Effects of (Co\(_{1/3}\)Nb\(_{2/3}\))\(^{4+}\) Substitution on Microstructure and Microwave Dielectric Properties of Li\(_2\)Ti\(_{1-x}\)(Co\(_{1/3}\)Nb\(_{2/3}\))\(_x\)O\(_3\) Ceramics for Applications in Ceramic Antenna

Wen-Shiush Chen, Ming-Lung Hung and Cheng-Hsing Hsu

Department of Electrical Engineering, National United University, Miao-Li, Taiwan

ABSTRACT

Dielectric properties of Li\(_2\)Ti\(_{1-x}\)(Co\(_{1/3}\)Nb\(_{2/3}\))\(_x\)O\(_3\) (x = 0.1–1.0) ceramics using a solid-state reaction method were investigated. Substitution ratio effects on different phase changes and dielectric characteristics of Li\(_2\)Ti\(_{1-x}\)(Co\(_{1/3}\)Nb\(_{2/3}\))\(_x\)O\(_3\) (x = 0.1–1.0) ceramics were improved because of the solid solution of (Co\(_{1/3}\)Nb\(_{2/3}\))\(^{4+}\) substitution in a Ti site. Therefore, optimal microwave dielectric properties of ε\(_r\) = 213.3, Q × f = 110,000 GHz, τ\(_r\) = 0 ppm/°C were achieved for Li\(_2\)Ti\(_{1-x}\)(Co\(_{1/3}\)Nb\(_{2/3}\))\(_x\)O\(_3\) ceramics sintered at 1150°C for 3 h, which is thus a favorable material for dielectric substrate applications involving a monopole antenna. The monopole antenna fed by a microstrip-line was printed on Li\(_2\)Ti\(_{1-x}\)(Co\(_{1/3}\)Nb\(_{2/3}\))\(_x\)O\(_3\) ceramic substrate.

1. Introduction

With the rapid development in radio frequency communication modules, high-performance microwave dielectric ceramics have received increasing research interest for reducing the size of communication devices [1,2]. For fabricating miniature devices, microwave dielectric ceramics require certain specification properties, namely high quality factor (Q × f), high dielectric constant (ε\(_r\)), and near-zero temperature coefficient of resonant frequency (τ\(_r\)) which have been extensively investigated because they consist of alternating compact of dielectric ceramic substrates [3,4]. Rock-salt type ceramics with a formula of A\(_B\)O\(_3\) such as Li\(_2\)TiO\(_3\), with excellent dielectric properties are currently used as commercial ceramics [5]. Lithium titanium (Li\(_2\)TiO\(_3\)) undergoes order-disorder phase transition at 1213°C and has a high dielectric constant of 22, high quality factor of 63,500 GHz, and a temperature coefficient of resonant frequency of 20.3 ppm/°C [6]. However, Li\(_2\)TiO\(_3\) is not cost efficient because of high sintering temperatures, low quality factor, and a high temperature coefficient of resonant frequency [7]. Therefore, new materials with the desired properties for scientific applications require further study.

