

BROADBAND COPLANAR WAVEGUIDE-FED WIDE-SLOT ANTENNA

A. Dastranj and M. Biguesh

School of Electrical and Computer Engineering
Shiraz University
Shiraz, Iran

Abstract—A large bandwidth wide-slot antenna, fed by coplanar waveguide (CPW), is proposed. Experimental investigations and detailed simulations are conducted to understand its behavior and to optimize for broadband operation. The impedance bandwidth, determined by 10-dB return loss of the proposed slot antenna using both measurement and simulation, is about 131% (2.8 to 14 GHz). In addition to be small in size, the antenna has low cross polarization, relatively high gain, and it exhibits stable far-field radiation characteristics in the entire operating bandwidth. The design with very wide operating bandwidth and improved radiation pattern is obtained by properly choosing the suitable slot shape, selecting similar feed patch shape, and tuning their dimensions. Numerical sensitivity analysis has been used to understand the effects of changes of various antenna dimensions and to optimize the performance of the designed antenna. Based on our computer simulations it is shown that the antenna dimensions parameters have uncorrelated effects on the upper edge of the bandwidth. Simulation results show that the impedance matching of this kind of antenna is sensitive to the feed-slot combination and feed gap width. The simulated and measured results for return loss, far-field E -plane and H -plane radiation patterns, and gain of the designed antenna are presented and discussed.

1. INTRODUCTION

Slot antennas are receiving huge attention in microwave and millimeter wave applications. These antennas have several useful properties such as low profile, light weight, easy integration with monolithic

microwave integrated circuits, low cost, easy fabrication, and stable radiation patterns [1–15]. Slot antennas have several attractive advantages over common microstrip antennas. They provide wide frequency bandwidth, good impedance matching, and a bidirectional or unidirectional radiation patterns. The coplanar waveguide (CPW) feeding mechanism also has many advantages over microstrip type feed lines, such as low dispersion, low radiation leakage, the ability to effectively control the characteristic impedance, and the ease of integration with active devices [16–18]. The antenna fed by a microstrip line may result in misalignment because of the required etching on both sides of the dielectric substrate. The alignment error can be eliminated if a CPW feed is used to excite the slot, since etching of the slot and feeding line is one sided.

Various shapes of CPW-fed slot antennas are proposed for bandwidth enhancement such as triangle-shaped [19], square slot antenna [20], circular slot [21], bow-tie slot [22], and hybrid slot [23]. In [24], a CPW-fed loop slot antenna with a tuning stub to enhance the bandwidth is presented, where by properly adjusting the location of a widened tuning stub, wide bandwidth was obtained. These bandwidth enhancement techniques using the CPW-fed slot antennas have increased impedance bandwidth from 34% to 60%. In [25], a CPW-fed rectangular slot antenna with the ground plane size of 100 mm × 100 mm is proposed. By using a U-shaped tuning stub, the impedance bandwidth of 110% is achieved for this antenna. Recently, a wideband single inductor-loaded CPW-fed slot antenna with 34.5% impedance bandwidth is presented in [26].

With development of communication systems and integrated circuit technologies, both size reduction and bandwidth enhancement are of major design concern, e.g., the internal antenna of handsets and RF front-ends [27]. Some researches have been done to enhance the operation bandwidth and reduce the antenna size with a thin substrate [28].

In this paper, we present a new configuration for a CPW-fed printed wide-slot antenna for broadband communication systems. Our designed antenna has a relatively small size and frequency coverage from 2.8 to 14 GHz for $S_{11} < -10$ dB. The antenna is designed for center frequency 8.5 GHz. Compared to the antenna designed in [25], our proposed CPW-fed slot antenna has a wider operation bandwidth, higher gain, lower cross polarization, and smaller size. A comprehensive sensitivity analysis has been carried out to understand the effects of various dimensional parameters and to optimize the performance of the final design. By choosing a suitable combination of feed patch and slot shape, and also tuning their sizes, an optimum

operating bandwidth is obtained. More importantly, we have obtained stable radiation patterns and low cross polarization across the whole band. The proposed CPW-fed slot antenna is simulated with commercially available packages such as Ansoft HFSS which is based on the finite element method and CST microwave studio which is based on the finite integral technique. The simulated and measured results of the return loss, gain, and far-field E - and H -plane radiation patterns of the designed antenna over the frequency band are presented. The simulation results have shown good agreement with the experimental data.

