

高熵 ReVO_4 陶瓷与微波介电性能

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摘 要: 采用固相反应法制备了 3 种高熵 ReVO_4 陶瓷, 对其物相结构、微观形貌和振动特征采用 X 射线衍射、扫描电子显微镜和 Raman 光谱进行表征, 并对微波介电性能进行了分析。结果表明: 所有陶瓷样品均表现出空间群为 $I4_1/amd$ 的四方锆石结构, 致密的微观结构使其展现出良好的微波介电性能。采用 Clausius-Mossotti 公式解释了介电常数的变化, 介电常数与离子极化率呈正相关; 品质因数与填充因子具有相似的变化趋势; 键价理论被用于反映晶格畸变的程度, 并与谐振频率温度系数具有强关联性。

关键词: 高熵陶瓷; 微波频率; 介电性能; 锆石结构; 钒酸盐

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1 Introduction

As a promising contender in ceramic industry, high-entropy ceramics (HECs) have an extensive application potential due to their abundant compositional adjustability, diverse structural variations, distinctive entropy effects, and customizable physicochemical properties^[1-2]. Similar to high-entropy alloys, HECs are single-phase solid solutions consisting of five or more elemental species occupying one crystallographic site with equal or nearly equal mole ratios^[3]. The unprecedented high-entropy effects in HECs make them a valuable resource for exploration^[4].

Previous research on high-entropy ceramics (HECs) primarily focused on investigating their mechanical properties, thermal conductivity, and ionic conductivity^[5-7]. In contrast, the exploration of the high-entropy effect on dielectric properties is still in its early stage, with most studies on colossal dielectric constant^[8], dielectric relaxation behavior^[9], and energy

storage properties^[10-11]. The emergence of fifth-generation wireless communication (5G) imposes stringent requirements on microwave dielectric materials, necessitating superior overall performance (*i.e.*, moderate relative permittivity, high quality factor, and near-zero temperature coefficient of resonance frequency)^[12-13]. The trade-off among the three performance indicators, however, imposes constraints on the pool of candidates available for practical applications.

Recent high-entropy design concept is incorporated into the investigation of innovative microwave dielectrics^[14-19]. For instance, $(\text{Mg}_{0.2}\text{Ni}_{0.2}\text{Zn}_{0.2}\text{Co}_{0.2}\text{Mn}_{0.2})_2\text{SiO}_4$ as a derivative of A_2BO_4 exhibits exceptional dielectric properties (*i.e.*, $\epsilon_r = 8.02$, $\tan\delta = 0.00051$ at 14.5 GHz, $\tau_f = -38.2 \times 10^{-6}/^\circ\text{C}$)^[14]. Also, an enhanced τ_f was reported in $(\text{La}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Ho}_{0.2}\text{Y}_{0.2})(\text{Nb}_{0.75}\text{V}_{0.25})\text{O}_4$ ceramic with a temperature coefficient of $-1.5 \times 10^{-6}/^\circ\text{C}$ ^[15]. High-entropy ceramics of $\text{Li}(\text{Gd}_{0.2}\text{Ho}_{0.2}\text{Er}_{0.2}\text{Yb}_{0.2}\text{Lu}_{0.2})\text{GeO}_4$ have some promising microwave dielectric properties (*i.e.*, $\epsilon_r = 7.2$, $\tan\delta = 0.00053$, and $\tau_f = -2.9 \times 10^{-6}/^\circ\text{C}$)^[16]. Lin *et al.*^[17-18]

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reported the A-site high-entropy ceramic of $\text{Sr}(\text{La}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{Gd}_{0.2})\text{AlO}_4$ and B-site high-entropy ceramic of $\text{SrLa}(\text{Al}_{0.25}\text{Zn}_{0.125}\text{Mg}_{0.125}\text{Ga}_{0.25}\text{Ti}_{0.25})\text{O}_4$, both exhibiting superior microwave dielectric properties. Xie *et al.*^[19] discovered that the microwave dielectric properties of high-entropy ceramic of $(\text{Mg}_{0.2}\text{Co}_{0.2}\text{Ni}_{0.2}\text{Li}_{0.4}\text{Zn}_{0.2})\text{Al}_2\text{O}_4$ surpass those of the MgAl_2O_4 matrix. Entropy engineering provides a pathway for designing innovative materials and optimizing their performance. While the emerging high-entropy design concept brings some possibilities to explore microwave dielectrics, it is still in its early stages and requires active exploration and experimentation to develop novel dielectric materials with optimized properties.

