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RESEARCH PAPER

Radome-covered substrate-integrated cavity-backed patch antenna surrounded by dielectric material

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The substrate-integrated cavity-backed patch antenna embedded in dielectric-coated structure is presented. The aperture of antenna is covered with composite radome. The close proximity of radome to antenna severely degrades input impedance matching. The dielectric coating, a thick dielectric material, significantly deteriorates radiation pattern of antenna due to propagation of surface waves in the surrounding dielectric coating. The proposed planar electromagnetic bandgap structure reduces the propagation of surface waves in the dielectric coating recovering deterioration in the radiation pattern of the antenna. The problem of input impedance mismatching of antenna is resolved by placing a metallic strip on the top of the radome. The simulated results are in good agreement with measured results.

Keywords: Cavity-backed antenna, Composite radome, Dielectric coating, EBG

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I. INTRODUCTION

Conventional antennas are not suitable for high-speed objects such as jet planes, rockets, or satellites due to large profile and massive air friction faced. Cavity-backed antennas are the most suitable types for such applications where these antennas do not protrude from the body. Cavity-backed patch antenna show superior performance because of better matching and significant suppression of surface waves [1, 2]. However, development of cavity-backed patch antennas requires two fabrication processes. The first process involves conventional printed circuit board (PCB) technology to develop microstrip patch layer and the second process requires computer numerical control machining or metal casting to fabricate metalized cavities. These two stage processes increase the total fabrication cost of antenna and make structure assembly complicated [3]. Substrate-integrated waveguide (SIW) has been suggested as an alternative fabrication technology for low-cost implementation of waveguide-like components and antennas using the standard PCB fabrication technology [4–8]. SIW cavity-backed patch antennas exhibit same radiation performance as that of conventional metal cavity-backed patch antennas along with advantages of low-profile, easy fabrication, and planar integration [9–12]. Electromagnetic bandgap (EBG) structures have aroused growing interest in antenna community in the last years. EBG structures can be categorized into following classes [13]: (1) EBG substrates and high-impedance surfaces used to reduce surface waves [14–18]; (2) defect resonator antennas that create high directivity over a narrow bandwidth [19–21]; (3) sources embedded in EBG materials that have high directivity due to the limited angular propagation allowed within the material [22, 23]. EBG materials have been successfully used to improve the performance of antennas [24, 25]. Based on EBG technology, many novel antennas have been investigated and developed by the researchers [26–29]. Most of the research work has been carried out on single substrate, i.e. antenna and EBG structure are fabricated on the same substrate for improving radiation performance of antennas. The use of vias for shorting patches may not be feasible in certain applications.

In this paper, planar EBG structure in the form of via less conducting patches is proposed and developed on dielectric coating surrounding substrate-integrated cavity-backed patch antenna. The performance of cavity-backed patch antenna is analyzed for various thicknesses of dielectric coating in which patch antenna is embedded. The broad beam radiation pattern is degraded severely with the increase in the thickness of dielectric coating. The proposed EBG structure reduces the propagation of surface waves in thick dielectric coating causing significant improvement in the radiation pattern of the antenna. The composite radome placed in the close proximity of radiating aperture of antenna produces input impedance mismatching. The metallic strip placed on the top surface of radome restores impedance matching of antenna. The antenna can find use in different wireless communication applications.

II. ANTENNA STRUCTURE AND DESIGN

The body of fast moving vehicles is covered with dielectric material for protection against different environmental

