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Miniaturization of SIW-Based Linearly Polarized Slot Antennas for Software-Defined Radar

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Abstract

Two substrate integrated waveguide (SIW)-based antennas for the application of software-defined radar are proposed and investigated herein. It is usually well known that SIWs are easily integrated, lightweight, have low insertion loss, and low interference levels compared to conventional microstrip structures. The primary function of the proposed antennas is to transmit continuous waves for indoor motion detection, with the lowest amount of loss and an appropriate amount of gain. Moreover, the results of this study show that the size of the antenna can be reduced significantly (i.e., by about 40%) by applying a meander line structure. The operating frequencies of the proposed antennas are both within the industrial, scientific, and medical band (i.e., 2.4–2.4835 GHz). Measured results of return loss are −16 dB and −20 dB at 2.435 GHz and 2.43 GHz, respectively, and the measured gain is 8.2 dBi and 5.5 dBi, respectively. Antenna design and verification are undertaken through commercially available full electromagnetic software.

Key Words: Linear Polarization (LP), Meander Line, Slot Antenna, Software-Defined Radar (SDR), Substrate Integrated Waveguide (SIW).

I. INTRODUCTION

Recently, as interest in the civil radar industry has increased, various studies relating to the general use of radar technology have been undertaken. Research on low-power and near-distance measuring radar while using the industrial, scientific, and medical (ISM) band-the frequency of which can be used without government permission-has generally increased, and there have been efforts to adapt this radar to software-defined radar (SDR) platforms. In general, microstrip patch antennas-which are conventional S-band SDR antennas-are preferred, owing to their high-volume efficiency.

However, their drawbacks are high power loss in transmission and a tendency to distort radiation patterns; these derive from their indispensable feeding structures. On the other hand, horn/waveguide-type antennas can handle high-power and high-gain conditions, but are large and heavy, resulting in space-allocation difficulties for system integration [1, 2]. The results of this study suggest that, considering their low distortion, low power loss, light weight, and high-volume efficiency, the use of novel substrate integrated waveguide (SIW)-based antennas is preferable to that of conventional microstrip and horn/waveguide-type antennas; the former of these have been proposed and analyzed in several configurations. SIW-based transmission lines can be materialized in common printed circuit boards (PCBs) and have the same operating principles as metallic rectangular waveguides [3, 4]. As a basic characteristic of standard waveguides, the dominant mode of SIW transmission lines is

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TE_{10} [1].

Moreover, interference with other devices can be minimized if the feeding part is materialized by SIW transmission lines [1]. Especially, the isolation characteristic is a key factor for SDR antennas, because transmitting and receiving antennas are placed in an adjacent location-and, in the case of applying the SIW transmission line structure, interference between the transmitting and receiving antennas can be considerably reduced.

Furthermore, this study addresses the meander-line structure, which is used to miniaturize the conventional ring-slotted SIW antenna and reduce its size by about 23%. To obtain return losses less than −15 dB and −20 dB, respectively, the optimal parameter values of an effective equivalent via radius and via gap widths were selected only under the operation of the TE_{10} mode propagating inside and without any higher-order modes. The proposed antennas are designed on RT/Duroid 5880 PCB; the thickness and relative permittivity of the board are 1.57 mm and 2.2 mm, respectively. In Section II, the relationships between the design parameters and antenna performance for both SIW-based antennas are described by simulation, using commercially available full electromagnetic software. Section III discusses the measurement results vis-à-vis the designed antennas and radar cross-section (RCS) detection radar experiments through the SDR platform; this is followed by a brief conclusion in Section IV.

II. SIW-BASED ANTENNA GEOMETRY AND DESIGN PROCEDURE

1. SIW-Based Ring-Slotted Antenna

Rather than a conventional microstrip patch antenna, an SIW structure-the use of which leads to reduced fringing loss and distortion otherwise caused by higher-order modes-is proposed, which uses metallic via arrays (Fig. 1).