ReVO_4 orthovanadates (Re = rare-earth elements) were selected as targeted materials to investigate the high-entropy microwave dielectrics. The size of rare-earth elements affects the polymorphs of ReVO_4 (*i.e.*, monoclinic and tetrahedral) and triggers intriguing phase transitions. Monoclinic scheelite and monazite structure is formed when larger A site ions such as Bi^{3+} and La^{3+} are present in the A site^[20–21], whereas smaller rare-earth elements (*i.e.*, from Nd^{3+} to Y^{3+}) prefer a tetrahedral zircon structure^[22]. Also, their dielectric performance can be adjusted through compositional engineering. For instance, BiVO_4 ^[23] has a dielectric constant ϵ_r of 68, $Q \times f$ of 6 500 GHz to 8 000 GHz, and a large negative τ_f of -243 to $-260 \times 10^{-6}/^\circ\text{C}$, and LaVO_4 ^[21] has ϵ_r of 14.2, $Q \times f$ of 48 197 GHz, and τ_f of $-37.89 \text{ ppm}/^\circ\text{C}$. The incorporation of LnVO_4 and BiVO_4 into a solid solution, however, results in a modification that yields a positive temperature coefficient of the resonance frequency. Zhou *et al.*^[24–25] adjusted the τ_f value of BiVO_4 to be near-zero via forming a composite of monoclinic scheelite and tetragonal zircon in $\text{BiVO}_4\text{--CeVO}_4$ and $\text{BiVO}_4\text{--YVO}_4$ systems. The crystal structure and dielectric properties of ReVO_4 orthovanadates provide an opportunity for the exploration of novel materials through high-entropy design.

This paper was to design a series of five-component entropy-stabilized ceramics of ReVO_4 , wherein the Re site was occupied by rare-earth elements (*i.e.*, La^{3+} , Ce^{3+} , Nd^{3+} , Sm^{3+} , Eu^{3+} , Gd^{3+} , Y^{3+}) in an equimolar ratio. The effect of rare-earth element on the crystal structure,

microstructure, and dielectric properties of ReVO_4 ceramics was investigated.

2 Experimental section

High-entropy ceramics of ReVO_4 were synthesized by a solid-phase method with high-purity rare-earth oxides (Re_2O_3 with a purity of $> 99.9\%$) and V_2O_5 . The ceramics with different chemical formulas, *i.e.*, $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2})\text{VO}_4$, $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Gd}_{0.2})\text{VO}_4$, and $(\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Y}_{0.2})\text{VO}_4$, were denoted as Eu-5RVO, Gd-5RVO, and Y-5RVO, respectively. The raw materials were weighed according to a stoichiometric ratio and mixed in a ball mill at a rotational speed of 300 r/min for 6 h. The slurry after milling was dried in an oven at 120°C for 24 h. After grinding, the powders were pre-fired in a Muffle furnace at 800°C for 6 h. Then the prepared powders were further ground for 6 h, dried, and added with a polyvinyl alcohol solution (PVA, 5%) as a binder. The granulated powders were sieved by a 80/120 mesh screen and then pressed into cylindrical bulks with a thickness of 5.5–6.5 mm and diameter of 10 mm under 10 MPa. The samples were heated at 550°C for 6 h to eliminate the binder and sintered at $1\,400\text{--}1\,500^\circ\text{C}$ for 6 h with an increment of 20°C to obtain the dense ceramics.

The crystal structure of the ceramics was analyzed by X-ray diffraction (XRD, PANalytical Co., the Netherlands). The apparent density was determined by the Archimede drainage method. The microstructure was evaluated by a model S-4800 scanning electron microscope (SEM, Hitachi High-Technologies Co., Japan). The dielectric properties at different microwave frequencies (*i.e.*, 1–20 GHz) were measured by a model Keysight E5071C vector network analyzer (Keysight Technologies Co., USA) in TE_{011} mode based on the Hakki-Coleman method. The temperature coefficient of resonant frequency (τ_f) was calculated by recording the frequency drifting at $25\text{--}85^\circ\text{C}$ (*i.e.*, f_{25} and f_{85}), which could be calculated by

