Ferroelectric-Dielectric Solid Solution and Composites for Tunable Microwave Application

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1. Introduction

Electric field tunable ferroelectric materials have attracted extensive attention in recent years due to their potential applications for tunable microwave device such as tunable filters, phased array antennas, delay lines and phase shifters (Maiti et al. 2007a; Rao et al. 1999; Romanofsky et al. 2000; Varadan et al 1992.; Zhi et al. 2002). \( \text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3 \) and \( \text{BaZr}_{1-x}\text{Ti}_x\text{O}_3 \) have received the most attention due to their intrinsic high dielectric tunability. However, the high inherent materials loss and high dielectric constant has restricted its application in tunable microwave device. Various methods have been investigated to lower the dielectric constant and loss tangent of pure ferroelectrics.

Forming ferroelectric-dielectric composite is an efficient method to reduce material dielectric constant, loss tangent and maintain tunability at a sufficiently high level. For binary ferroelectric-dielectric composite (such as BST+MgO) (Chang & Sengupta 2002; Sengupta & Sengupta 1999), with the increase of dielectrics content, the dielectric constant and tunability of composites decrease. In order to decrease the dielectric constant of binary composite, it is necessary to increase the content of linear dielectric, and the tunability will decrease inevitably due to ferroelectric dilution. Replacing one dielectric by the combination of dielectrics with different dielectric constants and forming ternary ferroelectric-dielectric composite can decrease the dielectric constant of composite and maintain or even increase the tunability. This is beneficial for tunable application. The \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3-\text{Mg}_2\text{SiO}_4-\text{MgO} \) and \( \text{BaZr}_{0.2}\text{Ti}_{0.8}\text{O}_3-\text{Mg}_2\text{SiO}_4-\text{MgO} \) composites exhibited relatively high tunability in combination with reduced dielectric permittivity and reduced loss tangent (He et al. 2010, 2011). With the increase of Mg\(_2\)SiO\(_4\) content and the decrease of MgO content in \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3-\text{Mg}_2\text{SiO}_4-\text{MgO} \) composite, the dielectric constant decrease and the tunability remain almost unchanged. For \( \text{BaZr}_{0.2}\text{Ti}_{0.8}\text{O}_3-\text{Mg}_2\text{SiO}_4-\text{MgO} \) composite, an anomalous relation between dielectric constant and tunability was observed: with the increase of Mg\(_2\)SiO\(_4\) content (>30 wt%), the dielectric constant of composite decreases and the tunability increases. The anomalous increased tunability can be attributed to redistribution of the electric field. \( \text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3-\text{Mg}_2\text{TiO}_4-\text{MgO} \) can also form ferroelectric (\( \text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3 \))-dielectric (\( \text{Mg}_2\text{TiO}_4-\text{MgO} \)) ternary composite and the dielectric constant can be decreased. With the increase of Mg\(_2\)TiO\(_4\) content and the decrease of MgO content, the tunability of \( \text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3-\text{Mg}_2\text{TiO}_4-\text{MgO} \) composite increase. The multiple-phase composites might complicate method to effectively deposit films, particularly if the dielectrics and ferroelectric are not compatible for simultaneous deposition or simultaneous adhesion with a substrate or with
each other. But ferroelectric-dielectric composite bulk ceramics show promising application, especially in accelerator: bulk ferroelectrics composites can be used as active elements of electrically controlled switches and phase shifters in pulse compressors or power distribution circuits of future linear colliders as well as tuning layers for the dielectric based accelerating structures (Kanareykin et al. 2006, 2009a, 2009b).

Forming ferroelectric-dielectric solid solution is another method to reduce material dielectric constant and loss tangent. Ferroelectric Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ can form solid solution with dielectrics Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$, La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$, La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$, and Nd(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ that have the same perovskite structure as the ferroelectrics (Xu et al. 2008, 2009). With the increase of the dielectrics content, the dielectric constant, loss tangent and tunability of solid solution decrease. Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ shows better dielectric properties than other solid solutions. Compared with ferroelectric-dielectric composite, forming solid solution can decrease the dielectric constant more rapidly when the doping content is nearly the same, and can also improve the loss tangent more effectively. On the other hand, ferroelectric-dielectric solid solution shows lower tunability than composites. The advantage of ferroelectric-dielectric solid solution is that single phase materials is favorable for the thin film deposition. The high dielectric field strength can be obtained easily in thin film to get high tunability.

In this chapter, we summarize the microstructures, dielectric tunable properties of ferroelectric-dielectric solid solution and composites, focusing mainly on our recent works.

