Zinc Aluminate-Based Composite Nanoparticles for Microwave Applications
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ABSTRACT: This paper reports the sol–gel preparation of ZnAl2O4 (ZA) and ZnAl2O4–TiO2 (ZAT) dielectric ceramic nanoparticles for fabricating prototype microstrip patch antennas. The prepared nanoparticles were polycrystalline in nature with their crystallite sizes of 9.4 and 11 nm, along with average grain diameters of 16 and 12 nm corresponding to samples ZA and ZAT. Dielectric properties were investigated using an LCR meter, which endorsed enhanced dielectric permittivity and decreased dielectric loss. Finally, prototype microstrip patch antennas named AZA and AZAT were fabricated using the prepared nanoparticles, and their performances were evaluated. Both antennas exhibited resonant peaks in the frequency range from 6.4 to 6.5 GHz. The antenna AZAT showed a return loss of −37.07 dB with a voltage standing wave ratio (VSWR) of 1.02 compared to the return loss of −19.42 dB, and a VSWR of 1.24 corresponds to AZA. The AZAT antenna’s improved return loss can be regarded as the increased dielectric permittivity and reduced tangent loss of the ZAT sample. Furthermore, the ZAT antenna evidenced increased/decreased forwarded/reflected power decreased reflection coefficient and an optimal VSWR value compared to that of the AZA antenna.

1. INTRODUCTION

An antenna is an electric conductor or conductor system that transmits/receives electromagnetic waves. A patch antenna is a metallic conductor connected to a grounded dielectric substrate. The miniaturization of microstrip patch antennas is essential in numerous applications, such as wireless networks, mobile telephone devices, global positioning satellites, and forthcoming wireless terminals. Patch antennas are highly demanded in modern wireless communication networks. Recent studies have focused on dielectric materials having a high-quality factor (\(Q \times f\)), high dielectric permittivity (\(\varepsilon_r\)), and resonant frequency (\(f\)) for dielectric resonators and microwave device substrates with a zero-temperature coefficient. High dielectric permittivity materials can efficiently decrease the size of the resonator since the dielectric wavelength (\(\lambda\)) is inversely proportional to \(\sqrt{\varepsilon_r}\) (\(\lambda = \lambda_0/\sqrt{\varepsilon_r}\)) where \(\lambda_0\) is the vacuum wavelength. To attain optimal frequency and stability for the transmitter of microwave components, the opposite of the loss tangent (\(Q = 1/\tan \delta\)) should be high. In addition, a minimum resonant frequency temperature coefficient is required to provide microwave components with reliability at various working temperatures. Consequently, several compound nanoparticles have been investigated, such as (Zr,Sn)TiO4, (Mg0.33Ta0.33)O3, and (Mg,Ca)TiO3.1–3 Zinc aluminate (ZnAl2O4), often known as gahnite, is a common spinel group material. The general formula is XY2O4, where X stands for divalent cations such as zinc, magnesium, calcium, and so on. The structure of this cation is tetrahedral. The Y site with the FD3m group symmetry is arranged on the octahedral sites of a face-centered cubic structure. Aluminum, iron, and other elements can occupy this Y site.4 The cubic cell is made up of 32 oxygen atoms with tetrahedral and octahedral cations. The excellent thermal strength, mechanical resistance, and small surface acidity of ZnAl2O4 allow it to be employed as a catalyst support.5 ZnAl2O4 is a semiconductor material with an optical band gap of 3.8 eV. Various methods have been reported in the literature to prepare nanoparticles, including solid-state reactions, co-precipitation, hydrothermal techniques, sol–gel methods, etc.6,7 Each method has its advantages and disadvantages. Naidu et al. investigated the electrical and magnetic behaviors of a nanoceramic magnesium ferrite doped with double lanthanide n-type semiconductors via a sol–gel approach. They measured the dielectric permittivity and observed it from 1.68 to 3.18, with a dielectric loss from