In the SIW-based ring-slotted antenna, the shorting via that connects the conductor plate inside a slot in the bottom plate performs an especially important role in matching antenna impedance and generating the required resonant frequency [1]. From the results of rigorous parametric studies, we know that a circularly polarized wave can be created through the installation of a shorting via at an asymmetric position [3, 4]. At this time, the shorting via is positioned on the y-axis to intentionally and simply generate the linearly polarized wave needed for SDR applications.

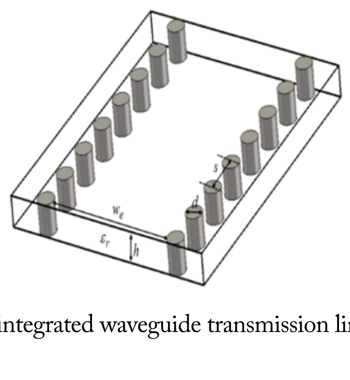
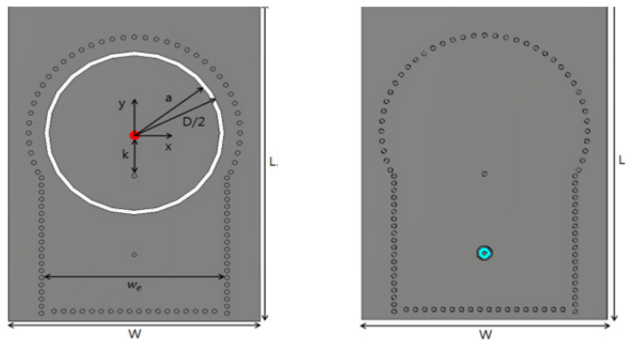


Fig. 1. Substrate integrated waveguide transmission line [1].



(a) (b)

Fig. 2. Configuration of substrate integrated waveguide (SIW)-based ring-slotted antenna. (a) Top view and (b) bottom view.

In Fig. 2, a is the radius of the circular patch and D is the diameter of the outside slot. Additionally, w_e is the effective equivalent width of the SIW structure. The equation pertaining to the relationship between the cutoff frequency and effective equivalent width is expressed as follows [5]:

$$f_c = \frac{1}{2w_e\sqrt{\mu\varepsilon}} \qquad w_e = w - \frac{d^2}{0.95s}, \tag{1}$$

where μ and ε are permeability and permittivity, respectively.

The plan for the antenna proposed in this study was that it would be used at 2.4–2.4835 GHz of the ISM standard, and at a channel bandwidth of 35 MHz (center frequency = 2.433 GHz). To satisfy the operating frequency band (2.415–2.45 GHz), the via radius and via gap are optimally selected and the cutoff frequency of the SIW structure is set at around 1.8 GHz. The effective equivalent width w_e was 57 mm; the via hole diameter d, 1.5 mm; and the distance between the two via holes s, 2.5 mm. As shown in [6], the relationship between the circular conductor plate diameter and the resonant frequency is given by

$$f_r = \frac{K_{11} \cdot c}{2\pi a \sqrt{\varepsilon_r}}, \tag{2}$$

where K_{11} is the first root of the derivative of the first Bessel function (K_{11} = 1.8412), c is the speed of light, ε_r is the relative permittivity of the employed dielectric, and a is the radius of the circular patch [6, 7].

However, in designing the antenna, Eq. (2) provides only rough boundaries for the design parameters; rigorous parametric study is needed to decide the optimal design parameters. The

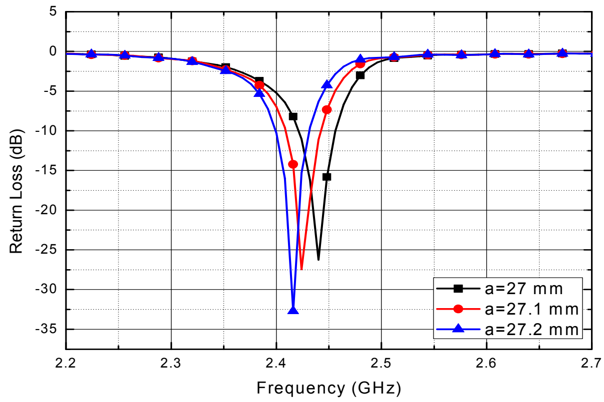


Fig. 3. Return loss values versus various circular patch radius *a* values.

