High-efficiency and ultra-thin electromagnetic wave absorption $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics in X-band

Hui Xie$^{1,2,*}$, Chaoqun Yang$^2$, Yingying Zhou$^1$, Zhaowen Ren$^3$, and Ping Liu$^2$

$^1$School of Materials Engineering, Xi’an Aeronautical University, Xi’an 710077, People’s Republic of China
$^2$School of Materials Science and Engineering, Xi’an Technological University, Xi’an 710021, People’s Republic of China
$^3$School of Materials Science and Engineering, Northwestern Polytechnical University, Xi’an 710072, People’s Republic of China

ABSTRACT

$x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics were fabricated by hot-press sintering. Their phase composition, morphology, element compositions, conductivity, dielectric properties as well as microwave absorption performance were examined by X-ray diffraction (XRD), scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS), multifunction digital four-probe meter and vector network analysis, respectively. The microwave absorption of the as-prepared $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics demonstrates excellent microwave absorbability. It is unexpectedly found that with a thickness of only 0.346 mm, $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ($x=0.2$) ceramic exhibits an absorption bandwidth of 3.7 GHz (8.7–12.4 GHz), being consequential to reflection loss less than $-10$ dB (over 90% of microwave absorption). It is as well discovered that the minimum reflection loss and absorption peak frequency of $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ($x=0.3$) with a thickness of 0.436 mm were $-45.43$ dB and 11.3 GHz, respectively. The prominent microwave absorption performance of the ceramic with such a thin thickness can be attributed to strong interfacial polarization, dielectric frequency dispersion, and good electromagnetic impedance matching. It indicates that the $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics with appropriate Al$_2$O$_3$ mass fraction and thickness showing good potential for effective microwave absorbing materials.
1 Introduction

With the speedy evolution of science and technology in the defense industry, the demands of electromagnetic microwave absorbing materials that can effectively reduce the reflection of electromagnetic waves at high temperature in a required frequency range are urgent [1–4]. Therefore, the tremendous emphasis has been made to high-temperature microwave absorption materials due to their better microwave attenuation capability, and many of them have been synthesized and used to suppress radar detection in militarily [5–8]. Microwave absorption materials need to meet thin thickness, wide absorbing bandwidth, light weight, and strong absorption [9–11]. In recent years, perovskite-structured materials (e.g., SrTiO$_3$, BaTiO$_3$ and CaTiO$_3$) have been extensively researched owning to their potential applications, such as capacitor, photocorrosion, solar cell, sensor, and superconductor [12–14]. In particular, SrTiO$_3$, as a member of perovskite structure materials family, has attracted increasing interest in dielectric properties and microwave absorption properties owing to its adjustable dielectric loss, low cost, and excellent temperature stability [15–17]. The most concerning advantage of such SrTiO$_3$ perovskite material is the flexible chemical composition by A- or B-site doping, by which one can adjust the electronic states. Therefore, the dielectric properties of SrTiO$_3$ ceramic depend not only on the synthesis process and particle size but also on the doping element kind and amount [18]. To enhance the microwave absorbing property of SrTiO$_3$, various transition metals and rare-earth ions were used as dopants [19, 20]. For example, when SrTiO$_3$ was doped with rare-earth elements, a vast number of defects and oxygen vacancies came forth [21]. The suitable substitution (La$^{3+}$/Gd$^{3+}$ in Sr$^{2+}$ site) can effectively change the carrier concentration of SrTiO$_3$ and microwave dielectric properties [22, 23].

Al$_2$O$_3$, as a metal oxide material, is widely used as a ceramic matrix to change physical properties of additive, due to its excellent properties such as low density, high strength, high hardness, oxidation resistance, corrosion resistance, and excellent electrical insulation, in national defense, aviation, aerospace and other fields [24, 25]. Therefore, Al$_2$O$_3$ is usually used as impedance matching regulator combined with ceramic absorbent to form ceramic composite absorbing material. Recently, some researchers have demonstrated the electromagnetic and microwave absorption properties of SrTiO$_3$/Al$_2$O$_3$ complex ceramics [26, 27].

In this study, different contents of Al$_2$O$_3$ with Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ were combined as ceramic composite absorbing material using hot-pressed sintering method. The microwave absorbing property in the X-band was studied initially. Additionally, the influence of Al$_2$O$_3$ content on the microstructure, dielectric behavior, electrical properties, and microwave absorption performances was studied.

