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DESIGN OF WIDEBAND TRIANGLE SLOT ANTENNAS WITH TUNING STUB

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Abstract—This paper presents a novel design of a triangle slot antenna fed by a coplanar waveguide. The antenna consists of a symmetric triangle slot tuned by a metal stub and slot hat. The antenna exhibits a wide bandwidth of 57% for X-band frequencies with an average gain of 4.5 dB and cross polarization level of −10 dB. In addition to being small in size, the coupling between the two elements of this type antenna is in the order of −15 dB or less, which makes it a good candidate for a phased array system. A linear array of 8-elements is simulated and results indicated that a steering angle of 50° is attainable without grating lobes.

1. INTRODUCTION

In applications where size, weight, cost, performance, ease of installation, and aerodynamic profile are constrains, low profile antennas like microstrip and printed slot antennas are required. Printed slot antennas fed by coplanar waveguide have several advantages over microstrip patch antennas. Slot antennas exhibit wider bandwidth, lower dispersion and lower radiation loss than microstrip antennas, and when fed by coplanar waveguide they also provide an easy means of parallel and series connection of active and passive elements that are required for improving the impedance matching, gain [1].

Bow-tie and coplanar waveguide fed bow-tie slot antennas are planar-type variations of the biconical antenna that has wideband characteristics. A number of bow-tie slot designs are recently introduced which demonstrate wide bandwidth that ranges from 17% to 40% [2–7]. However, in order to use these antennas in a phased array system, the antenna element size must be smaller than half the wavelength at the highest operating frequency to avoid grating lobes while scanning the main beam. Thus, the separation distance between elements must be small and such spacing results in high coupling, which causes scan blindness and anomalies within the desired bandwidth and scan volume.

In this paper, a novel design of a small slot triangle antenna that supports the wideband characteristics of a bow-tie slot antenna and the low coupling characteristics between similar elements is presented. The radiation characteristics of the antenna versus its geometrical parameters are presented. The main beam direction of this antenna can be redirected 90 degrees off its original direction by simply etching the slot across two perpendicular conducting planes without loss of its main characteristics. The numerical simulation and analysis for this class of antennas are performed using the Momentum software package of the Advanced Design System (ADS) by Agilent Technologies. The ADS simulator, Momentum, is based on the solution of the mixed potential integral equations (MPIE) using full wave Green's functions for layered structures and the method of moment (MoM) technique [8]. Verifications of the ADS results are further performed by using our developed finite difference time domain (FDTD) code supported by the CPML absorbing boundary [9], and by measurements of the return loss using the HP vector network analyzer 8510C.

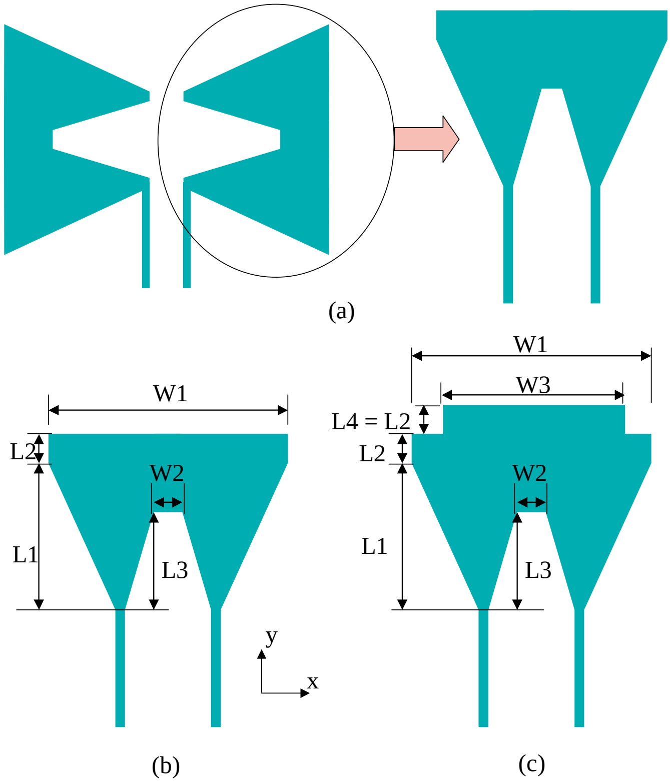

Figure 1. The proposed geometries of the triangle slot antennas with tuning stub. (a) Creating the geometry, (b) Initial design, and (c) Triangle slot with slot cap.