2. ANTENNA DESIGN

Wide-slot antennas have slot shapes such as rectangular, square, circular, etc. They also have various feed shapes such as T, cross, fork-like, bow-tie, radial stub, pi, double-T, circle, square, and rectangle [4–13]. The CPW-fed slot antenna used in this study employs an E-shaped feed patch to excite the E-shaped slot on the ground plane. We have used this combination because of its wide impedance bandwidth and good radiation characteristics.

In order to achieve wide operating bandwidth and good radiation patterns, we choose an E-shaped feed patch and similar slot shape. The width W_p and length L_p of the feed patch are about one third of the slot width W_s and slot length L_s . The feed patch size is close to, but less than $\lambda/4$ where λ is the wavelength of the lower frequency edge. Details of our proposed CPW-fed wide-slot antenna are shown in Figure 1. Dimensions of this antenna are, $W_s = 45$ mm, $L_s = 40$ mm, $W_1 = 14.2$ mm, $W_2 = 12.4$ mm, $W_g = 3$ mm, $W_t = 1$ mm, $W_m = 6.2$ mm, $G = 1$ mm, $S = 0.6$ mm, $L_p = 15.6$ mm, $W_p = 17.8$ mm, $h = 1$ mm, $h_p = 2.5$ mm, and $L = 9$ mm. The substrate size is selected as 85 mm \times 85 mm, and the relative dielectric constant and thickness of the substrate are chosen as $\epsilon_r = 4.4$ and $h_s = 1.6$ mm, respectively. These parameters are optimized for maximum efficiency. A substrate of low dielectric constant is used to obtain a compact structure that meets the demanding bandwidth specification. The characteristic impedance of the CPW line is 50Ω . As illustrated in the figure, a CPW, which has a signal strip of thickness G and a gap of distance S between the signal strip and the coplanar ground plane, is used to excite the E-shaped slot. The E-shaped feed patch strongly influences the performances of wide slot antenna. Thus, by choosing a suitable slot shape, selecting similar feed patch shape, and tuning their dimensions, the desired operating bandwidth without the need of quarter wave transformer is obtained in our design.

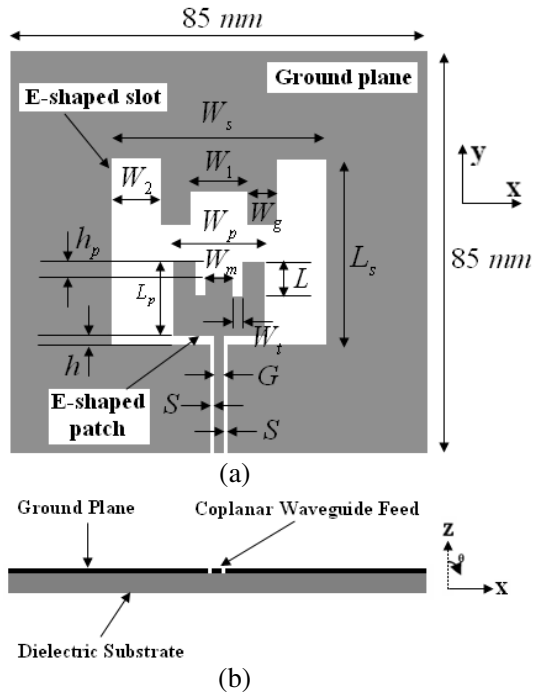


Figure 1. Configuration of the proposed CPW-fed slot antenna. (a) Top view. (b) Side view.

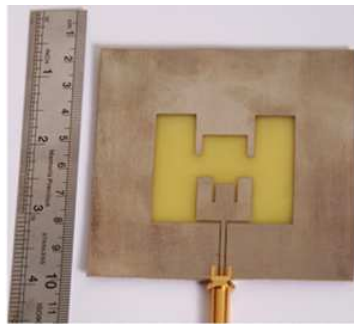


Figure 2. Photograph of the fabricated CPW-fed slot antenna.