Several studies have improved microwave dielectric properties, such as through the partial replacement of a B site in ceramic systems [8,9]. Hsu et al. reported that Zr substitution effectively improved the microwave dielectric properties of Ca\(_{3}\)Al\(_2\)Ti\(_4\)O\(_{13}\) ceramics [10]. Zhao et al. reported the effect of (Mg\(_{1/3}\)Nb\(_{2/3}\))\(^{4+}\) complex ion substitution on the microwave dielectric properties of CaTiO\(_3\) ceramics [11]. Moreover, Chen et al. revealed that (Zn\(_{1/3}\)Nb\(_{2/3}\))\(^{4+}\) complex ion substitution improved dielectric properties of Li\(_2\)TiO\(_3\) ceramics at microwave frequencies [12]. To develop Li\(_2\)TiO\(_3\)-based ceramics with an excellent microwave dielectric properties, the effects of (Co\(_{1/3}\)Nb\(_{2/3}\))\(^{4+}\) substitution for Ti on the sintering behavior, phase transition, microstructure and microwave dielectric properties of Li\(_2\)Ti\(_{1-x}\)(Co\(_{1/3}\)Nb\(_{2/3}\))\(_x\)O\(_3\) (x = 0.1–1.0) ceramics were studied because of the ionic radii of (Co\(_{1/3}\)Nb\(_{2/3}\))\(^{4+}\) (0.675 Å) are similar to that of Ti\(^{4+}\) (0.605 Å) [13]. Furthermore, the optimal microwave dielectric ceramic substrate was used in a monopole antenna fed by a microstrip line. This study developed a multi-band monopole antenna with Li\(_2\)Ti\(_{1-x}\)(Co\(_{1/3}\)Nb\(_{2/3}\))\(_x\)O\(_3\) (x = 0.1–1.0) ceramics comprising a hexagonal-ring with a hexagonal-stub.

2. Experimental Procedure

Samples of Li\(_2\)Ti\(_{1-x}\)(Co\(_{1/3}\)Nb\(_{2/3}\))\(_x\)O\(_3\) (x = 0.1–1.0) mixed according to the required stoichiometry were fabricated using the solid-state method from high-purity oxide powders (>99.9%), namely Li\(_2\)CO\(_3\), CoO, Nb\(_2\)O\(_5\), and TiO\(_2\). The powders were milled using an agate ball in distilled water for 12 h, and all mixtures were then dried. After passing through a 100-mesh sieve, dried mixtures were calcined at 800°C for 6 h. The calcined powders were ground for 12 h to form fine powder. Finally, the fine powder with 3 wt.% of a 10% solution of PVA as a binder was pressed into pellets with a diameter and thickness of 11 and 5 mm, respectively.
These pellets were sintered at temperatures of 1000°C –1210°C for 3 h in air.

Phase identification was performed through X-ray diffraction (XRD) data by using Cu Ka radiation and a graphite monochromator in the 2θ range of 10°-80° (Siemens D5000). Microstructural observations of the sintered samples were performed through scanning electron microscopy (SEM). The bulk density of the sintered samples was measured by using the liquid Archimedes method with distilled water as the liquid. The Hakki- Coleman dielectric resonator method, as modified and improved by Courtney, was used to measure the εr and Q × f values at microwave frequencies [14,15]. The dielectric resonator was positioned between two brass plates to form a cavity-like structure. A test cavity was placed over a thermostat, and the temperature ranged from 25°C to 80°C, with a heating rate and residence time of 1°C/min and 10 min, respectively, for each cycle. The change in resonant frequency was observed to calculate τr (ppm/°C).

3. Antenna Design

Figure 1 shows the geometry of the proposed antenna. The antenna was printed on a Li2Ti1−x(Co1/3Nb2/3)3O3 ceramic substrate with thickness h = 1.6 mm and relative permittivity 21.3. The proposed antenna has a dimension of a 30 × 35 mm². The primary structure of the proposed antenna included a hexagonal-ring with a hexagonal-stub structure and a 50 ohm microstrip feed line. The length of the microstrip feedline was 1.2 mm. Table 1 presents the other parameters, which were fixed.

The side length of the hexagonal-ring (W3 and W4) and hexagonal radiator (W5) were modified. Performance may be modified to have a relation with frequency by appropriately selecting the aforementioned parameters. Figure 1 shows the detail parameters of the proposed antenna. The antenna was initially simulated using Ansoft simulation software with a high frequency structure simulator. A model was then fabricated with the provided experimental results provided. Figure 2 shows the proposed antenna. Details of the antenna effects and measured results are presented and discussed.