2. ANTENNA GEOMETRY

The proposed geometries of the triangle slot antennas with tuning stub are shown in Fig. 1. The first design is created by rotating half of a bow-tie slot antenna by 90°, and introducing a tapered metal stub and upper rectangular slot to tune the antenna, as shown in Fig. 1. In the second design, we introduced a cap (hat) slot to improve the return loss level. As shown in Fig. 1, $W1$ is the width of the triangle, $W2$ in the upper width of the stub, $W3$ is the width of the slot hat, $L1$ is the height of the triangle, $L2$ is height of the rectangular slot, and $L3$ is the height of the tuning stub. The antenna is supported by a dielectric substrate of height equals to 32 mil and a relative dielectric constant of 3.38. The coplanar waveguide is designed for a $50\,\Omega$ characteristic

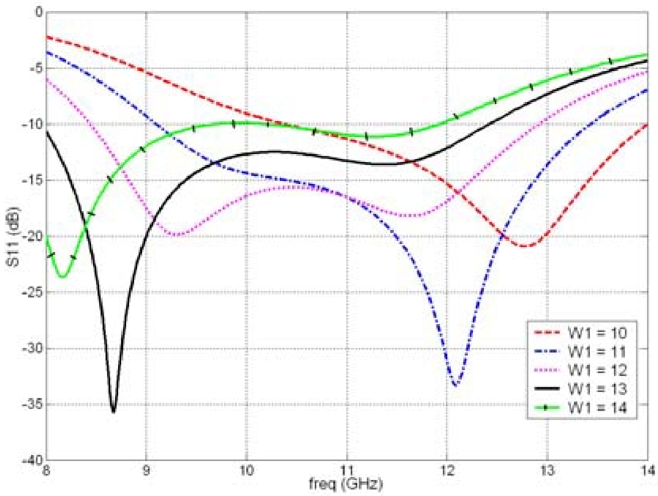

Figure 2. The effect of changing $W1$ on the return loss.

impedance with slot and feed line widths equal to 0.15 and 2.61 mm, respectively.

3. PARAMETRIC STUDY

In order to provide design criteria for this antenna, the effects of each geometrical parameter are analyzed. The parameters for the initial design of this antenna are studied based on ADS Momentum simulation results. The antenna dimensions ($W1$, $W2$, $L1$, $L2$ and $L3$) are chosen to be (12, 0.8, 8.5, 0.75 and 6 mm) and one parameter is changed at a time while the others are kept constant.

Figures 2, 3, 4, 5 and 6 show the effect of changing $W1$, $W2$, $L1$, $L2$ and $L3$, respectively. All the results in these figures show that this antenna has two resonant frequencies. As shown in Fig. 2, with the increase of W1 the two resonant frequencies shift to slightly lower frequencies. While the $W2$ variations, as shown in Fig. 3, control only the level of the return loss at the two resonant frequencies without changing their values or the antenna bandwidth. Figures 4, 5 and 6 show that changing any vertical dimension ($L1$, $L2$ and $L3$) can improve the antenna impedance bandwidth. As shown in Figs. 4 and 5, with the decrease of $L1$ and $L2$, the lower resonant frequency shifts to a lower frequency, and the higher resonant frequency shifts to a higher frequency resulting in an increase of the antenna impedance bandwidth

