Simplified Method for Measurements and Calculations of Coupling Coefficients and Q_O Factor of High-Temperature Superconducting Dielectric Resonators

Mohan V. Jacob, *Member, IEEE*, Janina Mazierska, *Senior Member, IEEE*, Kenneth Leong, *Member, IEEE*, and Jerzy Krupka, *Senior Member, IEEE*

***Abstract*—To accurately determine the surface resistance of high-temperature superconducting films, multifrequency measurements of S_{21}, S_{11}, and S_{22} and sophisticated data processing are required. As a result, surface resistance measurements and calculations for varying temperatures are very time consuming. In this paper, we introduce a simplified method for calculations of the unloaded Q (Q_o) factor, which require measurements of S_{11} and S_{22} at the lowest temperature only. For all other temperatures, only S_{21} measurements are needed. The method has been shown to give sufficiently accurate Q_o values and, hence, the surface resistance of superconducting samples, as compared to results obtained from S_{21}, S_{11}, and S_{22} measurements using the transmission-mode Q factor technique. The presented method has been tested under different coupling coefficients and frequencies.**

***Index Terms*—Dielectric resonator, high-temperature superconductors, surface resistance.**

I. Introduction

CRYOGENIC electronics is a fast growing branch of modern electronics especially since the discovery of high-temperature superconductors (HTSs) that allowed for significant reduction of losses and noise figures in filters and microwave oscillators. The quality of HTS films at microwave frequencies is assessed on the basis of surface resistance of the material. It is well known the surface resistance cannot be measured directly and is calculated from the loss equation of a resonating structure containing HTS films under test.

Different types of microwave resonators have been employed for measurements of surface resistance of HTSs such as a metallic cavity [1], microstrip [2], parallel plate [3], confocal [4], and dielectric rod resonators [5]. Dielectric resonators are known to provide high accuracy and sensitivity in wide range of temperatures and frequencies [6]. There are two types of dielectric resonators used for HTS microwave characterization: Hakki–Coleman (H–C) and open-ended resonators. The H–C structure consists of a dielectric rod sandwiched between two superconducting samples enclosed by a metallic cavity, which is schematically presented in Fig. 1. When a low-loss dielectric rod is employed, the total loss of the resonator depends mainly on the loss in the superconducting material. Surface resistance of HTS films, i.e., R_{SS}, is found from the loss equation [7]

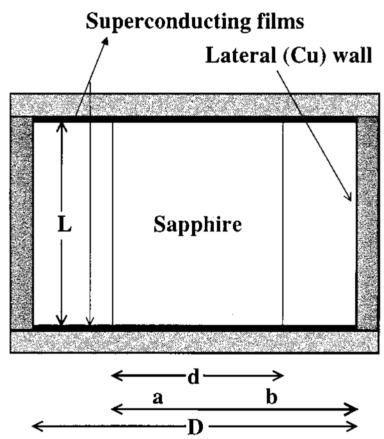

Fig. 1. Schematic diagram of the sapphire dielectric resonator.

$$R_{SS} = A_S\left(\frac{1}{Q_0} - \frac{R_{SM}}{A_M} - \rho_e \tan\delta\right) \tag{1}$$

where Q_o is the unloaded Q factor, A_S and A_M are the geometric factors of the superconducting endwalls and the lateral copper wall, R_{SM} is the surface resistance of copper, ρ_e is the energy filling factor, and $\tan\delta$ is the loss tangent of the dielectric material used (typically sapphire). The unloaded Q_0 factor is calculated from measured S-parameters of the resonator. The H–C type of resonator working in the transmission mode is currently under consideration as a standard test fixture for microwave characterization of HTS materials by the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronic Engineers (IEEE).

The accuracy of surface resistance measurements depends strongly on the accuracy of measurements and calculations of the unloaded Q_o factor of the resonator. For a very low coupling of the resonator, the unloaded Q_o factor can be assumed to be equal to the loaded Q_L factor ($Q_o \approx Q_L$) and, in such a

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M. V. Jacob, J. Mazierska, and K. Leong are with Electrical and Computer Engineering, James Cook University, Townsville, Qld. 4811, Australia (e-mail: Mohan.Jacob@jcu.edu.au).

J. Krupka is with the Institute of Microelectronics and Optoelectronics, Warsaw University of Technology, 00-662 Warsaw, Poland.

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case, measurements of S_{21} only for the transmission mode (or S_{11} for the reflection mode) are sufficient. However, it may not be practical to perform measurements at very weak coupling. For stronger coupling, providing the coupling at ports 1 and 2 of the resonator are the same, the Q_o factor can be calculated using the formula [8]

$$Q_0 = \frac{Q_L}{1 - |S_{21}|_{\max}}. \quad (2)$$

In practice, it is difficult to obtain equal coupling on both ports and, hence, the accuracy of (2) may not be sufficient for precise characterization of HTS films. Hence, to calculate the Q_o factor accurately under arbitrary coupling, the following equation [9] should be used:

$$Q_0 = Q_L(1 + k_1 + k_2) \quad (3)$$

where k_1 and k_2 are coupling coefficients to ports 1 and 2 of the resonator under test.