3. RESULTS AND DISCUSSION

In this section, we present our computer simulations and experimental results for the proposed CPW-fed wide-slot antenna. To double check

the accuracy of our simulations, we have compared the outcomes of both software simulator packages HFSS and CST. Both simulators show very close outcomes confirming that the simulated results are obtained with reasonable accuracy. In order to justify the simulation results, the designed antenna was fabricated on substrate with thickness $h_s = 1.6$ mm and $\epsilon_r = 4.4$. A photograph of the fabricated antenna is shown in Fig. 2.

The simulated and measured return losses of the designed CPW-fed wide-slot antenna are presented in Figure 3. From simulation results, it is seen that the proposed antenna has a good bandwidth of 131%, ranging from 2.8 to 14 GHz for $S_{11} < -10$ dB. As seen, the measured return loss is in close match with the 131% impedance bandwidth obtained by simulation. The impedance bandwidth is limited by matching between the feed patch shape and the wide slot on the ground plane.

The simulated results with Ansoft HFSS and the measured co- and cross-polar far-field E -plane (y - z plane) and H -plane (x - z plane) radiation patterns of the proposed antenna at 3, 8 and 14 GHz are presented in Figure 4. In this figure, the E_θ -field is the co-polar component, and the E_ϕ -field is the cross-polar component. In this figure, the simulated patterns are performed using Ansoft HFSS. The experimental results show good agreement with the simulation ones. It can be observed that the proposed antenna has the same radiation patterns over the entire frequency band. Specifically, the obtained patterns are symmetrical and almost omnidirectional in both planes. These patterns show that the designed antenna provides linear polarization with a cross polarization level about 35 dBi lower than the co-polarization level at boresight in all of the measured radiation patterns. The cross-polarization levels at other directions are also

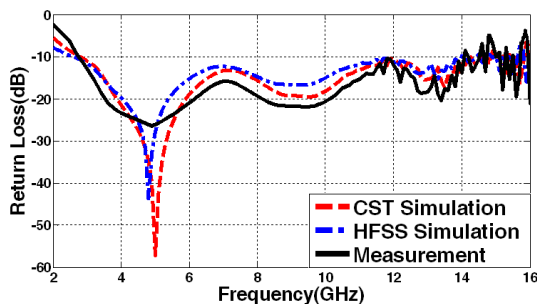


Figure 3. Simulated and measured return losses of the proposed antenna.

