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Recent progress on the dielectric properties of dielectric resonator materials with their applications from microwave to optical frequencies

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Abstract

The dielectric properties at microwave and millimeter-wave frequency are reported for practical dielectric resonator materials. The dielectric materials suitable for each application such as antenna duplexers for mobile phones, filters for cellular base station, millimeter-wave applications, and high temperature superconductors are introduced with their dielectric properties. Recently, valuable optical properties have been obtained by altering specific dielectric resonator materials.

Keywords: Antenna duplexer; Cellular base station; Dielectric loss; Dielectric resonator; High temperature superconductivity; Millimeter-wave; Refractive index; Transmittance

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1. Introduction

Since the 1970's, dielectric resonator materials have been developed and put into practical use for filters and oscillators at microwave frequency, miniaturizing these components and saving costs.[1–4] There has been concentrated effort to decrease the dielectric loss of these materials. In this paper, recent progress on the dielectric properties of dielectric resonator materials is reported with their practical applications. In addition, the optical properties, which are achieved in specific extremely low porosity dielectric materials are introduced.

2. Properties of dielectric resonator materials at microwave and millimeter-wave frequency

Dielectric resonator materials must have low dielectric loss tangent tanδ and stable temperature stability of resonant frequency. Due to these requirements, dielectric resonator materials are generally made of paraelectric dielectric ceramics. In this case, the complex permittivity at an angular frequency ω is given by the dielectric dispersion equation, which is expressed as the superposition of electronic and ionic polarization.

$$\varepsilon(\omega) - \varepsilon(\infty) = \frac{\omega_T^2(\varepsilon(0) - \varepsilon(\infty))}{\omega_\mathrm{T}^2 - \omega^2 - j\gamma\omega} \tag{1}$$

where ω_T and γ are the resonance frequency and damping constant of the infrared active lattice vibration modes, and $\varepsilon(\infty)$ is the permittivity due to the electronic polarization.

As the condition $\omega^2 << \omega_\mathrm{T}^2$ is adopted reasonably at microwave and millimeter wave frequency, the following equation is derived from Eq. (1).

$$\varepsilon\text{'}(\omega) - \omega(\infty) = \varepsilon'(0) - \varepsilon(\infty) \tag{2}$$

$$\tan\delta = \frac{\varepsilon''(\omega)}{\varepsilon\text{'}(\omega)} = \frac{\gamma}{\omega_\mathrm{T}^2}\omega \tag{3}$$

Thus, the dielectric constant is independent of frequency and the dielectric loss tangent increases proportionately to frequency in the frequency range from 10^9 to 10^{11} Hz.

Table 1 shows the dielectric properties of practical dielectric resonator materials. For notation, ε_r is the dielectric constant and Q is the quality factor that is the reciprocal of dielectric loss tangent; $Q = 1/\tan\delta$. As the

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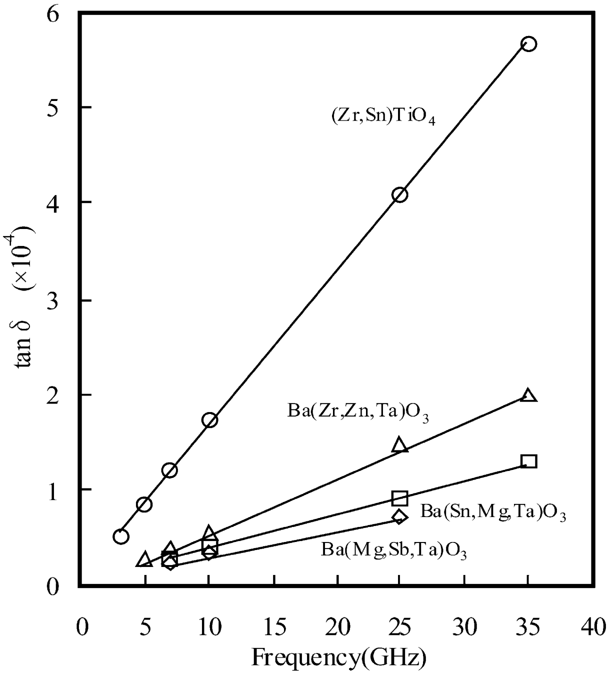


Fig. 1. Frequency dependence of tanδ from 1 to 35 GHz.

tanδ is proportional to frequency, the product of Q and frequency; $Q\times f$ is often used instead of Q as material constant.

