Analyzing Microstrip Antenna Miniaturization Methods for Wearable IoT Sensors

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***Abstract*—This paper analyzes the advantages and disadvantages of several methods for miniaturizing microstrip patch antennas. There are some ways to reduce the size of a microstrip antenna, including using a high relative permittivity (ε_r), attaching shorting pins, modifying the patch, adding slots, and using metamaterial. To fairly compare these methods, the simulation results of each method in terms of S-parameters, realized gain, and efficiency at a single frequency band of 2.45 GHz are detailed. Based on the analyzed simulation results, some miniaturization methods for wearable IoT sensors are recommended, and a miniaturized antenna with a small size but remains 15% higher efficiency and 2 dBi higher gain is proposed compared to the original square microstrip patch antenna.**

Keywords—miniaturized antenna, IoT sensor, wearable antenna, microstrip antenna, metamaterial.

I. Introduction

Microstrip patch antennas (MPAs) are the most commonly used in wireless applications because of their advantages including the planar surface, easy integration with circuit elements, small size, the possibility of multiband operation, and linear or circular polarization [1-2].

Thanks to easy integration with circuit elements, MPAs are chosen for IoT sensors. However, their size is still large compared to the total size of IoT sensors which are getting smaller and smaller.

Many studies on MPA miniaturization methods in general and for IoT sensors in particular have been presented in [3-8]. However, few studies comprehensively analyze and compare miniaturization methods over a single frequency range. Therefore, this study will analyze and compare MPA antenna miniaturization methods based on specific criteria such as size, bandwidth, performance, and realized gain at the only frequency band of 2.45 GHz. From there, propose a suitable solution for IoT sensors to ensure the antenna has circular polarization and is less affected by the human body.

II. Methods to Miniaturize Microstrip Antennas

In this section, methods for miniaturing microstrip antennas are analyzed. A square microstrip patch antenna (SMPA) is designed by using a 1.53 mm thick FR-4 substrate, which is a low-cost and common material for designing antennas and sensor circuits [1]. The structure of the square SMPA is shown in Fig. 1. No matching techniques are used in this design to make it as easy as possible to compare with its versions using miniaturization methods.

The square patch antenna has a realized peak gain of 2.22 dBi at 2.45 GHz, a radiation efficiency of 45%, a bandwidth of 4.1%, and a size of 52×52×1.6 mm^3. These results will be used in the next section for analysis and comparison with other antennas.

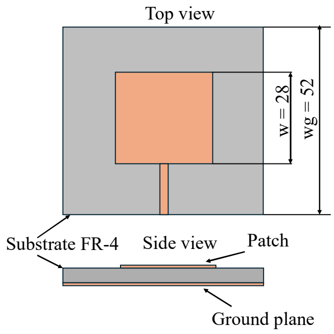

Fig. 1. A square microstrip antenna at 2.45 GHz using FR-4 substrate.

Firstly, using materials with high relative permittivity is discussed. Then, shorting pins are deployed in some positions to find the optimal position for the best performance of the antenna. Adding slots on the patch is analyzed to make the antenna polarize circularly. Finally, a simple metamaterial is used to demonstrate its advantages in improving gain and reducing the size of the antenna.

A. Using a high relative permittivity

The simplest way to decrease the size of an MPA is to use a substrate with a high relative permittivity (ε_r). The length and width of the patch are inversely proportional to the square root of ε_r as given in Eq. (1) [1].

$$L = \frac{c}{2f_0\sqrt{\varepsilon_r}} \tag{1}$$

Where c is the light velocity, f_0 is the center resonant frequency, and ε_r is the relative permittivity of the substrate. However, such a miniaturization method results in an increased level of surface wave excitation within the substrate and results in lower bandwidth as well as a decrease in radiation efficiency. In this session, we compare the performance of the SMPA in two cases using substrates FR-4 and Rogers RO3006 to improve these.