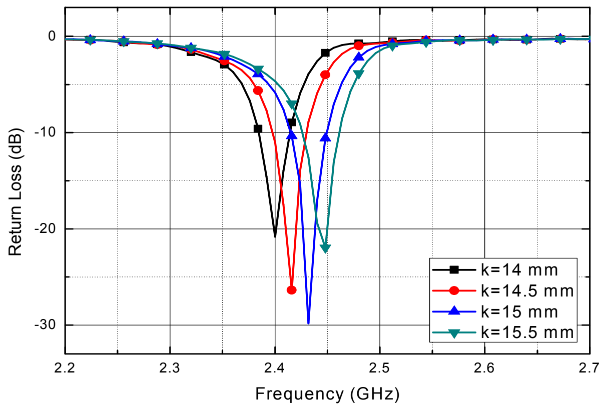


Fig. 4. Return loss values versus various shorting via position *k* values.

optimal values were found to be as follows: radius of the inner slot *a*, 27.12 mm; the outer slot diameter *D*, 57.25 mm; and the total antenna size, 112 mm × 80 mm ($L \times W$). Figs. 3 and 4 show the return loss properties versus resonant frequency.

The resonant frequency sensitively depends on the radius of the circular patch. As the radius increases, the resonant frequency is expected to decrease. It is clear that the position of the shorting via is another critical design factor for the SIW-based ring-slotted antenna.

2. SIW-Based Meandered-Slot Antenna

The previously designed SIW-based ring-slotted antenna in Fig. 2 has a total size of 112 mm × 80 mm ($L \times W$), and so it is relatively smaller than the conventional microstrip patch antenna. However, it is somewhat larger than most transmitting and receiving antennas for compact SDR hardware platforms used in indoor motion detection. To miniaturize the ring-slotted antenna as shown in Fig. 5, the meander line is applied to the circular slot, and the radius of the inner slot *a* is reduced to 21.4 mm; the radius of the inner slot of the ring-slotted antenna *a* is 27.12 mm. Hence, the total radiation area of the proposed antenna was reduced by 37.8% [8]. In designing the meandered structure, the length of the meander line is an

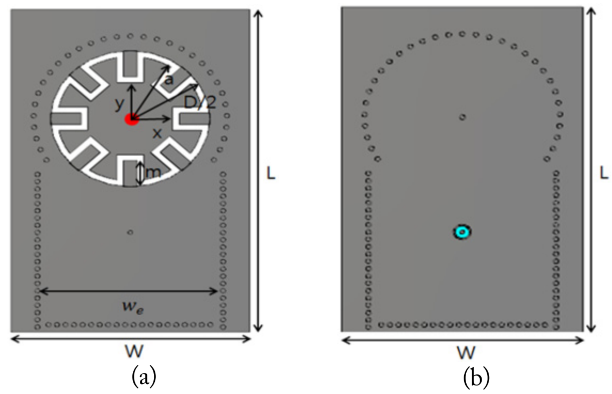


Fig. 5. Configuration of SIW-based meandered-slot antenna. (a) Top view and (b) bottom view.

