A Development of a Dielectric Composite Substrate Based on Barium Titanate-Epoxy Resin for a 5 GHz Microstrip Antenna

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Abstract: *This study focuses on investigating the potential of a barium titanate-epoxy resin composite as a substrate for a microstrip patch antenna at 5 GHz. Barium titanate exhibits excellent dielectric properties, and epoxy resin, known for its robust thermosetting polymer, was combined to create one composite material. The permittivity and loss tangent of the composite material were measured using the waveguide technique over a frequency range of 4 GHz to 6 GHz. To determine the compatibility of the composite substrate for a microstrip patch antenna at 5 GHz, the values of return loss and Voltage Standing Wave Ratio (VSWR) were analyzed. The barium titanate-epoxy resin sample resulted in a high permittivity value of 7.0208 and a low loss tangent of 0.0238, which can contribute to a compact antenna design with high efficiency. The fabricated antenna results in a return loss of -42.52 dB and VSWR of 1.137 at 5 GHz, showing its effectiveness for wireless communication applications.*

Keywords: Microstrip Patch Antenna; Dielectric Composite; Dielectric Properties; Waveguide

1. INTRODUCTION

Antennas are used to emit and receive electromagnetic waves that can propagate through free space. Dielectric materials are often used in antenna structures and are crucial for sensing applications, which enables us to gain understanding and develop innovative solutions [1]. Some of the sensing applications that can be further seen are radar, radio astronomy, and wireless communication systems.

The fabrication of the antenna dielectric can come from numerous types of materials, such as textiles [2], agricultural waste [3,4], and composite materials [5-8]. In this study, composite material has been our focus since composite materials, especially those that have a combination of ceramic fillers and polymers, show significant promise. In this study, the utilization of barium titanite-epoxy resin will be undergoing rigorous research since they have potential in high-frequency device applications [8,9]. It is shown that combining both materials can enhance the dielectric properties, making it more prominent for antenna applications [7,8,10-13].

Additionally, composite material and the metamaterial substrate can contribute to a high dielectric constant, which makes it much more desirable in compact antenna design. Furthermore, these materials can facilitate achieving a wideband frequency range, which is beneficial in applications that require broad bandwidths and multiple frequency operation. For example, the Shil et al. [14] study demonstrates the effectiveness of utilizing a metamaterial-based design and defective ground structure to improve the bandwidth of a circularly polarized antenna, which proves that the utilization of metamaterial gives a prominent solution for modern wireless communication applications. Further applications can be seen under Hasan et al. [6], who investigated the dielectric properties of an epoxy-barium titanate composite by fabricating the composite with different filler loadings and measuring its permittivity. On the other hand, the application of an epoxy-barium titanate dielectric composite material on a coaxial antenna for liver cancer treatment has been made by Mustafa et al. [15].

Knowing the new material's properties by characterizing and classifying it before applying it in any practical applications is essential. The parameters often related to material characterization are permittivity, permeability, loss, and conductivity because it is important to ensure the compatibility of the material for use in antennas and any other radio frequency application, for example, to meet the required specifications. Galupino et al. [16] utilize machine learning in order to estimate the permeability of soil-fly ash mixture before being applied to sustainable construction materials. Other than that, the complex permittivity and permeability were evaluated by a rectangular waveguide measurement technique based on a hybrid electromagnetic method, which uses an iterative process to fit the calculated values to the measured data in Karim et al. [17] works.

Since the barium titanate powder and epoxy resin are used in this study to create a solid composite material, it needs to be cured to achieve optimal mechanical properties and then measure the permittivity value through a waveguide technique and a Vector Network Analyzer (VNA) over a frequency range of 4 GHz to 6 GHz. Then, the sample will be tested as a substrate on a microstrip patch antenna. The effect of varying the parametric dimension of a patch antenna on return loss and the performance of the antenna, Voltage Standing Wave Ratio (VSWR), will be evaluated to determine the suitability for the application of the antenna at the 5 GHz frequency range.

The potential of barium titanate as a dielectric material on a microstrip patch antenna at 5 GHz is still under exploration. Thus, this study has been done to fill this gap by formulating a barium titanate-epoxy resin composite and evaluating its performance based on antenna characteristics like return loss and VSWR to test the suitability as a substrate for this patch antenna in the 5 GHz frequency range.