To use (3) for accurate calculations of the Q_o factor, multifrequency measurements of S_{21}, S_{11}, and S_{22} parameters are needed to determine the loaded Q_L and coupling coefficients k_1 and k_2. In order to remove effects of uncalibrated transmission lines, coupling, noise, and crosstalk from measured S-parameters sets, special data processing should be performed on each set as in the transmission-mode Q factor technique (TMQF) developed at the James Cook University, Townsville, Qld., Australia [10], [11].

Measurements of three multifrequency S-parameter data sets around the resonance for characterization of HTS films at several temperatures and power levels may require a very long time. In this paper, we have introduced a simplified and novel method for calculations of the coupling coefficients of dielectric resonators containing superconducting films. This method reduces the required time for measurement and data processing significantly, but provides sufficiently accurate measurements of the unloaded Q_o factor. The presented method is a modification of the TMQF technique allowing for reduction in the number of measurements taken and shortening the time of measurements without compromising accuracy.

II. TMQF

The most accurate values of the loaded Q_L factor and the coupling coefficients k_1 and k_2 are obtained by fitting multifrequency S_{21}, S_{11}, and S_{22} measured data to a circle on the Smith chart plane [11]. The S_{21}-parameter of an ideal resonator measured around the resonance form circles in the complex plane is shown in Fig. 2(a). However, practical measurements are often distorted from the ideal shape, rotated, and shifted from the origin [see Fig. 2(b)–(d)]. A procedure that involves fitting of an ideal Q circle to the measured data and a phase correction is often needed to remove effects of noise, uncalibrated measurement cables, connectors, coupling structures, crosstalk between the coupling loops, and impedance mismatch.

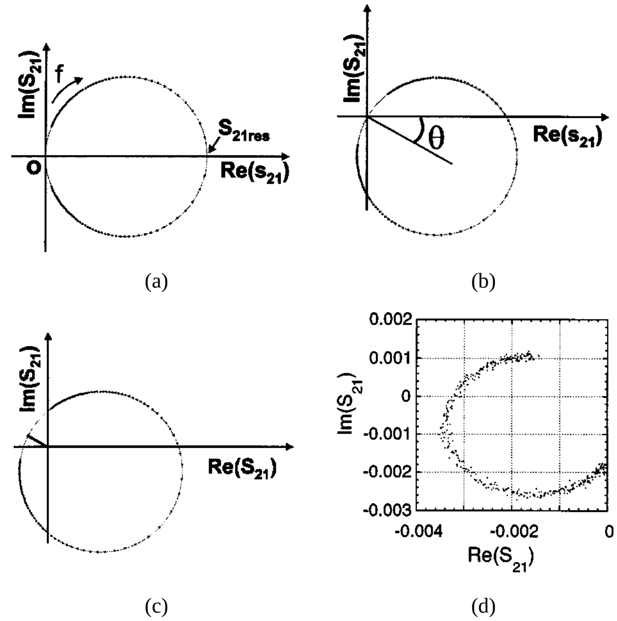

Fig. 2. S_{21} Q circle. (a) Ideal. (b) With phase shift. (c) With crosstalk. (d) As measured.

The following relationships are used for the Q circles fitting of transmission-mode dielectric resonators with $Q_L > 100$ in the TMQF technique [10], [11]:

$$S_{21}(\omega) = \frac{2R_c Y_{\text{ex1}} Y_{\text{ex2}}}{G_o(1+k_1+k_2)\left[1 + j2Q_L\,\dfrac{(\omega-\omega_L)}{\omega_L}\right]} \quad (4)$$

$$S_{\text{pp}}(\omega) = \frac{jQ_L S_{\text{ppd}} 2\dfrac{(\omega-\omega_L)}{\omega_o} + \left\{S_{\text{ppd}} + \dfrac{2R_c Y_{\text{exp}}^2}{G_o(1+k_1+k_2)}\right\}}{jQ_L 2\,\dfrac{(\omega-\omega_L)}{\omega_L} + 1} \quad (5)$$

where G_o is the conductance of an ideal dielectric resonator, R_c is the characteristic impedance of measurement system, Y_{ex1} and Y_{ex2} are external admittances including the coupling losses and reactances, p is the port number (1 or 2), and S_{ppd} is the detuned S-parameter value.

