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HTS Surface Wave Resonators

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A novel class of surface wave high-temperature superconductivity (HTS) resonators was investigated. The resonator consists of HTS film and one or two dielectric plates. One of the dielectric plates may be the HTS film substrate. Theoretical analysis of the resonator structure was carried out using the partial region method, with the 20 lowest waves being considered in every region. The resonant frequencies, quality of oscillations, and the field and current distributions were calculated. It was shown that there is a high-density and homogeneous microwave current flowing on the film surfaces. Experimental measurements carried out in the 3-cm wavelength range demonstrate good agreement with simulated data.

KEY WORDS: High temperature superconductivity (HTS); microwave resonator; surface impedance; surface wave.

1. INTRODUCTION

One of the first practical applications of high temperature superconductors (HTS) is in microwave passive devices [1,2]. For this purpose, devices are typically constructed from various forms of coupled microstrip resonators. On the other hand, the parallel-plate resonators are the usual alternatives used to investigate the fundamental physical parameters of the HTS films. In either case, high quality factor Q is essential, and two superconducting films are often required simultaneously. This has inevitably complicated both the fabrication and measurement processes. Especially, when working in the high-frequency part of the millimeter waveband the increasing level of designing difficulties and losses in the input microstrip and coaxial circuits can be critical.

For these reasons we have elaborated a new type of resonators using only one single metallic (or HTS) film. These resonators operate on the surface waves running along the metal. That can be surface waves running along a solitary metallic surface with a finite conductivity (Zennek wave) or along metal (even ideal) covered with dielectric [3]. First investigated by Zommerfeld, nowadays, surface electromagnetic waves are widely used in integrated optics, such as surface plasmons, and waves of image waveguide [3,4]. A feature of these waves is the high electromagnetic field intensity and, as a consequence, the high current density near the conducting surface [3].

The simplest surface wave resonators consist of a metallic rod or plate in a free space or in an empty waveguide [5]. Here, we investigate the more complicated resonance structure as shown schematically in Fig. 1. As can be seen in Fig. 1, resonator consists of metallic (HTS) film and two dielectric plates. One of the two plates may just be the substrate used to deposit HTS films. The length (along y) and the width (along z) of the resonator are l and w, respectively. The widths of the dielectric plates are d_1 and d_2 with permeabilities of ε_1 and ε_2, respectively. The film thickness h is assumed to be $h \ll d_1, d_2, l$, and w. The dimension of the rectangular waveguide is $a \times b$, and δ_1, δ_2 are the distances between the resonator and lower or upper broad waveguide walls, respectively. In general, the angle φ between the film plate and the broad waveguide walls is not equal to 90°, as it is in Fig. 1.

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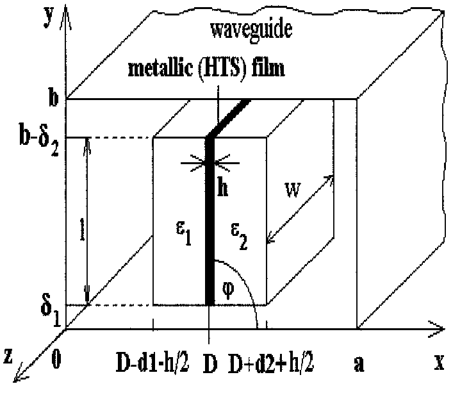

Fig. 1. Schematics of resonator in waveguide with $\varphi = 90°$ (i.e., the film plane is perpendicular to broad waveguide walls).

For $d_1 = d_2 = 0$, we have the known case of the metallic plate in a waveguide or in a free space ($a = b = \infty$). The fundamental resonance wavelength λ_r in the last case is approximately twice of the plate length l: $\lambda_r \approx 2l$ ($\lambda/2$-resonator). For $d_1 = d_2 = \delta_1 = 0$, it becomes a $\lambda/4$-resonator with $\lambda_r \approx 4l$[5]. To our knowledge, however, the general case of metallic film with dielectric plates (Fig. 1) has never been investigated.

