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DESIGN OF DOUBLE DIPOLE ANTENNA WITH ENHANCED USABLE BANDWIDTH FOR WIDEBAND PHASED ARRAY APPLICATIONS

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Abstract—In this paper, the regular microstrip-fed dipole antenna with simplified balun is modified to improve the usable bandwidth by increasing the stability of the radiation patterns. The presented antenna consists of two parallel dipoles of different lengths to obtain two main resonances. The distance between the two dipoles is adjusted to reduce the return loss between the two main resonances. A wide usable bandwidth of more than 84% is obtained with high radiation pattern stability. The proposed antenna is simple and small in size. The results of a modified two-element array configuration from this antenna show that it is very good candidate for wideband phased array applications.

1. INTRODUCTION

In the latest years, microstrip antennas have gained a wider and wider popularity. That is because they exhibit a low profile, small size, lightweight, low manufacturing cost, high efficiency, and an easy method of fabrication and installation. Furthermore, they are generally economical to produce since they are readily adaptable to hybrid and monolithic integrated circuits fabrication techniques at radio frequency (RF) and microwave frequencies [1]. The present areas that extensively explore microstrip antennas are phased arrays and spatial power combiners [2, 3]. In these applications, there is a particular interest to obtain an increased operational bandwidth of the array, which implicitly means the need for wideband antenna element.

The antenna element used in such applications needs also to have certain specifications to further improve the overall system performance. These include stable radiation patterns, polarization purity, and high gain and efficiency in the entire operating band. In addition, wide 3 dB beamwidth is required to allow for wide scanning capabilities. Besides, end-fire radiation with high front-to-back ratio is important to make it easy to realize a 2D array by stacking many cards of linear arrays. This allows space for RF front-end circuitry, such as low-noise amplifiers (LNA), mixers, etc., behind the antenna aperture [11]. The low coupling between array elements is also required in phased array systems in order to avoid scan blindness and anomalies within the desired bandwidth and scan volume. Among the most widely used printed antennas in phased array systems are tapered slot antennas (TSA) [4–9] and quasi-Yagi antennas [10–15].

The stripline-fed TSA array was originally introduced in [4]. Its potential for wideband (multi-octave) and relatively widescan arrays makes it good candidate for high-performance phased array systems [5–9]. However, these TSAs usually require a microstrip-to-slot or coplanar waveguide (CPW)-to-slot transitions as part of their feeding network, which not only increases the design complexity but also imposes a limit on their intrinsically broad frequency bandwidth [11]. In addition, they need large number of contoured vias, computed in [7] to be more than 7 vias/λ_g, to eliminate scan blindness, which adds more complexity and cost. Besides, they usually have larger electrical size than resonant type patches or slots and often suffer from the excitation of substrate modes, which can result in reduced efficiency, strong crosstalk between antennas in an array environment, and perturbed radiation patterns [13].

The microstrip-fed quasi-Yagi antenna is based on the Yagi-Uda antenna, firstly presented in 1928 [10]. The quasi-Yagi antenna consists of a half wavelength dipole and an approximately quarter wavelength rectangular director to increase the gain and improve the front-to-back ratio. This antenna exhibits much smaller size than the TSA. A large operational bandwidth of 48% for VSWR < 2 was demonstrated in the X band [11–14]. By replacing the dipole and the director of the quasi-Yagi antenna by a bow-tie the bandwidth improved to 60%, and the antenna size was reduced 20% [16]. Further research resulted in a novel microstrip-fed printed antenna, called printed Lotus antenna, with a modified balun [17]. The printed Lotus provides 57% bandwidth for VSWR < 1.5, and 60% relative to VSWR < 2. However, the balun in these designs is based on a half wavelength ($\lambda_g/2$) delay line, which is designed at the center frequency (f_c). This narrow band delay line limits the bandwidth of the antenna as reported in [17]. In addition, the radiation patterns are deteriorated as frequency goes way from f_c, especially in the E-plane.