2. Ferroelectric-dielectric composite

2.1 Ba$_{1-x}$Sr$_x$TiO$_3$ based composites

Various non-ferroelectric oxides, such as MgO, Al$_2$O$_3$, ZrO$_2$, Mg$_2$SiO$_4$ and MgTiO$_3$, were added to Ba$_{1-x}$Sr$_x$TiO$_3$ to reduce the dielectric constant and loss tangent and maintain the tunability at sufficient high level (Chang & Sengupta 2002; Sengupta & Sengupta 1997, 1999). It is better that non-ferroelectric oxide doesn’t react with ferroelectric Ba$_{1-x}$Sr$_x$TiO$_3$. MgO has low dielectric constant and loss tangent, can form ferroelectric (Ba$_{1-x}$Sr$_x$TiO$_3$)-dielectric (MgO) composite. BST-MgO composite shows better dielectric properties. Mg$_2$SiO$_4$ is also a linear dielectrics with low dielectric constant, but it can react with Ba$_{1-x}$Sr$_x$TiO$_3$ to form Ba$_2$(TiO)(Si$_2$O$_7$), as shown in Fig. 1. For 10 mol% Mg$_5$SiO$_4$ mixed Ba$_{0.6}$Sr$_{0.4}$TiO$_3$, the major phase is Ba$_{0.6}$Sr$_{0.4}$TiO$_3$, and no Mg$_2$SiO$_4$ phase can be found except for two unidentified peaks at 27.6° and 29.7° (relative intensity: ~1%). As the content of Mg$_2$SiO$_4$ increases from 20 to 60 mol%, the impurities phase of Ba$_2$(TiO)(Si$_2$O$_7$) is observed obviously and the relative content is increased with respect to the content of Mg$_2$SiO$_4$. For 60 mol% Mg$_2$SiO$_4$ mixed Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ ceramics sintered at 1220°C, the strongest diffraction peak is the (211) face of Ba$_2$(TiO)(Si$_2$O$_7$) (not shown in Fig. 1). Therefore, for Mg$_2$SiO$_4$ added Ba$_{0.6}$Sr$_{0.4}$TiO$_3$, it is not as we expected that the ferroelectric (Ba$_{0.6}$Sr$_{0.4}$TiO$_3$)-dielectric (Mg$_2$SiO$_4$) composite formed. The dielectric constants and unloaded Q values at microwave frequency were measured in the TE$_{015}$ dielectric resonator mode using the Hakki and Coleman method by the network analyzer. Table 1 summarizes $\varepsilon_r$ and the quality factor (Qx$f$=f$_0$/tan$\delta$, where f$_0$ is the resonant frequency) at microwave frequencies for some Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Mg$_2$SiO$_4$ ceramics. Increasing the Mg$_2$SiO$_4$ content results in a decrease of dielectric constant but has no obvious effect on the Qx$f$ value. The low Qx$f$ of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Mg$_2$SiO$_4$ ceramics restricts their microwave application, and so the tunability has not been measured furthermore. The low Qx$f$ is due to Ba$_2$(TiO)(Si$_2$O$_7$) which is a ferroelectrics with promising piezoelectric uses.
Table 1. Microwave dielectric properties of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Mg$_2$SiO$_4$ ceramics

| Mg$_2$SiO$_4$ content (mol%) | Sintering temperature (°C) | $f_0$(GHz) | $\varepsilon$ | tanδ | $Q_f$/GHz |
|-----------------------------|-----------------------------|-------------|-------------|------|-----------|
| 20                          | 1260                        | 1.79        | 683.7       | 0.016 | 112       |
| 40                          | 1240                        | 2.98        | 169.2       | 0.024 | 124       |

Fig. 1. The XRD patterns of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Mg$_2$SiO$_4$ ceramics. The Mg$_2$SiO$_4$ content is 10-60 mol%.

For Mg$_2$SiO$_4$-MgO added Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ ferroelectric (Ba$_{0.6}$Sr$_{0.4}$TiO$_3$)-dielectric (Mg$_2$SiO$_4$-MgO) composite is formed, as shown in Fig. 2 (He et al., 2010). With the decrease of MgO content and the increase of Mg$_2$SiO$_4$ content, the diffraction peaks from MgO decrease gradually and the diffraction peaks from Mg$_2$SiO$_4$ increase. Therefore, Mg$_2$SiO$_4$-MgO combination can prohibit the formation of Ba$_2$(TiO)(Si$_2$O$_7$) phase.

Fig. 3 shows the FESEM images of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Mg$_2$SiO$_4$-MgO composites sintered at 1350°C for 3h. The FESEM image and element mapping of 40Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-12Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-48MgO as determined by energy dispersive spectroscopy (EDS) are shown in Fig. 4. Three kind of different grains can be found clearly: light grains with average grain size of about 2µm, nearly round larger grains and dark grains with sharp corners. The element mapping of Si Kα1 and Ti Kα1 in Fig. 4 can show the distribution of MgSiO$_4$ and Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ grains clearly. Therefore, we can identify that light grains are Ba$_{0.6}$Sr$_{0.4}$TiO$_3$, the dark, larger grains are MgO, and dark grains with sharp corners are Mg$_2$SiO$_4$. With the decrease of MgO content and the increase of Mg$_2$SiO$_4$ content, more and more Mg$_2$SiO$_4$ grains with different size can be found (Fig. 4). It is consistent with the XRD results. We can conclude that Mg$_2$SiO$_4$ and MgO were randomly dispersed relative to ferroelectric Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ phase.

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Fig. 2. The XRD patterns of 40Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-60(Mg$_2$SiO$_4$-MgO) composite ceramics sintered at 1350°C for 3h. From bottom to top, the MgO content is 48 wt%, 36 wt%, 30 wt%, 24 wt% and 12 wt%, respectively.

Fig. 3. FESEM images of 40Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-60(Mg$_2$SiO$_4$-MgO) composites ceramics sintered at 1350°C for 3h. From (a) to (e), the MgO content is 48 wt%, 36 wt%, 30 wt%, 24 wt% and 12 wt%, respectively.
Because of the relatively low dielectric constant and loss tangent of \( \text{Mg}_2\text{SiO}_4 \) and \( \text{MgO} \), it is expected that \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( \text{Mg}_2\text{SiO}_4\)-\( \text{MgO} \) composites have lower dielectric constant and loss tangent. Fig. 5 shows the dielectric constant and loss tangent of \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( \text{Mg}_2\text{SiO}_4\)-\( \text{MgO} \) composite ceramics at 1MHz. The dielectric constant of composites is much smaller than that of \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3 \) (\( \varepsilon \approx 5160 \) at 1MHz) (Chang & Sengupta, 2002; Sengupta & Sengupta 1999). The loss tangent of \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( \text{Mg}_2\text{SiO}_4\)-\( \text{MgO} \) composites sintered at 1350°C is \( \approx 0.0003-0.0006 \), but the loss tangent of \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3 \) is \( \approx 0.0096 \) (Sengupta et al. 1999). Therefore, the composites have much smaller loss tangent than \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3 \).

The temperature dependence of dielectric properties for various \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( \text{Mg}_2\text{SiO}_4\)-\( \text{MgO} \) composites (sintering temperature: 1350°C) measured at 100kHz is illustrated in Fig. 6. Broadened and suppressed dielectric peaks and shifts of Curie temperature \( T_C \) are observed. For \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( 12\text{Mg}_2\text{SiO}_4\)-\( 48\text{MgO} \) ceramics, its \( \varepsilon_{\text{max}} \) is \( \approx 176.5 \) at \( T_C \approx 224 \text{K} \). As the relative content of \( \text{Mg}_2\text{SiO}_4 \) increase, \( T_C \) is shifted slightly to lower temperatures, thus resulting in a decrease in dielectric constant at a given temperature; at the meantime, \( \varepsilon_{\text{max}} \) decreases also. For \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( 30\text{Mg}_2\text{SiO}_4\)-\( 30\text{MgO} \), \( \varepsilon_{\text{max}} \) is \( \approx 140.1 \) at \( T_C \approx 216 \text{K} \) and for \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( 48\text{Mg}_2\text{SiO}_4\)-\( 12\text{MgO} \), \( \varepsilon_{\text{max}} \) is \( \approx 126.8 \) at \( T_C \approx 214 \text{K} \). With the decrease of temperature, the loss tangent increase.

