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Research Article

Tailoring configurational entropy and phase evolution in $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ ceramics for high-performance C-band dielectric resonator antennas

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Abstract

Achieving a near-zero temperature coefficient of resonant frequency (τ_f) while maintaining an ultra-high quality factor ($Q \times f$) remains a critical challenge for microwave dielectric ceramics in next-generation 5G/6G communication systems. Herein, we report a configurational entropy engineering strategy that tailors the phase evolution and dielectric properties of $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ (LBV@ x , $x = 0.05-0.9$) ceramics through controlled Bi^{3+} substitution. By systematically decreasing the configurational entropy from the high-entropy regime (>1.61 R) to the low-entropy regime (0.49 R), we trigger a phase transition from tetragonal zircon ($I4_1/amd$) to monoclinic scheelite ($I2/b$) at $x > 0.7$, driven by the combined effects of large ionic radius mismatch and entropy reduction. The high-entropy ceramic LBV@0.05 exhibits an exceptional $Q \times f$ of 96,870 GHz and a τ_f of -11.9 ppm/ $^{\circ}\text{C}$, whereas near-zero τ_f values of $+8.5$ and $+10.7$ ppm/ $^{\circ}\text{C}$ are achieved in the single-phase zircon LBV@0.1 and the zircon-scheelite composite LBV@0.8, respectively, thereby effectively mitigating the conventional trade-off between high

$Q \times f$ and temperature stability and offering a tunable pathway to balance these two critical parameters. The τ_f exhibits a non-monotonic dependence on Bi^{3+} content, transitioning from $-11.9 \text{ ppm}/^\circ\text{C}$ ($x = 0.05$) to $+132.0 \text{ ppm}/^\circ\text{C}$ ($x = 0.7$) and then to $-195.7 \text{ ppm}/^\circ\text{C}$ ($x = 0.9$), attributed to the competing effects of linear expansion coefficient, ionic polarizability, and dielectric anharmonicity. Furthermore, a C-band dielectric resonator antenna fabricated from LBV@0.1 demonstrates a peak gain of 6.88 dBi, a simulated radiation efficiency of 95.25%, and a bandwidth of 269 MHz at 5.449 GHz, validating the practical viability of these materials.

Keywords: Microwave dielectric ceramics; Structural evolution; Configurational entropy; Near-zero τ_f ; Dielectric resonator antenna.

1. Introduction

The rapid advancement of 5G and emerging 6G communication technologies has significantly increased the demand for high-performance microwave dielectric ceramics, particularly for essential RF components such as bandpass filters, dielectric resonator antennas, and low-loss substrates [1,2]. Modern 5G/6G systems impose stringent performance requirements on these materials, including a low dielectric constant ($\epsilon_r < 15$), a high quality factor ($Q \times f > 100,000 \text{ GHz}$, $\tan\delta = 1/Q$), and excellent temperature stability of the resonant frequency (τ_f within $\pm 10 \text{ ppm}/^\circ\text{C}$) [3,4].

Furthermore, compatibility with low-temperature co-fired ceramic (LTCC) technology and advanced packaging integration is increasingly required for fabricating compact, multifunctional RF modules [5]. Unfortunately, these three key

parameters are often entangled in a delicate trade-off, rendering the simultaneous optimization of low ϵ_r , high $Q \times f$, and near-zero τ_f one of the most formidable challenges in the field of microwave materials [6,7].

Among the various ceramic systems investigated for millimeter-wave applications, vanadate-based zircon-type ceramics with the general formula AVO_4 (A = trivalent rare-earth cation) have attracted considerable attention owing to their intrinsically low ϵ_r values, which stem from the presence of distorted $[AO_8]$ dodecahedra and relatively rigid $[VO_4]$ tetrahedra in their crystal structure [8]. These structural features render AVO_4 ceramics promising candidates for high-frequency applications where parasitic capacitance and signal crosstalk must be minimized. However, conventional single-cation AVO_4 ceramics have two critical drawbacks that severely impede practical deployment. First, they inherently exhibit large negative τ_f values (< -30 ppm/ $^{\circ}\text{C}$), originating from strong dielectric anharmonicity and insufficient compensation between the temperature coefficient of permittivity and the thermal expansion coefficient. Second, their $Q \times f$ values are generally modest ($< 50,000$ GHz), primarily due to A-site lattice distortion, localized strain fields, and associated phonon damping mechanisms [9-12]. These limitations have motivated extensive research into novel compositional and structural engineering strategies to break the performance deadlock in vanadate ceramics.

Recently, high-entropy ceramics have emerged as a promising class of functional materials for improving microwave dielectric properties, owing to their unique ability to stabilize structures through configurational entropy [13,14]. Constructing a

high-entropy zircon system by integrating multiple rare-earth ions at the A-site effectively minimizes lattice distortion, enhances the stability of the crystalline phase, and significantly improves $Q \times f$. For example, Zhang *et al.* [15] found that the high-entropy vanadate ($\text{Nd}_{0.2}\text{Eu}_{0.2}\text{Y}_{0.2}\text{Ho}_{0.2}\text{Yb}_{0.2}$) VO_4 stabilized a single zircon phase due to its high configurational entropy, which significantly reduced A-site lattice distortion and defect formation, yielding a high $Q \times f$ value of 76,400 GHz in the resulting tetragonal zircon ceramic. However, this high-entropy system still exhibited a relatively large negative τ_f value of -37.3 ppm/ $^{\circ}\text{C}$. Similarly, in the high-entropy system ($\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}$) VO_4 [16], increasing the average size of the A-site ions further stabilized the crystal structure, leading to a record ultra-high $Q \times f$ value of 107,200 GHz. Nonetheless, its τ_f value remained largely unchanged at -32.7 ppm/ $^{\circ}\text{C}$. Introducing an appropriate amount of Bi^{3+} at the A-site is an effective method to control the dielectric response and address the negative τ_f value in vanadium-based zircon ceramics. For instance, Zhou *et al.* [9,17] reported that the τ_f varied from -260 to $+176.3$ ppm/ $^{\circ}\text{C}$ in the $\text{Bi}_{1-x}\text{Ce}_x\text{VO}_4$ system and from -61.3 to $+103$ ppm/ $^{\circ}\text{C}$ in the $(\text{Bi}_{1-x}\text{Y}_x)\text{VO}_4$ ($0.4 \leq x \leq 1.0$) system, with near-zero values of $+17.8$ and -11.9 ppm/ $^{\circ}\text{C}$ achieved, respectively. In the $\text{Bi}_{1-x}\text{Ho}_x\text{VO}_4$ system [10], the τ_f exhibited a non-monotonic dependence on x , increasing from -140.4 ppm/ $^{\circ}\text{C}$ ($x = 0.1$) to $+76.68$ ppm/ $^{\circ}\text{C}$ ($x = 0.4$) and subsequently decreasing to -6.40 ppm/ $^{\circ}\text{C}$ ($x = 0.9$), yielding two near-zero τ_f compositions near $x \approx 0.17$ and $x \approx 0.83$. However, the influence mechanism of Bi^{3+} doping on the τ_f value and the associated structural evolution characteristics of vanadium-based high-entropy ceramics remains insufficiently

understood.

Motivated by these considerations, the present work strategically combines configurational entropy engineering with targeted Bi^{3+} doping to address the dual challenges of negative τ_f and the $Q \times f - \tau_f$ trade-off in vanadate zircon ceramics. A compositional series $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ (LBV@ x , $x = 0.05-0.9$) was designed using the high-entropy zircon $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})\text{VO}_4$ as the host matrix ($Q \times f = 107,200$ GHz, $\tau_f = -32.7$ ppm/ $^{\circ}\text{C}$). Through comprehensive structural characterization using X-ray diffraction, Rietveld refinement, Raman spectroscopy, and transmission electron microscopy, we establish a clear correlation between configurational entropy reduction, lattice stability, and structural evolution. The microwave dielectric properties are systematically evaluated, with particular emphasis on deciphering the non-monotonic τ_f dependence on Bi^{3+} content through detailed analysis of linear expansion coefficients, ionic polarizability, and dielectric anharmonicity. Furthermore, a C-band dielectric resonator antenna was prototyped and characterized to assess the practical viability of the optimized composition for next-generation wireless systems. This work offers a reliable method to address low $Q \times f$ and negative τ_f in single-phase vanadium-based zircon ceramics while providing new material support for advancing high-performance microwave devices.

2. Experimental and characterization

$(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ (denoted as LBV@ x , $x = 0.05-0.9$) ceramics were synthesized by conventional solid-state reaction from high-purity La_2O_3 , Ce_2O_3 , Nd_2O_3 , Sm_2O_3 , Eu_2O_3 , Bi_2O_3 , and NH_4VO_3 (99.99%, Aladdin). The rare-earth oxides

were pre-calcined at 1000 °C for 4 h, after which all reagents were weighed stoichiometrically. The as-weighed powders were transferred to a nylon jar containing zirconia balls and anhydrous ethanol, and ball-milled at 300 rpm for 4 h using a planetary ball mill. The mixtures were dried and calcined in alumina crucibles at 800 °C for 4 h to facilitate the primary reaction of the constituent oxides and yield pre-sintered powders. The resulting powders were ball-milled, granulated with 5 wt.% polyvinyl alcohol (PVA), and pressed into cylindrical pellets (10 mm in diameter and 5 mm in height). The green bodies were heated to 550 °C at 1.5 °C/min, held for 6 h for binder burnout, sintered at 825–1150 °C for 6 h at 5 °C/min in air, and furnace-cooled to room temperature.