4. Results and Discussions

Figure 3 presents XRD patterns of Li2Ti1−x(Co1/3Nb2/3)3O3 (x = 0.1–1.0) compositions sintered at 1000–1210°C for 3 h. The secondary phase was not detected in the XRD patterns for various (Co1/3Nb2/3)4+ contents and sintering temperatures. Moreover, with the increasing sintering temperature, no significant diffraction peak position shift was observed. These reflections with x = 0.1–0.3 could be adequately indexed according to Li2TiO3 type (ICDD-PDF: 33–0831) and monoclinic rock-salt type structure, fitting in C2/c space group for all specimens, which indicates the formation of solid solutions. With the increasing x, the intensity of the (002) index decreased, indicating a disordered rock-salt structure and fitting in the Fm-3 m space group at x = 0.5 and 0.7. This suggested an order–disorder phase transition to form a cubic system, which is in agreement with previous results.12 Moreover, when replacement ratios are 0.9 and 1.0, the structure is based on PFD # 82–1198, which is known as the cubic rock-salt structure of Li3NbO4.

This structure belongs to the I-43 m space group, indicating the formation of solid solutions. Moreover, diffraction peaks shifted to lower angles of 2θ (e.g. 2θ ~ 36°, 37°, 43° and 63°) with the increasing x value, which

| Table 1. Dimensions of the proposed antenna with the Li2Ti0.7(Co0.33Nb0.67)3O3 ceramic substrate. |
|---|---|---|---|---|---|
| W | L | H | G | L2 | W2 |
| 30 mm | 35 mm | 1.6 mm | 7.4 mm | 8.8 mm | 1.1 mm |

![Figure 1. Geometry of the proposed antenna: (a) front view, (b) back view, and (c) side view.](image-url)
indicated that the cell volume increased with x because of the substitution of (Co$_{1/3}$Nb$_{2/3}$)$_{4+}$, which has a high ionic radius, for Ti$^{4+}$, which has a small one.

Figure 4 shows the effect of substituting (Co$_{1/3}$Nb$_{2/3}$)$_{4+}$ on the Li$_2$TiO$_3$ ceramic microstructure at various sintering temperatures. The grain growth and porous microstructure of all samples can be observed at increasing sintering temperature. The uniform and dense surface morphology of Li$_2$Ti$_{0.7}$(Co$_{1/3}$Nb$_{2/3}$)$_{0.3}$O$_3$ samples can be obtained. However, an increase in pores and irregular grain is observed at higher sintering temperature when x = 0.3.

For this experiment, the optimal dielectric properties were observed at a sintering temperature of approximately 1150°C.

Figure 5 shows the variation in bulk density and relative density as a function of x for Li$_2$Ti$_{1-x}$(Co$_{1/3}$Nb$_{2/3}$)$_{x}$O$_3$ ceramics sintered at various sintering temperatures. With the increasing sintering temperature, bulk density increased to a maximum value and thereafter was saturated at the higher sintering temperature for all compositions. The increasing density was attributed to the grain growth of the sample (Figure 4). However,
very high sintering temperature evaporated Li, increased grain growth, and increased porosity, which subsequently reduced density. Furthermore, bulk density increased from 3.3 g/cm$^3$ to 3.89 g/cm$^3$ with the increasing $x$. The increasing bulk density may be attributable to the transformation of the Li$_2$TiO$_3$ phase, which has a theoretical density of 3.415 g/cm$^3$, into the Li$_3$NbO$_4$ phase, which has a theoretical density of 3.966 g/cm$^3$. Thus, relative density increased with the increasing substitution ratio. The relative density may directly affect the dielectric properties.