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1.12 \times 10^{-2} \text{ to } 2.6 \times 10^{-1}. Using this, they fabricated a microstrip patch antenna, which showed a voltage standing wave ratio of 1.66 dB, a gain of 5.73 dB, and an antenna efficiency of 69.82 at a resonant frequency of 14.9 GHz. Wang et al. reported the dielectric characteristics of Mg$_2$SiO$_4$-Li$_2$TiO$_3$-LiF ceramics with the addition of CaTiO$_3$ synthesized using the solid-state reaction. They claimed the enhanced quality factor was due to the increased relative density of the prepared composite. The obtained dielectric permittivity was 14.13, whereas the fabricated antenna based on this material resonated at 1.575 GHz with its return loss of −17.5 dB. Wang et al. reported the synthesis of ZnAl$_2$O$_4$ microwave dielectric ceramics produced by the solid-state reaction. They claimed the enhanced dielectric permittivity from 11.77 to 19.94 dB with a gain of 4.1 dBi with a voltage standing wave ratio (VSWR) values of 1.02.

2. MATERIALS AND METHODS

The synthesis of ZnAl$_2$O$_4$ (ZA) and ZnAl$_2$O$_4$-TiO$_2$ (ZAT) composite nanoparticles was carried out using titanium tetraisopropoxide (TTIP, Sigma-Aldrich), zirconium n-butoxide (ZrBoc, Sigma-Aldrich), aluminum nitrate nonahydrate (Al$_3$(NO$_3$)$_4$·9H$_2$O, Sigma-Aldrich), ethanol (C$_2$H$_4$OH, Sigma-Aldrich), ethylene glycol (EG, AR grade), polyethylene glycol (PEG), acetic acid (CH$_3$COOH), and nitric acid (HNO$_3$) (AR).

In the sol–gel synthesis process, 10 mL of DI water was mixed in 150 mL of C$_2$H$_4$OH and stirred. Then, 9 mL of TTIP was added to this solution and stirred on a hot plate for 4 h. The resultant particles were calcined at 700 °C. In another beaker, 40 mL of C$_2$H$_4$OH was mixed with 15 g of Al$_3$(NO$_3$)$_4$·9H$_2$O, and 0.4 mL of ethylene glycol was stirred for some time. Later, 6.60 g of (CH$_3$COO)$_2$Zn$\cdot$H$_2$O and 1.28 g of TiO$_2$ powder were added to this solution and stirred; 0.24 mL of HNO$_3$ was added to obtain the clear solution under continuous stirring at a temperature of 75 °C for 1 h. The prepared compound (1-x)ZnAl$_2$O$_4$-xTiO$_2$ (x = 0.4 concentration of TiO$_2$) was calcined in a furnace at a temperature of 700 °C for 1 h after being dried in a hot air oven at 180 °C and then ground. Hereafter, the ZnAl$_2$O$_4$ and (1-x)ZnAl$_2$O$_4$-xTiO$_2$ samples were named ZA and ZAT, respectively.

The prepared samples were examined using an X-ray diffractometer (XRD, X-Pert Pro, United Kingdom), Raman spectroscopy (BWTEK, Japan), transmission electron microscopy (TEM, TALOS F200S G2, USA), energy-dispersive X-ray spectroscopy (EDS), and a LCR meter (PSM1735 N4L, Newtowns4th Ltd., UK).

Figure 1 depicts a schematic diagram of antenna fabrication. In fabricating the prototype microstrip patch antennas, the fluorine-doped tin oxide substrates (FTO) with 2.2 mm thickness were used as substrates for the mechanical strength of the patch and SMA connection. The FTO substrates were cast using the pastes prepared using the ZA and ZAT nanoparticles. The microstrip patch antennas were coated with a silver layer for contact. Similarly, the bottom layer of the FTO substrates was also coated with a silver layer. Finally, the microstrip patch antennas were connected to an SMA coaxial connector by soldering, and their performances were studied using a vector network analyzer (VNA, R&S, ZVL, Germany).