The phase composition and crystal structure of the sintered samples were characterized by X-ray powder diffraction (XRD; X'Pert PRO, PANalytical, Netherlands). The microstructure and elemental distribution were observed via scanning electron microscopy (SEM; S-4800, Japan). The lattice structure was analyzed using high-resolution transmission electron microscopy (HR-TEM; JEOL, Japan) combined with selected-area electron diffraction (SAED) patterns. Vickers hardness was assessed with a Vickers indenter (EV-1000L, China). Flexural strength was determined via three-point bending on a universal testing machine (AG-150KN, Japan) using custom cylindrical fixtures. A Raman spectrometer (DXR, Thermo Electron, USA) was used to analyze the local vibrational modes. The bulk density was determined by Archimedes' method. The temperature dependence of ϵ_r was characterized using a dielectric measurement system (DMS-300, Partulab

Technologies, China). The fabrication process for the dielectric resonator antenna was simulated and optimized using Ansys HFSS software. A vector network analyzer (N5230A, Agilent, USA) was employed to evaluate the microwave dielectric properties in the TE₀₁₁ mode via the Hakki-Coleman method. The τ_f was characterized as the degree of drift of the resonant frequency within the range of 25 °C to 85 °C.

3. Results and discussion

Fig. 1(a) shows the XRD patterns of LBV@ x ($x = 0.05-0.9$) ceramics sintered at different temperatures. Within the range of $0.05 \leq x \leq 0.7$, all the XRD peaks of the samples corresponded to the tetragonal zircon phase of CeVO₄ ($I4_1/amd$, PDF#01-082-1969). No impurity phases were detected, indicating that Bi³⁺ ions were completely soluble in the matrix lattice, resulting in the formation of a single-phase solid solution. Upon further increasing the Bi³⁺ content to $x = 0.8$ and $x = 0.9$, additional diffraction peaks emerged, which could be indexed to the monoclinic scheelite-type BiVO₄ phase ($I2/b$, PDF#01-083-1699). Consequently, the LBV@ x system transitions from a single-phase zircon structure to a two-phase coexistence of tetragonal zircon and monoclinic scheelite. These observations indicate that the Bi³⁺ solubility limit in the LBV@ x system is approximately $x = 0.7$ (Fig. S1); beyond this threshold, the high-entropy tetragonal zircon framework becomes unstable. This structural instability originates from the larger ionic radius of Bi³⁺ (1.17 Å, CN = 8) relative to the La³⁺–Eu³⁺ cations (1.16–1.066 Å, CN = 8), which increases lattice strain and drives phase segregation.

Fig. 1(b) illustrates a distinct non-linear decrease in configurational entropy of

LBV@ x ceramics as the Bi^{3+} doping level (x) increases from 0.05 to 0.9. In the initial stage where x ranges from 0.05 to 0.5, the configurational entropy remains relatively high and stable (> 1.61 R). The curve is nearly flat, indicating that low-level Bi^{3+} substitution does not significantly disturb the high-entropy state of the A-site cations. As x exceeds 0.5, the entropy begins to drop sharply. It crosses from the high-entropy zone into the medium-entropy zone ($x = 0.7$ -0.8). At high Bi concentrations ($x = 0.9$), the entropy plummets to its lowest point (0.49 R), entering the low-entropy zone and signifying a transition from a high-entropy ceramic to a conventional ceramic structure. The reduction in configurational entropy (moving from high to low) may induce significant changes in the microstructure and physical properties of microwave dielectric ceramics [18,19]. Furthermore, the lattice distortion parameter (δ) is a critical metric that characterizes crystal structure disorder by quantifying the extent of lattice distortion induced by variations in ionic radii [20].

$$\delta = \sqrt{\sum_i c_i \left(1 - \frac{r_i}{\bar{r}}\right)^2} \quad (1)$$

where c_i and r_i are the concentration and ionic radius of the i -th A-site cation, and $\bar{r}$ is the average radius. The calculated δ reaches a maximum at $x = 0.3$ and decreases monotonically with increasing Bi content (Table S1), consistent with the trend in configurational entropy. The δ is 0.0335 for LBV@0.05, reflecting substantial local strain arising from the multi-component A-site; this value drops to 0.0181 at $x = 0.9$, as the high Bi^{3+} fraction drives the average A-site radius toward the ionic radius of Bi^{3+} .

To further examine the evolution of the crystal structure, the XRD patterns were analyzed by Rietveld refinement, and the results are shown in Fig. 1(c,d) and Fig. S2 (Supplementary Material). The weighted profile R -factors (R_{wp}) are all below 10%, and the goodness-of-fit parameters (χ^2) are less than 2, indicating reliable refinement results. The lattice parameters of LBV@ x ($x = 0.05-0.9$) ceramics are listed in Table S1 (Supplementary Material). In the two-phase region, the intensity of the diffraction peak for the monoclinic phase (M) increases as the Bi^{3+} substitution increases, while the intensity of the diffraction peak for the tetragonal phase (T) decreases. When $x = 0.8$, the proportions of the T phase and M phase are 81.64 wt.% and 18.36 wt.%, respectively. Upon increasing x to 0.9, the structure transforms to one predominantly composed of the monoclinic scheelite phase (96.71 wt.%). This structural evolution stems from the substantially larger ionic radius of Bi^{3+} than that of the other rare-earth cations. While increasing x expands the average A-site radius and induces severe lattice distortion, progressive Bi^{3+} substitution concurrently lowers configurational entropy and weakens the high-entropy stabilization effect. Thermodynamically, the monoclinic scheelite structure becomes increasingly favored under these conditions. As illustrated in the crystal structure diagrams (Fig. 1e), both zircon (tetragonal) and scheelite (monoclinic) structures in the LBV@ x system consist of $[\text{AO}_8]$ dodecahedra and $[\text{VO}_4]$ tetrahedra. However, their connectivity differs fundamentally: in zircon, these polyhedral units share edges, whereas in scheelite, they share corners exclusively. This different connection is expected to critically influence the microwave dielectric properties of the system.

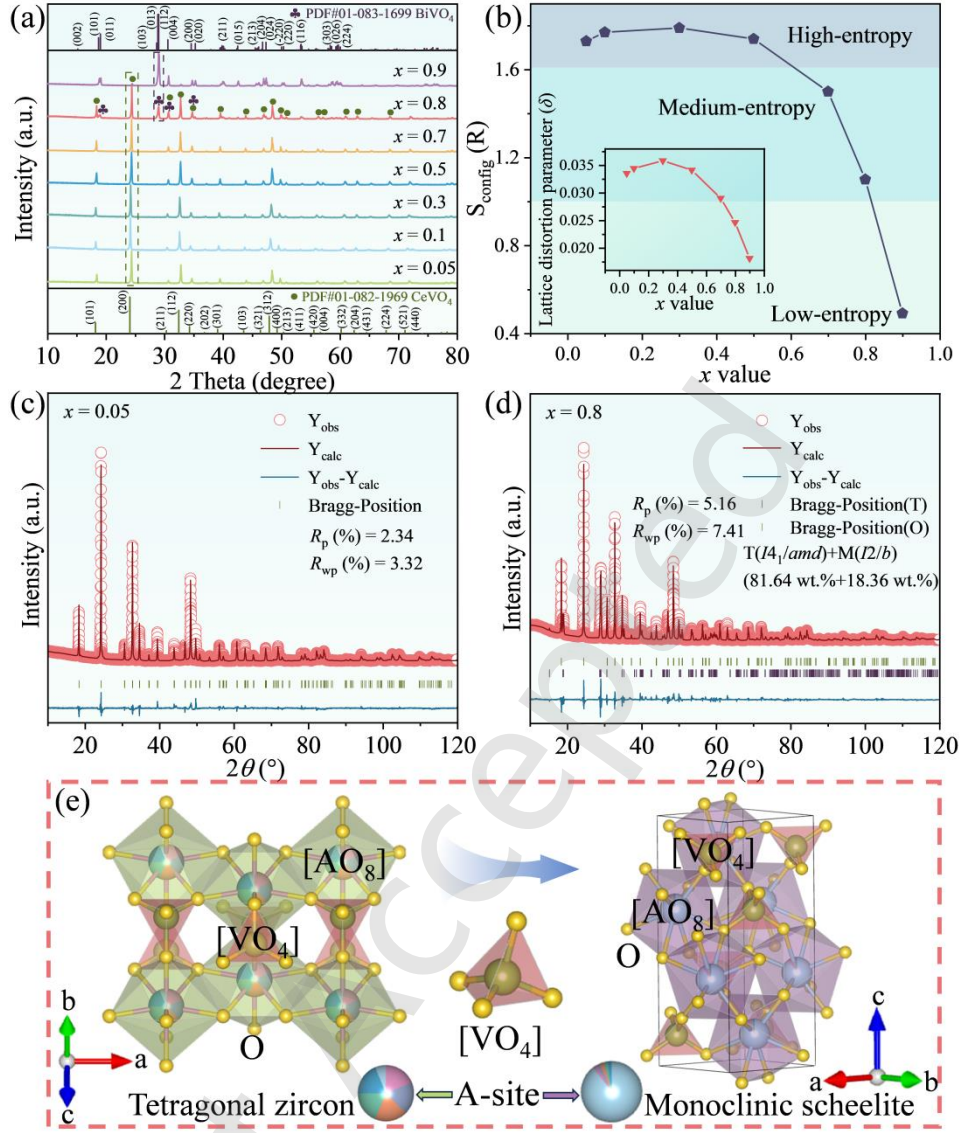


Fig. 1. (a) XRD patterns of the $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ ($0.05 \leq x \leq 0.9$) ceramics. (b) The variation of configurational entropy (ΔS_{config}) and lattice distortion parameter (δ) with the x value. (c,d) Rietveld refinement patterns of LBV@ x ($x = 0.05, 0.8$). (e) Schematic of crystal structure for zircon and scheelite phases.

