Design of a Planar Surface Wave Antenna with a Bidirectional Pattern Based on Periodic Structures for Telemetry Applications

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***Abstract* ─** A planar surface wave antenna (PSWA) that realizes a bidirectional radiation pattern with a low profile configuration is designed, fabricated and measured. The antenna consists of a planar dielectric slab loaded with periodic spiral patches and EBG structure, which are designed to support the propagation of the surface waves in the desired direction. The diffraction of surface waves at the edges of the ground plane generates a bidirectional radiation pattern. The radiation mechanism and performance of the PSWA are described and simulated with commercial CST software. The proposed antenna with only 1.6 mm thickness is fabricated and tested, which resonates at 2.4 GHz. The antenna is especially attractive for telemetry applications because of its low profile and weight.

***Index Terms* ─** Bidirectional radiation pattern, planar antenna, periodic structure, surface wave antenna.

I. INTRODUCTION

Wire inverted F antennas (WIFAs) are commonly used on small unmanned aerial vehicles (UAVs) for telemetry and command signals because of their bidirectional pattern [1]. However, the wire inverted F antennas similar to other wire antennas have disadvantages such as high aerodynamic drag and a high degree of electromagnetic coupling to the fuselage [2]. Another approach is to use the low profile surface wave antennas (SWAs) [3-8] and electromagnetic band gap (EBG) structures [9-15] to suppress the surface wave propagating along one side and support it along another side.

In [9-15], the surface waves are suppressed with EBG structures that made with periodic mushroom-like structure. Thus, in these antennas side-lobe falls down and the gain of broadside direction rises up. But in [3-8], the surface waves have important role in the low profile surface wave antennas. In these antennas, mushroom-like structure without via supports the surface waves. The surface waves propagate in a ground plane and diffraction rays from opposite edges will cancel each other in the broadside direction, resulting in a radiation null. Thus, an omnidirectional monopole-like radiation is generated. So, the low profile surface wave antenna can be a good idea to realize a bidirectional radiation pattern, like WIFA pattern.

In this paper, a novel planar surface wave antenna with a bidirectional radiation pattern based on low-profile SWA and EBG structure is proposed. The SWA consists of two parts: a patch to excite the surface waves, and a thin dielectric slab loaded with periodic spiral patches to support the surface waves. The EBG structure in the two lateral sides of the periodic patches can suppress the surface waves. Consequently, strong surface waves propagate in central side and their diffractions at the boundary of the ground plane form a bidirectional pattern. PSWA pattern is similar to the pattern of the WIFAs; however, PSWA is low-profile without aerodynamic drag. In fact, the PSWA is superior to the disadvantages of the WIFAs. The proposed planar surface wave antenna is so attractive for telemetry applications. The artificial ground plane is studied in details in Section II, then the radiation mechanism of the planar surface wave antenna is described in Section III and experimentally verified in Section IV.

II. THE NEW ARTIFICIAL GROUND PLANE

A. Surface waves in the structure

In [3], a thin slab loaded with periodic square patches and EBG structure has been discussed separately. A unique feature of the proposed antenna in this paper is an incorporation both of the thin grounded dielectric slab loaded with periodic spiral patches and the EBG

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structures to make a novel artificial ground as shown in Fig. 1. The dimensions of the periodic structure for the desired application are as follows:

$$s = 0.8\text{ mm},\ p = 6.8\text{ mm},\ g = 0.5\text{ mm},\ r = 0.31\text{ mm}, \tag{1}$$

where s is the gap width of the spiral line, p is the period of the periodic structure, g is the gap width between two spiral patches, r is the via-radius of the EBG structure. The substrate thickness, h, is 1.574 mm (62 mil) and the dielectric constant of the substrate, ε_r, is 2.2. Figure 2 shows the dispersion diagrams [3] of the two different periodic artificial surfaces using the CST software. The vertical axis shows the frequency and the horizontal axis represents the values of transverse wave numbers; *i.e.*, k_x and k_y. As shown in Fig. 2 (a), the surface wave is suppressed between 2.3 GHz and 2.5 GHz for the EBG structure of Fig. 1; *i.e.*, all the patches are connected to the ground with vertical vias. In contrast, for the patch loaded grounded slab, since the vertical vias are removed, the first surface wave mode exists in the desired frequency range as shown in Fig. 2 (b).

