Progress In Electromagnetics Research B, Vol. 1, 29–42, 2008

E-SHAPED PATCH SYMMETRICALLY LOADED WITH TUNNEL DIODES FOR FREQUENCY AGILE/BROADBAND OPERATION

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Abstract—Analysis of a frequency agile broadband E-shaped patch antenna (ESPA) symmetrically loaded with tunnel diodes is presented in this paper. The notch parameters such as notch-length, notch-width and position are optimized to achieve the optimum broadband operation of ESPA. Under the optimum conditions of ESPA (bandwidth 32.35%), the performance of the antenna is also analyzed as a function of bias voltage of tunnel diode. It may be mentioned that the proposed antenna can be operated in tunable band that varies from 1055 MHz (bandwidth 42.54%) to 1324 MHz (bandwidth 49.77%) with the bias voltage. Further, the radiated power of the proposed antenna is enhanced by 5.67 dB as compared to the E-shaped patch antenna.

1. INTRODUCTION

The microstrip antennas, in general, have inherent narrow bandwidth and low gain. Therefore, these antennas found very limited application in different fields. Hence serious efforts started among the scientific community to improve the bandwidth of the microstrip antenna. The conventional methods to widen the bandwidth are addition of parasitic patches, laterally [1] or vertically [2]. But, the stacked geometry increases the thickness of the antenna and the coplanar geometry increases its lateral size. Therefore, these geometries are less preferred for modern wireless communications that requires single-layer single-patch broadband microstrip antenna. In this regards, in 1995, Huynh and Lee [3] proposed a new kind of broadband antenna and reported that by cutting U-slot into the rectangular patch, the impedance bandwidth could exceed 30%. In 2001, Yang et al. [4] presented experimental study of E-shaped patch antenna

(ESPA) and reported that impedance bandwidth between 30.3% and 32.3% could be achieved by proper adjustment of parameters of the slot and the position of the feeding point. Recently (2007), Bzeih et al. [5] and Ang & Chung [6] separately presented new kind of ESPA to meet the requirements of various communication systems. Bzeih et al. [5] presented an enhanced E-shaped patch antenna with an impedance bandwidth exceeding 41% applicable for modern wireless communications such as personal communication system (PCS, 1850–1990 MHz), universal mobile telecommunications system (UMTS, 1920–2170 MHz), wireless local area networks (WLAN, 2400–2484 MHz), DCS (1710–1880 MHz) etc. In this order, Ang and Chung [6] designed an ESPA applicable for high-speed wireless communication systems and other wireless communication systems covering the 5.150–5.825 GHz frequency band.

The tunability of ESPA, with enhanced bandwidth and gain, at various resonance frequencies can be obtained by the proper selection of feed positions and changing the patch topology [4–6]. It is mentioned that loading of one or more active devices with the patch could enhance the bandwidth and gain of the microstrip patch antenna and its tunability can be improved by adjusting the bias voltage of the active device only [7, 8]. A frequency agile broadband E-shaped patch antenna using symmetrically loaded tunnel diodes is proposed to enhance the bandwidth (above 41%) and gain (up to 5.67 dB comparative to ESPA). The aim of this work is to present the effect of bias voltage of tunnel diode on the performance of ESPA. The proposed antenna is investigated using modal expansion cavity model and circuit theory concept. The results obtained are compared with simulated and experimental [4] results of ESPA. The details of investigations are given in the following sections:

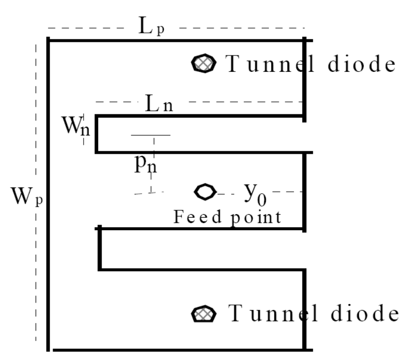

Figure 1. Top view of the proposed antenna.