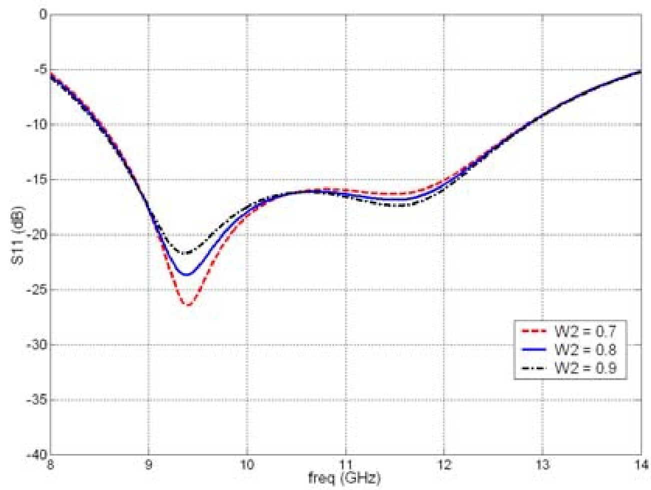

Figure 3. The effect of changing $W2$ on the return loss.

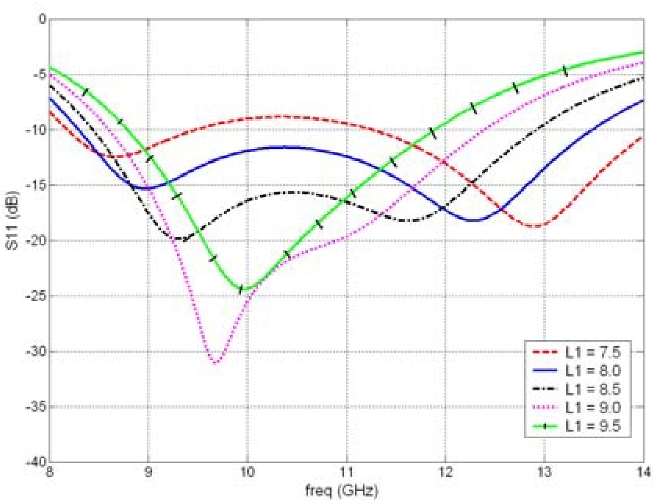

Figure 4. The effect of changing $L1$ on the return loss.

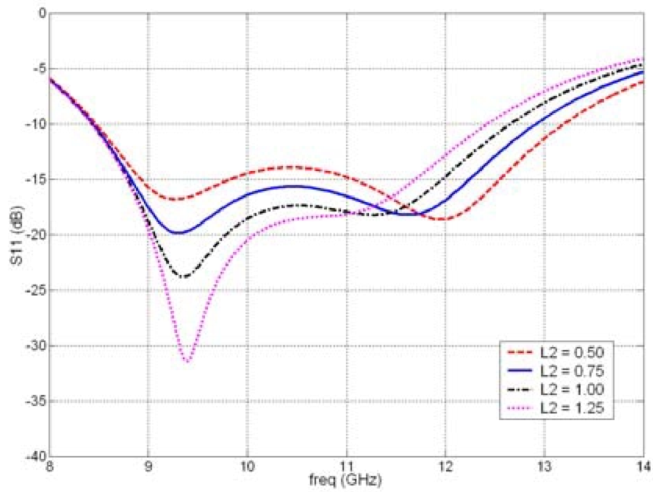

Figure 5. The effect of changing $L2$ on the return loss.

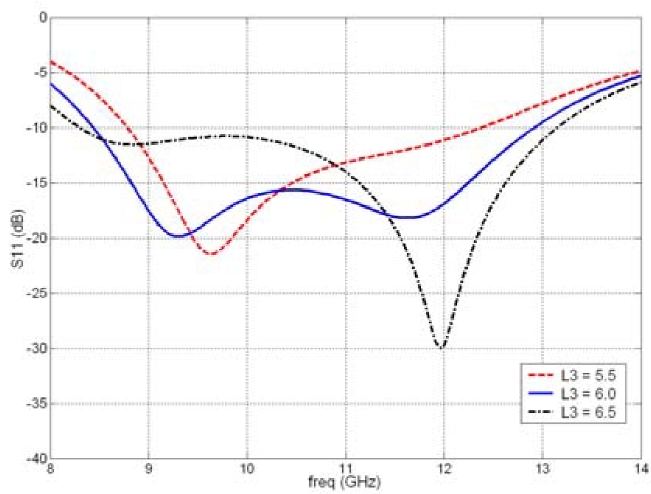

Figure 6. The effect of changing $L3$ on the return loss.

