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Design and Measurement of a Probe-Fed Open-Ended Rectangular Waveguide with Four-Stacked-Coupling-Aperture

***Abstract**. This paper presents a design and measurement of symmetric bidirectional pattern antenna implemented by using a probe-fed open-ended rectangular waveguide (OERW) vertically attached with four-stacked-coupling-aperture (FSCA). For the OERW without FSCA, it provides asymmetric beam in forwards and backwards directions. With the effect of FSCA, that asymmetry is amended to be symmetry, and propagates the WLAN frequency band of 2.4–2.5 GHz with the return loss better than 10 dB, and maximum gain of 7.04 dBi. A prototype antenna was fabricated and measured. Obviously, the preliminary measured results are very reassuring, and reasonably in good agreement with simulation results.*

Streszczenie.** W artykule zaprezentowano projekt I badania symetrycznej, dwukierunkowej anteny wykorzystującej otwarty prostokątny falowód pionowo usytuowany z czterema sprzężonymi aperturami. Umożliwia ona asymetrię strumieni w przód i w tył. Antena obsługuje sieci WLAN o częstotliwości 2.4-2.5 GHz z maksymalnym wzmocnieniem 7.04 dB. **Projekt i badania prostokątnego falowodu z czterema sprzężonymi aperturami

Keywords: Symmetrical beam antenna; Bidirectional antenna; Open-ended rectangular waveguide; Coupling aperture.
Słowa kluczowe: antena dwukierunkowa, falowód, apertura

Introduction

Point-to-point communication systems have promptly advanced and become one of the growing communication business over the late decades [1]-[2]. Particularly, point-to-point links between hosts and clients are required in numerous wireless communication systems over long distances, for examples, the microwave radio relay link, long length Wi-Fi, wireless WAN/LAN link, satellite communication, and home satellite television, etc. [2]-[4]. To increase the performance of the point-to-point communication desires a narrow-beam or pencil beam antenna with high gain [5], which is probably provided by a reflector antenna. To generate pencil beam for point-to-point communications, a symmetrical beam antenna is required for a primary feed [6], since the radiation pattern of the secondary antenna (reflector antenna) typically corresponds to that of the primary feed antenna [7]. However, it is not easy to obtain symmetrical radiation pattern because of the asymmetrical beamwidth between the *yz*- and *xz*-planes depending on the antenna structure [8].

The development of symmetrical beam antennas has been continuously researched and proceeded [9]-[12]. Among these symmetrical beam antenna designs, a triple-aperture waveguide antenna (TAWA) was lately introduced to be a primary feed antenna for reflector [11], because its structure is not complex. Nevertheless, the radiating section of TAWA is not small size. To further reduce the size of that radiating section, a probe-fed open-ended rectangular waveguide (OERW) with four-stacked-coupling-aperture (FSCA) antenna was preliminary studied for designing a symmetrical beam antenna in 2018 [12]. It was found that the effect of FSCA could transform the asymmetrical beam to be symmetry at -3 dB beamwidth. However, an equal beamwidth of both *yz*- and *xz*-planes at -10 dB could not accomplish yet. Therefore, this paper aims to continuously improve the FSCA for the better symmetrical beamwidth at -10 dB beamwidth. Using the microwave simulation tool, all antenna parameters are achieved and the best conditions are reported in the paper. Afterwards this introduction, next presents the detail of the antenna structure and its design. After that, the modifications completed to obtain the symmetrical pattern operated in the WLAN applications are illustrated. In addition, an experimental validation and discussion are also addressed followed by the summaries of this work.

Antenna structure and its design

Figure 1 depicts the geometry of the proposed antenna, which is consisted of the radiating section at the middle and FSCA section, where two coupling apertures are stacked on top and others two underneath the radiating section. This presented antenna is fed by a linear probe of length *l*, which is attached with a circular disc for improving impedance matching as well as adjusting the main beam direction of the antenna, located at the center of the radiating section at the bottom. This feeding probe is surrounded by OERW of width *a* height *b* and length *c*. For the coupling section, there are four identical one-open-ended apertures with the width a_1 height b_1 and length c_1. Note that the open-ended side of coupling aperture is laid along open aperture of the radiating section while their close-ended is back-to-back to each other with the separation of *s*. Using (1), the width of *a* and height of $b = a/R$ are calculated, where *R* is the ratio of *a/b* and $R \geq 1$ [13]; in this paper $R = 2.17$ is used.