$$\tau_f = \frac{1}{f_{25}} \cdot \frac{f_{85} - f_{25}}{85 - 25} \quad (1)$$

3 Results and discussion

Fig. 1 shows the XRD patterns of high-entropy

ceramics Eu-5RVO, Gd-5RVO, and Y-5RVO. It is evident from the well-defined diffraction peaks that these ceramics exhibit a good crystallinity. All the detected diffraction peaks for the three ceramics closely correspond to the standard card (JCPDS 96-152-7830), indicating their crystallization in a tetragonal zircon structure with a space group $I4_1/amd$. The enlarged graph

zooms in the most intense diffraction peak (200), displaying a slight shift towards higher angles from Eu-5RVO to Y-5RVO. This high-angle shift in the XRD patterns can be attributed to the gradual reduction in cation radius from Eu^{3+} (1.066 Å) to Gd^{3+} (1.053 Å) and ultimately to Y^{3+} (1.019 Å) with a coordination number of 8^[26].

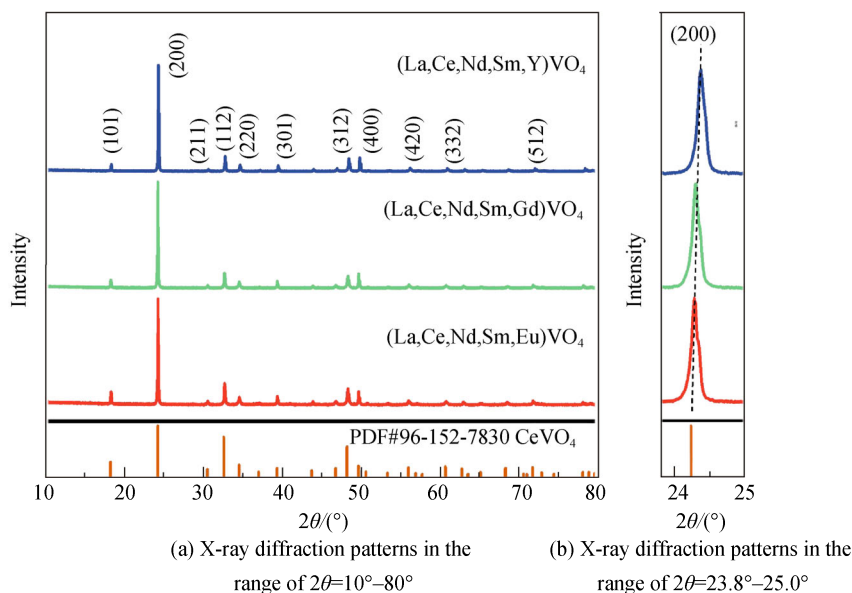


Fig. 1 X-ray diffraction patterns ($2\theta = 10^\circ\text{--}80^\circ$) of ceramics Eu-5RVO, Gd-5RVO, and Y-5RVO, and enlarged graph zooms shift of diffraction peak (200) near $2\theta = 23.8^\circ\text{--}25.0^\circ$

