# Microwave Properties of Low-Loss Polymers at Cryogenic Temperatures

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***Abstract*—Dielectric loss tangent and permittivity of polytetrafuoroethylene (Teflon), high-density (HD) polyethylene, and crosslinked polystyrene (Rexolite) were measured at temperature range from 28 to 84 K and frequency of approximately 18 GHz. The material properties were determined by measurements of the resonant frequency and the $Q$ factor of a $\mathrm{TE}_{011}$ mode cylindrical superconducting cavity containing a sample under test. It has been demonstrated that these materials exhibit very low losses at cryogenic temperatures ($2 \times 10^{-6}$ for Teflon, $5 \times 10^{-5}$ for HD polyethylene and $1.1 \times 10^{-4}$ for Rexolite). Due to low losses, these materials can be useful in construction of various high-$Q$ factor microwave devices for operation at cryogenic temperatures.**

***Index Terms*—Dielectric materials, microwave properties, polyethylene, Rexolite, Teflon.**

## I. Introduction

CRYOGENIC electronics is a fast growing branch of modern electronics, especially since the discovery of high-temperature superconductors that allowed for significant reduction of losses and noise figures in filters and microwave oscillators. Successful design and manufacturing of low-loss devices at cryogenic temperatures requires a careful choice of dielectric materials for their construction. To ensure a high-$Q$ factor of an electronic system, all the components should exhibit small losses. Single crystal dielectrics like sapphire, YAG, $SrLaAlO_4$, or quartz [1] are the lowest loss materials available. However, they are hard to machine into complicated shapes. Hence, various plastic materials, easier to machine, have been typically used as supports or other less demanding elements of a cryogenic microwave device or a cryogenic system. Teflon, polyethylene, and Rexolite have been on the market for many years, and are inexpensive and easy to fabricate and machine into a desired size and shape.

Information on microwave properties of Teflon, polyethylene, and Rexolite exists for wide range of frequencies, but at room and higher temperatures only [2], [3], and temperature dependence of loss tangent cannot be predicted. There is no data on complex permittivity of these materials available for cryogenic temperatures, except for one temperature (77 K) for Teflon and Rexolite [4]. In this paper, we present results of accurate measurements of the permittivity and loss tangent of three low-loss polymers in the cryogenic temperature range from 25 to 84 K using the dielectric resonator technique with superconducting thin films. We have been used an accurate multifrequency measurement and data processing technique [i.e., transmission-mode $Q$ factor (TMQF) technique] [5], [6], which accounted for noise, delay due to transmission lines and its frequency dependence, and crosstalk in measurement data. We also took into consideration variations of samples' dimensions with temperature to ensure high accuracy.

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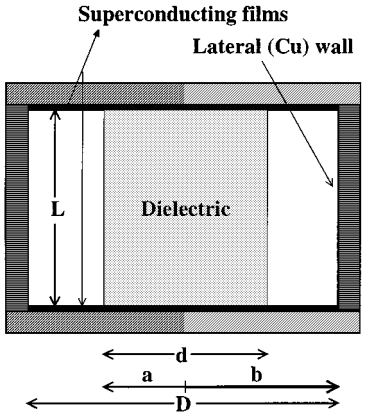


Fig. 1. Schematic of a $\mathrm{TE}_{011}$-mode dielectric resonator.

## II. Dielectric-Resonator Measurement Method

The dielectric resonator with high-temperature superconducting (HTS) plates technique has been used for measurements of low-loss polymer materials presented in this paper. A similar technique had been used before in [4], as mentioned in Section I, and to measure dielectric properties of single-crystal materials [7], [8]. The dielectric-resonator technique with HTS plates is a modification of the metallic dielectric resonator and the cavity perturbation techniques used in the past to characterize dielectric materials [9]–[14].

The schematic diagram of the dielectric resonator used in this study is shown in Fig. 1. The dielectric sample to be measured was enclosed in a copper cylindrical cavity between two HTS films, which allowed for high sensitivity of measurements. As the dielectrics under test exhibit low relative permittivity, the diameter "$d$" of the samples was chosen to be sufficiently large to ensure that electromagnetic fields are evanescent in the air region ($k_{\rho 2}^2 > 0$). In our experiments, we used dielectric samples having the aspect ratio (diameter to height) equal to two.