Group theory calculations reveal 12 Raman modes ($2A_g + 4B_{1g} + B_{2g} + 5E_g$) for the zircon phase ($I4_1/amd$) and 9 Raman modes ($3A_g + 6B_g$) for the scheelite phase ($I2/b$). As shown in Fig. 2(a), the Raman spectra provide direct evidence of the structural evolution driven by Bi^{3+} doping. The transition from a simplified,

broadened spectrum characteristic of a high-entropy zircon solid solution (at $0.05 \leq x \leq 0.7$) to a complex spectrum featuring superimposed modes of zircon and scheelite phases (at $0.8 \leq x \leq 0.9$) correlates perfectly with the XRD findings of a phase boundary crossing. As seen in the deconvoluted spectrum for $x = 0.05$ (Fig. 2b), distinct peaks correspond to symmetric stretching of V-O at 869 cm^{-1} [$A_{1g}(\nu_1)$], asymmetric stretching [$B_{1g}(\nu_3)$ and E_g around 795 and 808 cm^{-1}], bending modes [$A_{1g}(\nu_2)$, $B_{1g}(\nu_4)$], and external lattice modes ($< 200 \text{ cm}^{-1}$) [12,21]. The progressive broadening of Raman modes with increasing Bi^{3+} content arises from A-site ionic size mismatch and mass-fluctuation scattering that elevate elastic strain and phonon damping. These effects are initially attenuated by high configurational entropy at low x but intensify as entropy-driven lattice stabilization weakens beyond $x = 0.5$, with additional peak widening in the two-phase region attributable to interphase boundary and connectivity disorder. The position of the main $A_{1g}(\nu_1)$ mode shifts slightly due to changes in the average ionic radius and bond strength at the A-site as Bi^{3+} replaces the rare-earth mixture. The spectrum for $x = 0.9$ differs significantly from the lower doping samples. New peaks appear or existing ones split/shift, corresponding to the vibrational modes of the monoclinic scheelite structure. For instance, the strong peak at 822 cm^{-1} is characteristic of the symmetric stretching mode [$A_{1g}(\nu_1)$] of the $[\text{VO}_4]$ tetrahedra in the monoclinic scheelite phase.

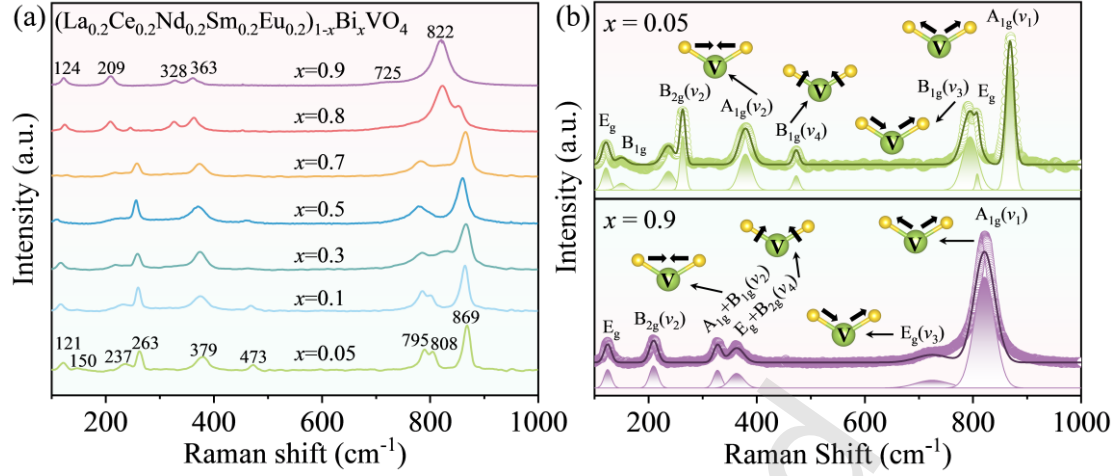


Fig. 2. (a) Raman scattering spectra of $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ ($0.05 \leq x \leq 0.9$)

ceramics. (b) Peak fitting plots of the Raman spectra for $x = 0.05$ and $x = 0.9$ ceramics.

To investigate the crystal structure of LBV@ x ceramics in detail, SAED and HR-TEM were performed on LBV@0.05 and LBV@0.9 compositions. The corresponding microstructural and crystallographic analyses are presented in Fig. 3. The SAED pattern of LBV@0.05 displays a regular array of diffraction spots indexed to the (211) , (141) , and $(1\bar{3}0)$ planes along the $[31\bar{7}]$ zone axis, which is consistent with the tetragonal zircon structure. The HRTEM image of LBV@0.05 reveals clear, continuous lattice fringes, indicating good crystallinity. The measured interplanar spacing (d) for the (211) plane is 0.3040 nm, which is slightly larger than that of single-phase zircon CeVO_4 ($d = 0.2949$ nm). The SAED pattern of LBV@0.9 shows a distinct change in symmetry and spot arrangement compared to LBV@0.05. The spots are indexed to the (112) , (200) , and $(11\bar{2})$ planes along the $[02\bar{1}]$ zone axis. This diffraction pattern corresponds to the monoclinic scheelite structure (characteristic of BiVO_4). The HRTEM image of LBV@0.9 also exhibits well-defined lattice fringes, suggesting that despite the phase change, the material maintains good crystallinity.

The measured interplanar spacing for the (112) plane is 0.3156 nm. Based on the Rietveld-refined parameters ($a = 5.1793 \text{ \AA}$, $b = 5.1030 \text{ \AA}$, $c = 11.6928 \text{ \AA}$, space group $I2/b$), the calculated $d_{(112)}$ is 0.3090 nm, which agrees with the HRTEM-measured value.

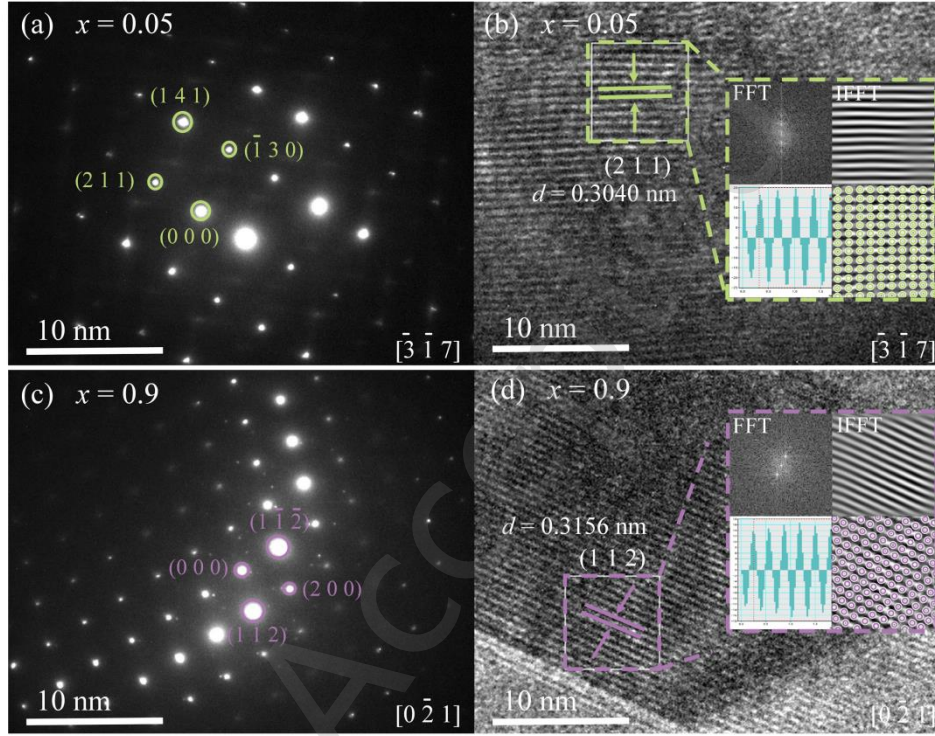


Fig. 3. SAED patterns and HRTEM images of $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ ceramics with (a,b) $x = 0.05$ and (c,d) $x = 0.9$.