3. RESULTS AND DISCUSSION

The ceramics were studied using XRD. Figure 2 depicts the XRD patterns of the ZA and ZAT samples, which indicate the crystalline nature of both. The XRD patterns show the dominant peaks of ZnAl$_2$O$_4$ at 2θ = 31.23, 36.83, 44.80, 49, 55.65, 59.34, 65.23, and 68.59° corresponding to the (220), (311), (400), (331), (422), (511), (440), and (531) planes. ZnO peaks at a Bragg angle of 2θ = 34.36, 47.46, 56.52, and 68.59° correspond to the SrGa$_2$O$_4$/CaGa$_2$O$_4$ sample. The patch antenna based on ZA was fabricated on FTO substrates, which was then coated with a silver layer. Similarly, the bottom layer of ZAT was also coated with a silver layer. Finally, the microstrip patch antennas were connected to an SMA coaxial connector by soldering, and their performances were studied using a vector network analyzer (VNA, R&S, ZVL, Germany).
62.75° were also noticed and assigned to the (002), (102), (110), and (103) planes, respectively.

On the other hand, the ZAT sample shows the additional peaks of an anatase-TiO2 peak at a Bragg angle of 2θ = 25.26°, which corresponds to the (101) plane and another rutile-TiO2 peak at 2θ = 27.48° of the (110) plane. The ZnAl2O4, anatase-TiO2, and rutile-TiO2, and ZnO peaks coincided with JCPDS card Nos. 00-005-0669, 00-021-1272, 01-021-1276, and 89-0510, respectively. Using Scherrer’s formula, the calculated crystallite sizes were 9.4 and 11 nm for the ZA and ZAT samples, respectively. The diffraction peaks observed for both samples were found to be consistent with those from previously reported works.14−16 The intensities of the rutile- and anatase-TiO2 peaks were varied as a function of TiO2 concentration.17 In addition, the peak positions were found shifted toward higher Bragg angles with increasing TiO2 concentration.

We performed Raman spectroscopy of ZA and ZAT samples, as shown in Figure 3. One can notice a peak of the Raman shift at 432 cm⁻¹, which indicates the E2 mode due to phonon mode of ZnO, and a defect peak originated at 275 cm⁻¹. There was a 1E1 peak observed, representing the oxygen vacancy.

Similarly, a peak of ZnAl2O4 can be observed, originating at 659 cm⁻¹, and was found to coincide with that in the reported works.18−20 After adding TiO2 in the ZnAl2O4, we noticed additional peaks of anatase- and rutile-TiO2. The peaks originated at 394, 514, and 634 cm⁻¹ were found to be associated with anatase-TiO2; however, the peaks of rutile-TiO2 were observed at 240 and 443 cm⁻¹.21

We investigated the surface morphology of ZA and ZAT nanoparticles using TEM. Figure 4 depicts the TEM micrographs of both samples. TEM micrographs are shown in Figure 4a,c,e that correspond to the ZA sample, whereas Figure 4b,d,f corresponds to the ZAT sample. As shown in Figure 4a,b, the prepared dielectric ceramic nanoparticles were found in a spherical shape arranged like the grains. The average diameters of ZA and ZAT grains were calculated to be 16 and 12 nm, respectively. Furthermore, Figure 4c,d depicts the high-resolution TEM (HRTEM) micrographs of the ZA and ZAT samples. The estimated d-spacing values of 0.46, 0.24, 0.28, and 0.20 nm were assigned to the ZnAl2O4 planes of (111), (311), (220), and (400), respectively. In addition, we also obtained the d-spacing values of 0.35 and 0.21 nm that correspond to the planes of (101) and (111) of anatase- and rutile-TiO2. Figure 4e,f shows the selected area electron diffraction (SAED) patterns of the ZA and ZAT samples, respectively, which evidenced the solid rings corresponding to the polycrystalline nature of both samples. The SAED patterns were found to well-match the XRD patterns depicted in Figure 2.

The elemental composition present in the ZA and ZAT samples was investigated by EDS measurements. Figure 5 depicts the EDS spectra, which evidenced the peaks of Zn, Al, O2, and Ti at 8.62, 1.48, 0.5, and 4.5 eV, respectively.