Alternative method of feeding such antennas is presented in [18–

25], where one half of the antenna; dipole or bow-tie, is printed on the top substrate layer and connected to the microstrip feedline, while the second half is placed on the bottom substrate layer and connected to the ground plane. Doing that avoids using balun and simplifies antenna geometry. In addition, one can obtain end-fire radiation patterns of good front-to-back ratio out of these designs [21, 23–25]. Wide bandwidths of 40%, 50% and 91% are obtained in [23, 24], and [25], respectively. The stability of the patterns in this design depends on the substrate height and the resonator itself. If the substrate height is large relative to the free space wavelength (λ_0) at the upper operating frequency, unstable patterns are obtained at higher frequencies [23, 25], which results in decreasing the usable bandwidth of the antenna. Also, if the antenna has only one main resonance at the operating band, distorted pattern is expected at high frequencies, where the antenna size is much bigger than $\lambda_g/2$. Such problems can be solved by using antennas with small substrate height, and multi-resonators, where each resonator preserves pattern stability around its resonant frequency.

This paper presents a new antenna design of wide bandwidth. The proposed antenna is fed by one microstrip line, and it consists of two parallel dipoles with different lengths to obtain at least two main resonances. The presented design has many advantages over all existing antennas used in phased arrays and power combiners. Beside its wide bandwidth and small size, the antenna exhibits stable radiation patterns, low cross polarization, high efficiency and gain, and wide 3 dB beamwidth, in the entire operating band. The return loss, input impedance and far field radiation characteristics of this antenna are presented. Results of a modified two-element array configuration are also presented. All results in this paper are based on a FDTD based code designed by the author.

2. ANTENNA GEOMETRY

The schematic and parameters of the proposed antenna are illustrated in details in Fig. 1. The antenna consists of two dipoles of different lengths. The left halves of the two dipoles are on the top substrate layer, while the right halves are on the bottom one. The upper and lower halves are then connected to a microstrip feed line with a truncated ground plane through two printed microstrip lines on the top and bottom layers. The truncated ground plane acts as a reflector to produce an endfire radiation pattern. The top layer, as shown in Fig. 1, can be divided into three sections. Section one is a 50Ω microstrip line of length L_f and width W_f. Section two is an extension of the feedline with length L_1, which is connected to the long dipole of length L_{d1}

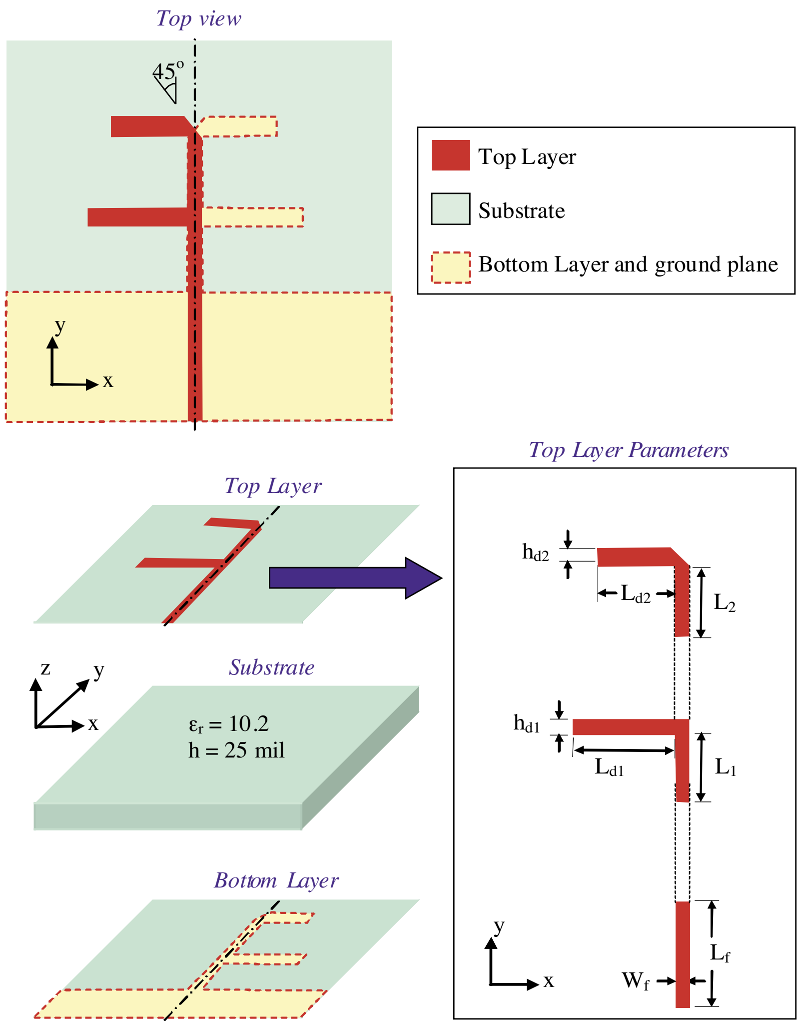

Figure 1. The geometry and parameters of the double dipole antenna.

and height h_{d1}. Section three is an extra extension of the feedline with length L_2, which is connected to the short dipole of length L_{d2} and height h_{d2} through a 45° mitered transition. The proposed antenna is printed on a Rogers RT/Duroid 6010/6010 LM substrate of a dielectric constant of 10.2, a conductor loss ($\tan\delta$) of 0.0023 and a thickness of 25 mil (0.635 mm).