Fig. 4(a-c) and Fig. S3 show the SEM images of $\text{LBV}@x$ ($x = 0.05-0.9$) ceramics sintered at their respective optimal temperatures. These optimal sintering temperatures were determined experimentally as those yielding the maximum bulk density, as quantified in Fig. S3(i). All ceramic samples display well-defined grain boundaries and exhibit low porosity. Energy-dispersive X-ray spectroscopy (EDS) elemental mapping was performed on representative $\text{LBV}@x$ samples ($x = 0.1$ and 0.9), with the results presented in Fig. S4. The corresponding elemental distribution maps for La, Ce,

Nd, Sm, Eu, Bi, and V reveal that all constituent elements are homogeneously distributed throughout both the grain interiors and boundaries in the low-Bi single-phase and high-Bi two-phase specimens. Within the spatial resolution of SEM-EDS mapping, no discernible Bi enrichment or elemental segregation at grain boundaries is observed. At $x = 0.8$, two distinct types of grains are visible, where the tetragonal zircon phase coexists with the monoclinic scheelite phase. EDS analysis in Fig. 4(e) reveals that the large round grains belong to the monoclinic scheelite phase (M), whereas the small rod-shaped grains are associated with the tetragonal zircon phase (T). As the Bi content increases, the grain size of LBV@ x ($x = 0.05$ - 0.9) ceramics grows from $3.68\ \mu\text{m}$ to $9.07\ \mu\text{m}$ (Fig. S3h), which might be due to the low inherent sintering temperature ($820\ ^\circ\text{C}$) of the monoclinic phase of BiVO_4 and the relatively rapid grain growth rate [5]. Fig. 4(d) presents the variation trends of bulk density and relative density in LBV@ x ($x = 0.05$ - 0.9) as a function of the x value. With an increasing Bi doping level, the bulk density monotonically increases (4.97 - $6.54\ \text{g/cm}^3$), whereas the relative density exhibits a marginal decline (98.68% - 95.97%). Notably, all samples maintain a relative density exceeding 95% , confirming effective densification across the entire compositional range. In addition, the mechanical robustness and structural endurance of microwave ceramic components are governed by Vickers hardness (H_v) and flexural strength. As shown in Fig. S5, both Vickers hardness and flexural strength of LBV@ x ceramics decrease monotonically with increasing Bi content, from $5.28\ \text{GPa}$ ($x = 0$) to $2.79\ \text{GPa}$ ($x = 1$) and from $137.8\ \text{MPa}$ ($x = 0$) to $72.5\ \text{MPa}$ ($x = 1$), respectively (Supplementary

Material). This mechanical weakening is attributed to the erosion of high-entropy stabilization and the intrinsically low hardness of the Bi-rich ceramics.

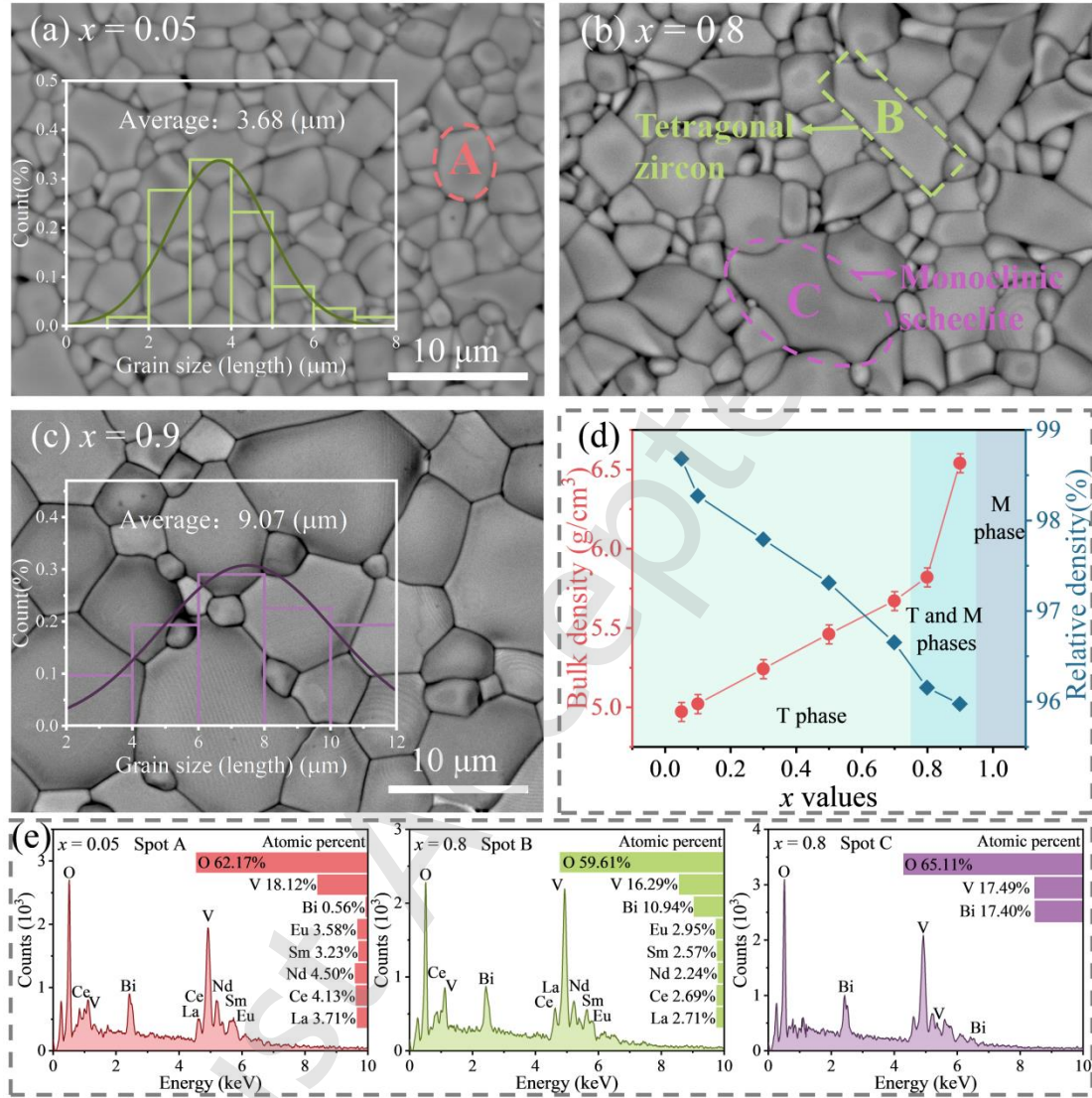


Fig. 4. SEM images of $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ ceramics and their corresponding grain size distributions: (a) $x = 0.05$, (b) $x = 0.8$, and (c) $x = 0.9$. (d) Variation of bulk density and relative density of $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ ceramics with x value. (e) EDS analysis of spots A, B, and C for LBV@0.05 and LBV@0.8 ceramics.

The microwave dielectric properties of LBV@ x ceramics at the optimal sintering temperature showed that the relative permittivity (ϵ_r) increases steadily from 11.84 ($x = 0$) to 68 ($x = 1$) as a function of x (Fig. 5a). Generally, porosity, ionic polarizability,

secondary phases, and chemical bonding characteristics are key factors that influence permittivity [22,23]. The porosity-corrected value ($\varepsilon_{r(\text{corr})}$) and theoretical value ($\varepsilon_{r(\text{C-M})}$) for the relative permittivity in LBV@ x ($x = 0.05-0.9$) ceramics can be calculated as follows [24,25]:

$$\varepsilon_{r(\text{corr})} = \varepsilon_r (1 + 1.5P) \quad (2)$$

$$\ln \varepsilon_r = V_1 \ln \varepsilon_{r1} + V_2 \ln \varepsilon_{r2} \quad (3)$$

$$\varepsilon_{r(\text{C-M})} = \frac{3V_m + 8\pi\alpha_m}{3V_m - 4\pi\alpha_m} \quad (4)$$

$$\alpha_m = 0.2(1-x)[5\alpha(\text{RE}^{3+})] + x\alpha(\text{Bi}^{3+}) + \alpha(\text{V}^{5+}) + 4\alpha(\text{O}^{2-}) \quad (5)$$

where P represents porosity, V_m refers to the molar volume, α_m indicates molecular polarizability, V_1 and V_2 represent the volume fractions, and ε_{r1} and ε_{r2} denote the permittivities of the composite materials. As x increases, the calculated $\varepsilon_{r(\text{C-M})}$ (15.10-42.72), the porosity-corrected $\varepsilon_{r(\text{corr})}$ (12.78-64.59), and the measured ε_r (12.53-60.91) of the LBV@ x ($x = 0.05-0.9$) ceramics all show a gradual increase, which is attributable to the incorporation of Bi^{3+} with a high ionic polarizability ($6.12 \text{ \AA}^3$), leading to a greater ionic polarizability per unit volume [17,26].