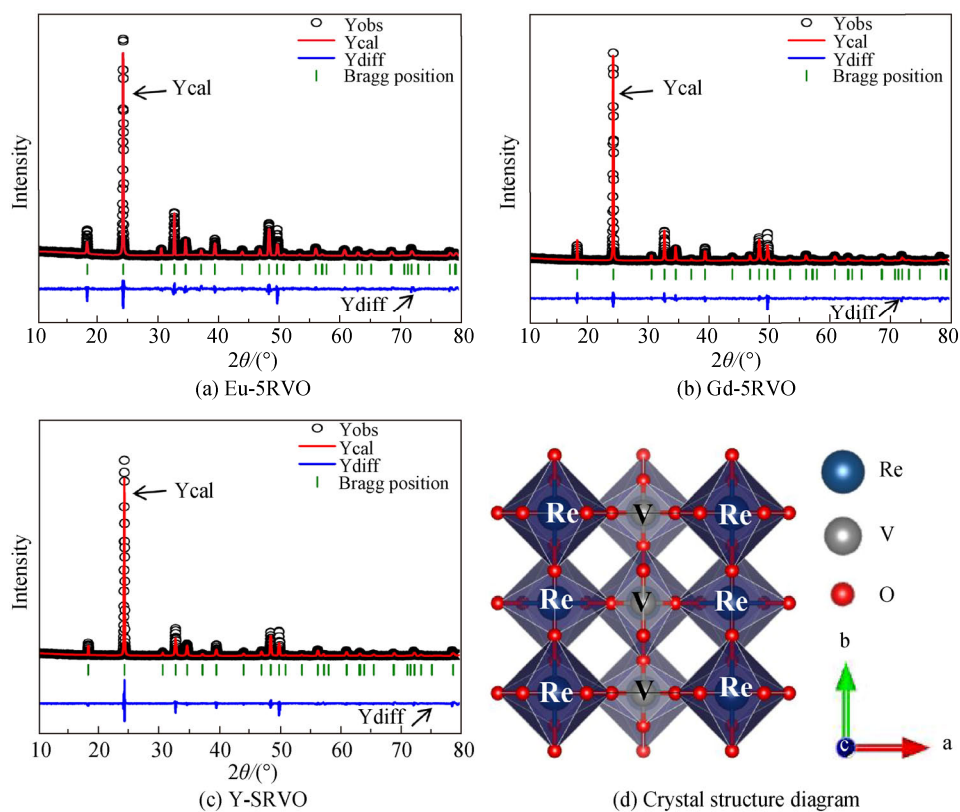


Fig. 2 Rietveld refinement plots and crystal structure diagram of zircon-type ceramics of ReVO_4

Table 1 Crystal structure data and Rietveld refinement reliability factors of ceramics Eu-5RVO, Gd-5RVO and Y-5RVO

Composition	Phase	Lattice parameters/ $\text{\AA}$ ^a		Reliability factors			$\rho_{\text{th}}(\text{g}\cdot\text{cm}^{-3})$
		$a = b$	c	$R_p/\%$	$R_{wp}/\%$	χ^2	
Eu-5RVO	Zircon	7.337 8(4)	6.447 4(6)	6.45	8.24	2.21	4.98
Gd-5RVO	Zircon	7.331 4(9)	6.442 5(7)	6.53	8.62	2.38	5.01
Y-5RVO	Zircon	7.310 7(5)	6.429 9(3)	7.25	5.97	2.71	4.78

a , b and c represent lattice parameters; R_p is profile factor; R_{wp} is weighted profile factor; $\chi^2 = (R_{wp} / R_{\text{exp}})^2$; ρ_{th} is theoretical density.

The Rietveld refinement was performed on powder XRD data to further verify the phase purity of ReVO_4 ceramics. A structural model based on a primary LaVO_4 zircon structure with La^{3+} bonded to eight O^{2-} atoms and V^{5+} in tetrahedral geometry was proposed. Noted that equal molar Ln^{3+} atoms are randomly accommodated in the La^{3+} site. The Rietveld refinements demonstrate an excellent convergence to reliable reliability factors, as shown in Figs. 2(a)–2(c). Fig. 2(d) shows the schematic crystal structure of LnVO_4 , wherein chains parallel to the axis are formed *via* alternating $[\text{VO}_4]$ tetrahedral and edge-sharing $[\text{ReO}_8]$ dodecahedra. Table 1 shows the crystal structure data and Rietveld refinement reliability

factors.

Fig. 3 shows the SEM images of fractured cross-section of high-entropy ceramics ReVO_4 and EDS mapping of ceramic Gd-5RVOs. In Fig. 3 (a)–3(c), the microstructure exhibits a dense and fine-grained morphology with grain sizes of 10 μm to 80 μm . The grain size distribution follows the normal distribution, and the mean grain sizes of ceramics are 34.51, 24.61, and 23.15 μm , respectively. In Fig. 3(d), a consistent and uniform composition of elements appears for Gd-5RVO, indicating a single-phase material. No visible porosity occurs, confirming the effective synthesis of the ceramics by sintering.