Fig. 2 shows S11 of SMPAs using Roger R03006 in two cases with (w/s) and without matching slots (wo/s). In the case of wo/s, S11 is higher than -10 dB. Thus, to increase the bandwidth, matching slots are deployed. Then, the bandwidth is 2.1%. Although the bandwidth decreases compared to the FR-4 SMPA, both the efficiency and the gain of the Roger R03006 SMPA antenna are higher as given in Tab. 1.

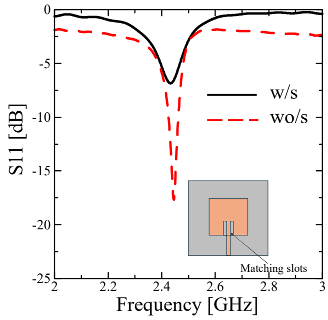

Fig. 2. Simulation resluts in S11.

B. *Attaching shorting pins*

Utilizing shorting pins is one of the methods to miniaturize the size of the antenna. The decrease in the size of the antenna aperture leads to a reduction in antenna directivity, which in turn impacts the antenna gain. Fig. 3 shows cases of adding a shorting pin on Line 1 and Line 2 or an array of *n* shorting pins. The radius *r* of the shorting pin is 0.5 mm.

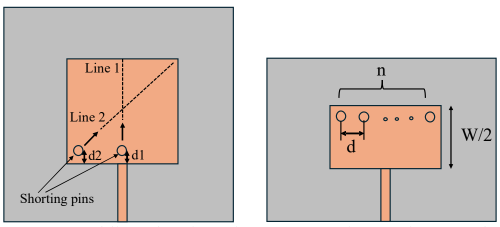

Fig. 3. Cases adding shorting pins: (a) one pin on Line 1 and Line 2 (b) an array of *n* shorting pins.

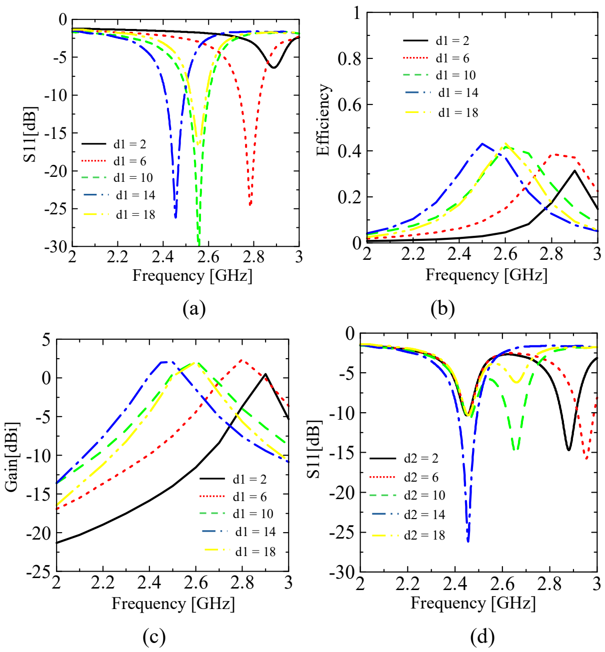

Fig. 4. Simulation results in S11, efficiency, and gain of the antenna adding a shorting pin on Line 1 and Line 2.

When d_1 increases, the resonant frequency increases. The positions symmetrical about the center of the patch have the same resonant frequency. The efficiency and loss decrease compared to the SMPA. The peak gain ranges from 2 dBi to 2.38 dBi, and the efficiency is 31% to 43% as shown in Figs. 4(a)(b)(c). When d_2 increases, the directional frequency of the antenna remains unchanged, however, S11 increases at 2.45 GHz, and a second higher directional frequency appears as shown in Fig. 4(d). Both Gain and hs decrease. The gain ranges from 1.3 dBi to 2 dBi while the efficiency reaches 39% to 43%. It can be seen that adding only one shorting pin cannot make SMPA smaller. Thus, an array of shorting pins is discussed.