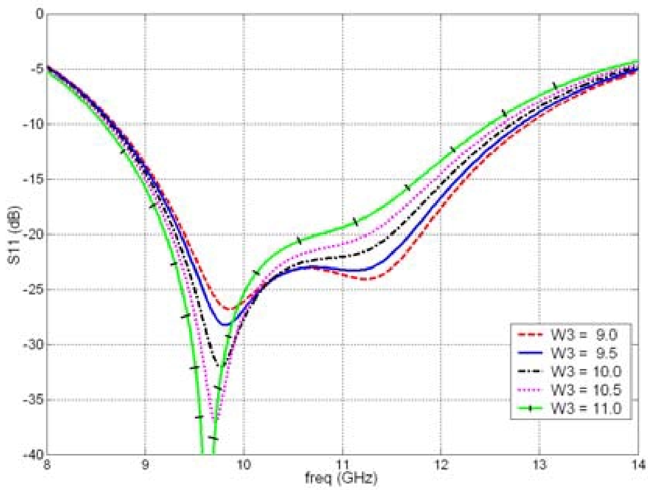

Figure 7. The effect of changing $W3$ on the return loss.

when the return loss level between the two resonant frequencies is less than -10 dB. On the contrary, as shown in Fig. 6, with the decrease of $L3$ the lower resonant frequency shifts to a higher frequency, and the higher resonant frequency shifts to a lower frequency.

From the results of Figs. 3 to 6, one may conclude that the most effective parameters for this configuration are $W1$, $L1$ and $L3$. These parameters are calculated as functions of λ_L and λ_H; the free space wavelength calculated at the lower and higher resonant frequencies, respectively. The outcomes of this analysis reveal that $W1$ should be around $0.37\,\lambda_L$, $L1$ around $0.33\,\lambda_H$ and $L3$ around $0.25\,\lambda_H$.

By adding a slot cap, as in the second design, we improved the return loss level to be less than -20 dB, and at the same time we maintained the overall impedance bandwidth, as shown in Fig. 7. The height of the cap is kept equal to $L2$ (0.75 mm) and the effect of varying the cap width ($W3$) is shown in Fig. 7. The value of $W3$ controls the return loss levels at the two resonant frequencies. As $W3$ decreases the impedance bandwidth increases, however the operating band of the antenna shifts to higher frequencies.

4. VERIFICATIONS

A triangle slot antenna with tuning stub and a slot cap of ($W1$, $W2$, $W3$, $L1$, $L2$, $L3$, $L4$) = (12.0, 0.8, 10.5, 8.5, 0.75, 6.0,

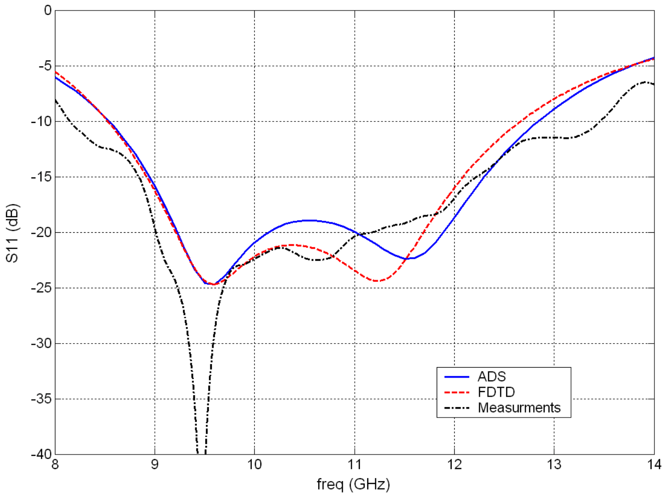

Figure 8. A comparison between the computed return loss using ADS Momentum and FDTD, and the measured return loss for a triangle slot with tuning stub and a slot cap of $W1$, $W2$, $W3$, $L1$, $L2$, $L3$ and $L4$ equal 12.0, 0.8, 10.5, 8.5, 0.75, 6.0 and 0.75 mm, respectively.