The dielectric permittivity (εr) of the synthesized samples was computed using the equation εr = Cd/(ε0A), where C is the capacitance value measured by the LCR meter, d is the thickness of the pellet, A is the area of the pellet, and ε0 is the permittivity of free space. Because of the limitation of the used LCR meter, the investigation of the dielectric characteristic was restricted to the frequency range of 200 kHz to 1 MHz. However, the goal of this test was to notice the common phenomenon of reducing dielectric permittivity with increasing frequency.

Furthermore, this trend is anticipated in a higher range of frequencies. As depicted in Figure 6, the dielectric permittivity...
was reduced as a function of frequency. This phenomenon can be understood by Koops’ and Wagner’s models. Our obtained dielectric permittivity values were 21.81 and 25.41, corresponding to ZA and ZAT samples. One can notice the increased dielectric permittivity after adding TiO₂ to ZnAl₂O₄, and the good trend can be explained by Clausis–Mossotti’s equation and the doping rule. Likewise, variation in dielectric permittivity is closely related to crystallite volume, size, and density. Notably, TiO₂ content significantly alters the dielectric permittivity, which is desirable for fabricating patch antennas with reduced dimensions. The decrease in dielectric permittivity with frequency is also revealed to be self-governing at higher frequencies. The interfacial polarization induces high dielectric permittivity at the lower frequency region. In other words, dipoles have sufficient time to polarize in a lower frequency range relative to the applied electric field, which leads to the movement of adjacent dipoles. By analogy, a dipole movement may be reluctant to abide by the applied field, particularly at a higher frequency range, representing a minimal dielectric permittivity. Regardless of temperature, the dielectric permittivity is reported to diminish with increasing frequency. For heterogeneous systems, Maxwell–Wagner interfacial polarization explains the frequency dispersion. The movement of neighboring dipoles at very low frequencies produced a positive and negative distribution of space charge to the electrode’s interface depletion layer, which resulted in high dielectric permittivity at low frequencies. The space charge was altered with an external electric field, and interface defects trapped multiple dipole moments. Lower temperature prevented the dipole molecules from aligning themselves. As a result, the enhanced temperature resulted in mobilization and alignment of the dipoles with the applied electric field. The thermal oscillation continued to rise, causing the temperature to increase and the alignment level to decrease. The dipole (or induced dipole) seemed to correspond with the increased kinetic energy with the external electric field due to the increased temperature. The fluctuation in the frequency resulted in the polarization of space charges. The dielectric response of the materials was mostly observed at lower

Figure 4. TEM micrographs (a,b), HRTEM images (c,d), and SAED patterns (e,f) of ZA and ZAT dielectric ceramic nanoparticles.

Figure 5. EDS spectrum of ZA (a) and ZAT (b) dielectric ceramic nanoparticles.

Figure 6. Dielectric permittivity of ZA and ZAT dielectric ceramic nanoparticles.
frequencies. The presence of two or more phases with varied electrical conductivities caused polarization of space charge.28

The variation of dielectric loss (tan δ) of ZA and ZAT samples as a function of frequency is shown in Figure 7. At the low-frequency value, the dielectric loss was found to be high and further decreased with increasing frequency due to the delay of hopping ions that occurs in proportion to the applied alternating current. As a result, it takes more energy to transport between levels, resulting in a much more significant energy loss at lower frequencies. According to a previous study, these losses are negligible in proportion to the relaxation time. Most dielectric ceramics exhibit strong interfacial polarization, enabling a huge leakage current and high charge carrier mobility. Due to the dipole relaxation time, the maximum dielectric loss can be noticed in the lower frequency region. The dielectric loss is also associated with structural or microdefects, porosity, microcrashes, and spontaneous crystallite orientation.29

The dielectric loss was negligible when the dipole relaxation time was larger than the time and frequency of the applied field.30 In simple words, the dielectric loss can be negligible in the higher frequency range as the hopping ions lag the frequency of the electric field at room temperature. Finally, when the frequency increases, the dielectric loss decreases. The ZAT sample indicates the lowest dielectric loss of 0.043 compared to 0.056 for ZA.