2. METHODOLOGY

2.1 Material

This study utilized composite materials, specifically barium titanate and epoxy resin. Barium titanate (BaTiO3) is recognized for its role as a ceramic material that serves as a filler in dielectric composites [18]. 60 g of nanosized barium titanate powder is used for one set of samples. Epoxy resin is a thermosetting polymer that holds together the fibers or fillers of composite materials. Epoxy resin requires a hardener to start the curing process since epoxy does not harden by itself through the cooling or drying process [19]. A curing agent is used to harden the surface of a material by increasing the bonding of the substance's molecular elements. The epoxy hardener undergoes partial curing, meaning it is partially set but not fully cured, before mixing up with another substance and leaving it set. The epoxy resin and hardener are mixed following the manufacturer's recommended weight ratio of 3:1, with 37.5 g of resin and 12.5 g of hardener. The densities of the epoxy resin and the barium titanate powder are 1.25 g/cm^3 and 6 g/cm^3, respectively.

2.2 Sample Preparation

The production of the sample begins by mixing 60 g of barium titanate with 37.5 g of epoxy solution. This mixture is then stirred using an overhead mixer for three minutes. Afterward, 12.5 g of epoxy hardener is added while the solution is heated to 50℃ on a hotplate, with stirring speeds adjusted to 500 rpm. This process might create air bubbles, which could decrease the material's impedance, impacting its permittivity and tensile strength [20]. Next, the blend is carefully transferred into a mold with 22.15 mm × 22.15 mm × 22.10 mm dimensions that match the waveguide opening used for testing the material's permittivity and a flat mold for antenna fabrication. Finally, the material is left to harden for 30 minutes in an oven set at 60℃, with the moderate heat helping to speed up the curing process. Raising the curing temperature improves the composite's heat deflection temperature and its mechanical properties by enhancing its resistance to deformation under heat. After this initial heat treatment, the composite undergoes a 24-hour curing period at room temperature. Once cured, the material is extracted from the mold and ready for permittivity testing, as shown in Fig. 1.

Permittivity value can be measured with various characterization methods – free space, resonant [21-24], or waveguide technique [17] – where, in this research, the waveguide technique was employed to measure the permittivity value. Additionally, a VNA was used to conduct wide-frequency measurements. The rectangular waveguide, set to operate in the dominant transverse electric (TE_{10}) mode, covered a frequency range of 4 GHz to 6 GHz. The dimensions of the sample were adjusted to match the 22.15 mm height of the waveguide, ensuring it precisely filled the waveguide's cross-sectional area. Before conducting permittivity measurements on the sample, the VNA underwent a comprehensive two-port Short-Open-Load-Thru calibration to eliminate errors due to device deficiencies. The VNA helped measure the phase and magnitude of S_{21}. An inverse method was utilized to calculate the permittivity and the composite material's loss tangent, where the phase and magnitude of S_{21} are needed [25].

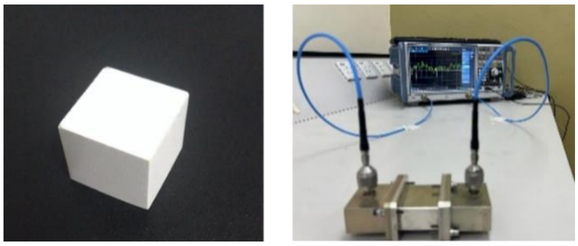

Fig. 1. Measurement of sample.

2.3 Antenna Design

The sample that was measured resulted in a permittivity value of 7.0208 and a loss tangent of 0.0238. The high permittivity value of this composite material influences the patch antenna size, which is suitable for fabricating compact antenna designs, and a low loss tangent indicates that the antenna radiates more input power, resulting in high efficiency [26]. These properties show the suitability of the barium titanate-epoxy resin composite for patch antenna application.

A microstrip patch antenna is lightweight, easy to manufacture, and cost-effective. The circuit can comprise both the microstrip antenna and feeds. Microstrip antennas are widely used in wireless communications due to their numerous benefits. Patch antennas are designed to meet specific application requirements, including resonance frequency, operating range, bandwidth, impedance matching, and radiation patterns [27]. Radiation patches can be made of copper or gold and have many shapes, including round, rectangular, square, elliptical, triangular, and ring, depending on the purpose [28]. In this study, the patch and the ground elements are made of copper, which provides excellent conductivity and efficiency in signal transmission and reception.

The following equations are used to design the antenna equation (1) to (3). Equation (1) is specialized in designing the width of the patch antenna (W), where c is the speed of light, f_r represents resonant frequency, and ε_r is the dielectric constant of the substrate [29]. Equation (2) calculates the effective dielectric constant, ε_{eff}, where h is the height of the dielectric substrate [30]. Equation (3) is used to calculate the length of the patch antenna, where L is the length of the patch antenna.

$$W = \frac{c}{2f_r\sqrt{\frac{\varepsilon_r + 1}{2}}} \tag{1}$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[\frac{1}{\sqrt{1 + 12\left(\frac{h}{W}\right)}}\right] \quad (2)$$

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} - 0.824h\left[\frac{(\varepsilon_{eff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{eff} - 0.258)\left(\frac{W}{h} + 0.8\right)}\right] \quad (3)$$

The detailed dimension design of the microstrip patch antenna is represented Table 1 and the structure of the patch antenna can be represented in Fig. 2.