2. THEORETICAL CONSIDERATIONS

The geometrical configuration of the E-shaped patch antenna with symmetrically loaded tunnel diodes is shown in Fig. 1. The microstrip patch is fed using a 50 ohm coaxial probe with the inner diameter of 0.127 cm. E-shaped patch antenna is considered as a rectangular patch of dimension $Lp \times Wp$ with two parallel notches of length Ln and width Wn introduced at one of its radiating edges positioned symmetrically with respect to the feed point y_0. The center part of the patch acts as a resonance circuit having inductance L and capacitance C. Due to the effect of notch, additional series notch inductance ΔL and gap capacitance ΔC are added respectively to the initial inductance L and capacitance C of the center part of the patch. And hence, another resonance circuit is introduced in the antenna due to the side part of the patch and the notch. It has inductance $L' = L + \Delta L$ and capacitance $C' = \frac{C\Delta C}{C+\Delta C}$ and it resonates at lower frequency than the center resonator. Thus ESPA behaves as two resonant circuits which couple together to give wide band operation. When a tunnel diode is loaded symmetrically with the patch, a resistance R_s and inductance L_s are added in series and a negative resistance $-R_D$ and junction capacitance C_D are next added in parallel to the equivalent circuit of the patch [9]. Due to the effect of tunnel diode the resonance feature of ESPA changes in such a way that its bandwidth is further increased. The placement (y) of tunnel diodes is so chosen that the device impedance (Z_d) be matched to the input impedance (Z_{in}) of the patch. Therefore the placement location (y) of the diode is given by

$$y = \frac{Lp}{\pi} \cos^{-1} \sqrt{\frac{Z_d}{Z_{in}}}$$

2.1. Impedance and Return Loss of the Antenna

The equivalent circuit of the proposed antenna is shown in Fig. 2. From this figure, one can take

$$Z_1 = R_S + j\omega L_S \tag{1}$$

$$Z_2 = \frac{R_D}{(j\omega C_D R_D - 1)} \tag{2}$$

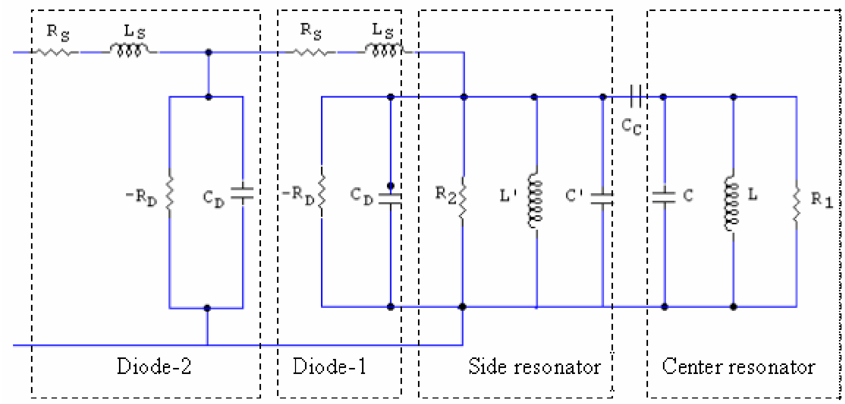

Figure 2. Equivalent circuit of the proposed antenna.

$$Z_3 = \frac{j\omega L R_1}{R_1 - \omega^2 LCR_1 + j\omega L} \tag{3}$$

$$Z_4 = \frac{j\omega L' R_2}{R_2 - \omega^2 L'C'R_2 + j\omega L'} + \frac{1}{j\omega C_c} \tag{4}$$

Among the values of various circuit parameters, the values of capacitance C and inductance L for center resonator, gap capacitance ΔC, notch inductance ΔL, R_1 & R_2 for center and side resonators and coupling capacitance C_c were calculated as [10–14] respectively.