0.75 mm) is simulated using our own developed FDTD code. The same antenna is fabricated and measured using the HP 8510C network analyzer. The ground plane is truncated at 1 cm away from the triangle slot. The computed return loss using the FDTD technique and ADS Momentum, and the measured return loss are depicted in Fig. 8, where a very good agreement can easily be noticed. According to the measurements, the antenna operates from 8.1 to 13.45 with around 50% bandwidth, which covers almost all the X-band and a part form the Ku-band.

5. RADIATION PROPERTIES

ADS Momentum considers an infinite substrate even when the antenna has a finite ground plane and as a result it produces zero fields in the x-y plane. Therefore, we used the FDTD to compute the radiation pattern instead, and used ADS to calculate the gain and the directivity for an antenna with finite ground plane that is truncated at 1 cm distance from the triangle slot. The radiation patterns in the x-z (H-plane) and the y-z (E-plane) as well as the x-y plane at 10 GHz are shown in Fig. 9. The antenna has an omni-directional pattern. The

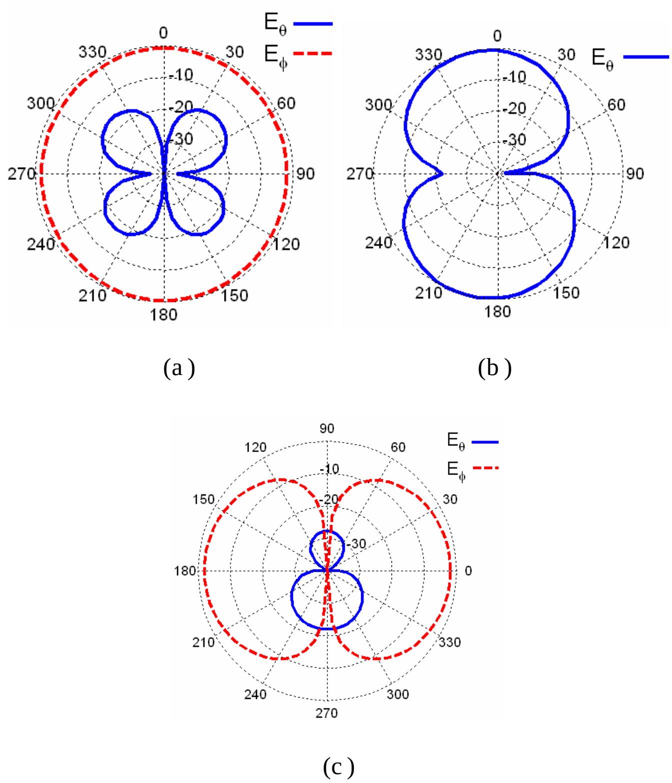

Figure 9. Radiation pattern at 10 GHz in the: (a) x-z plane (H-plane), (b) y-z plane (E-plane), and (c) x-y plane.

cross polarization level is -17 dB in the x-z plane, while it is zero in the y-z plane because of the symmetry of the antenna. The gain and directivity are calculated at selective frequencies that cover the entire operating band, and they are shown in Fig. 10. The antenna has an average gain of 4.5 dB with an average radiation efficiency of 94%.

6. ANTENNA ARRAYS

Two elements of this antenna are simulated with a parasitic upside-down triangle slot in between to decrease the coupling. The geometry and dimensions in mm of the two-element array are shown in Fig. 11, while Fig. 12 shows the coupling with and without the parasitic triangle slot, and the return loss in dB for two-element array. It is noticed that the coupling is less than -15 dB except in the range between 8 to

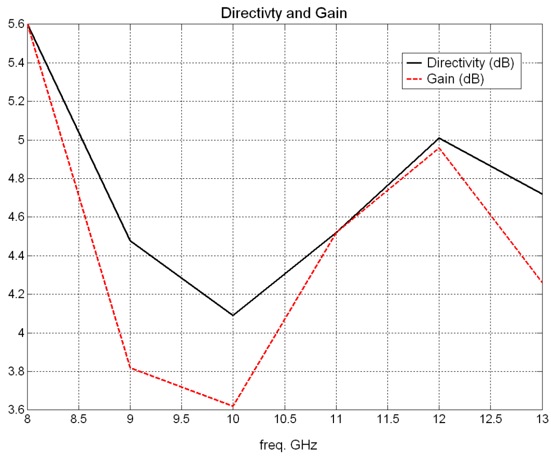

Figure 10. Computed gain and directivity as a function of frequency.