Equations (4) and (5) are of the fractional linear form $(a_1 t + a_2)/(a_3 t + 1)$, where t is the normalized variable equal to $2((\omega - \omega_L)/\Delta\omega_L)$ and ω_L is the loaded resonant frequency. Hence, the complex constants a_1, a_2, and a_3 can be obtained from the Q circle fitting procedure to the S_{21} data set, and the loaded Q_L factor is found as $\mathrm{Im}[a_3]$.

The coupling coefficients k_1 and k_2 are expressed in the TMQF technique as the sum of lossless and lossy terms $k = k_i + k_L$. The terms k_i and k_L are derived from the diameters d_1 and d_2 of the S_{11} and S_{22} Q circles and the diameters x and y of the associated coupling-loss circles

$$k_{1i} = \frac{x}{2\left[1 - \left(\dfrac{x}{d_1} + \dfrac{y}{d_2}\right)\right]} \quad (6a)$$

$$k_{1L} = \left(\frac{2}{d_1} - 1\right) k_{1i} \quad (6b)$$

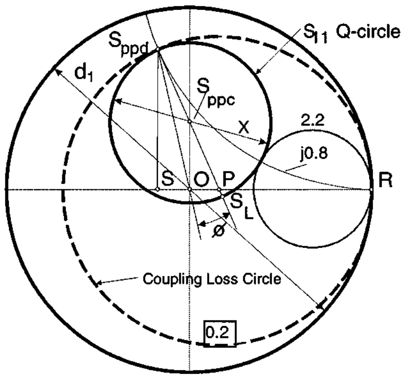

Fig. 3. S_{11} and the coupling-loss circles on the Smith chart.

$$k_{2i} = \frac{y}{2\left[1-\left(\frac{x}{d_1}+\frac{y}{d_2}\right)\right]} \tag{7a}$$

$$k_{2L} = \left(\frac{2}{d_2}-1\right)k_{2i} \tag{7b}$$

where d_1 is a diameter of the port–1 coupling-loss circle, d_2 is a diameter of the port–2 coupling-loss circle, x is the diameter of the S_{11} Q circle, and y is the diameter of the S_{22} Q circle. The circle diameters in the TMQF technique are found from the constants a_1, a_2, and a_3

$$\text{diameter of } Q \text{ circle} = \left|a_2 - \frac{a_1}{a_3}\right| \tag{8a}$$

and

$$\text{diameter of loss circle}|_{\text{port p}} = \frac{1-|S_{\text{ppd}}|^2}{1-|S_{\text{ppd}}|\cos\phi} \tag{8b}$$

where ϕ is the angle between the vectors $S_{\text{ppd}}O$ and $S_{\text{ppd}}S_{\text{ppc}}$, S_{ppd} is the detuned point, and S_{ppc} represents the center of the Q circle, as illustrated in Fig. 3 for the S_{11}-parameter. Point S_L represents the value of S_{pp} at resonance.

The phase of measured S_{11} and S_{22} data sets of a dielectric resonator loaded with superconducting films often needs to be corrected before computing the circle diameters, especially if there are long lengths of uncalibrated cables. In the TMQF technique, wide-band measurements are used to estimate the rate of change of the phase with frequency, and the S_{pp}-parameters data sets are corrected before applying the fitting procedures. The S_{21}-parameter measurements are much less sensitive to delays introduced by uncalibrated cables.

To use the TMQF technique for accurate characterization of HTS films in a wide range of temperatures (e.g., from 5 to 86 K spaced at 0.5 K) and RF power levels, measurements of three S-parameters for over 100 temperatures need to be taken around the resonance, each set consisting of 1601 points. For our measurement system, the total measurement time for one temperature is approximately 40 min, and 250-kB memory is needed for storage of logged data. Processing of S_{21}, S_{11}, and S_{22} data sets, including fitting to the Q circles and phase correction for one temperature takes approximately 10 min on a PIII computer. If the number of necessary parameters to be measured is reduced, this results in a significant savings of time. A method that requires measurements of coupling coefficients based on S_{11}- and S_{22}-parameters at one temperature only is presented in Section III.

III. Simplified Method for Q_o Factor Calculations at Varying Temperatures

As mentioned earlier, the unloaded Q_o factor of a dielectric resonator can be calculated using (3). Let us consider two measurements of a dielectric resonator at two different temperatures T_A and T_B. At temperature T_A, the unloaded Q_{oA} factor is

