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Design and Analysis of New Ultra-Wideband Linear Antenna Array for Wireless Applications

R. Gholami[1], B. Zakeri [2*], H. Mehrpour Bernety[3]

1- M.Sc. Student, Department of Electrical Engineering, Babol Noshirvani University of Technology, Babol, Iran
2- Assistant Professor, Department of Electrical Engineering, Babol Noshirvani University of Technology, Babol, Iran
3- M.Sc. Student, Department of Electrical Engineering, Babol Noshirvani University of Technology, Babol, Iran

ABSTRACT

This paper presents a low-cost compact planar microstrip-fed monopole antenna and its four-element array design for ultra-wideband (UWB) wireless communication and target detection applications, respectively, operating in the frequency span of 3-11GHz. A prototype was fabricated and then measured based on optimal parameters. The results of reflection coefficient (S_{11}) and radiation patterns are shown and discussed. There is a good consistency between the simulated S_{11} and the measured one. In addition, a 1×4 linear array design with a size of 100×34mm^2 is proposed to achieve a higher gain. Simulation shows that the array gain is increased about 6 dB in comparison with the single element through the whole UWB frequency range. The proposed array has an average of -15 dB side lobe level (SLL) in the mentioned range. And also, a -23 dB SLL is achieved by applying Dolph-Chebyshev amplitude distribution at 6 GHz. Simulation results confirm that the antenna exhibits a constant bidirectional radiation pattern with a high and flat gain in case of the array design.

KEYWORDS

Cross-Polar Pattern, Element Spacing, R eflection Coefficient, UWB Antenna, And UWB Array.

* Corresponding Author, Email: zakeri@nit.ac.ir

1- INTRODUCTION

In 2002, the Federal Communications Commission (FCC) of the United States officially released the regulation for Ultra-wideband (UWB) technology [1]. In this regulation, the frequency span of 3.1 GHz to 10.6 GHz is allocated for the unlicensed UWB measurements and communication applications. According to the released regulation, UWB technology has been regarded as one of the most promising wireless technologies, which promises to revolutionize high data rate transmission. It is also used in medical imaging, ground-penetrating radar (GPR), position location and tracking. Since an antenna acts like a filter for the generated ultra short pulse, one of the key issues is the design of a compact antenna with an ultra-wideband characteristic in UWB communication systems. There are a huge number of UWB single antenna constructions [2– 7].

The existing UWB antennas lack high gains and usually satisfy omnidirectional radiation patterns. However, applications such as target detections, 3D microwave imaging, sensor networks and RFID readers need high gains and narrow beamwidths [8] – [11]. UWB arrays can be good choices for the purpose of achieving directional radiation patterns. Much research has been investigated on this topic [12] – [18]. In [12], a UWB array of 2-5 antennas is investigated by simulation. Each antenna is designed for 6-8.5 GHz European UWB band with an elliptical-shaped radiator and is excited through a two-step stripline. In [13], a four-element microstrip antenna array is presented with Dolph-Chebyshev amplitude distribution to decrease SLL. The elements are identical and contain a U-shaped rectangular patch and partial ground to satisfy the UWB bandwidth. Ref [14] employed four identical compact planar circular slot microstrip antennas to compose a 1 × 4 UWB array with uniform amplitude distribution. Actually, the single element used in an Ultra-wideband array, plays a crucial role to meet the requirements of an approximately constant directive radiation pattern and a low side lobe level.

Another important parameter in an antenna array is the mutual coupling between the elements, which influences the performance of an antenna array. In addition, it may lead to the changes in array gain, side lobe level, array polarization, and its size. In [15], an analysis on mutual coupling in UWB compact arrays was presented. Initially, it addresses linear dipoles (narrow band) to approximate the coupling effects for UWB linear antenna array. [16] investigates on the mutual coupling effect for 2-element and 4-element UWB linear arrays. It is assumed that both antenna arrays are fed independently by uniform amplitude distributions.