Since the materials under test are isotropic, the $TE_{011}$ mode of operation was employed in our measurements. The real part of relative permittivity $\varepsilon_r$ of a dielectric was determined as the first root of the following transcendental equation [15] using software SUP12[1]:

$$k_{\rho 1} J_0(k_{\rho 1} b) F_1(b) + k_{\rho 2} J_1(k_{\rho 1} b) F_0(b) = 0 \tag{1}$$

where

$$F_0(\rho) = I_0(k_{\rho 2}\rho) + K_0(k_{\rho 2}\rho)\frac{I_1(k_{\rho 2}a)}{K_1(k_{\rho 2}a)}$$

$$F_1(\rho) = -I_1(k_{\rho 2}\rho) + K_1(k_{\rho 2}\rho)\frac{I_1(k_{\rho 2}a)}{K_1(k_{\rho 2}a)}$$

$$k_{\rho 1}^2 = \frac{\omega^2 \varepsilon_r}{c^2} - k_z^2$$

$$k_{\rho 2}^2 = k_z^2 - \frac{\omega^2}{c^2}$$

$$k_z = \pi / L$$

and $\omega$ is the angular frequency $(2\pi f)$, $c$ is velocity of light, $\varepsilon_o$ is free-space permeability, $\varepsilon_r$ is real relative permittivity of the sample, and $J_0, J_1, I_0, I_1, K_0, K_1$ denote corresponding Bessel and Hankel functions.

The loss tangent of a dielectric under test is found on the basis of the loss equation of the resonator and measured values of the $Q_0$ factor of the resonator, namely,

$$\tan\delta = \frac{1}{\rho_e}\left[\frac{1}{Q_0} - \frac{R_{SS}}{A_S} - \frac{R_{SM}}{A_M}\right] \tag{2}$$

where $Q_0$ is a measured unloaded $Q$ factor of the entire resonant structure, $R_{SS}$ and $R_{SM}$ are the surface resistance of the superconducting and the metallic parts of the cavity, respectively, $A_S$ and $A_M$ are the geometric factors of the superconducting part and metallic parts of the cavity, and $\rho_e$ is the electric energy-filling factor.

Geometric factors $A_S$, $A_M$, and $\rho_e$ to be used in (2) were computed using incremental frequency rules as follows [15]:

$$A_S = \frac{\omega^2 \mu_0}{4} \Big/ \frac{\partial \omega}{\partial L} \tag{3}$$

$$A_M = \frac{\omega^2 \mu_0}{2} \Big/ \frac{\partial \omega}{\partial a} \tag{4}$$

$$p_e = 2\left|\frac{\partial \omega}{\partial \varepsilon_r}\right| \frac{\varepsilon_r}{\omega}. \tag{5}$$

As superconducting plates, high-quality $YBa_2Cu_3O_7$ thin films ($R_{SS}$ of 400 $\mu\Omega$ at 10 GHz and 77 K) were used in the measurements. The values of $R_{SS}$ and $R_M$ used in (2) were measured using the sapphire resonator technique at frequency of 25 GHz at varying temperatures from 13 to 85 K. The method of surface resistance measurements was, in principle, the same as used by several groups [15], [16]. The main advantage (and difference) of our measurements was that the unloaded $Q_0$ factor was calculated from the exact equation, namely,

$$Q_0 = Q_L(1 + \beta_1 + \beta_2) \tag{6}$$

and not from the simplified equation

$$Q_o = \frac{Q_L}{1 - |S_{21}|_{\max}} \tag{7}$$

where $|S_{21}|_{\max}$ is the magnitude of the transmission coefficient at the resonant frequency and $\beta_1$ and $\beta_2$ are coupling coefficients of the resonator to the external circuitry. The loaded $Q_L$ factor and the coupling coefficients were obtained in our case from multifrequency measurements of $S_{21}$-, $S_{11}$-, and $S_{22}$-parameters measured around the resonance using the TMQF technique [5], [6]. The TMQF method accounts for noise, delay due to uncalibrated transmission lines and its frequency dependence, and crosstalk, which occurred in measurement data. Hence, our method provided more accurate values of $R_{SS}$ and $R_M$ for (2) than the 3-dB method used in [4]. Fig. 2 shows measured dependence of surface resistance $R_{SS}$ with temperature for the YBCO films used in the dielectric tests. The surface resistance of copper walls of the resonator was measured in the same way. The TMQF technique we used in our measurements allows for extracting the unloaded $Q_o$ factor with errors less than 1% even under relatively noisy conditions, in presence of delay effects due to uncalibrated transmission lines and frequency dependence of coupling reactance [5]. We assess repeatability of the measurement system when completely dismantled to be 2%. This uncertainty results in the most probable error (MPE) of