Figure 6 presents the dielectric constant of the Li$_2$Ti$_{1-x}$(Co$_{1/3}$Nb$_{2/3}$)$_x$O$_3$ (x = 0.1–1) ceramic system as a function of sintering temperature. The range of the $\varepsilon_r$ value of (Co$_{1/3}$Nb$_{2/3}$)$^{4+}$ substitution for Ti$^{4+}$ is 22.4–15.4, which increased to a maximum value with the increasing sintering temperature and thereafter remained constant at high sintering temperature for all compositions. The variation in the dielectric constant with various sintering temperatures was consistent with that of the bulk density, indicating that the dielectric constant was primarily controlled by the sample density. Moreover, the dielectric constant was affected by average ionic polarizability based on the modified Clausius-Mossotti equation. Table 2 presents the lattice constant, unit cell volume and ionic polarizability of Li$_2$Ti$_{1-x}$(Co$_{1/3}$Nb$_{2/3}$)$_x$O$_3$ ceramics. The crystal structure, unit cell volume, and ionic polarizability exhibits variation as a function of $x$. The dielectric constant decreased with increasing $x$, and exhibited the same trend as that of ionic polarizability.
Figure 7 presents the $Q \times f$ value of Li$_2$Ti$_{1-x}$(Co$_{1/3}$Nb$_{2/3}$)$_x$O$_3$ ($x = 0.1–1$) ceramic system as a function of sintering temperature. Bulk density is crucial for controlling microwave dielectric loss, which is also affected by lattice vibrational modes, pores, grain morphology, and secondary phase [16,17]. With the increasing sintering temperature, $Q \times f$ increased to a maximum value and thereafter remained constant at high sintering temperatures for all compositions. This phenomenon may be have been caused by the porous samples at low sintering temperature reducing the $Q \times f$ value. Moreover, reduction in $Q \times f$ value at high sintering temperature is attributed to the increased grain growth (Figure 4). The same trend is observed for bulk density. The $Q \times f$ values of the optimal sintering temperature were measured from 51,000 to 110,000 GHz with the increasing $x$ value, after which it decreased. The reduction in $Q \times f$ value was attributed to the increased grain growth, which increased with the $x$ value (Figure 4). Relative uniform morphology of the samples was observed at $x = 0.3$. Figure 8 presents the $\tau_f$ values of the Li$_2$Ti$_{1-x}$(Co$_{1/3}$Nb$_{2/3}$)$_x$O$_3$ ($x = 0.1–1$) ceramic system. The temperature coefficient of the resonant frequency is related to the microstructure, composition, porosity, and secondary phase of the material. No significant change in the $\tau_f$ value was observed with various sintering temperatures, which indicate that is almost independent of sintering conditions. In addition, the $\tau_f$ values of the Li$_2$Ti$_{1-x}$(Co$_{1/3}$Nb$_{2/3}$)$_x$O$_3$ ($x = 0.1–1$) ceramic system varied from 24.6 to −39.6 ppm/°C with increasing $x$. The variation in $\tau_f$ could be attributed to the distortion of
Figure 5. (a) Bulk density and relative density of the Li$_2$Ti$_{1-x}$(Co$_{1/3}$Nb$_{2/3}$)$_x$O$_3$ ($x = 0.1–1$) ceramics as a function of sintering temperature.

Figure 6. Dielectric constant of the Li$_2$Ti$_{1-x}$(Co$_{1/3}$Nb$_{2/3}$)$_x$O$_3$ ($x = 0.1–1$) ceramics as a function of sintering temperature.
the microstructure, crystal lattice, defects, and phase transition [18]. Significant changes were observed in the \( \tau_f \) value for different \( \text{(Co}_{1/3}\text{Nb}_{2/3})^{4+} \) contents, indicating that the \( \tau_f \) value was sensitive to the \( \text{(Co}_{1/3}\text{Nb}_{2/3})^{4+} \) content. A zero \( \tau_f \) value \( (\tau_f = 0 \text{ ppm/°C}) \) was obtained at \( x = 0.3 \) and a sintering temperature of 1150°C. Figure 9 shows simulated return losses for the proposed antenna in terms of the different side lengths of

Table 2. Lattice constants, unit cell volume, and ionic polarizability of Li₂Ti₁₋ₓ(\( \text{Co}_{1/3}\text{Nb}_{2/3})_x\text{O}_3 \) composite ceramic samples.