(1)
$$f_c = \frac{\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}}{2\pi\sqrt{\mu\varepsilon}},$$

where, f_c is the cut off frequency, μ is permeability, ε is permittiity, $m = 1$ and $n=0$.

Thus, the coice of dominant mode (TE_{10}) propagation is restricted in the range of $\lambda/2 < a < \lambda$. In the design, the width and height of OERW *a* of 0.78 λ and *b* of 0.35 λ are firstly designed to provide the dominant mode propagation at the center frequency of 2.45 GHz [12]-[14]. In addition, the length *c* of radiating section is selected at 1.11 λ to provide a resonance at the center frequency with a high gain [12]. Note that this length should be long enough for producing a closely symmetrical beam as much as it possible before continuously adjusting the FSCA. For the feeding, the probe length *l* of 0.22 λ with the attached circular disc of radius of 7.5 mm is selected for the reason of good impedance matching and improving main beam direction of this proposed antenna [12]. These values are fixed throughout the paper.

a)

b)

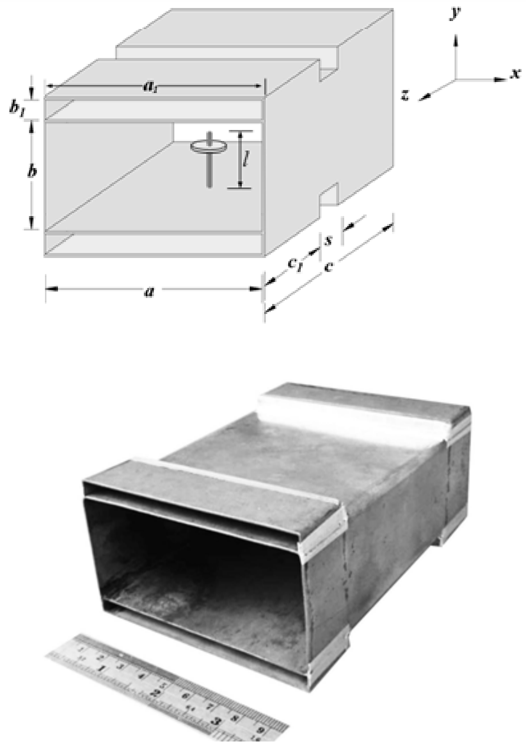


Fig.1. Geometry of the proposed antenna: (a) model and (b) prototype

It should be noted that this probe-excited OERW provides asymmetrically bidirectional pattern, that is the half power beam width (-3 dB beamwidth) for both *yz*- and *xz*-planes are different. From our previous work [12], it was found that the influence of the FSCA remedy the asymmetry bidirectional pattern to be the symmetry at only -3 dB beamwidth for both *yz*- and *xz*-planes. However, an equal -10 dB beamwidth was not yet achieved. Therefore, this work aims to further improve this lack by firstly adjusting the height of b_1; while, the width a_1 is fixed as the same widthwise as *a* of OERW, and length c_1 is initially set to be equal to that value from our previous work at 0.4 λ [12]. All optimum parameters are tabulated in Table 1. The simulated and measured results will be shown in the next section

Table 1. The parameters of the designed antenna

Parameters	Physical size (mm)	Electrical size (λ)
a	93.6	0.76
a_1	93.6	0.76
b	43	0.35
b_1	6.1	0.05
c	136	1.11
c_1	24	0.20
l	27	0.22
s	86	0.70

Simulation and measured results

This section illustrates the radiation and impedance properties of the proposed antenna. As mention in the previous section that the OERW without FSCA gives asymmetrical pattern, four apertures coupling are incorporated with the OERW whereby two apertures are vertically attached on top and the others two underneath the radiating section for improving the asymmetry beam to be the symmetry. Using the designed parameters as tabulated in Table 1, simulations are then carried out. Apparently, the bidirectional pattern is provided with the symmetrical beam. At the operating frequency of 2.4 GHz, 2.45 GHz and 2.5 GHz, both -3 dB and -10 dB beamwidths for both *yz*- and *xz*-planes of this proposed antenna without and with FSCA for the asymmetrical and symmetrical beams respectively are summarized as shown in Table 2. To accomplished these values, the height b_1, and the length c_1 of FSCA are considered.