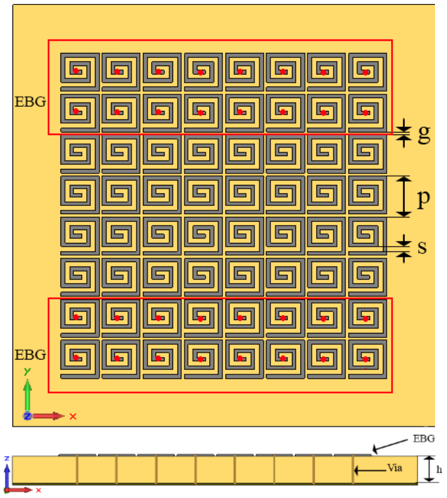
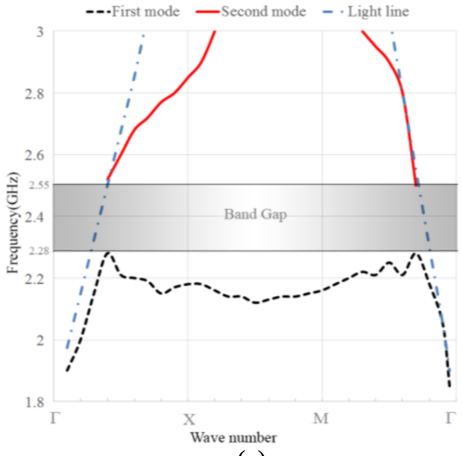
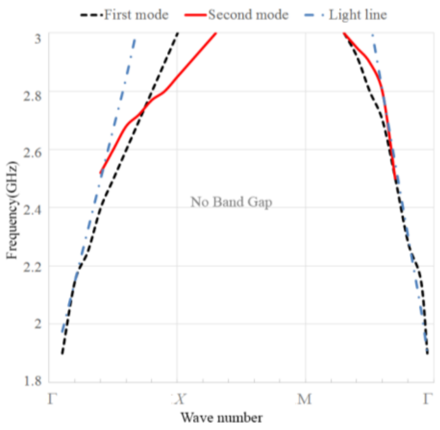


Fig. 1. The geometry of the novel proposed artificial ground plane.



(a)



(b)

Fig. 2. Dispersion diagram of the two artificial surfaces: (a) a EBG structure (with vias), and (b) a dielectric slab loaded with patches (without vias). Along the horizontal axis, Γ: $k_x = 0$, $k_y = 0$; X: $k_x = \pi/p$, $k_y = 0$; M: $k_x = \pi/p$, $k_y = \pi/p$.

These structures are combined to make a new artificial ground plane as shown in Fig. 1. There are four rows of periodic patches in the middle of the ground plane to support the propagation of the surface waves along ±*x* directions and two rows in each lateral side to suppress the surface wave propagating along ±*y* directions. In summary, with the novel artificial ground plane, the surface wave can be directed along one side.

B. Parametric studies of the unit cell

The unit-cell EBG structure is shown in Fig. 3, which includes a layer with metallization layout and shorted with the ground through a center via connection. In contrast to the traditional square patch layout [15], a spiral type is proposed for the size reduction. The layouts with number of turns N = 0, 1, 2, are shown in Figs. 3 (a)-(c), respectively. Other important parameters for the unit-cell spiral EBG are the gap s and width w of the spiral line [16]. According to Table 1, changing square patch to spiral patch results in that the frequency band gap decreases. Also, an increase of s causes the frequency band gap to decrease. Therefore, s = 0.8 mm is selected to obtain the band gap 2.3-2.5 GHz as shown in Fig. 3 (c). As a result, surface waves will be suppressed in this structure at frequency of 2.4 GHz. Note that in this parametric studies, other dimensions are the same as given in (1).

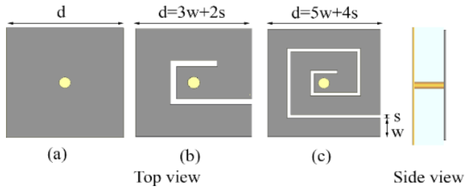


Fig. 3. A unit-cell EBG with: (a) rectangular layout (N = 0), (b) spiral layout (N = 1), and (c) spiral layout (N = 2) [16].

Table 1: Band gap of the three different unit-cell EBG

Unit Cell		Band Gap	
		f1 (GHz)	f2 (GHz)
a	-	5.70	7.80
b	S=0.2 mm	4.90	5.90
c	S=0.2 mm	2.55	2.85
	S=0.6 mm	2.40	2.68
	S=0.8 mm	2.28	2.55