According to [1], a quarter-wave patch antenna can be made by using an array of shorting pins. Fig. 5 shows simulation results when an array of *n* shorting pins is applied in cases *n* = 5, 7, and 9. In this analysis, *W* = 28, *d* = 2.5, *r* = 0.5 mm. The results revealed that when *n* increases, the resonant frequency moves to a higher band, and the efficiency and gain are higher. However, the gain is much lower than that of SMPA as shown in Fig.5.

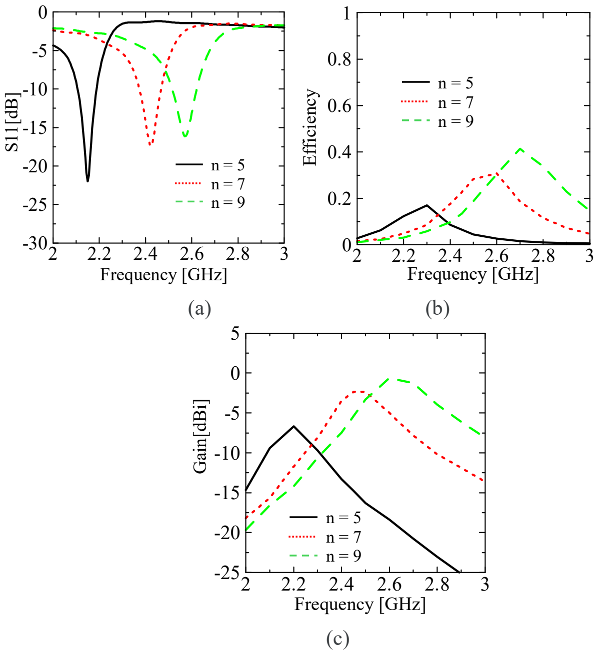

Fig.5. Simulation results in S11, efficiency, and gain of the antenna with an array of *n* shorting pins.

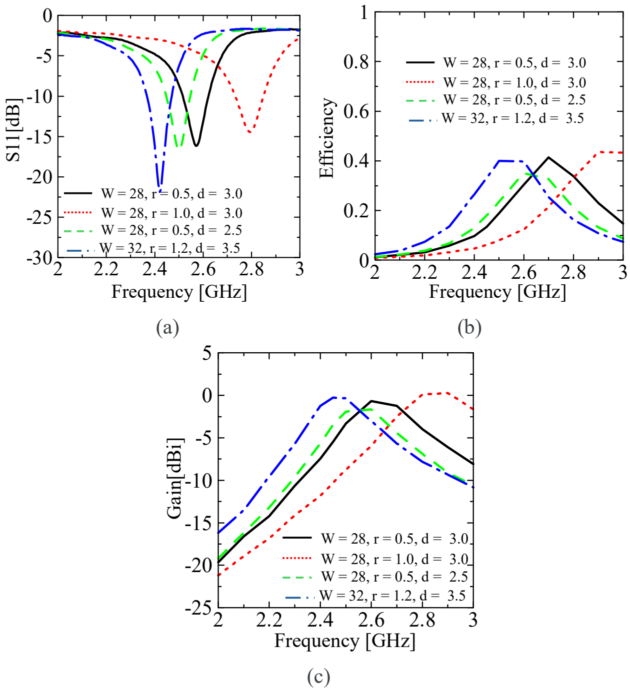

Fig. 6. Simulation results in S11, efficiency, and gain when *d* and *r* changes.

Next, the performance of the antenna with nine shorting pins is considered when d and r change. Simulation results are given in Fig. 6. When r increases, the resonant frequency moves to the higher band, and the efficiency is higher. If d is reduced, the resonant frequency shifts to the lower band and the efficiency is reduced. Based on these results, the parameters of W = 32, r = 1.2, and d = 3.5 are proposed for the antenna with the array of nine shorting pins. The gain, efficiency, and bandwidth are given in Tab. 1.

C. *Adding slots*

In the paper [7], the authors analyzed some configurations of slots to miniaturize the coaxially-fed patch antenna. However, just S11 and directivity were considered. In this study, two configurations are estimated as shown in Fig. 7. In the first case, two notches are added to both sides of the patch, and in the second case is to add one slot on the diagonal of the patch. The second case is considered to achieve both miniaturization and circular polarization that is good for on-body antennas or wearable IoT sensors. Simulation results of these cases are illustrated in Fig. 8.