Table 2. Simulated beamwidths of the proposed antenna

Frequency (GHz)	-3 dB beamwidth			
	without FSCA		with FSCA	
	yz-plane	*xz*-plane	*yz*-plane	*xz*-plane
2.4	48°	46°	49°	49°
2.45	49°	47°	50°	50°
2.5	51°	48°	51°	51°
Frequency (GHz)	-10 dB beamwidth			
	without FSCA		with FSCA	
	yz-plane	*xz*-plane	*yz*-plane	*xz*-plane
2.4	85°	82°	82°	84°
2.45	84°	82°	82°	84°
2.5	87°	82°	83°	85°

To consider the influence of the height b_1 to the radiation pattern, both -3 dB and -10 dB beamwidths for both *yz*- and *xz*-planes are depicted in Fig.2. Obvious that the heighten b_1 produces the narrower –3 dB and -10 dB beamwidths for *yz*-plane in contrast to *xz*-plane; they keep about the same vales except b_1 heighten than 0.05 λ for -10 dB beamwidth. The -3 dB beamwidth for both *yz*- and *xz*-planes are identical when the height shorten than 0.06 λ, while the closer -10 dB beamwidths for both planes are obtained when b_1 is about 0.05 λ. Thus, in this paper, b_1 of 0.05 λ is chosen.

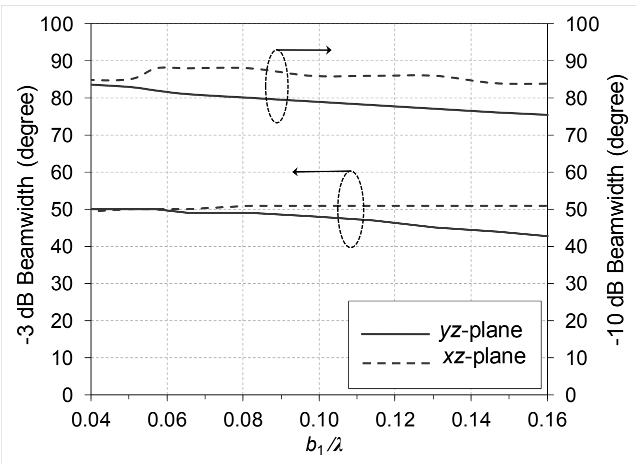


Fig.2. Simulated beamwidths of the OERW with FSCA for various height b_1.

In addition to the height b_1, the length c_1 is further illustrated to increasingly more symmetrical beamwidth at -10 dB as shown in Fig. 3. Apparently, the longer length c_1 produces the narrower beamwidth for both planes until c_1 of 0.28 λ and then becomes widen again. Note that for c_1 longer than 0.28 λ, the -10 dB beamwidth for *yz*-plane cannot achieve since its field strength is higher than -10 dB. For the -3 dB beamwidth, both *yz*- and *xz*-planes are identical when c_1 equal to 0.16 λ to 0.22 λ, 0.31 λ and longer than 0.48 λ. Meanwhile, the best condition of the closest -10 dB beamwidth with 2 degree difference for *yz*- and *xz*-planes can be obtained when c_1 is equal to 0.2 λ; this vale is selected in the design. Furthermore, the comparison between the simulated -3 dB beamwidth of the proposed antenna without and with the FSCA at the frequencies of 2.40 GHz, 2.45 GHz and 2.50 GHz are tabulated in Table 2. It is found that the proposed antenna without FSCA provides dissimilar beamwidths of both *yz*-plane and *xz*-plane for the three frequencies. In other word, the incidence of asymmetry is observed. However, the proposed antenna with vertically two coupling apertures on top and others two underneath the radiating section, the -3 dB beamwidths of both *yz*- and *xz*-planes for the three frequencies become symmetry.