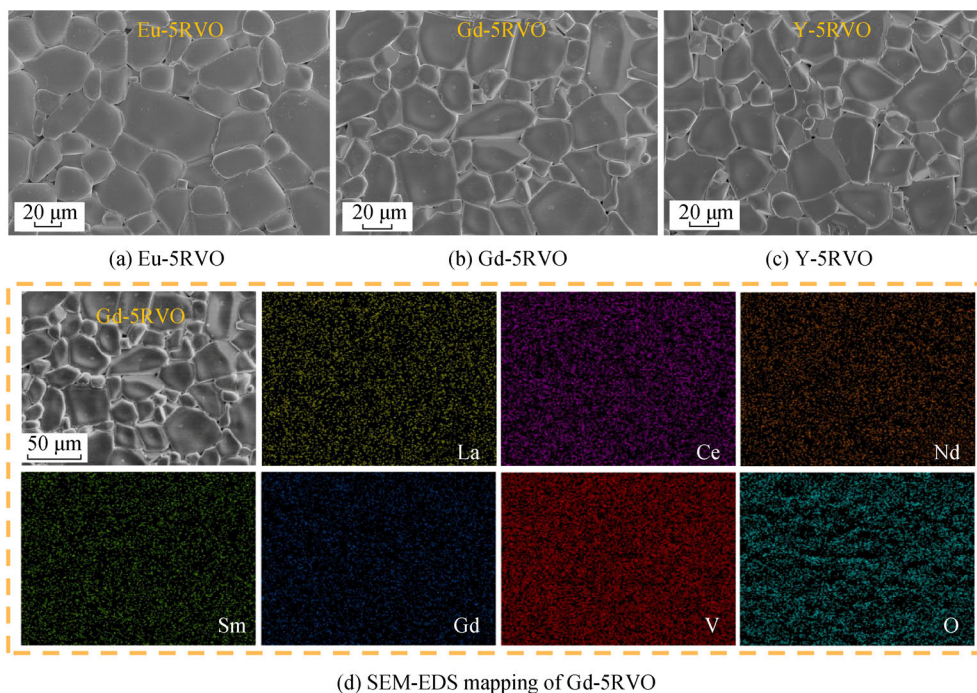


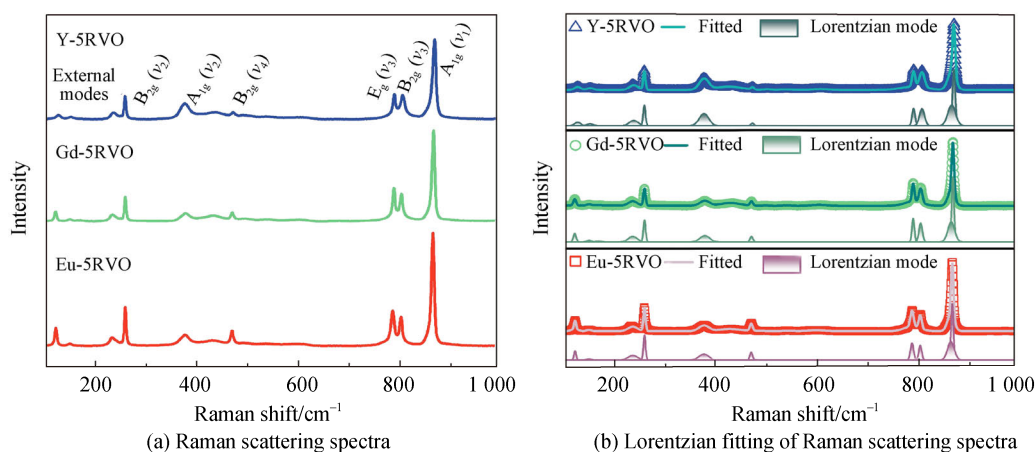
Fig. 3 SEM images of ceramics ReVO_4 and EDS mapping of ceramic Gd-5RVO as a representative

The structural and morphological analysis demonstrates that the ceramics exhibit a predominantly single crystal phase. To further investigate the dynamic and structural properties of these ceramics, their phonon characteristics were examined. According to the factor

group analysis, zircon with a tetragonal structure belonging to the I_{41}/amd space group presents 12 Raman modes (with $2A_{1g} + 4B_{1g} + B_{2g} + 5E_g$ symmetries) and 7 infrared ones ($3A_{2u} + 4E_u$)^[27]. Fig. 4 shows the Raman spectra and the Lorentzian fitting of high-entropy

ceramics of ReVO_4 at different frequencies (*i.e.*, 100–1000 cm^{-1}). Clearly, the spectra exhibit a prominent Raman band at 870 cm^{-1} , which can be attributed to the symmetric stretching mode of $[\text{VO}_4]$ tetrahedra. The Raman spectrum has two bands at 814 cm^{-1} and 796 cm^{-1} , corresponding to the anti-symmetric stretching vibrations of $[\text{VO}_4]$. The symmetric bending vibrations of $[\text{VO}_4]$ exhibit two prominent peaks at approximately 260 cm^{-1}

and 380 cm^{-1} , while the asymmetric bending vibrations manifest as a Raman band centered at 475 cm^{-1} . The external modes occur below 239 cm^{-1} . As the atomic mass of rare-earth elements decreases from Eu to Gd and Y, the main peaks at 870 cm^{-1} shift slightly towards higher wavenumbers^[22]. This slight difference in Raman features could result in significant variations in their dielectric properties.