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conditions. The antennas used in such vehicles are covered with radome for protection. Generally, the radome is placed sufficiently away from the radiating aperture of the antenna. However, the provision of sufficient space between antenna and radome is not possible for aforesaid objects due to limitations on the available space. Hence, the radome is placed close to the antenna. To investigate the effects of radome on the performance of antenna, the radome is placed in close proximity to rectangular patch antenna. Furthermore, the patch antenna is surrounded by the dielectric coating to explore its effects on the radiation characteristics of antenna. The patch antenna is designed on the RT/Duroid 5880 substrate at 2.8 GHz using electromagnetic simulator high frequency structure simulator (HFSS) as shown in Fig. 1. The length and width of the patch are L and W, respectively. The thickness of the substrate is h and the dielectric constant is ε_r. The patch antenna is fed by the coaxial probe and backed by the substrate-integrated cavity made of metallic vias. Since the dimensions of the patch are finite, the fields at the edges of the patch undergo fringing. The effective dielectric constant that takes into account fringing is determined [30];

$$\varepsilon_{reff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12h}{W}\right)^{\frac{-1}{2}}, \quad \text{for } \frac{W}{h} > 1. \quad (1)$$

Due to fringing, the patch of microstrip antenna looks greater electrically than its physical dimensions. The extension in the length ΔL is determined as:

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff} + 0.3)([W/h] + 0.264)}{(\varepsilon_{reff} - 0.258)([W/h] + 0.8)}. \quad (2)$$

The effective length of the patch becomes ($L = \lambda/2$ for the dominant TM_{010} mode with no fringing):

$$L_{eff} = L + 2\Delta L. \quad (3)$$

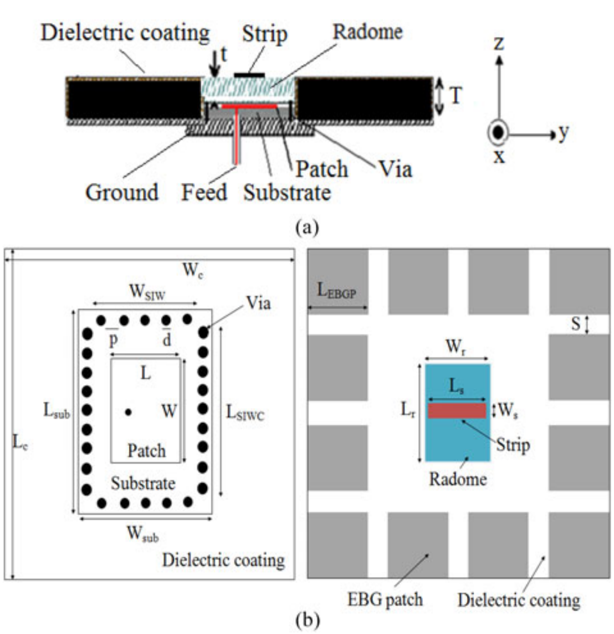

Fig. 1. SIW cavity-backed antenna (a) side view and (b) top view.

For the dominant TM_{010} mode, the resonant frequency of the microstrip antenna is determined as:

$$(f_r)_{010} = \frac{1}{2L_{eff}\sqrt{\varepsilon_{reff}}\sqrt{\varepsilon_0\mu_0}} = \frac{1}{2(L + 2\Delta L)\sqrt{\varepsilon_{reff}}\sqrt{\varepsilon_0\mu_0}}. \quad (4)$$

For an efficient radiator, the width of the microstrip patch antenna is determined as:

$$W = \frac{1}{2f_r\sqrt{\varepsilon_0\mu_0}}\sqrt{\frac{2}{\varepsilon_r + 1}} = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}. \quad (5)$$

where c is the velocity of light in free space.

The actual length of the patch is determined as:

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\varepsilon_0\mu_0}} - 2\Delta L. \quad (6)$$

The diameter of via and pitch of substrate-integrated cavity are determined as [31]:

$$d < \frac{\lambda_g}{5}, \quad (7)$$

$$p < 2d. \quad (8)$$

The antenna is embedded in dielectric coating possessing thickness T, dielectric constant ε_{rc}, and loss tangent tan δ_c. The antenna is covered with composite radome possessing thickness t. The proposed EBG structure consists of square patches around he radome in square configuration. The period of EBG structure is S. The dimensions of the cavity-backed patch antenna surrounded by dielectric coating are shown in Table 1.