In this paper, the fundamental oscillation mode of the resonance structure shown in Fig. 1 is studied. We show that in this mode, the microwave currents flow primarily in the metallic film along the y direction. The resonance frequency is mainly determined by dimension l (along y), and dimension w (along z) is significant only when $w \ll l$. That is, the fundamental mode of resonance is formed by spreading the planar quasi-uniform wave along y. Because of their close similarities in field distributions, this mode is easily excited by the fundamental wave of rectangular waveguide H_{10}. The characteristics of high microwave current density and homogeneity also make this mode of excitation very perspective in devices using array of Josephson junctions (e.g., Josephson generator). In addition, the fundamental mode can also be used for measuring of the complex conductivity, surface impedance, pinning, and viscosity of the vortices and the like. The ease of resonance excitation combines with relatively easy fabrication (in fact, surface wave resonator is a HTS film on the substrate in an empty waveguide) makes it a very attractive alternative for microwave filters operated in millimeter wave range. It is also a much simpler structure to combine with ferrite films to obtain tunable microwave filters.

2. THEORY

To calculate the fields, the current distribution, the natural frequencies, and quality factor Q of the resonator, we used the partial region method [6]. First, the eigenwaves of the loaded infinite ($w = \infty$) waveguide were determined. For this purpose the waveguide was divided into four partial regions:

I. $0 < x < a,\ 0 < y < \delta_1$;
II. $0 < x < a,\ b\text{-}\ \delta_2 < y < b$;
III. $0 < x < D,\ \delta_1 < y < b\text{-}\ \delta_2$;
IV. $D < x < a,\ \delta_1 < y < b\text{-}\ \delta_2$.

The expansion of the eigenwave electromagnetic fields in terms of the LM and LE waves of empty waveguide was used. The 20 lowest waves were considered in every region. The tangent components of electrical $\vec{E}$ and magnetic $\vec{H}$ fields were equaled on borders of areas to obtain the fields and the wavenumbers of the eigenwaves of the loaded infinite waveguide. With the presence of the HTS films, it was assumed that the ratio between the tangent components of the electric E_τ and magnetic H_τ fields at $x = D \pm h/2$ was defined by the HTS film thickness and its surface impedance Z_S [7] and can be expressed as:

$$\frac{E_\tau}{H_\tau} = Z_S\, cth\left(\frac{h}{\tilde{\lambda}}\right). \tag{1}$$

where the surface impedance of the bulk HTS Z_S is defined as

$$Z_S = R_S + jX_S = j\omega\mu_0\tilde{\lambda} = \frac{j\omega\mu_0\lambda_L}{\sqrt{1 + j\omega\mu_0\sigma_n\lambda_L^2}}. \tag{2}$$

The parameters $\lambda_L = \lambda_L.\ (t)$ and $t = T/T_c$ are the London penetration depth and reduced temperature, respectively. Empirically, the temperature dependence of λ can be approximately described by

$$\left(\frac{\lambda_L(0)}{\lambda_L(t)}\right)^2 = 1 - t^\gamma. \tag{3}$$

For $YBa_2Cu_3O_{7\text{-}\delta}$ (YBCO) films, the normal state conductivity σ_n appeared in Eq. (2) can further be approximated as [8]:

$$\sigma_n(t) = \sigma_n(1)(t^{\gamma-1} + \alpha(1 - t^\gamma)). \tag{4}$$

Where $\sigma_n(1)$ is the conductivity at $T = T_c$ and α is an empirical parameter to be determined. Thus, there are five film parameters (T_c, $\lambda_L(0)$, $\sigma_n(1)$, γ, and α), depending on the film quality, remaining to be determined experimentally.