2 Experimental details

2.1 Fabrication of $x$Al$_2$O$_3$–$(1-x)$Sr$_{0.85}$Gd$_{0.15}$TiO$_3$

$x$Al$_2$O$_3$–$(1-x)$Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ ceramics with different $x$ values ($x = 0.2, 0.3, 0.4,$ and $0.5$) were prepared by hot-press sintering. All raw materials including TiO$_2$ (CP), SrCO$_3$ (AR), Gd$_2$O$_3$ (99.999%) and Al$_2$O$_3$ (AR) were acquired from Sinopharm Chemical Reagent Co., Ltd. Firstly, TiO$_2$, SrCO$_3$, and Gd$_2$O$_3$ were mixed in ethanol and ball-milled according to the stoichiometric ratio of Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ powder. Subsequently, Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ and Al$_2$O$_3$ powders were mixed in proportion by ball milling according to the stoichiometric ratio of Sr$_{0.85}$Gd$_{0.15}$TiO$_3$, where the ball milling speed is 300 rpm. After 12 h of ball milling, the mixture was dried in an oven at 80 °C for 5 h and sifted with a 100-mesh sieve. Secondly, the mixture was pre-calcined for 3 h at 1300 °C in an alumina crucible to obtain Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ powder. Subsequently, Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ and Al$_2$O$_3$ powder were mixed in proportion by ball milling at 300 rpm for 12 h and dried at 80 °C for 5 h. To obtain high-density ceramics, they were prepared by hot-press sintering at 1350 °C under 30 MPa for 2 h with a graphite mold in vacuum. Eventually, the as-prepared complex ceramics were cooled down followed by furnace cooling to room temperature in the vacuum hot pressing sintering furnace.

2.2 Characterization

Phase compositions and crystalline structure of these samples were observed using X-ray powder diffraction (XRD, X’Pert PRO, PANalytical) with CuK$\alpha$ radiation at room temperature. The XRD patterns were measured from 10° to 90° at 4°/min. Field-emission scanning electron microscopy (SEM, VEGA3 SBH, TESCAN, Czech Republic) was used to
characterize the microstructure features and morphology of the fracture cross-section of the sintered ceramics, and their chemical compositions were measured using the energy dispersive spectroscopy (EDS) technique. The direct current (DC) electrical conductivities were examined by the ST2235 multifunction digital four-probe tester. The apparent density and relative density were tested using the Archimedean method based on the ASTMC 373-88 standard. The prepared ceramics were cut into rectangular bars with 22.86 × 10.16 × 2.00 mm and a vector network analyzer (E8362B, Agilent technology, USA) was utilized to measure the complex permittivity by the waveguide method in X-band (8.2–12.4 GHz).

3 Result and discussion

3.1 Phase composition analysis

XRD patterns of $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics with different $x$ values are displayed in Fig. 1. For each sample, the primary phase is the perovskite phase of SrTiO$_3$ (PDF#: 84-0443) and mixed with diffraction peaks of $\text{Al}_2\text{O}_3$ and the impurity phase of $\text{SrAl}_{12}\text{O}_{19}$ (PDF#: 70-0947), which may be related to the chemical reaction. It can be inferred that during sintering process, SrTiO$_3$ reacted with partial $\text{Al}_2\text{O}_3$ to form $\text{SrAl}_{12}\text{O}_{19}$ in all samples by solid-state diffusion at high temperature in the reduction atmosphere. Therefore, each sample exhibits multiple phases of SrTiO$_3$, $\text{SrAl}_{12}\text{O}_{19}$ and $\text{Al}_2\text{O}_3$. Furthermore, XRD analysis indicates that the diffraction peak intensities of $\text{Al}_2\text{O}_3$ and $\text{SrAl}_{12}\text{O}_{19}$ rise gradually with the increasing adding content of $\text{Al}_2\text{O}_3$ from 20 to 50 wt%. It can also be seen that all the samples show similar patterns indicating that the $\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ are crystallized into a cubic perovskite structure.