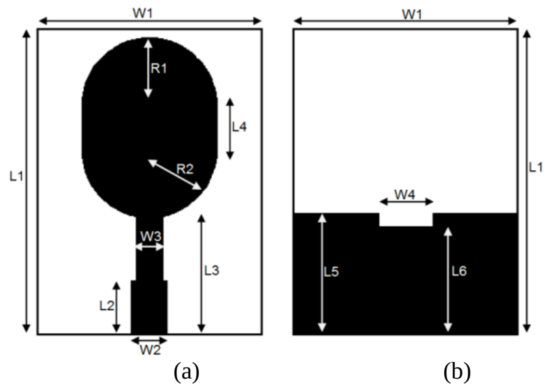
In this paper, we propose a novel UWB microstrip-fed antenna with a semi-elliptical radiating patch. Indeed, it is a combination of two semi-circular patches and a rectangular patch. As mentioned above, the single element of an antenna array is of paramount importance. There would be many microstrip antennas designed for UWB applications. However, the lack of suffice effective designs for satisfying array demands while keeping UWB characteristics directed us toward the design of this novel single element. This structure has been utilized to construct a 1×4 linear antenna array in order to achieve a better SLL and a more directive pattern than the previous designs as confirmed by the simulation results presented and discussed in detail in the paper.

The rest of this paper is organized as follows. Section 2 describes the configuration of the single antenna and reviews its characteristics such as the co- and cross-polarized radiation patterns, group delay, and the simulated and measured S_{11}. In section 3, the proposed array design is discussed in detail and the main features like side lobe level, array gain, and E- and H- plane patterns are fully studied. Conclusion is provided in section 4.

2- SINGLE ELEMENT DESIGN AND SIMULATION RESULTS

A. Geometry

A UWB antenna was initially designed. The top and bottom view of the proposed UWB antenna is shown in Figure 1. It is in the x-y plane (W1 along x-axis and L1 along y-axis). As illustrated, the antenna contains a tapered microstrip line, a semi-elliptical radiating patch, and a defected ground structure. The width (W2) of the feeding microstrip line is set to have the impedance of 50 Ω. Salient parameters of the proposed antenna are shown in Table 1. The substrate chosen here is TACONIC TLC-30. Its thickness is 1.58 mm, the relative permittivity (ε_r) is 3 and the metal cladding thickness is 35 μm.



(a) (b)

Figure 1: Antenna Layout a) Top View and b) Bottom View

TABLE 1
ANTENNA PARAMETERS

Parameters	Size (mm)
L1	34
L2	6
L3	13
L4	5
L5	13.5
L6	12
W1	25
W2	4
W3	3
W4	6
R1	7.5
R2	7.5

B. Parametric Study

The proposed antenna is simulated by a CST Microwave Studio commercial software as well as Transient Solver. Simulation results confirm the ultra-wideband characteristic of the proposed antenna.

A parametric study was carried out to achieve ultra-wideband frequency span by using CST Microwave Studio. Obviously, each geometrical parameter has effects on the performance of the proposed antenna.

The simulated reflection coefficient of the antenna as a function of frequency for different values of *W3* (w3=2, w3=3, w3=4) with other parameters fixed is shown in Figure 2. Actually, a tapered microstrip feed line has been chosen to obtain a wider bandwidth. This type of feed line has a significant effect on the bandwidth of the proposed antenna. When W3 is set to be 2mm, it shows a proper behavior for the frequencies between 3GHz and 6GHz, but it deteriorates the reflection coefficient for the frequency span of 6GHz to 9GHz. When W3=4, an opposite behavior is obtained in comparison with the previous case. Figure 2 confirms that when it is set to 3 mm, both positive aspects of the previous two cases are satisfied and consequently it is the optimal parameter.

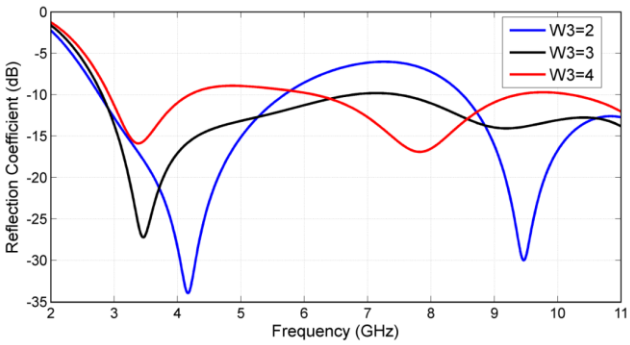


Figure 2: The effect of W3

Figure 3 shows the effect of L5 on the reflection coefficient while other parameters are fixed. The reflection coefficient for three different values of L5 (L5=12 L5=13.5, L5=15) is presented below. L5 should be set at 13.5 to achieve an ultra-wideband characteristic. The reflection coefficient goes above the -10 dB line in the frequency range of about 4.5 GHz to 9.5 GHz by increasing the size of L5.