III. THE PLANAR SURFACE WAVE ANTENNA

A PSWA based on the proposed periodic structure is designed to radiate at 2.4 GHz as shown in Fig. 4. The input reflection coefficient of the antenna is about 30 dB at 2.4 GHz as shown in Fig. 5. The PSWA consists of two parts; a circular patch fed by a 50 Ω coax cable to excite surface waves, and a thin dielectric slab loaded with 20×20 periodic spiral patches and EBG structure. There are 16 rows of periodic patches in the middle of the ground plane to support the propagation of the surface waves along $\pm x$ directions and in each lateral side there are 2 rows of periodic patches with via to suppress the surface waves propagating along $\pm y$ directions. Consequently, the surface waves will be propagated only along $\pm x$ direction, it is observed clearly in Fig. 6, which shows the surface current of the antenna in two cases; before and after adding vias. The surface waves excited by the circular patch are radiated from the edge of the ground plane, and diffraction rays from the opposite edges will cancel each other in the broad-side direction. Thus, a bidirectional radiation is generated, as observed in Fig. 7. The maximum realized gain of the antenna is about 8.7 dB in xz plane and about 0.7 dB in yz plane. This pattern has a deep null in the broad-side direction and the antenna beams are at $\theta = 36°$ ($-40°$) with a realized gain of 8.7 dB (8.5 dB).

The antenna is simulated with the 14 cm×14 cm square ground plane. The circular patch of the antenna has a radius of 49.6 mm and its height from PEC ground is 0.787 mm. The periodic patches dimensions and dielectric substrate properties are the same as given in (1).

In order to see the effect of vias or EBG structure on the radiation pattern, the pattern of the PSWA are plotted in two cases; with and without vias as shown in Fig. 8. As can be observed, the gain increases 4 dB in xz plane and decreases about 4.3 dB in yz plane, by adding vias to the antenna.

In order to compare the properties of the proposed PSWA with those of a WIFA antenna, the WIFA antenna as shown in Fig. 9 is designed and simulated at 2.4 GHz. The antenna PEC ground plane is a 110×110 mm^2 square and other dimensions of the WIFA are as follows:

$$H = 13 \text{ mm},\ S = 4.1 \text{ mm},\ L = 18.5 \text{ mm}.$$

The gain and input reflection coefficient of both antennas are presented in Fig. 10 and Fig. 12, respectively. It is observed from Fig. 10 that, the maximum gain of the proposed antenna is increased at about 4 dB than that of the WIFA antenna.

In order to compare the properties of the proposed PSWA with those of a new WIFA antenna, the loaded WIFA antenna as shown in Fig. 11 is compared at 2.4 GHz. The antenna PEC ground plane is a 60×60 mm^2 and other dimensions of the WIFA are as follows (unit of these parameters are mm) [17]:

$$l = 28,\ t = 6,\ t_1 = 6,\ h_1 = 15,\ h_2 = 2,\ w = 2,\ s = 0.4.$$

The properties of the above antennas are presented in Table 2. From this table, although the gain of the loaded WIFA antenna is more than the WIFA antenna (from 4.7 dB to 8.9 dB), its thickness is increased. While with the proposed planar surface wave antenna (PSWA), we can increase gain and decrease antenna thickness.

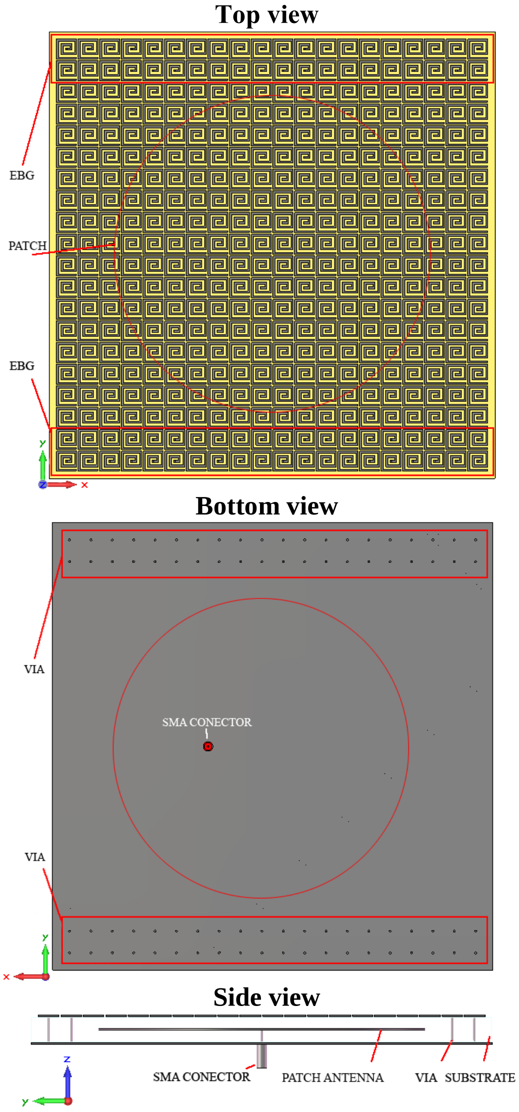


Fig. 4. The geometry of the PSWA.