The operation of this antenna depends mainly on both the high dielectric constant substrate material and antenna shape. Due to the high dielectric constant substrate material, most of the electromagnetic field is concentrated in the dielectric between the conductive strip and the ground plane and travels on the surface in the transverse directions in y and x directions, supported by the electric currents in the two halves of the dipoles, and the fringing fields at the far edges of the dipoles, respectively. However, the fringing field is much weaker. The truncated ground plane reflects the radiated fields in the $-y$ direction, which results in an end fire radiation.

The antenna shape is playing the main role in the antenna operating bandwidth, because it acts as a matching circuit connected to the open circuited terminal of the microstrip feedline. The lengths of the long and short dipoles control the lower and upper operating frequencies, respectively. The distance between the two dipoles and the distance between the first dipole and the truncated ground plane control the return loss level between in the two main resonances. Initial dimensions were suggested based on this knowledge, and then we modified theses dimensions to improve the bandwidth and enhance the radiation stability of the antenna.

3. ANTENNA RESULTS

The final design of this antenna has $L_1 = 5.2$, $L_{d1} = 5.7$, $h_{d1} = 0.6$, $L_2 = 4.15$, $L_{d2} = 2.7$, and $h_{d2} = 0.75$ mm. The input impedance and return loss of the final design are presented in Figs. 2 and 3, respectively. The real part of the input impedance is slightly oscillating around 50Ω between 5.3 and 15.3 GHz, while the imaginary part is fluctuating around zero, which shows the wideband characteristics of this antenna. The antenna is resonating around 5, 6, 8, 10, 12, 14 and 16 GHz. Two of these resonances may result from the lengths of the two dipoles. The longitudinal feed line along with each dipole may act as two quarter-wavelength monopole antennas. The truncation of the substrate and the ground plane also may interfere with the aforementioned resonances and change their locations, and it may cause extra resonances. By tuning the antenna parameters the return loss level between resonances is reduced and as a result wide bandwidth is obtained. The antenna operates over a wide range that extends from 5.5 GHz to 14.2 GHz. Therefore, this antenna is a good candidate for the modern wireless communications applications that require ultra wideband.

In addition, it is worth mentioning here that in spite of its large bandwidth, the width of the antenna is only 12 mm, which is approximately equivalent to 0.23 and 0.69 free space wavelength at the lower and upper operating frequencies, respectively. This length

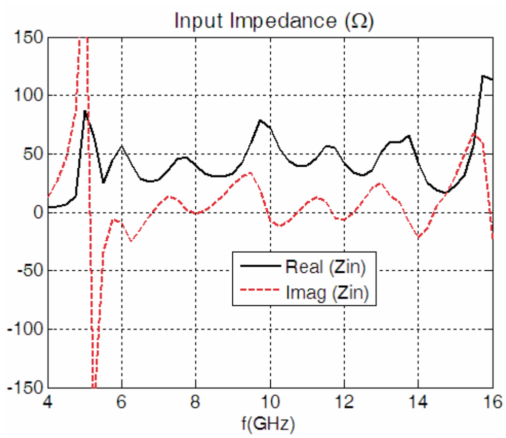

Figure 2. The input impedance of the double dipole antenna.

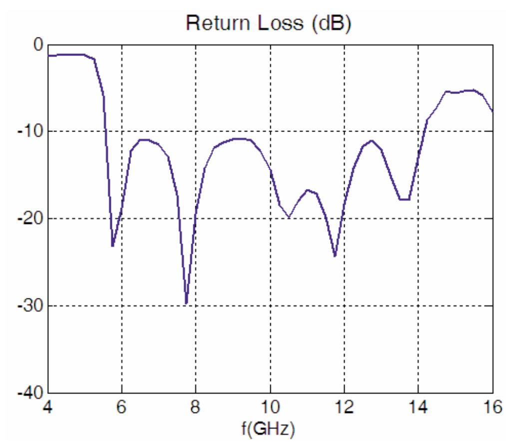

Figure 3. The return loss of the double dipole antenna.

allows this antenna to fit into phased arrays with only minor grating lobes at the frequencies.