$$Q_{0A} = Q_{LA}(1+k_{1A}+k_{2A}) \tag{9}$$

and the coupling coefficients k_{1A} and k_{2A} are described as

$$k_{1A} = \frac{Q_{0A}}{Q_{\text{ext}1A}} \tag{10a}$$

$$k_{2A} = \frac{Q_{0A}}{Q_{\text{ext}2A}}. \tag{10b}$$

At temperature T_B, the unloaded Q_{0B} factor is

$$Q_{0B} = Q_{LB}(1+k_{1B}+k_{2B}) \tag{11}$$

and coupling coefficients can be described as

$$k_{1B} = \frac{Q_{0B}}{Q_{\text{ext}1B}} \tag{12a}$$

$$k_{2B} = \frac{Q_{0B}}{Q_{\text{ext}2B}}. \tag{12b}$$

Hence, the unloaded Q factors at temperatures T_A and T_B can be presented as

$$Q_{0A} = Q_{LA}\left[1+Q_{0A}\left(\frac{1}{Q_{\text{ext}1A}}+\frac{1}{Q_{\text{ext}2A}}\right)\right] \tag{13}$$

$$Q_{0B} = Q_{LB}\left[1+Q_{0B}\left(\frac{1}{Q_{\text{ext}1B}}+\frac{1}{Q_{\text{ext}2B}}\right)\right]. \tag{14}$$

Equation (13) can be rewritten as

$$\frac{\frac{Q_{0A}}{Q_{LA}}-1}{Q_{0A}} = \frac{1}{Q_{\text{ext}1A}}+\frac{1}{Q_{\text{ext}2A}}. \tag{15}$$

If we assume that the external Q factors (Q_{ext}) at both temperatures T_A and T_B are the same, $Q_{\text{ext}1A} = Q_{\text{ext}1B}$ and $Q_{\text{ext}2A} = Q_{\text{ext}2B}$.

By substituting (15) into (14), the following expressions for the unloaded Q_{oB} factor at temperature T_B are obtained:

$$Q_{0B} = \frac{Q_{LB}}{1-\frac{Q_{LB}}{Q_{0A}}\left(\frac{Q_{0A}}{Q_{LA}}-1\right)} \tag{16}$$

or

$$Q_{0B} = \frac{Q_{LB}}{1-\frac{Q_{LB}}{Q_{0A}}(k_{1A}+k_{2A})}. \tag{17}$$

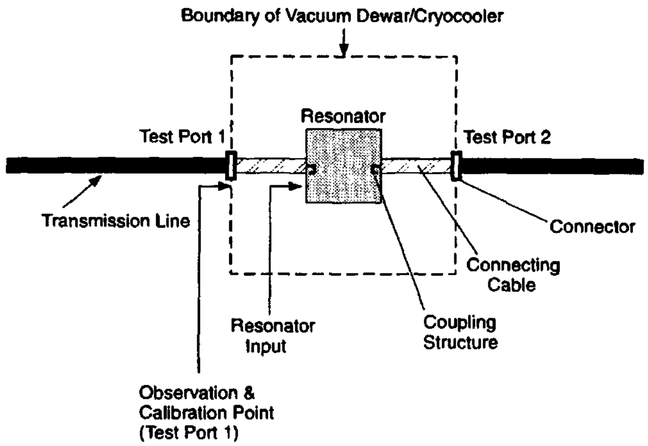

Fig. 4. Reference plane of the resonator and positions of coupling loops.

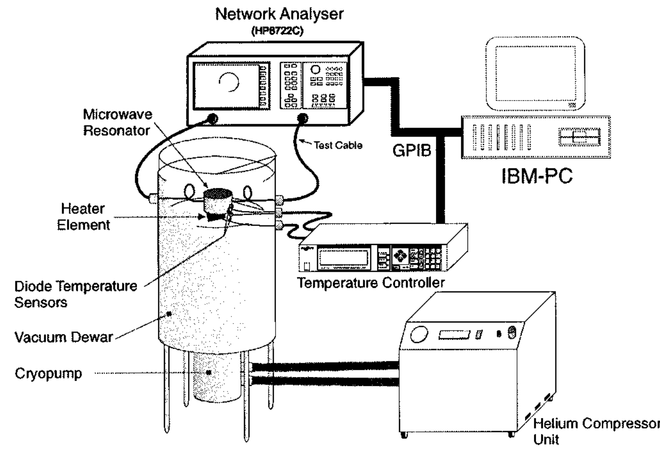

Fig. 5. Measurement system.

Equations (16) or (17) can be used for a set of j temperatures to obtain a characteristic of Q_{0j} versus temperature.

The assumption of the external Q factors being constant with temperature varying can be considered correct if parameters of the external circuitry do not vary with the temperature of the resonator. This requires the reference plane of the coupling to be defined at the external terminals of a cryostat in which the resonator is housed (Fig. 4). This implies that cables inside the cryostat are considered as a part of the resonator and, hence, a phase correction procedure needs to be used to eliminate their influence from measured parameters, as in [11] and [12].

IV. Verification of the Proposed Q_0 Measurement Method

To verify the presented method for simplified (but accurate) measurements of surface resistance of HTSs at varying temperatures, we performed measurements of sapphire dielectric resonators with high-quality $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films. The unloaded Q factors obtained using the full TMQF technique and the simplified method have been compared and presented in Section V. In order to be certain that the developed technique is valid under all measurement conditions, we have used two different resonators (working at frequencies of 10 and 25 GHz), i.e., four pairs of different YBCO samples and two values of couplings for each resonator in the tests. The measurement system we used for the verification is illustrated in Fig. 5.