Therefore the input impedance of E-shaped patch with two resonators can be derived as

$$Z_e = \frac{Z_3 Z_4}{Z_3 + Z_4} \tag{5}$$

The impedance of the circuit of E-shaped patch with a diode at its one end can be derived as (Fig. 2)

$$Z_{ed2} = Z_1 + \frac{Z_2 Z_3 Z_4}{Z_2 Z_3 + Z_3 Z_4 + Z_4 Z_2} \tag{6}$$

Therefore, from Fig. 2, one can get the impedance of the proposed antenna containing two diodes and E-shaped patch as

$$Z_{in} = Z_1 + \frac{Z_2 Z_{ed2}}{Z_2 + Z_{ed2}} \tag{7}$$

The return loss (RL) is given as

$$RL = 20 \log_{10} |\Gamma|, \qquad \Gamma = (Z_{in} - Z_0)/(Z_{in} + Z_0) \tag{8}$$

where Z_0 is the characteristic impedance of the feeding line (50 ohm).

2.2. Operating Frequency

The operating frequency of a tunnel diode oscillator circuit is given as

$$Im[Y] = 0$$

where Y is the admittance of the circuit as seen by the negative resistance $-R_D$. From the circuit shown in the Fig. 2, the value of Im$[Y]$ can be derived as

$$\mathrm{Im}\left[Y\right] = \frac{Y_1 \begin{pmatrix} \omega^2\left(-\omega^2 L_e L_s C_e C_D + R_s L_e C_D + R_e L_s C_D + R_e L_e C_D\right) \\ +X_1\omega\left\{R_e R_s C_D + \omega^2 L_e C_D\left(R_s C_e - C_D\right)\right\} \end{pmatrix}}{\omega^4 \begin{pmatrix} \left(-\omega^2 L_e L_s C_e C_D + R_s L_e C_D + R_e L_s C_D + R_e L_e C_D\right)^2 \\ +\omega^2\left\{R_e R_s C_D + \omega^2 L_e C_D\left(R_s C_e - C_D\right)\right\}^2 \end{pmatrix}}$$

where

$$\begin{aligned} X_1 &= \omega^4\left(2R_s L_s L_e C_e C_D - L_s^2 L_e C_D\right) \\ &\quad +\omega^2\{2R_e R_s L_s C_D - R_s L_e C_D(R_e + R_s) - R_s L_e C_e - L_e L_s\} + R_e R_s \\ Y_1 &= \omega^5 L_e L_s^2 C_e C_D \\ &\quad +\omega^3\left\{R_s^2 L_e C_e C_D - 2R_s L_s L_e C_D - R_e L_s C_D\left(L_e + L_s\right) - L_e L_s C\right\} \\ &\quad +\omega\left(R_e R_s^2 C_D + R_e L_e + R_e L_s + R_s L_e\right) \end{aligned}$$

and $R_e = \frac{R_1 R_2}{R_1+R_2}$, $L_e = \frac{LL'}{L+L'}$ and $C_e = \frac{(C+C')C_c}{C+C'+C_c}$.

Therefore the operating frequency of the proposed antenna can be given as

$$\begin{aligned} &Y_1\omega\left(-\omega^2 L_e L_s C_e C_D + R_s L_e C_D + R_e L_s C_D + R_e L_e C_D\right) \\ &+X_1\left\{R_e R_s C_D + \omega^2 L_e C_D\left(R_s C_e - C_D\right)\right\} = 0 \end{aligned} \tag{9}$$

Here the junction capacitance C_D depends on bias voltage as [9]

$$C_D = A\left(\frac{q\varepsilon}{2}\right)^{1/2}\left(\frac{np}{n+p}\right)^{1/2}\left(V_D - V\right)^{-1/2} \tag{10}$$

where $\varepsilon = \varepsilon_0\varepsilon_r$ and ε_r is relative permittivity of the medium, q is charge on an electron, $\frac{np}{n+p}$ is the concentration of the charge, V_D is the diffusion potential, A is junction area and V is the bias voltage.