Fig. 5(b) shows that the $Q \times f$ values of LBV@ x ($x = 0.05-0.9$) ceramics decrease from 96,870 GHz ($x = 0.05, f = 12.1799 \text{ GHz}$) to 18,768 GHz ($x = 0.9, f = 5.0128 \text{ GHz}$). The $Q \times f$ values of LBV@ x ($x = 0.05-0.9$) are lower than that of pure tetragonal zircon ($\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{VO}_4$ (107,200 GHz, $x = 0$) but higher than that of pure monoclinic scheelite BiVO_4 (6,500 GHz, $x = 1$) [16,27], indicating that the crystal structure and bonding characteristics significantly influence the intrinsic loss. The $Q \times f$ value is intrinsically linked to dielectric loss, which is primarily determined

by lattice anharmonicity and intrinsic phonon damping [28,29]. As seen in Fig. 2(a), the Raman peaks are significantly broadened, which arises from the high configurational entropy and the random distribution of five different rare-earth cations (La, Ce, Nd, Sm, Eu) at the A-site. According to the damped harmonic oscillator model, the Full Width at Half Maximum (FWHM) of the Raman mode (Table S2) is directly proportional to the phonon damping rate (Γ). Broader peaks indicate shorter phonon lifetimes and stronger anharmonic interactions. Consequently, significant peak broadening typically leads to increased dielectric loss and a lower $Q \times f$ value. As the Bi^{3+} content increases into the two-phase region ($x > 0.7$), the structural transition to a lower-symmetry phase and the introduction of phase boundaries further increase the dielectric loss. The DC resistivity reflects the concentration and mobility of charge carriers. High resistivity suppresses leakage conduction loss and is therefore beneficial for obtaining a high $Q \times f$ and improved frequency selectivity [30,31]. With increasing Bi^{3+} content, the DC resistivity of $\text{LBV}@x$ ($x = 0.05\text{-}0.9$) ceramics gradually declines ($3.35 \times 10^9\text{-}6.04 \times 10^6 \text{ } \Omega \cdot \text{cm}$) (Fig. S6). Correspondingly, the dielectric loss ($\tan \delta$) of $\text{LBV}@x$ ceramics increases at lower frequencies (50 kHz–1 MHz), exhibiting an inverse relationship with the $Q \times f$ value (Fig. S7). This trend is likely attributable to a reduction in the relative density of the ceramics, which diminishes the barrier to electron migration and thereby facilitates charge transport [32]. As a result, leakage current increases, leading to a deterioration in the $Q \times f$ value.

As illustrated in Fig. 5(c), the τ_f of $\text{LBV}@x$ ceramics exhibits a non-monotonic dependence on Bi^{3+} content: it initially increases, reaches a maximum, and

subsequently decreases. Specifically, τ_f rises from -11.9 ppm/ $^{\circ}\text{C}$ in LBV@0.05 to a peak value of $+132.0$ ppm/ $^{\circ}\text{C}$ in LBV@0.7, then declines to -195.7 ppm/ $^{\circ}\text{C}$ in LBV@0.9. Notably, near-zero τ_f values of $+8.5$ ppm/ $^{\circ}\text{C}$ and $+10.7$ ppm/ $^{\circ}\text{C}$ were achieved in the tetragonal zircon-type LBV@0.1 high-entropy ceramic and the LBV@0.8 composite ceramic, respectively. The τ_f depends on the temperature coefficient of permittivity (τ_{ε}), the coefficient of linear expansion (α_L), and temperature coefficient of ion polarizability (τ_{am}), indicated as follows [33,34]:

$$\tau_f = -\left(\alpha_L + \frac{1}{2}\tau_{\varepsilon}\right) \quad (6)$$

$$\tau_{\varepsilon} = \frac{1}{\varepsilon_r} \left(\frac{\partial \varepsilon_r}{\partial T} \right) = \frac{(\varepsilon_r - 1)(\varepsilon_r + 2)}{3\varepsilon_r} \left(\frac{1}{\alpha_m} \frac{d\alpha_m[T, V(T)]}{dT} - 3\alpha_L \right) \quad (7)$$

$$\tau_{am} = \frac{1}{\alpha_m} \frac{d\alpha_m[T, V(T)]}{dT} = \frac{1}{\alpha_m} \left(\frac{\partial \alpha_m}{\partial T} \right)_V + \frac{1}{\alpha_m} \left(\frac{\partial \alpha_m}{\partial V} \right)_T \left(\frac{\partial V}{\partial T} \right)_P \quad (8)$$

Fig. 5(d) shows the linear expansion data for LBV@ x ($x = 0.05$ -0.9) ceramics as temperature increases, with α_L values calculated over the range 25–500 $^{\circ}\text{C}$. The α_L values range from 7.70 ppm/ $^{\circ}\text{C}$ for LBV@0.05 to 14.12 ppm/ $^{\circ}\text{C}$ for LBV@0.9, indicating an upward trend as x increases. As presented in Table 1, the calculated τ_{ε} and τ_{am} values both initially decrease and subsequently increase, whereas the τ_f values exhibit an inverse behavior. Notably, as τ_f transitions from negative to positive (or vice versa), τ_{ε} undergoes a corresponding sign reversal, indicating an inverse functional relationship between these parameters.

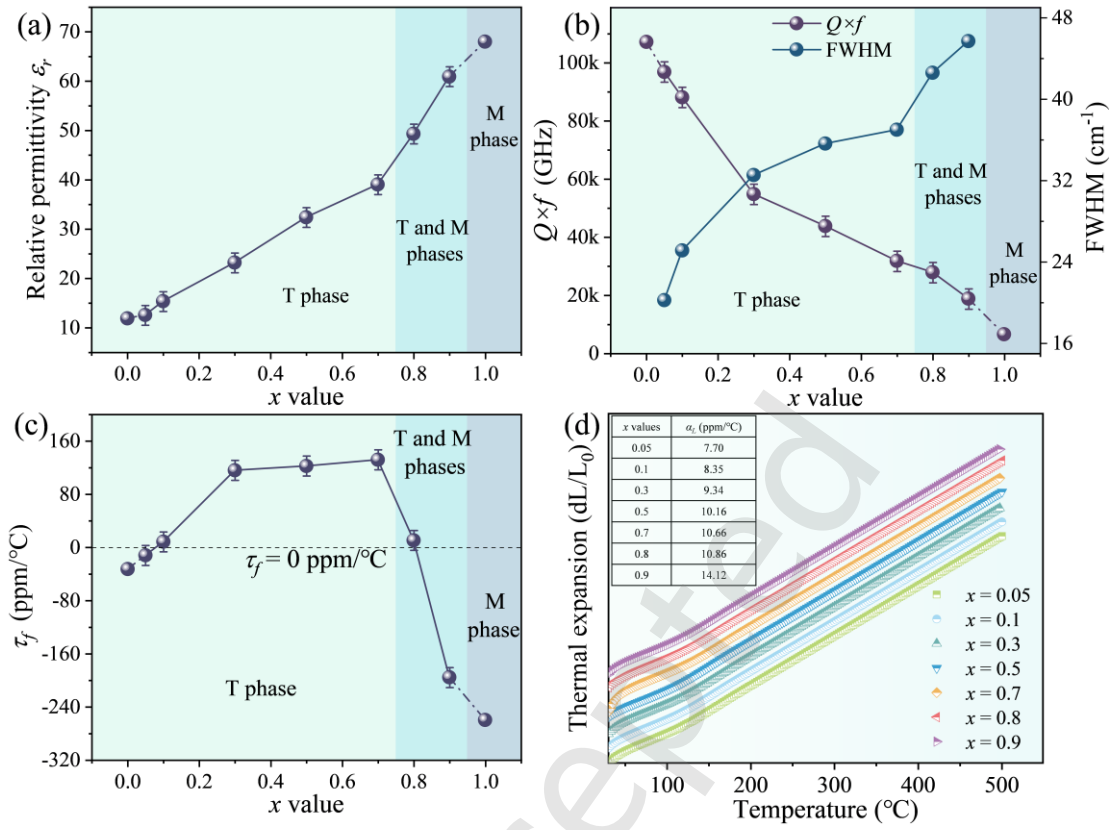


Fig. 5. The (a) ϵ_r , (b) $Q \times f$, and (c) τ_f of $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ ceramics as a function of x . (d) The coefficient of linear expansion α_L of $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ ceramics.