There is another issue worthy noting that the standard lattice parameter of SrTiO$_3$ is 3.905 Å (ICSD-94573) [28], which is larger than $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ with different $x$ values ($x = 0.2$, $3.89695$ Å, $x = 0.3$, $3.89104$ Å, $x = 0.4$, $3.89064$ Å and $x = 0.5$, $3.88755$ Å). This may be attributed to two aspects: on the one hand, the Sr$^{2+}$ (ion radius 1.44 Å) [29] are replaced by the smaller Gd$^{3+}$ (ion radius 1.195 Å) [21], On the other hand, the B-site Ti$^{4+}$ (0.605 Å) [30] are partly substituted by Al$^{3+}$ (0.57 Å) [31].

3.2 Morphology analysis

Figure 2 displays both SE and BSE images of the fractured cross-sections of $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics. These photos are from the fracture surface of the ceramic samples. Different microstructures, especially grain size, can be observed obviously, which changes over the adding $\text{Al}_2\text{O}_3$ contents. It also indicates that all the $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics have high density in microstructures, indicating the ceramics are dense, well-sintered, and nearly non-porous. The relative densities of all ceramics are more than 97.5% (Table 1).

It can be indicated from the BSE photos in Fig. 2b, d, f, h, the bright region becomes smaller with the increasing adding $\text{Al}_2\text{O}_3$ content; however, dark region gradually grows. Combing with the XRD observations in Fig. 1, it can be derived that the bright region stands for $\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ and the dark region symbolizes $\text{Al}_2\text{O}_3$ and $\text{SrAl}_{12}\text{O}_{19}$. Meanwhile, the secondary phase $\text{SrAl}_{12}\text{O}_{19}$ gradually becomes uniform with the increasing of the adding $\text{Al}_2\text{O}_3$ content. This result is in line with the XRD result as shown in Fig. 1. There is a factor that can be used to explain this phenomenon: the atomic number and backscattered electron yield have an important effect on the variation of the BSE signal [27]. Therefore, the distribution of constituent chemical elements of a sample can be visualized by BSE images, and the
greater the atomic number of the chemical element is, the brighter the contrast there is displayed in BSE images.

As shown in Fig. 3, the EDS pattern of 30%Al₂O₃−70%Sr₀.₈₅Gd₀.₁₅TiO₃ confirms the presence of elements of Al, O, Ti, Sr and Gd. The bright region contain elements of Ti, Gd, Sr and O, which means Gd³⁺ ions doped into SrTiO₃. The dark region must exist elements of Al, Sr, and O, proving that the dark area maybe SrAl₁₂O₁₉.

### 3.3 Electrical conductivity

The dependence of electrical conductivity on Al₂O₃ contents of xAl₂O₃−(1−x)Sr₀.₈₅Gd₀.₁₅TiO₃ ceramics is presented in Fig. 4. In this study, the conductivity determined by the 4-probe DC measurement is the total conductivity. In general, SrTiO₃ is one kind of insulators and it possesses weak electrical conductivity [19]. However, the electrical conductivity can be improved by doping high valence ions. From Fig. 4, it could be contended that the electrical conductivity of the ceramic gradually decreases as the Al₂O₃ content increases. It can be explained by two factors: on the one instance, the content of the Al₂O₃ is gradually increased, while the Sr₀.₈₅Gd₀.₁₅TiO₃ content decreased, which leads to the conductivity of the sample declined. The above phenomenon is mainly due to the conductivity of Al₂O₃ is lower than Sr₀.₈₅Gd₀.₁₅TiO₃; on the second instance, the ionic conductivity is a result of the oxygen vacancies that form for electroneutrality [27]. Due to the decrease of Sr₀.₈₅Gd₀.₁₅TiO₃, the concentration of the Gd³⁺ replaced Sr²⁺ in the A-site was decreased. According to charge compensation mechanisms, the content of oxygen vacancy is reduced as the decrease of Gd³⁺ content. At the same time, the concentration of carriers declined, which results in the conductivity of the entire ceramics decreased. As a conclusion, conductivity decreased notably with an increase in the concentration of Al₂O₃.