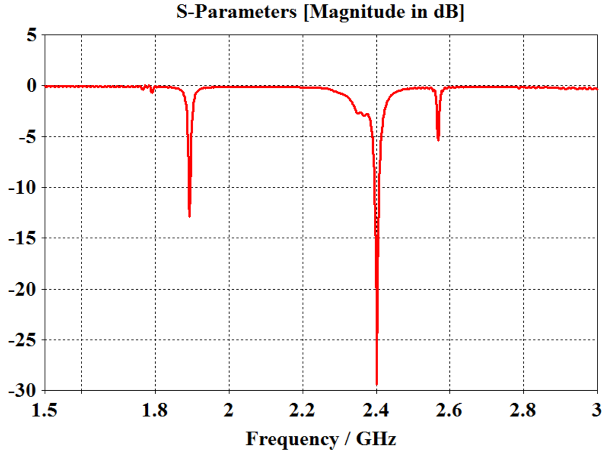
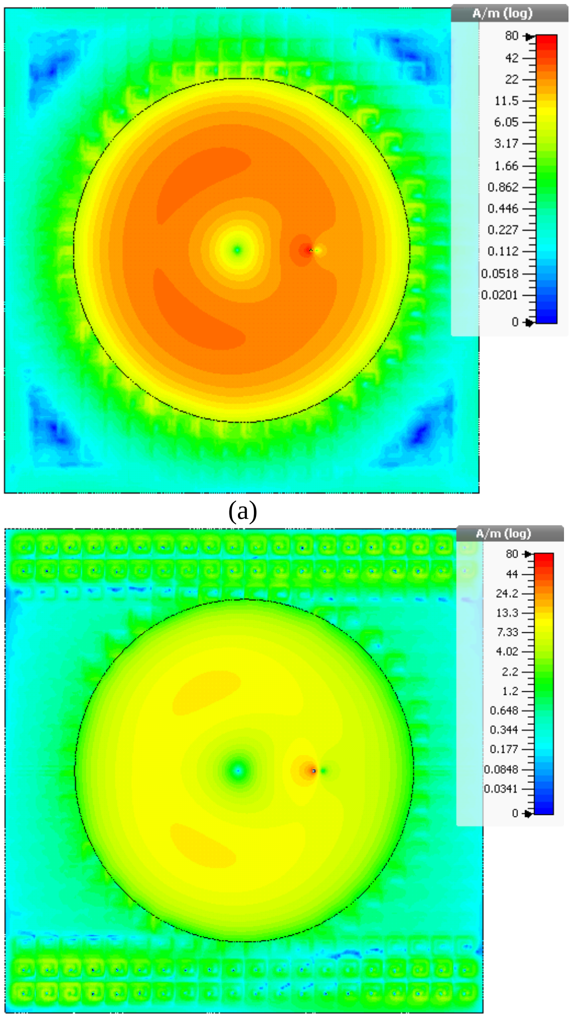


Fig. 5. Reflection coefficient of the proposed PSWA.



(a)

(b)

Fig. 6. The surface currents of the PSWA: (a) with vias and (b) without vias.

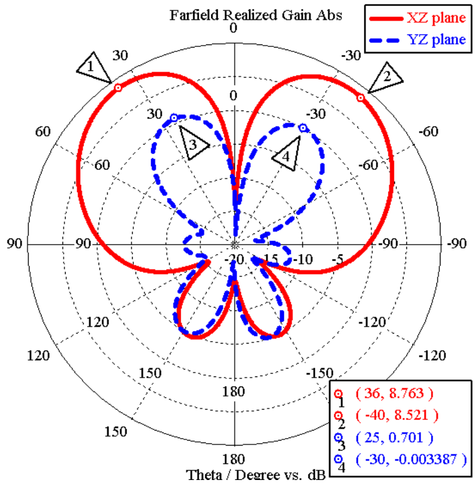
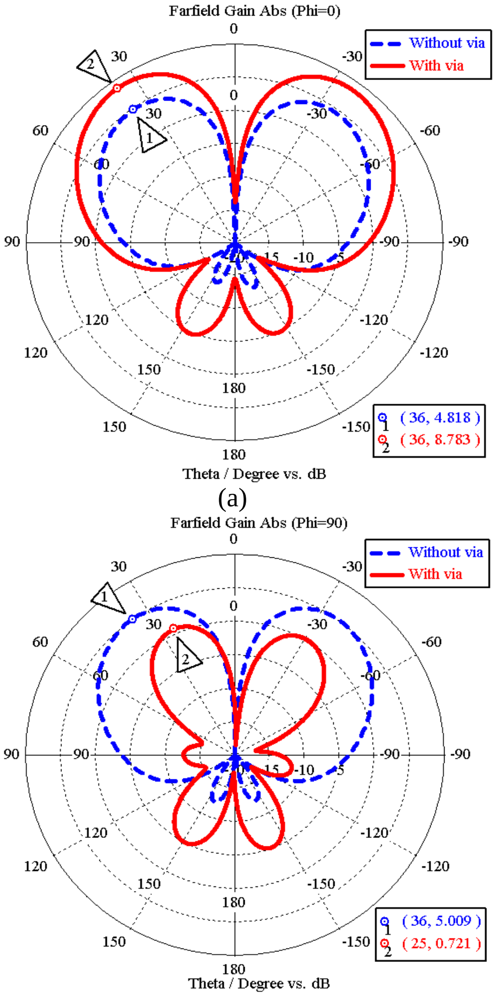