2.3. Radiation Pattern

Considering E-shaped patch as a rectangular patch, the radiation pattern of the proposed antenna can be calculated as [15]

$$E(\phi) = \frac{jk_0 WpV_O e^{-jk_0 r}}{\pi r}\cos(kh\cos\theta)\left[\frac{\sin\left(\frac{k_0 Wp}{2}\sin\phi\sin\theta\right)}{\frac{k_0 Wp}{2}\sin\phi\sin\theta}\right]$$

$$\cos\left(\frac{k_0 Lpe}{2}\sin\theta\sin\phi\right)\cos\phi \qquad \text{where } 0 \leq \phi \leq \frac{\pi}{2} \tag{11}$$

$$E(\theta) = -\frac{jk_0 WpV_O e^{-jk_0 r}}{\pi r}\cos(kh\cos\theta)\left[\frac{\sin\left(\frac{k_0 Wp}{2}\sin\phi\sin\theta\right)}{\frac{k_0 Wp}{2}\sin\phi\sin\theta}\right]$$

$$\cos\left(\frac{k_0 Lpe}{2}\sin\theta\sin\phi\right)\cos\theta\sin\phi \quad \text{where } 0 \leq \theta \leq \frac{\pi}{2} \tag{12}$$

where V_O is the radiating edge voltage, r is the distance of an arbitrary point, k & k_0 are propagation constants in dielectric medium and free space and Lpe is effective length of the patch.

3. DESIGN SPECIFICATIONS

Specifications of Ge tunnel diode are as: series resistance $R_s = 2.5\,\Omega$, series inductance $L_s = 9.1750\,\text{nH}$, negative resistance $R_D = -105\,\Omega$, junction capacitance $C_D = 2.0132\,\text{pF}$ (mid-value for calculation of f_r and f_s), self resonance frequency $f_s = 0.8969\,\text{GHz}$, resistive cut-off frequency $f_r = 4.8210\,\text{GHz}$, Junction area $A = 8.150 \times 10^{-6}\,\text{cm}^2$, Charge concentration $\frac{np}{n+p} = 4.17 \times 10^{19}\,\text{cm}^{-3}$, diffusion potential $V_D = 1.1\,\text{V}$ [16] and bias voltage $V = 60 - 350\,\text{mV}$ [17].

Specifications of ESPA are as: patch length $Lp = 50\,\text{mm}$, patch width $Wp = 70\,\text{mm}$ feed point $y_0 = 10\,\text{mm}$ and height $h = 10\,\text{mm}$. The two parallel notches of length $Ln = 40\,\text{mm}$ and width $Wn = 6\,\text{mm}$ are positioned symmetrically with respect to the feeding point such as $Pn = 10\,\text{mm}$. Here the relative permittivity of used air substrate material is $\varepsilon_r = 1$. The design frequency of the antenna is 2.15 GHz.

4. CALCULATIONS AND DISCUSSION OF RESULTS

The return loss of the antenna was calculated using (8); the resulting data are shown in Figs. 3–6 and 8. The variation of return loss

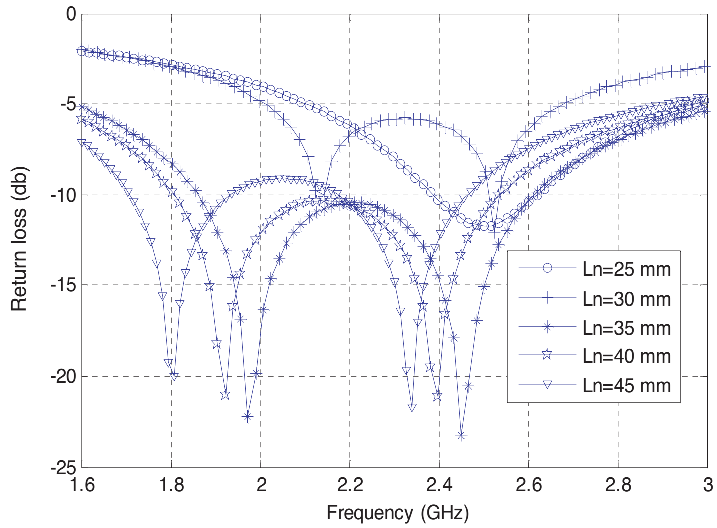

Figure 3. Variation of return loss with frequency at different notch length for ESPA.