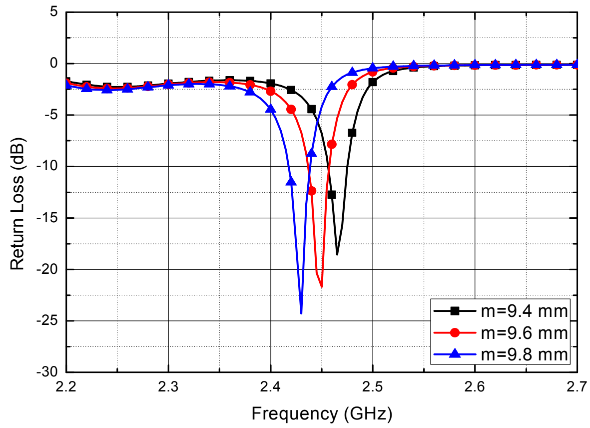


Fig. 6. Return loss values versus various meander line *m* values.

important factor with regards to resonant frequency and impedance matching, as shown in Fig. 6. The resonant frequency can be reduced by increasing the length of the meander line. It is expected that the meander line lowers the resonant frequency by increasing the reactance elements in the radiating area.

Additionally, the optimized outer slot diameter *D* is 46.6 mm. The total size of the antenna is 110 mm × 70 mm ($L \times W$).

III. Measurement Results

1. Antenna Performance

First, the return loss characteristics of the simulated and manufactured SIW-based ring-slotted antenna were investigated (Fig. 7). The bandwidth of the simulated antenna under the criterion of less than −10 dB ranged from 2.43 to 2.465 GHz; the required channel bandwidth was 35 MHz. In addition, the bandwidth of the manufactured antenna under the criterion of less than −10 dB ranged from 2.415 to 2.45 GHz, and the channel bandwidth was almost identical to the simulation result.

We checked the linear polarization (LP) properties needed to develop SDR platforms; Fig. 8 shows the Co-pol. and X-pol. characteristics of the given Model 1 antenna.

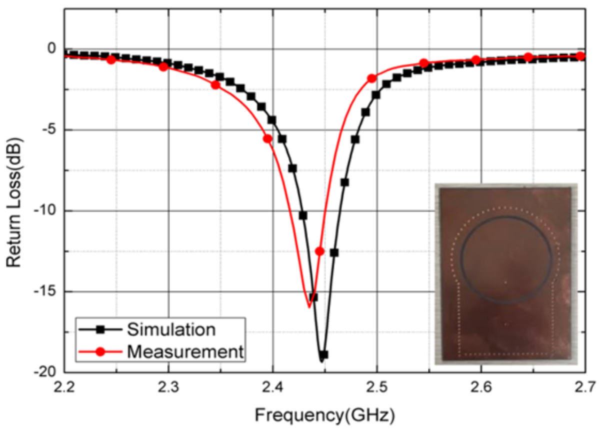
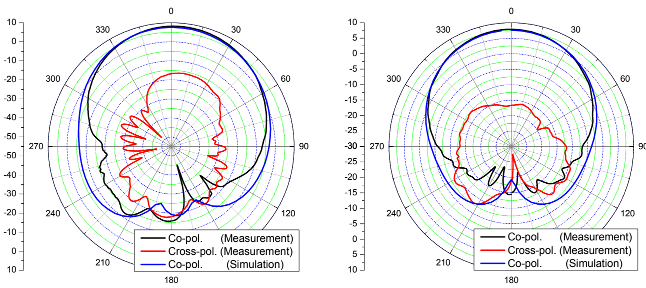


Fig. 7. Results of the simulated and measured return losses of the Model 1 antenna.



(a) (b)

Fig. 8. Simulated and measured radiation patterns of Model 1 at 2.435 GHz. (a) At E-plane and (b) at H-plane.

As shown in Fig. 8(a) and (b), the antenna gain exceeds 8 dBi at 2.435 GHz, and the half-power beam width (HPBW) is 78°, which is a wide beam width. It is noted that the Co-pol. and X-pol. at the bore sight of the antenna correspond to the V-pol. and H-pol., respectively, and that the difference between the Co-pol. and X-pol. is −23 dB and −25 dB, respectively. This therefore indicates that the proposed antenna has high-purity linear polarization properties. In terms of return losses, the results of the measured and simulated antenna strongly align. Figs. 9 and 10 delineate the return loss property and the measured radiation pattern of the SIW-based meandered-slot antenna, respectively.