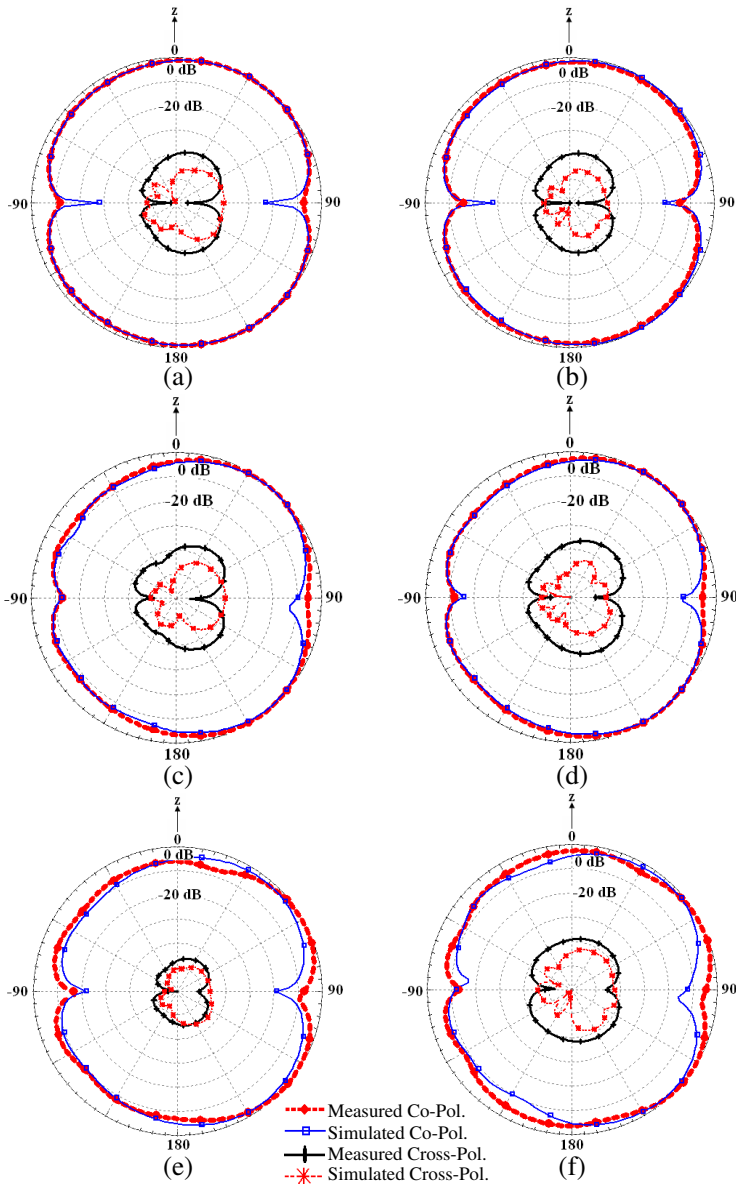


Figure 4. Simulated and measured radiation patterns of the proposed antenna. (a) *E*-plane at 3 GHz, (b) *H*-plane at 3 GHz, (c) *E*-plane at 8 GHz, (d) *H*-plane at 8 GHz, (e) *E*-plane at 14 GHz, (f) *H*-plane at 14 GHz.

considerably small. The maximum cross-polarization over the total sphere for all frequencies is less than -28 dBi, indicating excellent polarization purity. We have to mention that since the resonance frequency of higher order modes is out of the operating band of the designed antenna, these modes are considerably suppressed. As a result, the antenna radiation pattern has a low cross-polarized field across the entire operating frequency. The results show that the radiation patterns at higher frequency are slightly distorted, which is due to the seriously unequal phase distribution of the electrical fields on the slot. However, the radiation patterns of the designed antenna are acceptable for most broadband applications.

Using computer simulations, we have seen that the size of the ground plane determines the radiation pattern deterioration over the entire frequency band. When the size of the ground plane is increased to a certain value $85 \text{ mm} \times 85 \text{ mm}$, the optimum radiation pattern is obtained. However, further increasing of the ground plane deteriorates the antenna radiation pattern. In addition, the size of ground plane affects the operating bandwidth of the proposed antennas, and a larger ground plane ruins the operating bandwidth.

The simulated and measured gains of the proposed antenna versus frequency are presented in Figure 5. It can be seen that the gain of the proposed antenna remains relatively constant over the entire bandwidth. The antenna peak gain is approximately 6.9 dBi. Also, the gain variation within the bandwidth is less than about 2.5 dBi. Figure 5 shows that the simulated gain is in good agreement with the measured gain across the entire frequency band.

For our designed antenna, based on the measured return loss, radiation patterns, polarization purity, and antenna gain, the overall bandwidth is seen to be the same as its impedance bandwidth. Preserving the radiation patterns and excellent polarization purity are extremely important factors in designing broadband antennas. Many of the existing broadband, single-element, printed antennas achieve broadband operation from two different points of view: Impedance matching and radiation pattern, which cannot be achieved together. However, our proposed antenna presents excellent radiation parameters over the entire bandwidth. To conclude, these attractive characteristics are due to the combination of the E-shaped slot and similar feed patch shape. According to our results, the proposed wide-slot antenna is useful for broadband direction finder (DF) systems, as well as satellite and communication applications.

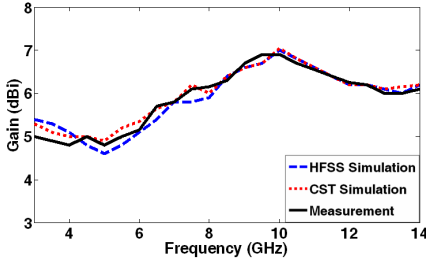


Figure 5. Simulated and measured gains of the proposed CPW-fed slot antenna.