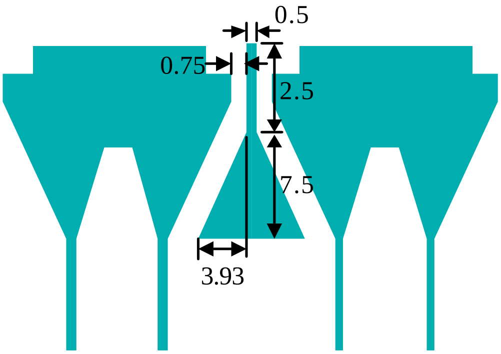

Figure 11. Geometry of two-element array of the triangle slot antenna with a separating upside-down triangle slot to decrease the coupling.

9 GHz, with a 2 mm separation distance between the two elements. This makes the antenna suitable for phased array systems because the edge-to-edge distance (d) as a function of λ_0 from 8 to 13 GHz (d/λ_0) ranges from 0.37 to 0.6, which is considered optimum for narrow beamwidth and lowering grating lobe requirements within this wide range of frequencies. Fig. 13 shows that the main beam can be steered to 50° without grating lobes using only 8-element array.

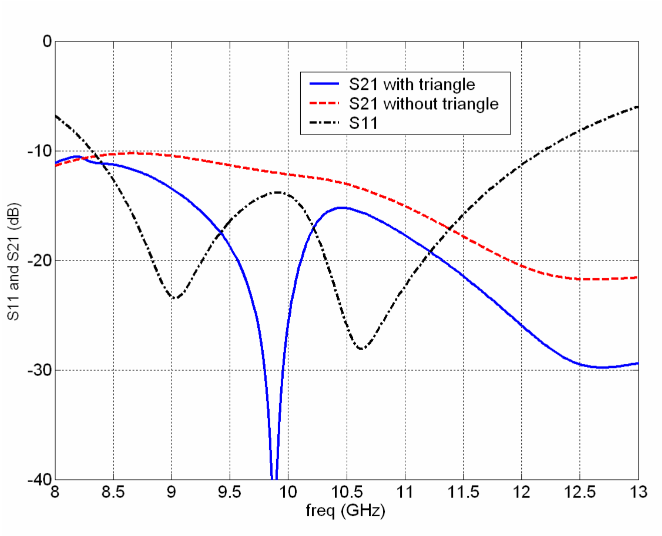

Figure 12. Return loss and coupling in dB for the two-element array in Fig. 11 with and without the upside-down separating triangle.

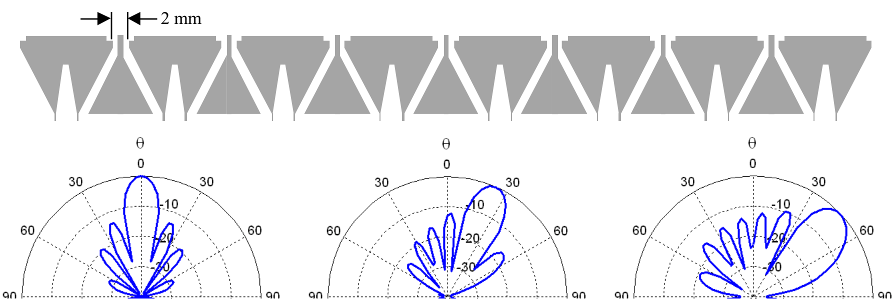

Figure 13. E_ϕ in the x-z plane (H-plane) with 8-element array of the triangle slot antenna with tuning stub at 10 GHz, at a scanning angle of (a) 0° (b) 30° and (c) 50°.

