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Phase stabilization strategy for robust high $Q\times f$ values in $MgSiO_3$-based ceramics for millimeter-wave applications

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ABSTRACT

$MgSiO_3$ ceramics hold promise for millimeter-wave applications owing to their low relative permittivity and cost-effectiveness, but their performance is limited by polymorphism and phase transitions. To mitigate these challenges, we strategically introduced Ge^{4+} ions to stabilize the orthoenstatite (OEN) phase and prepared $MgSi_{1-x}Ge_xO_3$ ceramics via a solid-state method. X-ray diffraction (XRD) and Raman spectroscopy confirmed a phase transition from clinoenstatite (CEN) to OEN with increasing Ge^{4+} concentration, resulting in a predominantly OEN phase at $x \geq 0.15$. Scanning Electron Microscopy (SEM) revealed that Ge^{4+} influenced grain size, uniformity and density. The relative permittivity ε_r increased from 6.07 ± 0.11–7.10 ± 0.09 with increasing x, while the temperature coefficient τ_f decreased monotonically. Optimal $Q\times f$ values of 140,000 ± 11,000 GHz at 13.1 GHz and 216,880 ± 12,840 GHz at 24.4 GHz were achieved at $x = 0.15$. After one year, the microwave dielectric properties remained robust, underscoring the potential of $MgSiO_3$ for practical millimeter-wave applications.

1. Introduction

From the advent of 2 G, 3 G and 4 G networks to the current 5 G era, communication technological advancements have led to a remarkable increase in signal transmission speeds and a shift to higher frequency bands, reaching into the microwave spectrum (300 MHz to 300 GHz) [1]. Signal transmission necessitates the use of base stations as conduits. To accommodate signals across a spectrum of frequency bands, these stations must be equipped with critical materials for efficient signal transmission. For high-frequency signals, microwave dielectric ceramics are considered as an excellent choice for the transmission medium. The ideal parameters of the ceramics include a low relative permittivity to minimize cross-coupling with conductors, thereby reducing the propagation time of electronic signals; a high-quality factor (low dielectric loss) to mitigate transmission losses and ensure the integrity of electronic signal transmission; and a near-zero temperature coefficient of resonant frequency to enhance frequency stability across a range of operating temperatures [2].

In the case of microwave ceramics with a low relative permittivity, the central material systems are Al_2O_3, Mg_2SiO_4, $MgSiO_3$, Y_2BaCuO_5, and $Mg_4Nb_2O_9$ [3–7]. Among these, magnesium silicates are particularly advantageous due to their natural abundance, ease of extraction, and cost-effectiveness [8]. Additionally, the silica-oxygen tetrahedra within magnesium silicate structures contain numerous covalent bonds, which contribute to their low relative permittivity and low dielectric loss [9]. This combination of properties makes magnesium silicates a more widely utilized and thoroughly researched material in the field of microwave ceramics. Magnesium silicates, specifically Mg_2SiO_4 and $MgSiO_3$, are characterized by their elemental ratios, with Mg_2SiO_4 having a ratio of Mg:Si:O= 2:1:4 and $MgSiO_3$ a ratio of Mg:Si:O= 1:1:3. Mg_2SiO_4 has been extensively studied due to its low relative permittivity ($\varepsilon_r \sim 6.8$) and ultra-high $Q\times f$ value (270,000 GHz) [4]. However, its

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