Next we analyze the resonator characteristics by dividing the infinite loaded waveguide into three partial regions along z, namely,

I. $z > 0$;
II. $-w < z < 0$;
III. $z < -w$.

The tangential components of electrical and magnetic fields were again equaled on borders of areas. The fields in the first and the third regions were expanded in the empty waveguide wave fields. The fields in the second region were expanded in the eigenwave fields of loaded waveguide. The resonant frequencies of such resonator and the field distributions were then calculated. As an example, in Fig. 2 the calculated dependence of resonant frequencies F_r of the metallic plate in the center of rectangular (10×23 mm^2) waveguide on its width is shown. For comparison, the experimental data are also plotted in the same figure. The results demonstrate good agreement between measured and simulated data.

It is seen that there are the fundamental mode (I) and the higher-order modes (II–IV), in which currents flowing in the z direction. The resonant wavelength of fundamental mode $\lambda_r = c/F_r$ (c is the velocity of light) can be approximately represented, in this case, as $\lambda_r = 2(l + \Delta)$. Where Δ is determined by the fields outside the resonator. In the case of no dielectrics, we have as $w \to 0$, $\Delta \to 0$, and as $w \to \infty$, $\Delta \approx 5.5$ mm. Whereas in the case of resonator with dielectric plates, the resonant wavelength becomes $\lambda_r = 2(l_\varepsilon + \Delta_\varepsilon)$ with conditions of: $l_\varepsilon = l/\sqrt{\varepsilon_{eff}}$; $\varepsilon_{eff} = \varepsilon(d_1, d_2, \varepsilon_1, \varepsilon_2)$ effective dielectric permeability, $1 < \varepsilon_{eff} < \max\{\varepsilon_1, \varepsilon_2\}$; and $\Delta_\varepsilon = \Delta(l_\varepsilon, w)$, $\Delta_\varepsilon < \Delta$.

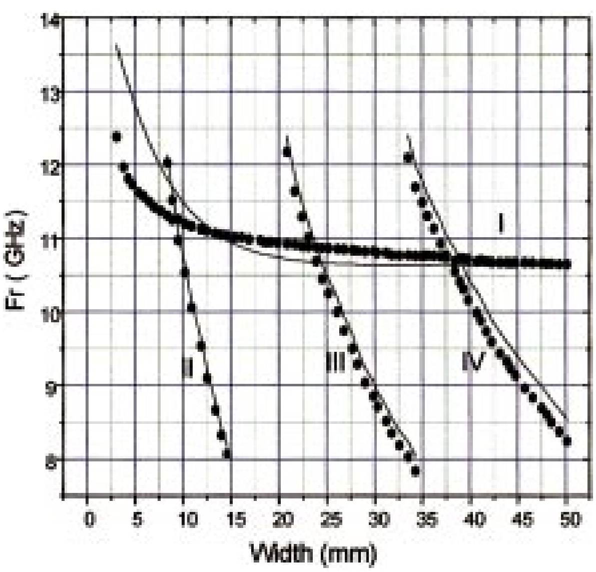

Fig. 2. Resonant frequencies of copper film, without dielectrics, locates at the center of the standard 3-cm band rectangular waveguide with $l = 8.8$ mm, $\varphi \approx 0$. (Solid line, theory; dots, experiment).

The unloaded Q factor of the surface wave resonator was calculated by the following expression;

$$\frac{1}{Q_0} = \frac{1}{Q_S} + \frac{1}{Q_d} \tag{5}$$

where Q_s is the Q factor owing to losses in the 6 metallic surfaces $S = \Sigma_{i=1}^{6} S_i$: (i.e., in the two narrow and two broad waveguide walls and in the both HTS film surfaces), and Q_d is due to the losses in dielectrics. The following formula were used for calculating the respective Q factors

$$\frac{1}{Q_S} = \sum_{i=1}^{6}\frac{1}{Q_{S_i}};\ Q_{S_i} = \frac{2\pi F_r W}{P_{S_i}};\ Q_d = \frac{2\pi F_r W}{P_d}. \tag{6}$$

