Bandwidth Enhancement of Small Square Monopole Antenna Using Self-Complementary Structure for Microwave Imaging System Applications

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Abstract ─ A novel printed monopole antenna for ultra-wideband (UWB) applications is designed based on self-complementary structure as a matching network. The proposed antenna consists of a square radiating patch and a self-complementary structure located next to feed line, which provides a wide usable fractional bandwidth of more than 100% (3.04-11.43 GHz). Self-complementary matching network is created, by cutting two rectangular ring slots on the ground plane and by inserting two rectangular rings coupled elements in the top layer; hence, additional resonances are excited and much wider impedance bandwidth can be produced. The designed antenna has a small size of 14×22 mm^2, about 0.15λ×0.25λ at 4.3 GHz. It is shown that simulated and measured results agree well with each other and demonstrate the usefulness of the proposed antenna for UWB applications. The proposed antenna exhibits almost omni-directional radiation patterns with low cross-polarization levels and provides an acceptable gain over whole band.

Index Terms ─ Babinet's equivalence principle, microwave imaging system, self-complementary structure, square monopole antenna.

I. INTRODUCTION

One of key issues in ultra-wideband (UWB) imaging systems is the design of a compact antenna while providing wideband radiation characteristics over the whole operating band. Consequently, a number of printed microstrip antennas with different geometries have been experimentally characterized [1]-[2]. These types of UWB antennas are also suitable for the short-range indoor and outdoor communications [3]. However, for radar systems, such as an UWB microwave imaging system for detection of breast tumor, a moderate gain directional antenna is advantageous. In addition to an UWB impedance bandwidth, as defined by the minimum return loss of 10 dB, the UWB antenna is required to support a very short pulse transmission with negligible distortion. This is necessary to achieve precision imaging without ghost targets. Several UWB antenna designs with compact size and low distortion have been proposed for the use in the medical imaging systems [4-6]. Each has its own merits and drawbacks. Some of the proposed antennas have no planar structure, whereas others have low-gain and/or low radiation efficiency. The unipolar and antipodal Vivaldi antennas presented in the literature [7, 8] satisfy the requirements for imaging systems in terms of bandwidth, gain, and impulse response. However, the achieved performance is at the expense of significant size, which has a length of several wavelengths.

In this paper, a simple method for designing a novel and compact microstrip-fed monopole antenna with multi resonance performance based on self-complementary structure for UWB applications has been presented and discussed. The proposed self-complementary structure is designed using the Babinet's equivalence principle to achieve impedance matching throughout a wide frequency range, such that Z_{in} has constant value for all frequencies [9]. To the authors' knowledge, it is the first time that a self-complementary matching network consisting of two rectangular ring slots on the ground plane and two rectangular ring coupled elements in the top layer is used to increase the bandwidth of an ordinary square patch monopole antenna. The size of the designed antenna is smaller than the UWB antennas reported recently [2]-[8]. Good return loss and radiation pattern characteristics are obtained in the frequency band of interest, 3.04-11.43 GHz.

II. ANTENNA CONFIGURATION

The square monopole antenna fed by a 50 Ω microstrip line is shown in Fig. 1, which is printed on an FR4 substrate with the thickness of 0.8 mm, dielectric constant of 4.4, and the loss tangent of 0.018. The basic antenna structure consists of a square patch, a feed line, and a ground plane. All dimensions of the antenna are given in Table 1. To increase the bandwidth of the antenna, we propose to insert a self-complementary structure as shown in Fig. 1. Self-complementary structure includes two rectangular rings on the patch side and two rectangular ring slots in the ground plane. The

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resonant behavior of the self-complementary structures used here introduces new resonance frequencies and consequently improves the bandwidth of the antenna. Opening two rectangular ring slots of suitable dimensions on the ground plane results in a much enhanced impedance bandwidth. Regarding defected ground structures (DGS), creating slots in the ground plane provides an additional current path. Moreover, this structure changes the inductance and capacitance of the input impedance, which in turn leads to a change in the bandwidth. The DGS applied to a microstrip line causes a resonant character of the structure transmission with a resonant frequency controllable by changing the shape and size of the slot [10]. Therefore, by cutting two rectangular ring shaped slots at the ground plane and carefully adjusting its parameters, much enhanced impedance bandwidth can be achieved.