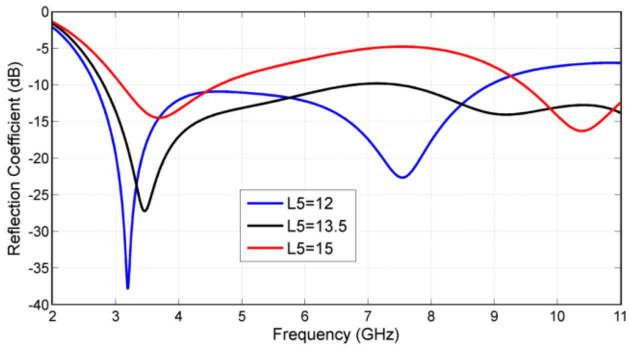


Figure 3: The effect of L5

C. Radiation Pattern of the Single Element

The simulated co- and cross-polarized radiation patterns of the proposed antenna in E-plane (φ=90) and H-plane (φ=0) at three individual frequencies of 4GHz, 6GHz and 10GHz are shown in Figure 4. It shows that the antenna can give a nearly omnidirectional characteristic in the H-plane and quasi omnidirectional pattern in the E-plane. The antenna exhibits stable radiation patterns and a perfect cross polar isolation in the entire band of operation. Also, at the high-end frequency near to 10.0GHz, the cross polarization in the H-plane pattern is increased. It is so primarily because of the fact that the antenna becomes electrically large at high frequencies and many other high-order resonant modes are excited.

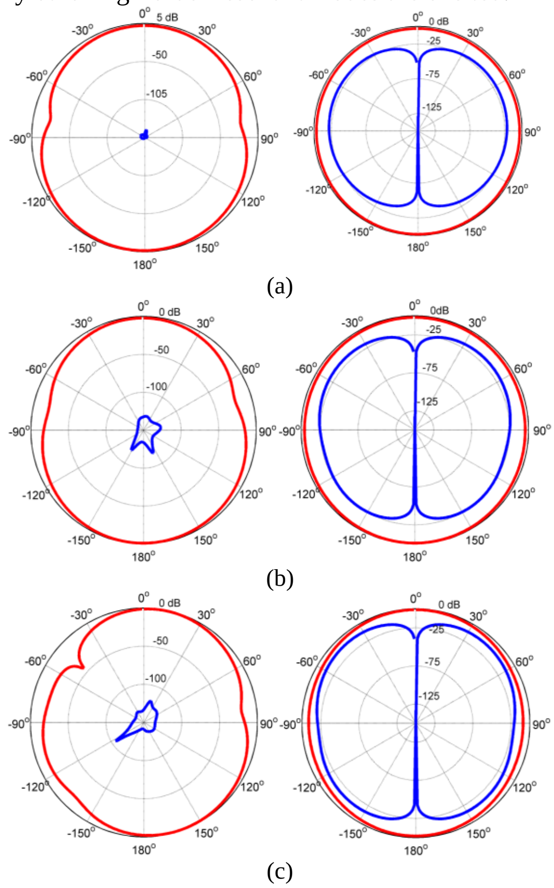


Figure 4: Co (red) and Cross (blue) Polarized Patterns at 4 GHz, b) 6 GHz, and c) 10 GHz in E-plane (Left) and H-plane (Right)

D. Group Delay

The shape of the transmitted electrical pulse should not be distorted by the antenna in UWB systems. A benchmark for this purpose is an acceptable group delay. Group delay is defined as the derivative of the far field phase with respect to the frequency which represents the distortion of pulse signal [19]. The group delay needs to be constant, in the range of (-1 ns, 1 ns) [20] over the entire band to avoid distortion of the radiated and received pulse. Figure 5 shows that our proposed antenna has a small group delay less than 0.5 ns over the frequency span of 4GHz to 11GHz, and, in comparison to [13], our design has a more constant group delay.