Fig. 7. The 2D radiation patterns of the PSWA.



(a)

(b)

Fig. 8. Radiation patterns of the PSWA: (a) xz plane and (b) yz plane.

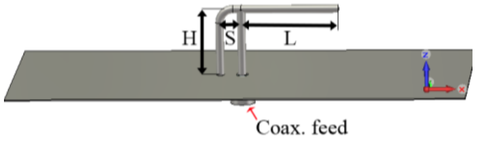


Fig. 9. The geometry of the WIFA.

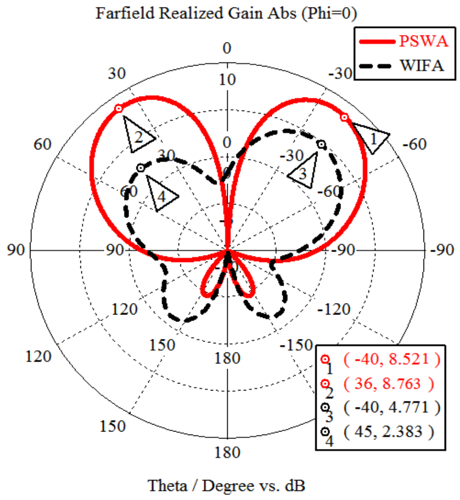


Fig. 10. The 2D radiation patterns of the PSWA and the WIFA (xz plane).

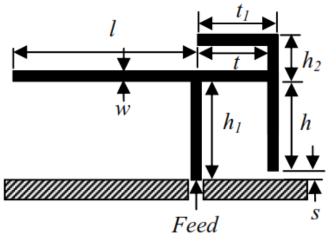


Fig. 11. The geometry of the loaded WIFA [17].

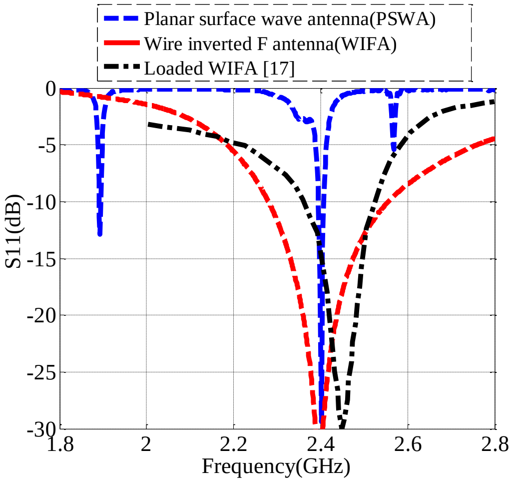


Fig. 12. Reflection coefficient of the PSWA, the WIFA and the loaded WIFA.

Table 2: The properties of the proposed PSWA, the WIFA and the loaded WIFA

Properties	Proposed Antenna	WIFA Antenna	Loaded WIFA [17]
Max. gain (dB)	8.7 (back & front)	4.7 (front) 2.3 (back)	8.9
Return loss	Narrower	Wide	Narrow
Dimensions (mm^2)	140×140	110×110	60×60
Thickness	1.6 mm	13 mm	17 mm
Aerodynamic drag	Very low	High	Higher
Pattern-type	Bidirectional	~Omni.	Omni.

Figure 13 illustrates the realized gain of the both antennas over frequency range of 2300 MHz to 2500 MHz. From this figure, it is obvious that the proposed antenna has very sensitive dimensions versus the operational frequency. If we shift from 2.4 GHz, the gain is decreased dramatically. Therefore, this fact is a disadvantage of the proposed antenna where there is not this range of sensitivity in the WIFAs. However, when the operational frequency is 2.4 GHz or very near it, the proposed low profile PSWA can be a good idea to realize a bidirectional radiation pattern. Because the gain is increased from 4.7 dB to 8.7 dB and the antenna thickness is reduced from 13 mm to 1.6 mm against the WIFA antenna. In fact, the PSWA is superior to the disadvantages of the WIFA such as high aerodynamic drag and a high degree of electromagnetic coupling to the fuselage. Therefore, the proposed antenna exhibits a great potential when a high gain bidirectional radiation pattern and a low-profile antenna are desired.