The quantities appearing in the above expressions are energy of the system W, the power losses in the ith metallic surface P_{S_i} the total power losses in the metallic walls $P_S = \Sigma_{i=1}^{6}\ P_{S_i}$, the power losses in both dielectrics P_d, and the total absorbed power in the resonator $P = P_S + P_d$, respectively. They are further calculated by

$$W = \int_0^a dx \int_0^b dy \int_{-\infty}^{+\infty} dz \left\{\frac{\varepsilon\varepsilon_0}{4}\vec{E}^2 + \frac{\mu_0}{4}\vec{H}^2\right\}; \tag{7}$$

$$P_d = \int_{V_d}\!\!\int\!\!\int \tan\delta \times \frac{\varepsilon\varepsilon_0}{4} \times \vec{E}^2\, dV; \tag{8}$$

$$P_{S_i} = \frac{1}{2}\int_{S_i}[\vec{E}_\tau \times \vec{H}_\tau]d\vec{S} \tag{9}$$

where V_d is the volume occupied by the dielectrics and $\tan\delta$ is the loss tangent of the dielectrics.

The simulated distribution of the microwave current density I in the HTS film under the action of the absorbed power of $P = 1$ mW is shown in Fig. 3. The values are determined by the tangential component of magnetic field H_τ on the film surfaces. It is immediately apparent that the current distribution is far more homogeneous in the present surface resonator than in the case of the microstrip resonator [8]. One further peculiarity of the microwave surface wave resonator to be noted is the high current densities in the HTS films resulted from the electromagnetic field concentrating nearby conducting surfaces. Both of these unique characteristics suggest the use of HTS surface wave resonators in the devices with Josephson junction array. The larger the resonator

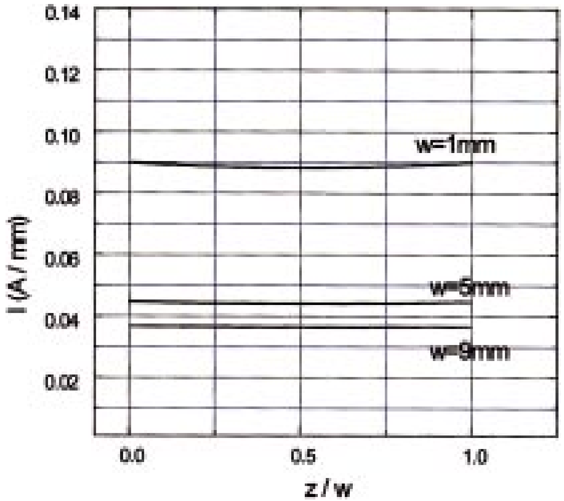

Fig. 3. The distribution of the microwave current density in the HTS film under the action of the absorbed power $P = 1$ mW; $l = 8.8$ mm, $R_s = 0.5$ mΩ, $a = 23$ mm, $b = 10$ mm, $\varphi = 90°$; $\varepsilon_1 = 25$, $\varepsilon_2 = 9.8$, $D = 11.5$ mm, $d_1 = d_2 = 0.5$ mm.

width w, the smaller the current density inhomogeneity, and hence the larger total current can flow in the structure. For instance, with $w = 9$ mm and $l = 8.8$ mm, we obtain I(z = 4.5 mm)/I(z = 0) = I(z = 4.5 mm)/I(z = 9 mm) = 0.993 and the total current is 0.34 Å per 1 watt of the absorbed power (see Fig. 3).

3. EXPERIMENT AND RESULTS

We have investigated microwave surface wave resonators made from pure copper and YBCO films grown on single crystalline $LaAlO_3$ substrates. The dimensions of the substrates are $l = 10$ mm, $w = 5$ mm or $w = 10$ mm, and $d_1 = 0.5$ mm (see Fig. 1), respectively. The YBCO films were about 0.4 μm in thickness. The $LaAlO_3$ substrate, having a permeability of $\varepsilon_1 = 25$, served as one of the dielectrics in the surface wave resonator. The temperature dependence coefficient of ε_1 was less than 1.6×10^{-3} over the temperature range from 50–100 K, as was confirmed by investigating the surface wave resonator with copper films. The second dielectric was sapphire with $\varepsilon_2 = 9.8$ and $d_2 = 0.5$ mm or $d_2 = 1.0$ mm, respectively. Measurements were also conducted without the second dielectric (i.e., $d_2 = 0$ and $\varepsilon_2 = 1$) in some cases.