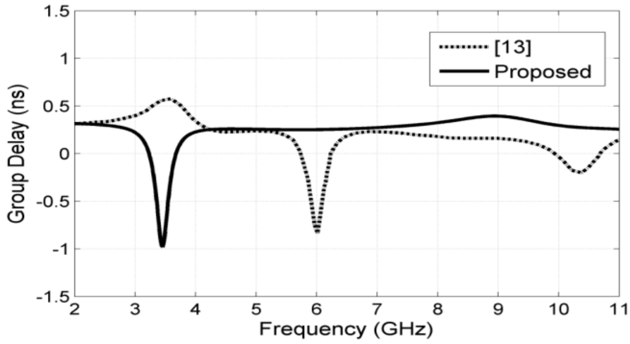


Figure 5: Group Delay comparison of the antenna in [13] and the proposed antenna

3- MEASUREMENT RESULTS

E. Antenna Configuration

The proposed antenna has been fabricated on a dielectric substrate of TACONIC TLC-30 with the relative permittivity (ε_r) of 3 and the thickness of 1.58 mm. Then, a SMA connector is soldered on the port of the feeding microstrip line. The photograph of the antenna can be seen in Figure 6. The size of proposed antenna is reduced about one half in compared to the one given in [13].

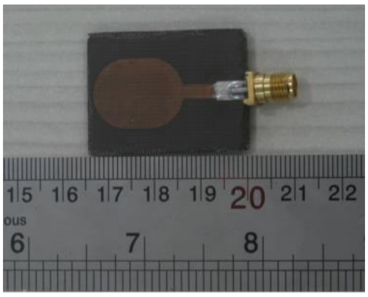


Figure 6: Antenna Photograph

F. Measured Reflection Coefficient

The reflection coefficient performance of the fabricated prototype was measured by using a HP 8510 network analyzer. The simulated and measured reflection coefficients of the proposed antenna due to the optimum parameters are shown in Figure 7. The measured S_{11} is under -10 dB line in the frequency range of 3.1GHz to 10.6GHz, required for UWB systems. The experimental result has shifted slightly compared to that of the simulated S_{11}. This may be due to the errors of antenna fabrication and the SMA connector soldering, which affect the measurement though not considered in the simulation.

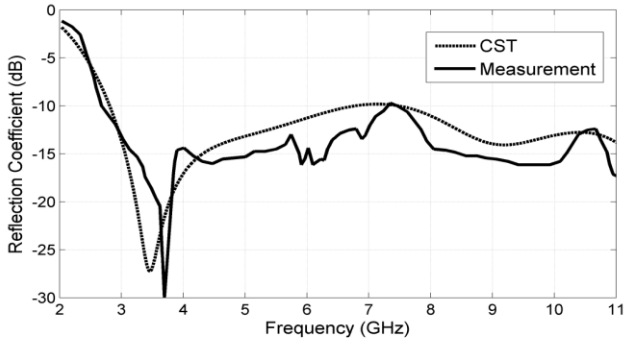


Figure 7: Simulated and Measured S_{11}

4- LINEAR ARRAY DESIGN

G. Array Configuration

Four UWB antennas are placed along the E-plane in a uniform linear array configuration as shown in Figure 8. E-plane structure is proposed due to simple fabrication and high gain features. For narrowband antenna arrays, the element spacing should be less than one wavelength λ to avoid grating lobes and also to minimize the fading correlation and mutual coupling between elements. But in ultra-wideband antenna arrays, which operate at very large frequency bandwidth, it is not obvious how the element spacing should be in terms of wavelengths to avoid grating lobes in the whole UWB frequency span.

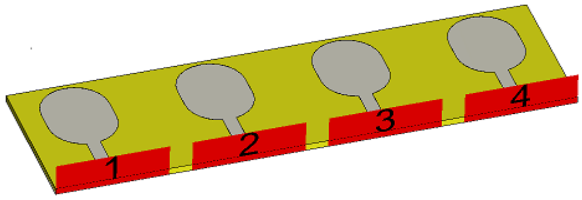
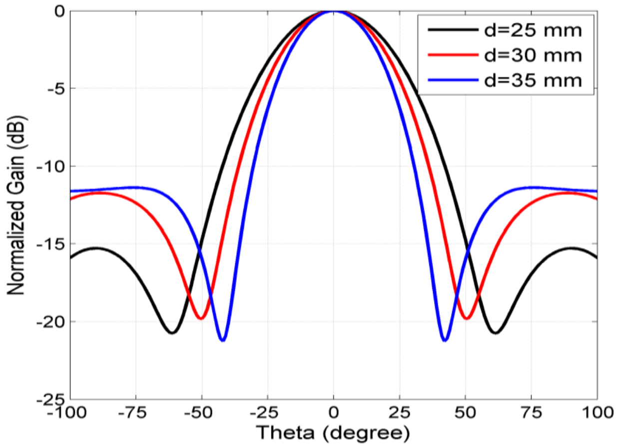


Figure 8: Array Configuration

H. Element Spacing Optimization

Applying parametric studies can be a good solution to reduce the effect of element spacing on the antenna array performance. In this paper, the mutual coupling effect on the performance of UWB linear antenna array such as SLL and the array gain is studied. Initially, we use uniform amplitude and phase distributions. The mentioned UWB array is fed by means of four microstrip lines independently to consider mutual coupling between antennas regardless of the feeding network. The distance between elements, which is called d here, is the most important parameter that affects mutual coupling. Obviously, a large distance results in less mutual coupling effects, and consequently a better isolation between array elements can be achieved.