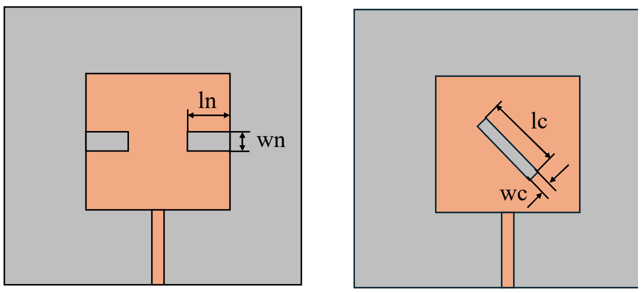

Fig. 7. Configurations of slots on the patch: (a) two notches (W = 23.7, w_n = 5.85, l_n = 2) (b) one slot on the diagonal (W = 28, lc = 10, wc = 1) (unit: mm).

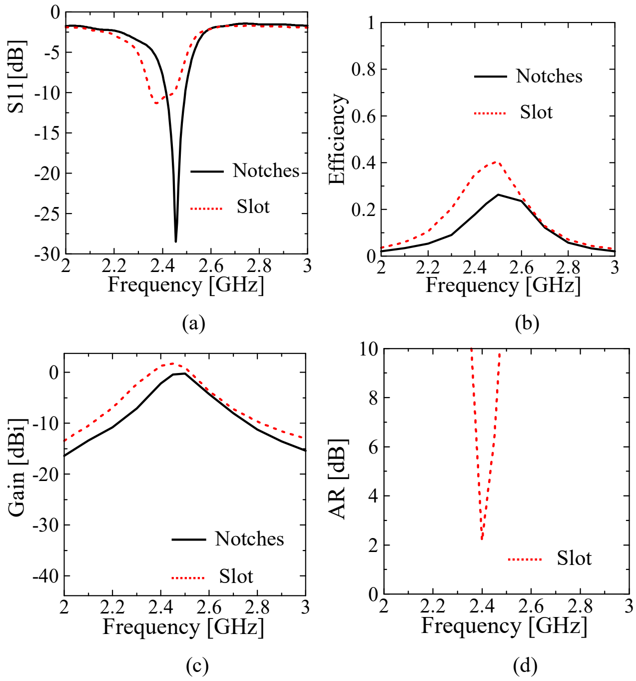

Fig. 8. Simulation results of the antenna with slots.

In the case of two notches, the results show that the size of the SMPA can be significantly reduced but its performance in gain, efficiency, and bandwidth is negatively affected. In the case of the slot, the circular polarization is achieved but there is no reduction in size.

D. *Applying metasurface*

In this section, the performance of the antenna with a simple metasurface is considered. The structure of the antenna is shown in Fig. 9. The unit cell of $m \times m$ metasurface is a square patch on FR-4 with the size $d_u \times d_u$, the distance between unit cells is g. Fig. 10 shows simulation results in cases m = 4, 5, and 6, h = 2 mm, g = 1. It can be seen that when m increases the resonant frequency shifts to a higher band, and the efficiency and the gain are reduced. The simple 4×4 metasurface can reduce the size of the antenna from W = 28 mm to W = 27.3 mm, and increase the gain.

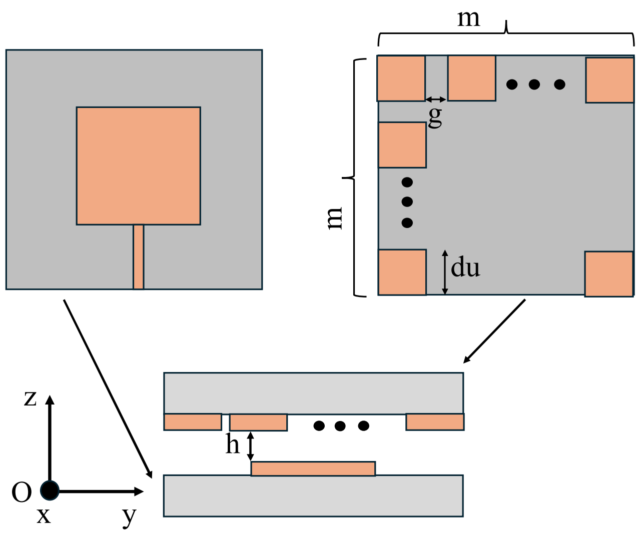

Fig. 9. Structure of the antenna with a simple metasurface.