We have compared the dielectric properties of ZA and ZAT with the reported ones in Table 1. It shows the variation of dielectric properties in the range from 9.02 to 18.7, with 450 in another case.31–39 Such variations in dielectric properties depend on various parameters such as the material’s ability depending on its doping levels in host material/composite type, pellet size of the sample used for the dielectric measurement, and temperature. Comparatively, the ZA and ZAT samples exhibited higher dielectric permittivity and tangent loss measured at 1 MHz. The well-known dielectric permittivity and tangent loss behavior tend to decrease with an increased frequency. Here, in our study, due to the frequency limitation of the used LCR meter, we could measure up to 1 MHz; however, it further decreases in the higher frequency range.

We have theoretically computed the patch width of the microstrip antennas using an expression,

\[ W = C \left( \frac{1}{2 \sqrt{\varepsilon_r + 1}} + \frac{1}{2} \right) / \sqrt{\varepsilon_r + 1} / 2 \]

where \( f_0 \) is the resonant frequency.40 Furthermore, an effective permittivity \( (\varepsilon_{r,\text{eff}}) \) can be estimated by an expression

\[ \varepsilon_{r,\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + \frac{12h}{w} \right]^{0.5} \]

where \( h \) is the thickness of the substrate. Similarly, one can compute the patch length \( (L) \) using the simple expression

\[ L = L_{\text{eff}} - 2\Delta L \]

where \( L_{\text{eff}} \) is the effective length. This effective length can be further calculated using the formula

\[ L_{\text{eff}} = c / \sqrt{\varepsilon_{r,\text{eff}}} \]

where \( \varepsilon_{r,\text{eff}} \) is the effective permittivity. The length expansion on the two extremities of the patch length due to fringing fields can be evaluated using the expression

\[ \Delta L = 0.412\left(\varepsilon_{r,\text{eff}} + 3\right)\left(\varepsilon_{r,\text{eff}} + 0.264\right) \]

\[ \left[\varepsilon_{r,\text{eff}} - 0.258\right] \left[\varepsilon_{r,\text{eff}} + 0.8\right] \]

lated values of \( \varepsilon_{r,\text{eff}} \) \( W, L, L_{\text{eff}} \) and \( \Delta L \) were 16.73, 0.0068, 0.004, 0.0056, and 0.0006 m, respectively, for the ZA sample. Similarly, 19.3216, 0.0064, 0.0041, 0.0053, and 0.0006 m were the values of \( \varepsilon_{r,\text{eff}} \) \( W, L, L_{\text{eff}} \) and \( \Delta L \) for the ZAT sample.

The proposed prototype of microstrip patch antennas were fabricated on FTO substrates for wireless communication applications. The as-synthesized ZA and ZAT nanoparticles were screencoated on FTO substrates, and hereafter, the respective antennas were named AZA and AZAT. The silver paste was used on both sides of the antennas for the electrical contacts. In a similar way, a silver-conductive paint was employed on both sides of the barium strontium titanate-based antenna.41 Later, an SMA coaxial connector of the single feed was connected to the microstrip patch antennas by the