In the verification process, we measured S_{21}-, S_{11}-, and S_{22}-parameters of the dielectric resonator at all temperatures and applied the TMQF technique to remove effects of noise, uncalibrated measurement cables, connectors, coupling structures, and crosstalk from the measured data sets. We then used two techniques, i.e., the TMQF technique and the "simplified" method, to find coupling coefficients, a loaded Q_L factor, and an unloaded Q_o factor. In the full TMQF technique, coupling coefficients k_1 and k_2 were calculated from multifrequency measurements of S_{11} and S_{22} at every temperature and the Q_o factor was found according to (3) as

$$Q_0[T] = Q_L[T]\big(1 + k_1[T] + k_2[T]\big). \tag{18}$$

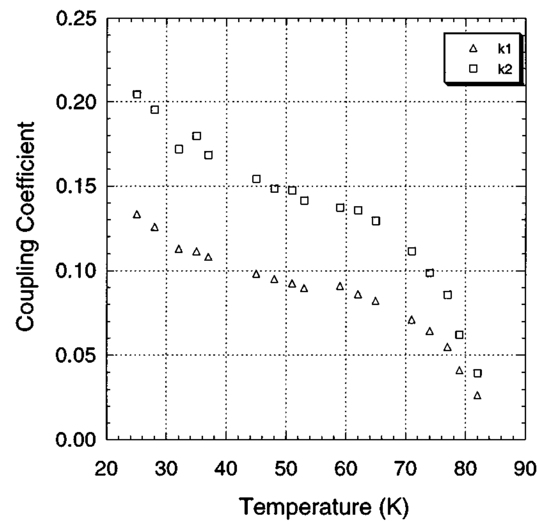

Fig. 6. Coupling coefficients at port 1 (k_1) and port 2 (k_2) as a function of temperature at 10 GHz for sample #1.

In the simplified method, the coupling coefficients were calculated using the TMQF technique from S_{11} and S_{22} data at the lowest temperature (T_A) and the Q_o factor was computed on the basis of (17) as

$$Q_0[T] = \frac{Q_L[T]}{1 - \dfrac{Q_L[T]}{Q_{0A}}\,(k_{1A} + k_{2A})}. \tag{19}$$

The loaded $Q_L[T]$ factor in both methods was obtained in the same way; namely, from S_{21} data sets measured at every temperature and applying the Q circle fit of the TMQF technique. Once the Q_o factor was calculated using either (18) or (19), the average surface resistance of the YBCO thin films was calculated using (1).

V. Results and Discussion

A. Verification Using 10-GHz Resonator

The first verification test was based on a sapphire dielectric resonator working at 10 GHz. The cavity of the resonator

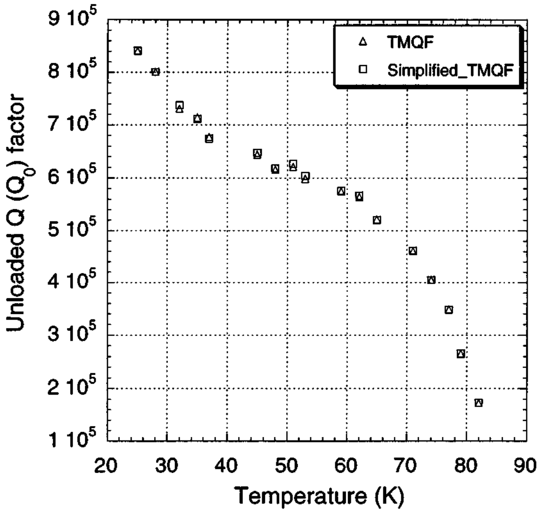

Fig. 7. Unloaded Q factor using the TMQF and simplified TMQF methods as a function of temperature at 10 GHz for sample #1.

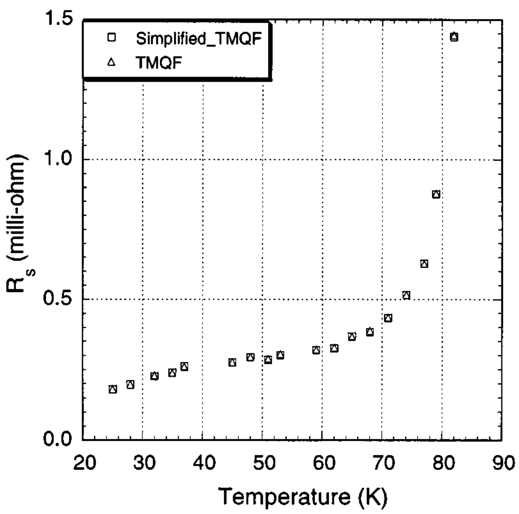

Fig. 8. Surface resistance of YBCO thin film (sample #1) using the TMQF and simplified TMQF methods as a function of temperature at 10 GHz.

was made of copper, and for endwalls, we used YBCO thin films. The cavity had the following dimensions: 24-mm diameter and 7.41-mm height. The sapphire rod had 12.32-mm diameter and 7.41-mm height. The geometric factors of the cavity were 27 628.07 (sidewalls) and 281.23 (endwalls).