7. EFFECT OF BENDING THE ANTENNA

One approach to obtain radiation in the y-direction (end fire) for this type antenna is by making a 90° bend around the middle of the antenna. The geometry of the antenna after bending is shown in Fig. 14, where the antenna is bent at the end of the tuning stub. One would then expect a figure of eight pattern for the E_ϕ component

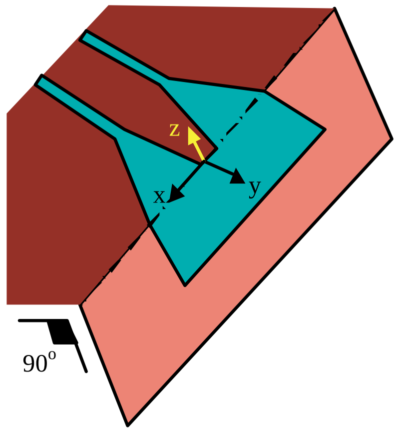

Figure 14. Geometry of the antenna after bending.

in the x-y plane (H-plane) with a resulting cross-polarized field. In the y-z plane (E-plane), we expect that the E_θ would have a maximum at 90° because of the vertical field between the edge of the tuning stub and the lower edge of the triangle slot, in addition to two maximums at 0° and 180° because of the horizontal electric current in y-direction flowing in the tuning stub. Since there is no reason to have a null in between these maxima, one would expect a uniform E_θ between 0° and 180°. At the same time, no cross polarization is expected because of the symmetry of the antenna.

The bent antenna is simulated using the FDTD code. The radiation patterns are shown in Fig. 15, where the simulation results are confirming the expectations addressed in the above paragraph. The cross polarization level in the x-y plane is -10 dB, relative to the copolarized field within the 3 dB beamwidth area. A comparison between the computed return loss using the FDTD simulations after and before bending is shown in Fig. 16, where one notices an increase in the bandwidth approaching 58%. A comparison between the measured return loss and the FDTD results is shown in Fig. 17. According to the measurements, the bent antenna operates from 8.25 to 14.8 GHz with a return loss smaller than -10 dB, for a bandwidth of 57%.

8. COMPARISON WITH BOW-TIE ANTENNAS

In order to demonstrate the advantages of this triangle slot antenna, it is worth comparing it with the class of printed and slot bow-tie antennas recently presented in [3–7]. This comparison will focus on

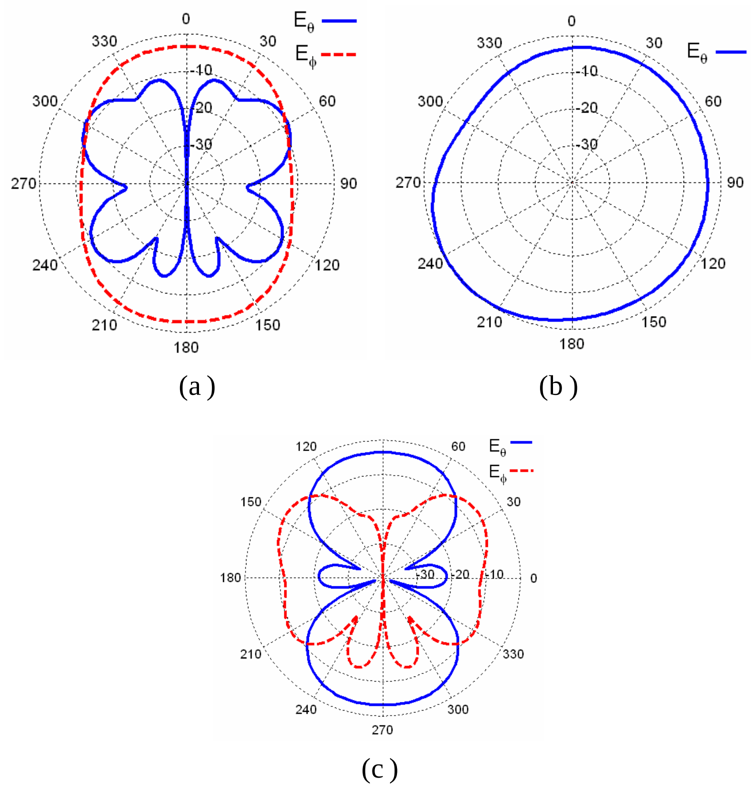

Figure 15. Radiation pattern at 10 GHz for the antenna after bending in the: (a) x-z plane, (b) y-z plane (E-plane), and (c) x-y plane (H-plane).