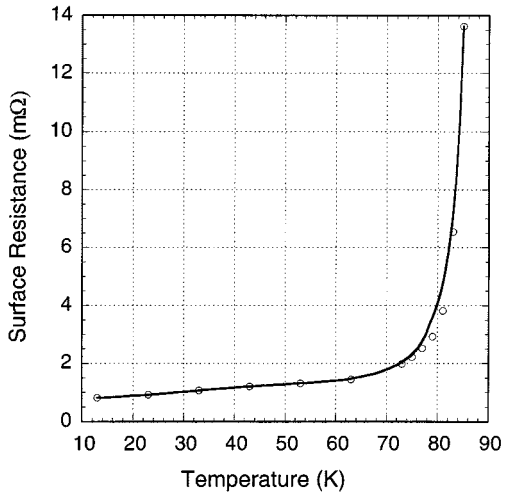


Fig. 2. Surface resistance of $YBa_2Cu_3O_{7-\delta}$ superconducting films versus temperature used in measurements of polymer samples.

TABLE I
GEOMETRIC FACTORS AND ENERGY-FILLING FACTOR OF DIELECTRIC RESONATOR WITH TEFLON, POLYETHYLENE, AND REXOLITE

| | Teflon | Polyethylene | Rexolite |
|---|---|---|---|
| $A_S$ (Ω) | 459.9 | 419.5 | 420.59 |
| $A_M$ (Ω) | 8632.8 | 10451.5 | 9893.9 |
| $\rho_e$ | 0.8939 | 0.9198 | 0.9217 |

[1]J. Krupka, software in FORTRAN to calculate surface resistance of superconductors or copper, permittivity, and loss tangent of dielectric materials, resonant frequency of differing TE and TM modes, 2000.

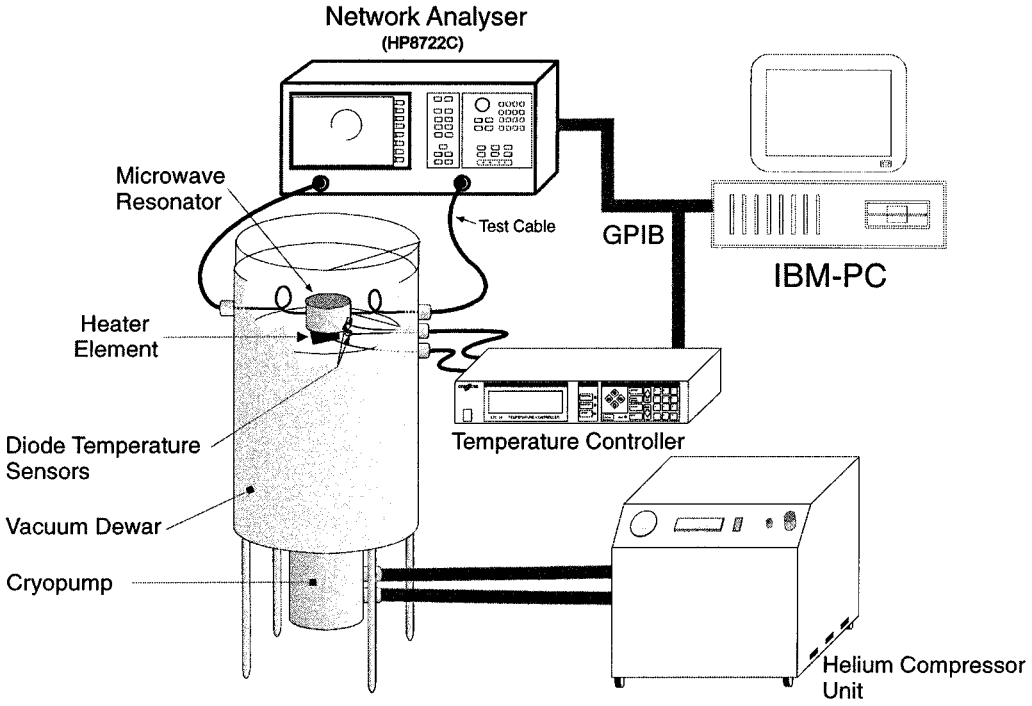


Fig. 3. Experimental setup to measure the $Q$ factor and $f_{\rm res}$ of the dielectric resonator containing the dielectric material to be measured.

4.4% in surface resistance measured with our 10-GHz sapphire resonator [17].

As measurements of low-loss polymers were performed at different frequencies other than 25 GHz, measured values of $R_M$ and $R_{SS}$ were scaled, assuming the square root of frequency dependence for the surface resistance of copper and the frequency square law for the surface resistance of superconductors.