Fig. 6 shows the effect of applied field on the tunability of the \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( \text{Mg}_2\text{SiO}_4\)-\( \text{MgO} \) composites at 100kHz. The tunability of \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( 12\text{Mg}_2\text{SiO}_4\)-\( 48\text{MgO} \) at 100kHz under at \( 2\text{kV/mm} \) is 10.5%. With the increase of \( \text{Mg}_2\text{SiO}_4 \) content, the tunability of \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( 24\text{Mg}_2\text{SiO}_4\)-\( 36\text{MgO} \) decreases slightly to 9.2%. Further increasing \( \text{Mg}_2\text{SiO}_4 \) content results in a slight increase of tunability: \( \text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( 48\text{Mg}_2\text{SiO}_4\)-\( 12\text{MgO} \) composite has tunability of 10.2%.

Fig. 4. FESEM image and element mapping of \( 40\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3\)-\( 12\text{Mg}_2\text{SiO}_4\)-\( 48\text{MgO} \) as determined by energy dispersive spectroscopy (EDS).
Fig. 5. Dielectric constant (solid) and loss tangent (open) of $40\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$60(\text{Mg}_2\text{SiO}_4$-$\text{MgO})$ composite ceramics sintered at different temperature (measure frequency: 1MHz).

Fig. 6. Variation of dielectric constant (solid) and loss tangent (open) with temperature for $40\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$60(\text{Mg}_2\text{SiO}_4$-$\text{MgO})$ ceramics measured at 100kHz.
Fig. 7. The tunability of 40Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-60(Mg$_2$SiO$_4$-MgO) composites at 100kHz (sintering temperature: 1350°C).

| MgO content (wt.%) | $f_0$ (GHz) | $\varepsilon$ | $\tan\delta$ | $Q\times f$ (GHz) |
|-------------------|------------|---------------|---------------|-----------------|
| 12                | 5.74       | 74.59         | 0.023         | 250             |
| 24                | 5.74       | 77.72         | 0.019         | 302             |
| 30                | 5.80       | 77.12         | 0.021         | 276             |
| 36                | 5.96       | 74.39         | 0.017         | 351             |
| 48                | 5.33       | 93.86         | 0.014         | 381             |

Table 2. Microwave Dielectric Properties of 40Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-60(Mg$_2$SiO$_4$-MgO) ceramics

The room temperature microwave dielectric properties of 40Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-60(Mg$_2$SiO$_4$-MgO) composites were summarized in Table 2. With the increase of Mg$_2$SiO$_4$ content, the dielectric constant remain almost the same and the $Q\times f$ value decrease.

Mg$_2$TiO$_4$ is a low loss tangent linear dielectrics and Mg$_2$TiO$_4$ added Ba$_{1-x}$Sr$_x$TiO$_3$ shows better tunable dielectric properties (Chou et al. 2007; Nenasheva et al. 2010). The XRD patterns of 40Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-xMgO-(60-x)Mg$_2$TiO$_4$ (Fig. 8) show that ferroelectric (Ba$_{0.6}$Sr$_{0.4}$TiO$_3$)-dielectric (MgO-Mg$_2$TiO$_4$) composite is formed. On the other hand, impurity phase BaMg$_6$Ti$_6$O$_{19}$ is found in Mg$_2$TiO$_4$ doped Ba$_{0.6}$Sr$_{0.4}$TiO$_3$. The formation of BaMg$_6$Ti$_6$O$_{19}$ depends on Ba/Sr ratio. BaMg$_6$Ti$_6$O$_{19}$ forms in Mg$_2$TiO$_4$ doped Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ and Ba$_{0.55}$Sr$_{0.45}$TiO$_3$ but not Ba$_{0.5}$Sr$_{0.5}$TiO$_3$. Mg$_2$TiO$_4$-MgO combination can prohibit the formation of BaMg$_6$Ti$_6$O$_{19}$ phase. The FESEM images (Fig. 9) show clearly three kind of grains: Ba$_{0.6}$Sr$_{0.4}$TiO$_3$, Mg$_2$TiO$_4$ and MgO.

Table 3 shows the microwave dielectric properties of 40Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-xMgO-(60-x)Mg$_2$TiO$_4$ ceramics. With the increase of MgO content, the dielectric constant decrease due to lower
dielectric constant of MgO. For x=0-36 wt%, the Q×f value remain unchanged. As a whole, the loss tangent is too high to be used for tunable microwave application.

Fig. 8. The XRD patterns of 40Ba_{0.6}Sr_{0.4}TiO_{3}-xMgO-(60-x)Mg_{2}TiO_{4} ceramics

Fig. 9. FESEM images of 40Ba_{0.6}Sr_{0.4}TiO_{3}-xMgO-(60-x)Mg_{2}TiO_{4} composites ceramics sintered at 1400°C for 3h.
Table 3. Microwave dielectric properties of $40\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$x\text{MgO}-(60-x)\text{Mg}_2\text{TiO}_4$ ceramics

Increasing Sr/Ba ratio can decrease the dielectric constant and loss tangent of $\text{Ba}_{1-x}\text{Sr}_x\text{TiO}_3$. $40\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$-$x\text{MgO}-(60-x)\text{Mg}_2\text{TiO}_4$ will have lower dielectric constant and loss tangent than $40\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$-$x\text{MgO}-(60-x)\text{Mg}_2\text{TiO}_4$. We prepared $40\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$-$x\text{MgO}-(60-x)\text{Mg}_2\text{TiO}_4$ ceramics and measured the tunability (Fig. 10). With the increase of $\text{Mg}_2\text{TiO}_4$ content, the tunability of composite increases. The tunability of $40\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$-$12\text{MgO}$-$48\text{Mg}_2\text{TiO}_4$ is 16.6% at 2kV/mm and 28.5% at 3.9kV/mm, respectively. The corresponding value of $40\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$-$60\text{Mg}_2\text{TiO}_4$ is 13.6% and 24.0% respectively. The higher tunability of $40\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$-$12\text{MgO}$-$48\text{Mg}_2\text{TiO}_4$ is due to its higher dielectric constant ($\varepsilon=150.2$) than $40\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$-$60\text{Mg}_2\text{TiO}_4$ ($\varepsilon=127.8$).