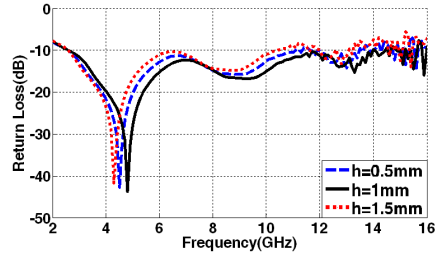


Figure 6. Simulated return losses of the CPW-fed slot antenna for various feed gaps.

4. SENSITIVITY ANALYSIS

A comprehensive numerical sensitivity analysis is investigated to demonstrate the effect of parameters h , W_g , W_t , L , and h_p on the performance of the designed CPW-fed slot antenna most effectively. These five parameters are set as variable and their effects on the impedance bandwidth are studied. It is found through the simulation that the operating bandwidth of the proposed antenna critically depends on the combination of the feed patch and slot shape. In order to achieve a high level of electromagnetic coupling to the feed line, a large slot is used in a CPW-fed printed slot antenna. Therefore, varying the feed patch shape or slot shape changes the coupling property and in turn this change in coupling affects the matching between the feed patch shape and the wide slot on the ground plane. On the other hand our simulation study show that, for optimum performance the feed and slot shapes should be similar and the feed patch has to occupy an area of about one third of the slot size.

Although a CPW-fed wide-slot antenna provides a wide operating bandwidth, we have to note that its operating bandwidth is limited due to the degradation of the radiation patterns at the upper edge of the impedance bandwidth. Through the study of different slot shapes, we found that currents flowing on the edge of the slot increase the cross-polarization component and cause the main beam to tilt away from the broadside direction in the E and H -plane radiation patterns.

For the proposed slot antenna, the first parameter under study is the feed gap h , which determines the matching between the feed-line and the wide-slot antenna. It is found that good impedance matching can be obtained by enhancing the coupling between the slot and feed. When the coupling is increased to a certain value, the optimum operating bandwidth can be obtained. However, if the

coupling is increased more than this value, the impedance matching deteriorates, showing that over coupling also degrades the impedance matching. Figure 6 shows the simulated return losses of the proposed antenna obtained by Ansoft HFSS with feed eed gaps 0.5 mm, 1 mm, and 1.5 mm. The results show that the frequency corresponding to the lower edge of the bandwidth is clearly independent of the feed gap h , but the frequency corresponding to the upper edge is heavily dependent on this parameter. It is clear that h is an important parameter that influences the return loss.

Figure 7 shows the simulated return losses of the proposed antenna for various W_g . This parameter changes the electric field distribution on the wide slot, and reduces the slot size and effective radiation area at the same time. As the results show, this parameter mainly affect the high frequency performance, however, the low frequency properties of the proposed antenna is clearly independent of the W_g . Based on these results, the optimum value of W_g is 3 mm.

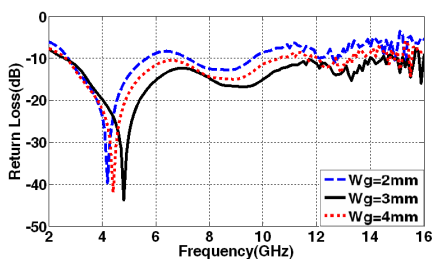


Figure 7. Simulated return losses of the CPW-fed slot antenna for various W_g .

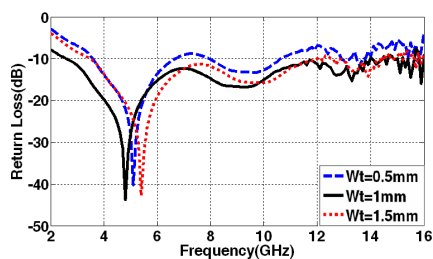


Figure 8. Simulated return losses of the CPW-fed slot antenna for various W_t .

