frequency using the following formula:

$$Q_{pn} = \mathrm{Re}(f_{pn}) / \left[2\mathrm{Im}(f_{pn})\right]. \quad (18)$$

Secondly an HTS CPW line resonator with a ferrite component shown in Fig. 1 with electrode (0) absent is considered. In this case, the following formula can be determined for the complex resonance frequency f_{pn} of the CPW resonator using the procedure described above and formulas (9), (11):

$$f_{pn} = f_{0n}\left\{1 - \frac{N\mu_0\lambda}{2L_e} - m_1 + \frac{j}{2}\left[\mathrm{tg}(\delta_e) + \frac{NR_{sc}}{2\pi f_{0n} L_e} + 2m_2\right]\right\} \quad (19)$$

where the parameters m_1 and m_2 are expressed by formulas (16), (17) with G_x and G_y given in formula (14) with

$$F_x(x,y) = \frac{1}{\pi}\left(\int_{-w_f/2}^{-w_1/2} J_2(x_1) F_{1x}\,dx_1 + \int_{w_1/2}^{w_f/2} J_2(x_1) F_{1x}\,dx_1 - \int_{-w/2}^{w/2} J_1(x_1) F_{1x}\,dx_1\right) \quad (20)$$

$$F_y(x,y) = \frac{1}{\pi}\left(-\int_{-w_f/2}^{-w_1/2} J_2(x_1) F_{1y}\,dx_1 - \int_{w_1/2}^{w_f/2} J_2(x_1) F_{1y}\,dx_1 + \int_{-w/2}^{w/2} J_1(x_1) F_{1y}\,dx_1\right)$$

$$F_{1x} = \frac{y - y_1}{(x - x_1)^2 + (y - y_1)^2}$$

$$F_{1y} = \frac{x - x_1}{(x - x_1)^2 + (y - y_1)^2}. \quad (21)$$

Here $J_1(x_1)$ and $J_2(x_1)$ are the functions which describe the distribution of the dimensionless MW current amplitude across the central conductor (2) and ground plane electrodes (2a) (see Fig. 1), respectively.

It can be noted that the perturbation method leads to correct results if the variation of the parameters due to the perturbation is small. This is satisfied when the absolute values of the terms containing the parameters m_1 and m_2 in (15) and (19) are considerably smaller than one.

IV. Analysis of the Results

A reduced numerical analysis of formulas (15)–(18) was made for a MS resonator with a strip line width $w = 0.25$ mm, a dielectric spacer thickness $t_1 = 0.5$ mm, a width and thickness of the ferrite layer $w_f = 3$ mm and $t_f = 0.01$ mm [Fig. 1 without electrodes (2a)]. In this case an unperturbed resonance frequency of the first mode $\mathrm{Re}(f_1) = 3$ GHz [see also formula (7)] and an unperturbed quality factor $Q_1 = \mathrm{Re}(f_1)/2\mathrm{Im}(f_1) = 3000$ (which *a priori* takes into account the individual parameters of the dielectric layers and electrodes $t = 0.3\,\mu$m, $R_{sc} = 0.36$ mΩ, $\lambda = 0.35\,\mu$m, $k_1 = k_2 = 0$, and of the Cu ground plane) were used as initial parameters in the computations. An uniform MW current distribution in the $x0y$ plane of the strip was assumed and the parameters of the ferrite were chosen to be close to those of YIG material at 77 K: $M = 235$ mT, $\alpha = 0.000\,125$ [8], [12].