Fig. 1 shows the frequency dependence of tanδ from 1 to 35 GHz for several materials shown in Table 1. As predicted from Eq. (2), tanδ increases proportionately to frequency. These dielectric properties were measured by the dielectric resonator method from 1 to 10 GHz[5] and by the $TE_{01\delta}$ mode cavity method using NRD guide from 10 to 35 GHz.[6]

Table 1
Microwave properties of dielectric resonator materials

Materials	ε_r	$Q\times f$ (GHz)	τ_f (ppm/°C)
$MgTiO_3$–$CaTiO_3$	21	56,000	0–6
$Ba(Sn,Mg,Ta)O_3$	24	240,000	0–6
$Ba(Mg,Ta,Sb)O_3$	24	350,000	0–6
$Ba(Zr,Zn,Ta)O_3$	30	180,000	0–6
$Ba_2Ti_9O_{20}$	38	55,000	4
$(Zr,Sn)TiO_4$	38	60,000	0–6
$CaTiO_3$–$NdAlO_3$	43	47,000	0–6
$Ba(Sm,Nd)_2Ti_4O_{12}$	80	10,000	0–6
$(Ba,Pb)Nd_2Ti_4O_{12}$	92	5000	0–6
$(Ba,Pb)(Nd,Bi)_2Ti_4O_{12}$	110	2500	0–6

The temperature coefficient of resonant frequency τ_f is defined by the following equation.

$$\tau_f = -\frac{1}{2}\tau_\varepsilon - \alpha \tag{4}$$

where τ_ε is the temperature coefficient of dielectric constant and α is the linear thermal expansion coefficient of the dielectric specimen.

Fig. 2 shows the temperature dependence of resonance frequency and tanδ. High temperature stability of resonant frequency is obtained by selecting the composition of each material.

2.1. Materials for microwave and millimeter-wave applications

Fig. 3 shows the most commonly utilized three dominant modes for dielectric resonators. The TEM mode dielectric resonator is characterized by a guided mode field distribution of a TEM mode with standing wave of