Table 1. The τ_f , α_L , τ_ϵ , τ_{am} , $\tau_{am}-3\alpha_L$, $\epsilon_r(\text{C-M})$, $\epsilon_r(\text{corr})$, ϵ_r at 1 MHz, and τ_ϵ at 1 MHz of $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ ceramics.

x values	$\epsilon_r(\text{C-M})$	$\epsilon_r(\text{corr})$	τ_f (ppm/°C)	α_L (ppm/°C)	τ_ϵ (ppm/°C)	τ_{am} (ppm/°C)	$\tau_{am}-3\alpha_L$ (ppm/°C)	ϵ_r at 1MHz	τ_ϵ at 1MHz (ppm/°C)
0.05	15.10	12.78	-11.9	7.70	8.39	24.99	1.88	13.94	21.59
0.1	15.12	15.73	8.5	8.35	-33.71	18.82	-6.24	21.70	-22.71
0.3	15.25	23.93	116.1	9.34	-250.89	-3.24	-31.26	27.10	-138.64
0.5	15.70	33.67	122.6	10.16	-265.52	6.56	-23.92	37.33	-153.28
0.7	15.98	40.97	132.0	10.66	-285.32	10.56	-21.42	42.30	-224.59
0.8	27.96	52.15	10.7	10.86	-43.11	29.99	-2.57	55.10	-27.84
0.9	42.72	64.59	-195.7	14.12	363.15	59.98	17.61	69.43	314.70

The dielectric temperature spectrum is an essential tool for evaluating how relative permittivity changes with temperature. Fig. 6 illustrates the temperature-dependent variation of ϵ_r for LBV@ x ($x = 0.05-0.9$) ceramics over a

frequency range from 50 kHz to 1 MHz. Ceramic materials of identical composition exhibit higher ε_r values at lower frequencies. This frequency-dependent behavior arises from additional polarization mechanisms—such as interfacial (space-charge) and dipolar polarizations—that remain active in the low-frequency regime [35,36]. In contrast, at microwave frequencies, the dielectric response of LBV@ x ceramics is predominantly governed by ionic displacement polarization, as slower polarization processes are no longer operative. Linear fitting was used to obtain τ_ε values at 1 MHz over the range of 30–90 °C, revealing a decrease from 21.59 ppm/°C for LBV@0.05 to –224.59 ppm/°C for LBV@0.7, followed by an increase to 314.70 ppm/°C for LBV@0.9, consistent with the trends observed at microwave frequencies.

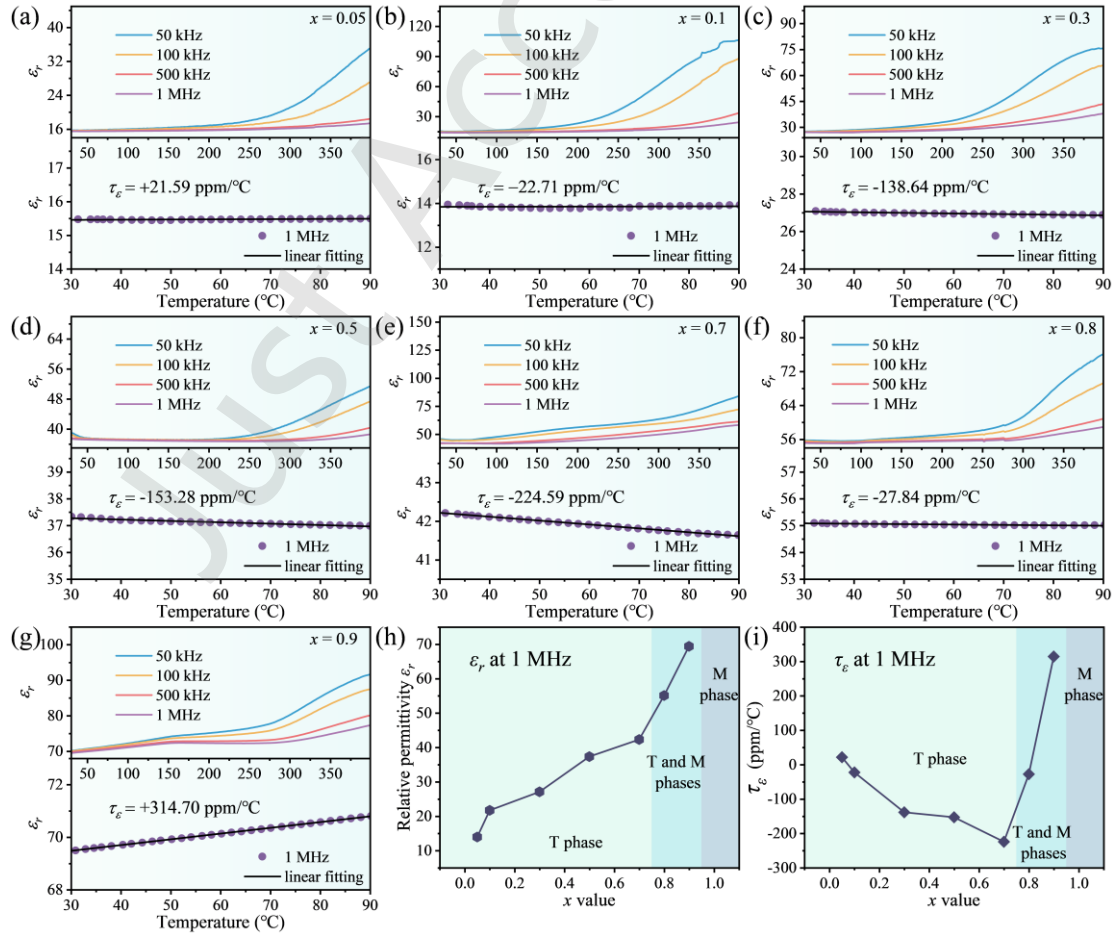


Fig. 6. Dielectric temperature spectra at low frequencies of (a) LBV@0.05, (b) LBV@0.1, (c)

LBV@0.3, (d) LBV@0.5, (e) LBV@0.7, (f) LBV@0.8, and (g) LBV@0.9. The (h) ε_r and (i) τ_e

(30–90 °C) of LBV@ x ceramics at 1 MHz.

The optimal sintering temperature of the LBV@0.7 ceramic is 925 °C, below the melting point of the silver (Ag) electrode (961 °C) [37], indicating its suitability for low-temperature co-fired ceramic (LTCC) applications. To assess the chemical compatibility of LBV@0.7 with Ag electrodes for LTCC applications, LBV@0.7 ceramic was co-fired with 20 wt.% Ag powder at 925 °C for 4 h. As shown in Fig. 7(a), the XRD pattern of the LBV@0.7-Ag composite sintered at 925 °C displays only the diffraction peaks of the tetragonal zircon phase and metallic Ag, confirming their chemical compatibility. Backscattered electron (BSE) imaging (Fig. 7b) reveals two distinct grain morphologies corresponding to the LBV@0.7 ceramic matrix and the Ag electrode phase, with no interdiffusion or interfacial reaction products observed, further confirming their excellent chemical compatibility. Compared with previously reported AVO₄-based systems (Fig. 7c), the variable-configuration high-entropy LBV@ x ceramics developed here exhibit substantially enhanced microwave dielectric performance at low dopant concentrations, notably higher $Q \times f$ values and an improved, compositionally tunable temperature coefficient of resonant frequency (τ_f). In particular, LBV@0.05 ($Q \times f = 96,870$ GHz and $\tau_f = -11.9$ ppm/°C) and LBV@0.1 ($Q \times f = 88,120$ GHz and $\tau_f = +8.5$ ppm/°C) achieve balanced properties, making them promising for high-frequency microwave device applications.

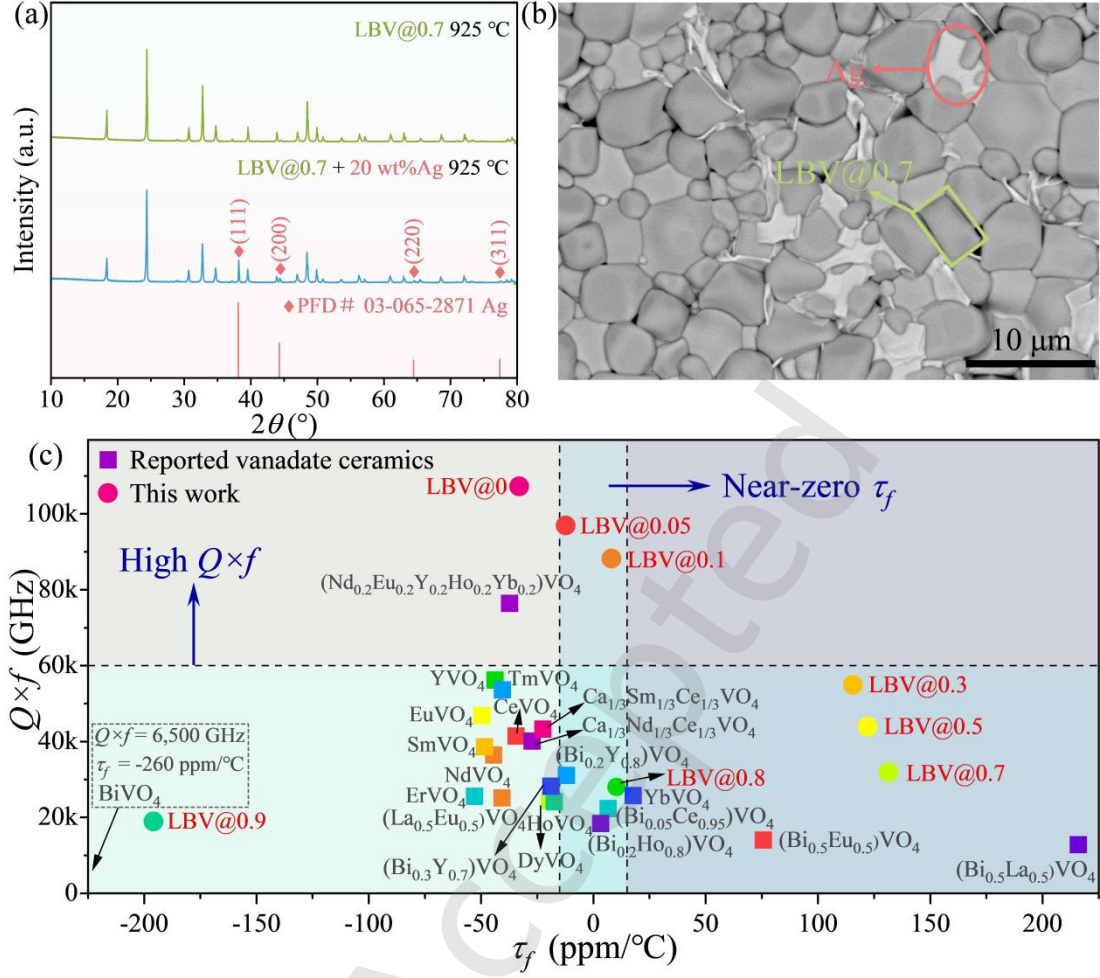


Fig. 7. (a) XRD patterns of the $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ with Ag cofired at 925 °C. (b) BSE image of 80 wt.% LBV@0.7 + 20 wt.% Ag composite ceramic. (c) Comparison of $Q \times f$ and τ_f values in AVO₄-based microwave dielectric ceramics.