The radiation patterns for this antenna are shown in Figs. 4 and 5, at selective frequencies that cover almost the entire operating band. In the H-plane (y-z), as shown in Fig. 4, the antenna provides end fire radiation patterns in the entire band, with high front-to-back ratios between 13 and 30 dB. The maximum cross polarization level is around -10 dB considering only the 3 dB beamwidth range. The 3 dB beamwidth spans from 60° to 150°. According to the E-plane (x-y) shown in Fig. 5, the antenna is also providing end fire radiation

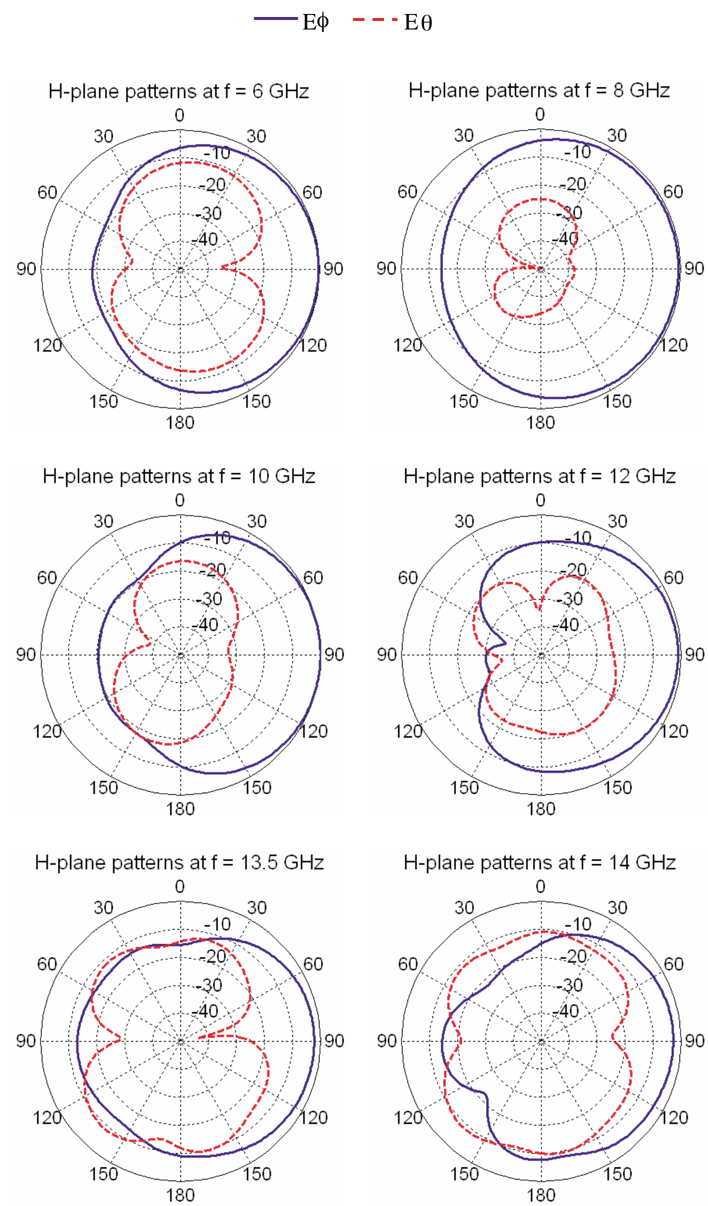

Figure 4. The radiation patterns for single element double dipole antenna in the H-plane.