![Fig. 10. The tunability of $40\text{Ba}_{0.5}\text{Sr}_{0.5}\text{TiO}_3$-$x\text{MgO}-(60-x)\text{Mg}_2\text{TiO}_4$ composites at 10kHz.](image)

### 2.2 BaZr$_x$Ti$_{1-x}$O$_3$ based composites

BaZr$_x$Ti$_{1-x}$O$_3$ can form ferroelectric-dielectric composite with MgO (Maiti et al. 2007b, 2007c, 2008). High tunability and low loss tangent of the BaZr$_x$Ti$_{1-x}$O$_3$: MgO composites are
Fig. 11. The XRD patterns of 40BaZr_{0.2}Ti_{0.8}O_{3}-(60-x)Mg_{2}SiO_{4}-xMgO composites ceramics sintered at 1350°C for 3h. (a) x=48wt%, (b) x=36wt%, (c) x=30wt%, (d) x=24wt%, (e) x=12wt%.

Fig. 12. FESEM images of 40BaZr_{0.2}Ti_{0.8}O_{3}-(60-x)Mg_{2}SiO_{4}-xMgO composites ceramics sintered at 1350°C for 3h. From (a) to (e), x=48 wt%, 36 wt%, 30 wt%, 24 wt% and 12 wt%, respectively.
reported, but the sintering temperature is as high as 1500°C. We prepared BaZr$_{0.2}$Ti$_{0.8}$O$_3$-Mg$_2$SiO$_4$-MgO composite ceramics at 1350°C (He et al. 2011). The formation of ferroelectric (BaZr$_{0.2}$Ti$_{0.8}$O$_3$)-dielectric (Mg$_2$SiO$_4$-MgO) composite was proved by XRD patterns (Fig. 11). Similar to Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Mg$_2$SiO$_4$-MgO composites, three kind of grains: BaZr$_{0.2}$Ti$_{0.8}$O$_3$, Mg$_2$SiO$_4$ and MgO, can be identified (Fig. 12 and Fig. 13).

Fig. 13. FESEM image and element mapping of 40BaZr$_{0.2}$Ti$_{0.8}$O$_3$-12Mg$_2$SiO$_4$-48MgO as determined by energy dispersive spectroscopy (EDS).

Fig. 14. Dielectric constant (solid) and loss tangent (open) of 40BaZr$_{0.2}$Ti$_{0.8}$O$_3$-(60-x)Mg$_2$SiO$_4$-xMgO composites ceramics sintered at various temperature (measure frequency: 1MHz).
Fig. 14 shows the dielectric constant and loss tangent of BaZr$_{0.2}$Ti$_{0.8}$O$_3$-Mg$_2$SiO$_4$-MgO composite ceramics at 1MHz. With the increase of sintering temperature from 1300°C to 1350°C, the dielectric constant of the composites increase and the loss tangent decrease.

Fig. 15. Variation of dielectric constant (solid) and loss tangent (open) with temperature for 40BaZr$_{0.2}$Ti$_{0.8}$O$_3$-(60-x)Mg$_2$SiO$_4$-xMgO ceramics (sintering temperature: 1350°C) measured at 100kHz.

Fig. 16. The tunability of 40BaZr$_{0.2}$Ti$_{0.8}$O$_3$-(60-x)Mg$_2$SiO$_4$-xMgO composite ceramics at 100kHz at room temperature (sintering temperature: 1350°C).
Increasing Mg$_2$SiO$_4$ content tends to decrease the dielectric constant of composites. The dielectric constant and loss tangent of composite sintered at 1350°C is ~125-183 and ~0.0010-0.0016, respectively, which is smaller than that of BaZr$_{0.2}$Ti$_{0.8}$O$_3$ (Maiti et al. 2007b). The temperature dependence of dielectric properties for BaZr$_{0.2}$Ti$_{0.8}$O$_3$-Mg$_2$SiO$_4$-MgO composites (sintering temperature: 1350°C) measured at 100kHz is illustrated in Fig. 15. Compared with pure BaZr$_{0.2}$Ti$_{0.8}$O$_3$ bulk ceramic (Maiti et al. 2007b), broadened and suppressed dielectric peaks and shifts of Curie temperature $T_c$ are observed with the addition of Mg$_2$SiO$_4$ and MgO. The results are similar to that of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Mg$_2$SiO$_4$-MgO. For 40BaZr$_{0.2}$Ti$_{0.8}$O$_3$-12Mg$_2$SiO$_4$-48MgO ceramics, its $\varepsilon_{\text{max}}$ decreases to ~215.5 and $T_c$ shifts to lower temperature ~246K. For 40BaZr$_{0.2}$Ti$_{0.8}$O$_3$-48Mg$_2$SiO$_4$-12MgO, $\varepsilon_{\text{max}}$ is ~157.7 at ~240K. Fig. 16. shows the tunability of the BaZr$_{0.2}$Ti$_{0.8}$O$_3$-Mg$_2$SiO$_4$-MgO composites at 100kHz at room temperature. The tunability of 40BaZr$_{0.2}$Ti$_{0.8}$O$_3$-12Mg$_2$SiO$_4$-48MgO under 2kV/mm is 15.6%. With the increase of Mg$_2$SiO$_4$ content, the tunability of 40BaZr$_{0.2}$Ti$_{0.8}$O$_3$-30Mg$_2$SiO$_4$-30MgO decreases slightly to 14.2%. Further increasing Mg$_2$SiO$_4$ content results in an anomalous increase of tunability: 40BaZr$_{0.2}$Ti$_{0.8}$O$_3$-48Mg$_2$SiO$_4$-12MgO composite has lower dielectric constant than 40BaZr$_{0.2}$Ti$_{0.8}$O$_3$-12Mg$_2$SiO$_4$-48MgO but slightly higher tunability (17.9%).