Table 1. Dimensions of SIW cavity-backed patch antenna with EBG structure.

Parameter	Description	Dimension
L	The length of patch	32.2 mm
W	The width of patch	50 mm
H	The thickness of substrate	3.175 mm
ε_r	Dielectric constant of substrate	2.2
T_{max}	Maximum thickness of dielectric coating	12 mm
ε_{rc}	Dielectric constant of dielectric coating	3.9
tan δ_c	Loss tangent of dielectric coating	0.0487
L_c	The length of dielectric coating	200 mm
W_c	The width of dielectric coating	200 mm
L_{SIWC}	The length of substrate-integrated cavity	67 mm
W_{SIWC}	The width of substrate-integrated cavity	44 mm
d	The diameter of vias	3 mm
p	The spacing between vias	5 mm
L_{EBGP}	The length of square EBG patch	42.5 mm
S	Period of EBG structure	10 mm
L_r	Length of radome	80 mm
W_r	Width of radome	50 mm
ε_{rr}	Dielectric constant of radome	3.9
tan δ_r	Loss tangent of radome	0.0778
L_s	Length of strip	38 mm
W_s	Width of strip	10 mm

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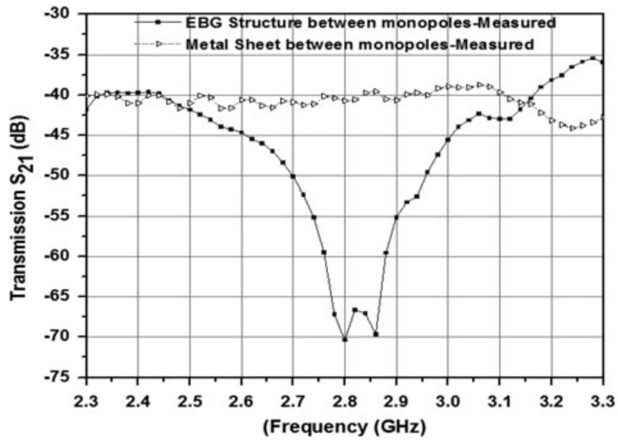

Fig. 2. Measured transmission characteristics of EBG structure.

III. ELECTROMAGNETIC BAND GAP STRUCTURE

EBG surfaces can be used for suppressing the surface waves and improvement of the radiation pattern of the antenna [32]. The performance of EBG structure can be analyzed using direct and indirect approaches with the help of full-wave electromagnetic numerical simulation software tools. The direct method involves the extraction of scattering parameters (*S*-parameters) between the two ports placed across the EBG structure [33]. The indirect method involves extracting dispersion diagram from an extensive procedure [33, 34]. The proposed electromagnetic band gap structure is designed using the guide lines [32] and analyzed by the direct method [33, 35]. The transmission across the EBG structure is evaluated using two small monopoles, one for the transmission and one for the reception, for determining surface wave suppression experimentally. The measured transmission S_{21} between monopoles shows surface wave suppression band centered at 2.8 GHz in which the signal is strongly attenuated in the presence of the proposed EBG structure between monopoles as shown in Fig. 2. The transmission between monopoles with metal sheet is also measured.

IV. PARAMETRIC ANALYSIS

The cavity-backed patch antenna shows broad beam radiation characteristics (3 dB beam width in *E* and *H* planes are 105 and 66°, respectively) and good return loss (−18 dB) in the absence of dielectric coating and radome ($T = 0$ mm and $t = 0$ mm). The return loss S_{11} and radiation pattern of cavity-backed patch antenna embedded in the dielectric coating are analyzed for various thicknesses of dielectric coating ($T = 6$, 9, and 12 mm) and radome ($t = T - 3$ mm). The return loss of patch antenna is increased with the increase in the thickness of radome as shown in Fig. 3. The radiation pattern of the antenna is degraded with the increase in the thickness of dielectric coating as shown in Figs 4 and 5. The narrowing of radiation pattern can be understood by studying surface current distribution. The surface current is confined near the radiating patch when there is no dielectric coating on the ground plane. For dielectric coating thickness of 12 mm, the surface currents are penetrated into the dielectric

