Enhanced-Gain Planar Substrate-Integrated Waveguide Cavity-Backed Slot Antenna with Rectangular Slot Window on Superstrate

Hyunseong Kang and Sungjoon Lim

A novel substrate-integrated waveguide (SIW) cavity-backed slot antenna is proposed in this study to achieve enhanced-gain performance. The peak gain is remarkably improved with the use of an SIW cavity and metallic superstrate. The superstrate comprises a single rectangular slot window and two half-wavelength patches. The gain can be enhanced by combining the in-phase radiating fields. Further, the 10 dB bandwidth of the proposed antenna ranges from 2.32 GHz to 2.49 GHz, which covers the wireless local area network band. The measured peak gain is 9.44 dBi at 2.42 GHz.

Keywords: Enhanced-gain antenna, substrate-integrated waveguide, cavity-backed slot antenna.

I. Introduction

High-gain antennas have various applications such as in satellite platforms, radar systems, routers, and repeater systems. A number of enhancement techniques for antenna gain have been studied [1]–[2]. To realize enhanced-gain performance, a cavity-backed slot antenna (CBSA) is employed in this study because of its unidirectional characteristic. The merits of the CBSA include a wide bandwidth, when compared with a microstrip patch antenna, and low mutual coupling effect [3]–[4]. Although it has very respectable performance, the fabrication of a CBSA, especially its metallic cavity, is difficult.

Substrate-integrated waveguide (SIW) technology is a promising counterpart of the waveguide cavity [5]–[6]. Because an SIW can be realized on a printed circuit board (PCB) structure, it can be easily integrated with planar microwave systems. Moreover, when compared with a microstrip line resonator, the SIW resonator has a higher Q factor [7].

In this paper, we propose a novel enhanced-gain planar slot antenna backed by an SIW cavity for 2.4 GHz wireless local area network (WLAN) applications. Because the cavity of the conventional CBSA is replaced with an SIW, the thickness of the antenna structure is reduced, thus making it compatible with the PCB fabrication process. In addition, the superstrate employs a rectangular slot window to further increase the gain of the proposed CBSA.

II. Design

Figure 1 shows the three-dimensional, top, and side views of the configuration of the proposed antenna. It is built on two cost-effective FR4 substrates and one FR4 superstrate, with a floating air gap between the superstrate and substrates. The proposed antenna mainly consists of three parts: the SIW CBSA, the feeding part, and the superstrate.

1. SIW CBSA

The SIW CBSA can replace a bulky metallic CBSA. In the SIW CBSA, the metal wall and internal material of the metallic cavity are replaced with silver via arrays and the FR4 substrate of the SIW, respectively. Because the SIW CBSA is sandwiched between two (top and bottom) metal surfaces, a

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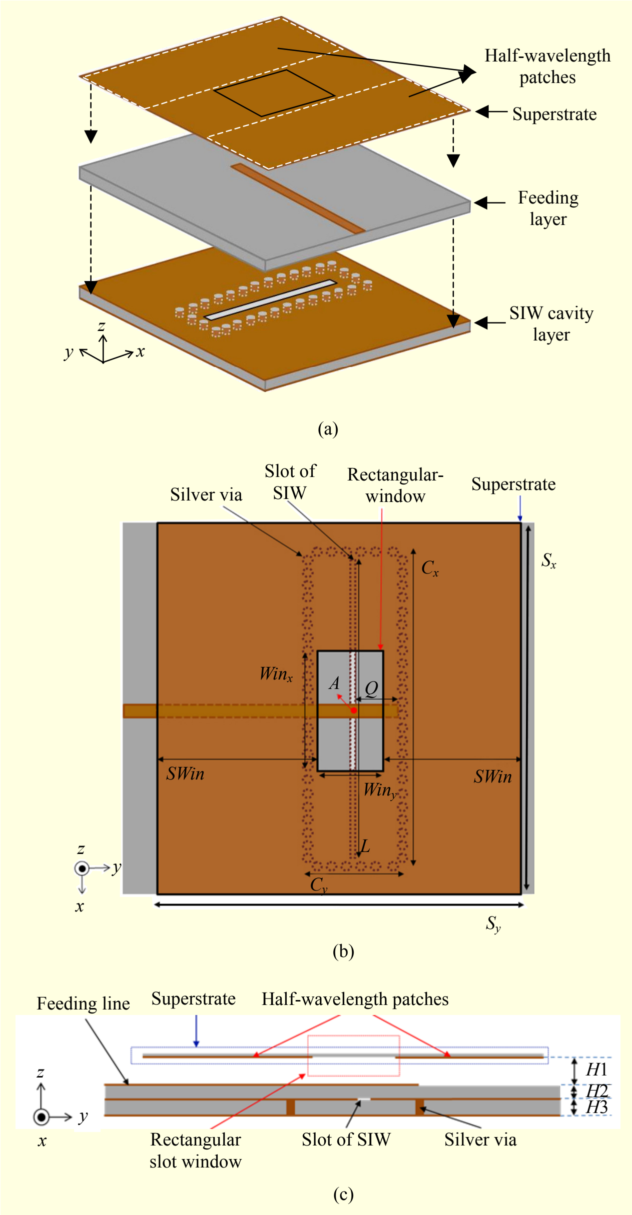

