

EBG-Integrated Microstrip Antenna Sensor for Moisture and Iron Screening in *Andrographis paniculata* Powder

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ABSTRACT: This study presents an electromagnetic-bandgap (EBG)-integrated rectangular microstrip antenna fabricated on a 0.5-mm-thick polyester Mylar substrate for screening controlled nominal water-addition and nominal iron-powder addition conditions in *Andrographis paniculata* powder. The sensing structure comprises a rectangular microstrip patch, a rectangular ring stub, and a 7×1 transverse-electric (TE)-polarized woodpile EBG array designed for operation at 2.50 GHz. The antenna-to-EBG separation was 10 mm. The fabricated prototype had a measured S_{11} of -13.94 dB at 2.50 GHz, a 10-dB impedance bandwidth of 2.488–2.512 GHz (0.96%), and a measured gain of 5.16 dBi. Compared with the baseline antenna, the EBG-integrated configuration increased the measured gain by 1.35 dBi. Powder samples were prepared at controlled nominal water-addition and nominal iron-powder addition levels and evaluated using a one-port microwave reflection measurement. At 2.50 GHz, the mean reflected-power response of the EBG-integrated antenna decreased from 0.02667 mW at the nominal 0% water-addition condition to 0.00063 mW at the nominal 100% condition. For the nominal iron-powder addition experiment, the corresponding mean reflected-power response decreased from 0.01954 mW at 0% to 0.00061 mW at 100%. The results are reported as mean $\pm$ standard deviation from repeated measurements under the controlled setup. The proposed system shows potential as a compact and nondestructive screening platform for controlled herbal-powder conditions. Because water-addition levels were not verified by reference moisture analysis and the iron-powder addition levels were not verified by independent elemental analysis, the results should not be interpreted as quantitative moisture measurements or quantitative iron-concentration measurements. The proposed system is intended for screening controlled nominal iron-powder addition conditions. Future work should establish calibration against reference analytical methods and evaluate independently prepared sample batches measured on different days.

1. INTRODUCTION

Andrographis paniculata is an important medicinal herb that has been widely used in traditional medicine and reported to have antipyretic, antiviral, and antibacterial activities [1–5]. Its bioactive properties support its use in herbal products for relieving symptoms associated with colds, fever, and cough. To ensure consistent product quality, recent studies have investigated cultivation, post-harvest handling, drying conditions, and physicochemical characteristics of *A. paniculata* [6–11]. However, herbal powders remain susceptible to quality variations caused by moisture uptake, storage conditions, particle-size variation, and the presence of foreign materials or metallic contaminants. Therefore, reliable monitoring methods are required to support herbal-powder quality control.

Conventional methods for moisture and metal analysis can provide accurate measurements; however, they may require laboratory instruments, sample preparation, chemical reagents, or relatively long analysis times. Microwave sensing offers a nondestructive alternative because dielectric and conductive properties affect a material's electromagnetic response. Changes in moisture content modify the effective permittivity of herbal powder, whereas conductive material can alter the reflected electromagnetic signal. Microstrip antennas are attractive sensing elements because they are compact, low-cost, and readily integrated with measurement systems [12–18]. For the intended powder-screening application, the antenna should provide adequate impedance matching at the selected operating frequency, stable one-port reflection measurements under fixed sample placement, sufficient electromagnetic coupling to the powder sample, compact and low-profile geometry, simple fabrication, and compatibility with a practical sample holder or

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future in-line measurement fixture. Maximum far-field gain is not the sole design objective because the proposed system uses a fixed near-field measurement configuration. Instead, the design should provide a balanced trade-off among matching, field distribution, gain, structural simplicity, and integration feasibility.

Various microstrip-antenna configurations, including dual-layer patch antennas, stub-loaded structures, ring-slot antennas, and L-shaped designs, have been investigated to improve impedance matching, bandwidth, gain, and radiation characteristics [19–27]. In addition, electromagnetic bandgap (EBG) structures have been applied to control surface-wave propagation and enhance antenna performance. Previous studies have used EBG and related periodic structures to modify antenna gain, radiation characteristics, and electromagnetic-field behavior [20, 26–39]. Microwave and antenna-based approaches have also been investigated for moisture-related sensing applications [12–15]. Nevertheless, the development of a compact EBG-integrated microstrip sensor for screening moisture-related variation and controlled nominal iron-powder addition conditions in *A. paniculata* powder remains limited.

This work presents a 2.50 GHz rectangular microstrip sensor incorporating a rectangular ring stub and a 7×1 woodpile EBG array. A rectangular microstrip patch was selected as the baseline sensing element because of its planar geometry, low profile, compact size, simple fabrication, and straightforward integration with a one-port vector-network-analyzer measurement system. The rectangular ring stub was incorporated to adjust the input impedance and surface-current distribution. A woodpile EBG structure was subsequently introduced to modify the electromagnetic field distribution and improve radiation characteristics. The final configuration was selected after comparing TE-polarized, TM-polarized, and combined TE-TM-polarized EBG arrangements in terms of reflection coefficient, impedance bandwidth, gain, radiation pattern, surface-current distribution, and structural simplicity. The proposed configuration is designed to improve impedance matching, gain, and field distribution while maintaining a compact structure suitable for powder-sensing experiments. The contributions of this work are as follows: 1) the design and experimental validation of a rectangular microstrip antenna integrated with a ring stub and a TE-polarized woodpile EBG array on a polyester Mylar substrate, 2) the experimental characterization of reflected-power responses to controlled nominal water-addition and nominal iron-powder addition conditions in *A. paniculata* powder.

The major findings of this study are summarized as follows:

The proposed antenna structure offers a clear and systematic tuning procedure. Its configuration can be adapted to support the screening of moisture-related variation and conductive-material addition conditions while maintaining operation at 2.50 GHz. The operating frequency was adjusted based on antenna designs reported in [15] and [37].

Incorporating a rectangular-ring stub improves antenna radiation characteristics and gain without significantly degrading the reflection coefficient, $|S_{11}|$ (dB).

Integrating an electromagnetic bandgap (EBG) structure improves radiation characteristics relevant to microwave

screening of moisture-related variation and nominal iron-powder addition conditions while preserving satisfactory reflection-coefficient performance, S_{11} .

The novelty of this work lies in the integration and experimental evaluation of a compact ring-stub-loaded microstrip antenna with a single-layer, 7×1 TE-polarized woodpile EBG structure for one-port microwave screening of controlled nominal water-addition and nominal iron-powder addition conditions in *Andrographis paniculata* powder. The study does not claim that the individual patch-antenna or EBG concepts are unprecedented. Rather, it investigates their combined implementation as a compact sensing platform and evaluates the corresponding reflected-power responses under controlled nominal water-addition and iron-powder addition conditions.

The present experiments evaluate water-addition and iron-powder addition conditions separately under controlled laboratory conditions. The system has not been validated for simultaneous multi-contaminant conditions, naturally contaminated samples, or interference from variations in particle size, sample density, packing condition, storage history, and other constituents. Accordingly, the present results do not establish analyte-specific selectivity in complex herbal-powder matrices.

2. MATERIALS AND METHODS

2.1. Antenna and EBG Design

A rectangular microstrip antenna was designed as a baseline sensing element for the proposed microwave measurement system to operate at 2.50 GHz. The electromagnetic performance of the proposed antenna was simulated using Computer Simulation Technology (CST) Microwave Studio at 2.50 GHz, which was selected as the nominal sensing frequency for evaluating changes in the electromagnetic response of *Andrographis paniculata* powder. The baseline antenna consisted of a rectangular radiating patch, a microstrip feed line, and a ground plane fabricated on a polyester Mylar substrate. Fig. 1 shows the powder sample and baseline antenna configuration. The baseline rectangular patch antenna was chosen for the present application because it offers a compact planar sensing surface and can be fabricated using standard printed conductive layers on a flexible polyester Mylar substrate. Its simple geometry also facilitates consistent placement relative to the powder tray and straightforward integration with the one-port reflection measurement setup. For this near-field screening application, the key requirement was not maximum gain alone, but rather adequate impedance matching and electromagnetic interaction with the powder sample at the selected frequency of 2.50 GHz.

To modify the input impedance and surface-current distribution, a rectangular ring stub was introduced around the radiating patch. Figs. 2(a) and 3(a) show the baseline antenna geometry and ring-stub-loaded antenna geometry, respectively. The gap between the radiating patch and the ring stub produces capacitive coupling, whereas the current paths on the patch and ring stub provide an inductive contribution. Therefore, the ring-stub-loaded configuration can be represented by the equivalent LC model shown in Fig. 3(b). This reactive coupling was used to adjust the resonant response and electromagnetic field distri-

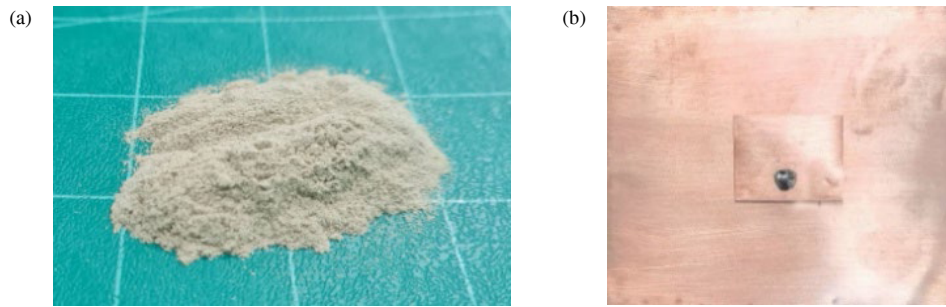


FIGURE 1. (a) *Andrographis paniculata* powder sample and (b) baseline rectangular microstrip antenna used in this study.

TABLE 1. Geometrical parameters of the proposed microstrip antenna and woodpile EBG structure.