To explore the potential application of LBV@ x ceramics, a cylindrical dielectric resonator antenna (DRA) was designed and fabricated using the LBV@0.1 ceramic with near-zero τ_f and high $Q \times f$. Fig. 8(a) illustrates the geometry of both the simulated and fabricated dielectric resonator antenna. The substrate is constructed from FR4 epoxy ($\epsilon_r = 4.4$, $\tan\delta = 0.02$) and has dimensions of 50 mm $\times$ 50 mm $\times$ 0.50 mm (length $\times$ width $\times$ height) [38]. The designed dimensions of the DRA are summarized in Table S3 (Supplementary Material). Fig. 8(b) shows the three-dimensional

simulated radiation pattern of the DRA at 5.449 GHz, along with representative application scenarios. Fig. 8(c) shows the H-plane and E-plane radiation patterns at the center resonant frequency, both exhibiting excellent radiation characteristics. At 5.449 GHz, the simulated S_{11} parameter is -56.13 dB, and the bandwidth is 269 MHz. However, the measured center frequency shifts slightly to 5.335 GHz, with a bandwidth of 211 MHz (Fig. 8d). The minor discrepancies between the simulated and measured results are likely attributable to fabrication tolerances, connector losses, and environmental perturbations during testing [39,40]. The simulated gain and radiation efficiency at 5.449 GHz indicate that the designed antenna achieves a peak gain of 6.88 dBi and a radiation efficiency of 95.25% (Fig. 8e). Across the operational bandwidth of 5.329–5.598 GHz, the antenna maintains a radiation efficiency exceeding 90% and a high gain of 4.23–6.88 dBi, attributable to the inherently low dielectric loss of the LBV@0.1 ceramic, which demonstrates the promising potential of LBV@ x ceramics for C-band dielectric resonator antenna applications.

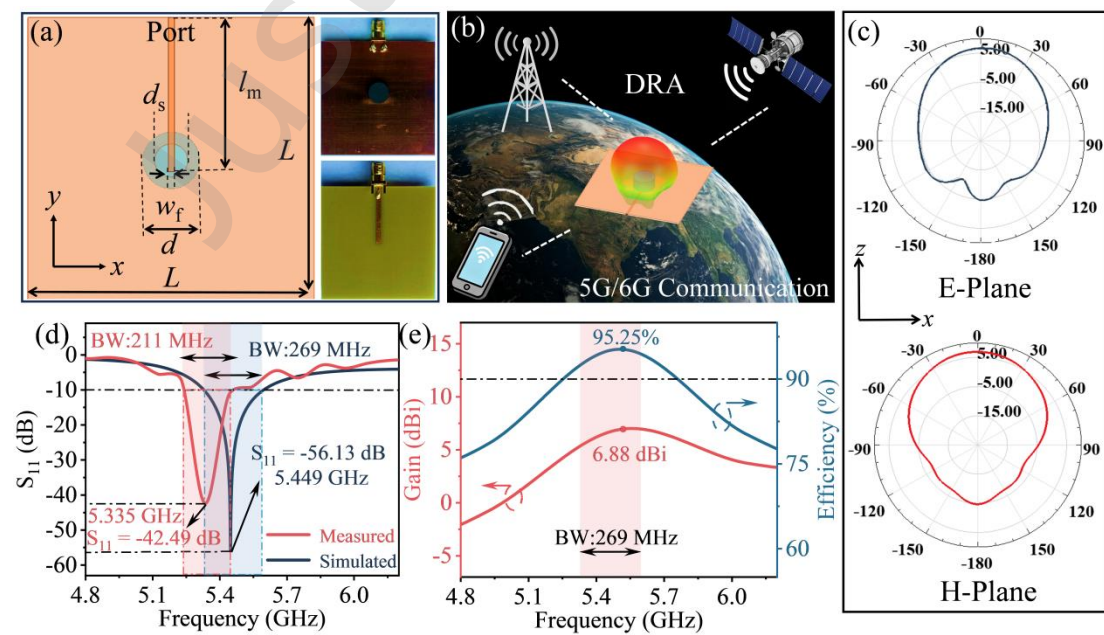


Fig. 8. (a) Geometry of the simulated and fabricated dielectric resonator antenna for LBV@0.1 ceramic. (b) Simulated 3D far-field radiation patterns. (c) Simulated radiation patterns in the E-plane and H-plane. (d) Simulated and measured return loss (S_{11}) at various resonant frequencies. (e) Simulated gain and efficiency of the designed DRA.

4. Conclusions

In this work, a series of variable configurational-entropy ceramics $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})_{1-x}\text{Bi}_x\text{VO}_4$ (LBV@ x , $x = 0.05-0.9$) were successfully synthesized via the conventional solid-state reaction method. The primary objective was to tailor the microwave dielectric properties, specifically τ_f and $Q \times f$, by introducing Bi^{3+} ions into the high-entropy zircon lattice. Structural analyses confirmed that the ceramics crystallized in a single-phase tetragonal zircon structure for $0.05 \leq x \leq 0.7$. However, upon increasing the Bi^{3+} content to $x \geq 0.8$, a structural transition to a monoclinic scheelite phase occurred, driven by the larger ionic radius of Bi^{3+} and the associated entropy change. Rietveld refinement of XRD data, Raman spectroscopy, and TEM analysis corroborated this phase evolution, revealing a transition from edge-sharing $[\text{AO}_8]$ polyhedra in the zircon phase to corner-sharing $[\text{AO}_8]$ polyhedra in the scheelite phase. Bi^{3+} substitution tunes τ_f non-monotonically from a negative value, through positive values, and back to a negative value, allowing for the achievement of near-zero τ_f values in the high-entropy ceramic LBV@0.1 (+8.5 ppm/°C, zircon) and composite ceramic LBV@0.8 (+10.7 ppm/°C, zircon/scheelite composite). High-entropy ceramic LBV@0.05 exhibited superior microwave dielectric properties with a low ε_r of 12.53, a high $Q \times f$ of 96,870 GHz,

and a negative τ_f of -11.9 ppm/ $^{\circ}\text{C}$. The high $Q \times f$ is attributed to the high configurational entropy stabilizing the lattice, while excessive Bi^{3+} doping ($x > 0.7$) increased dielectric loss due to phase-boundary scattering and reduced resistivity. To assess the practical applicability of these materials, a cylindrical dielectric resonator antenna was designed and fabricated using the LBV@0.1 ceramic. The antenna performed well in the C-band at 5.449 GHz, with a wide bandwidth of 269 MHz, a high gain of 6.88 dBi, and a simulated radiation efficiency of 95.25%. These results indicate that LBV@ x ceramics are promising candidates for high-performance components in 5G/6G communication systems, offering a viable solution to the challenge of balancing high quality factors and temperature stability in microwave dielectrics.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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References

- [1] Liu YJ, He GQ, Zhang WJ, *et al.* Low loss and temperature-stable $\text{Y}_3\text{MgAl}_3\text{GeO}_{12}$ microwave dielectric ceramics for X-band applications. *J Adv Ceram* 2025, **14**: 9221136.
- [2] Zhan Y, Li LX. Low-permittivity and high- Q value $\text{Li}_2\text{Mg}_3\text{Ti}_{1-x}(\text{Zn}_{1/3}\text{Nb}_{2/3})_x\text{O}_6$ microwave dielectric ceramics for microstrip antenna applications in 5G millimeter wave. *J Alloy Compd* 2021, **857**: 157608.
- [3] Wang DW, Zhang SY, Wang G, *et al.* Cold sintered $\text{CaTiO}_3\text{-K}_2\text{MoO}_4$ microwave dielectric ceramics for integrated microstrip patch antennas. *Appl Mater Today* 2020, **18**: 100519.
- [4] Wang XY, Liu T, Cao ZK, *et al.* Lattice vibrational characteristics and structure-property relationships of $\text{Ca}(\text{Mg}_{1/2}\text{W}_{1/2})\text{O}_3$ microwave dielectric ceramics with different sintering temperatures. *Ceram Int* 2022, **48**: 1415–1422.
- [5] Zhou D, Pang XL, Wang DW, *et al.* BiVO_4 based high k microwave dielectric materials: A review. *J Mater Chem C* 2018, **6**: 9290–9313.
- [6] Wang W, Wang X, Bao J, *et al.* Low-permittivity $\text{BaCuSi}_4\text{O}_{10}$ -based dielectric ceramics: An available solution to connect low temperature cofired ceramic technology and millimeter-wave communications. *Chem Eng J* 2024, **494**: 153172.
- [7] Liu C, Xu MZ, Kang XP, *et al.* Advances in low-temperature co-fired ceramics for next-generation electronics applications. *Adv Mater* 2026, **38**: e17514.
- [8] Errandonea D. High pressure crystal structures of orthovanadates and their properties. *J Appl Phys* 2020, **128**: 040903.
- [9] Guo HH, Zhou D, Liu WF, *et al.* Microwave dielectric properties of temperature-stable zircon-type $(\text{Bi}, \text{Ce})\text{VO}_4$ solid solution ceramics. *J Am Ceram Soc* 2020, **103**: 423–431.