|                | a (Å) | b (Å) | c (Å) | \( \beta \) | Unit Cell Volume (Å³) | Ionic Polarizability |
|----------------|-------|-------|-------|------------|-----------------------|---------------------|
| \( \text{Li}_2\text{Ti}_x(\text{Co}_{1/3}\text{Nb}_{2/3})_{1-x}\text{O}_3 \) | \( 5.039 \) | \( 8.826 \) | \( 9.626 \) | \( 99.746^\circ \) | \( 17.585 \) | \( 3.751 \) |
| (Monoclinic System) | \( 5.079 \) | \( 8.846 \) | \( 9.717 \) | \( 99.992^\circ \) | \( 17.917 \) | \( 3.750 \) |
| \( \text{Li}_2\text{Ti}_x(\text{Co}_{1/3}\text{Nb}_{2/3})_{1-x}\text{O}_3 \) | \( 4.158 \) | | | \( \text{(Cubic System)} \) | \( 17.980 \) | \( 3.744 \) |
| (Monoclinic System) | \( 4.178 \) | | | \( \text{(Cubic System)} \) | \( 18.240 \) | \( 3.739 \) |
| \( \text{Li}_2\text{Ti}_x(\text{Co}_{1/3}\text{Nb}_{2/3})_{1-x}\text{O}_3 \) | \( 8.420 \) | | | \( \text{(Cubic System)} \) | \( 18.655 \) | \( 3.731 \) |
| (Cubic System) | \( 8.437 \) | | | \( \text{(Cubic System)} \) | \( 18.773 \) | \( 3.727 \) |

Figure 7. Quality factor \( (Q \times f) \) of the Li₂Ti₁₋ₓ(\( \text{Co}_{1/3}\text{Nb}_{2/3})_x\text{O}_3 \) \( (x = 0.1–1) \) ceramics as a function of sintering temperature.

Figure 8. Temperature coefficient of resonant frequency \( (\tau_f) \) of the Li₂Ti₁₋ₓ(\( \text{Co}_{1/3}\text{Nb}_{2/3})_x\text{O}_3 \) \( (x = 0.1–1) \) ceramics as a function of sintering temperature.
Figure 9. Simulated return loss for proposed antenna with various side lengths: (a) W3, (b) W4, and (c) W5.

Figure 10. Measured and simulated return loss for proposed antenna with the Li$_2$Ti$_{0.7}$(Co$_{1/3}$Nb$_{2/3}$)$_{0.3}$O$_3$ substrate.
the hexagonal-ring (W3 and W4) and hexagonal radiator (W5). W3 of 12.9–14.9 mm affected the impedance bandwidth (return loss less than –10 dB) and high-frequency band response (frequency > 5 GHz) of the proposed antenna. In addition, Figure 9(b) presents the effect of the side length of hexagonal-ring W4 on impedance matching. Varying W4 from 9.4 to 11.4 mm affected the impedance bandwidth of the proposed antenna for \( f = 2.45 \) GHz. Finally, the optimal impedance matching (return loss \( \geq 10 \) dB) for multi-band frequencies was obtained for W5 = 2.4 mm [Figure 9(c)].

Figure 10 compares the simulated and measured return losses as functions of frequency. For validating the measured results, the simulation results obtained through EM simulation software are shown in Figure 3. The simulated result is consistent with the measured data, confirming the measurement accuracy. The measured values indicated that the monopole antenna with a hexagonal-ring and a hexagonal radiator structure provides covering frequencies from multi-band frequencies (2.45, 5.2, and 7.1 GHz), which is termed 10 dB return loss. The results confirmed that the proposed monopole antenna is suitable for multi-band frequencies.
The radiation characteristics were also studied. Figure 11 presents the radiation patterns on the E- and H-planes for the proposed antenna at 2.45 and 5.2 GHz. The obtained radiation patterns were consistent with those of the monopole antenna with a hexagonal-ring and hexagonal radiator structure. The patterns in the x-y plane for co-polarization are approximately omni-directional and symmetrical to the antenna axis because of the symmetrical structure of the proposed antenna.