Variable	Meaning	Size (mm)
W	Width of the polyester Mylar film base plate	120
W_1	Width of the radiating patch	30
W_2	Width of the outer rectangular ring stub	120
W_3	Width of the inner rectangular ring stub	15
W_4	Width of the electromagnetic bandgap (EBG) sheet	120
L	Length of the polyester Mylar film base plate	90
L_1	Length of the radiating patch	21
L_2	Length of the outer rectangular ring stub	90
L_3	Length of the inner rectangular ring stub	15
t_1	Thickness of the rectangular microstrip antenna	0.3
t_2	Thickness of the ground plane	0.3
h_1	Height of the polyester Mylar film base plate	0.5
r_1	Radius of the copper conductor wire in the TE-polarized EBG	1
r_2	Radius of the copper conductor wire in the TM-polarized EBG	1
y_1	Width of the vertical EBG base	10
a	Spacing between the antenna and the EBG sheet	10

bution in the sensing region. The ring-stub-loaded configuration was selected because it provides a simple planar approach for tuning the resonant response without requiring a multilayer antenna structure or a substantial increase in the overall footprint. By modifying the current path around the patch, the ring stub was expected to improve the radiation characteristics and field distribution while preserving a practical geometry for powder-screening experiments.

The antenna geometry was optimized using full-wave electromagnetic simulation. The design variables included the patch dimensions, feed-line geometry, feed position, outer and inner ring-stub dimensions, coupling gap, ground-plane dimensions, and substrate properties. The optimization objective was to obtain an acceptable impedance match at 2.50 GHz while maintaining a compact configuration for powder-sensing experiments. Table 1 lists final geometrical parameters of the proposed antenna and woodpile electromagnetic bandgap (EBG) structure.

A wire-based woodpile EBG structure was subsequently incorporated behind the ring-stub-loaded antenna to modify electromagnetic field distribution. The EBG structure consisted of periodically arranged copper conductors. Three

EBG arrangements were examined: transverse-electric (TE)-polarized, transverse-magnetic (TM)-polarized, and combined TE-TM-polarized configurations, as shown in Fig. 4. The reflection coefficient, 10-dB impedance bandwidth, realized gain, radiation pattern, and surface-current distribution were evaluated using full-wave simulation.

EBG unit cell was interpreted using an equivalent inductive-capacitive model, in which conductive wires provide an inductive contribution, and air gaps between adjacent wires provide a capacitive contribution. The influence of inter-wire spacing was investigated for values of 8, 10, 12, and 14 mm. Fig. 5 shows the EBG unit-cell geometry, effective-permittivity response, and simulated reflection-coefficient responses. Figs. 6 and 7 show simulated radiation patterns and surface-current distributions for investigated configurations, respectively.

Based on full-wave simulation results, a single-layer 7×1 TE-polarized woodpile EBG array with an antenna-to-EBG separation of 10 mm was selected for fabrication. This configuration achieved the highest simulated gain of 5.85 dBi and the widest simulated 10-dB impedance bandwidth of 2.449–2.526 GHz among the investigated EBG arrangements, while maintaining a simulated S_{11} of -15.88 dB at 2.50 GHz. The

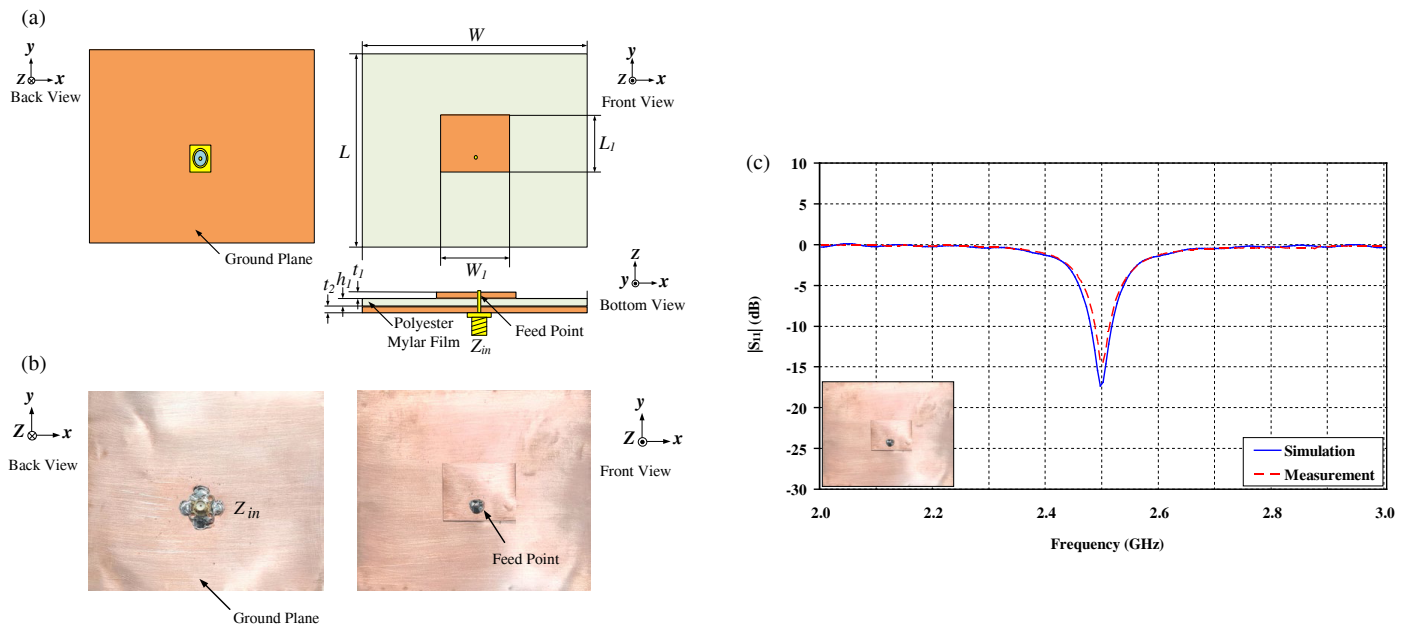


FIGURE 2. Baseline rectangular microstrip antenna: (a) simulated antenna geometry, (b) fabricated prototype, and (c) simulated and measured reflection coefficients (S_{11}).

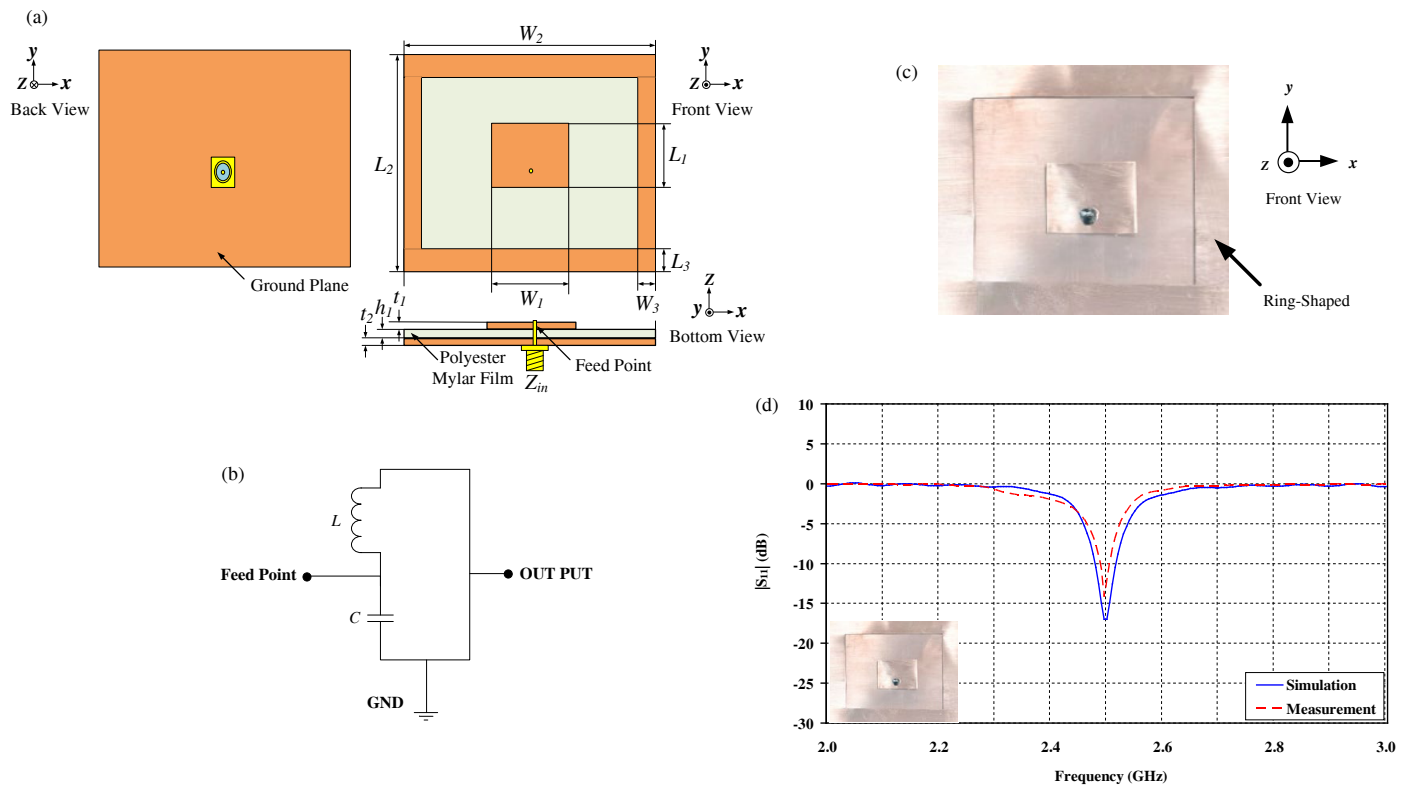


FIGURE 3. Rectangular ring-stub-loaded microstrip antenna: (a) geometry, (b) equivalent LC model, (c) fabricated prototype, and (d) simulated and measured reflection coefficients (S_{11}).