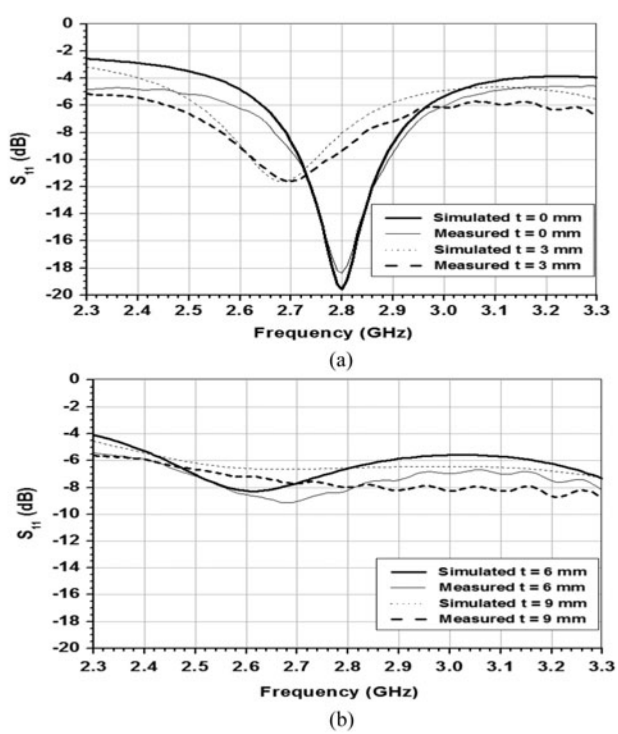

Fig. 3. Return loss S_{11} of antenna for various radome thicknesses. (a) $t = 0$, 3 mm (b) $t = 6$, and 9 mm.

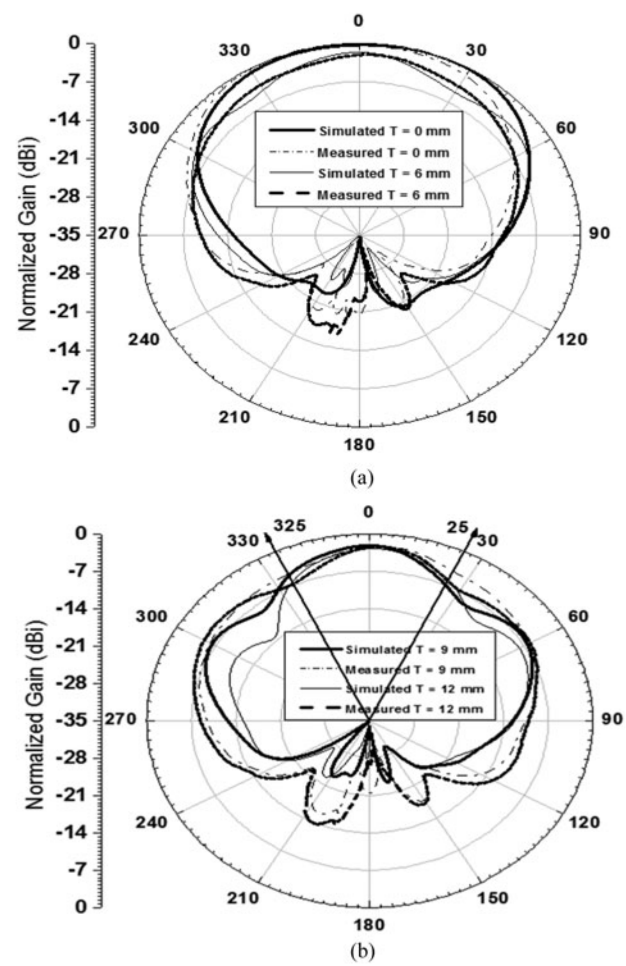

Fig. 4. Effect of dielectric coating on *E*-plane (*YZ*-plane) radiation pattern of antenna ($f = 2.8$ GHz). (a) $T = 0$ and 6 mm, (b) $T = 9$ and12 mm.