with frequency at different notch length (Ln) is shown in Fig. 3. It shows that for small notch length, ESPA has only one resonance frequency but as notch length further increases another lower resonance frequency appears. It is observed that lower resonance frequency decreases with increasing notch length. So, notch length plays a crucial role in controlling the resonance frequencies of ESPA. Fig. 4 depicts that notch width (Wn) has matching effect on the performance of ESPA. As notch width increases matching at lower resonance improve but degrade at second resonance. Opposite to it, matching at lower resonance degrades and improves at higher resonance for small values of notch width. The effect of notch position (Pn) on the performance of ESPA is shown in Fig. 5. It is found that as notch position increases the bandwidth of ESPA increases. When notch position becomes even larger, the return loss between two resonance frequencies becomes larger than -10 db and ESPA behaves as dual band rather than broadband antenna. Thus notch length, notch width and notch position play important role in controlling the performance of ESPA. Yang et al. [4], Bzeih et al. [5] and Ang & Chung [6] have experimentally reported the similar results.

The return loss curve for optimum design parameters is shown in Fig. 6 and the bandwidth of 32.35% is achieved with lower and higher resonance frequencies at 1.923 GHz (approx. 1.9 GHz) and

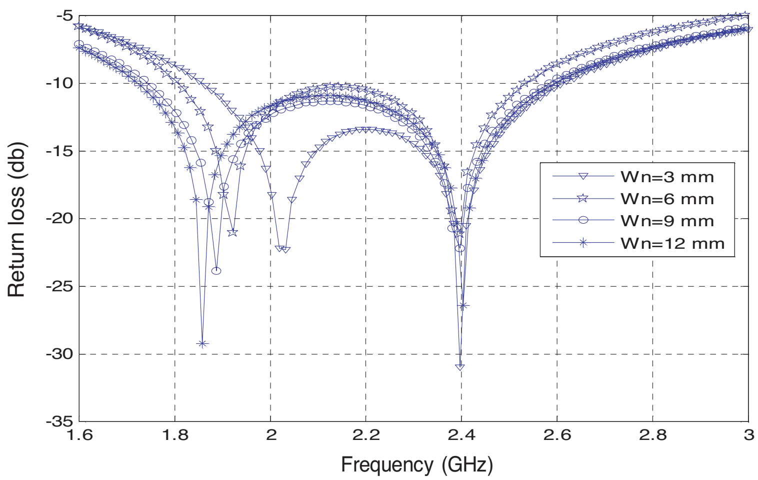

Figure 4. Variation of return loss with frequency at different notch width for ESPA.

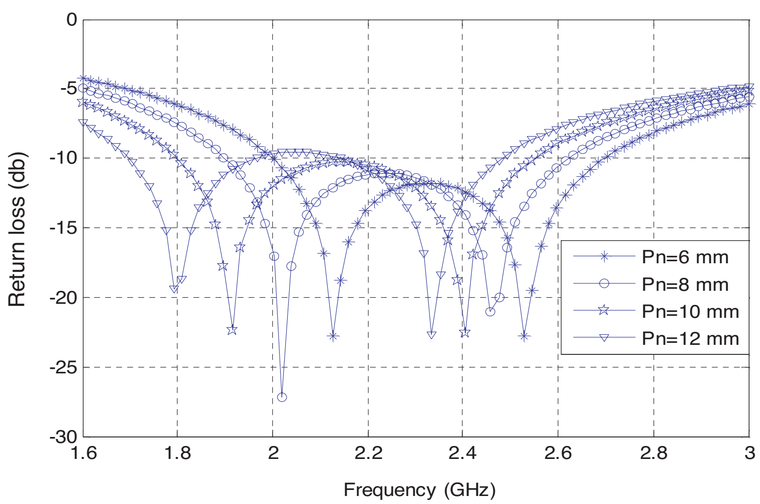

Figure 5. Variation of return loss with frequency at different notch position for ESPA.