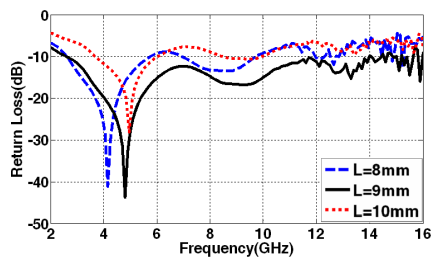


Figure 9. Simulated return losses of the CPW-fed slot antenna for various L .

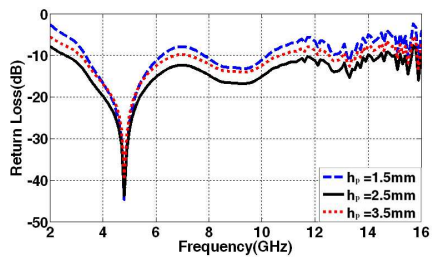


Figure 10. Simulated return losses of the CPW-fed slot antenna for various h_p .

The simulated return losses of the proposed CPW-fed slot antenna for various W_t , 0.5 mm, 1 mm and 1.5 mm are presented in Figure 8. This factor affects the performance of the proposed antenna most effectively. As shown in Figure 8, the return loss deteriorates within the whole band as W_t changes. The best value for W_t in the designed antenna is 1 mm.

Figures 9 and 10 show the relationship of L and h_p versus return loss, respectively. It can be seen that the frequencies corresponding to the lower edge and the upper edge of the bandwidth strongly depend on this parameter. The optimum values of L and h_p are 9 mm and 2.5 mm, respectively.

Through extensive simulations via HFSS and CST Microwave Studio softwares, it is found that the radiation patterns and cross-polarization of the proposed antenna critically depend on the slot size. A larger slot on the ground plane increases the magnitude of the higher order modes and changes the phase distribution on the slot. Consequently, the cross-polarization increases and the radiation patterns deteriorate. The gain of the designed antenna strongly depends on the E-shaped patch and the slot size. By enlarging these parameters the effective radiation area and the gain of the antenna increase.

5. UNCORRELATEDNESS

In this section, based on looking at the upper edge of the bandwidth, the correlation between the antenna main parameters is investigated. The upper edge of the bandwidth (f_h) for $S_{11} < -10$ dB versus h and h_p are listed in Tables 1 and 2, respectively. In this study we suppose that f_h is the random variable. The variances of the f_h in Tables 1 and 2 are $\sigma_1^2 = 1.27$ and $\sigma_2^2 = 5.74$, respectively. The variance of the

Table 1. The upper edge of the bandwidth (f_h) for $S_{11} < -10$ dB versus h .

h	0.5	0.6	0.7	0.8	0.9	1	1.1	1.2	1.3	1.4	1.5
f_h	11.45	12.15	12.93	13.48	13.82	14	13.62	13.1	12.26	11.3	10.35

Table 2. The upper edge of the bandwidth (f_h) for $S_{11} < -10$ dB versus h_p .

h_p	1.5	1.7	1.9	2.1	2.3	2.5	2.7	2.9	3.1	3.3	3.5
f_h	6.2	7.9	9.6	10.5	12.8	14	12.47	10.18	9.52	8.1	6.8

f_h in the case that h and h_p vary and the other parameters of the antenna are fixed is $\sigma_3^2 = 7.08$ which the details are not presented. It follows that $\sigma_3^2 \cong \sigma_1^2 + \sigma_2^2$. These results and random variables theory show that these antenna dimensions parameters (h and h_p) have uncorrelated effects on the upper edge of the bandwidth. Although not shown, similar results were obtained for the other antenna dimensions parameters.

6. CONCLUSION

A broadband CPW-fed slot antenna is presented, and excellent agreement was obtained using computer simulations and experimental results. The proposed antenna shows a wide bandwidth of over 131%. In addition to be small in size, the antenna exhibits stable far-field radiation characteristics in the entire operating bandwidth and has a relatively high gain and low cross polarization. By choosing suitable combinations of feed patch, slot shapes and tuning their sizes, an optimum operating bandwidth was obtained. Based on these characteristics, the proposed slot antenna can be useful for broadband satellite and wireless communication applications.

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