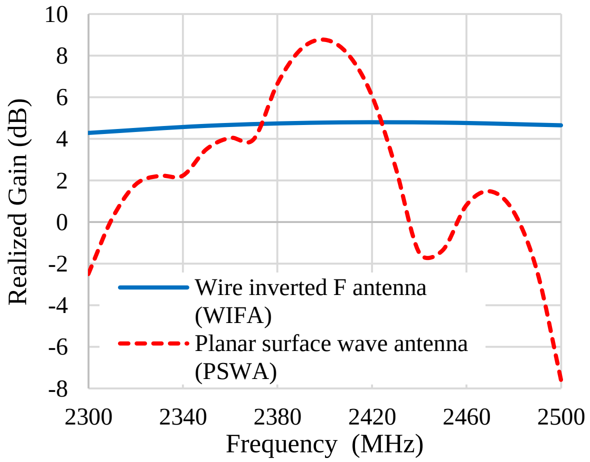
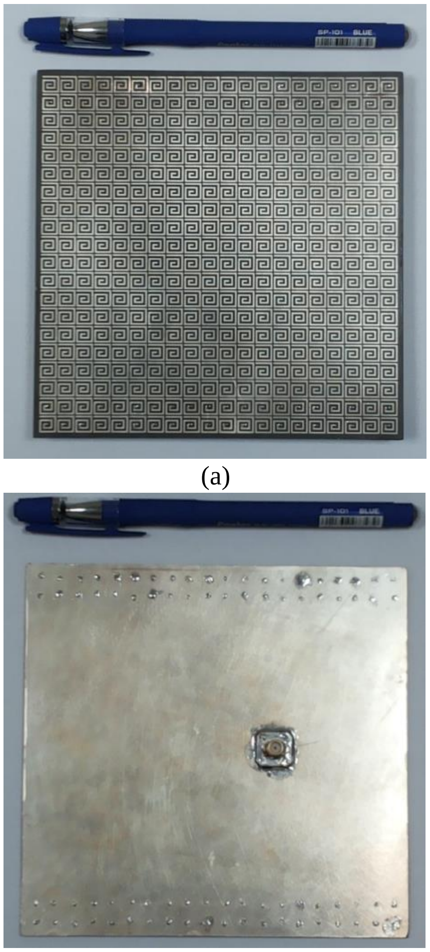


Fig. 13. The realized gain of the PSWA and the WIFA.

IV. EXPERIMENTAL RESULTS

To verify the concept of the PSWA, an antenna prototype with the same dimensions as given in Section III is fabricated and measured.

Figure 14 (a) shows the photo of the 20×20 periodic spiral patches fabricated on the RT/duroid 5880 high-frequency laminate ($\varepsilon_r = 2.2$). Figure 14 (b) shows a back view of the fabricated PSWA and a 50 Ω SMA connector that is soldered to the patch embedded in middle of dielectric slab. The connector is shifted 20 mm along +*x* direction.


(a)

(b)

Fig. 14. Photos of a fabricated PSWA: (a) top view and (b) back view.

Figure 15 presents the measured return loss of the PSWA with a comparison with the CST simulation results. According to the measured results, the antenna resonates at 2.38 GHz with a return loss of about -18 dB, which agrees with the simulation results. The radiation patterns of the PSWA are measured at the resonant frequency of 2.38 GHz. The measured radiation patterns agree well with the CST simulations in Fig. 16, and a WIFA-like pattern has been obtained. The pattern has a deep null in the broad-side direction and the antenna beam is at about θ = ± 38°direction with a gain of 8 dB. The cross-polarisation is about -20 dB lower than the co-polarization in the beam direction. As shown in Fig. 16, because of existence of vias, the gain of yz plane decreases than the xz plane. As shown in Fig. 16 (b), this reduction is about 7.2 dB in measured result and about 4 dB in simulated result. It shows that in practice, the vias reduce the surface wave less than measured result. But the reduction is enough to make a WIFA-like pattern.

Figure 17 shows the comparison between simulated and measured gain of the PSWA. The difference of maximum gain is 0.75 dB in the both cases. The presented experimental results verify the simulation results and demonstrate the radiation performance of the PSWA.