## III. Measurements of Microwave Properties of Teflon, Polyethylene, and Rexolite

All measurements of dielectric properties of Teflon, Rexolite, and polyethylene were performed using the same pair of superconducting YBCO thin films. The dielectrics under test were machined into cylindrical shapes of 7.52-mm height and 15.02-mm diameter. The copper cavity was of 24 mm in diameter and 7.4 mm in height. The geometrical factors of the resonator used for the dielectric tests are shown in Table I.

The measurement system, which consists of a network analyzer (HP 8722C), closed cycle refrigerator (APD DE-204), temperature controller (LTC-10), vacuum Dewar, and personal computer (PC) is presented in Fig. 3. The resonator containing a dielectric sample was cooled from room temperature to around 25 K and then $S$-parameters ($S_{21}$, $S_{11}$, and $S_{22}$) were measured as a function of increasing temperature using the network analyzer. The measurement and calculation procedures used for calculations of $\varepsilon_r$ and $\tan\delta$ were as described in Section II; with the thermal expansion of dielectrics taken additionally into consideration. The relative permittivity of the sample under test was calculated from the measured resonant frequency using (1) and the loss tangent of the material was calculated using (2) from the measured unloaded $Q_0$ factor.

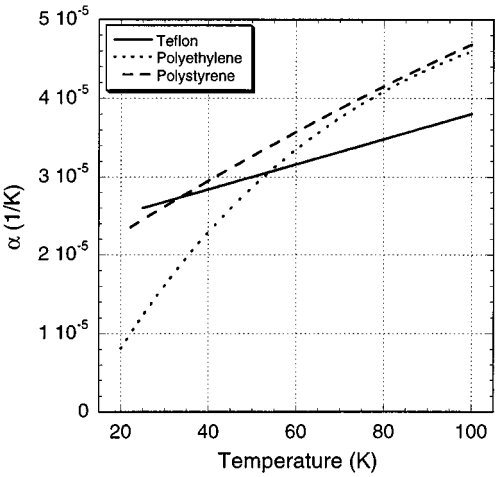


Fig. 4. Temperature coefficients of Teflon, polyethylene, and polystyrene versus temperature after [18] and [19].

The $Q$ factor and resonant frequency of the resonating structure with Teflon was measured at varying temperatures from 28 to 84 K. The resonant frequency of the Teflon resonator was 18.920 GHz. Variation of dimensions of Teflon with temperature were taken into consideration in the calculations of the relative permittivity using data provided in [18]. Fig. 4 shows the temperature dependence of the thermal linear expansion coefficient used in (1) for computations of $\varepsilon_r$ of Teflon and polyethylene based on [19] and polystyrene based on [18].

The real part of relative permittivity for Teflon, polyethylene, and Rexolite samples measured at differing temperatures is shown in Fig. 5. For Teflon, $\varepsilon_r$ of 2.10 was obtained at temperature of 28 K, and 2.09 at 84 K. When temperature increased from 28 to 84 K, a decrease in $\varepsilon_r$ of 0.48% has been observed, taking into consideration variations of dimensions of Teflon

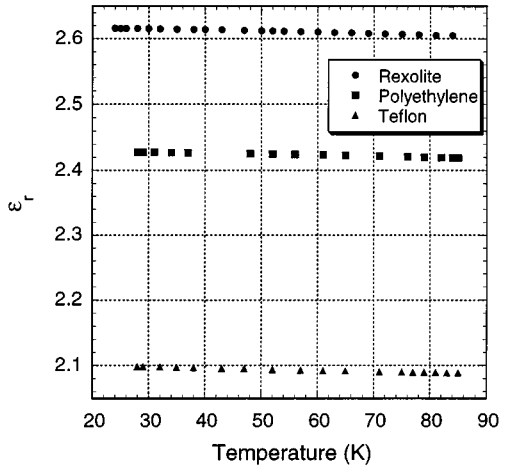


Fig. 5. Real part of permittivity of Teflon (at 18.92 GHz), polyethylene (at 17.652 GHz), and Rexolite (at 16.986 GHz) versus temperature.