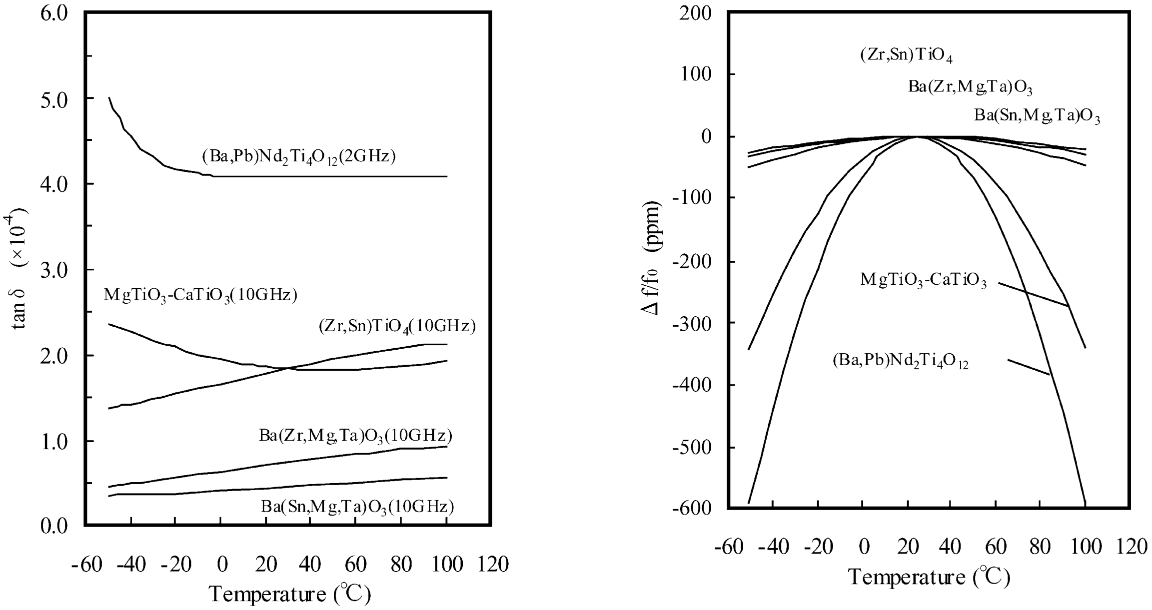
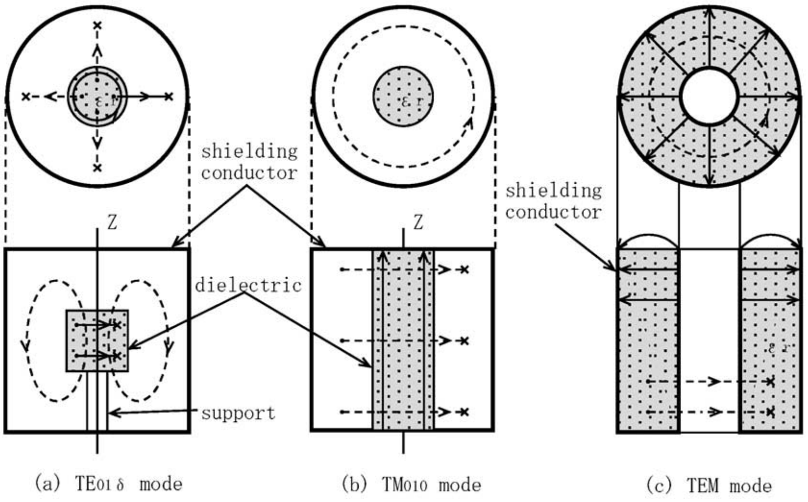


Fig. 2. Temperature dependence of resonant frequency and tanδ.



(a) $TE_{01\delta}$ mode (b) TM_{010} mode (c) TEM mode

Fig. 3. Three dominant modes for dielectric resonators.

a quarter wavelength. This mode dielectric resonator causes significant size-reduction of the component.

The TM_{010} mode dielectric resonator is characterized by a TM mode field distribution. This mode resonator has the middle levels of unloaded Q and size reduction effect between the $TE_{01\delta}$ and TEM mode resonators.

The $TE_{01\delta}$ mode dielectric resonator is characterized by a dominant TE mode field distribution, the field of which leaks in the direction of wave propagation. A high unloaded quality factor can be achieved using this mode.

2.2. Materials for antenna duplexer of mobile phones

Fig. 4 shows an example of an antenna duplexer. For the miniaturization of an antenna duplexer, the quarter wavelength TEM mode dielectric resonator is popularly used for such applications.

The unloaded Q of the dielectric resonator is determined by the dielectric loss tangent of the material and the conduction loss of the shielding electrode. Fig. 5 shows the unloaded Q of $\lambda/4$ TEM mode dielectric resonator with outer diameter of 3 mm. For the calculation of conduction loss, the conductivity of $\sigma = 4.8\times10^{-7}$ [$\Omega^{-1}\mathrm{cm}^{-1}$] was used. This value can be practically obtained by the firing of silver paste or by the copper electroless plating.