3. Ferroelectric-dielectric solid solution

Forming ferroelectric-dielectric solid solution is another method to reduce material dielectric constant and loss tangent. Some non-ferroelectric complex oxides with perovskite structures have relatively low dielectric constant and low loss tangent. It is expected that they can be combined with barium strontium titanate to reduce material dielectric constant and loss tangent. Furthermore, it is possible for them to form solid solutions with barium strontium titanate because they have the same perovskite structure as barium strontium titanate. Single phase material is favorable for the thin film deposition. On the other hand, some perovskite oxide has positive temperature coefficient of dielectric constant and it can decrease the temperature coefficient of dielectric constant of barium strontium titanate above Curie temperature.

3.1 Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Sr(Ga$_{0.5}$Ti$_{0.5}$)O$_3$ solid solution

Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ has a comparatively small dielectric constant (27 at 1MHz), a positive temperature coefficient of dielectric constant (120ppmK$^{-1}$) and a low dielectric loss (Q=8600 at 10.6 GHz) (Takahashi et al. 1997). The lattice constant (a=0.3949nm) of cubic perovskite structure Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ is very close to that of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ (a=0.3965nm). Therefore, Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ will be possible to form solid solution with Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ and reduce the dielectric constant of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$. The XRD results (Fig. 17.) prove that solid solution can be formed between Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ and Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ under the preparative conditions (Xu et al. 2008). Fig. 18 shows the FESEM images of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ ceramics sintered at 1600°C for 3h. The effect of Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ content on the average grain size in not very obvious. We can also see that 0.9Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-0.1Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ has higher porosity than other compositions. The morphology of 0.5Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-0.5Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ shows difference from that of other three compositions. The temperature dependence of dielectric properties for various Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-
Fig. 17. The XRD patterns of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ ceramics sintered at 1600°C for 3h. From bottom to top, the Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ content is 10, 20, 30 and 50mol%, respectively. The intensity is plotted on a log scale.

Fig. 18. FESEM images of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ ceramics sintered at 1600°C for 3h. From (a) to (d), the Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ content is 10, 20, 30 and 50mol%, respectively.
Sr(Ga0.5Ta0.5)O3 ceramics (sintering temperature: 1600°C) measured at 100kHz is illustrated in Fig. 19. Broadened and suppressed dielectric peaks and shifts of Curie temperature Tc are observed with the addition of Sr(Ga0.5Ta0.5)O3. For 0.9Ba0.6Sr0.4TiO3-0.1Sr(Ga0.5Ta0.5)O3 ceramics, its εmax decreases to ~ 686 and Tc shifts to lower temperature ~250K. As more Sr(Ga0.5Ta0.5)O3 is added to Ba0.6Sr0.4TiO3, Tc shifts to lower temperatures, thus resulting in a decrease in dielectric constant at a given temperature and εmax. For 0.8Ba0.6Sr0.4TiO3-0.2Sr(Ga0.5Ta0.5)O3, εmax is ~335 at ~200K and for 0.5Ba0.6Sr0.4TiO3-0.5Sr(Ga0.5Ta0.5)O3, εmax is ~95 at ~100K. On the other hand, loss tangent increases on cooling. For 0.9Ba0.6Sr0.4TiO3-0.1Sr(Ga0.5Ta0.5)O3 ceramics, there is small peak around ~250K. The loss tangent of 0.5Ba0.6Sr0.4TiO3-0.5Sr(Ga0.5Ta0.5)O3 ceramics (not shown) is almost independent on temperature and fluctuates around 0.004 at the temperature range of 60K-300K.

Fig. 19. Variation of dielectric constant (solid) and loss tangent (open) with temperature for Ba0.6Sr0.4TiO3-Sr(Ga0.5Ta0.5)O3 ceramics (sintering temperature: 1600°C) measured at 100kHz: From (a) to (c), the Sr(Ga0.5Ta0.5)O3 content is 10, 20, and 50 mol%, respectively.

Fig. 20. The tunability of 0.9Ba0.6Sr0.4TiO3-0.1Sr(Ga0.5Ta0.5)O3 and 0.7Ba0.6Sr0.4TiO3-0.3Sr(Ga0.5Ta0.5)O3 at 100 kHz (sintering temperature: 1600°C).
Fig. 20 shows the tunability of the Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ solid solutions at 100kHz, showing that the tunability decreases as the dielectric Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ content increases. The decrease in the dielectric constant and tunability of 0.9Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-0.1Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ results from the Ga and Ta substitution into B-site Ti and Sr substitution into A-site Ba in barium strontium titanate. 0.9Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-0.1Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ has a dielectric tunability 16% under 2.63 kV/mm versus a dielectric constant $\varepsilon=534$. The tunability of 0.7 Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-0.3Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ drops to be 5.7% under 2.63 kV/mm.

The microwave dielectric properties of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ solid solutions were listed in Table 4. With the increase of Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ content, the dielectric constant decrease and the $Q\times f$ value increase. The $Q\times f$ value of the solid solution is not high except 0.5Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-0.5Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$. The low relative density maybe is the main reason: the relative density of 0.9Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-0.1Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$, 0.8Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-0.2Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ and 0.7Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-0.3Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ ceramics sintered at 1600°C for 3h is 82%, 89% and 88%, respectively.

| Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ content(mol%) | $f_0$(GHz) | $\varepsilon$ | $\tan\delta$ | $Q\times f$(GHz) |
|-------------------------------|------------|--------------|--------------|-----------------|
| 10                            | 1.73       | 592.4        | 0.015        | 115             |
| 20                            | 2.05       | 375.3        | 0.013        | 158             |
| 30                            | 2.49       | 236.9        | 0.012        | 208             |
| 50                            | 4.68       | 79.6         | 0.0039       | 1200            |

Table 4. Microwave dielectric properties of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Sr(Ga$_{0.5}$Ta$_{0.5}$)O$_3$ solid solutions

3.2 Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ solid solution
La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ with low dielectric constant and loss tangent can form solid solutions with BaTiO$_3$ or SrTiO$_3$ in the whole compositional range (Avdeev 2002; Lee 2000). As shown in Fig. 21., La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ form solid solution with Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ (Xu et al. 2009).