TE-polarized configuration was therefore selected as the best overall compromise among impedance matching, bandwidth, radiation characteristics, field modification, and structural simplicity. The single-layer arrangement was preferred over more complex multilayer alternatives because it is easier to fabricate, align, and integrate into a compact powder-screening fixture.

2.2. Prototype Fabrication and Antenna Characterization

The selected antenna configuration, consisting of a rectangular microstrip patch, a rectangular ring stub, and a 7×1 TE-polarized woodpile EBG array, was fabricated for experimental evaluation. The radiating patch, ring stub, microstrip feed line, and ground plane were fabricated on a polyester Mylar sub-

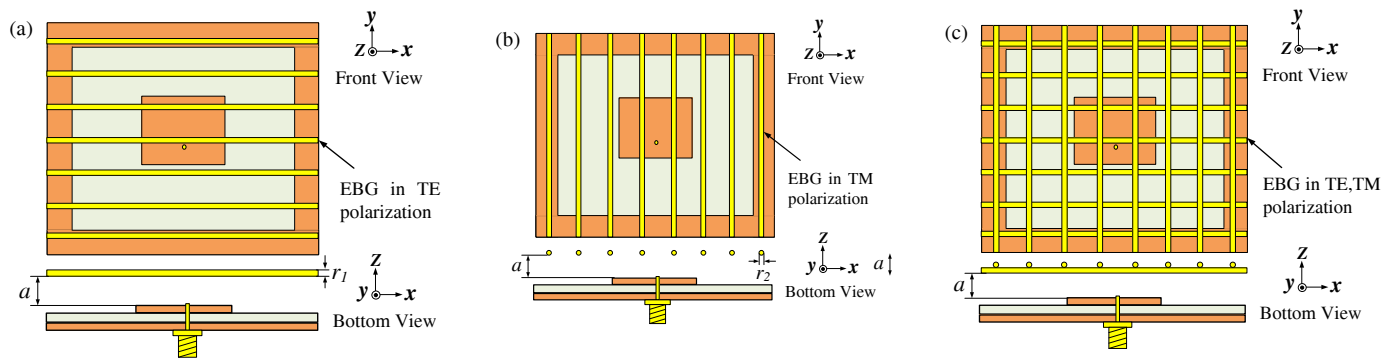


FIGURE 4. Woodpile electromagnetic bandgap (EBG) configurations investigated in this study: (a) TE-polarized, (b) TM-polarized, and (c) combined TE-TM-polarized arrangements.

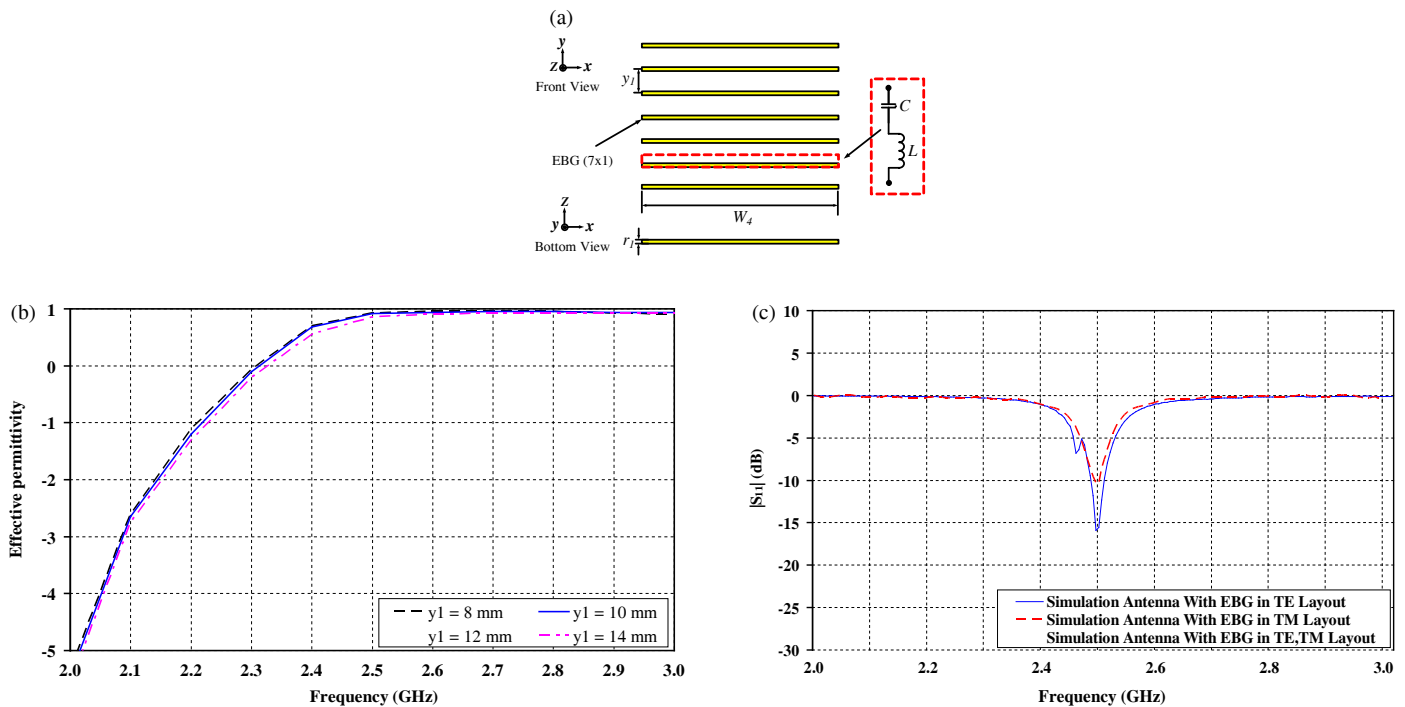


FIGURE 5. EBG analysis: (a) unit-cell geometry, (b) effective permittivity for the investigated inter-wire spacings, and (c) simulated reflection coefficients (S_{11}) of the EBG-integrated antenna configurations.

strate. The EBG array was assembled from copper conductors according to the selected TE-polarized configuration. Table 1 lists geometrical parameters of the fabricated structure.

The reflection coefficient of the fabricated antenna was measured using a Keysight E5071C ENA vector network analyzer. Before measurement, the analyzer was calibrated using a one-port open-short-load (OSL) calibration at the end of the measurement cable. This procedure established the calibration reference plane at the antenna input. The reflection coefficient was measured over the frequency range of 2.0–3.0 GHz with 801 equally spaced frequency points. Figs. 8(a) and 8(b) show the fabricated prototype and reflection-coefficient measurement arrangement, respectively.

Radiation characteristics were measured at 2.50 GHz in the Microwave Engineering Laboratory using the gain-substitution method. Measured parameters included the reflection coefficient

(S_{11}), antenna gain, and radiation patterns in the E -plane and H -plane. S_{11} results were compared with corresponding voltage standing wave ratio (VSWR) values; however, VSWR data are not presented in this paper. A calibrated rectangular microstrip antenna was used as the reference antenna. The antenna under test and the reference antenna were separated by a distance of 240 mm, corresponding to one wavelength at the operating frequency. The separation distance was measured between their phase centers. The antennas were aligned under co-polarized, boresight conditions. For radiation-pattern measurements, the antenna under test was rotated from -30° to $+30^\circ$ in 3° increments in both the E -plane and H -plane, as shown in Fig. 9. Measurements were conducted in the Microwave Engineering Laboratory in an anechoic chamber lined with radio-frequency absorbers. Fig. 9 shows simulated and measured normalized radiation patterns, and Subsection 3.1 discusses the corresponding quantitative results.

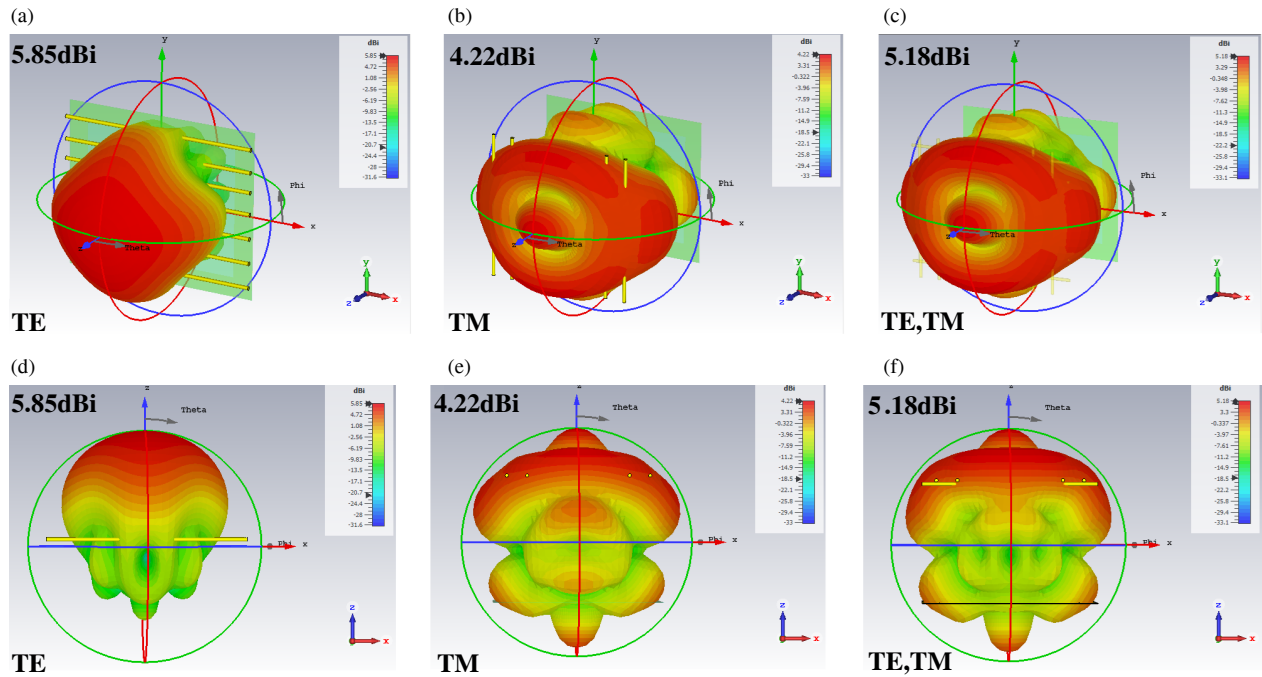


FIGURE 6. Simulated radiation patterns of the EBG-integrated antenna for (a), (d) TE-polarized, (b), (e) TM-polarized, and (c), (f) combined TE-TM-polarized EBG arrangements.