In addition, the complementary coupled rings on the top layer are playing an important role in the broadband characteristics of this antenna, because it can adjust the electromagnetic coupling effects between the patch and the ground plane, and improves its impedance bandwidth without any cost of size or expense. This phenomenon occurs because, with the use of a complementary coupled structure in transmission line distance, additional coupling is introduced between the bottom edge of the square patch and the ground plane [8].

The first step in the design of the antenna is to determine the initial dimensions of the structure. These parameters, including the substrate are $W_{Sub} \times L_{Sub} = 14 \times 22$ or about $0.15\lambda \times 0.25\lambda$ at 4.3 GHz (the first resonance frequency). There is flexibility in choosing the width of the radiating patch. This parameter mostly affects the antenna bandwidth. As W decreases, so does the antenna bandwidth, and vice versa. The length of the radiating patch is approximately $\frac{\lambda_{lower}}{4}$, where λ_{lower} is the wavelength of the lower frequency of the bandwidth. λ_{lower} frequency of lower edge of the usable band depends on a number of parameters such as the width of the radiating patch as well as the thickness and dielectric constant of the substrate on which the antenna is fabricated [8]. The important step in the design is to choose L_r (the length of the new resonators). L_r is set to resonate at $0.25\lambda_g$, where $L_{r3} = 2L_P + 1.75W_P$, and $L_{r4} = 2L_P + 0.75W_P$, λ_g corresponds to wavelength of resonance frequencies (10.5 GHz is the third resonance frequency and 11.4 GHz is the fourth resonance frequency) [8]. The parameters of this antenna are studied by changing one parameter at a time while others are kept fixed. Ansys HFSS simulations are used to optimize the design and agreement between the simulation and measurement is obtained [11].

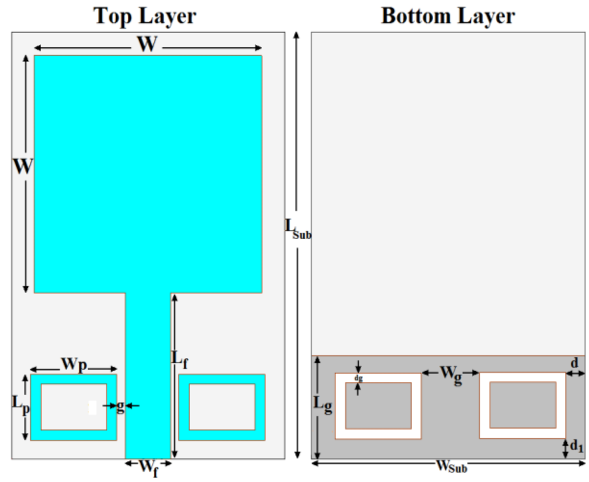


Fig. 1. Geometry of the proposed square monopole antenna with self-complementary matching network.

Table 1: The proposed monopole antenna dimensions

Parameter	Value (mm)	Parameter	Value (mm)
W_{Sub}	14	L_{Sub}	22
W_f	1.5	L_f	8
W	12	L_g	5
W_p	5	L_p	3
W_g	2	d	1
d_1	2	g	0.25

III. RESULTS AND DISCUSSION

The designed square monopole antenna is fabricated on FR4 substrate by fast PCB prototyping machine. The simulated and experimental results of the input impedance and radiation characteristics are presented and discussed in this section.

Figure 2 shows the return loss characteristics for an ordinary printed square monopole antenna, a monopole antenna with two modified rectangular ring slots on the ground plane, and a monopole antenna with a pair of rectangular ring self-complementary structures. As shown in Fig. 2, in the proposed antenna configuration, the ordinary square monopole can provide the fundamental and next higher resonant radiation band at 4.3 and 8.1 GHz, respectively, in the absence of the self-complementary structure. The upper frequency bandwidth is significantly affected by using the rectangular ring slots on the ground plane. This behavior is mainly due to the fact that creating slots in the ground plane provides an additional current path. In addition, by inserting two rectangular ring coupled elements on the top of these slots, the impedance bandwidth is effectively improved at the upper frequency [10]. It is observed that by using this modified self-complementary structure, additional third (10.5 GHz) and fourth

(11.4 GHz) resonances are excited respectively, and hence, the bandwidth is increased. It is also noticed that the resonance frequencies introduced by self-complementary structure are different and smaller than the ones due to having only slot rings in the ground and ones due to having only metallic rings on the upper plane.