Figure 9 illustrates the H-plane normalized gains at different frequencies of 3GHz, 6GHz and 10GHz, for three various element spacing values of d=25 mm, d=30 mm and d=35mm. This parametric study is done to find optimal d with respect to the lowest SLL over the whole UWB frequency range. As confirmed by the results, when d is set to 25mm, the lowest average SLL in the operating bandwidth is obtained. Hence, d=25 mm is the optimal distance for our design.



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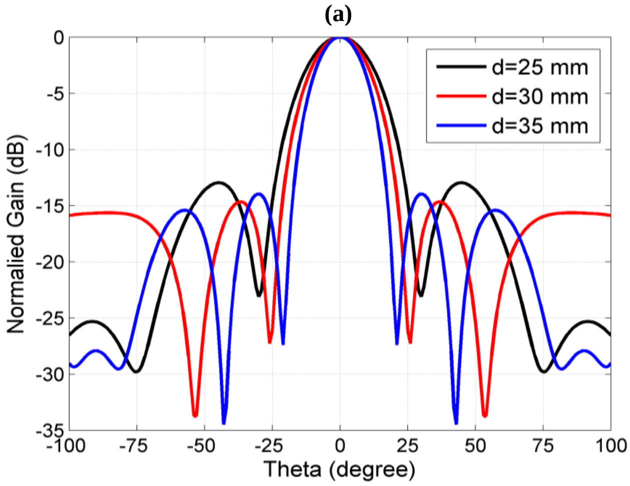

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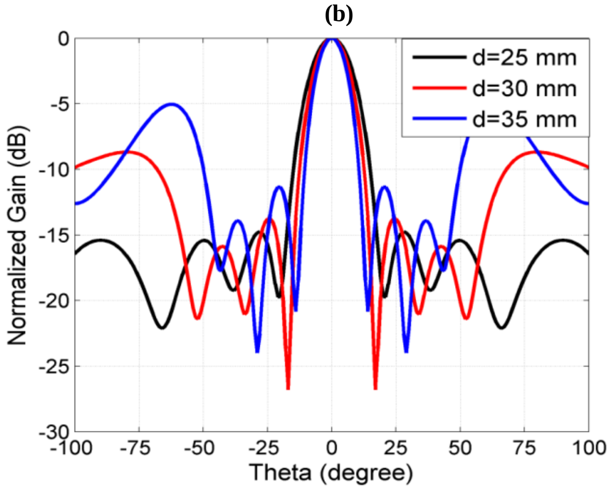


(c)

Figure 9: Normalized Gain at a) 3GHz, b) 6GHz, and c) 10GHz

The following relation [21] states that the half power beamwidth of a uniform linear array decreases in case of decreasing (λ/d) for a fixed number of elements:

$$HPBW = 2\sin^{-1}(0.4429\frac{\lambda}{Nd}) \quad (1)$$

where λ is the wavelength, N is the number of array elements, and d is the element spacing value. Figure 9 verifies that sharper beamwidths are achieved by increasing frequency for a fixed element spacing value, and also by increasing element spacing value for a constant frequency in the proposed antenna.

There is always a trade-off between half power beamwidth and SLL [13]. To achieve lower side lobe levels, some tapering amplitude distribution methods were proposed such as binomial, triangular, Taylor and Dolph-Chebyshev. Here, we use Dolph-Chebyshev method to reduce the side lobe level. The amplitudes of the elements are 0.58, 1, 1, and 0.58, respectively, to achieve -20 dB side lobe level. Figure 10 shows H-plane patterns of our antenna array for two cases of uniform distribution and Dolph-Chebyshev distribution in comparison with the four-element array pattern with Dolph-Chebyshev amplitude distribution in [13] at 6GHz. By applying Dolph-Chebyshev coefficients to the proposed array, a 10dB SLL improvement is obtained in comparison with the case of uniform distribution. Besides, the SLL is reduced about 8dB in comparison with the four-element array in [13], at 6GHz.