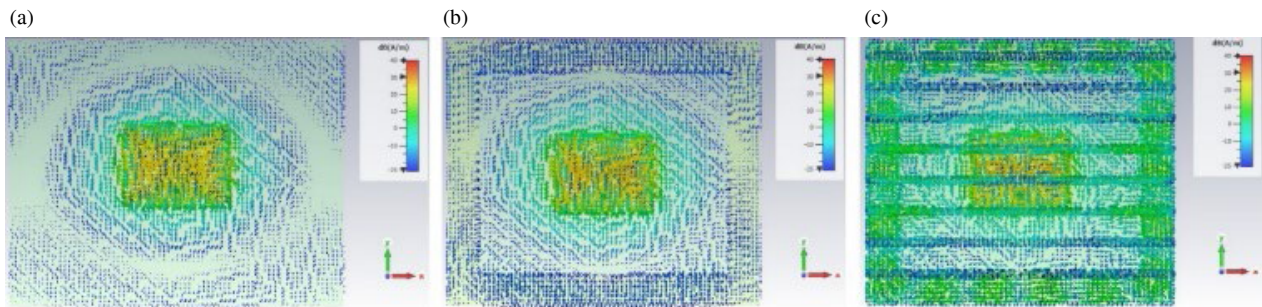


FIGURE 7. Simulated surface-current distributions of the EBG-integrated antenna for (a) TE-polarized, (b) TM-polarized, and (c) combined TE-TM-polarized EBG arrangements.

2.3. Powder-Sample Preparation and Nominal Condition Definitions

Commercially dried *Andrographis paniculata* powder was obtained from World Grow Co., Ltd., Mae Sai District, Chiang Rai Province, Thailand. Before sample preparation, the powder was homogenized and stored in sealed containers at a temperature below 25°C until use. For each experimental condition, a 10.00 g portion of the powder was weighed using an analytical balance with a readability of 0.0001 g.

The nominal water-addition levels were 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%, expressed relative to the initial dry-powder mass. Each sample was mixed using a medical-grade mixer for 10–30 min to promote uniform water distribution. The prepared samples were then transferred to sealed containers and equilibrated for 5–10 min at a temperature below 25°C before microwave measurements. For each nominal water-addition condition, ten independent samples were prepared for each measurement batch.

The nominal water-addition level was calculated relative to the initial dry-powder mass as

$$MC_{db}(\%) = \left(\frac{m_{water}}{m_{dry}} \right) \times 100$$

$$= W_{add}(\%) = \left(\frac{m_{water}}{m_{dry}} \right) \times 100 \quad (1)$$

where m_{water} is the mass of added deionized water, and m_{dry} is the initial mass of dry *Andrographis paniculata* powder. Reference moisture-content determination by oven drying was not performed in the present study. Therefore, the nominal water-addition levels should not be interpreted as gravimetrically verified moisture contents.

Nominal iron-powder addition conditions were prepared separately using 10.00 g portions of *Andrographis paniculata* powder. The iron powder, with a supplier-stated purity of 100%,

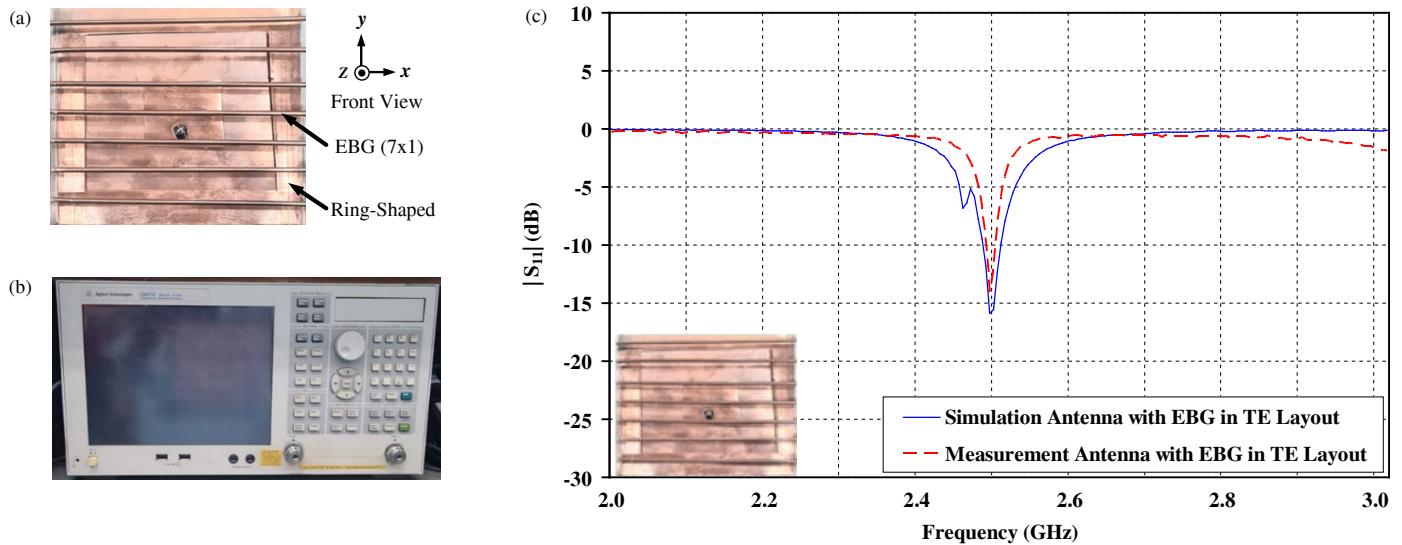


FIGURE 8. Fabricated EBG-integrated microstrip antenna and reflection-coefficient measurement arrangement: (a) fabricated prototype, (b) vector network analyzer measurement setup, and (c) simulated and measured reflection coefficients (S_{11}).

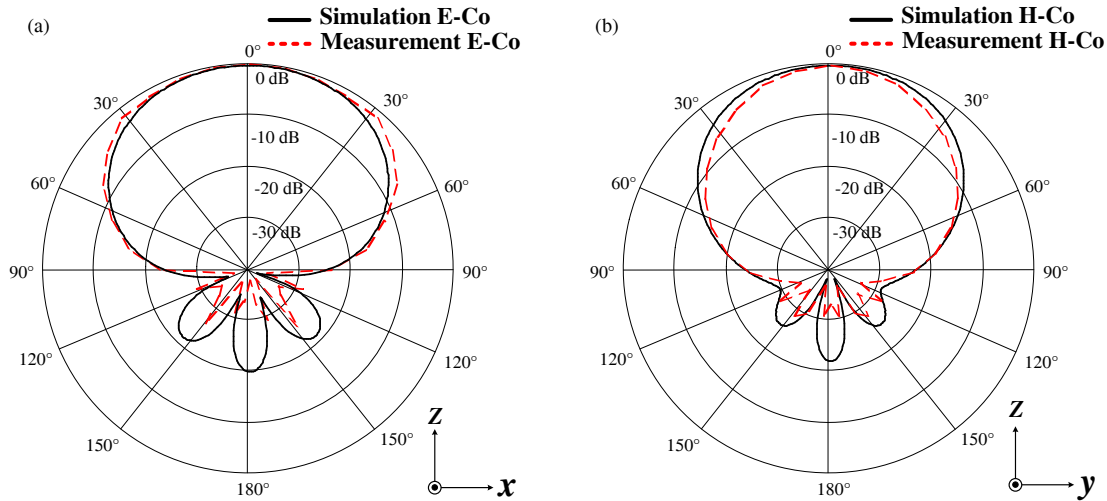


FIGURE 9. Simulated and measured normalized radiation patterns of the EBG-integrated microstrip antenna at 2.50 GHz: (a) E -plane and (b) H -plane.

was obtained from S.C., affiliated with Server Today (Thailand) Co., Ltd.

Predetermined masses of iron powder were added to obtain nominal iron-powder addition levels of 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%, expressed relative to the initial mass of *A. paniculata* powder. For an initial powder mass of 10.00 g, the corresponding added iron-powder masses were 0, 1.00, 2.00, 3.00, 4.00, 5.00, 6.00, 7.00, 8.00, 9.00, and 10.00 g, respectively. Each mixture was mechanically blended using a medical-grade mixer for 5–10 min and then allowed to settle in a sealed container for 5–10 min before microwave measurements.

The nominal iron-powder addition level was calculated relative to the initial mass of *Andrographis paniculata* powder as

$$C_{\text{Fe,rel}} (\%) = \frac{m_{\text{Fe}}}{m_{\text{powder}}} \times 100 \quad (2)$$

where m_{Fe} is the mass of added iron powder, and m_{powder} is the initial mass of *Andrographis paniculata* powder before mixing. Independent chemical quantification of iron was not performed in the present study. Therefore, the nominal iron-powder addition levels should not be interpreted as chemically verified iron concentrations.