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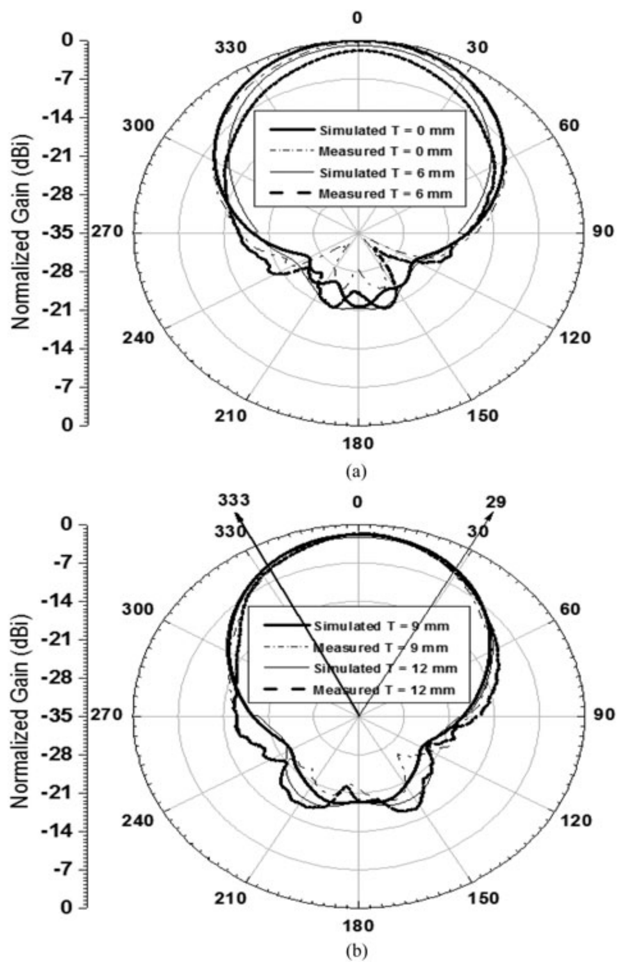

Fig. 5. *H*-plane (*XZ*-plane) radiation pattern for various dielectric coating thicknesses ($f = 2.8$ GHz). (a) $T = 0$ and 6 mm, (b) $T = 9$ and 12 mm.