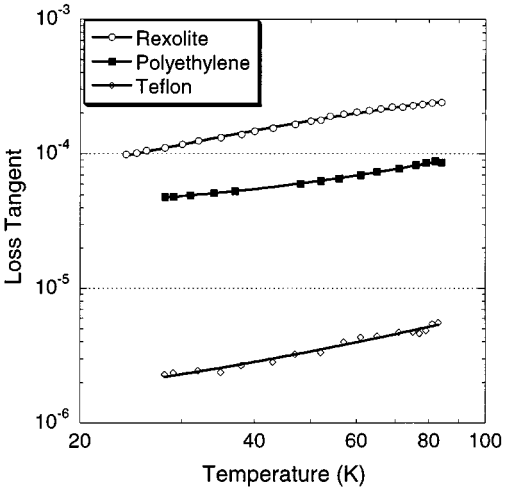


Fig. 6. Dielectric loss tangents of Teflon (at 18.92 GHz), polyethylene (at 17.652 GHz), and Rexolite (at 16.986 GHz) versus temperature.

at cryogenic temperatures according to [18]. Measurements of the polyethylene and Rexolite samples resulted in the resonant frequencies of 17.652 and 16.986 GHz, respectively. Variations of the dimensions of polyethylene at cryogenic temperatures according to [19], as per Fig. 4, were used in calculations of $\varepsilon_r$. For rutile, the thermal linear expansion coefficient of polystyrene [18] was used, as no data for Rexolite could be found. $\varepsilon_r$ of polyethylene was obtained to be 2.43 at temperature of 28 K decreasing by 0.36% to 2.42 at 84 K. For Rexolite, $\varepsilon_r$ of 2.62 was measured at 28 K and 2.61 at 84 K, giving the variation in $\varepsilon_r$ of 0.40%. When the thermal expansion phenomenon is not taken into consideration, constant values of the real part of relative permittivity (2.042, 2.375, and 2.572 for Teflon, polyethylene, and Rexolite, respectively) versus temperature are obtained. These values are in agreement with results for Teflon (2.048) and Rexolite (2.504) at 77 K in [4] measured at 9.95 and 13.0 GHz, respectively.

Measured dielectric loss tangents of Teflon, polyethylene, and Rexolite [calculated from the $Q$ factor measurements using (2)] are shown in Fig. 6. The Teflon sample shows the smallest loss of the three materials; $2.30 \times 10^{-6}$ at 28 K and $5.56 \times 10^{-6}$ at 84 K. For polyethylene, we obtained the loss tangents of $4.80 \times 10^{-5}$ at 28 K and $8.62 \times 10^{-5}$ at a temperature of 84 K. Rexolite exhibited $\tan\delta$ of $11.03 \times 10^{-5}$ and $23.97 \times 10^{-5}$, respectively. The loss tangent of Teflon increased nearly 1.4 times with temperature varying from 28 to 84 K. For the same temperature change, the increase in loss tangent was 0.9 times and 1.2 times for the polyethylene and the Rexolite samples, respectively.

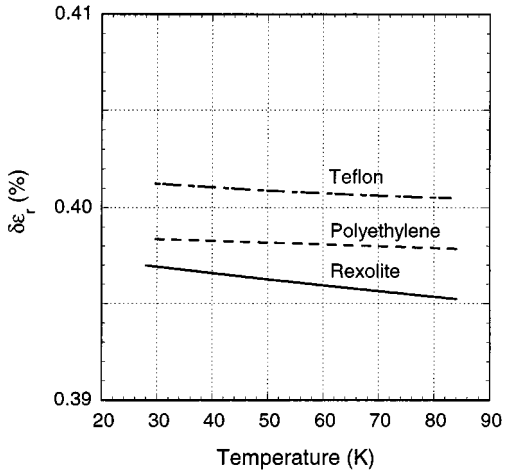


Fig. 7. MPE in permittivity versus temperature for 0.2% uncertainty in the samples' dimensions.

Our measurements of $\tan\delta$ at 18.92 and 16.986 GHz give approximately 60% smaller value for Teflon and 25% for Rexolite at 77 K, as compared to [4] (at 9.95 and 13.0 GHz, respectively) due to more accurate calculation procedures and possible differences between samples.

## IV. Error Analysis of Measured Parameters $\varepsilon_r$ and $\tan\delta$

Accuracy of measurements of the real part of relative permittivity presented in this paper depends mostly on accuracy of the resonant frequency measurements using a vector analyzer and on uncertainty in dimensions of dielectric samples. Uncertainty in frequency measurements is determined by the phase noise of the HP 8722C and with a 1-Hz option used for measurements, and we assumed it to be negligible. To ensure high accuracy of $\varepsilon_r$ tests, we took into account the thermal expansion phenomenon of materials under test at cryogenic temperatures using values of the thermal expansion coefficients according to [18] and [19] in the calculations. However, there is a probability that real values of the thermal coefficients of our samples are different than values used, and this might have affected the accuracy of calculations. Also, there is a finite accuracy in machining the samples.