Like the SIW-based ring-slotted antenna (Model 1), the Co-pol. and X-pol. of the meandered-slot antenna (Model 2) are both measured to determine their linear polarization properties. The bandwidth of the simulated antenna was 2.4165–2.4435 GHz, and the required channel bandwidth was 27 MHz. Additionally the bandwidth of the manufactured antenna was 2.4175–2.4425 GHz, and the center frequency was identical to the simulation result. Fig. 10 shows the radiation pattern, and that the gain of the meandered-slot antenna exceeds 5 dBi at 2.43 GHz and the HPBW was 87°, thus indicating a wide beam width.

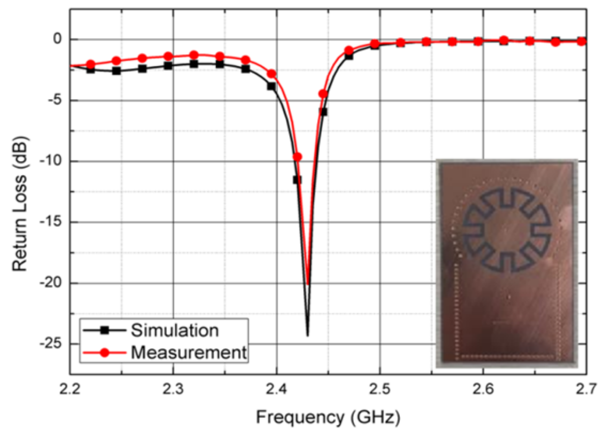
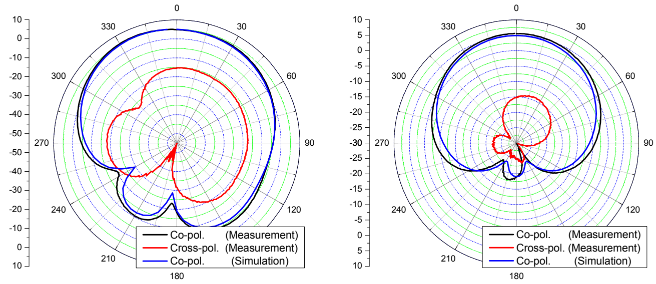
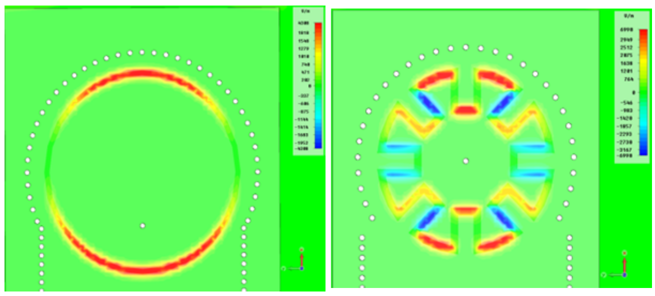


Fig. 9. Simulated and measured return losses of Model 2 antenna.



(a) (b)

Fig. 10. Simulated and measured radiation patterns of Model 2 at 2.43 GHz. (a) At E-plane and (b) at H-plane.



(a) (b)

Fig. 11. Electric field distributions inside the radiation cavity at each resonant frequency. (a) At Model 1 antenna and (b) at Model 2 antenna.

With regards to LP purity, the results show that the meandered-slot antenna also has a high-purity linear polarization property. Moreover, the LP property of both antennas could be verified through the use of animated field distributions (Fig. 11).

