Superconducting Microstrip Resonator with Yttrium Iron Garnet Single Crystals

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***Abstract*—A magnetically tunable microstrip superconducting resonator using an yttrium–iron–garnet (YIG) single crystal was demonstrated experimentally. Tunability of 200 MHz at a center frequency of 5.3 GHz was observed, and a quality factor of 965 with minimum insertion loss of 19.5 dB was measured for a half-wavelength microstrip line consisting of a YIG–YBCO–MgO composite structure. The dispersion relation of the resonator was analyzed using the spectral-domain method and discussed with experimental results on the mixed states of TEM and magnetostatic-wave modes. Power dependence of the characteristics is also discussed.**

***Index Terms*— Ferrite, magnetically tunable resonator, microstrip line, YBCO, YIG single crystal.**

I. Introduction

Applications of high-temperature superconductors to microwave devices have been extensively studied by many workers to obtain ultra low-loss high-performance circuits and devices. Superconducting resonator structures of interest are microstrip-line resonators fabricated on dielectric MgO substrates and dielectric resonators with superconducting walls. Recently, little effort has been devoted to ferrite–superconductor composite devices such as circulators and phase shifters without significant conductor losses [1], [2] or to magnetically tunable filters using the vortex effect under weak magnetic fields [3]. The authors have studied for the first time a magnetically tunable superconducting microstrip-line filter using yttrium–iron–garnet (YIG) film grown epitaxially on a gadolinium–gallium–garnet (GGG) substrate, and discussed the magnetic loss of the YIG film on the GGG substrate, which significantly reduces the quality factor of the filter [4]. The GGG substrate is necessary to mechanically support and to epitaxially grow YIG film, but it is not necessity for bulk YIG single crystal.

This paper investigates magnetically tunable superconducting half-wavelength microstrip-line resonators using YBCO and bulk YIG single crystal, discusses the magnetically tunable characteristics of the resonators in experimental results, and presents calculated dispersion relation.

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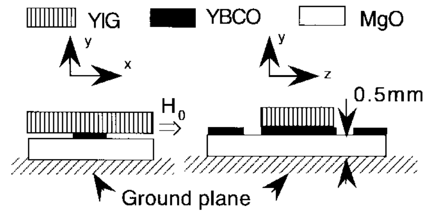

Fig. 1. Magnetically tunable superconducting half-wavelength microstrip line resonator.

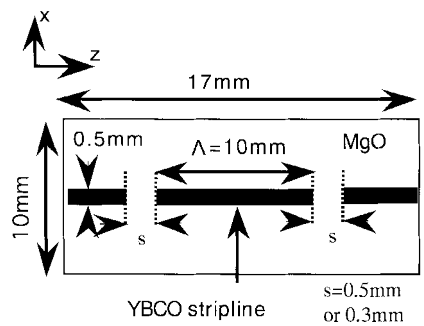

Fig. 2. Layout for a superconducting half-wavelength microstrip line resonator.

II. Experiment

Fig. 1 shows a superconducting microstrip-line resonator composed of sandwiched structures of MgO substrate with a YBCO $(YBa_2Cu_3O_7)$ circuit and YIG single crystal. The YIG single crystal was arranged on the YBCO strip to obtain strong interaction of RF fields with the superconductor [4]. A half-wavelength microstrip single resonator on 17 mm $\times$ 10 mm MgO substrates was designed with a 50-Ω characteristic impedance, 10-mm length, and 0.5-mm width. It was coupled with input and output lines with $s = 0.3$ and 0.5-mm capacitive gaps, as shown in Fig. 2. The YBCO grown by laser deposition is 6000-Å thick and has a T_C of 86 K [4], [5]. The YIG single crystal was used to achieve magnetically tunable resonator characteristics to change susceptibility using an applied dc magnetic field, and to eliminate the effect on the lossy GGG substrate, which reduces the quality factor [4]. The YIG is a 10 mm $\times$ 10 mm, 1 mm thick in (1 1 0) plane with a magnetic linewidth of $\Delta H = 1$ Oe at room temperature and at X-band. The YIG is the same length as the half-wavelength of the resonator, which is a typical YIG single crystal used for magnetostatic-wave devices [6].