5. Conclusion

Microwave dielectric properties of (Co<sub>1/3</sub>Nb<sub>2/3</sub>)<sup>1+x</sup> substituted for Ti<sup>4+</sup> to form Li<sub>2</sub>Ti<sub>x</sub>(Co<sub>1/3</sub>Nb<sub>2/3</sub>)<sub>1-x</sub>O<sub>3</sub> (x = 0.1–1) ceramics prepared using the conventional solid-state oxides method were investigated. The dielectric constant and temperature coefficient of the resonant frequency of the Li<sub>2</sub>Ti<sub>x</sub>(Co<sub>1/3</sub>Nb<sub>2/3</sub>)<sub>1-x</sub>O<sub>3</sub> (x = 0.1–1) ceramics decreased with increasing x. However, as x increased, the Q x f values for the optimal sintering temperature reached a maximum and then decreased. The reduction in Q x f can be attributed to the increasing grain growth with the increasing x value. Compared to previous research about x = 0 for Li<sub>2</sub>TiO<sub>3</sub> ceramic (ε<sub>r</sub> ~ 22, Q x f ~ 63,500 GHz, and τ<sub>f</sub> ~ 20.3 ppm/°C) sintered at 1213°C [6], a obvious improvement in the microwave dielectric properties has been accomplished. Excellent microwave dielectric properties (ε<sub>r</sub> ~ 21.3, Q x f ~ 110,000 GHz and τ<sub>f</sub> value ~ 0 ppm/°C) can be obtained for Li<sub>2</sub>TiO<sub>x</sub>(Co<sub>1/3</sub>Nb<sub>2/3</sub>)<sub>1-x</sub>O<sub>3</sub> ceramics (x = 0.3) sintered at 1150°C for 3 h. On the other hand, a planar monopole Li<sub>2</sub>TiO<sub>x</sub>(Co<sub>1/3</sub>Nb<sub>2/3</sub>)<sub>1-x</sub>O<sub>3</sub> ceramic antenna with a hexagonal-ring and hexagonal radiator structure was investigated. The side lengths of a hexagonal-ring (W3 and W4) and a hexagonal radiator (W5), were tuned to obtain multi-band performance with the measured return-loss response of the designed Li<sub>2</sub>TiO<sub>x</sub>(Co<sub>1/3</sub>Nb<sub>2/3</sub>)<sub>1-x</sub>O<sub>3</sub> ceramic antenna at 2.45, 5.2, and 7.1 GHz. The antenna has a simple structure, omni-directional characteristics in the H-plane, simple fabrication, and easy integration with other circuitries. The proposed antenna is suitable for multi-band applications.

Acknowledgments

This work was supported by the Ministry of Science and Technology of the Republic of China under grants MOST 106-2622-E-239-005-CC3, MOST 107-2221-E-239-024-MY2, MOST 107-2218-E-006–046, and MOST 109-2224-E-006–006.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