Fig. 1. Geometry of proposed antenna: (a) 3D view, (b) top view with geometrical dimensions, and (c) side view (Note that S_y = 146, S_x = 150, $SWin$ = 60, Win_y = 26, Win_x = 62, C_y = 32, C_x = 120, L = 110, Q = 20, $H1$ = 3, $H2$ = 0.54, and $H3$ = 1.6 [units: mm]).

parallel-plate waveguide (PPW) mode can be excited between the two metallic planes. By the PPW mode, leakage will occur on the substrate, which will cause a degradation of efficiency and distortion of the pattern. However, the side silver vias of the SIW cavity can suppress this leakage. As opposed to conventional annular and rectangular slot antennas, which have bidirectional radiation patterns, a unidirectional broadside radiation pattern can be achieved in an SIW CBSA because of the bottom metal plane. Therefore, the gain is improved at boresight when compared with the slot antenna.

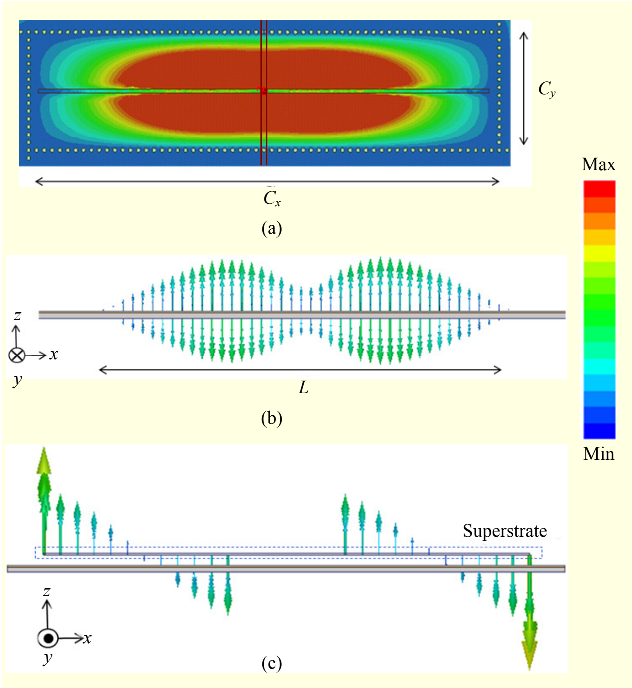

Fig. 2. Simulated E-field distributions: (a) magnitude of the E-field inside the SIW cavity, (b) vector of the E-field in the slot of the SIW (side view from y-axis), and (c) vector of the E-field on the superstrate (side view from x-axis).

First, the SIW cavity is designed. The resonant frequency of the SIW cavity is determined with the following equation:

$$f_{mn0} = \frac{1}{2\pi\sqrt{\mu_r \varepsilon_r}} \sqrt{\left(\frac{m\pi}{W_{\text{eff}}}\right)^2 + \left(\frac{n\pi}{L_{\text{eff}}}\right)^2}, \quad (1)$$

where μ_r, ε_r, W_{eff}, and L_{eff} denote the relative permeability, permittivity, and effective width and length of the SIW cavity, respectively. Moreover, W_{eff} and L_{eff} are found by

$$W_{\text{eff}} = C_x - 1.08\frac{d^2}{p} + 0.1\frac{d^2}{C_x} \quad (2)$$

and

$$L_{\text{eff}} = C_y - 1.08\frac{d^2}{p} + 0.1\frac{d^2}{C_y}, \quad (3)$$

where p and d denote the via diameter and the distance between the centers of adjacent vias, respectively [8]. Although the resonant frequency of the TE_{100} mode is lower than that of the TE_{010} mode, the TE_{010} mode is used in this work because it provides a higher gain. Moreover, it is related to the length of a slot (L). Additionally, a one-wavelength slot is selected instead of a half-wavelength slot to achieve enhanced gain. Therefore, L is chosen to be 110 mm, and the corresponding C_x is 120 mm, which is slightly greater than L. Next, to generate the TE_{010} mode in the 2.4 GHz band, C_y is determined to be 32 mm from (1), (2), and (3).