the antenna size and impedance bandwidth. The bow-tie antennas available in the open literature provides a maximum bandwidth of 40% with antenna size equivalent to $0.4\,\lambda_{0L}$ and $0.6\,\lambda_{0H}$, where λ_{0L} and λ_{0H} are the free space wavelength calculated at the lower and upper limits of the operating frequency band of the antenna. The triangle slot antenna, designed in this paper, provides a bandwidth of 57% with size equivalent to $0.33\,\lambda_{0L}$ and $0.54\,\lambda_{0H}$. Consequently, the triangle slot antenna is smaller than the available printed and slot bow-tie antennas and it provides a wider bandwidth.

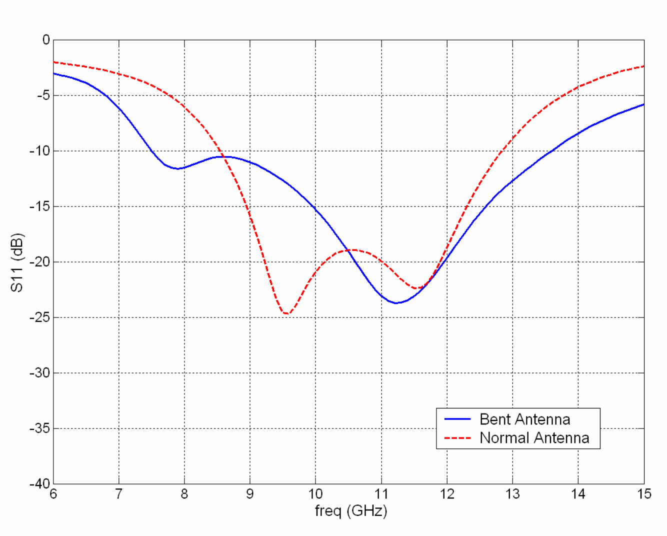

Figure 16. Comparison between the computed return loss of the antenna using the FDTD code after and before bending.

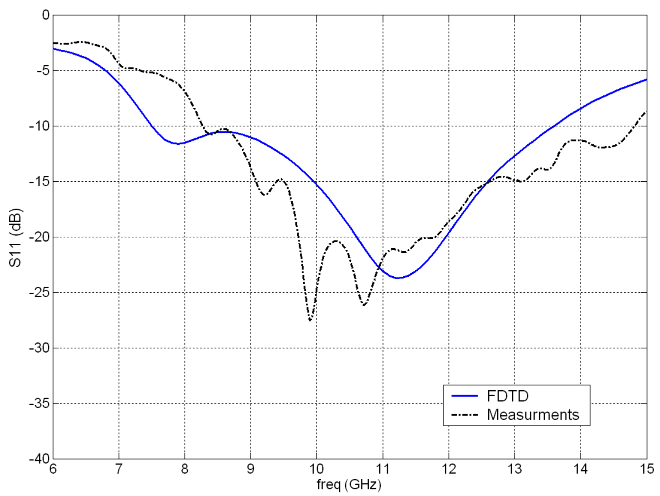

Figure 17. Comparison between the computed return loss of the bent antenna using the FDTD code and the measurement results.

9. CONCLUSION

A novel design of a small size triangle slot antenna with tuning stub is proposed and designed for wide band operation in the X-band. The effect of bending the antenna to obtain end-fire radiation has also been studied. This antenna shows a wide bandwidth (57%) and low cross polarization level in the E-plane and H-planes (-10 dB), and an average gain of 4.5 dB. These features exceeds those of available printed and slot bow-tie antennas. Low coupling between elements of this antenna in a linear array configuration is achieved with only 2 mm separation distance. These characteristics make this novel, small size, triangle slot antenna suitable for being an element in a phased array system that requires wide bandwidth, high gain, small size, narrow beamwidth and large scanning capabilities.

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