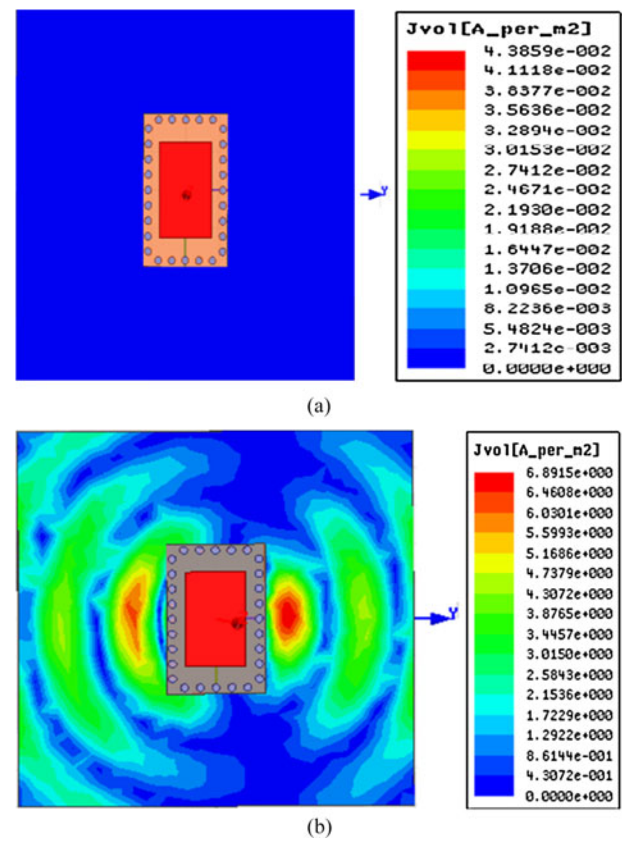

Fig. 6. Current distribution of antenna. (a) No dielectric coating, (b) 12 mm dielectric coating.

coating, as shown in Fig. 6, exciting surface waves in the dielectric coating and hence the degradation (narrowing) of radiation pattern (simulated $\theta_E \times \theta_H = 50^\circ \times 6^\circ$). The gain of antenna is also reduced by 2 dB due to close proximity of radome with radiating aperture of the antenna.

V. EXPERIMENTAL RESULTS

The proposed EBG structure is placed on dielectric-coated structure to restore broad beam radiation pattern of cavity-backed patch antenna (Fig. 7). The EBG structure consisting of conducting patches acts as the barrier to reduce propagation of surface waves in the dielectric coating and confines current distribution near the radiating aperture of the antenna. Therefore the radiation pattern of the antenna is improved, i.e. 3 dB beam width in the *E*-plane is increased/restored as shown in Fig. 8. Figure 8 also shows the measured cross-polarization components of electric and magnetic fields confirming linear polarization characteristics of antenna. The gain of antenna is plotted in Fig. 9. After implementation of EBG structure, broad beam radiation pattern (measured $\theta_E \times \theta_H = 100 \times 64^\circ$) and 6 dBi gain is achieved. The metallic strip on the top surface of radome improves return loss to -16.5 dB with 118 MHz impedance bandwidth as shown in Fig. 10.

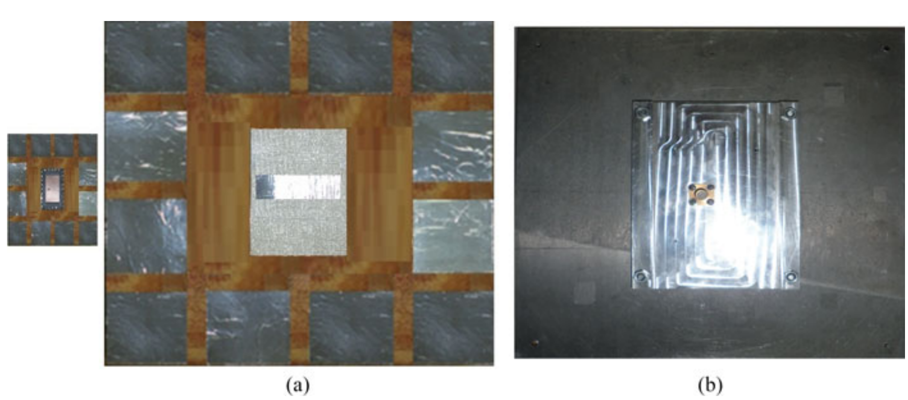

Fig. 7. Fabricated cavity-backed antenna. (a) Top view, (b) bottom view.