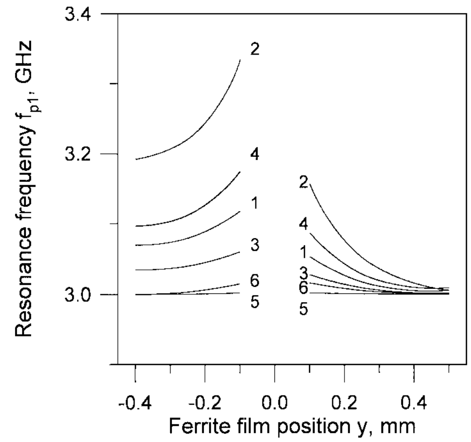

Fig. 2. Dependence of the resonance frequency f_{p1} on the position y of the ferrite film in the MS resonator computed from (15): $B = \mu_0 H_e = 10$ mT (curves 1, 3, and 5); $B = 30$ mT (curves 2, 4, and 6); $\varphi = 0$ (curves 1 and 2); $\varphi = \pi/4$ (curves 3 and 4): $\varphi = \pi/2$ (curves 5 and 6).

A complete numerical analysis (allowing the resonator parameters to be computed directly from the individual parameters of the components of the layered structure) was made for the basic resonance mode of a CPW resonator structure [Fig. 1 without bottom electrode (0)] consisting of a high quality YBCO strip and ground plane electrodes (2), (2a) ($t = 0.3\,\mu$m, $w = 0.4$ mm, $w_1 = 0.6$ mm, resonator length $l = 12$ mm, $R_{sc} = 0.3$ mΩ, $\lambda = 0.35\,\mu$m, $k_1 = k_2 = 0$) deposited on an $LaAlO_3$ substrate (1) ($t_1 = 0.5$ mm, $\varepsilon_1 = 24.5$ and $\mathrm{tg}(\delta_1) < 3 10^{-5}$ [23]) and separated by a dielectric layer (3) ($t_3 = 0.05$ mm, $\varepsilon_3 = 2.4$, $\mathrm{tg}(\delta_3) = 2\,10^{-5}$) from the YIG ferrite film ($w_f = 3$ mm, $t_f = 0.015$ mm, $\varepsilon_f = 16.7$, $\mathrm{tg}(\delta_f) = 5\,10^{-5}$ [24], $M = 235$ mT [8], $\alpha = 0.0002$), which is deposited on gadolinium–gallium–garnet (GGG) substrate (5) ($t_5 = 0.5$ mm, $\varepsilon_5 = 12.5$, $\mathrm{tg}(\delta_5) = 2\,10^{-4}$ [24]). In the computations, the MW current in the HTS CPW resonator was assumed to be distributed uniformly over the cross sections of four narrow strips with dimensions $t \times \lambda$, placed at the edges of the central and ground-plane electrodes.

For the both types of resonators, the direction of the shift of the resonance frequency due to the coupling effect of the ferrite to the resonator is determined by the sign of the term m_1 [see (15)–(17), (19)]. This term possesses a negative sign when

$$H_e < H_r = -\frac{1}{2}H_M + \frac{1}{2}\sqrt{H_M^2 + \frac{8\pi^2 f_{0n}^2}{\gamma_e^2}} \quad (22)$$

and the sign is positive when $H_e > H_r$. As a result, the resonance frequency is shifted to higher values if $H_e < H_r$ and to lower ones if $H_e > H_r$. Fig. 2 shows the dependence of the resonance frequency on the position of the ferrite film in the MS resonator computed from (15) when $H_e < H_r$. Maximum coupling (and a maximum shift of the resonance frequency) occurs when the field H_e is parallel ($\varphi = 0$) to the strip direction and the ferrite film is placed between the ground plane and MS line (-0.5 mm $< y < 0$), close to the latter (Fig. 2, curves 1 and 2). A ferrite situated close to the top surface of the MS line ($y > 0$)