[1] Reaney IM. Microwave dielectric ceramics for resonators and filters in mobile phone networks. J Am Ceram Soc. 2006;89:2063–2072. IdledisD.
[2] Cava RJ. Dielectric materials for applications in microwave communications. J Mater Chem. 2001;11(1):54–62.
[3] Ahn C-W, Nahm SN, Lim Y-S, et al. Microstructure and Microwave Dielectric Properties of Ba(Co 1/3 Nb 2/3)O<sub>3</sub> Ceramics. Jpn J Appl Phys. 2002;41(1):5277-5280.
[4] Li Q, Qi JQ, Wang YL, et al. Improvement of temperature-stable BaTiO<sub>3</sub>-based dielectrics by addition of Li<sub>2</sub>C<sub>2</sub>O<sub>3</sub> and <sub>sub</sub>Co<sub>3.0</sub> J Euro Ceram Soc. 2001;21(12):2217–2220.
[5] Castellanos M, West AR. Order–disorder phenomena in oxides with rock salt structures: the system Li<sub>2</sub>TiO<sub>3</sub>–MgO. J Mater Sci. 1979;14(2):450–454.
[6] Bian JJ, Wang L, Yuan LL. Microwave dielectric properties of <sub>sub</sub>Li<sub>x</sub>2+<sub>x</sub>Ti<sub>1-x</sub>O<sub>3</sub> +<sub>x</sub>MgO system (0≤x≤0.1). Mater Sci Eng B. 2009;164(2):96–100.
[7] Bian JJ, Dong YF. New high Q microwave dielectric ceramics with rock salt structures: (1–x)Li<sub>2</sub>Tio<sub>x</sub> +<sub>x</sub>MgO system (0≤x≤0.5). J Euro Ceram Soc. 2010;30(2):325–330.
[8] Chen WS, Yu CC, Hsu CH, et al. Temperature coefficient of resonant frequency tuning of microwave dielectric based on Zr substitutions for Ti on Ca<sub>3</sub>Sm<sub>2</sub>Ti<sub>3</sub>O<sub>12</sub> ceramic system. J Mater Sci: Mater Electron. 2017;28:6461–6466.
[9] Tseng CF, Wei TC, Lu SC. Influence of A-site Ba substitution on microwave dielectric properties of <sub>sub</sub>BaMg<sub>1</sub>–(x)O<sub>3</sub> (A=Zr; Sn) ceramics. Ceram Int. 2014;40(5):7081–7085.
[10] Hsu C-H, Huang C-J. Preparation, structural and microwave dielectric properties of <sub>sub</sub>CaLa(4/3Zn<sub>1/3</sub>Ti<sub>1-x</sub>)–0.15 ceramics. J Alloys Compd. 2014;587:45–49.
[11] Zhao F, Yue ZX, Zhang YC, et al. Microstructure and microwave dielectric properties of <sub>sub</sub>Ca(1–x) (Mg1/3Nb2/3)xO3 ceramics. J Euro Ceram Soc. 2005;25(14):3347–3352.
[12] Chen GH, Xu H-R, Yuan CL. Microstructure and microwave dielectric properties of <sub>sub</sub>Li<sub>2</sub>TiO<sub>x</sub>–(Zn1/3Nb2/3)–0.3O3 ceramics. Ceram Int. 2013;39(5):4887–4892.
[13] Chen HT, Tang B, Zhang SR. Microwave Dielectric Properties of Ba<sub>3</sub>−<sub>x</sub>Nd<sub>x</sub>TiO<sub>3</sub> Ceramic by the (Co<sub>1/3</sub>Nb<sub>2/3</sub>)<sup>4+</sup> Substitution. Kuala Lumpur, Malaysia: 2131 In Proceeding of the 2017 Asia-Pacific Engineering and Technology Conference (APETC2017). 2017.
[14] Hakki BW, Coleman PD. A dielectric resonator method of measuring inductive capacitances in the millimeter range. IEEE Trans Microwave Theory Tech. 1962(4):402–410.
[15] Courteney WE. Analysis and Evaluation of a Method of Measuring the Complex Permittivity and Permeability Microwave Insulators. IEEE Trans Microwave Theory Tech. 1970;18(8):476–485.
[16] Silverman BD. Microwave absorption in cubic strontium titanate. Phys Rev. 1962;125(6):1921–1930.
[17] Tamura H. Microwave dielectric losses caused by lattice defects. J Euro Ceram Soc. 2006;26(10–11):1775–1780.
[18] Chen XY, Bai SX, Zhang WJ. Low temperature sintering and microwave dielectric properties of Bi<sub>3</sub>B<sub>2</sub>O<sub>5</sub>–0.25CaTiO<sub>3</sub>–0.75(Li<sub>1/2</sub>Nd<sub>1/2</sub>)TiO<sub>3</sub> ceramics. J Alloys Compd. 2012;541:132–136.