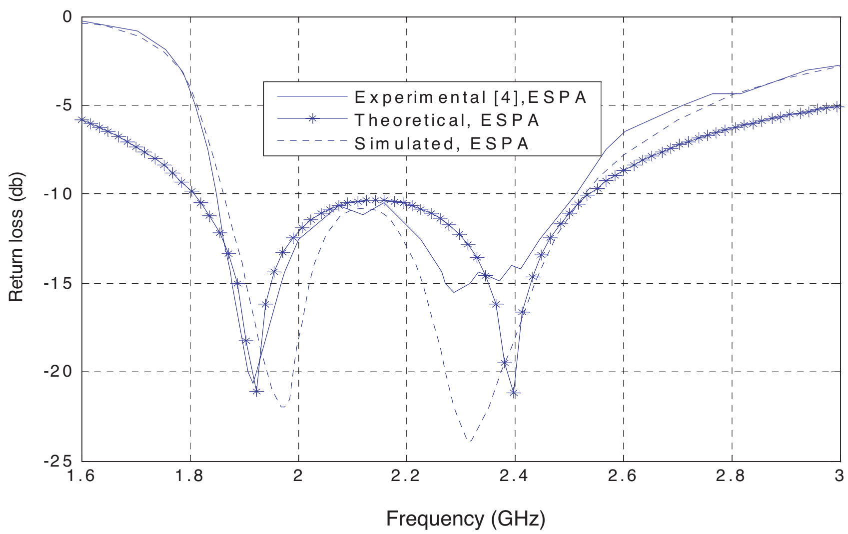

Figure 6. Optimized return loss curve for ESPA.

2.399 GHz (approx. 2.4 GHz) respectively. The theoretical result is in good agreement with simulated and experimental [4] results. In addition, Fig. 7 shows the E-plane radiation patterns of ESPA at lower resonance frequency ($fl = 1.9$ GHz) and higher resonance frequency ($fh = 2.4$ GHz). It is noted that the theoretical radiation patterns of ESPA are much identical to the experimental radiation patterns [4]. Thus theoretical results, together with the experimental results, justify the veracity of the proposed method.

When tunnel diode is symmetrically loaded with the E-shaped patch a great shift in resonance frequencies of ESPA is observed towards relatively higher end of frequency (Fig. 8). In addition to it, the higher resonance frequency decreases linearly from 2.964 GHZ to 2.634 GHz with increasing bias voltage while a very little change in lower resonance frequency (from 2.348 GHZ to 2.326 GHz) is observed with bias voltage, as shown in Fig. 9. Srivastava et al. [8] also reported similar variation in resonance frequency with bias voltage. The decrease in the resonance frequencies is because of the fact that the operating frequency depends inversely on the square root of effective capacitance of the proposed antenna whereas the effective capacitance is obtained by adding equivalent capacitance of the proposed antenna and junction capacitance of the diode which itself increases with increasing bias voltage. It is noted that the tunable band of operation decreases with increasing bias voltage (Fig. 8). It is highest 1324 MHz

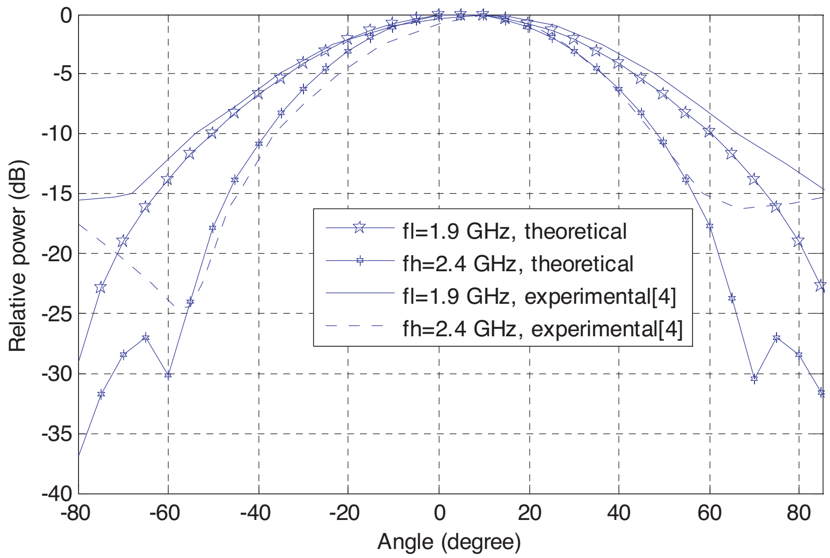

Figure 7. E-plane radiation patterns for ESPA.