### 3.4 Dielectric properties

It is well identified that the microwave absorbing performances of materials are mainly administered by the relative complex permittivity ($ε_r = ε' - jε''$) and permeability ($μ_r = μ' - jμ''$) [32, 33]. The frequency dependence of $ε_r$ and $μ_r$ for the ceramics was measured by a vector network analyzer, as presented in Fig. 5. It is unambiguous that the complex permittivity of xAl₂O₃−(1−x)Sr₀.₈₅Gd₀.₁₅TiO₃ is a functional of frequency in the measured frequency range.
of X-band for the ceramics. The real part of complex permittivity ($\varepsilon'$) represents the electric energy storage capability, and the imaginary part of complex permittivity ($\varepsilon''$) symbolize the electric energy loss capability, respectively [34]. It is considered that the variation of Al$_2$O$_3$ adding content results in the change of $\varepsilon'$ and $\varepsilon''$. As shown in Fig. 5a, $\varepsilon'$ decreases as the raising of $x$ value in $x$Al$_2$O$_3$–$(1-x)$Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ ceramics. For instance, $\varepsilon'$ dramatically decreases from 678.58 to 329.16 at 8.2 GHz when the Al$_2$O$_3$ content changes from 20 to 50 wt%. This can be explained as follows: introducing Gd in SrTiO$_3$ could provoke lattice distortion and break the polarity of the cubic SrTiO$_3$, then inducing defect dipoles $[\text{Gd}_{\text{dip}} - \text{V}_{\text{dip}}]$. Therefore, defect dipoles would reorient toward the electromagnetic field direction when Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ was exposed to the electromagnetic field, leading to orientational polarization. With $x$ value increases, the content of Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ decreases, resulting in the reduced orientational polarization. In addition, it can be noted that the $\varepsilon'$ of the ceramics decreases gradually as frequency increases, presenting distinct frequency dispersion behaviors and induced by the polarization, which is advantageous to broadening the microwave absorption bandwidth. Figure 5b exhibits the $\varepsilon''$ of the ceramics with different Al$_2$O$_3$ contents, which confirms the existence of multiple relaxation processes in all samples. As displayed in Fig. 5b, $\varepsilon''$ increases gradually with the value of $x$ rising in $x$Al$_2$O$_3$–$(1-x)$Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ samples except for sample $x = 0.2$. The higher $\varepsilon''$ indicates a better dielectric loss capacity in the electromagnetic wave range. Moreover, these samples possess multiple loss peaks with all Al$_2$O$_3$ contents. This may be contributed to multiple polarization and relaxation processes, accompanying with interfacial polarization, orientational polarization, and defect dipole polarization [27]. Figure 5c displays dielectric loss tangent ($\tan\delta$) that is universally implemented to assess the dielectric loss capacity of microwave absorbing materials. It is unequivocal that the dielectric loss enhances prominently overall with increasing Al$_2$O$_3$ content in the ceramics.

Fig. 3 Elemental distribution of fracture surface of 30%Al$_2$O$_3$–70%Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ ceramic: a BSE; b Ti; c Al; d O; e Sr; f Gd

Fig. 4 Electrical conductivity of $x$Al$_2$O$_3$–$(1-x)$Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ ceramic samples

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3.5 Microwave absorption properties

Generally, excellent impedance matching between the surface of absorbing materials and atmosphere can prevent the electromagnetic wave from reflecting before it spreading into absorbing materials. Additionally, electromagnetic wave can be strongly absorbed through the high capability of dissipation and attenuation of absorbing materials. These two factors (i.e., impedance matching and high attenuation capability) are fundamental to an outstanding microwave absorbing material [35]. The reflection loss (RL) value of the complex ceramics was simulated by calculating the complex permittivity and thickness based on the transmission line theory, displayed as follows [36, 37]:

\[
\text{RL} = 20 \log \left| \frac{Z_{\text{in}} - Z_0}{Z_{\text{in}} + Z_0} \right| \tag{1}
\]

\[
Z_{\text{in}} = Z_0 \sqrt{\frac{\mu_r}{\varepsilon_r}} \tanh \left( j \frac{2\pi fd}{c} \sqrt{\frac{\mu_r}{\varepsilon_r}} \right) \tag{2}
\]

Herein, \( Z_{\text{in}} \) is the normalized input impedance at the junction between atmosphere and ceramics, \( Z_0 \) is the normalized impedance of free space, \( \mu_r = 1 \) for non-magnetic material in any circumstance, \( f \) is the frequency of electromagnetic wave, \( d \) is the thickness of the ceramics and \( c \) is the velocity of light. According to Eqs. (1) and (2), it is not difficult to draw that both the frequency range of absorption peak and thickness of the microwave absorbing materials are important to fix the practical application fields of it.