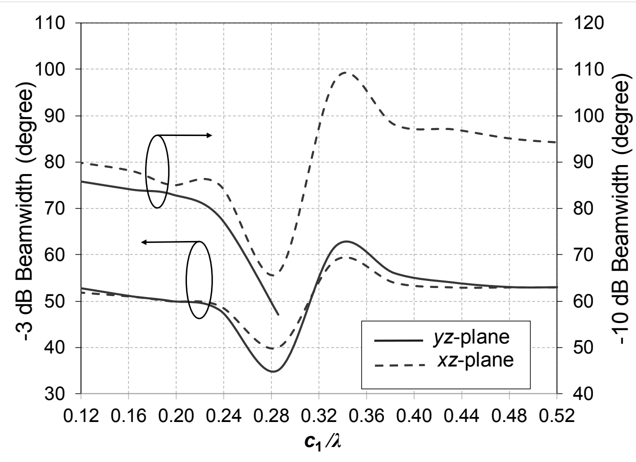


Fig.3. Simulated beamwidths of the OERW with FSCA for various for various length c_1.

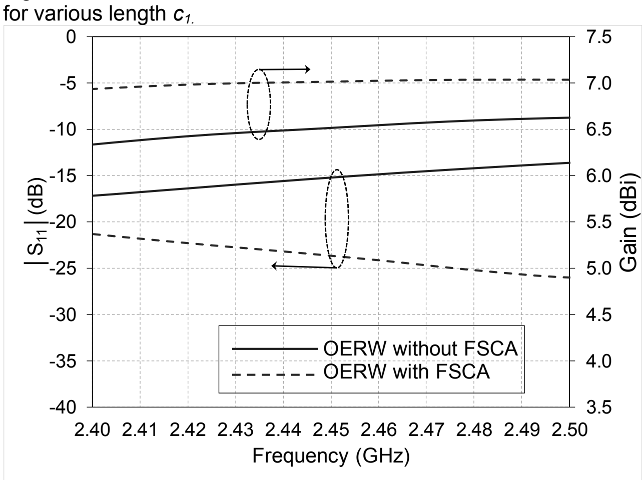


Fig.4. Simulated $|S_{11}|$ and gain of the proposed antenna with and without FSCAs

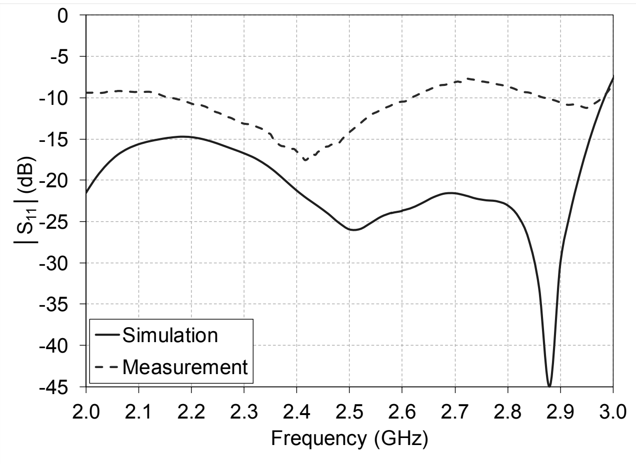
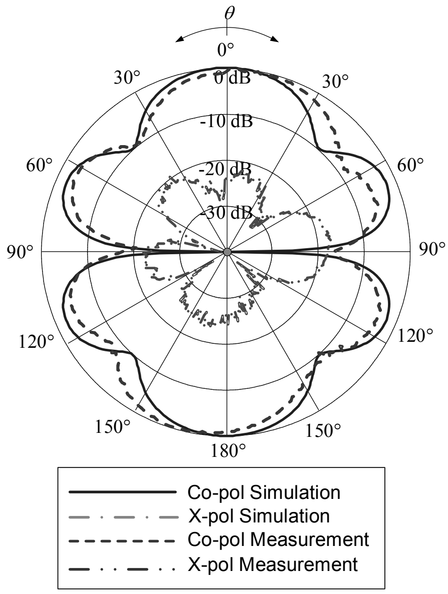