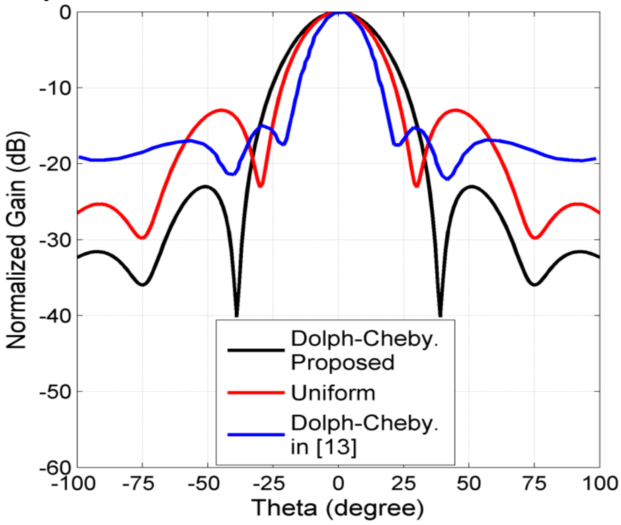


Figure 10: Normalized Gain Comparison of the antenna in [13] and the proposed antenna (for both uniform and Dolph-Chebyshev distributions)

Figure 11 shows the array gain for three different element spacing values and the single element in the UWB frequency range. In most of the frequencies between 3 GHz and 11 GHz, the gain of the array is about 6dBi more than that of the single element. The array gain is increased and the element spacing value increased until a grating lobe is produced. Grating lobes usually occur around d=λ. By increasing the frequency, the element spacing becomes electrically large with respect to wavelength, and hence the effect of mutual coupling decreases, which results in gain enhancement. The results in Figure 11 confirm that the proposed array follows this rule. The value of λ at 10 GHz is 30mm. Consequently, for d ≥ 30mm, grating lobe appears in lower frequencies in comparison with the case d=25 mm is used. This phenomenon results in gain decrease at lower frequencies for d>30 mm. The array gain for d=25 mm is stable through the bandwidth and also has an approximately linear increasing curve. Figure 12 illustrates an array gain comparison between the proposed array and the arrays in [13] and [22]. The element spacing values for the antenna array in [13] is 44 mm and in [22] is 28 mm. Although the element spacing value in our array structure (d= 25 mm) is less, the average gain of our design is more, and the curve of the gain is more flat. As mentioned above, the gain decrease of the proposed array for larger frequencies is noticeably less than the designs given in [13] and [22].

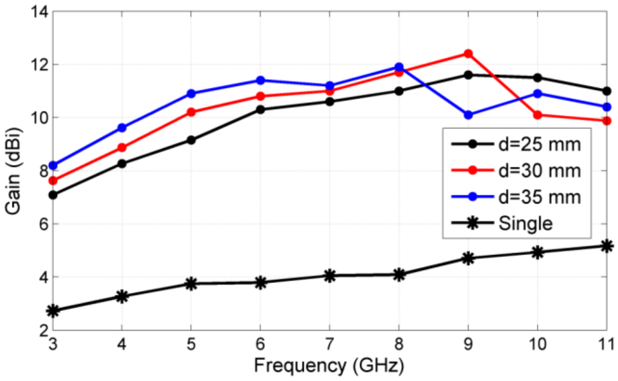


Figure 11: Antenna Gain for Array and Single Element Structures

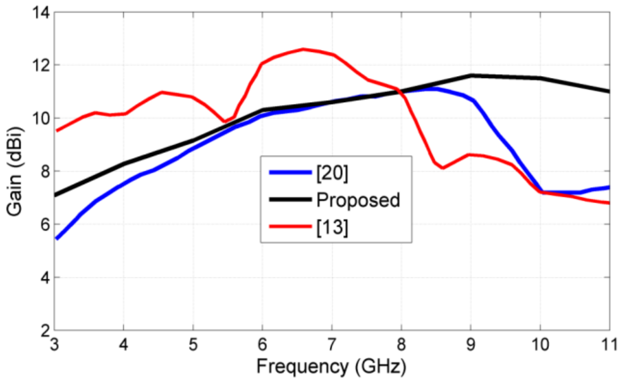
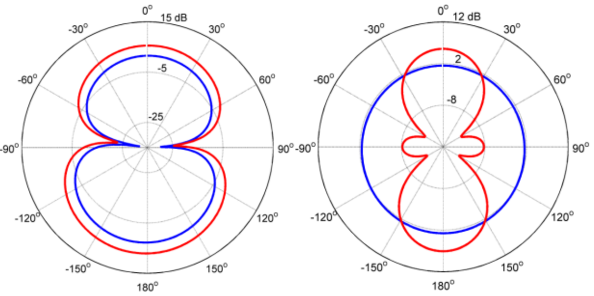