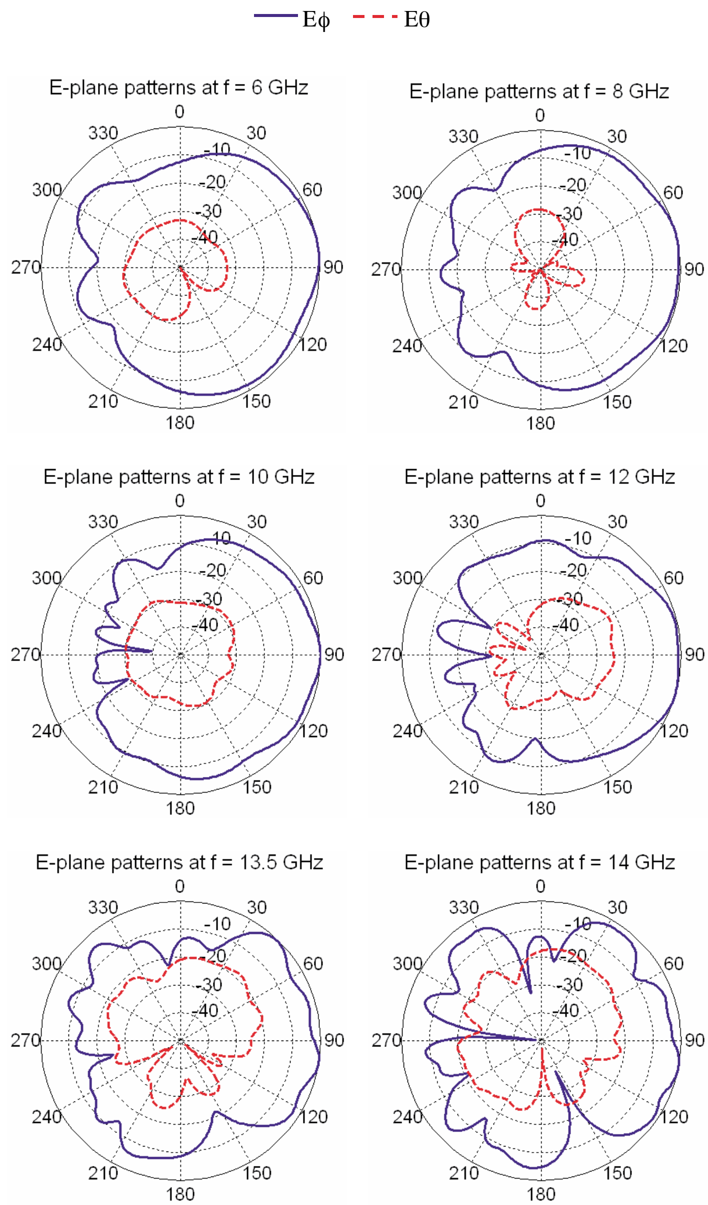

Figure 5. Radiation patterns for single element double dipole antenna in the E-plane.

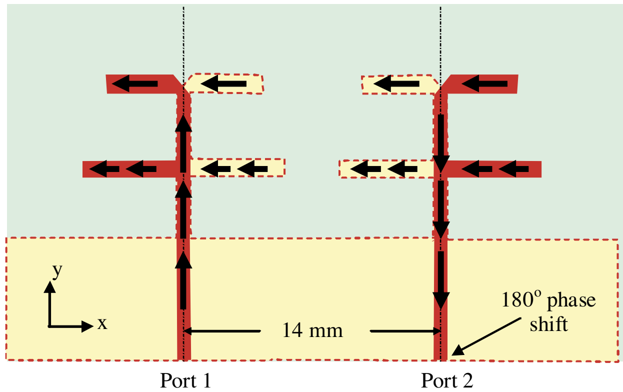

Figure 6. Geometry for a two-element double dipole antenna array.

patterns in the entire band, which is slightly distorted at 13.5 and 14 GHz. The 3 dB beamwidth spans from 65° to 120° between 6 and 14 GHz.

These results show that the usable bandwidth of this antenna is between 5.5 and 13.5 GHz, which is approximately 84%. Consequently, this antenna provides a great improvement over all present antennas in terms of usable bandwidth. Comparing this antenna with the one presented in [25], this antenna shows 24% improvement in the usable bandwidth.

4. RESULTS OF MODIFIED TWO-ELEMENT ARRAY CONFIGURATION

To test the performance of this antenna in arrays, unconventional array configuration is used to improve the radiation characteristics of the array. The proposed two-element array configuration is shown in Fig. 6. The second element is mirrored along the y-axis, and consequently a 180° phase shift is introduced at port 2 to have the same current direction in both elements. The current direction is roughly illustrated in Fig. 6. This modification is required especially at high frequencies, where the effect of the substrate height is significant, in order to provide balanced patterns. Also, this modification reduces the cross polarization level, because the electric fields between the upper and lower layers in z-direction and the electric currents in the y-direction in one antenna are opposite to those of the other antenna. The distance between elements should be as small as possible to reduce the grating lobes at high frequencies; therefore it is chosen to be 14 mm.