![Fig. 21. The XRD patterns of (a) 10, (b) 20, (c) 30, (d) 40, (e) 50 and (f) 60 mol% La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ mixed Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ ceramics.](www.intechopen.com)
The microwave dielectric properties of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$–La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ ceramics were investigated. For different composition, the optimal sintering temperature is different. If the sintering temperature exceeds the corresponding value, the sample’s rim and then interior became dark-blue in color, due to partial reduction of Ti$^{4+}$ (d$^0$) to Ti$^{3+}$ (d$^1$) associated with the oxygen loss from the lattice. Fig. 22 shows the dielectric constant and Qf of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$–La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ ceramics sintered at optimal temperature. $\varepsilon$ decreases with the increase of La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ content, from $\varepsilon_r=338.2$ for 0.9Ba$_{0.6}$Sr$_{0.4}$TiO$_3$–0.1La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ to $\varepsilon_r=47$ for 0.4Ba$_{0.6}$Sr$_{0.4}$TiO$_3$–0.6La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$. Qf value increases with increasing amounts of La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$. High Qf value of 9509 GHz with dielectric constant of 46.7 was obtained for 0.4Ba$_{0.6}$Sr$_{0.4}$TiO$_3$–0.6La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ at 5.69 GHz.

Fig. 22. Dielectric constant and quality factor of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$–La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ compositions as a function of La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ content.

Fig. 23. The tunability of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$–La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ compositions measured at 100kHz and room temperature.
The tunability of $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$\text{La(Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ ceramics is shown in Fig. 23. $\text{La(Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ decreases the tunability of $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$ abruptly. The tunability of $0.9\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.1\text{La(Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ is only 3.7% under 1.67 kV/mm, although its Qf reaches 979GHz. Increasing $\text{La(Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ content decreases the tunability further: the tunability of $0.8\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.2\text{La(Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ is 0.5% under 2.08 kV/mm.

The typical FESEM images of $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$\text{La(Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ ceramics sintered at optimal temperature and the energy dispersive spectroscopy of $0.9\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.1\text{La(Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ were shown in Fig. 24. For $0.4\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.6\text{La(Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$, dense ceramics were obtained, but higher porosity can be observed for the other three compositions. The high Qf value of $0.4\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.6\text{La(Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ can be related to its higher relative density. The chemical composition calculated from energy dispersive spectroscopy were listed in Table 5. We can see that the measured At% is consistent with the theoretical value within the error range. The result also proves the formation of solid solution further.

![FESEM images](image1)

![Energy dispersive spectroscopy](image2)

**Table 5.** The chemical composition of $0.9\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.1\text{La(Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$

| Element | Wt% | At%   | Theoretical At% |
|---------|-----|-------|-----------------|
| OK      | 21.15 | 56.99 | 60.61          |
| MgK     | 00.53 | 0.95  | 1.01           |
| SrL     | 18.65 | 9.18  | 7.27           |
| BaL     | 28.76 | 9.03  | 10.91          |
| TiK     | 24.19 | 21.77 | 19.19          |
| LaL     | 06.71 | 2.08  | 2.02           |
3.3 $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$\text{La(Zn}_{0.5}\text{Ti}_{0.5})\text{O}_3$ and $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$\text{Nd(Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ solid solution

La($\text{Zn}_{0.5}\text{Ti}_{0.5})\text{O}_3$ have a comparatively small dielectric constant ($\varepsilon=34$ at 10GHz), a negative temperature coefficient of the resonance frequency ($\tau_f=-52\text{ppmK}^{-1}$) and a low dielectric loss.

![Fig. 25. The XRD patterns of (a) 10, (b) 20, (c) 30, (d) 40, and (e) 50 mol% La($\text{Zn}_{0.5}\text{Ti}_{0.5})\text{O}_3$ mixed $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$ ceramics.](image1)

![Fig. 26. The XRD patterns of (a) 10, (b) 20, (c) 30, (d) 40, and (e) 50 mol% Nd($\text{Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ mixed $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$ ceramics.](image2)
(Qf=59000 GHz) (Cho et al. 1997). For Nd(Mg$_{0.5}$Ti$_{0.5}$)O$_3$, the corresponding value is 26, -49 ppmK$^{-1}$ and 36900 GHz, respectively (Cho et al. 1999). XRD analysis showed that they can form solid solution with Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ (Fig. 25 and 26), but their microwave dielectric properties is inferior to that of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$.

![Graph showing dielectric constant and quality factor of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ compositions as a function of La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ content.](image)

Fig. 27. Dielectric constant and quality factor of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$–La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ compositions as a function of La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ content.

Fig. 27 show the dielectric constant and Qf of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$–La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ ceramics. The dielectric constant of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$–La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ solid solution decrease as the La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ content increases. The Qf values of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$–La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ increase monotonously with increasing La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ content. The highest Qf value of 5674 GHz was achieved in 0.5Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-0.5La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ but reduced to 377 GHz for 0.9Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-0.1La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$. The effect of La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ on the microwave dielectric properties of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$ solid solution is similar to that of La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$. The Qf value of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ is lower obviously than that of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ system although their relative density is higher than that of the corresponding Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-La(Mg$_{0.5}$Ti$_{0.5}$)O$_3$.

| Nd(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ content (mol%) | sintering temperature (°C) | $f_0$(GHz) | $\varepsilon$ | Qf(GHz) |
|------------------------------------------|--------------------------|-----------|-------------|--------|
| 20                                       | 1500                     | 2.68      | 198.3       | 535    |
| 20                                       | 1550                     | 2.83      | 193.0       | 615    |
| 30                                       | 1500                     | 4.05      | 93.0        | 880    |
| 30                                       | 1550                     | 4.30      | 94.7        | 1137   |

Table 6. Microwave dielectric properties of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Nd(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ solid solutions

Table 6 lists the microwave dielectric properties of some Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-Nd(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ ceramics. Although increasing Nd(Mg$_{0.5}$Ti$_{0.5}$)O$_3$ content can increase the Qf value, the Qf value is not ideal: they are even lower than that of Ba$_{0.6}$Sr$_{0.4}$TiO$_3$-La(Zn$_{0.5}$Ti$_{0.5}$)O$_3$ system.
The tunability of $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$\text{La}($\text{Zn}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ ceramics is shown in Fig. 28. The tunability of $0.9\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.1\text{La}($\text{Zn}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ is only 2.7\% under 1.67 kV/mm. It is even smaller than that of $0.9\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.1\text{La}($\text{Mg}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ although $0.9\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.1\text{La}($\text{Zn}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ has higher dielectric constant and loss tangent than that of $0.9\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.1\text{La}($\text{Mg}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$. Similarly, increasing $\text{La}($\text{Zn}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ content decreases the tunability of $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$\text{La}($\text{Zn}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ further. We can see that the dielectric properties of $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$\text{La}($\text{Mg}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ is better than that of $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$\text{La}($\text{Zn}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$.