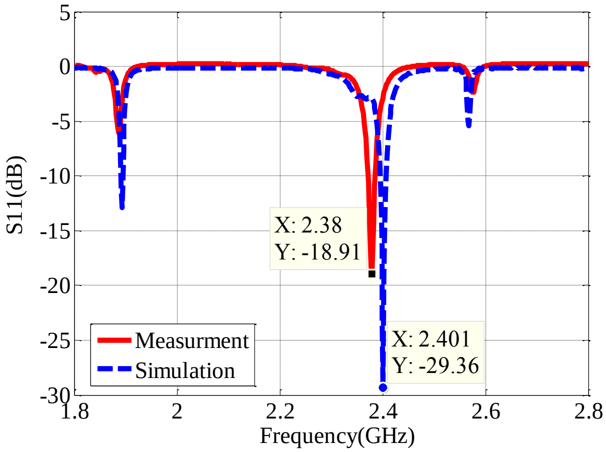
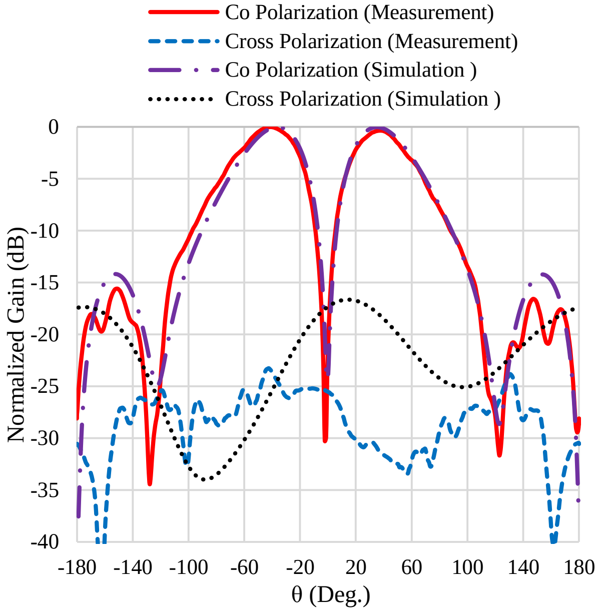


Fig. 15. Comparison between the simulated and measured return loss of the PSWA.



(a)

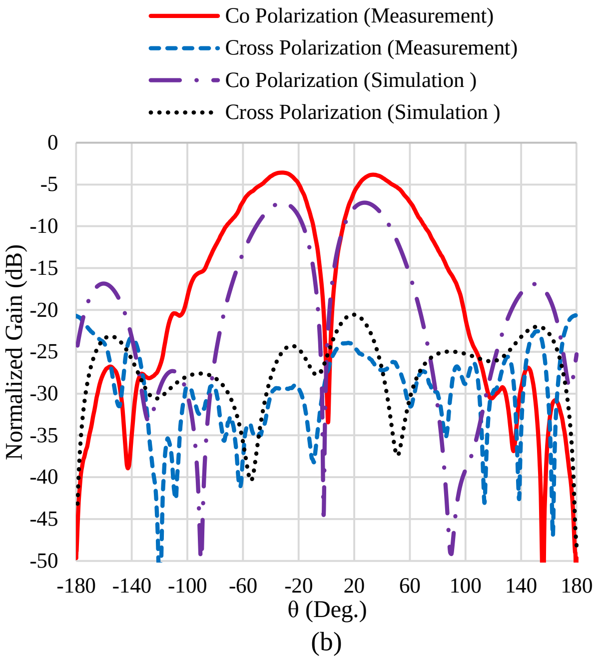


Fig. 16. Comparison between the simulated and measured normalized gain of the PSWA: (a) xz plane and (b) yz plane.

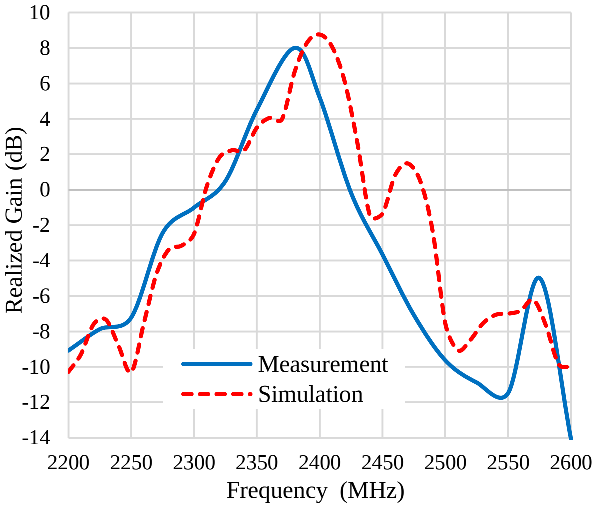


Fig. 17. Comparison between simulated and measured realized gain of the PSWA.

V. CONCLUSION

This paper has presented a planar surface wave antenna (PSWA) that radiates a bidirectional radiation pattern with a low-profile configuration. The low-profile property has been realized using a novel artificial ground plane. The radiation performance of the PSWA was described and parametric studies were performed. An antenna prototype was fabricated and tested, which resonated at 2.38 GHz with a gain of 8 dB and WIFA-type radiation pattern. In contrast to the WIFA, the PSWA has low-profile configuration without a high aerodynamic drag. The proposed planar surface wave antenna exhibits a great potential for telemetry applications when a bidirectional radiation pattern and a low-profile antenna are desired.