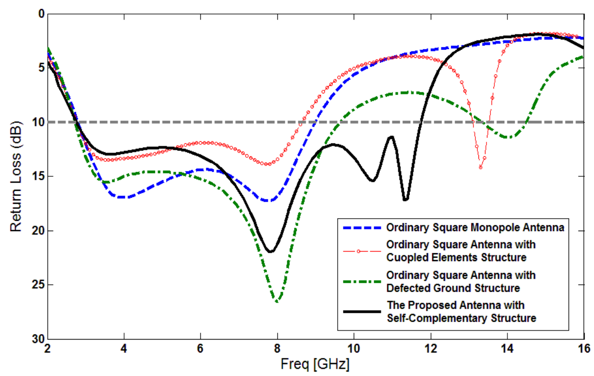


Fig. 2. Comparison of simulated return loss characteristics for ordinary square monopole antenna, monopole with two modified rectangular ring slots on the ground plane, and monopole with a pair of rectangular ring self-complementary structures.

The simulated current distributions on the radiating patch and the ground plane for the proposed antenna at 10.5 GHz (third resonance) and at 11.4 GHz (fourth resonance) are plotted in Figs. 3 and 4, respectively. As shown in Figs. 3 and 4, the current is concentrated on the edges of the interior and exterior of the rectangular ring slots and coupled elements at these resonance frequencies.

In order to understand the phenomenon behind the self-complementary structure effects on decreasing resonance frequency and generation of new additional resonances frequencies, the electrical lengths of the corresponding resonating parts due to electromagnetic coupling between self-complementary structures are plotted on Fig. 5. Regarding coupling between the elements of self-complementary structure, since the polarization of the two antennas are reversed, the surface current direction is changed on the other side of the structure [12]. Therefore, we can claim that the resonator lengths shown in Fig. 5 are longer than the ones of the isolated rings and slots so that new resonance frequencies are appeared in the lower frequencies as shown in Fig. 2. In addition, by inserting coupled elements on the other side of substrate, the electromagnetic coupling is effectively improved. The rectangular rings coupled elements can be regarded as parasitic resonators electrically coupled to the rectangular ring slots. As shown in Fig. 5, the electrical current for the new generated resonances frequency does continue its direction along the bottom or top side of substrate.

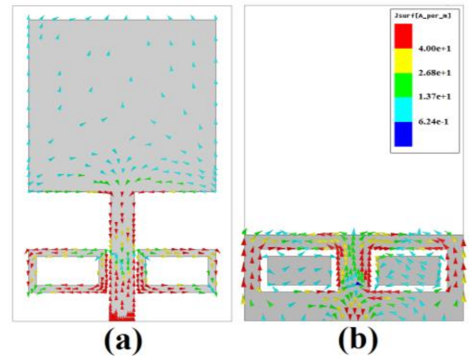


Fig. 3. Simulated surface current distributions for the proposed monopole antenna at third resonance frequency (10.5 GHz): (a) on the radiating patch, and (b) on the ground plane.

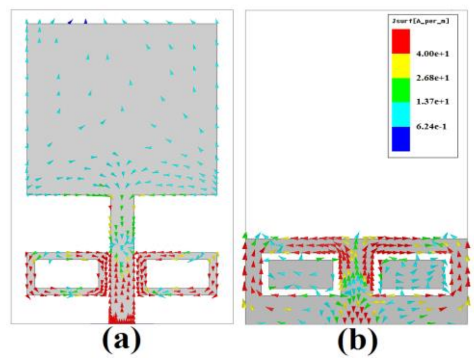


Fig. 4. Simulated surface current distributions for the proposed monopole antenna at fourth resonance frequency (11.4 GHz): (a) on the radiating patch, and (b) on the ground plane.