Table 1. Dimension of microstrip patch antenna

Parameters	Description	Value (mm)
W	Width of patch antenna	26.6
W_s	Width of substrate	36.2
W_f	Width of feedline	3.0
G	Gap between feedline and patch	0.4
L	Length of patch antenna	18.6
L_S	Length of substrate	28.2
L_G	Length of the gap	8.85
H_g	Height of ground	0.035
H_s	Height of substrate	1.6

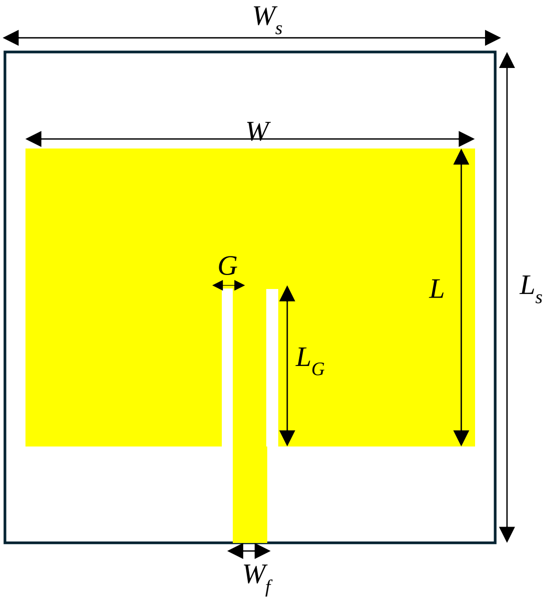

Fig. 2. Structure of microstrip patch antenna.

3. RESULT AND DISCUSSION

3.1 Parametric Study on Return Loss Analysis

Fig. 3 illustrates the construction of the patch antenna, employing barium titanate and epoxy resin as the substrate materials. The optimization of the antenna's length and width was performed using Computer Simulation Technology (CST) software. Then, the measurements for the antenna were carried out using a VNA.

(a)

(b)

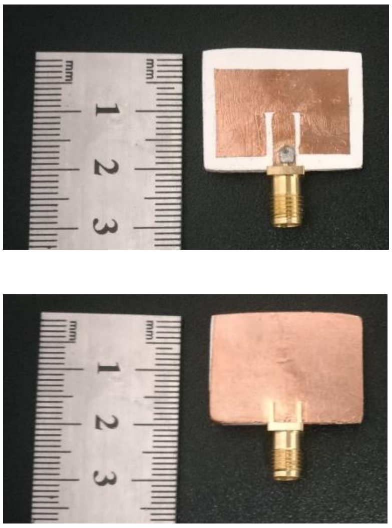

Fig. 3. (a) Front view and (b) back view of fabricated microstrip.

3.1.1 Analysis of width of patch toward return loss

Fig. 4 illustrates the patch antenna's varying width affecting the return loss performance. The patch width results with 26.6 mm, giving the best return loss performance within 5 GHz frequency at -37.95 dB. The performance of other width lengths (W = 28.6 mm, W = 30.6 mm, W = 32.6 mm) shows slightly higher return loss values, implying less efficiency but still giving significant return loss results. Achieving low return loss is important in maximizing power transfer and minimizing signal reflection.

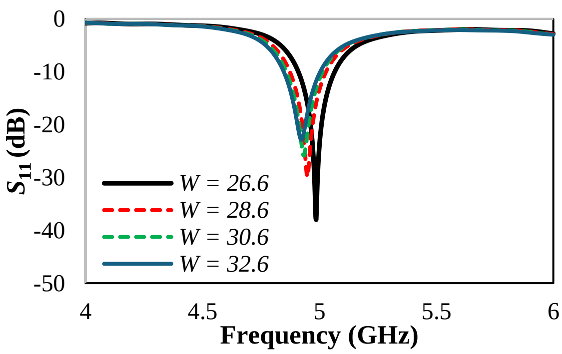

Fig. 4. Effect of varying width of patch antenna toward S_{11}.

3.1.2 Analysis of length of patch toward return loss

Fig. 5 shows the effect of the length of the patch antenna on return loss performance. The patch length of 18.6 mm suggests the best return loss performance, -37.96 dB, within 5 GHz. The performance of another length of patch size (L = 16.5 mm, L = 22.5 mm, L= 22.6 mm) shows higher return loss values, indicating a less efficient but still significant return loss performance compared to L=18.6 mm. This result gives vital information to optimize the design because it shows minimal signal reflection and maximum efficiency at the target frequency.