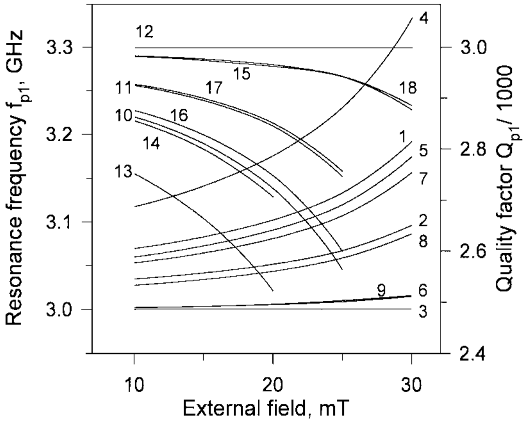

Fig. 3. Dependence of the resonance frequency f_{p1} (curves 1–9) and the quality factor Q_{p1} (curves 10–18) of the MS resonator on the magnetic-field strength $B = \mu_0 H_e$. The positions of the ferrite film in the resonator are $y = -0.4$ mm (curves 1–3 and 10–12), $y = -0.1$ mm (curves 4–6 and 13–15), and $y = 0.1$ mm (curves 7–9 and 16–18). The values of the field-orientation angle are $\varphi = 0$ (curves 1, 4, 7, 10, 13, and 16), $\varphi = \pi/4$ (curves 2, 5, 8, 11, 14, and 17), $\varphi = \pi/2$ (curves 3, 6, 9, 12, 15, and 18).

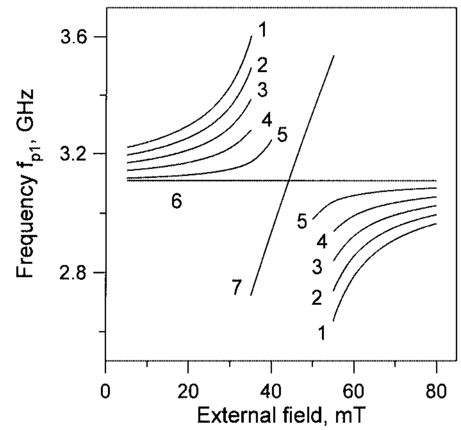

Fig. 4. Dependence of the resonance frequency of the CPW resonator on the magnetic-field strength $B = \mu_0 H_e$ computed from (19) for the field-orientation angles $\varphi = 0, \pi/6, \pi/4, \pi/3, \pi/2$ (curves 1–5, respectively). Unperturbed resonance frequencies of the resonator and the ferrite layer are shown by curves 6 and 7, respectively.

can efficiently couple with the resonator (Fig. 3, curves 1 and 2) as well if $\varphi = 0$. Coupling between the MS resonator and ferrite is rather ineffective (the shift of the resonance frequency is minimum) when the external field H_e is oriented perpendicularly $(\varphi = \pi/2)$ to the MS line (Fig. 2, curves 5 and 6). The field dependencies of the resonance frequency and the quality factor of the MS resonator computed from (15) are shown in Fig. 3. It can be seen that the magnetic tunability of the resonance frequency is a maximum when $\varphi = 0$ if the ferrite is placed close to the MS between the ground plane and strip (Fig. 3, curve 4). On the other hand, more MW losses are coupled from the ferrite to the resonator in this case and the quality factor of the resonator decreases significantly (Fig. 3, curve 13). If $\varphi = 0$, a relatively good magnetic tunability of the resonator can be obtained by placing the ferrite layer close to the top surface of the resonator (Fig. 3, curve 7). An increase of φ from 0 to $\pi/2$ leads to a gradual decrease of the magnetic tunability of the resonator and the tuning effect is very weak at $\varphi = \pi/2$ for the case with the ferrite layer placed near the ground plane (Fig. 3, curve 3). Here, the MW losses resulting from the ferrite film are low and the resonator is characterized by the highest quality factor (Fig. 3, curve 12). It can also be noted that tuning of the resonance frequency can be achieved by a change of the external field-orientation angle even if the field is not strong (see, e.g., curves 4 and 6 in Fig. 3, calculated for $\varphi = 0$ and $\varphi = \pi/2$, respectively).