![Graph showing tunability vs. applied electric field for different compositions](image-url)

Fig. 28. The tunability of $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$\text{La}($\text{Zn}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ compositions measured at 100kHz and room temperature.

4. Discussion

Forming ferroelectric-dielectric solid solution and composite both can reduce the dielectric constant of ferroelectrics efficiently, but has different effect on the dielectric properties of ferroelectrics. (1). Forming solid solution can decrease the dielectric constant of ferroelectrics more rapidly when the doping content is nearly the same. The dielectric constant of $0.5\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.5\text{La}($\text{Mg}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ is 55, which is far lower than that of 60 wt\% MgO-mixed $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$ ($\varepsilon$=118) (Chang & Sengupta 2002; Sengupta & Sengupta 1999) although the doping content in 60 wt\% MgO-mixed $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$ is higher and MgO has lower dielectric constant than La($\text{Mg}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$. (2). Forming solid solution can improve the loss tangent of ferroelectrics more effectively. The Qf value of $0.5\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.5\text{La}($\text{Mg}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ and 60 wt\% MgO-mixed $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$ is 9367GHz and 750GHz (Chang & Sengupta 2002; Sengupta & Sengupta 1999), respectively. Even for loose $0.9\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.1\text{La}($\text{Mg}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ ceramics, its Qf value (979GHz) is much higher than that of $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$\text{Mg}_2\text{TiO}_4$-$\text{MgO}$. In the preparation process of microwave dielectric ceramics, the formation of secondary phase should be prevented. (3). Forming multiphase composite can maintain sufficiently high tunability. $0.5\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$0.5\text{La}($\text{Mg}_{0.5}\text{Ti}_{0.5}$)$_3$O$_3$ has lost tunability completely, but the tunability of 60 wt\% MgO-mixed $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$ at 2kV/mm and 8kV/mm is 10\% and 38\%, respectively (Chang & Sengupta 2002; Sengupta & Sengupta 1999).
Some authors addressed the dielectric response of ferroelectric-dielectric composites theoretically and various composite models were used to evaluate the dielectric constant, tunability, and loss tangent (Astafiev 2003; Sherman et al. 2006; Tagantsev et al. 2006). As Tagantsev stated (Tagantsev et al. 2006), mixing a tunable ferroelectric with a linear dielectric may modify the electrical properties of the material due to mainly two effects: (i) “doping effect”,–effect of doping of the ferroelectric lattice via the substitution of the ions of the host material and (ii) “composite effect”–effects of redistribution of the electric field in the material due to the precipitation of the non-ferroelectric phase at the grain boundaries or in the bulk of the material. The first effect results primarily in a shift and smearing of the temperature anomaly of the permittivity. The second effect leads to a redistribution of the electric field in the material. For ferroelectric-dielectric solid solutions, “composite effect” can be excluded. We can deduce that the addition of low loss perovskite dielectric influenced the chemistry and microstructure of the material, which resulted in the change of dielectric properties of materials. In ferroelectric-dielectric solid solution, a high degree of structural disorder due to random cation arrangement in both A- and B-sites is present, addition of pervoskite dielectrics apparently destroys the ferroelectric state, leading to the sharp decrease of tunability. For ferroelectric-dielectric composites, “doping effect” can be ignored. The effect of the dilution-driven field redistribution in the material is the main manifestation of addition of the dielectric into ferroelectrics in two-phase or multiphase composite. The reduction of the volume of ferroelectric, which is responsible for tuning, causes suppression of the tunability of the material. In ferroelectric-dielectric composites, ferroelectrics host lattice remains unchanged and the decrease of tunability is mainly due to ferroelectric dilution. “Destruction” in solid solution and “dilution” in composite has different effect on the tunability. Therefore, forming ferroelectric-dielectric solid solution can cause the decrease of tunability more sharply.

In ferroelectric-dielectric composite, the big contrast in the values of dielectric constants of linear dielectrics and the ferroelectric affects the redistribution of the electric field around the dielectrics. The dielectric constant of the ferroelectric under applied electric field becomes in-homogeneously distributed over the volume of the ferroelectric. The overall tunability of the composite, thus changes. Two competitive phenomena affect the tunable properties of the ferroelectric when it is diluted with a dielectric (Sherman et al. 2006). First, the reduction of the volume of ferroelectric, which is responsible for tuning, will cause suppression of the tunability of the material. Second, the redistribution of the electric field surrounding the linear dielectrics will affect the local tuning of the ferroelectric. Depending on the shape of the linear dielectrics and on the dielectric constants of the components, the impact of each of these two effects on the composite tunability is different and the second effect may be stronger (Sherman et al. 2006). In ferroelectric-dielectric composite BaZr$_{0.2}$Ti$_{0.8}$O$_3$-Mg$_2$SiO$_4$-MgO, with the increase of Mg$_2$SiO$_4$ content and the decrease of MgO content, the volume of ferroelectric BaZr$_{0.2}$Ti$_{0.8}$O$_3$ decrease due to smaller density of Mg$_2$SiO$_4$ than that of MgO, the tunability of composite will be suppressed. It is the fact as MgO content decreases from 48 wt% to 30 wt%. The anomalous increased tunability in BaZr$_{0.2}$Ti$_{0.8}$O$_3$-Mg$_2$SiO$_4$-MgO composite with MgO content < 30wt% can be attributed to redistribution of the electric field. Mg$_2$SiO$_4$ and MgO have different dielectric constants, they will have different effects on the redistribution of the electric field. The combination of linear dielectrics with different dielectric constants can result in the change of dielectric constant and loss tangent and even increase the tunably by affecting the redistribution of the electric field in the composite. As MgO content decreases from 30 wt% to 12 wt%, the increase of the
tunability due to redistribution of the electric field exceeds the decrease of the tunability due to ferroelectric dilution, so the tunability of composite ceramics increases anomalously. The almost unchanged tunability in Ba_{0.6}Sr_{0.4}TiO_3-Mg_2SiO_4-MgO composite can also be explained. No similar result was observed in BST-Mg_2TiO_4-MgO composite: with the increase of MgO content and the decrease of Mg_2TiO_4 content, the dielectric constant and tunability decrease monotonously. The tunability of 40Ba_{0.5}Sr_{0.5}TiO_3-48Mg_2TiO_4-12MgO ceramics at 2kV/mm is 16.6%, but the corresponding tunability of 40Ba_{0.5}Sr_{0.5}TiO_3-12Mg_2TiO_4-48MgO is only 5.7%.