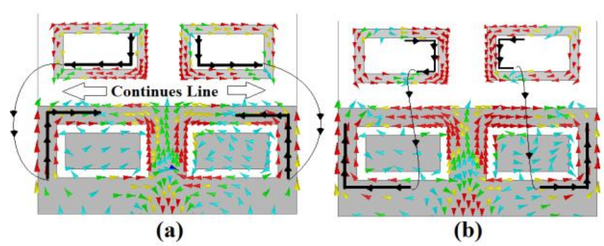


Fig. 5. Simulated surface current distributions show the new resonator electrical lengths due to electromagnetic coupling between self-complementary structures: (a) at the third resonance frequency (10.5 GHz), and (b) at the fourth resonance frequency (11.4 GHz).

In order to investigate the effects of the separation distance between self-complementary matching network and microstrip feed-line on the proposed antenna, the return loss characteristics for various gap distance lengths are analyzed and results are illustrated in Fig. 6. It is observed that the impedance bandwidth is effectively improved at the upper frequency band as separation distance is changed. It is seen that the frequency of the lower edge of bandwidth is improved with decreasing the gap, but the matching becomes poor for lower frequencies. By adjusting this separation distance, the electromagnetic coupling between the lower edge of the square patch and the ground plane can be properly controlled [10].

Another important parameter of this structure is the rectangular ring length (W_P). By adjusting W_P, the upper edge of the frequency bandwidth can be properly controlled. The simulated return loss characteristics for various rectangular ring lengths are illustrated in Fig. 7. It is seen that the upper-edge frequency of the impedance bandwidth is increased with decreasing W_P, but the matching becomes poor for lower band.

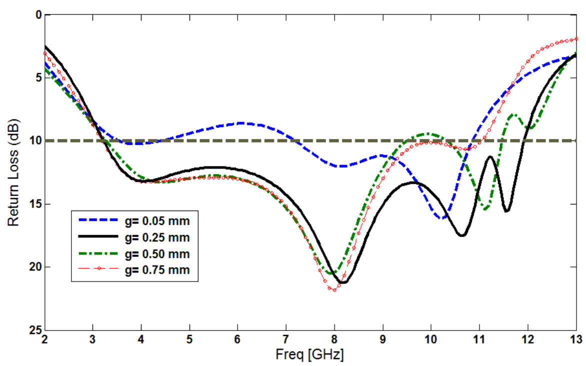


Fig. 6. Simulated return loss characteristics of the proposed antenna with different values of separation distance between self-complementary matching network and microstrip feed-line.

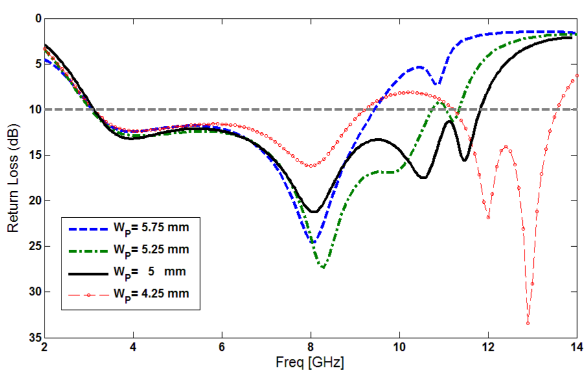


Fig. 7. Simulated return loss characteristics of the proposed antenna with different values of W_P.

Figure 8 shows the effects of the self-complementary structure on the maximum gain in comparison to the same antenna without them. As shown in Fig. 8, the ordinary square antenna has a gain that is low at 3 GHz and increases with frequency. However, the gain of the ordinary square antenna is decreased in the higher frequency band with the use of the self-complementary structure; the proposed antenna gain has a flat property which is advantageous for microwave imaging applications.

In UWB microstrip antennas analysis, the transfer function is transformed to time domain by performing the inverse Fourier transform. Fourth derivative of a Gaussian function is selected as the transmitted pulse. Therefore, the output waveform at the receiving antenna terminal can be expressed by convoluting the input signal and the transfer function. The input and received wave forms for the face-to face and side-by-side orientations of the antenna are shown in Fig. 9. The results of the calculations using the CST software [13] indicated that the shape of the pulse is preserved in most cases, especially in the first configuration. Using the reference and received signals, it becomes possible to quantify the level of similarity between signals [3].