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REFERENCES

[1] H. Nakano, Y. Asano, and J. Yamauchi, “A wire inverted F antenna on a finite-sized EBG material,” *IEEE International Workshop on*, pp. 13-16, Mar. 2005.

[2] B. R. Motlhabane and D. Gray, “TE-monopole radiation pattern DRA for UAVs,” *Antennas and Propagation (ISAP), International Symposium on*, pp. 499-502, Oct. 29, 2012-Nov. 2, 2012.

[3] F. Yang, A. Aminian, and Y. Rahmat-Samii, “A novel surface-wave antenna design using a thin periodically loaded ground plane,” *Microw. Opt. Technol. Lett.*, vol. 47, pp. 240-245, Nov. 2005.

[4] F. Yang, Y. Rahmat-Samii, and A. Kishk, “Low-profile patch-fed surface wave antenna with a monopole-like radiation pattern,” *Microwaves, Antennas & Propagation, IET*, vol. 1, pp. 261-266, Feb. 2007.

[5] A. Al-Zoubi, F. Yang, and A. Kishk, “A low-profile dual-band surface wave antenna with a monopole-like pattern,” *Antennas and Propagation, IEEE Transactions on*, vol. 55, no. 12, pp. 3404-3412, Dec. 2007.

[6] F. Yang, A. Aminian, and Y. Rahmat-Samii, “A low profile surface wave antenna equivalent to a vertical monopole antenna,” *IEEE Antennas Propag. Soc. Symp. 2004.*, vol. 2, 2004.

[7] F. Yang, Y. Rahmat-Samii, and A. Kishk, “A novel surface wave antenna with a monopole type pattern: A thin periodically loaded slab excited by a circular disk,” in *IEEE Antennas and Propagation Society, AP-S International Symposium (Digest)*, vol. 1 A, pp. 742-745, 2005.

[8] F. Y. F. Yang, A. Al-Zoubi, and A. Kishk, “A dual band surface wave antenna with a monopole like pattern,” *2006 IEEE Antennas Propag. Soc. Int. Symp.*, 2006.

[9] D. Sievenpiper, L. Zhang, R. F. J. Broas, N. G. Alexopolous, and E. Yablonovitch, “High-impedance electromagnetic surfaces with a forbidden frequency band,” *IEEE Transactions on Microwave Theory & Techniques*, vol. 47, no. 11, pp. 2059-74, Nov. 1999.

[10] F. Yang and Y. Rahmat-Samii, *Electromagnetic*

Band Gap Structures in Antenna Engineering. Cambridge University Press, Cambridge, UK, 2009.

[11] C. R. Simovski, P. de Maagt, and I. V. Melchakova, "High-impedance surfaces having stable resonance with respect to polarization and incidence angle," *IEEE Trans. Antennas Propag.*, vol. 53, pp. 908-914, 2005.

[12] H. Mosallaei and Y. Rahmat-Samii, "Periodic bandgap and effective dielectric materials in electromagnetics: Characterization and applications in nanocavities and waveguides," *IEEE Trans. Antennas Propag.*, vol. 51, pp. 549-563, 2003.

[13] R. Abhari and G. V. Eleftheriades, "Metallo-dielectric electromagnetic bandgap structures for suppression and isolation of parallel-plate noise in high-speed circuits," *IEEE Trans. Microw. Theory Tech.*, vol. 51, no. 6, pp. 1629-1639, June 2003.

[14] T. Kamgaing and O. M. Ramahi, "A novel power plane with integrated simultaneous switching noise mitigation capability using high impedance surface," *IEEE Microw. Wireless Compon. Lett.*, vol. 13, no. 1, pp. 21-23, Jan. 2003.

[15] S. Shahparnia and O. M. Ramahi, "Simple and accurate circuit models for high-impedance surfaces embedded in printed circuit boards," in *Proc. IEEE Antennas Propagat. Symp.*, vol. 4, pp. 3565-3568, June 2004.

[16] C.-L. Wang, G.-H. Shiue, W.-D. Guo, and R.-B. Wu, "A systematic design to suppress wideband ground bounce noise in high-speed circuits by electromagnetic-bandgap-enhanced split powers," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 12, pp. 4209-4217, Dec. 2006.

[17] D. K. Karmokar and K. M. Morshed, "Analysis of inverted-F and loaded inverted-F antennas for 2.4 GHz ISM band applications," *Journal of Electrical Engineering*, *IEB*, vol. EE 36, no. 2, pp. 4-9, 2009.