2. RCS Detection Radar Experiment

In this study, to determine the maximum distance at which a moving target could be detected by the antenna, detection was confirmed by changing the distance between stages. The detection experiment was performed inside a building, in a real-world

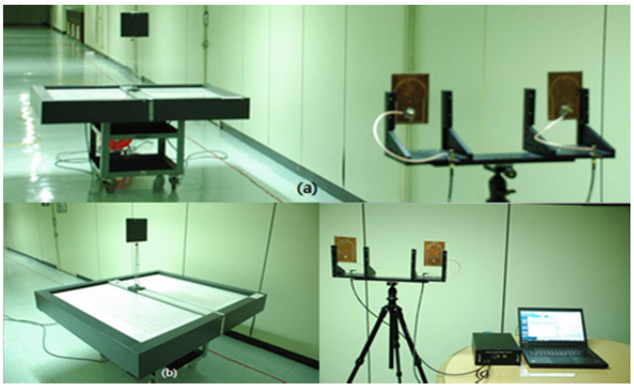


Fig. 12. Radar cross-section (RCS) detection experiment environment. (a) Initial distance of 10 m, (b) target RCS, and (c) software-defined radar platform and substrate integrated waveguide (SIW) antenna.

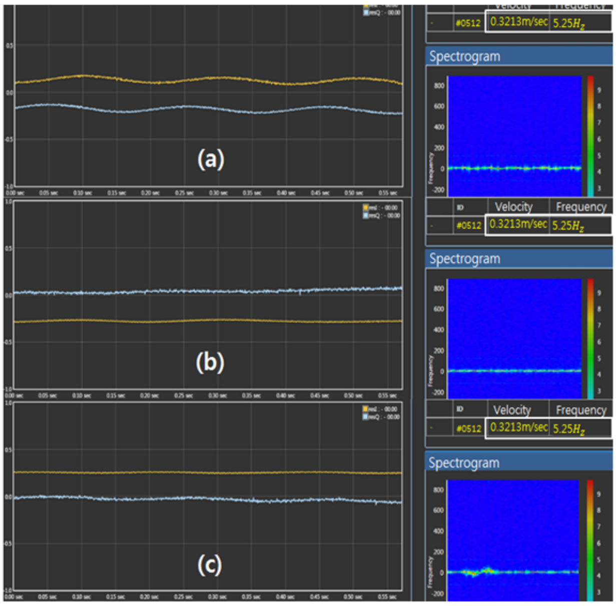


Fig. 13. Results of the radar cross-section (RCS) detection experiment, by distance. (a) At 10 m, (b) 20 m, and (c) 30 m.

application. The metal plate-which has 1 m^2 of RCS-was set to move toward the bore-sight direction of the antenna. A moving target with a constant RCS and constant velocity can be identified through signal analysis of the returned Doppler frequency.

Fig. 12 illustrates the test environment of the RCS detection experiment. The experiment was carried out under several conditions, at 10–30 m from the antenna surface.

The moving velocity of the RCS was set to be 0.3 m/s, and the Doppler frequency that corresponds to the moving target was found to be 5 Hz. Experiments for other cases were executed to validate our systems.

Fig. 13 shows the detection results as per the SDR software, depending on target distance. The amplitude of the signal decreases as the distance increases, but the detected velocity and Doppler frequency have constant values of 0.321 m/s and 5.25 Hz, respectively. These values correspond to the initial setup velocity of 0.3 m/s and the expected Doppler frequency of 5 Hz.

Therefore, according to the experimental results, the antenna proposed and described in this paper can detect the motion of a target that is 30 m from the antenna.

IV. CONCLUSION

This paper proposes, and describes the design of, an S-band radar antenna mounted on an SDR platform. Since an SDR antenna requires a high-isolation characteristic, the SIW structure was applied and the antenna design parameters were optimized and determined throughout this repetitive parametric study. Moreover, in an RCS detection experiment using an SDR platform, the velocity and Doppler frequency of the RCS at a distance of 30 m from the antenna were detected. It was shown that the proposed SIW-based slotted antenna is a good and appropriate candidate for indoor motion detection.

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