To assess possible errors in the $\varepsilon_r$ calculation, we performed the error analysis of $\varepsilon_r$ calculations as a function of uncertainty in dielectric samples dimensions using the software SUP12. Figs. 7 and 8 show uncertainties in relative permittivities of Teflon, Rexolite, and polyethylene for 0.2 and 1% uncertainties in dimensions, respectively. The performed analyses show that $\delta\varepsilon_r$ is approximately twice the uncertainty in dimensions for all three polymers and decreases slightly with an increase of

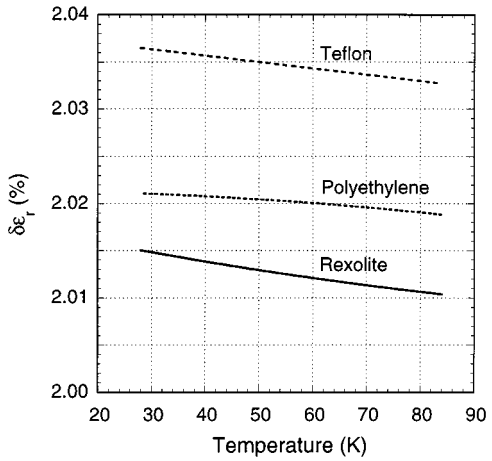


Fig. 8. MPE in permittivity versus temperature for 1% uncertainty in the samples' dimensions.

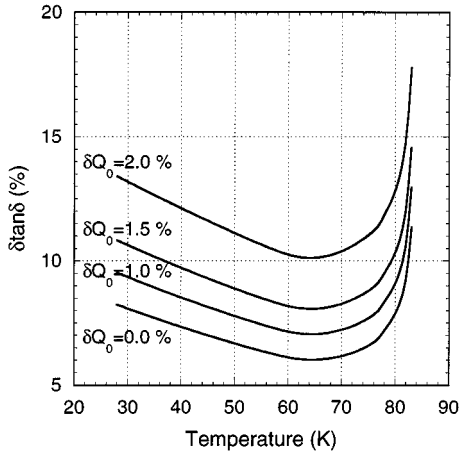


Fig. 9. MPE in loss tangent of Teflon versus temperature for varying uncertainty in $Q_o$.

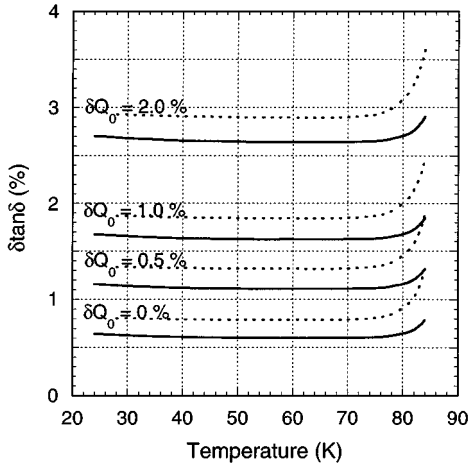


Fig. 10. MPE in loss tangent of polyethylene (dash line) and Rexolite (solid line) versus temperature for varying uncertainty in $Q_o$.

temperature from 28 to 85 K. The influence of the uncertainty in dimensions is the highest for Teflon due to the lowest permittivity of this polymer.

We assess that uncertainty in dimensions of our samples was 0.25% (due to machining accuracy and uncertainty in the thermal expansion coefficient) giving measurement errors in $\varepsilon_r$ of materials under test of approximately 0.5%.

Accuracy in the loss-tangent measurements using the dielectric resonator method is associated mainly with errors in the $Q_0$ factor measurements. Other contributing factors include errors in surface resistance values of the superconducting plates and the copper walls, as well as errors in estimation of geometric factors. To assess the MPE in the loss tangent of measured dielectric materials, an equation describing the MPE has been derived on the basis of the differential uncertainty method, as in [20].

For a multivariable function $\tan\delta = f(x_1, x_2, \ldots, x_n)$, the relative error $\Delta\tan\delta/\tan\delta$ can be expressed as

$$\frac{\Delta\tan\delta}{\tan\delta} \equiv \delta\tan\delta = \sum_{k=1}^{n}\left|\tan\delta_{x_k}\left[\frac{\Delta x_k}{\tan\delta}\right]\right|. \tag{8}$$

By considering various parameters influencing $\tan\delta$ [see (2)], the MPE in $\tan\delta$ can be expressed as

$$\begin{aligned}\delta\tan\delta = \Bigg[&\left|\frac{\Delta\rho_e}{\rho_e}\right|^2 + \left|\left(\frac{-1}{Q_0\rho_e\tan\delta}\right)\frac{\Delta Q_0}{Q_0}\right|^2 \\ &+\left(\frac{R_{SS}}{A_S\rho_e\tan\delta}\left(\left|\frac{\Delta R_{SS}}{R_{SS}}\right|+\left|\frac{\Delta A_S}{A_S}\right|\right)\right)^2 \\ &+\left(\frac{R_{SM}}{A_M\rho_e\tan\delta}\left(\left|\frac{\Delta R_{SM}}{R_{SM}}\right|+\left|\frac{\Delta A_M}{A_M}\right|\right)\right)^2\Bigg]^{1/2}.\end{aligned} \tag{9}$$