ν_1 , ν_2 , ν_3 , and ν_4 represent the symmetric stretch, symmetric bending, antisymmetric stretch, and antisymmetric bending, respectively.

Fig. 4 Room-temperature Raman - spectra and Lorentzian fitting of ceramics ReVO_4

Fig. 5(a) shows the bulk density of high-entropy ceramics of ReVO_4 as a function of sintering temperature. Initially, the density of the three ceramics increases with increasing sintering temperature, and reaches the maximum values (*i.e.*, 4.79, 4.89 and 4.63) at 1 480, 1 440 °C and 1 460 °C, respectively. Subsequently, there is a slight decrease in the relative density. The maximum relative densities exceed 95%.

Fig. 5(b) shows the dielectric permittivity of all high-entropy ceramics of ReVO_4 . The ϵ_r initially increases and subsequently decreases with increasing the sintering temperature, which can be attributed to

variations in the density of each composition. The relative permittivity can be determined by the Clausius-Mossotti formula ($\epsilon_{\text{th}} = \frac{3V_m + 8\pi\alpha}{3V_m - 4\pi\alpha} = \frac{3 + 8\pi\alpha/V_m}{3 - 4\pi\alpha/V_m}$, where V_m and α represent the molar volume and molecular polarizability), from which a proportional relationship is derived between the relative permittivity and the unit ion polarizability and cell volume (α/V_m)^[28]. The increase in permittivity from Eu-5RVO to Gd-5RVO to Y-5RVO can mainly be attributed to the contribution of ion polarization^[28], resulting in an increase in α/V_m (from 0.186 5 for Eu-5RVO to 0.186 8 for Y-5RVO).

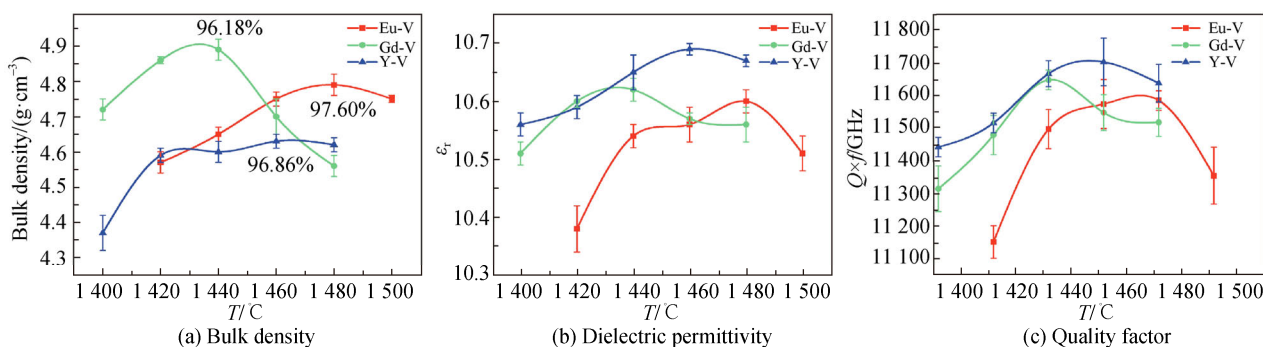


Fig. 5 Bulk density, dielectric permittivity, and quality factor of ceramics ReVO_4 sintered at different temperatures

In Fig. 5(c), the $Q \times f$ value of each composition also exhibits a distinct correlation with bulk density, reaching its peak and subsequently declining. In addition, the packing fraction (PF) defined as the volume of packed ions/volume of unit cell is a fundamental intrinsic factor that positively correlates to the $Q \times f$ value. An increase in PF value leads to a decrease in the lattice vibration space, resulting in a decrease in $\tan \delta$ ^[15]. In general, as the cell volume V_m decreases (see Table 1), there is an increase in packing fraction leading to an increase in $Q \times f$, which aligns with experimental observations. The ceramic Y-5RVO exhibits a maximum $Q \times f$ value, accompanied by an impressive PF of 55.80%.