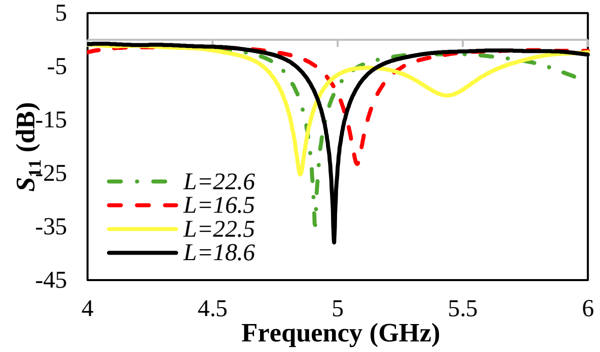

Fig. 5. Effect of varying length of patch antenna toward $S_{11.}$

3.1.3 Overall performance of patch antenna

Fig. 6 shows that the antenna resonates around 5 GHz by observing the depth of the S_{11} parameters at this frequency. The S_{11} parameters indicate how much power is reflected from the antenna, which means the lower the value, the $S_{11,}$ the less power is reflected. The measurement shows a minimum of -42.52 dB at the resonant frequency, indicating minimum power reflection. At the same time, the simulation result shows a slightly higher minimum value of -38.12 dB, indicating a good result, though not as optimal as the measured result. Minor differences between the simulation and the measurement result could be due to the fabrication process or measurement setup. Still, both the simulated and the measured results show a bandwidth where S_{11} is below -10 dB using barium titanite-epoxy resin composite as substrate, providing a decent bandwidth for the antenna, making it suitable for application around the 5 GHz frequency range. Using barium titanite-epoxy resin composite as a substrate likely contributes to good dielectric properties, such as higher permittivity and low loss, which are advantageous for antenna performance.

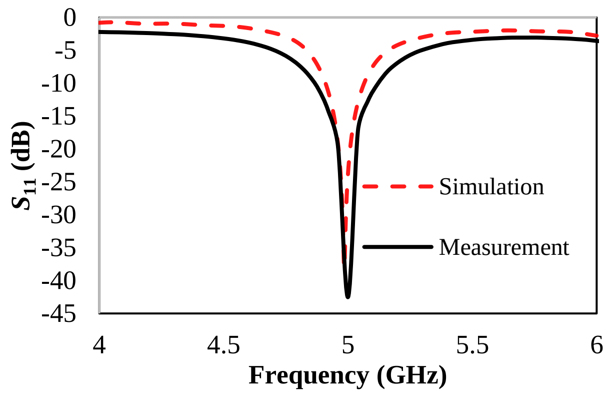

Fig. 6. Effect on S_{11} by applying final dimensions of (*W*) 26.6 mm × (*L*) 18.6 mm on patch antenna.

3.2 Voltage Standing Wave Ratio

Fig. 7 demonstrates that the patch antenna exhibits a VSWR of 1.137 at 5 GHz, suggesting an almost ideal impedance match with the transmission line. A VSWR below two is typically considered adequate for most antenna applications, while a VSWR of one represents a perfect match, ensuring that all the power from the source is transmitted efficiently with no reflections.

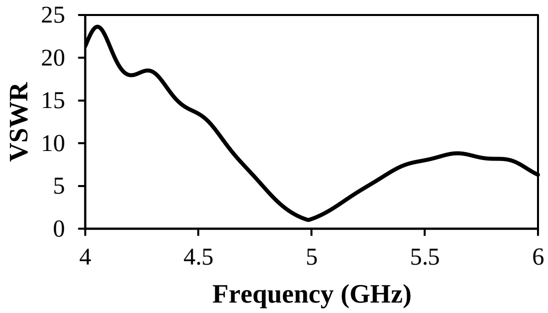

Fig. 7. VSWR at 5 GHz.

4. CONCLUSION

This study shows that using barium titanate-epoxy resin composite material as a substrate for microstrip patch antenna is effective in achieving high efficiency for wireless communications applications. With a permittivity value of 7.0208 and a loss tangent of 0.0238, the design of a compact and efficient antenna becomes feasible. The experimental results showed that the antenna achieved a return loss of -42.52 dB and a VSWR of 1.137 at the resonant frequency of 5 GHz. These findings show that the barium titanate-epoxy resin composite enhances the antenna's dielectric properties, making it suitable for high-frequency applications. Future work could focus on optimizing composite formulations and antenna designs to improve performance further and broaden the application scope of this promising material in advanced wireless communication systems.

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