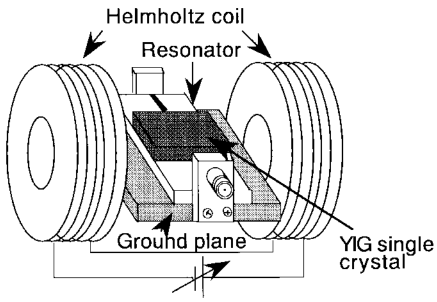

Fig. 3. Test structure with Helmholtz coil.

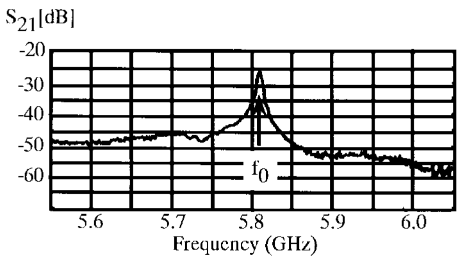

Fig. 4. Characteristics of superconducting half-wavelength microstrip resonators without the YIG.

The resonator test structure of Fig. 1 was shielded by aluminum foil to suppress the radiation loss arising from the discontinuities between the input–output terminals and the stripline.

The dc magnetic field was applied in the transverse direction to the wave propagation (as shown in Figs. 1 and 3) by a pair of Helmholtz coils of 300 turns each. Such a magnetic-field direction has less demagnetizing effect and strong interaction between the superconductor and surface-wave mode [4]. The magnetic-field intensity at the center of the coil was about 200 G per ampere. The test setup was then immersed into liquid nitrogen together with the Helmholtz coil.

Experiments were conducted in the frequency range from 5.55 to 6.05 GHz, and at the liquid-nitrogen temperature of 77 K. The resonator characteristics without the YIG were first examined to confirm the effect of the superconductor. The result is shown in Fig. 4. The loaded quality factor Q_L of 1050 and an insertion loss of −26 dB can be observed at the center frequency of 5.81 GHz for the capacitive air gap of 0.5 mm. This resonator quality factor is much lower than that of conventional superconducting resonators, which yield unloaded Q_U of 10^4 or more at 6 GHz, because the surface impedance of YBCO is about 100 $\mu\Omega$ at 4.2 K [5]. Hence, the low Q_L may be due to the imperfect suppression of the radiation mode resulting from discontinuities of the terminals.

Magnetic-field dependence on the superconducting resonator was confirmed experimentally. No significant changes of the center frequency or Q_L are observed for magnetic fields up to 10^3 G. However, for very weak magnetic fields (less than 1 G), a center-frequency change of about 1 MHz was observed due to the vortex effect of the YBCO [3].

The characteristics of the magnetically tunable resonator were next investigated by applying the YIG single crystal. Fig. 5 shows a typical frequency response of the microstrip-line resonator for the capacitive air gap of 0.5 mm, as a function of the dc magnetic field, up to 790 Oe. It can be seen from the figure that the center frequency f_0 can be tuned magnetically from 5.24 to 5.42 GHz, for a useful range of 200 MHz. Fig. 6 shows the magnetic-field dependence of f_0 and Q_L. The maximum Q_L of 965 can be read from the figure, which is close to the value of the resonator without YIG (Fig. 4). Thus, no significant increase of magnetic loss at 77 K was found, though such loss had been observed for the YIG film with the GGG substrate [4]. However, it has a high insertion loss of 20 dB. To reduce the insertion loss of the resonator, a resonator with a narrow capacitive gap (0.3 mm) was examined, as shown in Fig. 7. The magnetic field dependence of f_0 and Q_L of the resonator is similar to that of Fig. 6, but the insertion loss of the resonator at 77 K was 12 dB, with a maximum Q_L of 762. (The Q_L of a half-wavelength resonator using a copper microstrip line with a YIG film substrate was 166 at room temperature at 6.3 GHz.)