Fig. 6 presents computed coupling coefficients obtained using the full TMQF technique from multifrequency measurements of S_{11}- and S_{22}-parameters at frequency of 10 GHz and temperature range from 28 to 85 K. Fig. 7 shows the Q_o factor values calculated using the TMQF and simplified method presented in this paper. The maximum difference between Q_o factor values calculated from both methods is 1%. The surface resistance of the YBCO thin films under test calculated using the Q_o factors obtained using the accurate and the simplified method is shown in Fig. 8. The agreement between both the methods is very good, and the differences between results of both methods are below 1.5%. This is considered very satisfactory taking into consideration the savings in measurement and processing time.

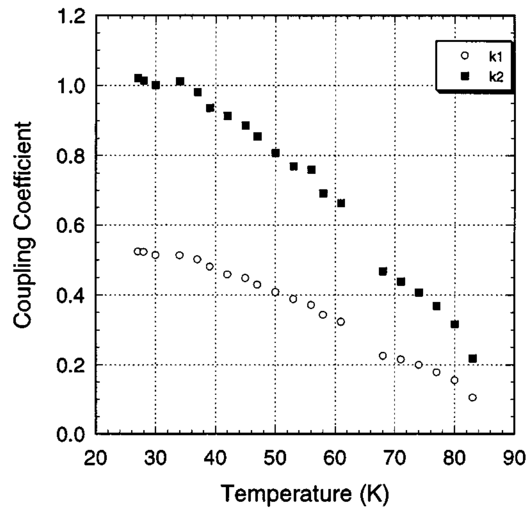

Fig. 9. Coupling coefficients at port 1 (k_1) and port 2 (k_2) as a function of temperature at 10 GHz for sample #2.

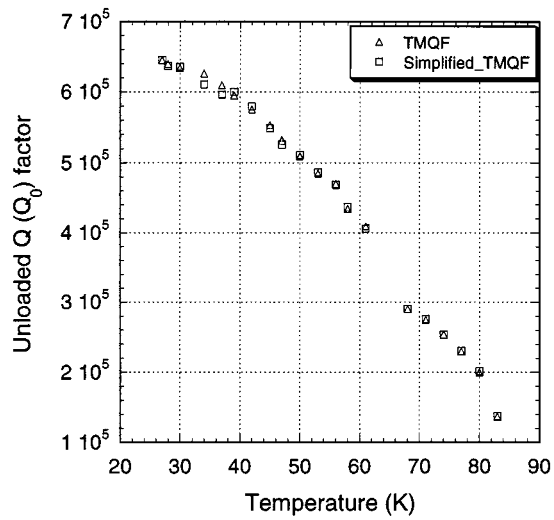

Fig. 10. Unloaded Q factor using the TMQF and simplified TMQF methods as a function of temperature at 10 GHz for sample #2.

The full multifrequency measurements of S_{11}, S_{21}, and S_{22} for the full TMQF technique at all temperatures (from 25 to 85 K at an interval of 2 K) took approximately 20 h and 6 MB of hard-disk space to store the measurement data. The time required to perform measurements of the S_{11}, S_{21}, and S_{22} parameters at 25 K and S_{21} measurements only for all other temperatures was 12 h and 2 MB of hard-disk space. To carry out the data processing for all S-parameters using the TMQF technique for all temperatures took approximately 3 h, while the simplified method required less than 1 h. Therefore, using the new technique we were able to save about 8 h and 4 MB of hard-disk space for each test of HTS films pair without compromising the accuracy of results.

The verification procedure was repeated with the 10-GHz resonator with a different set of YBCO films and bigger coupling coefficients. Figs. 9 and 10 show measured coupling coefficient k_1 and k_2 using the full TMQF technique and the Q_0 factors obtained by both the methods at 10-GHz frequency for differing

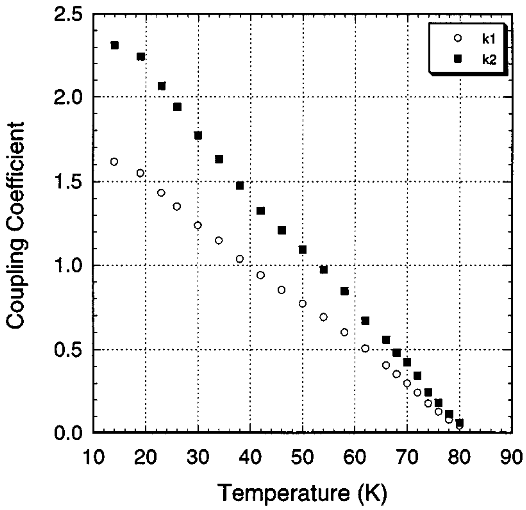

Fig. 11. Coupling coefficients at port 1 (k_1) and port 2 (k_2) as a function of temperature at 25 GHz for sample #3.