Fig. 5 Frequency-dependent a real part, b imaginary part, and c loss tangent of the permittivity of \( x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3 \) ceramics
Figure 6a–d exhibits the frequency-dependent calculated RL values of $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics with different Al$_2$O$_3$ adding contents and thicknesses. As can be seen from Fig. 6a, when the adding amount of Al$_2$O$_3$ is 20 wt%, the minimum RL ($RL_{\text{min}}$) value is $-40.43$ dB at 9.06 GHz with a thickness of only 0.346 mm. Besides, the absorbing bandwidth when $RL \leq -10$ dB ($RL_{-10}$) is 3.7 GHz covered from 8.7 to 12.4 GHz. For 30% A+SGT, it is observed that the $RL_{\text{min}}$ value can reach to $-45.43$ dB at 11.26 GHz with a thickness of only 0.436 mm and the absorption bandwidth ($RL_{-10}$) is 3.2 GHz (9.2–12.4 GHz). The absorption bandwidth ($RL_{-10}$) of 40% A+SGT and 50% A+SGT is 3.3 GHz (8.9–12.2 GHz) and 1.9 GHz (10.5–12.4 GHz), respectively.

Furthermore, Fig. 6 shows that the frequency of absorption peak shift to the left as the thickness increases, resulting in the RL peaks shift to lower frequency range. For the ceramics explored in this work, the quarter-wavelength matching model can be implemented to interpret this phenomenon. In addition, the correlation between the thickness and RL peaks obey the formula as following [38–40]:

$$f_m = \frac{nc}{4d_m \sqrt{\mu_r \mu_i}} \quad (n = 1, 3, 5 \ldots)$$  (3)

Herein, $f_m$ and $d_m$ are the matching frequency of absorption peak and the matching thickness of absorber. Accordingly, as the matching thickness increases, the RL peak shifts to the lower frequency.
The microwave absorption properties of $x$Al$_2$O$_3$–(1–$x$)Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ ceramic materials prepared in this work and other typical microwave absorption materials are listed in Table 2. Absorbing materials with wider absorption bandwidth lower than –10 dB is highly demanded in the EWM application. To this end, the bandwidth of RL$_{-10}$ was highlighted for comparison in Table 2. From Table 2, it can be discovered that compared with other microwave absorption materials, the $x$Al$_2$O$_3$–(1–$x$)Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ ceramic composites possess wider effective absorption bandwidth, stronger absorbing peaks, and obviously thinner. Consequently, $x$Al$_2$O$_3$–(1–$x$)Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ ceramic materials with ultra-thin and excellent microwave absorption properties provide an attractive option for electromagnetic wave absorption applications.

As described above, these advantages are mainly attributed to the high real part of permittivity, the relatively favorable imaginary part of permittivity, enhanced impedance matching characteristic and attenuation matching characteristic. As we all know, the effective microwave absorption performance should satisfy not only microwave attenuation but also impedance matching [53, 54]. Figure 7 displays the frequency dependence of impedance matching of $x$Al$_2$O$_3$–(1–$x$)Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ ceramics and the impedance of free space ($Z_0 = 377 \Omega$). To achieve the perfect impedance matching, the impedance value of free space and absorbing material should be as equal as possible. In comparison, 20%A+SGT and 30%A+SGT are relatively close to the impedance of the free space, so they have good impedance matching performance. Nevertheless, for the microwave attenuation, it is necessary to make as much as

### Table 2 Microwave absorbing properties of $x$Al$_2$O$_3$–(1–$x$)Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ and other microwave absorption materials