To assess errors in our measurements of $\tan\delta$, we assumed uncertainties in $R_{SS}$ and $R_{SM}$ of 4.5%, and 0.5% in $A_S$, $A_M$, and $\rho_e$, as discussed in Section II. Calculated errors in measured loss tangent values of Teflon for assumed uncertainties in the $Q_0$ factor measurements of 0%, 0.5%, 1%, and 2% are presented in Fig. 9.

TABLE II
COMPARISON OF PROPERTIES OF TEFLON, POLYETHYLENE, AND REXOLITE AT 28 AND 84 K

| | Temp. (K) | Teflon | Polyethylene | Rexolite |
|---|---|---|---|---|
| Height (mm) | 28 | 7.39±0.02 | 7.41±0.02 | 7.46±0.02 |
| | 84 | 7.41±0.02 | 7.42±0.02 | 7.47±0.02 |
| Diameter (mm) | 28 | 14.73±0.04 | 14.80±0.04 | 14.80±0.04 |
| | 84 | 14.77±0.04 | 14.82±0.04 | 14.83±0.04 |
| Permittivity | 28 | 2.10±0.01 | 2.43±0.01 | 2.62±0.01 |
| | 84 | 2.09±0.01 | 2.42±0.01 | 2.61±0.01 |
| tanδ ($\times 10^{-5}$) | 28 | 0.23±0.03 | 4.80±0.14 | 11.03±0.29 |
| | 84 | 0.56±0.10 | 8.62±0.26 | 23.97±0.70 |
| Frequency (GHz) | | 18.920 | 17.652 | 16.986 |

It is interesting to note that the MPE in $\tan\delta$ for Teflon reaches a minimum between 60–70 K. At a low-temperature region, the $\delta\tan\delta$ increases due to the very low loss of the material $(\tan\delta < 3\times10^{-6})$ and resulting smaller sensitivity of the measurement system. At temperatures above 70 K, the MPE is high due to the significant increase of the surface

resistance of the HTS films close to the critical temperature. Uncertainty in $\tan\delta$ is determined by the uncertainty in the $Q_0$ factor measurements. The system repeatability error in the unloaded $Q$ factor of our measurement system is assessed to be 2% at most. Therefore, the MPE in measured loss tangent of Teflon is less than 13.5% in the most sensitive temperature zones and less than 11% for temperatures between 50–70 K.

Fig. 10 shows the MPEs in loss tangent for polyethylene and Rexolite samples. The $\delta\tan\delta$ are smaller and much less temperature dependent than Teflon. This is attributed to higher loss tangent of these materials, as compared to Teflon. The calculated errors in loss tangent for polyethylene and Rexolite are bigger than errors in the $Q_0$ factor measurements by 0.8% and 0.65%, respectively. Hence, we assess that $\tan\delta$ of polyethylene and Rexolite was measured with errors smaller than 3% in the entire temperature range.

## V. Conclusions

We have studied the microwave properties of Teflon, polyethylene, and Rexolite samples at cryogenic temperatures. A comparison of the samples' dimensions, a real part of the relative permittivity, and loss tangent of three polymers under test, were measured at temperatures of 28 and 84 K, as shown in Table II.

We have found that at a temperature of 28 K, Teflon exhibited very low-loss tangent of approximately $2 \times 10^{-6}$, polyethylene of $4.8 \times 10^{-5}$, and Rexolite of $1.1 \times 10^{-4}$. From the performed error analysis, we concluded that measurements of loss tangent were carried out with errors below 3% for polyethylene and Rexolite, and below 13.5% for Teflon for temperatures from 28 to 80 K. To achieve higher accuracy of measurements of $\tan\delta$, a different method based on the whispering-gallery modes needs to be used. Errors in the real part of the relative permittivity were at most 0.5% for all three materials. Although our data are in agreement with the earlier work [4] based on different samples, we would like to point out that microwave properties of polymers from different manufacturers may differ due to impurity content and manufacturing process.

We hope that this paper's presented data will assist in applications of Teflon, polyethylene, and Rexolite in microwave systems.