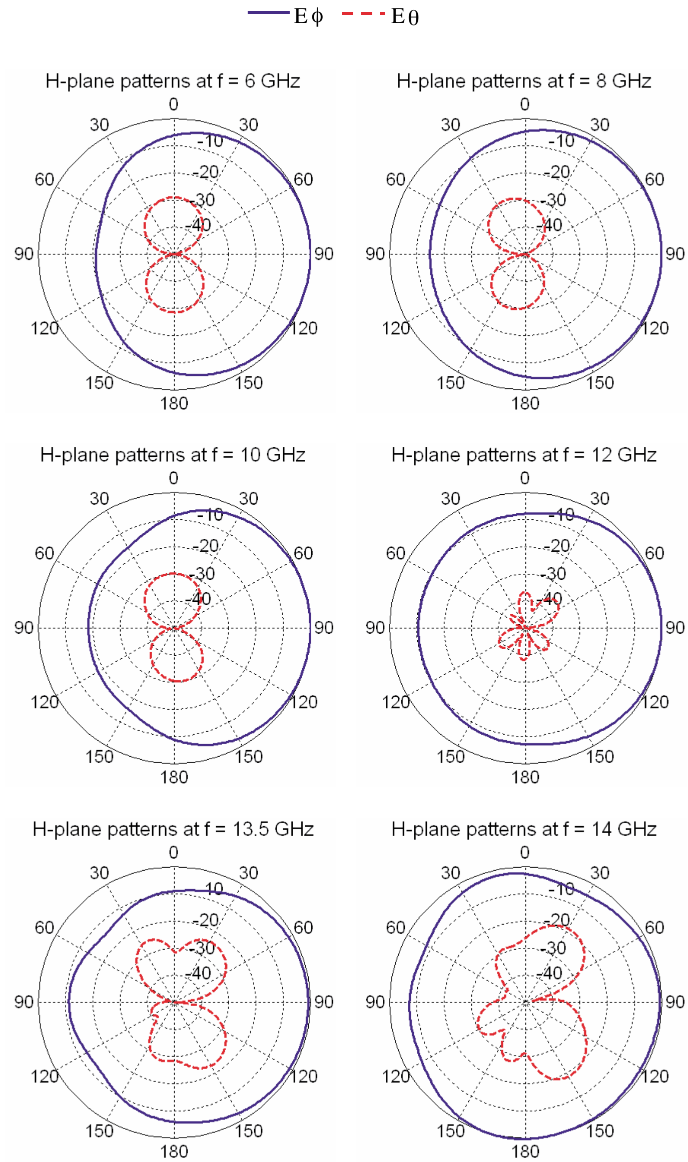

Figure 7. Radiation patterns in the *H*-plane for the two-element array shown in Fig. 6.