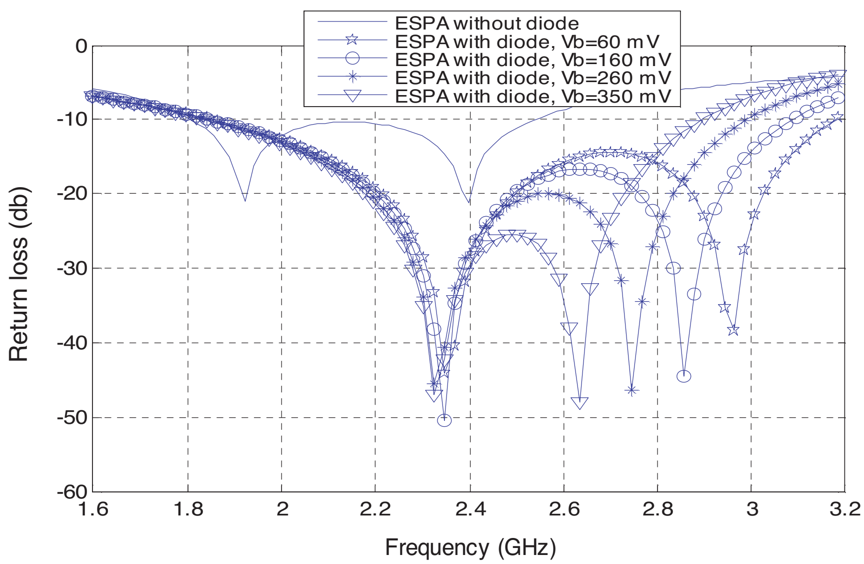

Figure 8. Variation of return loss with frequency at different bias voltage for proposed antenna.

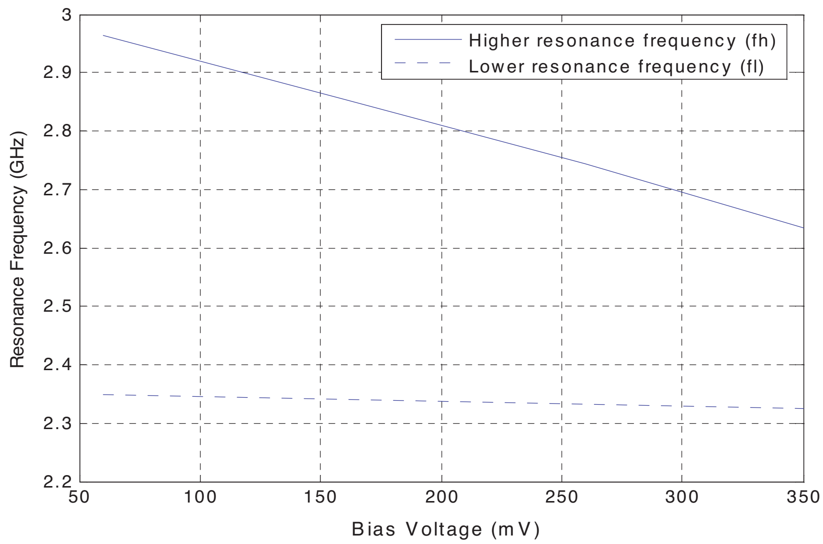

Figure 9. Variation of resonance frequency with bias voltage for proposed antenna.