All prepared samples were subsequently measured according to the microwave protocol described in Subsection 2.4. The sample mass, container type, powder-bed thickness, sample-to-antenna distance, settling time, and ambient measurement conditions were maintained constant for all nominal water-addition and nominal iron-powder addition conditions.

The iron-powder addition experiment was designed as a controlled proof-of-concept study to examine the microwave response to conductive material added to the herbal-powder matrix. It does not represent naturally occurring heavy-metal contamination, and the nominal addition levels should not be in-

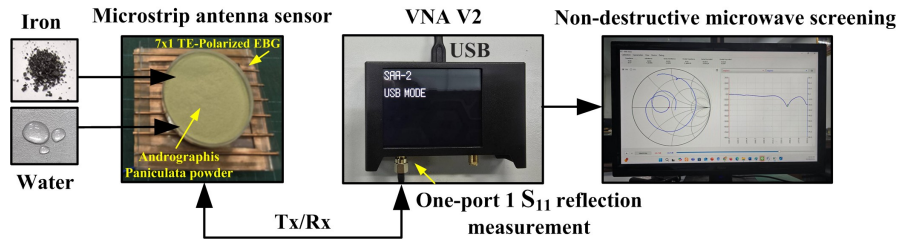


FIGURE 10. One-port S_{11} reflection-measurement configuration for controlled nominal water-addition and nominal iron-powder addition conditions of *Andrographis paniculata* powder. The EBG behind the antenna is a 7×1 single-layer, TE-polarized woodpile structure.

terpreted as practically relevant contamination concentrations. Validation using independently quantified iron concentrations and real herbal-powder samples is required for analytical application.

2.4. Microwave Measurement Protocol

Microwave measurements were performed using the EBG-integrated microstrip antenna described in Subsections 2.1 and 2.2. The antenna was operated at the nominal sensing frequency of 2.50 GHz, and the antenna-to-EBG separation was maintained at 10 mm throughout the experiments. Fig. 10 shows the powder-measurement configuration.

Each prepared powder sample was placed in an identical non-conductive circular tray and positioned at a fixed distance of 0.2 mm from the EBG structure. The sample mass was maintained at 10.00 g for all conditions. The tray had a radius of 50 mm, and the powder-bed thickness was maintained at approximately 2.5–3.0 mm. To minimize measurement variability caused by sample placement, the powder surface was leveled using a powder compaction press, and the tray orientation was kept consistent throughout all measurements.

The reflected response was measured using a V2 vector network analyzer (VNA). Before data acquisition, the instrument was calibrated at the end of the measurement cable, defining the reference plane at the antenna input. Sensing measurements were performed using a one-port reflection configuration. The VNA directly measured the complex reflection coefficient, S_{11} , from 1.0 to 3.0 GHz at 0.1-GHz intervals. For antenna characterization, the reflection coefficient was reported in decibels as

$$S_{11,dB} = 20\log_{10} |S_{11}| \quad (3)$$

The incident source power was set to $P_{inc} = 15$ dBm, corresponding to 31.62 mW at the calibrated reference plane. For powder-screening experiments, reflected power was derived from the measured reflection coefficient according to

$$P_{ref,dBm} = P_{inc,dBm} + S_{11,dB} \quad (4)$$

The reflected power in milliwatts was calculated as

$$P_{ref,mW} = 10^{P_{ref,dBm}/10} \quad (5)$$

Here, S_{11} is the complex reflection coefficient measured by the VNA; $|S_{11}|$ is its linear magnitude; $S_{11,dB}$ is the reflection coefficient expressed in dB; $P_{inc,dBm}$ is the incident power in dBm; and $P_{ref,dBm}$ and $P_{ref,mW}$ are the reflected power in dBm and mW, respectively. Accordingly, $S_{11,dB}$ is used to

describe antenna impedance matching, and $P_{ref,mW}$ is used to present the microwave response of the powder samples.

Before measurement, each sample was allowed to settle for 5–10 min. The ambient temperature was maintained at 25°C, while the relative humidity was kept below 10%. The powder mass, tray geometry, powder-bed thickness, sample-to-antenna distance, and tray orientation were controlled during measurements. Repeated microwave measurements were acquired under the fixed measurement configuration for each nominal condition. Tables 5 and 6 report the number of technical replicates analyzed for the water-addition and iron-powder addition datasets, respectively. The measurement order was randomized to reduce systematic bias. At 2.50 GHz, the reflected-power response was summarized as mean $\pm$ standard deviation (SD), and the coefficient of variation was calculated as $CV = (SD/mean) \times 100\%$. These repeated measurements represent within-setup technical replicates and quantify short-term measurement variability under the controlled laboratory conditions. They do not establish inter-day, inter-operator, inter-device, or inter-batch reproducibility.

2.5. Data Processing and Statistical Analysis

The reflected-power response at 2.50 GHz was derived from the measured reflection coefficient as described in Section 2.4. Repeated measurements were analyzed for each controlled nominal water-addition and nominal iron-powder addition condition. Tables 5 and 6 report the number of technical replicates for each dataset. The results were summarized as mean $\pm$ standard deviation (SD), and the coefficient of variation was calculated as $CV = (SD/\bar{x}) \times 100\%$, where $\bar{x}$ is the mean reflected power. The repeated measurements were treated as technical replicates under controlled setup and used to characterize short-term within-setup variability. The present analysis does not establish inter-day, inter-operator, inter-device, or inter-batch reproducibility.

3. RESULTS AND DISCUSSION

3.1. Antenna and EBG Performance

The antenna performance was evaluated in three stages: the baseline rectangular microstrip antenna, the rectangular ring-stub-loaded antenna, and the antenna integrated with a woodpile electromagnetic bandgap (EBG) array. All configurations were designed for operation near 2.50 GHz. The baseline an-

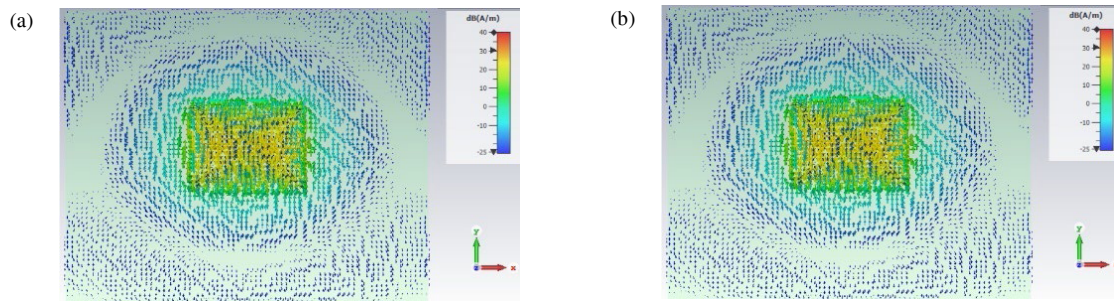


FIGURE 11. Simulated surface-current distributions of (a) the baseline rectangular microstrip antenna and (b) the rectangular ring-stub-loaded microstrip antenna at 2.50 GHz.

TABLE 2. Simulated and measured performance of the baseline and rectangular ring-stub-loaded microstrip antennas at 2.50 GHz.

Antenna configuration	Condition	$ S_{11} $ (dB)	BW (%) and frequency range (GHz)	Gain (dBi)
Baseline antenna	Simulation	-17.32	3.40 (2.455–2.540)	4.03
Baseline antenna	Measurement	-14.51	3.32 (2.459–2.542)	3.81
Ring-stub-loaded antenna	Simulation	-16.99	1.40 (2.490–2.525)	5.26
Ring-stub-loaded antenna	Measurement	-14.18	3.19 (2.465–2.545)	4.98

tenna was used as the reference configuration for assessing the effects of the ring stub and EBG structure.

Fig. 2(c) shows simulated and measured reflection-coefficient responses of the baseline antenna. The simulated 10-dB impedance bandwidth extended from 2.455 to 2.540 GHz, corresponding to 3.40%, whereas the measured bandwidth extended from 2.459 to 2.542 GHz, corresponding to 3.32%. At 2.50 GHz, simulated and measured reflection coefficients (S_{11}) were -17.32 dB and -14.51 dB, respectively. Simulated and measured gains were 4.03 and 3.81 dBi, respectively. These results indicate that the baseline prototype retained an acceptable impedance match at the design frequency. The small differences between simulated and measured results may be attributed to fabrication tolerances, uncertainty in substrate properties, connector and cable effects, and measurement uncertainty.

A rectangular ring stub was subsequently incorporated around the radiating patch. Fig. 3 shows the antenna geometry, equivalent LC model, fabricated prototype, and reflection-coefficient responses. Fig. 12 compares the simulated surface-current distributions of the baseline and ring-stub-loaded antennas. The ring stub modified the current distribution around the patch and extended the current path along the surrounding conductive structure. The ring-stub configuration achieved simulated and measured gains of 5.26 and 4.98 dBi, respectively, compared with 4.03 and 3.81 dBi for the baseline antenna. Thus, the measured gain increased by 1.17 dBi relative to the baseline configuration.

The simulated ring-stub antenna had a 10-dB impedance bandwidth of 2.490–2.525 GHz (1.40%), whereas the fabricated ring-stub antenna had a measured bandwidth of 2.465–2.545 GHz (3.19%). The simulated and measured reflection coefficients (S_{11}) at 2.50 GHz were -16.99 dB and -14.18 dB,

respectively. Table 2 summarizes the comparison of baseline and ring-stub antenna characteristics. Although the measured $|S_{11}|$ of the ring-stub antenna at 2.50 GHz was slightly lower in magnitude than that of the baseline antenna, both configurations satisfied the conventional -10 dB impedance-matching criterion at the operating frequency.