Figure 12: Array Gain Comparison for the antenna arrays in [13], [20], and the proposed array

I. Simulated Radiation Pattern and reflection coefficient for Optimized Array

E-plane and H-plane radiation patterns of the optimized array, with d=25 mm, are shown in Figure 13 for the frequencies of 3GHz, 6GHz, and 10GHz. The radiation pattern intensity is increased noticeably for both E-plane and H-plane, for array configuration in comparison with the single element design in the whole UWB band. Although the antenna becomes more directive in general, the directivity of the array in H-plane is obviously enhanced, while the enhancement in E-plane is less due to the characteristics of linear array. It indicates that the H-plane patterns are more directional with frequency increment because the radiations of the antenna elements add up in the H-plane. Another feature to be stated is that the H-plane radiation patterns, which are nearly omnidirectional for a single element design, become bidirectional for the four-element array design.



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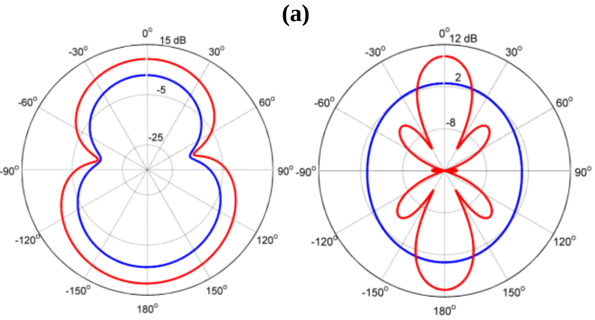

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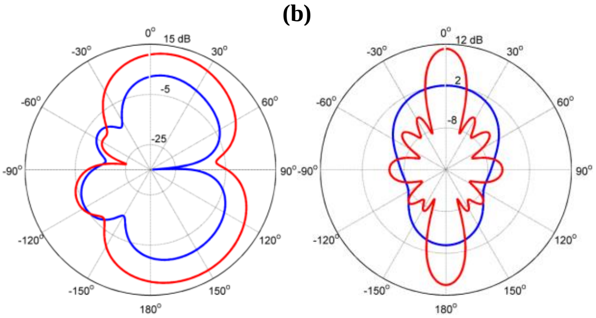


(c)

Figure 13: E-plane (left) and H-plane (right) patterns for single (blue) and array (red) designs at a) 3 GHz, b) 6 GHz, and c) 10 GHz

The simulated reflection coefficients of the optimized array antenna are shown in Figure 14. This figure shows that S_{11} is under -10 dB line in the frequency range of 3.1GHz to 10.6GHz, required for UWB systems.

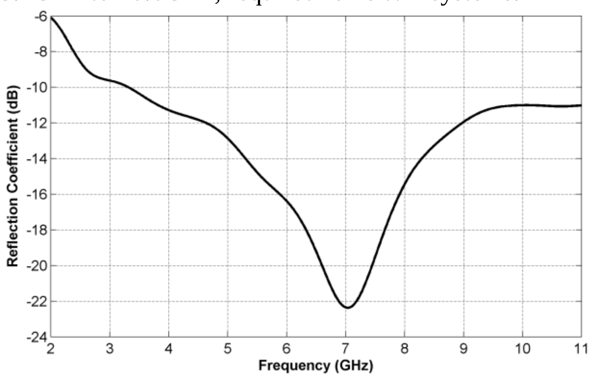
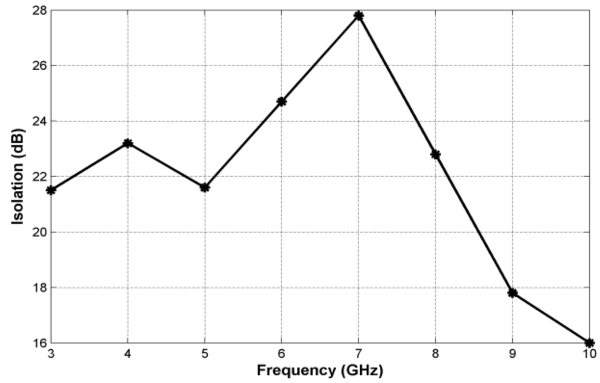