The temperature coefficient of resonant frequency (τ_f) value exhibits a value of $-27.99 \times 10^{-6}/^\circ\text{C}$ for Eu-5RVO, $-23.75 \times 10^{-6}/^\circ\text{C}$ for Gd-5RVO, and $-21.70 \times 10^{-6}/^\circ\text{C}$ for Y-5RVO. The temperature coefficient of resonant frequency (τ_f) is affected by lattice distortion, which in turn affects a phonon transfer. The bond valence (V) is a reliable indicator for qualitatively reflect the

extent of lattice distortion, the deviation of valence signifies an increase in lattice distortion. The bond valence can be determined by^[29]:

$$v_{ij} = \exp\left(\frac{R_{ij} - d_{ij}}{b}\right) \quad (2)$$

$$V_i = \sum_j v_{ij} \quad (3)$$

where R_{ij} is the bond valence parameter^[29]; d_{ij} is the bond length of atoms i and j ; and b is a universal constant equal to 0.37 Å. Table 2 shows the τ_f value and B-site bond valence (V_{V-O}) of the ceramics. The τ_f value increases as the B-site bond valence increases from 6.85 to 8.55. Some previous studies reported a correlation between bond valence and τ_f ^[30–31]. The abnormally large bond valence arises from the exceptionally short bond length^[21–22, 31], potentially indicating a more stable structural arrangement. Furthermore, the enhanced temperature stability can be attributed to the structural robustness induced by high-entropy effect.

Table 2 The sintering temperature, microwave dielectric properties, ion polarizability, packing fraction, bond length and bond valence of ceramics Eu-5RVO, Gd-5RVO and Y-5RVO

Composition	Sintering temperature/ $^\circ\text{C}$	Dielectric permittivity	Quality factor/GHz	Temperature coefficient of resonant frequency/ $(\times 10^{-6}/^\circ\text{C}^{-1})$	Ionic polarizability/ $\text{\AA}^3$	Molar ionic Polarizability/ V_m	Packing fraction/%	Bond length of V–O/ $\text{\AA}$	Bond valence of V–O
Eu-5RVO	1 480	10.60	11 586	−27.99	16.184 0	0.186 5	55.40	1.604	6.85
Gd-5RVO	1 440	10.62	11 649	−23.75	16.154 0	0.186 6	55.50	1.554	7.84
Y-5RVO	1 460	10.69	11 704	−21.70	16.046 0	0.186 8	55.80	1.522	8.55

4 Conclusions

A series of high-entropy ceramics of ReVO_4 were synthesized by a solid-state reaction method. All the ceramics were a tetragonal zircon structure with a space group $I4_1/amd$. The phase structure, microscopic morphology, and vibration characteristics of high-entropy ceramics of ReVO_4 were analyzed, and the microwave dielectric properties were analyzed by the Clausius-Mossotti formula, packing fraction, and bond valence theory. The results showed that ceramic Y-5RVO exhibited an optimal microwave dielectric properties (*i.e.*, ϵ_r of 10.69, $Q \times f$ of 11 704 GHz, and τ_f of $-21.70 \times 10^{-6}/^\circ\text{C}$). It was indicated that the high-entropy ceramics of ReVO_4 could be used as competitive

microwave dielectric materials.

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High-Entropy Ceramics ReVO_4 and Microwave Dielectric Properties

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Extended Abstract

Introduction Microwave dielectric ceramics are widely used in microwave frequency (*i.e.*, 300 MHz–300 GHz) circuits as communication electronic components such as resonators, filters, and antennas. The dielectric permittivity (ϵ_r), quality factor ($Q \times f$) and the temperature coefficient of resonant frequency (τ_f) are the main performance index to measure the quality of microwave dielectric ceramics. However, there is a constraint relationship between the performance parameters. In general, the giant ϵ_r may cause

a large dielectric loss and a low $Q \times f$, and the volatility of ε_r originates an enormous τ_f value. Therefore, materials with superior intrinsic microwave dielectric properties are rare. The existing methods of controlling microwave dielectric properties mainly include ion substitution, composite control, laminated control and non-stoichiometric ratio control. These methods often require sacrificing one parameter to satisfy other parameters. High-entropy strategy is a novel regulation method used in inorganic materials. High-entropy ceramics refer to a ceramic system with a configuration entropy (S_c) of 1.5R. The high-entropy effect, sluggish diffusion effect, lattice distortion effect and synergy in components (i.e., cocktail effect) are four special effects of high-entropy ceramics. The high-entropy strategy shows a great potential in dielectric ceramics due to these unique effects. In this paper, high-entropy strategy was used to design rare-earth vanadate ceramics. The impact of high-entropy structure on the microwave dielectric properties was investigated.