The YBCO films used in this study were deposited on $LaAlO_3$ by pulsed laser deposition. The laser source was a KrF excimer laser operated at 248 nm with an energy density of about 2.5 J/cm^2 and a repetition rate of 5 Hz. During deposition the substrate temperature was kept at 840°C (as determined by an infrared pyrometer and the actual temperature was in the vicinity of 750°C) to within 1°C. The oxygen pressure was kept at 0.28 torr. Details of the deposition conditions and system setup can be found in [9]. The films obtained were all highly c-axis oriented with an in situ superconducting transition temperature around 90 K.

In this work, we report the temperature dependencies of the fundamental mode frequency F_r and the quality factor Q of the HTS surface wave resonator. Both F_r and Q were measured at a fixed temperature by the standing wave coefficient technique [10]. To increase the measurement precision, F_r was measured using match-terminated waveguide. To obtain such purpose, the matching load was located beyond the resonator (at $z < -w$; see Fig. 1). Furthermore, to optimize the coupling between the resonator and the waveguide, the angle φ between film plane and broad walls of waveguide (see Fig. 1) has to be small, practically $\varphi \leq 10°$. Indeed, it was evident that when the above conditions were fulfilled, the resonance curve was extremely narrow and sufficiently high. To measure Q the critical coupling was fixed with short-circuit plunger beyond the resonator in place of matched load. This method is unsuitable for frequency measurements owing to frequency pulling. The measurement precision of Q and F_r was better than 10% and 20 MHz, respectively.

The typical results of F_r (T) and $Q(T)$ obtained from the present HTS surface wave resonator situated in a standard 3-cm rectangular waveguide are shown in Fig. 4 and Fig. 5, respectively. For comparison, the theoretical curves of F_r (T) and $Q(T)$ obtained by using the above described model and appropriate parameters are displayed in the same figures. The parameters used for obtaining the theoretical curves were the critical temperature T_c, London penetration depth at 0 K, $\lambda(0)$, normal conductivity at $T = T_c$, $\sigma(1)$, exponent γ and residual resistance rate α. The T_c values of the YBCO films were determined by the standard four-probe transport measurements performed on control samples made in the same deposition run. The $\lambda(0)$ value was inferred from previous stripline resonator measurement [11,12]. The remaining parameters were determined by measuring the surface resistance R_s. These measurements were made at a frequency of 67 GHz by replacing the copper end face of a cylindrical cavity resonator with vibration of H_{011} type by an HTS

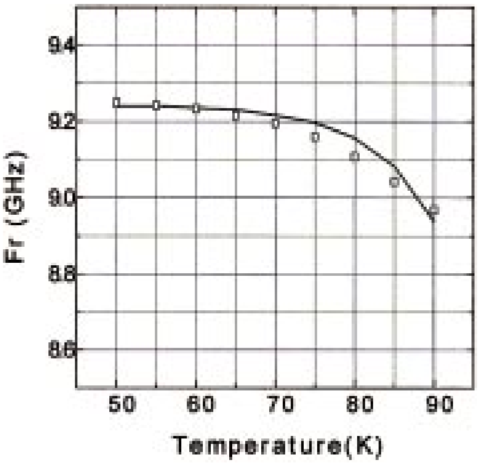

Fig. 4. Measured (squares) and simulated (line) dependence of resonant frequency of the HTS surface wave resonator on temperature in case l = 10 mm, w = 5 mm, $d_1 = d_2$ = 0.5 mm; h = 0.4 μm, ε_1 = 25, ε_2 = 9.8, φ = 11°, T_c = 91 K, $\lambda_L(0)$ = 0.2 μm, $\sigma_n(1) = 1.5 \cdot 10^6\ (\Omega \cdot \mathrm{m})^{-1}$, γ = 4, α = 15.