Figure 14: Simulated S_{11} of proposed array

The isolation curves of the co- and cross-polarized radiation patterns of the proposed antenna in E-plane (φ=90) and H-plane (φ=0) are shown in figure 15. These curves illustrated the isolation values between co- and cross-polarized in dB. The array antenna exhibits a perfect cross polar isolation in the entire band of operation, about more than 16 dB for H-plane and more than 145 dB for E-plane.



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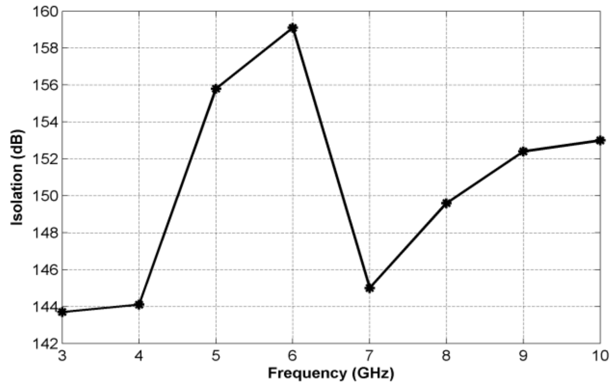

(b)

Figure 15: Isolation values in dB between Co- and Cross-Polarized radiation patterns for H-plane (a) and E-plane (b)

5- Conclusions

In this paper, a complete study of the proposed single element microstrip-fed UWB antenna and its four-element E-plane array has been presented. The single antenna has a compact size of 25×34×1.58mm^3. Good consistency between the simulated and measured reflection coefficients was observed for the UWB frequency span. The omnidirectional pattern of the single antenna made it suitable for any UWB applications. However, to satisfy the requirements of target detection applications, a 1×4 array design was proposed. A small element spacing value (d=25mm) is achieved by a parametric study method. The simulated array gain was increased about 6dBi in UWB range compared to that of the single one. In addition, to achieve a lower side lobe level, the Dolph-Chebyshev coefficient method has been chosen for the amplitudes of the array elements resulted in a 10dB SLL improvement in comparison with the case of uniform distribution. Finally, E-plane and H-plane radiation patterns of the optimized array were illustrated and compared to the single element patterns. The results showed that a remarkable increment in directivity can be obtained in H-plane. In conclusion, the features such as flat gain and stable pattern for both the single and array configurations make this design appropriate for UWB wireless and target detection applications, respectively.

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7- BIOGRAPHIES

Reza Gholami was born in Sari, Iran, in June 1989. He received both of his B. Sc and M. Sc. degrees in Electrical engineering-Electromagnetics from Babol Noshirvani University of Technology (NIT), Babol, Iran in 2011 and 2013, respectively. He has been the author of several papers and some will be published in near future. His research areas include Computational Electromagnetics, Antenna and Phased Arrays Antennas Design and Measurement, and Electromagnetic Optimization by Evolutionary Algorithms.

Bijan Zakeri was born in Babol, Iran, in 1974. He received his B.Sc. degree in electrical and electronics engineering from the University of Guilanin 1990, and M.Sc. and PhD degrees in Electrical Engineering- Fields Branch from Amirkabir University of Technology (Tehran polytechnic) in 1993 and 2007, respectively. From 1993 to 2007, he was with Islamic Azad University as a lecturer. In addition, he was the technical manager and radar system designer of an industrial corporation from 1999 to 2010. He is currently an assistant professor of Faculty of Electrical and Computer Engineering in Babol Noshirvani University of Technology. His main research interests include antenna design, RF and Microwave, and radar system design. He has authored several journal and conference paper.

Hossein Mehrpourbernety (M’76) was born in Sari, Iran, in September 1987. He received his B. Sc degree in Electrical Engineering in Communication Branch from Ferdowsi University of Mashhad, Mashhad, Iran, in 2010. He is currently pursuing the M. Sc. Degree Communication Branch form Babol Noshirvani University of Technology, Babol, Iran. He became a student member of IEEE in January 2012. He has been the author of several conference papers and some will be published in near future. His main research interests are in small, planar ultra-wideband and super-wideband antennas and electromagnetic scattering.