### Table 1. Comparison of Dielectric Properties of Various Materials

| Material                      | Dielectric Permittivity (\( \varepsilon_r \)) | Dielectric loss (tan δ) | Obtained at frequency | ref |
|-------------------------------|---------------------------------------------|------------------------|------------------------|-----|
| \( \text{LaCo}_{0.5}\text{Fe}_{0.5}\text{O}_3 \) | 13.5 | 0.0045 | 2 GHz | 31 |
| \( \text{Mg}_0.1\text{Nb}_{0.9}\text{O}_3 - \text{ZnAl}_{2}\text{O}_4 - \text{TiO}_2 \) | 13.1 | - | - | 32 |
| \( \text{PTFE/ZnAl}_{2}\text{O}_4 - \text{TiO}_2 \) | 13.4 | 0.0085 | - | 33 |
| \( 0.8\text{ZnAl}_{2}\text{O}_4 - 0.17\text{TiO}_2 \) | 13.15 | 0.00047 | 5 MHz | 34 |
| \( 0.8\text{ZnAl}_{2}\text{O}_4 - 0.21\text{TiO}_2 \) | 11.4 | - | 6.5 GHz | 35 |
| \( \text{Bi}_2\text{Ti}_3\text{O}_12 \) | 450 | 0.001 | 1 MHz | 36 |
| \( \text{Ca}_{0.9}\text{Zn}_{0.1}\text{Al}_{2}\text{O}_4 \) | 9.02 | - | 1 MHz | 37 |
| \( \text{Zn}_{0.7}\text{Ti}_{0.3}\text{Al}_{2}\text{O}_4 \) | 13.51 | - | 1 MHz | 38 |
| \( 0.5\text{ZnAl}_{2}\text{O}_4 - 0.5\text{TiO}_2 \) | 18.7 | 0.000013 | - | 39 |
| \( \text{ZnAl}_{2}\text{O}_4 \) (ZA) | 21.81 | 0.034 | 1 MHz | present work |
| \( 0.6\text{ZnAl}_{2}\text{O}_4 - 0.4\text{TiO}_2 \) (ZAT) | 25.41 | 0.043 | 1 MHz | |

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soldering method. The insets of Figure 8 show the fabricated prototypes of AZA and AZAT antennas.

![Figure 8](image)

**Figure 8.** Return loss with the inset digital images of AZA and AZAT microstrip patch antennas.

In fabricating the prototype microstrip patch antennas, we followed the microwave theory and used the obtained dielectric permittivity values. The sizes of the patches for the AZA and AZAT antennas were 6.82 × 4.41 and 6.43 × 4.11 mm, respectively. Return loss of an antenna is related to the input and output of the signals. When the load is mismatched, the applied power is not delivered to the load. As a result, it causes the return of power. The antenna and cable’s main characteristics in matching the system are the return loss and VSWR measurements. An antenna that is not properly matched or mismatched reflects more RF energy than it transmits. This reflected energy redirected to the transmitter distorts the signal and decreases the efficiency of the transmitted power and hence the communication range.

Figure 8 depicts the return loss of the prototype microstrip patch antennas measured in the operating frequency range from 5 to 8 GHz using a vector network analyzer with a 50Ω feeding load mechanism. The AZA antenna exhibited a return loss of −19.42 dB at a resonant frequency of 6.50 GHz, whereas AZAT showed its better performance with a return loss of −37.07 dB at a resonant frequency of 6.41 GHz. We can correlate this better performance of the AZAT antenna with the improved dielectric permittivity value to 25.41 from 21.81. Furthermore, the bandwidth of the resonant frequency was estimated to be 1.43 GHz compared to 0.6 GHz of the AZA antenna. This result indicates that ZAT dielectric ceramic material is promising for fabricating microstrip patch antennas for application in C-band communication. Additionally, the use of nanoparticles enables the decreased size of the patch owing to an increased dielectric permittivity with its low-cost fabrication. In a similar study, a patch antenna was fabricated using dielectric ceramic nanoparticles and used for its application in GPS communication. Remarkably, our antennas demonstrated resonant frequencies between 6.4 and 6.5 GHz, and therefore, these are suitable for C-band communication.

We have compared the performance of both antennas with the reported ones, as shown in Table 2. We notice a variation in dielectric permittivity and loss in accordance with the selection of the frequency used for the dielectric measurements.

Comparatively, Thiruramanathan et al. reported the dielectric permittivity and loss of 450 and 0.001 measured at 1 MHz. The dielectric permittivity was relatively high with the minimum tangent loss, and the antenna resonated at 2.45 GHz with its return loss of −4.95 dB. Another work reported by Jalal et al. demonstrated the antenna’s return loss of −25 dB at the resonant frequency of 1.575 GHz, with the used material having a dielectric permittivity of 9.02 measured at 1 MHz. Furthermore, the same group reported the increased dielectric permittivity of 13.51, with the composite materials by replacing the Ca with the TiO₂ as measured at a frequency of 1 MHz. In this case, the antenna resonated at the frequency of 1.57 GHz with a return loss of −28.71 dB. Similarly, Huang et al. claimed a dielectric permittivity of 18.7 and a loss tangent of 0.000013, but they did not report the frequency value at which the dielectric properties were studied. Based on these parameters, the antenna showed its return loss of −37 dB at 2.55 GHz. In the present study, both samples (ZA and ZAT) exhibited high dielectric permittivity and tangent loss at a frequency of 1 MHz. However, it is expected to further decrease if tested in the high-frequency range, as reported in several works. Remarkably, the AZA and AZAT antennas resonated in the C-band frequency range with reasonably enhanced bandwidth. No similar work has been reported to our best knowledge using these materials in fabricating a C-band microstrip patch antenna.