| Absorber and content | Thickness (mm) | Bandwidth (RL < -10 dB) (GHz) | RL$_{\text{min}}$ (dB) | Refs. |
|----------------------|---------------|-------------------------------|-----------------|------|
| 20 wt%Al$_2$O$_3$ – 80 wt% Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ | 0.346 | 3.7 | -40.43 | This work |
| 30 wt%Al$_2$O$_3$ – 70 wt% Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ | 0.436 | 3.2 | -45.43 | This work |
| 40 wt%Al$_2$O$_3$ – 60 wt% Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ | 0.468 | 3.3 | -41.34 | This work |
| 50 wt%Al$_2$O$_3$ – 50 wt% Sr$_{0.85}$Gd$_{0.15}$TiO$_3$ | 0.479 | 1.9 | -42.95 | This work |
| 95 wt% SrTiO$_{3}$ + 5 wt%SrAl$_{12}$O$_{19}$ | 0.234 | 1.4 | -13.8 | [27] |
| 70 wt%BaFe$_{12}$O$_{19}$ + 30 wt%Ni$_{81}$Zn$_{19}$Fe$_2$O$_4$ | 2.2 | 1.2 | -38 | [41] |
| 50 wt% 6H-SiC + 0.2 wt%MWCNT | 2.3 | 1.6 | -58.9 | [42] |
| 70 wt% polyglyrrole/Fe$_2$O$_4$ | 2.5 | 4 | -41.6 | [43] |
| 60 wt% C@NiCo$_2$O$_4$@Fe$_3$O$_4$ | 3.4 | 2.1 | -43 | [44] |
| 50 wt% MXene(Ti$_2$C$_2$T$_7$)/Co$_3$O$_4$ | 2 | 6.2 | -35 | [45] |
| 30 vol% BaFe$_{12}$O$_{19}$@C | 2.11 | 6.6 | -56.95 | [46] |
| 40 wt% C@Fe$_3$O$_4$@MWCNTs | 1.5 | 4.6 | -20.6 | [47] |
| 30 wt% Ti$_6$MWCNTs@Fe | 2 | 3.25 | -42.53 | [48] |
| 30 vol% RGO/Co$_3$O$_4$ | 2 | 4.3 | -24.4 | [49] |
| 28 vol%Ce$_2$Fe$_7$N$_3$–6 + Co-based microwires gridding | 1.36 | 3.6 | -20.86 | [50] |
| 40 wt% Nd$_2$Fe$_{17}$ | 1.8 | 3.8 | -32.5 | [51] |
| 30 wt% short carbon fibers@TiO$_2$ | 1 | 2.4 | -14.9 | [52] |
possible microwave dissipation and attenuation within the interior of the microwave absorbing materials. The strong dielectric dispersion of $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ is beneficial to balance these two contradictory requirements for making it as exceptional microwave absorption material. Meanwhile, the multiple interfaces among $\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$, $\text{Al}_2\text{O}_3$, and $\text{Sr}_{12}\text{Al}_{19}$ can be considered as capacitor-like structures, which would result in enhanced interface polarization and demonstrates a significant contribution to electromagnetic wave attenuation. Finally, the process of $\text{Gd}^{3+}$ ions replacing $\text{Sr}^{2+}$ ions will produce oxygen vacancies, free electrons, and defective dipoles to enhance the polarization of the dipole [55]. Consequently, the prepared $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics have a great potential for producing microwave absorbing materials with ultrathin thickness and high-performance properties.

4 Conclusions

In summary, $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics were prepared by hot-press sintering. The influence of $\text{Al}_2\text{O}_3$ content on the electrical conductivity, dielectric, and microwave absorption performance of the complex ceramics was also explored. When the $\text{Al}_2\text{O}_3$ content is 20 wt%, the ceramic shows exceptional microwave absorbing performance that the minimum reflection loss reaches $-40.43$ dB at 9.06 GHz with a thickness of only 0.346 mm and the absorption bandwidth less than $-10$ dB is 3.7 GHz (8.7–12.4 GHz). The microwave absorption properties of $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics with other $\text{Al}_2\text{O}_3$ contents prepared in this work are also excellent. It indicates that the $x\text{Al}_2\text{O}_3-(1-x)\text{Sr}_{0.85}\text{Gd}_{0.15}\text{TiO}_3$ ceramics with fitting constituent and thickness have the great potential and promising applications in the microwave absorption field. It was also found that the microwave dielectric properties were heavily influenced by the $\text{Al}_2\text{O}_3$ content, indicating that we can obtain the ideal material with excellent microwave absorption performance by controlling the amount of $\text{Al}_2\text{O}_3$.

Acknowledgements

This work was financially supported by the National Nature Science Foundation of China (Grant No. 51701148), Natural Science Basic Research Plan in Shaanxi Province of China (Grant No. 2019JQ-916) and Key Laboratory of Photoelectric Functional Materials and Devices, Shaanxi (Grant No. 2015szsj-59-1).

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