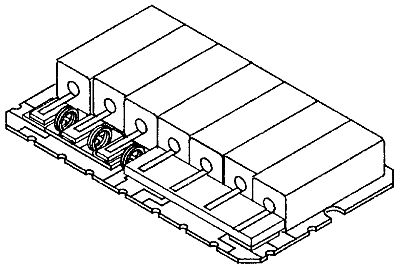


Fig. 4. Antenna duplexer using TEM mode dielectric resonator.

For the miniaturization of 900 MHz band antenna duplexer, the dielectric materials $(Pb,Ba)Nd_2Ti_4O_{12}$ or $Ba(Bi,Nd)_2Ti_4O_{12}$ with ε_r of 90 are popularly used. For the 2 GHz band antenna duplexer, the materials with ε_r from 20 to 40 are used to obtain the higher unloaded Q.

2.3. Materials for filters in cellular base station

For the filters of cellular base stations, dielectric resonator material should have an extremely low dielectric loss tangent and third inter-modulation distortion level in order to prevent the increase of heat and the interference between signals in high power processing.[7,8]

Fig. 6 shows an antenna filter for a cellular base station using the TM_{110} dual-mode dielectric resonators.[9] The TM mode dielectric resonator is suitable for the high power application due to a construction that aids the release of heat. Materials such as $(Zr,Sn)TiO_4$,

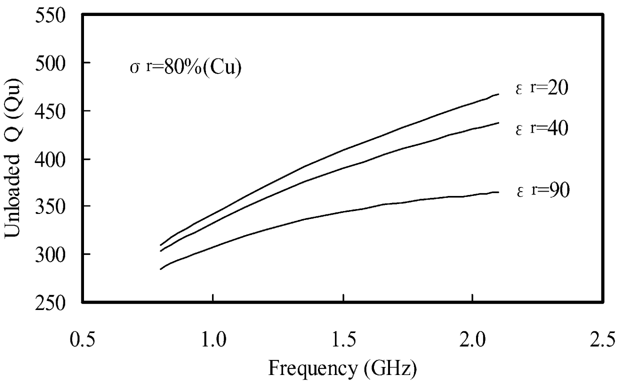


Fig. 5. Unloaded Q of $\lambda/4$ TEM mode dielectric resonator with ε_r of 20, 40 and 90.

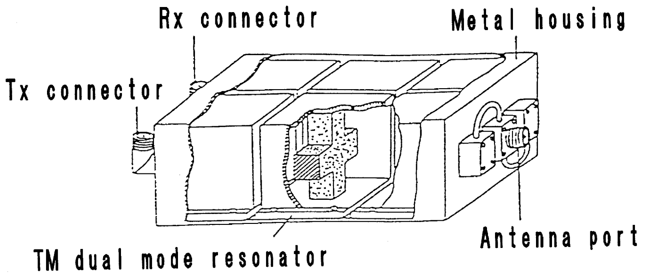


Fig. 6. Antenna filter for cellular base station using TM_{110} dual-mode dielectric resonator.

$CaTiO_3$–$NdAlO_3$ and Ba(Zr,Zn,Ta)O_3 are used for this application as they satisfy both high ε_r and high Q value.

2.4. Materials for millimeter-wave applications

At very high frequency such as millimeter-wave, dielectric materials with extremely low loss are also required to enable low loss filters. Complex perovskite materials based on Ba(Zn,Ta)O_3 and Ba(Mg,Ta)O_3 have very high Q values suitable for such millimeter-wave applications. As the sizes of each components become much smaller for millimeter-wave applications, thin film technology and microfabrication processes are applied to integrate components to dielectric substrates. Consequently the sizes of pores in the substrates should be reduced to the level less than that defined by the design rule to avoid breaks or shorts of fine lines. Fig. 7 shows a TE_{010} mode dielectric filter with center frequency of 30 GHz,utilizing Au thin film as electrode.[10] The TE_{010} mode resonators are formed on the Ba(Sn,Mg,Ta)O_3 zero porosity substrate with $\varepsilon_r = 24$ and have the unloaded Q of 1600 (Fig. 8).