The magnitude of the E-field inside the SIW cavity can be seen in Fig. 2(a), which verifies the TE_{010} mode. The proposed antenna has been simulated with a finite element method (FEM)–based ANSYS HFSS simulation tool. The E-field distribution on the one-wavelength slot is shown in Fig. 2(b). The E-field is very small at the point A (Fig. 1(b)) of the feeding line; thus, the impedance is easily matched, as shown in Fig. 2(b). Furthermore, the E-field has two in-phase maximum points along the one-wavelength slot, and it is equivalent to two magnetic current distributions. The length of the current source is inversely proportional to the beamwidth, so the beamwidth is narrower on the *z*-*x* plane, while the directivity is enhanced on the *z*-*y* plane. Therefore, the peak gain is increased along the boresight direction. It is operated like a two-dipole antennas array.

2. Gain Enhancement with Superstrate

A superstrate is introduced to further increase the gain (see Fig. 1). The superstrate consists of one rectangular slot window and two half-wavelength patches. The rectangular slot window is etched at the center of the superstrate. Moreover, the EM energy radiated from the SIW slot is coupled with the rectangular window of the superstrate, and then it is radiated from the two half-wavelength patches. The superstrate is designed to have a half-wave distance from the rectangular slot window to the edge, and it is operated as two half-wavelength patches. Therefore, the magnetic source from the fringing field on each edge is in phase. Figure 2(c) shows the vector of the E-field on the superstrate. When the superstrate is placed above the SIW, one more resonance occurs at 2.6 GHz when *SWin* = 54 mm. The second resonance is determined by the length between the edge of the superstrate and the window (*SWin*). The second frequency is shifted by changing *SWin*, and the first frequency from the SIW cavity is fixed. By manipulating the second frequency, the two resonances gather at one frequency, so the radiation is generated efficiently.

The other factors to be considered while designing the superstrate are Win_x and S_x. The length of the window on the superstrate (Win_x) shows an effect similar to the slot of the SIW structure. Namely, the resonant frequency of the superstrate is slightly shifted by Win_x. Additionally, the width of the superstrate (S_x) should be greater than the length of the slot of the SIW; otherwise, the radiation will have less directivity because the radiation power from the slot is not totally affected by the superstrate. The expected gain patterns from the simulation results are shown in Fig. 3. The superstrate consists of two half-wavelength patch antennas along the *y*-axis, as shown in Fig. 1(a). The phase differences of the two radiating sources are zero, as shown in Fig. 2(c). Therefore, the radiation pattern of the superstrate is similar to that of the two-element

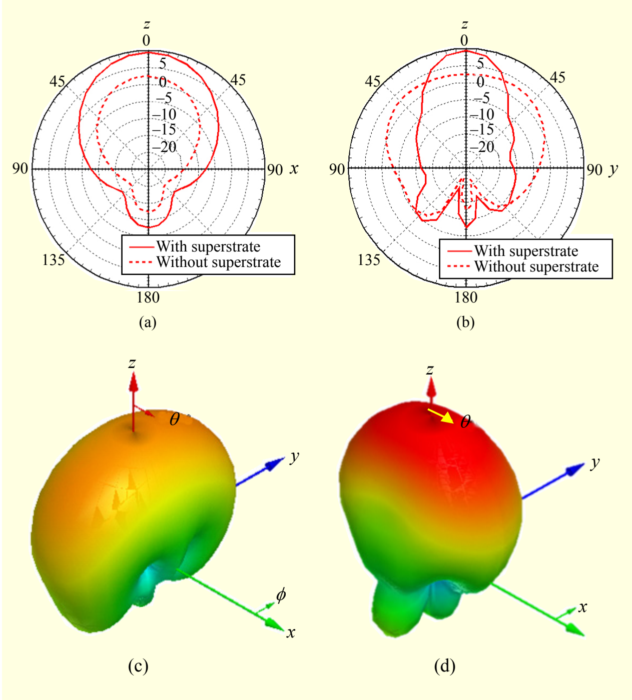

Fig. 3. Simulated gain patterns of the SIW cavity-backed slot antenna with and without the superstrate at 2.45 GHz on the (a) *z*-*x* and (b) *z*-*y* planes. 3D patterns (c) without and (d) with the superstrate.

array along the *y*-axis. Moreover, the radiation power that spreads to the *z*-*y* plane by the SIW cavity is directed to the *z*-*x* axis owing to the inverse proportion between the radiation source and beamwidth, so the radiation gain becomes much greater along the *z*-direction.