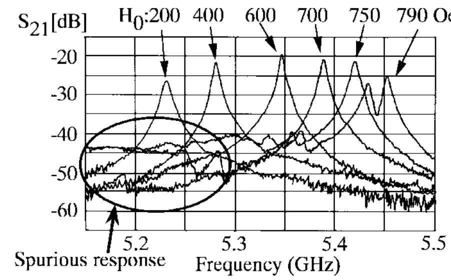

Fig. 5. Frequency response of the tunable resonator for a different magnetic field.

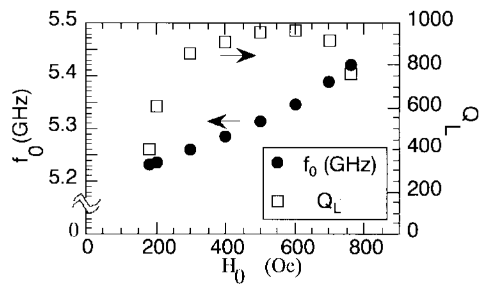

Fig. 6. Magnetic-field dependence of f_0 and Q_L for the resonator.

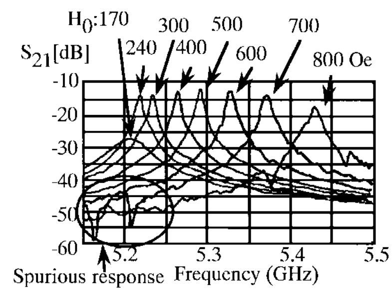

Fig. 7. Magnetic-field dependence of the resonator for a narrow capacitive air gap.

The high sensitivity of the resonator response to the magnetic field of 600 Oe of Figs. 6 and 7 may be due to the tight coupling between the electromagnetic field on the superconducting strip through direct contact between the YIG and YBCO. The magnetic tunability of the resonator is limited by the generation of the magnetiostatic-wave mode, as discussed in Section III.

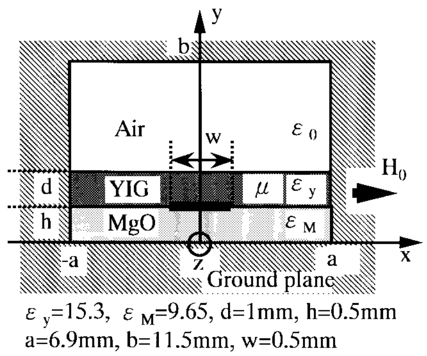

Fig. 8. Geometry of the microstrip line.

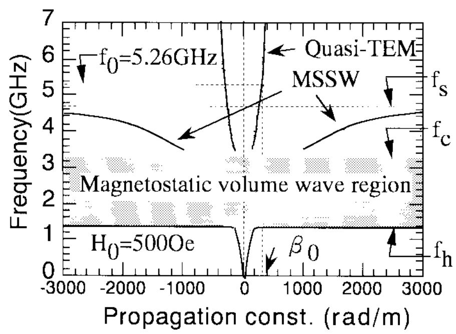

Fig. 9. Calculated dispersion curve of the line.

III. Discussions with Dispersion Relations

To compare the experimental results with theory, the dispersion relation of the microstrip line with a YIG–YBCO–MgO substrate was calculated by using the spectral-domain method [7], [8]. The exact analysis of the superconducting microstrip line with YIG is more complex. We assume the exact solution of the dispersion relation is derived for the TEM mode, and therefore, does not include the full spectrum of the magnetostatic-wave modes [8], [9]. We further assume the superconducting strip is a perfect conductor. Even if these assumptions are false, the fundamental characteristics of the line will be preserved [8].

The geometry of the problem, which consists of a YIG–MgO sandwich structure, is shown in Fig. 8. The line is surrounded with an electric wall having the dimensions $2a \times b$ to obtain the Fourier transform. The tensor susceptibility of the ferrite (YIG) is given by

$$\begin{aligned}
\hat{\mu} &= \mu_0 \begin{bmatrix} 1 & 0 & 0 \\ 0 & \mu & j\kappa \\ 0 & -j\kappa & \mu \end{bmatrix} \\
\mu &= 1 + \frac{\omega_h \omega_m}{\omega_h^2 - \omega^2} \\
\kappa &= \frac{\omega \omega_m}{\omega_h^2 - \omega^2} \\
\omega_h &= \gamma \mu_0 H_0 \\
\omega_m &= \gamma \mu_0 M_0 \\
\gamma &= 1.76 \times 10^{11}\ \mathrm{rad/(T \cdot s)} \\
4\pi M_0 &= 2350\ \mathrm{G} \quad (\text{at } 77\ \mathrm{K})
\end{aligned} \tag{1}$$

and the dc magnetic field is applied in the x-direction in Fig. 8 [8].