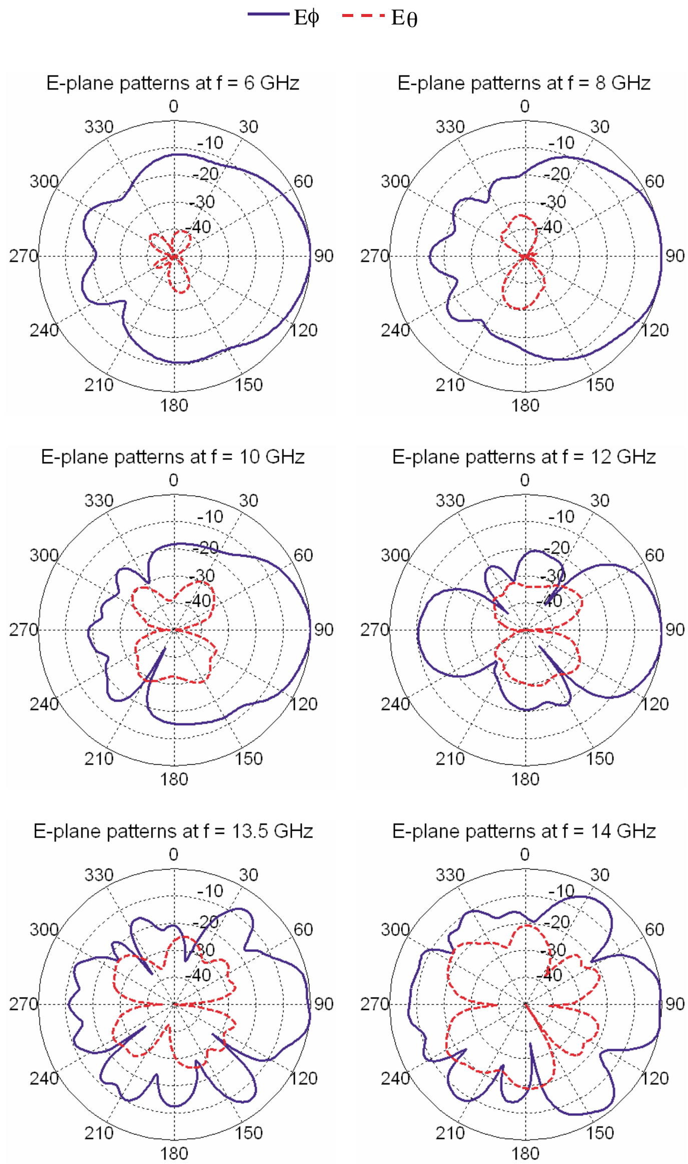

Figure 8. Radiation patterns in the E-plane for the two-element array shown in Fig. 6.

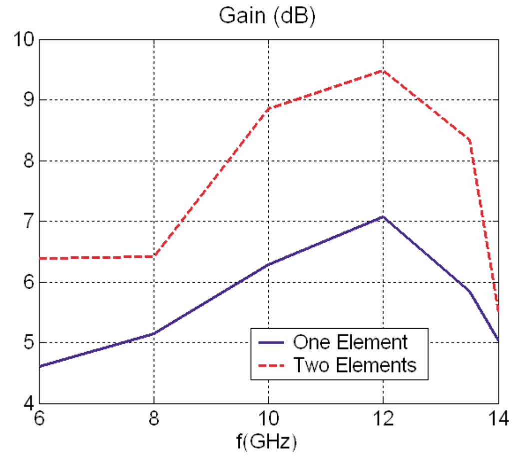

Figure 9. The gain for single element and two-element array.

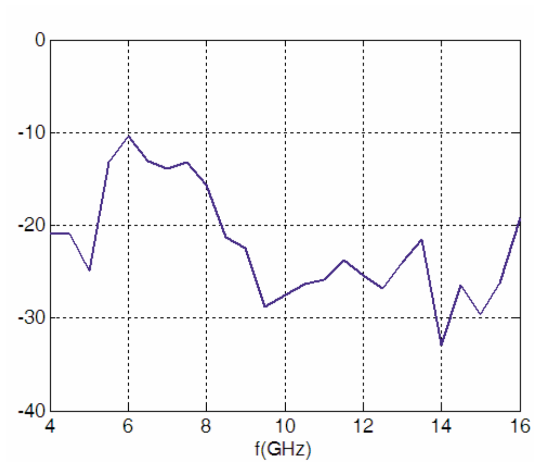

Figure 10. The coupling between elements in the two-element array shown in Fig. 6.

Figures 7 and 8 show the radiation patterns in the H- and E-planes, respectively, for the two element array at 6, 8, 10, 12, and 14 GHz. To show the improvement when using this array configuration, the radiation patterns in the H-plane presented in Figs. 4 and 7 for one element and two element array, respectively, are compared. In the two-element antenna array the cross polarization level is reduced significantly, and the 3 dB beamwidth is much wider. In the E-plane, shown in Fig. 7, the cross polarization level is also reduced, and is completely eliminated in the direction of maximum gain, due to array symmetry.

The gain for one element and two-element array is depicted in Fig. 9. The gain for one element changes from 4.7 to 7.1 dB with an average value of around 6 dB. For the two-element array, the minimum gain is 5.5 dB, the maximum is 9.4 dB, and the average is around 8 dB. Finally, the coupling between elements is presented in Fig. 10. The coupling is between −10 and −20 dB before 8 GHz, then it becomes between −33 and −20 dB from 8 to 16 GHz.

5. CONCLUSION

A new antenna design of two parallel dipoles is presented for wideband wireless communication and phased array applications. The proposed antenna design is characterized by high pattern stability, which results in significant improvement in the usable bandwidth over all similar designs. The antenna provides a wide usable bandwidth of 84%. The one element antenna produces endfire radiation pattern with high front-to-back ratio, low cross polarization level, wide beamwidth, and high gain, and these characteristics are enhanced more by using the modified two-element arrays. The antenna is excellent candidate for many applications in wireless communications and phased arrays.

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