The gain increases further because of the combination of the SIW cavity and the superstrate. The size of the superstrate is 146 mm × 150 mm, and the size of the rectangular window is 62 mm × 26 mm. In addition, the conductor is etched on the bottom of the FR4 substrate, as shown in Fig. 1. In the final design stage, the impedance matching is considered. Similar to an aperture-coupled antenna, the impedance is easily matched to 50 Ω using the length of the open stub (Q), in Fig. 1(b), which is realized on the feeding line layer.

To demonstrate the gain enhancement from the superstrate, the simulated gain patterns of the SIW CBSA having the superstrate are compared with those without the superstrate, as shown in Fig. 3. Along the boresight (*z*) direction, the peak gain increases by 6.84 dBi from 2.6 dBi to 9.44 dBi. As mentioned above, the directivity is observed to be greater on the *z*-*y* plane, as shown in Figs. 3(c) and 3(d). Similar gain improvement can be achieved with a four-element array, where rectangular microstrip patch antennas are built on the same FR4 substrate. However, the proposed antenna occupies less space than conventional antenna arrays, which require additional feeding networks.

III. Experimental Results

Figure 4 shows a picture of the fabricated antenna prototype. Figure 5 shows a comparison of the simulated return loss and measured return loss. The measured 10 dB bandwidth ranges from 2.32 GHz to 2.49 GHz, and the simulated 10 dB bandwidth ranges from 2.28 GHz to 2.49 GHz. Both the simulation and measurement results are in sound agreement.

Figure 6 shows the simulated and measured radiation patterns of the proposed antenna. The simulated and measured peak gains at 2.42 GHz are 9.44 dBi and 9.52 dBi, respectively. The discrepancy between the simulation and measurement results is due to the connector and cable. In addition, the front-to-back ratio is 18.7 dB because of the SIW back cavity. Moreover, the radiation efficiency is approximately 69% despite a lossy FR4 substrate.

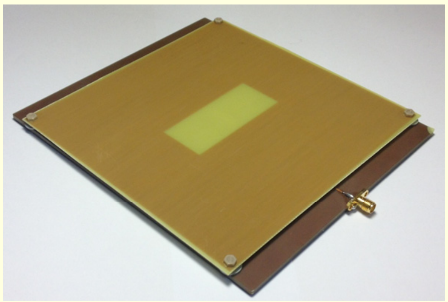

Fig. 4. Picture of the proposed antenna prototype.

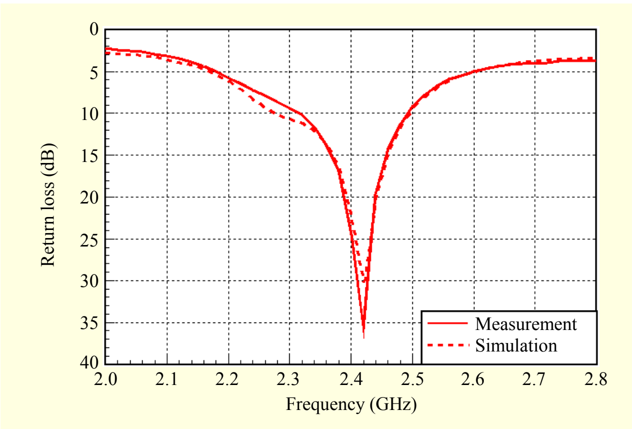

Fig. 5. Measured and simulated return losses of proposed antenna.

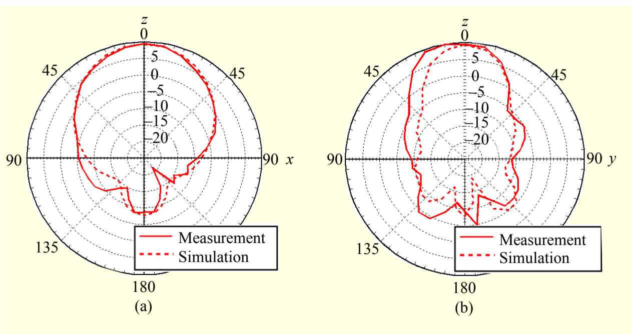

Fig. 6. Measured and simulated gain patterns (in dB) on the (a) z-x and (b) z-y planes.

IV. Conclusion

In this paper, a novel enhanced-gain planar slot antenna was proposed for 2.4 GHz WLAN applications. The high Q-factor of the SIW cavity and superstrate improve the radiation performance of the proposed antenna. Because the superstrate consists of one rectangular window and two half-wavelength patches, the peak gain increases from 2.6 dBi to 9.44 dBi, despite using lossy FR4 substrates. Further, the measured 10 dB bandwidth ranges from 2.32 GHz to 2.49 GHz. In addition, the PCB-compatible SIW cavity facilitates easy and cost-effective fabrication. Therefore, it is a suitable candidate for WLAN repeaters or routers that require an enhanced-gain performance.

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