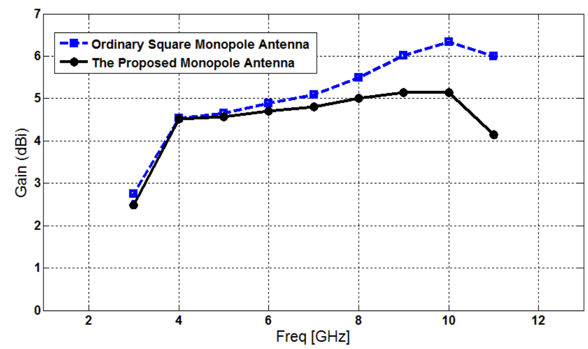
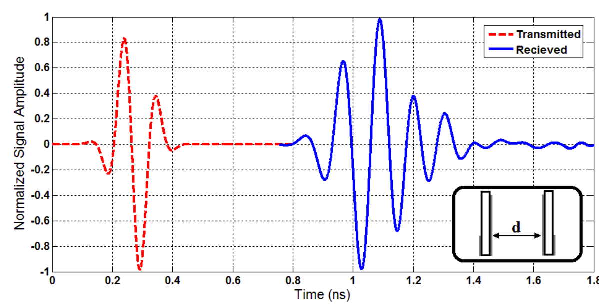
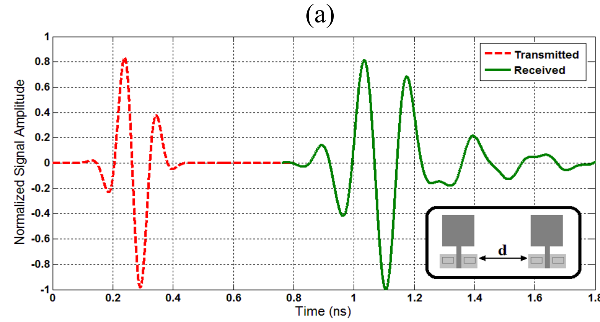


Fig. 8. Simulated maximum gain comparisons for the ordinary square antenna and the proposed antenna.



(a)



(b)

Fig. 9. Transmitted and received pulses: (a) side by side, and (b) face to face.

The proposed antenna with optimal design is fabricated as shown in Fig. 10 and measured. Figure 11 compares the measured and simulated VSWR characteristics of the proposed antenna. The fabricated antenna has the frequency band of 3.04 to over 11.43 GHz. The slight discrepancy between simulated and measured results is mostly due to a number of parameters such as possible errors in fabricated antenna dimensions as well as nonuniformity of the thickness and the dielectric constant of the low cost FR4 substrate over the wide range of simulation frequencies.

Figure 12 and Fig. 13 depict the measured and simulated radiation patterns, the co-polarization and cross-polarization in the *H*-plane (*x*-*z* plane) and *E*-plane (*y*-*z* plane), at different frequencies in the operation band. These patterns demonstrate that the antenna actually radiates over a wide frequency band. It can be seen that the radiation patterns in *x*-*z* plane are nearly omni-directional even at higher frequencies, and also the cross-polarization levels are low. These radiation characteristics show that the proposed antenna is a promising candidate for UWB microwave imaging applications.

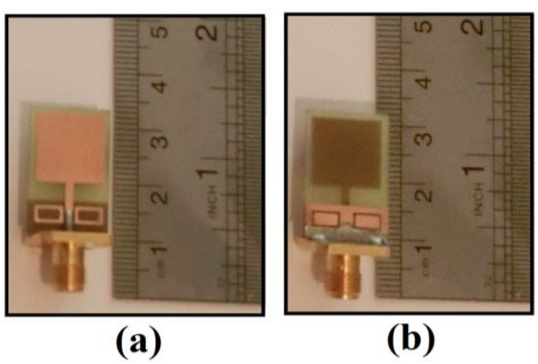


Fig. 10. Photograph of the realized printed square monopole antenna: (a) top view, and (b) bottom view.