The VSWR value is directly related to the transmission of maximum power from the transmitter to an antenna to act as an ideal one. This happens only when the input impedance is found matching with the transmitter impedance. With this, one can calculate the VSWR using the expression $VSWR = V_{\text{max}}/V_{\text{min}} = (1 + |\rho|)/(1 - |\rho|) = (1 + S_{11})/((1 - S_{11})$, where $\rho = (VSWR - 1)/(VSWR + 1)$.

Accordingly, we obtained the VSWR values with respect to operating frequency, as shown in Figure 9 (left axis). We can observe a low VSWR value for the AZAT antenna compared to that for the AZA antenna. This indicates the increased efficiency of the AZAT antenna. The estimated VSWR value

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**Table 2. Performance Comparison of Various Microstrip Patch Antennas**

| Material                  | Dielectric permittivity ($\varepsilon_r$) at 1 MHz | Dielectric loss (tan δ) at 1 MHz | Resonant frequency (GHz) | Return loss (dB) | Bandwidth (MHz) | VSWR | Ref   |
|---------------------------|----------------------------------------------------|---------------------------------|--------------------------|-----------------|-----------------|------|-------|
| Bi₂Ti₃O₇                 | 450                                                | 0.001                           | 2.45                     | −4.95           | -               | 3    | 36    |
| Ca₀.₃Zn₀.₇Al₂O₄           | 9.02                                               | -                               | 1.575                    | −25             | 135             | 37   |       |
| Zn₀.₅Ti₃O₇Al₂O₄          | 13.51                                              | -                               | 1.57                     | −28.71          | 270             | 38   |       |
| S₀.₅ZnAl₂O₄-0.₅ TiO₂      | 18.7                                               | 0.000013                        | 2.55                     | −37             | 205             | 39   |       |
| ZnAl₂O₄ (ZA)             | 21.81                                              | 0.034                           | 6.50                     | −19.42          | 600             | 1.24 | present work |
| 0.₆ZnAl₂O₄-0.₄ TiO₂ (ZAT) | 25.41                                              | 0.043                           | 6.41                     | −37.07          | 1430            | 1.02 |       |
of the AZA antenna was 1.24 at a resonant frequency of 6.50 GHz. Remarkably, for the AZAT antenna, the VSWR value was 1.02 at a resonant frequency of 6.41 GHz. The estimated VSWR values of the AZA and AZAT antennas usually coincide with the obtained results using the vector network analyzer. VSWR depends on the reflection coefficient of the antenna under the test, whereas a higher ratio indicates a high mismatch rather than a perfect matching (i.e., a 1:1 ratio). This improved performance of the AZAT antenna can be attributed to the increased dielectric permittivity and decreased dielectric loss, whereas the better performance of the AZAT antenna is notable, which suggests its potential application in C-band communication.

## 4. CONCLUSIONS

ZnAl₂O₄ (ZA) and ZnAl₂O₄–TiO₂ (ZAT) nanoparticles were prepared and investigated for their structural, compositional, morphological, and dielectric properties using the sol–gel method. Both samples exhibited a polycrystalline nature with the formation of spherical grains with their mean diameters of 16 and 12 nm. The dielectric permittivity and dielectric loss of the formation of spherical grains with their mean diameters of 16 and 12 nm. The dielectric permittivity and dielectric loss attributes to the increased dielectric permittivity and decreased forwarded powers compared to the AZA antenna. Finally, both prototype antennas demonstrated their resonant frequency within 6.4–6.5 GHz.

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