Helmholtz equations in the YIG region in the hybrid form, obtained from Maxwell's equation with (1), are given by

$$\begin{aligned}
&\frac{\partial^2}{\partial y^2}\tilde{E}_x - P\tilde{E}_x = Q\tilde{H}_x \\
&\frac{\partial^2}{\partial y^2}\tilde{H}_x - R\tilde{H}_x = S\tilde{E}_x \\
&P = \beta^2 + \hat{k}_n^2 - \omega^2 \varepsilon_y \mu_0 \mu_{ef} \\
&Q = j\hat{k}_n \omega \mu_0 \frac{\kappa}{\mu} \\
&R = \beta^2 + \frac{1}{\mu}\hat{k}_n^2 - \omega^2 \varepsilon_y \mu_0 \\
&S = -j\hat{k}_n \omega \varepsilon_y \frac{\kappa}{\mu} \\
&k_n = \frac{n\pi}{2a}, \qquad n\text{: integer.}
\end{aligned} \tag{2}$$

The solutions of (2) after Fourier transform are given by

$$\begin{aligned}
\tilde{E}_x &= F_+ + K_- F_- \\
\tilde{H}_x &= K_+ F_+ + F_- \\
F_+ &= A \sinh \gamma_+ y + B \cosh \gamma_+ y \\
F_- &= C \sinh \gamma_- y + D \cosh \gamma_- y \\
K_+ &= \frac{S}{\gamma_+^2 - R} \\
K_- &= \frac{Q}{\gamma_-^2 - P} \\
\gamma_\pm^2 &= \frac{1}{2}\left(-Y \pm \sqrt{Y^2 - 4Z}\right) \\
Y &= -P - R \\
Z &= PR - QS
\end{aligned}$$

where $\tilde{}$ denotes the Fourier transform.

Boundary conditions, including current distributions in the strip, together with fields in the air and MgO regions, lead to an eigenvalue equation in the form of the Green's function. The dispersion relation was derived through

$$\left[\begin{array}{ccc|ccc}
K_{11}^{xx} & \cdots & K_{1I}^{xx} & K_{11}^{xy} & \cdots & K_{1J}^{xy} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
K_{I1}^{xx} & \cdots & K_{II}^{xx} & K_{I1}^{xy} & \cdots & K_{IJ}^{xy} \\
\hline
K_{11}^{yx} & \cdots & K_{1I}^{yx} & K_{11}^{yy} & \cdots & K_{1J}^{yy} \\
\vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\
K_{J1}^{xx} & \cdots & K_{JI}^{xx} & K_{J1}^{xy} & \cdots & K_{JJ}^{xy}
\end{array}\right]
\begin{bmatrix} a_1 \\ \vdots \\ a_I \\ b_1 \\ \vdots \\ b_J \end{bmatrix} = 0 \tag{3}$$

where a_i, b_j are the unknown coefficients. Thus, a nontrivial solution of the matrix $\boldsymbol{K}$ reduces to the dispersion relation.

Fig. 9 shows the typical dispersion curve calculated numerically from (3) for an applied magnetic field of 500 Oe.