Fig.5. The simulated and measured S_{11} versus frequency

Figure 4 presents the simulated S_{11} and gain of the proposed antenna. Apparently, the proposed antenna without and with FSCAs provide the minimum gains of 6.34 dBi and 6.94 dBi, and maximum gains of 6.63 dBi and 7.04 dBi, respectively, for S_{11} < -10 dB operating in WLAN frequency. Comparing between the proposed antenna without and with FSCAs, it is clearly that the proposed antenna with FSCA gives the better S_{11} as well as higher gain over the other covered the interested band as depicted in Fig. 4.

a)



b)

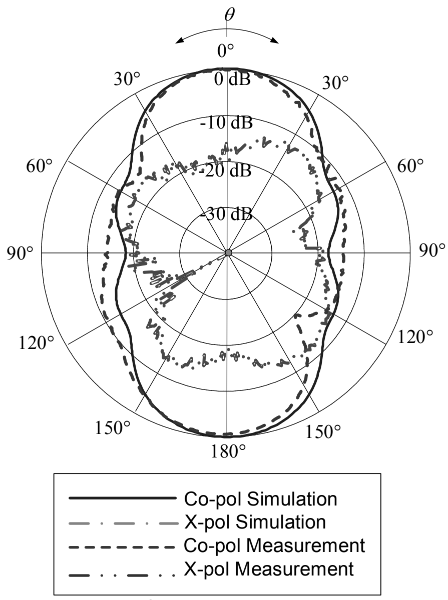


Fig.6. Radiation pattern of the proposed antenna in: (a) *yz*-plane, (b) *xz*-plane

To confirm the simulation, a prototype antenna was fabricated from copper with the designed dimensions as in Table 1. A photograph of the prototype antenna including coaxial feeding port connected via SMA 50-ohm connector is shown in Fig. 1 (b). Using an E5071C Network Analyzer, radiation and impedance characteristics of the proposed antenna are measured and discussed. Figure 5 shows the comparison between simulated and measured S_{11} versus the frequency ranging from 2 GHz to 3 GHz. Obvious that they provide a good return loss with similar trend of S_{11} less than -10 dB over the interested band (2.4 GHz to 2.5 GHz); the simulated and measured return loss are better than -10 dB ranging from 2 GHz to 2.98 GHz and 2.16 GHz to 2.62

GHz, respectively. Beside the impedance properties, its radiation pattern is also considered. Figure 6 shows the simulated and measured radiation patterns of the proposed OERW with FSCA in both *yz*-and *xz*-planes at the center frequncy of 2.45 GHz. Apparently, it provides the symmetrical bidirectional pattern at both -3 dB and -10 dB beamwidths for both *yz*-and *xz*-planes. Note that the radiation pattern in xy-plane is round with an equal amplitude of electric feild. In addition, the simulation radiation patterns are verified by the measured one. It is clear that they provide the symmetrical bidirectional pattern as proposed, and they are reasonably in good agreement. It should be pointed out that this antenna provides a linear polarization with no cross-polarization in the simulation and the cross-polarization less than -12 dB for the measurement. It should be noted that the discrepancy between simulated and measured results is occurred from the exclusion of the connector and cable in the simulation.

Conclusions

A probe-fed OERW with FSCA antenna producing the symmetrical beam is preliminary designed and measured in this paper. The antenna structure consists of the radiating probe-fed OERW stacked with two identical coupling apertures on top and others two underneath the radiating section. In the process, the width and heigh of an OERW are firstly designed to propage the dominant mode. By adjusting the heigh and length of FSCA, the asymmetrical bidirectional beam is altered to be symmetry at both -3 dB and -10 dB beamwidths. This proposed antenna provides S_{11} better than -10 dB with the maximum gain of 7.04 dBi over the interested frequency range from 2.4 GHz to 2.5 GHz. To validate the simulation results, antenna prototype was fabricated and measured. Apparently, the simulation results show the similar trend with the measured results. Nevertheless, for most primary feed antennas, a symmetrical unidirectional pattern antenna is used. Therefore, the development on rectifying this bidirectional beam to be symmetrical unidirectional beam is on going for our further work.

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