Dependence of the resonance frequency of the CPW resonator on the external magnetic-field strength computed from (19) using the above initial parameters is shown in Fig. 4. It can be seen that the resonance frequency is shifted toward higher frequencies if $\mu_0 H_e < \mu_0 H_r = 45$ mT, whereas the converse is true for the case when $H_e > H_r$, as discussed above. In principle, the magnetic tuning behavior of the CPW resonators with a ferrite component is similar to that of the MS resonators. It can be shown that the tuning factor is maximum when the field is parallel to the central strip direction and the ferrite film is placed close to the resonator structure. Dependencies

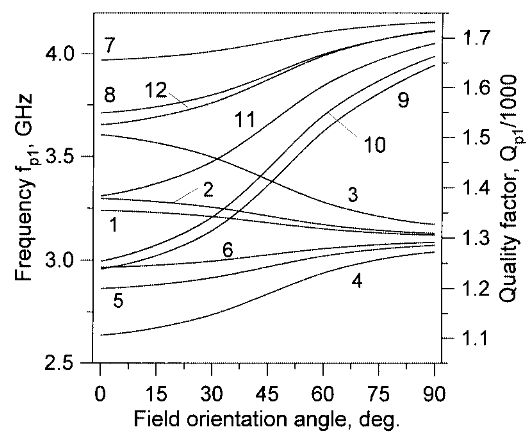

Fig. 5. Dependence of the resonance frequency (curves 1–6) and the quality factor (curves 7–12) of the CPW resonator on the field-orientation angle φ computed from (19) for the field strengths $B = 10, 20, 35, 55, 65, 80$ mT (curves 1–6, respectively, and curves 7–12, respectively).

of the resonance frequency f_{p1} and the quality factor Q_{p1} on the field-orientation angle calculated from (19) are shown in Fig. 5. The resonance frequency is more sensitive to the field strength and the field-orientation angle in the ferrimagnetic resonance region $H_e \sim H_r$ although, in this case, the resonator is characterized by a lower value of the quality factor (Fig. 5, curves 3 and 9). It can also be noted that f_{p1} and Q_{p1} versus φ dependencies for the angle ranges $0 < \varphi < \pi/6$ and $\pi/3 < \varphi < \pi/2$ are not so pronounced as for the angles $\pi/6 < \varphi < \pi/3$ (Fig. 5, curves 1–6).

Formulas (15) and (19) were obtained by taking into account only the spatially uniform ferrimagnetic resonance. However, the nonuniform magnetic field of the MW currents may lead to the excitation of magnetostatic waves (MSWs) in the ferrite [11], [12] and to an additional decrease of the quality factor of the resonator. It can also be noted that the characteristics of such HTS resonators can be destroyed at high levels of MW power as both the ferrite and HTS materials manifest strongly nonlinear characteristics in electromagnetic fields of high intensity [6], [16], [25].

V. Experiment and Discussion

The MS resonator structures of meander type were used for the experimental study of the magnetic tuning effect because of their small dimensions, which simplifies the problem of application of the tuning magnetic field. Structures containing a 30-μm-thick and 0.3-mm-wide copper MS meander line formed on a standard MW substrate ($\varepsilon = 2.44$), a 10-μm-thick epitaxial YIG film prepared on a 0.5-mm-thick GGG substrate, a 0.5-mm-thick $LaAlO_3$ spacer, and a copper ground plane were used in experiments performed at room temperature. The planar dimensions of all components were 5 mm $\times$ 5 mm. These components were clamped together to form the layered MS resonator structures with the ferrite film placed close to the strip (resonator 1: MW substrate/Cu–MS/YIG/GGG/$LaAlO_3$/Cu ground plane) or to the ground plane (resonator 2: MW substrate/Cu–MS/$LaAlO_3$/GGG/YIG/Cu ground plane). The magnetic field was applied parallel to the plane of the structure and was varied over angles $\varphi = 0$ and $\varphi = \pi/2$ with respect to the main part (about 70%) of the strip length in meander.