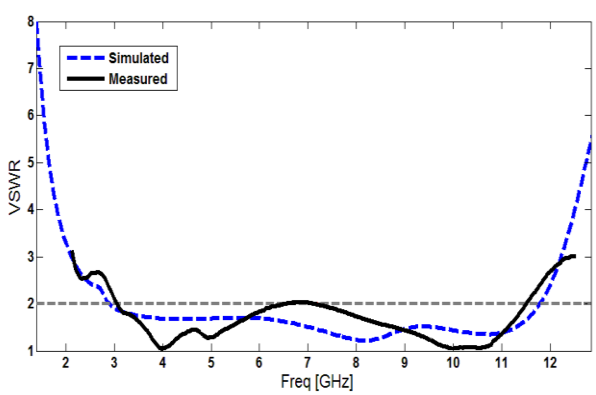


Fig. 11. Measured and simulated VSWR for the proposed antenna.

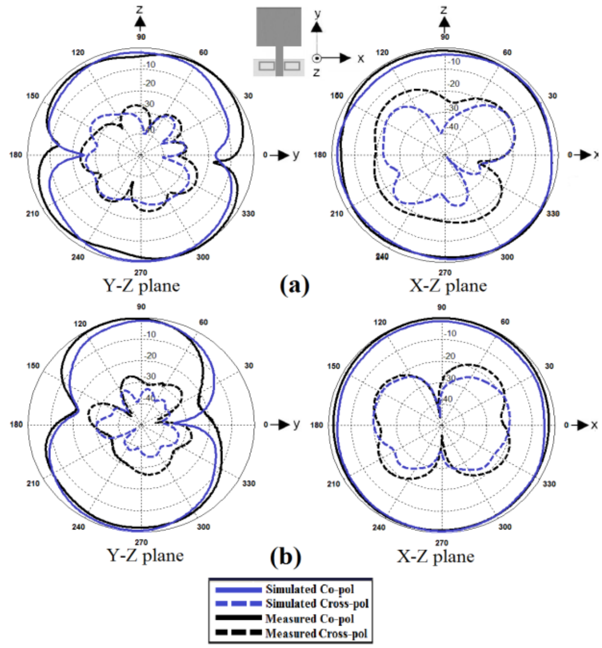


Fig. 12. Measured and simulated radiation patterns of the proposed antenna: (a) first resonance frequency (4.3 GHz), and (b) second resonance frequency (8.1 GHz).

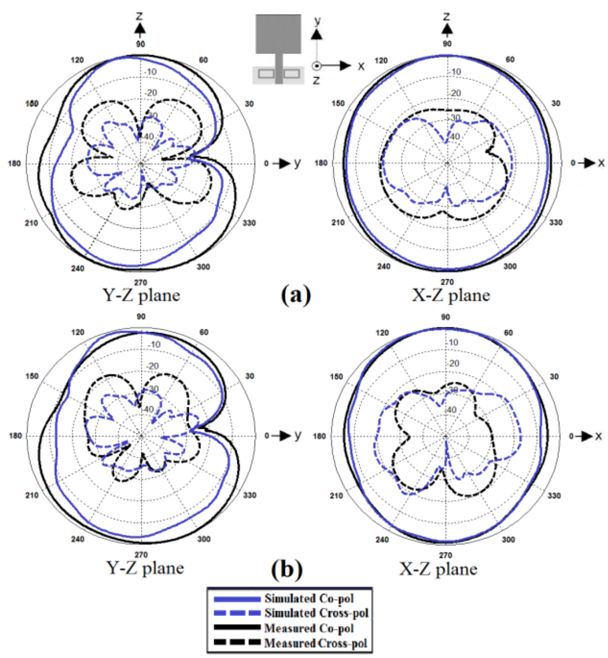


Fig. 13. Measured and simulated radiation patterns of the proposed antenna: (a) third resonance frequency (10.5 GHz), and (b) fourth resonance frequency (11.4 GHz).

IV. CONCLUSION

In this paper, a compact printed monopole antenna with multi resonance characteristics with a novel matching network based on self-complementary structure has been proposed for UWB applications. In this structure, by cutting two rectangular ring slots on the ground plane and by inserting two rectangular ring coupled elements in the top layer, the self-complementary structure is created; hence, additional resonances are excited and much wider impedance bandwidth is achieved. The fabricated antenna has an impedance bandwidth of 3.04 to 11.43 GHz which covers the frequency range of UWB systems. Furthermore, in this band gain level is satisfactory varying between 3 to 5 dBi. The proposed antenna is small, low cost and can be easily fabricated.

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