There are two branch modes in the dispersion curve depicted in Fig. 9. One is the TEM mode, which is the main mode of the line. The other is the magnetostatic surface-wave (MSSW) mode for the frequency domain between $f_c = \gamma\mu_0\sqrt{H_0(H_0 + M_0)}/2\pi$ and $f_s = \gamma\mu_0(H_0 + M_0/2)/2\pi$. The latter exhibits weak nonreciprocities and a magnetostatic

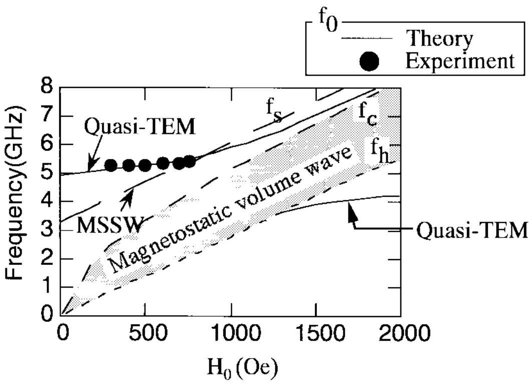

Fig. 10. Magnetic-field dependence of dispersion curve for fixed propagation constant $\beta_0 = \pi/10$ mm.

backward-volume wave (MSBVW) mode, which radiates the wave in the dc magnetic-field direction of x [8]. From another point of view, the microstrip line with YIG proposed here operates as a magnetostatic-wave transducer [8], [9]. However, this is beyond the scope of this paper. Therefore, this dispersion curve of MSBVW between $f_h = \gamma\mu_0 H_0/2\pi$ and f_c is not given.

The resonance frequency f_0 can be estimated by choosing point β_0 in Fig. 9; half-wavelength $\Lambda = 10$ mm $= \pi/\beta_0$ on the curve. The f_0 of 5.26 GHz at 500 Oe can be read from the figure at point β_0 and corresponds to the experimental value of 5.31 GHz at 500 Oe of Fig. 6.

We can discuss the magnetic tunability of the resonator by rewriting the dispersion curve of Fig. 9 as a curve with a fixed propagation constant $\beta_0 = \pi/\Lambda$ and changing the applied magnetic field, as shown in Fig. 10. The experimental results of Fig. 6 are also plotted in Fig. 10.

From the dispersion curves of Figs. 9 and 10, it is found that the spurious responses, along with resonance in Figs. 5 and 7, are the frequency responses of the MSSW mode [9]. This mode will degrade the resonator response in the configuration discussed here. Thus, experimental results agree well with theory.

In the experiments, the effect of the YIG on Q_L with magnetic loss ΔH was not found at 77 K. This may be a negligible effect on the temperature dependence of the magnetic linewidth ΔH for the pure YIG crystal. However, to develop resonance characteristics, the YIG slab should be less than 1-mm thick, considering the reduction of radiation loss due to the discontinuity of the strip line.

Finally, we measured the power dependency of the resonator with YIG at 77 K, as shown in Fig. 11, for different air gaps s in the strip-line resonator of Fig. 2. It can be seen from the figure that the resonator input power can significantly reduce Q_L. The saturation level is -10 dB, which is a considerably lower power level than for the case without YIG [5], as by open circles. This may be attributed to the nonlinear effect of the YIG single crystal.

IV. Conclusion

Magnetically tunable superconducting single resonators using YIG single crystal have been demonstrated. A tunability of 200 MHz with maximum Q_L of 965 has been achieved for a half-wavelength microstrip line in which a YIG single crystal is put onto the superconducting strip. The dispersion relation for the experimental result was briefly discussed with the theory on mixed solutions of TEM and magnetostatic-wave modes, and agreed well with the predicted value. Tuning range of the resonator was about 3.7% at 5.4 GHz, but this can be further enhanced approximately 28% by changing the magnetic-field direction [10].

To develop the resonator characteristics further, the discontinuity problems between YIG and the microstrip line should be investigated, and temperature dependence of the magnetic loss of the YIG should be studied. As a result, a superconducting filter using a YIG single crystal was developed and exhibited better magnetic tunable characteristics than the YIG film.

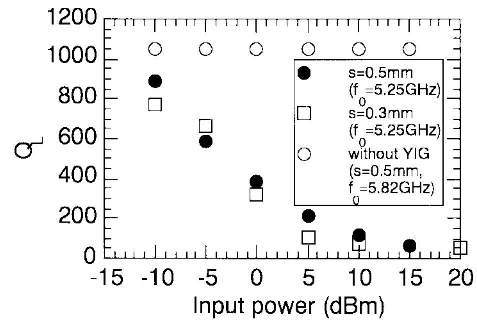

Fig. 11. Power dependence of the resonator at 77 K.

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