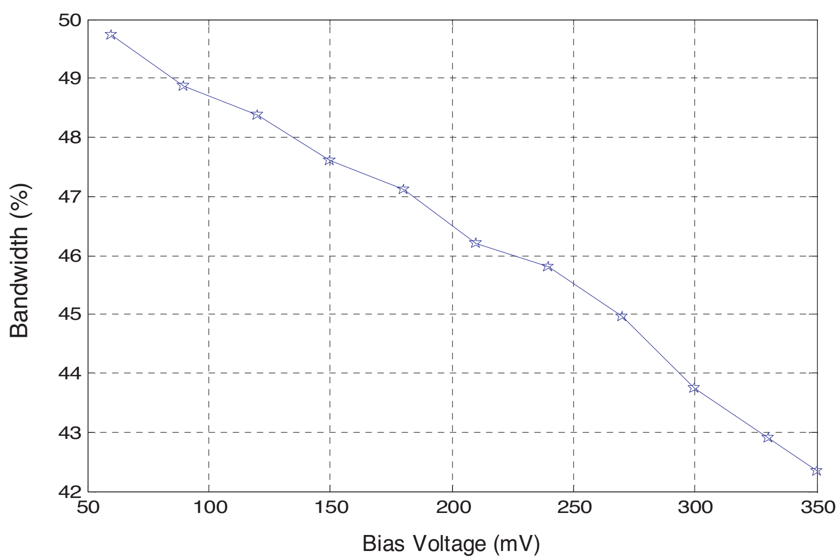

Figure 10. Variation of bandwidth with bias voltage for proposed antenna.

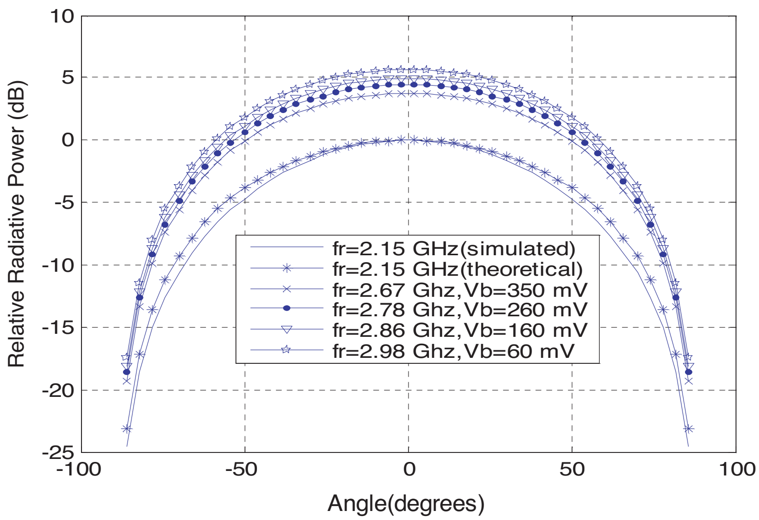

Figure 11. Radiation patterns for the proposed antenna.

(bandwidth 49.77%) at lowest bias voltage $Vb = 60\,\mathrm{mV}$ and lowest 1055 MHz (bandwidth 42.54%) at highest bias voltage $Vb = 350\,\mathrm{mV}$. So, the bandwidth of the proposed antenna is much better than the earlier reported results [4, 5] for the entire range of bias voltage (60–350 mV), as shown in Fig. 10.

The radiation patterns for ESPA (at 2.15 GHz, without tunnel diode) and for the proposed antenna (at 2.67 GHz, 2.78 GHz, 2.86 GHz and 2.98 GHz with their corresponding bias voltages) are shown in the Fig. 11 for which data calculations were made using equations (11) & (12). It is observed that the radiation pattern of the proposed antenna depends on bias voltage. It is noticed that the proposed antenna radiates 3.76 dB–5.67 dB more power as compared to the ESPA. This is attributed to the fact that the radiation depends directly on the frequency and frequency depends inversely on the bias voltage.

5. CONCLUSIONS

It is concluded that the antenna can be used to achieve the electronic tuning with the help of bias voltage. By the proper adjustment of bias voltage only, the bandwidth between 42.54% and 49.77% can be achieved. The antenna can be used over a wide range of frequencies for modern wireless communication systems in the frequency band of 1055 MHz–1324 MHz.

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