- [10] Xiang HC, Zhang YH, Chen JQ, *et al.* Structure evolution and τ_f influence mechanism of $\text{Bi}_{1-x}\text{HoVO}_4$ microwave dielectric ceramics for LTCC applications. *J Mater Sci Technol* 2024, **197**: 1–8.
- [11] Li W, Fang L, Sun YH, *et al.* Crystal structure and microwave dielectric properties of rare-earth vanadates: ReVO_4 (Re = Nd, Sm). *J Electron Mater* 2016, **46**: 1956–1962.
- [12] Dai YM, Chen JW, Tang Y, *et al.* Relationship between bond characteristics and microwave dielectric properties of REVO_4 (RE = Yb, Ho) ceramics. *Ceram Int* 2023, **49**: 875–881.
- [13] Wang JX, Ren YX, Zhu XK, *et al.* Novel medium-entropy $\text{Ca}_3(\text{Co}_{0.25}\text{Zn}_{0.25}\text{Mg}_{0.25}\text{Cu}_{0.25})_2\text{SiV}_2\text{O}_{12}$ microwave dielectric ceramics with high $Q \times f$ and near-zero τ_f . *J Adv Ceram* 2025, **14**: 9221110.
- [14] Su L, Wang HH, Zhou YC. High-entropy ceramics: From paradigm formation to ordered development. *J Adv Ceram* 2026, **15**: 9221301.
- [15] Zhang YH, Xiang HC, Wu XY, *et al.* Low dielectric loss in vanadium-based zircon ceramics via high-entropy strategy. *J Adv Ceram* 2025, **14**: 9221012.
- [16] Xiang HC, Wu XY, Chen JQ, *et al.* High-entropy vanadium-based zircon ceramics with ultra-low dielectric loss and thermal stability for 5G/6G communication systems. *J Alloy Compd* 2026, **1073**: 189062.
- [17] Zhou D, Li J, Pang LX, *et al.* Crystal structure, infrared spectra, and microwave dielectric properties of temperature-stable zircon-type (Y, Bi) VO_4 solid-solution ceramics. *ACS Omega* 2016, **1**: 963–970.
- [18] Hou X, Li C, Gou T, *et al.* Improvement of microwave dielectric properties of (Ca, Sr) TiO_3 -based ceramics by high-entropy design. *J Am Ceram Soc* 2025, **108**: e20630.

- [19] Zhang LQ, Xiang PW, Lai YM *et al.* Tailoring microwave dielectric properties through high-entropy strategy in spinel-type titanium ceramics. *J Mater Chem C* 2026, **14**: 8971–8984.
- [20] Zhou Y, Huang Y, Huang Q, *et al.* Entropy-driven design of ultra-low loss olivine $\text{CaY}_{1-x}(\text{Nd}_{0.25}\text{Sm}_{0.25}\text{Eu}_{0.25}\text{Yb}_{0.25})_x\text{GaO}_4$ microwave dielectric ceramics for 5G dielectric resonator antennas. *J Eur Ceram Soc* 2026, **46**: 118205.
- [21] Zhang Z, Chen J, Tang Y, *et al.* Crystal structure, far-infrared spectroscopy, and microwave dielectric properties of two novel vanadates $\text{CaRECeV}_3\text{O}_{12}$ (RE = Nd, Sm). *Ceram Int* 2023, **49**: 23173–23179.
- [22] Yang HY, Zhang SR, Yang HC, *et al.* Usage of P–V–L bond theory in studying the structural/property regulation of microwave dielectric ceramics: A review. *Chem Front* 2020, **7**: 4711–4753.
- [23] Tang Y, Li M, Xiang H, *et al.* Mechanism of ionic polarizability, bond valence, and crystal structure on the microwave dielectric properties of disordered $\text{Li}_{10}\text{MTi}_{13}\text{O}_{32}$ (M = Zn, Mg) spinels. *Mater Adv* 2023, **4**: 1345–1353.
- [24] Yao HY, Lin YW, Chang TH. Dielectric properties of BaTiO_3 –epoxy nanocomposites in the microwave regime. *Polym* 2021, **13**: 1391.
- [25] Shannon RD. Dielectric polarizabilities of ions in oxides and fluorides. *J Appl Phys* 1993, **73**: 348–366.
- [26] Hao SZ, Zhou D, Hussain F, *et al.* Novel scheelite-type $[\text{Ca}_{0.55}(\text{Nd}_{1-x}\text{Bi}_x)_{0.3}]\text{MoO}_4$ ($0.2 \leq x \leq 0.95$) microwave dielectric ceramics with low sintering temperature. *J Am Ceram Soc* 2020, **103**: 7259–7266.

- [27] Valant M, Suvorov D. Chemical compatibility between silver electrodes and low-firing binary-oxide compounds: Conceptual study. *J Am Ceram Soc* 2000, **83**: 2721–2729.
- [28] Yang HY, Ou CT, Liu H, *et al.* A review of microwave dielectric ceramics: From fundamental mechanisms and property regulation to advanced preparation, applications, and data-driven discovery. *J Adv Ceram* 2026, **15**: 9221320.
- [29] Peng S, Zhang Y, Yi TL. Research Progress of $\text{Ba}(\text{Zn}_{1/3}\text{Nb}_{2/3})\text{O}_3$ microwave dielectric ceramics: A review. *Materials* 2023, **16**: 423.
- [30] Li CC, Zhu GB, Chen DQ, *et al.* Phase-driven property modulation in BiVO_4 ceramics via multi-ion substitution for next-generation wireless communication. *ACS Appl Mater Interfaces* 2025, **17**: 66835–66865.
- [31] Liu K, Liu C, Li J, *et al.* Relationship between structure and properties of microwave dielectric ceramic $\text{Li}_{(1+x)}\text{MgTi}_3\text{O}_8$ based on Li non-stoichiometry. *J Materiomics* 2023, **9**: 279–288.
- [32] Wu FF, Sun RX, Du C, *et al.* P^{5+} -enhanced novel samarium niobate ultralow-loss microwave ceramics as dielectric resonator for X-band antenna applications. *Adv Funct Mater* 2025, **35**: 2421225.
- [33] Wakino K, Minai K, Tamura H. Microwave characteristics of $(\text{Zr}, \text{Sn})\text{TiO}_4$ and $\text{BaO-PbO-Nd}_2\text{O}_3\text{-TiO}_2$ dielectric resonators. *J Am Ceram Soc* 1984, **67**: 278–281.
- [34] Wang XB, Ai MJ, Long FX, *et al.* Achieving near-zero thermal expansion over a wide temperature range in $(\text{Hf}, \text{Ta})(\text{Fe}, \text{Cr})_2$ alloys. *Microstructures* 2025, **5**: 2025097.
- [35] Rayssi Ch, Kossi SEI, Dhahri J, *et al.* Frequency and temperature-dependence of dielectric permittivity and electric modulus studies of the solid solution $\text{Ca}_{0.85}\text{Er}_{0.1}\text{Ti}_{1-x}\text{Co}_{4x/3}\text{O}_3$ ($0 \leq x \leq$

0.1). *RSC Adv* 2018, **8**: 17139–17150.

- [36] Althumairi NA, Hjiri M, Aldukhayel AM, *et al.* Recent advances in dielectric and ferroelectric behavior of ceramic nanocomposites: Structure property relationships and processing strategies. *Nanomaterials* 2025, **15**: 1329.
- [37] Lu K, Jin ZH. Melting and superheating of low-dimensional materials. *Curr Opin Solid St M* 2001, **5**: 39–44.
- [38] Wang SQ, Shi HT, Lin HC, *et al.* Microstrip antenna design and its application in moisture detection. *Sensors* 2026, **26**: 4291.
- [39] Wang ZW, Guo HH, Huang YY, *et al.* Synergistic dual-phase and microstructure engineering toward temperature-stable, ultra-low loss Li_2TiO_3 -based microwave dielectric ceramic. *Adv Funct Mater* 2026, **36**: e18002.
- [40] Zubair M, Jabbar A, Tahir FA, *et al.* A high-performance sub-THz planar antenna array for THz sensing and imaging applications. *Sci Rep* 2024, **14**: 17030.