film [13]. By adjusting $\sigma(1)$, γ, and α for each film, the best fit between Eqs. (1)–(4) and the experimental data were obtained. Figure 6 shows the results of fitting the simulated curve $R_s(T)$ to the experimental data shown in Figs. 4 and 5 with T_c = 91 K, $\lambda(0)$ = 0.2 μm [12], $\sigma_n(1) = 1.5 \times 10^6\ (\Omega \times m)^{-1}$, γ = 4, and α = 15, respectively. As can be seen in Fig. 6, the data were better described in the lower temperature region. However, if we use $\lambda(0)$ = 0.4 μm observed in the more granular films [11], the fit (not shown here) describes the high-temperature data better. The apparent discrepancy reflects that the classical two-fluid model may have been inadequate to account for the behaviors over the whole temperature range. Indeed, the effects of d-wave symmetry of the HTS order parameter have been found to result in a variety of peculiar microwave properties [14,15]. Nevertheless, we note that the general agreement demonstrated here is indicative of the viability of the present technique.

It is noted that the shift of the resonant frequency F_r, caused by changes of surface reactance X_s, can reach several hundred MHz over a temperature span of 40 K (see Fig. 4). The technique thus provides a useful and convenient alternative for studying the microwave properties of HTS films. Most recently, up to ~600 MHz frequency shift has been obtained on films having better R_s; R_s(70 K) = 21 mΩ as compared to R_s(70 K) = 29 mΩ for films shown in Figs. 4–6.

The quality Q of the HTS resonator (Fig. 5) at T < 70 K was determined predominantly by losses in the copper walls of the waveguide. Higher Qs are expected by using thicker dielectric plates with higher dielectric permeability and by placing resonator into an over-sized waveguide. The maxi-

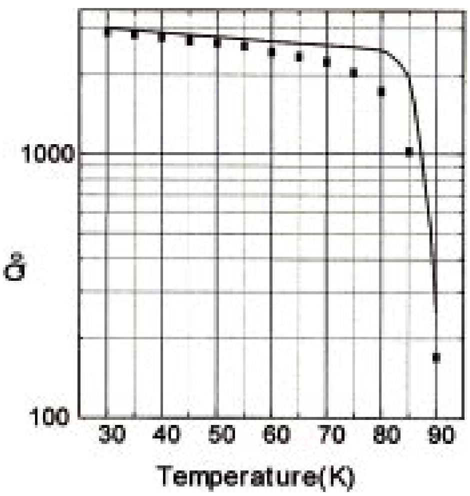

Fig. 5. Measured (squares) and simulated (line) temperature-dependent Q factor of the HTS surface wave resonator. The fitting parameters are the same as those used in Fig. 4.

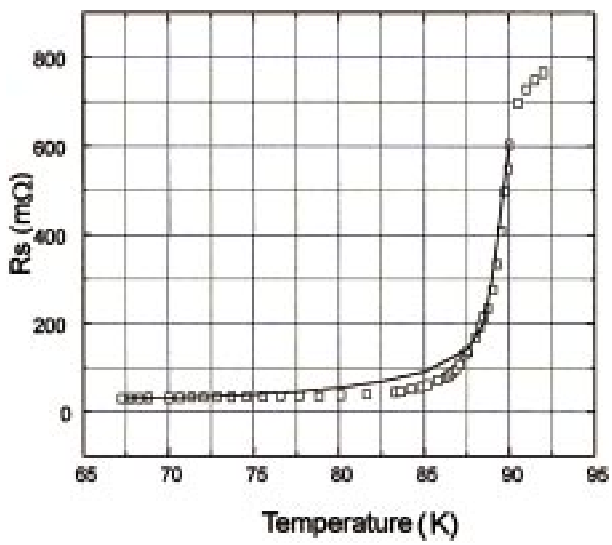

Fig. 6. Measured (squares) and simulated (line) temperature dependence of the surface resistance of the surface resonator YBCO film. The fitting parameters are the same as those used in Figs. 4 and 5.

mum theoretical Q value for $R_s = 0.5$ mΩ is equal to $\sim 8 \times 10^4$.