In the next experiment, a 0.24-μm-thick and 0.5-mm-wide YBCO MS meander line, prepared on a 5 mm $\times$ 5 mm $\times$ 0.5 mm $LaAlO_3$ substrate, was used together with the YIG ferrite component described above. The meander was formed using the photolithography and ion milling procedures from a YBCO film ($T_c \approx 89$ K, $J_c \approx 10^6$ A/cm^2 at $T = 77$ K) deposited by a laser ablation process. This MS resonator contained the following layers: YBCO–MS/$LaAlO_3$/YIG/GGG/Cu–ground plane (resonator 3). Measurements were made at 77 K in a magnetic field, which was parallel to approximately 60% of the MS line length.

The MS resonator structures were assembled into a cylinder-shaped measuring fixture with an outer diameter of 18 mm. The ends of 50-Ω semirigid coaxial lines were used to excite the resonator and to receive the transmitted MW signal. The fixture was placed between the poles of a small electromagnet and the field direction in the plane of the structure could be changed by turning of the fixture around its principal axis. The electromagnet could be sunk into the liquid nitrogen together with the fixture for measurement of the parameters of YBCO resonators at 77 K.

The measured transmission characteristics of resonators 1 and 2 are given in Figs. 6 and 7. Each of the measured responses, presented in Fig. 6, is characterized as exhibiting two different peaks. The external field is not strong, $H_e < H_r$, and, therefore, the peak appearing at low frequencies corresponds to that of the ferrimagnetic resonance, while the peak of the MS resonator appears at higher frequencies. A maximum sensitivity of the resonance frequency to the field strength is observed for the case when the ferrite film is placed close to the MS (resonator 1) and when the field is parallel to the main part of the strip length ($\varphi = 0$, Fig. 6, curves 1–3). The tunability of the same resonator is less (Fig. 6. curves 1, 4, and 5) when $\varphi = \pi/2$, which is in a qualitative accordance with the results of the calculations. The tunability factor was very small for resonator 2 with the ferrite film placed close to the ground plane for both cases of field orientation $\varphi = 0$, $\varphi = \pi/2$ (Fig. 7). This can be explained by the fact that the MW current direction is opposite in different sections of the meander and

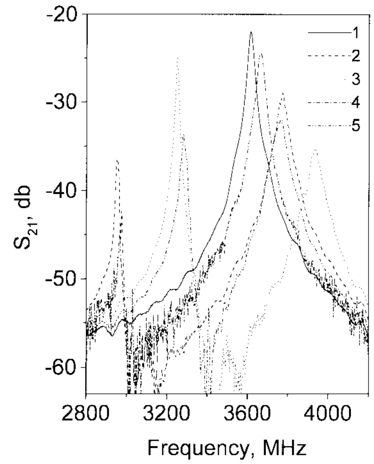

Fig. 6. Transmission characteristics of the Cu MS resonator 1 with a YIG component measured at room temperature. Magnetic field $B = 0$ mT (curve 1), 55 mT (curves 2 and 4), and 69 mT (curves 3 and 6) is applied parallel to the plane of the structure. The main part of the MS is parallel (curves 2 and 3) or perpendicular (curves 4 and 5) to the external field direction.

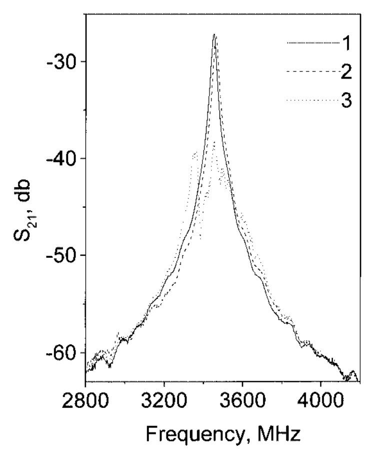

Fig. 7. Transmission characteristics of the Cu MS resonator 2 with a YIG component measured at room temperature. Magnetic field $B = 0$ mT (curve 1), 55 mT (curve 2), and 69 mT (curve 3) is applied parallel to the plane of the structure and perpendicular to the main part of the MS.