Fig. 11 compares simulated surface-current distributions of the baseline and ring-stub-loaded antennas.

As shown in Fig. 11, the ring stub modified the surface-current distribution by extending the current path around the radiating patch. This redistribution is consistent with the measured gain increase of the ring-stub-loaded antenna.

The EBG structure was then evaluated to further modify the field distribution and radiation characteristics of the ring-stub-loaded antenna. The investigated EBG arrangements included TE-polarized, TM-polarized, and combined TE-TM-polarized configurations, as shown in Fig. 4. Fig. 5 shows effective-permittivity responses and simulated reflection-coefficient characteristics, and Figs. 6 and 7 show corresponding radiation patterns and surface-current distributions, respectively.

Table 3 summarizes the simulated performance comparison. Among the investigated configurations, the 7×1 TE-polarized woodpile EBG arrangement with a 10 mm antenna-to-EBG separation achieved the highest simulated gain, 5.85 dBi, and the widest simulated 10-dB impedance bandwidth, 2.449–2.526 GHz (3.09%). The simulated reflection coefficient at 2.50 GHz was -15.88 dB. This configuration was therefore selected for prototype fabrication and experimental evaluation because it provided the most favorable simulated balance among impedance matching, bandwidth, gain, radiation characteristics, and structural simplicity for the intended compact powder-screening application.

TABLE 3. Simulated performance comparison of the microstrip antenna with different woodpile EBG configurations at 2.50 GHz.

EBG configuration	Layers	Units	$ S_{11} $ at 2.50 GHz (dB)	10-dB impedance bandwidth, GHz (%)	Gain at 2.50 GHz (dBi)
TE polarization	1	7	−15.88	3.09 (2.449–2.526)	5.85
TM polarization	1	8	−10.05	1.31 (2.492–2.525)	4.22
Combined TE-TM polarization	2	7×8	−10.05	1.31 (2.492–2.525)	5.18

TABLE 4. Simulated and measured performance of the EBG-integrated microstrip antenna at 2.50 GHz.

Condition	$ S_{11} $ at 2.50 GHz (dB)	10-dB impedance bandwidth, GHz (%)	Gain at 2.50 GHz (dBi)
Simulation	−15.88	2.449–2.526 (3.09)	5.85
Measurement	−13.94	2.488–2.512 (0.96)	5.16

Fig. 8 shows the fabricated EBG-integrated antenna and measurement arrangement. Table 4 compares simulated and measured antenna characteristics. The measured reflection coefficient (S_{11}) at 2.50 GHz was −13.94 dB, confirming that the fabricated antenna satisfied the conventional $S_{11} < -10$ dB impedance-matching criterion at the design frequency. The measured gain was 5.16 dBi, which was 0.69 dBi lower than the simulated value of 5.85 dBi and 1.35 dBi higher than the measured gain of the baseline antenna. The measured 10-dB impedance bandwidth extended from 2.488 to 2.512 GHz, corresponding to 0.96%, whereas the simulated bandwidth extended from 2.449 to 2.526 GHz, corresponding to 3.09%. Thus, the measured bandwidth was substantially narrower than predicted by simulation. This discrepancy may be associated with fabrication tolerances, uncertainty in the dielectric properties and thickness of the polyester Mylar substrate, conductor and connector losses, feed-line effects, antenna-to-EBG alignment, and limitations of the measurement environment. Fig. 9 compares simulated and measured E -plane and H -plane radiation patterns. The measured patterns retained the expected directional behavior, although deviations from the simulated responses were observed.

Overall, the ring stub increased the measured gain relative to the baseline antenna, and the selected TE-polarized EBG configuration produced a further gain increase while maintaining $S_{11} < -10$ dB at 2.50 GHz. However, the measured bandwidth of the EBG-integrated prototype was narrower than that of both the simulation and the baseline/ring-stub configurations. The EBG-integrated antenna was therefore used as the microwave sensing element in the subsequent nominal water-addition and nominal iron-powder addition experiments.

3.2. Moisture-Screening Performance

The moisture-screening performance of the proposed antenna was evaluated using *Andrographis paniculata* powder samples prepared at different controlled nominal water-addition levels. Fig. 10 shows the microwave measurement configuration.

Measurements were conducted using a VNA V2 vector network analyzer controlled by VNA V2 software in a one-port reflection configuration. The VNA measured the reflection coefficient, S_{11} , from 1.0 to 3.0 GHz at 0.1-GHz intervals. For the powder-screening analysis, the reflected power was derived from the measured S_{11} according to the procedure described in Subsection 2.4.

The EBG-integrated microstrip antenna was operated at 2.50 GHz with an incident source power of 15 dBm, corresponding to 31.62 mW, at the calibrated reference plane. For each measurement, the powder sample was placed in the fixed measurement configuration described in Subsection 2.4. The sample mass, nonconductive tray, powder-bed thickness, sample-to-antenna distance, tray orientation, and ambient measurement conditions were maintained constant to reduce variability unrelated to the nominal water-addition condition.

Fig. 12(a) and Table 5 present moisture-screening results. The mean reflected-power response decreased from 0.02684 ± 0.00016 mW at the nominal 0% water-addition condition to 0.00063 ± 0.000003 mW at the nominal 100% condition. The coefficient of variation ranged from 0.117% to 1.206%, indicating low short-term within-setup variability under the controlled measurement configuration. The error bars in Fig. 12(a) represent ± 1 SD. Because the nominal water-addition levels were based on added-water mass and were not verified by oven drying, the results should be interpreted as screening of controlled nominal conditions rather than calibrated quantitative moisture measurements.

3.3. Microwave Screening of Nominal Iron-Powder Addition Conditions

The microwave screening performance of the proposed antenna was evaluated using *Andrographis paniculata* powder samples prepared at different controlled nominal iron-powder addition levels. The microwave measurement configuration was identical to that used for the nominal water-addition experiments described in Subsection 3.2. The EBG-integrated microstrip

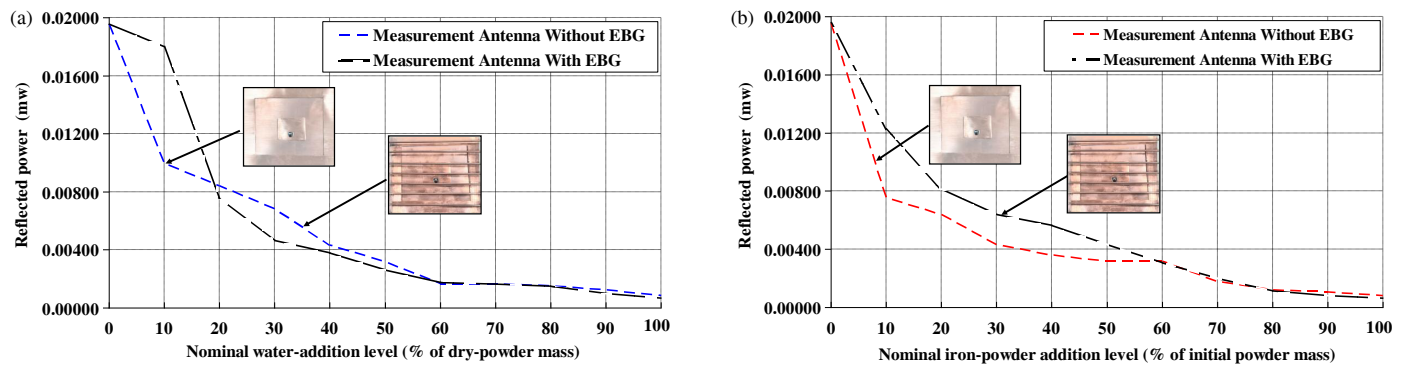


FIGURE 12. Mean reflected-power responses at 2.50 GHz for (a) controlled nominal water-addition conditions and (b) controlled nominal iron-powder addition conditions of *Andrographis paniculata* powder. Error bars represent ± 1 SD. The numbers of technical replicates are reported in Tables 5 and 6. The nominal water-addition and iron-powder addition conditions are not reference-verified moisture contents or independently quantified iron concentrations.

TABLE 5. Reflected-power response at 2.50 GHz for *Andrographis paniculata* powder under controlled nominal water-addition conditions. Values are reported as mean $\pm$ SD from $n = 106$ technical replicates.

Nominal water-addition level (% of initial dry-powder mass)	Reflected power (mW), mean $\pm$ SD	CV (%)	n
0	0.02684 ± 0.00016	0.596	106
10	0.01794 ± 0.00012	0.670	106
20	0.00760 ± 0.00001	0.117	106
30	0.00462 ± 0.00001	0.312	106
40	0.00378 ± 0.00001	0.258	106
50	0.00260 ± 0.000003	0.155	106
60	0.00174 ± 0.00002	1.206	106
70	0.00163 ± 0.00001	0.526	106
80	0.00147 ± 0.00001	0.667	106
90	0.00098 ± 0.00000	0.126	106
100	0.00063 ± 0.000003	0.554	106

Note: Water-addition levels are controlled nominal values expressed relative to the initial dry-powder mass. $CV = (SD/\bar{x}) \times 100\%$, where $\bar{x}$ is the mean reflected power. Here, $n = 106$ denotes repeated VNA acquisitions under the fixed measurement setup for each nominal water-addition condition; it does not denote 106 independently prepared powder samples. The measurements are technical replicates under the controlled setup and quantify short-term within-setup variability only. They do not represent gravimetrically verified moisture contents, independent sample batches, or inter-day or inter-operator reproducibility. The reflected-power measurements were acquired using an incident source power of 15 dBm (31.62 mW) at the calibrated reference plane.

antenna operated at 2.50 GHz with an incident source power of 15 dBm, corresponding to 31.62 mW at the calibrated reference plane. The sample mass, container, powder-bed thickness, antenna-to-sample distance, and ambient measurement conditions were maintained constant for all measurements.