Methods High-entropy ceramics of ReVO_4 were synthesized by a solid-phase method with high-purity rare earth oxides (Re_2O_3 with a purity of > 99.9%) and V_2O_5 . The ceramics with different chemical formulas ($\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Eu}_{0.2}\text{VO}_4$, ($\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Gd}_{0.2}\text{VO}_4$, and ($\text{La}_{0.2}\text{Ce}_{0.2}\text{Nd}_{0.2}\text{Sm}_{0.2}\text{Y}_{0.2}\text{VO}_4$, were denoted as Eu-5RVO, Gd-5RVO, and Y-5RVO, respectively. The raw materials were weighed according to a stoichiometric ratio and mixed in a ball mill at a rotational speed of 300 r/min for 6 h. The slurry after milling was dried in an oven at 120 °C for 24 h. After grinding, the powders were pre-fired in a Muffle furnace at 800 °C for 6 h. Then the prepared powders were further ground for 6 h, dried, and added with a polyvinyl alcohol solution (PVA, 5%) as a binder. The granulated powders were sieved by a 80/120 mesh screen and then pressed into cylindrical bulks with a thickness of 5.5–6.5 mm and diameter of 10 mm at 10 MPa. The samples were heated at 550 °C for 6 h to eliminate the binder and sintered at 1400–1500 °C for 6 h with an increment of 20 °C to obtain the dense ceramics.

The crystal structure of the ceramics was analyzed by X-ray diffraction (XRD, PANalytical Co., the Netherlands). The apparent density was determined by Archimedes' drainage method. The microstructure was evaluated by a model S-4800 scanning electron microscope (SEM, Hitachi High-Technologies Co., Japan). The dielectric properties at different microwave frequencies (i.e., 1–20 GHz) were measured by a model Keysight E5071C vector network analyzer (Keysight Technologies Co., USA) in TE_{011} mode based on the Hakki-Coleman method. The temperature coefficient of resonant frequency (τ_f) was calculated via recording the frequency drifting at 25–85 °C (i.e., f_{25} and f_{85}).

Results and discussion The high-entropy ceramics Eu-5RVO, Gd-5RVO, and Y-5RVO exhibit a tetragonal zircon structure with a space group $I4_1/amd$. The SEM images of the fractured cross-section of high-entropy ceramics ReVO_4 show uniform grains and clear grain boundaries, along with the spatial distribution of elements based on EDS analysis. The ceramics all exhibit a dense microstructure, as well as a promising microwave dielectric performance. The dielectric permittivity is analyzed via the Clausius-Mossotti formula, which is positively correlated to ion polarization. The quality factor is primarily determined by the packing fraction. The bond valence theory is used to reflect the degree of lattice distortion, having a strong relationship with the temperature coefficient of resonance frequency. The results show that the high-entropy strategy can effectively regulate the microwave dielectric properties.

Conclusions A series of high-entropy ceramics of ReVO_4 were prepared by a solid-state reaction method. All the ceramics were a tetragonal zircon structure with a space group $I4_1/amd$. The phase structure, microscopic morphology, and vibration characteristics of high-entropy ceramics ReVO_4 were analyzed, and the microwave dielectric properties were analyzed by the Clausius-Mossotti formula, packing fraction, and bond valence theory. The results showed that ceramic Y-5RVO exhibited an optimal microwave dielectric properties (i.e., ε_r of 10.69, $Q \times f$ of 11 704 GHz, and τ_f of $-21.70 \times 10^{-6}/^\circ\text{C}$). It was indicated that the high-entropy ceramics of ReVO_4 could be used as competitive microwave dielectric materials.

Keywords high-entropy ceramic; microwave frequency; dielectric properties; zircon structure; vanadate