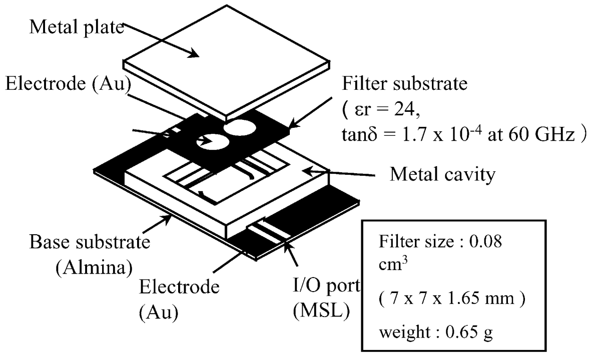


Fig. 7. TE_{010} mode millimeter-wave filter.

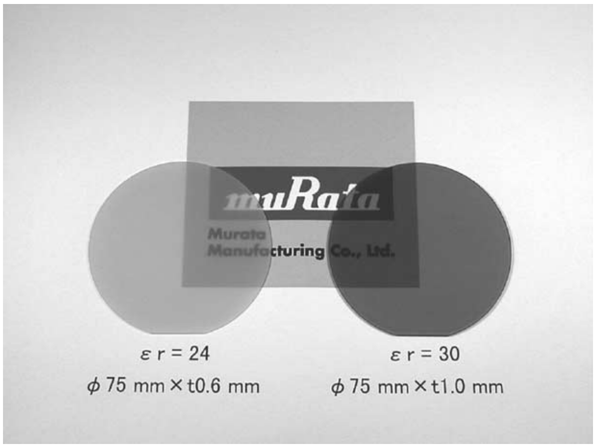


Fig. 8. Zero porosity dielectric substrates for millimeter-wave filter.

2.5. Materials for high temperature superconductivity

Great efforts are been paid to realize the filters for cellular base stations by utilizing the high-temperature superconductors. $YBa_2Cu_3O_{7\text{-}\delta}$ (YBCO) thin films on $LaAlO_3$ substrate are progressing in applications. As Fig. 9 shows, Ba(Sn,Mg,Ta)O_3 is a promising candidate for low-temperature microwave dielectrics as it has extremely high $Q \times f$ value of 1,000,000 GHz at 70 K.[11]

Fig. 10 shows the comparison of surface resistance at 10 GHz between YBCO thin film and Bi2223 thick film.[12] Although the obtained Rs of Bi2223 thick film is

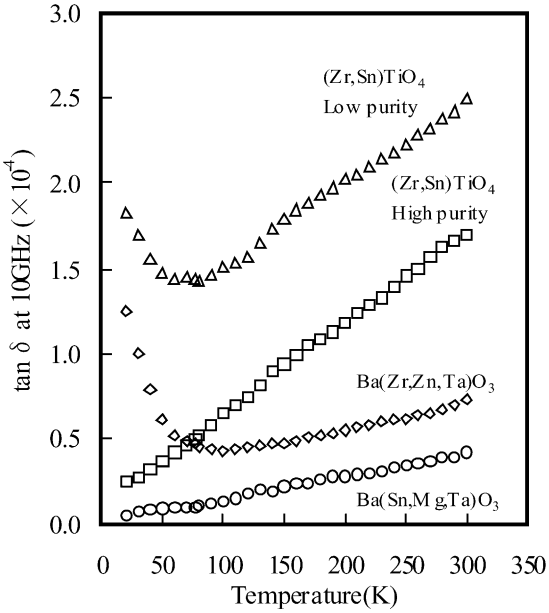


Fig. 9. Temperature dependence of tanδ for dielectric resonator materials.