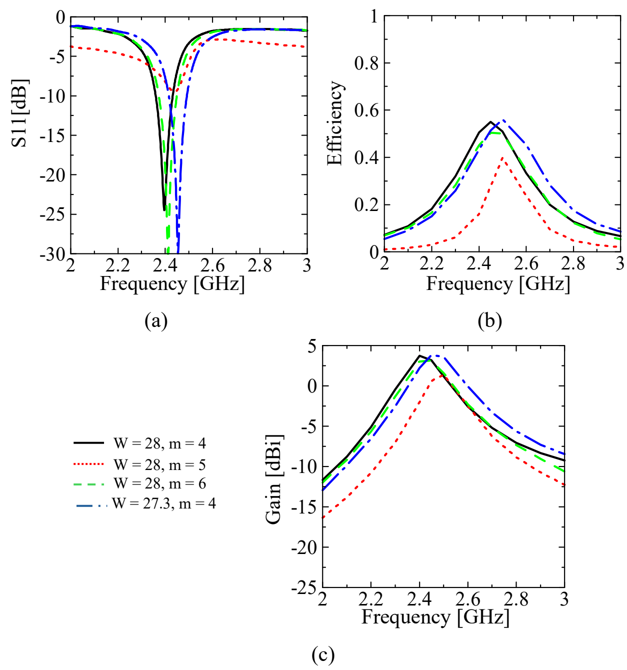

Fig. 10. Simulation results in S11, efficiency, and gain when m = 4, 5,6.

TABLE I. A COMPARISON BETWEEN MICROSTRIP ANTENNA MINIATURIZATION METHODS

Methods	Total Size [mm^3] and W×W [mm^2]	Realized Gain and Backlobe [dBi]	Bandwidth [%]	Efficiency [%]
SMPA	52×52×1.6 28x28	2.22; -9.83	3.33	45
Sec. A	35.5x35.5x1.6; 23.5x23.5	3.7; -1.26	1.52	78
B	40x40x1.6; 32.5x16.25	-0.266; -6.1	4.3	40
C (two notches)	47.7x47.7x1.6; 23.7x23.7	-0.4; -10.6	3.39	25
D	51.3x51.3x	3.8	3.1	60

III. DISCUSSION AND THE PROPOSED ANTENNA

Tab. 1 summarizes simulation results presented in previous sections and shows that almost all methods to miniaturize an SMPA reduce its gain, efficiency, and bandwidth. Using metasurfaces is the only method that improves the gain, bandwidth, and efficiency of the antenna. However, the height of the antenna increases because a distance between the antenna and the metasurface is necessary.

TABLE II. THE PROPOSED ANTENNAS COMBINE TWO MINIATURIZED METHODS

Methods	Size [mm^3]	Bandwidth [%]	Realized Gain [dBi]	Efficiency [%]
4x4 metasurface + a slot on the diagonal	50×50×5.17	3.8	3.7	55
4×4 metasurface + an array of nine shorting pins	40.3×40.3×4.3	4.4	0.17	42.5

Based on the simulation results, a miniaturized SMPA can be done by combining some methods above-mentioned. Especially, the other methods can combined with a metasurface to improve the performance of the antenna. To demonstrate this idea. We have done simulations to miniaturize the antenna by combining the metasurface with adding slots and shorting pins. The simulation results are summarized in Tab. 2. The combination of the methods makes the antenna smaller and gets a higher performance. In the future, an optimized metasurface will be researched to miniaturize the SMPAs.

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