4. CONCLUSION

A new type of microwave resonators operated based on the surface wave running along a HTS film was investigated. The resonator consists of HTS film and one or two dielectric plates. One of the dielectric plates may just be the substrate used for depositing HTS films. Theoretical analysis of the resonator structure was carried out using the partial region method, with the 20 lowest waves being considered in every region. It was found that the fundamental resonant mode was derived from spreading along the HTS film the planar quasi-uniform surface wave. As a consequence, there is a high-density and homogeneous microwave current flowing on the film surfaces. This mode is easily excited in an empty waveguide. The resonant frequencies, quality of oscillations, and the field and current distributions were calculated.

The above theory was tested by experiments carried out in the 3-cm wavelength range. The results demonstrate good agreement between measured and simulated data. There are two main peculiarities of the microwave surface wave resonators. First, they are simple in structure. Second, high current density and homogeneity in the HTS film can be obtained intrinsically. Therefore these resonators can be potentially used in devices with Josephson junction array, for measuring the microwave properties of the HTS films, and in the tunable microwave filters, especially at mm range waveband.

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REFERENCES

1. M. J. Lancaster, *Passive Microwave Device Applications of High Temperature Superconductors* (Cambridge University Press, Cambridge, 1997).
2. J. Gallop, *Supercond. Sci. Technol.* **10,** A120 (1997).
3. M. J. Adams, *An Introduction to Optical Waveguides* (John Wiley and Sons, Chichester, New York, Brisbane, Toronto, 1981).
4. Y. R. Shen, *The Principles of Nonlinear Optics* (John Wiley and Sons, Chichester, New York, Brisbane, Toronto, 1981).
5. L. Lewin, *Advanced Theory of Waveguides* (Butterworth, London, 1975).
6. R. F. Harrington, *Field Computation by Moment Method* (Macmillan, New York, 1968).
7. M. W. Coffey and J. R. Clem. *Phys. Rev. B.* **17,** 9872 (1992).
8. O. G. Vendik, I. B. Vendik, and D. I. Kaparkov, *IEEE Trans. MTT* **5,** 469 (1998).
9. K. H. Wu, R. C. Wang, S. P. Chen, H. C. Lin, J. Y. Juang, T. M. Uen, and Y. S. Gou, *Appl. Phys. Lett.* **69,** 421 (1996).
10. E. L. Ginston, *Microwave Measurements* (McGraw-Hill, New York, Toronto, London, 1957).
11. M. C. Hsieh, T. Y. Tseng, S. M. Wei, C. M. Fu, K. H. Wu, J. Y. Juang, T. M. Uen, and Y. S. Gou, *Chin. J. Phys.* **34,** 606 (1996).
12. J. C. Booth, J. A. Beall, D. A. Rudman, L. R. Vale, R. H. Ono, C. L. Holloway, S. B. Qadri, M. S. Osofsky, E. F. Skelton, J. H. Claassen, G. Gibson, J. L. MacManus-Driscoll, N. Malde, and L. F. Cohen, *IEEE Trans. Appl. Supercond.,* (in press).
13. G. A. Melkov, A. L. Kasatkin, and V. Y. Malyshev, *Low Temp. Phys.* **9,** 680 (1994).
14. H. Srikanth, B. A. Willemsen, T. Jocobs, S. Sridhar, A. Erb, E. Walker, and R. Flükiger, *Phys. Rev. B.* **55,** R14733 (1997).
15. S. Kamal, R. Liang, A. Hosseini, D. A. Bonn, and W. N. Hardy, *Phys. Rev. B.* **58,** R8933 (1998).