the magnetic fields of these sections are compensated at some distance from the strip, causing a decrease of the coupling efficiency of such a resonator with the ferrite layer placed near the ground plane. The measured quality factor of these Cu MS resonators was $Q \sim 100$, which is mainly determined by the MW losses in the copper electrodes at $H < H_r$ and was seen to decrease additionally at $H \sim H_r$ due to losses in the ferrite material.

The resonance frequency and quality factor of the YBCO MS resonator 3 measured without any external field were 4.68 GHz and 660, respectively (Fig. 8, curve 1). Increasing the magnetic field to 77 mT leads to an increase of the frequency to 4.76 GHz and to a decrease of the quality factor to 500 (Fig. 8, curve 2) The tunability of the resonator for such fields was approximately 8 MHz/mT. The tunability factor will be higher for cases of thicker ferrite layer and smaller distances between the MS line and ferrite component (in our case, these parameters were 10 μm and 0.5 mm, respectively). In the ferrimagnetic resonance region, the quality factor of

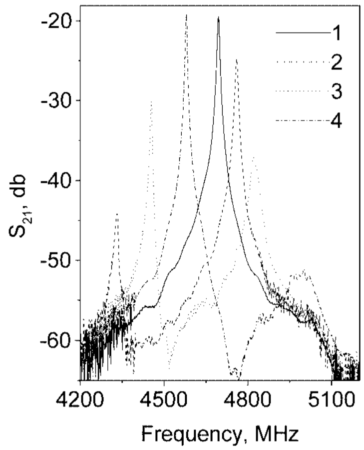

Fig. 8. Transmission characteristics of the YBCO MS resonator 3 of meander type with a YIG component measured at 77 K. The field $B = 0,\ 77,\ 85,\ 93$ mT (curves 1–4, respectively) is applied parallel to the plane of the structure and approximately 60% of the strip length is parallel to the field.

the resonator decreases strongly due to the MW losses of the ferrite film (Fig. 8, curve 3). The quality factor was higher (approximately 900, Fig. 8, curve 4) for the case when resonance frequency of the ferrite layer is higher than that of the resonator $f_{fm} > f_0$ (or $H > H_r$). However, such values of the quality factor were significantly smaller when compared with those measured for the same MS structure without any ferrite component (YBCO–MS/$LaAlO_3$/Cu–ground plane structure; $Q \geq 1600$ and $f_0 = 4.13$ GHz in parallel field $H \leq 100$ mT at $T = 77$ K). Additional MW losses could be caused by the substrate (GGG) of the ferrite film and by the surfaces of the different layers being in a mechanical contact with each other in the resonator structure. Such MW losses would be expected to be less in monolithic versions of the layered structure.

VI. Conclusion

In conclusion, the MW characteristics of HTS MS and CPW resonator structures containing a tangentially magnetized ferrite layer have been investigated using the perturbation method. The formulas, relating the resonance frequency and quality factor to the complex permittivity, permeability, and kinetic inductance of the layers of the structure have been obtained and analyzed. It has been shown that a maximum magnetic tuning effect of the frequency can be expected when the ferrite film is placed close to the strip and the field is oriented along the resonator $(\varphi = 0)$. Tuning of the resonance frequency of MS and CPW resonators can be performed by changing both the magnetic-field strength and the field-orientation angle. The conditions of obtaining a maximum tuning effect have been investigated in the example of a copper MS resonator, containing a YIG film component. Qualitative agreement of the experimental results with the calculated ones has been obtained. A version of a YBCO MS resonator with a YIG ferrite component has also been investigated and its transmission characteristics have been measured at 77 K.

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D. Dew-Hughes, photograph and biography not available at time of publication.