Fig. 12(b) and Table 6 present iron-powder screening results. The mean reflected-power response decreased monotonically from 0.019544 ± 0.000023 mW at the nominal 0% iron-powder addition condition to 0.000612 ± 0.000001 mW at the nominal 100% condition. The coefficient of variation ranged from 0.015% to 0.303%, indicating low short-term variability under the fixed measurement configuration. The observed reflected-power difference between 0% and 100% nominal iron-powder addition conditions was 0.018932 mW, corresponding to a dynamic range of approximately 15.1 dB.

3.4. Limitations and Practical Implications

Table 7 compares the proposed antenna with selected EBG-integrated antenna configurations reported in previous studies. The proposed EBG-integrated microstrip antenna was developed as a compact microwave platform for screening controlled nominal water-addition and nominal iron-powder addition conditions in *Andrographis paniculata* powder. The fabricated antenna operates at 2.50 GHz and incorporates a rectangular ring stub and a single-layer 7×1 TE-polarized woodpile EBG array. The EBG-integrated prototype achieved a measured gain of 5.16 dBi, representing a 1.35-dBi increase relative to the baseline antenna. The proposed configuration provides a planar, low-profile structure suitable for non-destructive measurements in a fixed powder-sample fixture.

TABLE 6. Reflected-power response at 2.50 GHz for *Andrographis paniculata* powder under controlled nominal iron-powder addition conditions. Values are reported as mean $\pm$ SD from $n = 500$ technical replicates.

Nominal iron-powder addition level (% of initial powder mass)	Mean reflected power (mW)	SD (mW)	CV (%)	n
0	0.019544	0.000023	0.116	500
10	0.012246	0.000002	0.015	500
20	0.008134	0.000025	0.303	500
30	0.006361	0.000017	0.268	500
40	0.005600	0.000014	0.245	500
50	0.004297	0.000002	0.043	500
60	0.003055	0.000002	0.066	500
70	0.001981	0.000001	0.062	500
80	0.001092	0.000001	0.092	500
90	0.000788	0.000002	0.248	500
100	0.000612	0.000001	0.168	500

Note: Nominal iron-powder addition levels are controlled values expressed relative to the initial mass of *Andrographis paniculata* powder. $CV = (SD/x) \times 100\%$, where x is the mean reflected power. Here, $n = 500$ denotes repeated VNA acquisitions under the fixed measurement setup for each nominal iron-powder addition condition; it does not denote 500 independently prepared powder samples. The measurements are technical replicates under the controlled setup and quantify short-term within-setup variability. They do not represent independently verified iron concentrations, independent sample batches, or inter-day or inter-operator reproducibility. Reflected-power measurements were acquired using an incident source power of 15 dBm (31.62 mW) at the calibrated reference plane.

TABLE 7. Structural and antenna-performance comparison of selected EBG-integrated antenna configurations. Direct gain comparison should be interpreted cautiously because of differences in antenna type, operating frequency, aperture size, EBG structure, and application objective.

Reference	Frequency (GHz)	Antenna shape and EBG shape				Arrangement	Gain (dBi)
		Antenna shape	Shape	EBG Units (No.)	Layers		
[28]	5	Conical Horn	Square	24×24	1	TE, TM	19.70
[29]	10	Horn	Wires	23×1	2	TE	20.90
[30]	10	Horn	Wires	6×1	2	TE	24.10
[31, 32]	10–11.5	Rectangular Waveguide	Woodpile	5×5	3	TE, TM	16.20
[36]	19.0–20.4	Waveguide Horn	Wires	37×1	1	TE	23.20
[15]	1.91–2.33	Cantenna	Woodpile	2×6	2	TE, TM	7.81
Proposed	2.50	Rectangular microstrip	Wires	7×1	1	TE	5.16

Note: Iron-powder addition levels are controlled nominal values expressed relative to the initial mass of *Andrographis paniculata* powder. $CV = (SD/\bar{x}) \times 100\%$. The measurements are technical replicates under the controlled setup and do not represent independently verified iron concentrations or independent sample batches. The reflected-power measurements were acquired using an incident source power of 15 dBm (31.62 mW) at the calibrated reference plane.

Compared with the horn- and waveguide-based EBG antennas listed in Table 7, the measured gain of 5.16 dBi is lower. This difference is expected because horn and waveguide antennas generally have larger apertures and are designed primarily to achieve higher far-field directivity and gain. Direct gain comparisons should therefore be interpreted cautiously because the cited systems differ in antenna type, operating frequency, aperture size, EBG geometry, substrate, sensing distance, and application objective. The present planar antenna was designed for compact near-field powder screening, in which low pro-

file, simple fabrication, and compatibility with a fixed sample holder are important design considerations.

The repeated measurements in Tables 5 and 6 quantify short-term within-setup variability through the reported standard deviations and coefficients of variation. These technical replicates do not establish inter-day, inter-operator, inter-device, or inter-batch reproducibility. Future validation should therefore include independently prepared sample batches, measurements on multiple days, operator-to-operator evaluation, and comparison with reference analytical methods.

Several limitations should be considered when the present results are interpreted. First, experiments were conducted under controlled laboratory conditions using powder obtained from a single source. The microwave response may vary with cultivation location, supplier, drying process, storage history, particle-size distribution, sample density, and packing conditions. Second, the nominal water-addition conditions were calculated from added-water mass and were not verified by oven drying. Similarly, the nominal iron-powder addition conditions were prepared by mass addition and were not independently verified by elemental analysis. Accordingly, the reported responses should not be interpreted as calibrated quantitative measurements of moisture content, iron concentration, or heavy-metal contamination level.

Third, the reflected-power response can be influenced by powder-bed thickness, sample-to-antenna distance, container properties, ambient temperature, relative humidity, particle size, and packing density. In addition, the response is not expected to be uniquely selective to iron with variations in moisture or other conductive and dielectric materials. The present experiments evaluated separately prepared nominal water-addition and nominal iron-powder addition conditions. Further investigations should examine mixed water–iron conditions, other conductive contaminants, naturally variable herbal-powder samples, and lower iron-powder addition levels that are more relevant to practical screening. These studies are necessary to assess selectivity, robustness, and the applicability of the proposed platform under realistic conditions.

4. CONCLUSION

A rectangular microstrip antenna incorporating a rectangular ring stub and a 7×1 transverse-electric (TE)-polarized woodpile electromagnetic-bandgap (EBG) array was designed and experimentally evaluated at 2.50 GHz. The fabricated EBG-integrated prototype achieved a measured reflection coefficient of -13.94 dB at 2.50 GHz, a 10-dB impedance bandwidth of 2.488–2.512 GHz (0.96%), and a measured gain of 5.16 dBi. Relative to the baseline antenna, the EBG-integrated configuration increased the measured gain by 1.35 dBi while maintaining $S_{11} < -10$ dB at the intended operating frequency.

The proposed antenna was evaluated using *Andrographis paniculata* powder prepared at controlled nominal water-addition and nominal iron-powder addition levels. At 2.50 GHz, the mean reflected-power response decreased from 0.02684 ± 0.00016 mW at the nominal 0% water-addition condition to 0.00063 ± 0.000003 mW at the nominal 100% condition. For nominal iron-powder addition, the mean reflected-power response decreased from 0.019544 ± 0.000023 mW at 0% to 0.000612 ± 0.000001 mW at 100%. The repeated measurements were summarized as mean $\pm$ standard deviation and coefficient of variation, providing an assessment of short-term within-setup variability under the controlled laboratory configuration.

The proposed system should be interpreted as a compact, nondestructive microwave screening platform for controlled nominal water-addition and nominal iron-powder addition conditions, rather than as a quantitative moisture assay, iron-

concentration assay, or heavy-metal detection method. Nominal water-addition conditions were not verified by oven drying, and nominal iron-powder addition conditions were not independently verified by elemental analysis. The present results do not establish analyte-specific selectivity for iron in the presence of multiple contaminants or uncontrolled sample variations.

Further work should evaluate mixed water-iron conditions, other conductive contaminants, naturally variable powder samples, and lower practically relevant iron-powder addition levels. It should also include calibration against gravimetric moisture measurements and validated elemental-analysis methods, together with inter-day, inter-operator, inter-device, and inter-batch reproducibility assessments. These steps are required before the proposed system can be considered for quantitative herbal-powder quality-control applications.

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REFERENCES

- [1] Satayaviwat, J., “Fa Talai Jon: Integrative research for COVID-19 infection treatment,” *The Journal of Chulabhorn Royal Academy*, Vol. 4, No. 1, 1–14, 2022.
- [2] Boonsawek, B., W. Supan, P. Sombood, and P. Vichitvejpaisai, “Drug interactions of andrographis paniculata in anesthesia,” *The Journal of Chulabhorn Royal Academy*, Vol. 5, No. 1, 35–43, 2023.
- [3] Chantsanga, S., N. Viriyakesom, and S. Tansuwanwong, “A study on the identity of medicinal plants used for skin disease treatment in traditional thai medicine,” *J. Sci. Technol. Udon Thani Rajabhat Univ.*, Vol. 12, No. 1, 17–32, 2024.
- [4] Booncherd, C. and S. Anugoolpracha, “Outcomes and costs of favipiravir, molnupiravir, remdesivir and andrographis paniculata during the COVID-19 outbreak, kut chum district, yasothon province,” *Journal of Health Science of Thailand*, Vol. 33, No. 1, 108–119, 2024.
- [5] Puakpong, S., J. Sangsawang, and N. N. Usana-ampaipong, “Inhibition of staphylococcus aureus on cotton fabric by extracts from stems and leaves of andrographis paniculata,” *Recent Science and Technology*, Vol. 16, No. 3, 762–771, 2024.