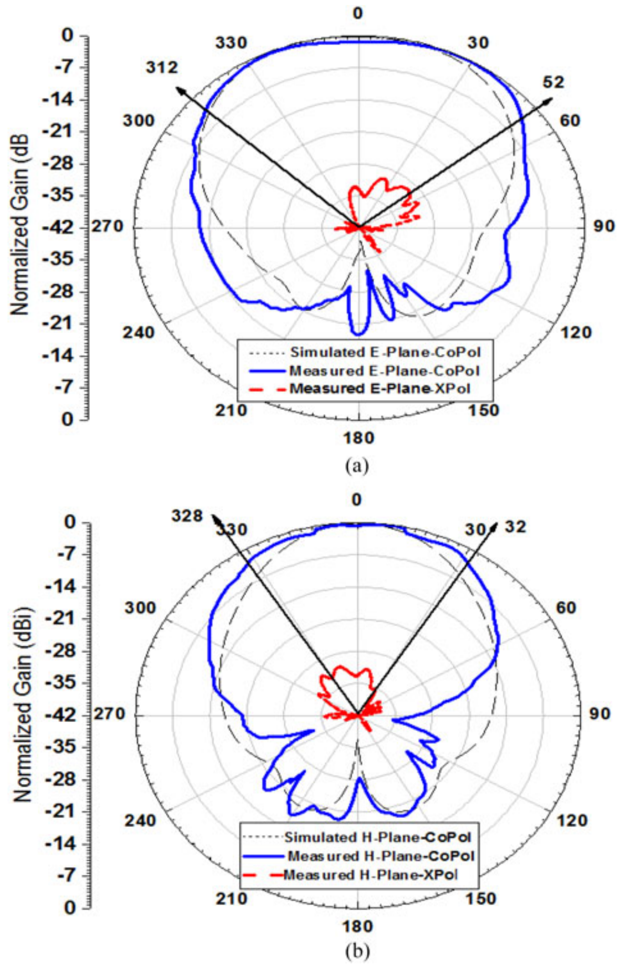

Fig. 8. Improvement in the radiation pattern of antenna due to EBG structure (f = 2.8 GHz). (a) E-plane, (b) H-plane.

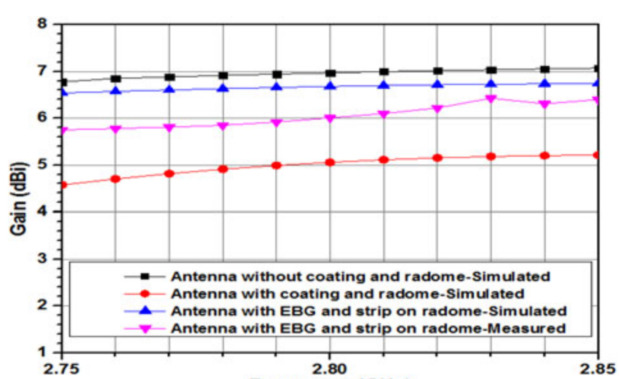

Fig. 9. Gain of the substrate-integrated cavity-backed patch antenna.

V. CONCLUSION

Substrate-integrated cavity-backed patch antenna embedded in dielectric coating has been proposed and developed. The effect of radome and dielectric coating on the performance of antenna is investigated. Increased thickness of dielectric coating and radome severely degrades radiation pattern and impedance matching of the antenna. The proposed EBG structure and strip placed on radome restore radiation characteristics and impedance matching of cavity-backed patch antenna.

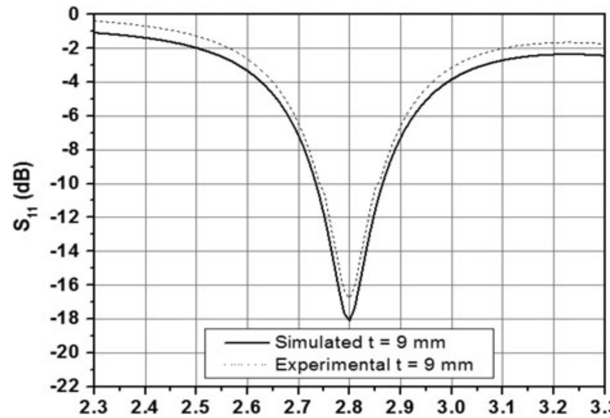

Fig. 10. Simulated and measured return loss S_{11} of the antenna after implementation of strip on radome.

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