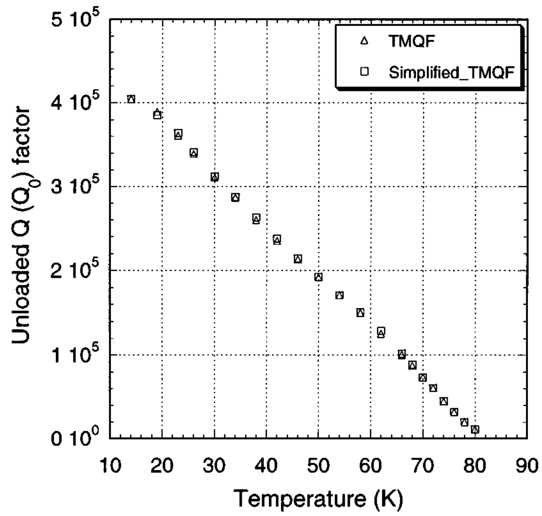

Fig. 13. Calculated unloaded Q factor using the TMQF and simplified TMQF methods as a function of temperature at 25 GHz for sample #3.

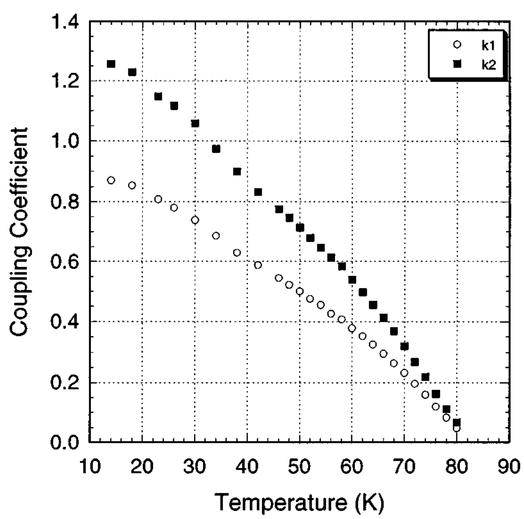

Fig. 12. Coupling coefficients at port 1 (k_1) and port 2 (k_2) as a function of temperature at 25 GHz for sample #4.

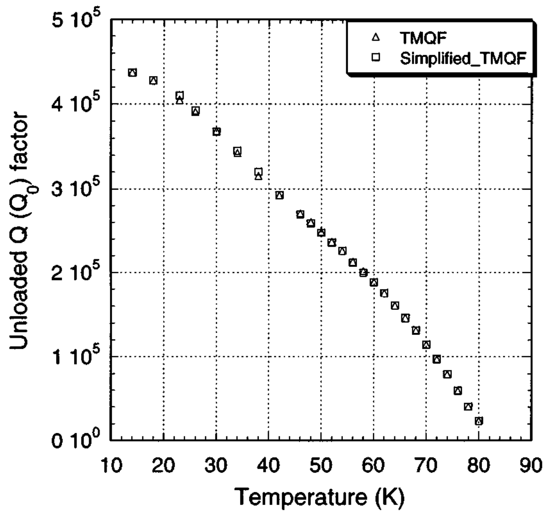

Fig. 14. Calculated unloaded Q factor using the TMQF and simplified TMQF methods as a function of temperature at 25 GHz for sample #4.

temperatures. The maximum error in Q_0 factor values for the simplified method was less than 0.8%.

B. Verification of the Simplified TMQF Technique Using 25-GHz Resonator

For verification of the simplified technique at a different frequency (25 GHz), we have used a sapphire dielectric resonator with sidewalls made of silver-plated copper and with YBCO superconducting thin-film endwalls. The cavity dimensions were 9.5-mm diameter and 3-mm height, and the sapphire rod was 5-mm diameter and 3-mm length. The geometric factors of the cavity were 22 326.5 (sidewalls) and 281.37 (endwalls).

Figs. 11 and 12 show two sets of measured coupling coefficients k_1 and k_2 at 25 GHz for two separate measurements at differing temperatures. The corresponding unloaded Q_0 factors calculated using the full TMQF technique and the simplified technique are shown in Figs. 13 and 14, respectively. The maximum difference between results of two methods is 0.7% (Fig. 13) and 1% (Fig. 14) for the stronger and weaker couplings, respectively.