## References


[1] J. Krupka, K. Derzakowski, M. E. Tobar, J. Hartnett, and R. G. Geyer, "Complex permittivity of some ultralow loss dielectric crystals at cryogenic temperatures," *Meas. Sci. Technol.*, vol. 10, pp. 387–392, 1999.

[2] A. von Hippel, *Dielectric Materials and Applications*. Norwood, MA: Artech House, 1995.

[3] L. Chen, C. K. Ong, and B. T. G. Tan, "Amendment of cavity perturbation method for permittivity measurement of extremely low-loss dielectrics," *IEEE Trans. Instrum. Meas.*, vol. 48, pp. 1031–1036, Dec. 1999.

[4] R. Geyer and J. Krupka, "Microwave dielectric properties of anisotropic materials at cryogenic temperatures," *IEEE Trans. Instrum. Meas.*, vol. 44, pp. 329–331, Apr. 1995.

[5] K. Leong, "Precise measurements of surface resistance of HTS thin films using a novel method of $Q$-factor computations for sapphire dielectric resonators in the transmission mode," Dept. Elect. Comput. Eng., Ph.D. dissertation, James Cook Univ., Townsville, Qld., Australia, 2000.

[6] K. Leong and J. Mazierska, "Accurate measurements of surface resistance of HTS films using a novel transmission mode $Q$-factor technique," *J. Superconduct.*, to be published.

[7] J. Krupka, R. G. Geyer, M. Kuhn, and J. Hinken, "Dielectric properties of single crystal $Al_2O_3$, $LaAlO_3$, $NdGaO_3$, $SrTiO_3$, and MgO at cryogenic temperatures and microwave frequencies," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 1886–1890, Oct. 1994.

[8] C. Zuccaro, I. Ghosh, K. Urban, N. Klein, S. Penn, and N. M. Alford, "Materials for HTS-shielded dielectric resonators," *IEEE Trans. Appl. Superconduct.*, vol. 7, pp. 3715–3718, June 1997.

[9] Y. Kobayashi and M. Katoh, "Microwave measurement of dielectric properties of low-loss materials by the dielectric rod resonator method," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 586–592, July 1985.

[10] J. Krupka, "An accurate method for permittivity and loss tangent measurements of low dielectric using $TE_{01d}$ dielectric resonators," in *Proc. 5th Int. Dielectric Mater. Applicat. Conf.*, 1988, pp. 322–325.

[11] H. Tamura, H. Matsumoto, and K. Wakino, "Low temperature properties of microwave dielectrics," *Jpn. J. Appl. Phys.*, vol. 28, pp. 21–23, 1989.

[12] T. Nishikawa, K. Wakino, H. Tamura, H. Tanaka, and Y. Ishikawa, "Precise measurement method for temperature coefficient of microwave dielectric resonator material," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1987, paper J-6, pp. 277–280.

[13] R. Geyer, "Dielectric characterization and reference materials," NIST, Boulder, CO, NIST Tech. Note 1338, 1990.

[14] J. Konopka and I. Wolf, "Dielectric properties of high $T_c$ substrates up to 40 GHz," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, 1992, pp. 1027–1030.

[15] J. Krupka, M. Klinger, M. Kuhn, A. Baranyak, M. Stiller, J. Hinken, and J. Modelski, "Surface resistance measurements of HTS films by means of sapphire dielectric resonators," *IEEE Trans. Appl. Superconduct.*, vol. 3, pp. 3043–3048, Sept. 1993.

[16] C. Wilker, Z.-Y. Shen, V. X. Nguyen, and M. S. Brenner, "A sapphire resonator for microwave characterization of superconducting thin films," *IEEE Trans. Appl. Superconduct.*, vol. 3, pp. 1457–1460, Mar. 1993.

[17] J. Mazierska, "Dielectric resonator as a possible standard for characterization of high temperature superconducting films for microwave applications," *J. Superconduct.*, vol. 10, no. 2, pp. 73–84, 1997.

[18] Y. S. Touloikian, R. K. Kirby, R. E. Taylor, and T. Y. R. Lee, "Thermal expansion—Nonmetallic solids," in *Thermophysical Properties of Matter Data Series*. New York: Plenum, 1977, vol. 13.

[19] D. J. Lacks and G. C. Rutledge, "Simulation of the dependence of mechanical properties of polyethylene," *J. Phys. Chem.*, vol. 98, pp. 1222–1231, 1994.

[20] J. Mazierska, J. Krupka, and T. Kośiuk, "Resonant measurements of surface resistance of high $T_c$ superconducting films: How good or bad are they?," *J. Superconduct.*, vol. 8, no. 6, pp. 681–689, 1995.



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