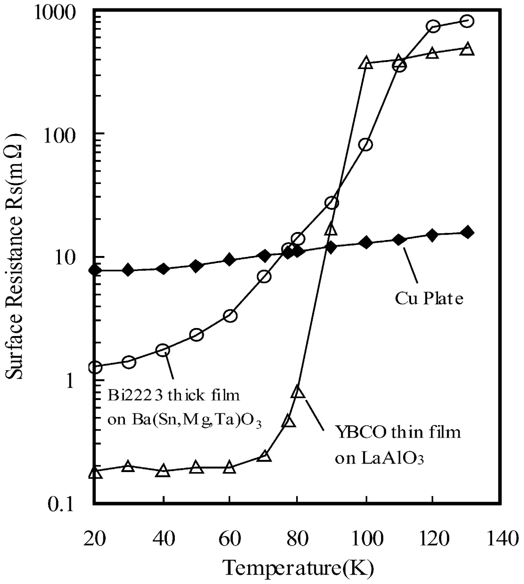


Fig. 10. Surface resistance of superconductors at 10 GHz.

not sufficiently high, due to the imperfect *c*-axis-alignment, it has the possibility for future improvement.

3. Translucent substrate ceramics derived from dielectric resonator materials

By improving the densification of ceramics, most materials generally tend to obtain translucency. We developed highly densified extremely low porosity substrates made of Ba(Sn,Mg,Ta)O_3 dielectric material,which attain practical use as optical materials. The composition area which shows practical optical characteristics are larger than that which shows excellent dielectric properties because there is no limitation based on temperature stability of resonant frequency. At optical frequency, ionic polarization does not occur and only electronic polarization is dominant and contributes to the refractive index.

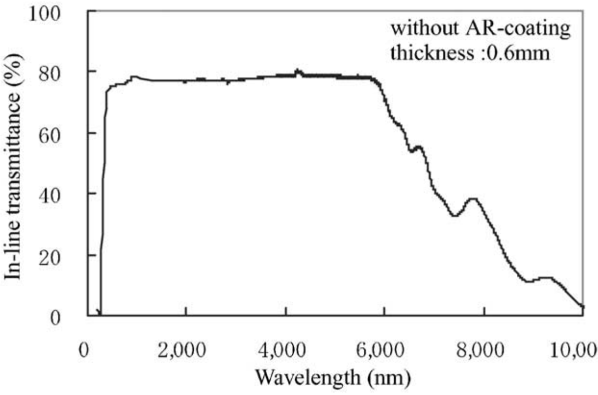


Fig. 11. Transmittance spectrum of Ba(Sn,Mg,Ta)O_3 translucent substrate.

Table 2
Refractive indices of substrates

Wavelength (nm)	Refractive	Index
	TE mode	TM mode
633	2.074	2.074
1300	2.040	2.040
1550	2.035	2.035

No birefringence.

Fig. 11 shows the transmittance of a Ba(Sn,Mg,Ta)O_3 translucent substrate. This spectrum shows the wide transmission range from visible 400 nm to middle infrared 6 μm wavelength. As the transmittance of this substrate is very close to theoretical 77.1% of perfectly transparent materials with refractive index 2.074, there is little internal loss of absorption or scattering (the transmissivity is 99.5% with 0.5 mm thickness). Table 2 shows the refractive indexes for Transverse Electric Field and Transverse Magnetic Field at wavelengths 633, 1350 and 1500 nm. The outstanding characteristics are that this material has high refractive index and no birefringence. As we can not find such characteristics in conventional glasses, we expect this material could contribute to miniaturization of optical elements such as diffractive optical elements and dichroic prisms and so on.

4. Conclusions

This paper described the characteristics of dielectric resonator materials at microwave and millimeter-wave frequencies with their applications. Newly developed optical characteristics, derived from specific dielectric resonator materials are reported. So far various dielectric materials have been developed. Today we are able to choose a material from a range for a specific application. New materials are now being developed and the dielectric properties are being improved for coming applications.

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