VI. Conclusion

A simplified (TMQF) method has been developed for accurate measurements and calculations of the unloaded Q factor of dielectric resonators at varying temperatures. The measurements of sapphire resonators with high-temperature superconducting end plates at 10 and 25 GHz in a temperature range from 25 (14 K at 25 GHz) to 86 K and differing coupling resulted in errors less than 1% as compared to the full TMQF. Hence, we can say that the accuracy of the simplified method is acceptable and can be applied for the accurate measurements of the surface resistance of HTSs. The novel method allows for significant reduction of number of measurements data, 40% decrease of measurement time, and 65% savings in computer memory used.

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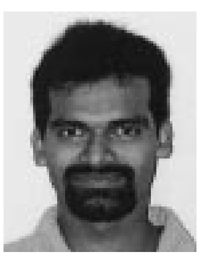

Mohan V. Jacob (A'00–M'01) was born in Kerala, India, in 1968. He received the Masters degree in physics from the Mahatma Gandhi University, Kerala, India, in 1991, and the Ph.D. degree from the University of Delhi, Delhi, India, in 1999.

In 1992, he began his research carrier at the George Sudharsan Center for Physics and Computer Science, Kottayam, India, in the field of laser propagation through a turbulent media. From September 1997 to December 1999, he was a Visiting Research Fellow at the James Cook University, Townsville, Qld., Australia. Since 2000, he has been a Post Doctoral Fellow at the James Cook University. His research interests are the microwave properties of superconductors and dielectrics, design of superconducting filters for mobile communication, and modeling of nonlinear surface impedance of superconducting materials at high microwave power levels.

Dr. Jacob is a Chartered Physicist of the Institute of Physics. He is a member of the American Physical Society and the Institute of Physics. He was the recipient of a 1997 Senior Research Fellowship awarded by the Council of Scientific and Industrial Research, India.

Janina Mazierska (SM'83) received the M.S.E.E. and Ph.D. degrees from the Warsaw University of Technology, Poland, in 1970 and 1979, respectively.

From 1972 to 1982, she was with the Institute of Electronic Fundamentals, Warsaw University of Technology, Warsaw, Poland, where she specialized in modeling of fast semiconductor devices for computer-aided design of pulse and microwave circuits. From 1983 to 1987, she was with the Department of Physics, University of Jos, Jos, Nigeria, under a Polish–Nigerian intergovernmental agreement, during which time she assisted in the development of an electronics/applied physics degree. Since 1987, she has been with the James Cook University, Townsville, Qld., Australia, where she is currently an Associate Professor in electrical and computer engineering. Her current research interests are microwave properties of HTSs and dielectric materials for applications in cellular and personal communication systems (PCSs). In 1991 and 1996, she was a Stanford University Visiting Scholar with the Ginzton Laboratory, Stanford University, Stanford, CA. She has authored or co–authored 84 papers and conference presentations.

Dr. Mazierska is a member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S) Transnational Committee, the IEEE Prize Papers/Scholarship Awards Committee, and the IEEE Meeting and Services Committee. She is a Region 10 Conference coordinator and a North Queensland Section vice-chair.

Kenneth Leong (S'91–M'92) was born in Townsville, Qld., Australia, in 1969. He received the B.Eng. (with honors) and Ph.D. degree in electrical engineering from the James Cook University, Townsville, Qld., Australia, in 1994 and 2000, respectively.

He is currently a Research Officer in the School of Engineering, James Cook University, where he is involved with microwave measurements on materials including high-T_c thin-film superconductors and dielectrics for applications in wireless communications. In 1997, he developed a precise method of Q factor computations for dielectric resonators working in the transmission mode. His novel development is known as the TMQF, which is currently being utilized at the James Cook University for accurate measurements of the surface resistance parameter of high-T_c thin-film superconductors.

Dr. Leong is a member of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S).

Jerzy Krupka (M'00–SM'01) was born in Cracow, Poland, in 1949. He received the M.Sc. (with honors), Ph.D., and habilitation degrees from the Warsaw University of Technology, Warsaw, Poland, in 1973, 1977, and 1989, respectively.

Since 1973, he has been with the Institute of Microelectronics and Optoelectronics, Warsaw University of Technology, where he is currently a Professor. His research is mainly concerned with measurements of electric and magnetic properties of materials at microwave frequencies and numerical methods of electromagnetic-field theory. He was a leader and took part in several research projects on these subjects in the U.S. and U.K. He has authored or co-authored over 100 papers in international journals, encyclopedias, and conference proceedings.

Dr. Krupka was an Editorial Board member of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES from 1994 to 1998. He was the recipient of the 1999 Best Paper Award in Measurements Science and Technology (U.K.).