- [6] Hamid, M. A., R. Adam, F. Ramli, and R. Wahab, "Antioxidant activity of andrographolide from andrographis paniculata leaf and its extraction optimization by using accelerated solvent extraction: Antioxidant activity of andrographolide from andrographis paniculata leaf," *Journal of Tropical Life Science*, Vol. 13, No. 1, 157–170, 2023.
- [7] Kundu, A., S. Bisui, U. Layek, and P. Karmakar, "Studies in the seed ecology and seedling Phenology of Andrographis paniculata (Brum. f.) Wall. ex Ness in West Bengal, India," *Plant Science Today*, Vol. 11, No. 2, 2024.
- [8] Sarode, P. V. and S. T. Landge, "Physicochemical analysis of Kalmegh (andrographis paniculata) whole plant," *World Journal of Pharmaceutical Research*, 2024.
- [9] Sharangi, A. B., S. O. Rab, M. Saeed, N. M. Alabdallah, S. Siddiqui, *et al.*, "Bioformulation-mediated response of Kalmegh (Andrographis paniculata Wall. ex Nees, Family Acanthaceae) for growth, yield, and quality," *ACS Omega*, Vol. 10, No. 7, 6927–6938, 2025.
- [10] Talei, D., T. Radjabian, and M.-R. Vaez-Mahdavi, "Optimizing nutrient solution regime to enhance yield, biochemical composition, and antioxidant capacity in andrographis paniculata," *Journal of Medicinal Plants and By-products*, Vol. 14, No. 5, 498–503, 2025.
- [11] Royani, A., N. M. Mubarak, M. Hanafi, C. Verma, P. D. N. Lotulung, M. E. Prastya, A. Alfantazi, and A. Manaf, "Effect of solvent polarity on yield extract, antioxidant and antibacterial activities of phytochemicals from andrographis paniculata leaves," *Indian Chemical Engineer*, Vol. 67, No. 1, 1–15, 2025.
- [12] Bansode, P. S., H. A. Tanti, A. C. Joshi, Y. J. Gaikwad, R. C. Aiyer, and S. A. Gangal, "Microstrip patch antenna as a paper moisture sensor," in *Journal of Physics: Conference Series*, Vol. 2426, No. 1, 012061, 2023.
- [13] Khan, M. T., X. Q. Lin, C. Zhe, and A. Saboor, "Design, analysis and validation of a microstrip patch antenna with enhanced coupling for leaf moisture sensing: An IoT approach," *Frontiers in Physics*, Vol. 12, 1402326, 2024.
- [14] Pramanik, S. K., M. S. Hossain, and S. M. M. Islam, "Noncontact soil moisture estimation using continuous wave radar and deep learning," *IEEE Sensors Journal*, Vol. 24, No. 17, 28 419–28 426, September 2024.
- [15] Naktong, W., K. Puangnak, N. Phanthuna, S. Prapakarn, N. Prapakarn, and N. Wattikornsirikul, "An adjusted waveguide antenna with a woodpile-shaped EBG for eucalyptus wood moisture content measurement," *Trends in Sciences*, Vol. 21, No. 6, 7645, 2024.
- [16] Balanis, C. A., *Antenna Theory: Analysis and Design*, 4th ed., John Wiley & Sons, 2016.
- [17] Stutzman, W. L. and G. A. Thiele, *Antenna Theory and Design*, John Wiley & Sons, 2012.
- [18] Chen, J.-H., C.-Y. Cheng, C.-M. Chien, C. Yuanyai, T.-H. Chen, and S.-T. Chen, "Multiple performance optimization for microstrip patch antenna improvement," *Sensors*, Vol. 23, No. 9, 4278, 2023.
- [19] Zhang, Y., Y. Zhang, K. Huang, S.-J. Liu, X. Y. Zhang, and Q. H. Liu, "A reconfigurable patch antenna with linear and circular polarizations based on double-ring-slot feeding structure," *IEEE Transactions on Antennas and Propagation*, Vol. 70, No. 12, 11 389–11 400, December 2022.
- [20] Aliqab, K., S. Lavadiya, M. Alsharari, A. Armghan, M. G. Daher, and S. K. Patel, "Design and fabrication of a low-cost, multi-band and high gain square tooth-enabled metamaterial superstrate microstrip patch antenna," *Micromachines*, Vol. 14, No. 1, 163, 2023.
- [21] Sathishkumar, N., V. Nandalal, and R. Natarajan, "Design of a compact double-square-ring-shaped dual-band antenna for WiMAX/WLAN applications," *Wireless Personal Communications*, Vol. 128, No. 3, 2073–2084, 2023.
- [22] Guo, H., Y. Chen, Q. Wu, J. Wang, Y. He, Y. Cao, and M. Li, "A multi-frequency omnidirectional antenna based on a ring-shaped structure," *Micromachines*, Vol. 14, No. 5, 994, 2023.
- [23] Kola, K. S., A. Chatterjee, and S. Bhattacharya, "An array of slotted concentric-ring shaped printed radiators for DSRC applications," in *2023 IEEE Silchar Subsection Conference (SILCON)*, 1–6, Silchar, India, November 2023.
- [24] Cheng, G., B. Huang, Z. Huang, and L. Yang, "A high-gain circularly polarized filtering stacked patch antenna," *IEEE Antennas and Wireless Propagation Letters*, Vol. 22, No. 5, 995–999, May 2023.
- [25] Sellak, L., A. Khabba, J. Amadid, S. Chabaa, S. Ibnyaich, and A. Zeroual, "Design and Optimization of a Multiband Extra Wideband Ring Patch Antenna for 5G mm-Wave Communication at 28/60/80 GHz Using MLPNN based K-fold cross validation method," in *ITM Web of Conferences*, Vol. 69, 04003, 2024.
- [26] Al-Hinaai, A.-M., A. N. Caruso, T. D. Fields, M. Z. M. Hamdalla, and K. C. Durbhakula, "Gain enhancement of a patch antenna using wideband modified split ring resonator," in *2024 International Applied Computational Electromagnetics Society Symposium (ACES)*, 1–2, Orlando, FL, USA, May 2024.
- [27] Ta, L. P., D. Nakayama, and M. Hirose, "Design of a high-gain X-band electromagnetic band gap microstrip patch antenna for CubeSat applications," *Electronics*, Vol. 14, No. 11, 2216, 2025.
- [28] Wongsan, R., P. Duangtang, and P. Mesawad, "Dimension reduction of conical horn antennas by adding structure of metamaterial," in *2015 IEEE Asia Pacific Conference on Wireless and Mobile (APWiMob)*, 214–217, Bandung, Indonesia, August 2015.
- [29] Duangtang, P., P. Mesawad, and R. Wongsan, "Creating a gain enhancement technique for a conical horn antenna by adding a wire medium structure at the aperture," *Journal of Electromagnetic Engineering and Science*, Vol. 16, No. 2, 134–142, 2016.
- [30] Kamphikul, P., U. Mankong, and R. Wongsan, "Creating a gain improvement technique for a horn antenna using a metamaterial structure inserted with a thin dielectric sheet," *The Open Electrical & Electronic Engineering Journal*, Vol. 13, No. 1, 30–40, 2019.
- [31] Ponti, C., P. Baccarelli, S. Ceccuzzi, L. Tognolatti, and G. Schettini, "Resonant-cavity antennas with tapered and wideband EBG superstrates," in *2021 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, 301–304, Honolulu, HI, USA, August 2021.
- [32] Ponti, C., P. Baccarelli, S. Ceccuzzi, and G. Schettini, "3D additive manufacturing of tapered EBG layers for a resonant-cavity antenna," in *2022 IEEE 21st Mediterranean Electrotechnical Conference (MELECON)*, 564–568, Palermo, Italy, June 2022.
- [33] Vasilyan, H., O. Lapuz, R. A. Susantyoko, A. Almheiri, and M. Alyammahi, "Structure-resistance relationship of 3d printed electrically conductive woodpile-structured metamaterials," in *Proceedings of the ASME 2022 International Mechanical Engineering Congress and Exposition*, Vol. 86656, V003T03A053, Columbus, Ohio, USA, October 2022.
- [34] Vázquez-Peralvo, J. A., A. Tamayo-Domínguez, G. Pérez-Palomino, J. M. Fernández-González, and T. Wong, "3D inductive frequency selective structures using additive manufacturing and low-cost metallization," *Sensors*, Vol. 22, No. 2, 552, 2022.
- [35] So, H. and K. Maruta, "Sector design using multiband antenna with metamaterial reflector for cellular UAV system," *IEEE Ac-*

- cess, Vol. 10, 4924–4933, 2022.
- [36] Ikram, M., K. Sultan, A. T. Mobashsher, M. Moosazadeh, and A. Abbosh, “Wide-angle beam steering closed-form pillbox antenna fed by substrate-integrated waveguide horn for on-the-move satellite communications,” *Sensors*, Vol. 24, No. 3, 732, 2024.
- [37] Naktong, W., N. Wattikornsirikul, S. Sakulchat, S. Promput, and M. Kumngern, “Circular microstrip antenna with electromagnetic band gap on polyester mylar film substrate for metal detection applications in river prawns,” *Progress In Electromagnetics Research B*, Vol. 112, 1–14, 2025.
- [38] Chaipanya, P., W. Kongka, N. Wongpanyanurak, C. Wongplueksa, N. Thongnuam, W. Suksaart, K. Phapatanaburi, S. Santalunai, and N. Santalunai, “High-efficiency dual-band switched beam antenna with back lobe suppression using parasitic elements and patch etching for 5G,” *Scientific Reports*, Vol. 15, No. 1, 29582, 2025.
- [39] Wattikornsirikul, N., S. Sakulchat, W. Naktong, and S. Promput, “Dipole antenna with U and L-shaped stubs on multiple I-shaped EBG for digital television applications,” *Progress In Electromagnetics Research B*, Vol. 113, 87–99, 2025.