We can also see that ternary compositions ferroelectric-dielectric composite shows some advantages over binary compositions. (1). We can decrease the dielectric constant of ternary composites and remain the tunability almost unchanged (in Ba_{0.6}Sr_{0.4}TiO_3-Mg_2SiO_4-MgO), even increase the tunability (in BaZr_{0.2}Ti_{0.8}O_3-Mg_2SiO_4-MgO), without increasing the content of linear dielectrics. In order to decrease the dielectric constant of Ba_{0.6}Sr_{0.4}TiO_3-MgO, it is necessary to increase the content of linear dielectrics MgO, and the tunability will decrease inevitably. The tunability of Ba_{0.6}Sr_{0.4}TiO_3-MgO decreases with the increase of MgO content (Chang & Sengupta 2002). For Ba_{0.6}Sr_{0.4}TiO_3-Mg_2SiO_4-MgO composite, their dielectric constant decrease to 85-97, the tunability at 2kV/mm can be kept at around 10%. (2). The sintering temperature of ternary compositions BaZr_{0.2}Ti_{0.8}O_3-Mg_2SiO_4-MgO and Ba_{0.6}Sr_{0.4}TiO_3-Mg_2SiO_4-MgO can be reduced to 1350°C, which is 100°C and 150°C lower than the normal sintering temperature of BST-MgO (~1450°C) and BZT-MgO (~1500°C), respectively. The sintering temperature of BST-Mg_2TiO_4-MgO composite is also lower than that of BST-MgO.

On the other hand, ternary composition is helpful for the formation of ferroelectric-dielectric composite and can prevent from the formation of undesired phase. Forming ferroelectric-dielectric composite is an effective method to reduce the dielectric constant and loss tangent of ferroelectric and maintain higher tunability. The key is that the linear dielectrics with low dielectric constant and loss tangent should not react with ferroelectrics. For binary composition Ba_{0.8}Sr_{0.2}TiO_3-Mg_2SiO_4, it is expected to form ferroelectric (Ba_{0.6}Sr_{0.4}TiO_3)-dielectric (Mg_2SiO_4) composite, but undesired impurity phase Ba_{2}(TiO)(Si_2O_7) is formed among Ba_{0.6}Sr_{0.4}TiO_3-Mg_2SiO_4 composite. Ba_{2}(TiO)(Si_2O_7) deteriorate the properties of composites. MgO and Mg_2SiO_4 combination can prevent from the formation of Ba_{2}(TiO)(Si_2O_7) and ferroelectric (Ba_{0.6}Sr_{0.4}TiO_3) and dielectric (Mg_2SiO_4 and MgO) composite is obtained. Similarly, Mg_2TiO_4 can react with Ba_{1-x}Sr_xTiO_3 (x=0.5 and 0.6) to form BaMg_2Ti_6O_{19}, but no BaMg_6Ti_6O_{19} formed in BST-Mg_2TiO_4-MgO composite. Therefore, maybe ternary compositions can open a new route to decrease the dielectric constant and loss tangent of ferroelectrics and remain higher tunability. In future work, it is necessary to search new combination of linear dielectrics. Even if one linear dielectric may react with ferroelectrics, some linear dielectrics combination is possible to form ferroelectric-dielectric composite with ferroelectrics. This will expand the select range of linear dielectrics.

The multiple-phase ferroelectric-dielectric composites are useful for tunable microwave applications requiring low dielectric constant and make the impedance match more easily. The ferroelectric-dielectric composite bulk ceramics show promising application, especially in accelerator, as active elements of electrically controlled switches and phase shifters in pulse compressors or power distribution circuits of future linear colliders as well as tuning layers for the dielectric based accelerating structures (Kanareykin et al. 2006, 2009a, 2009b). The ferroelectric bulk ceramics can also be used in ferroelectric lens (Rao et al. 1999).
The ferroelectric-dielectric composites might complicate method to effectively deposit films. Therefore, the advantage of ferroelectric-dielectric solid solution over composite is that single phase materials is favorable for the thin film deposition. At the meantime, the tunability of solid solution can be increase to relatively high level by increasing applied electric field. Generally, linear dielectric with perovskite structure can form solid solution with ferroelectric BST. Different linear dielectrics has different effects on the dielectric properties. Among studied solid solution, $\text{Ba}_{0.6}\text{Sr}_{0.4}\text{TiO}_3$-$\text{La}(\text{Mg}_{0.5}\text{Ti}_{0.5})\text{O}_3$ shows better properties. It is necessary to increase the density of the solid solution, meanwhile, prevent the reduction of Ti$^{4+}$.

5. Conclusion

Forming ferroelectric-dielectric composite and solid solution can reduce the dielectric constant of ferroelectrics efficiently, but the mechanisms affecting dielectric properties differ in composites and solid solutions. Forming ferroelectric-dielectric solid solution can improve the loss tangent of ferroelectrics more effectively and is beneficial to film deposition. Forming ferroelectric-dielectric composite is more efficient to decrease the dielectric constant of ferroelectrics to a low value and maintain tunability at a sufficiently high level.

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