Tunnel Diode Loaded Microstrip Antenna with Parasitic Elements

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ABSTRACT

The present work describes the circuit model based analysis of symmetrically tunnel diode loaded microstrip antenna with parasitic elements. To optimize the antenna characteristics, a systematic study has been carried out as a function of tunnel diode bias voltage, space between parasitic patch and fed patch. The results obtained from antenna radiation pattern depict that an improvement of 5.8 MHz in bandwidth can be achieved if the symmetrically tunnel diode is loaded with patch along with parasitic elements of gap \( (s) = 3.6 \) cm. It has also been noted that at this state the radiations are more powerful i.e. 0.5647 dB as compared to single patch design.

Keywords: Microstrip Antenna; Symmetrically Tunnel Diode Loaded Patch and Parasitic Patch

1. Introduction

Microstrip patch antennas have attracted widespread interest due to their small size, light weight, low profile and low cost as well as to the fact that they are easy to manufacture, suitable to planar and non planar surfaces, mechanically robust, easily integrated with circuits but their narrow bandwidth and low gain make these antennas for limited use [1,2]. In the multi-channel application a small instantaneous bandwidth is required over a large frequency range. A tunable microstrip antenna provides an alternative to wideband operation in which an antenna with small bandwidth is tuned over a large frequency band [3]. Active device loaded patch is widely used to make a tunable antenna [4]. Several researchers have used parasitic elements along the radiating and non-radiating edges of the fed patch to achieve additional gain [5].

In the present paper the radiation characteristics and resonance behavior of the symmetrically tunnel diode loaded microstrip antenna with parasitic elements at radiating edges has been studied by using circuit model approach for the first time. Consequently various antenna parameters such as input impedance, VSWR, return losses etc. are evaluated as a function of frequency for different bias voltages. The effect of separation \( (s) \) between the patch and parasitic elements is also investigated for different bias voltages.

2. Antenna Geometry and Its Equivalent Circuit

Tunnel diode loaded microstrip antenna is shown in Figure 1, in which rectangular microstrip antenna (RMSA) is considered as a parallel combination of \( R, L \) and \( C \).

The value of which are given as [6]

\[
C = \frac{\varepsilon \varepsilon_0 W}{2 h} \cos^{-2} \left( \frac{\pi y_0}{l} \right) \quad (1)
\]

\[
L = \frac{1}{\omega^2 C} \quad (2)
\]

\[
R = \frac{Q}{\omega C} \quad (3)
\]

Figure 1. Symmetrically tunnel diode loaded rectangular microstrip antenna (RMSA).
where

\[ Q = \frac{\varepsilon \sqrt{\varepsilon_r}}{4 \varepsilon \varepsilon_0 f h} \]

here, \( \varepsilon_r \) is effective permittivity of the medium which is given by [6].

\[ \varepsilon_r = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left( 1 + \frac{10 h}{W} \right)^{-1/2} \]  

(4)

where \( c \) is the velocity of light, \( f \) is the design frequency, \( \varepsilon_r \) is the relative permittivity of the substrate material, \( l \) and \( W \) are length and width of the rectangular patch and \( h \) is thickness of the substrate material. \( y_o \) is \( Y \)-coordinate of the feed point. The equivalent circuit of the tunnel diode is shown in Figure 2, in which \( R_s \) is resistance, \( L_s \) is inductance, \( -R_D \) is negative resistance and \( C_D \) is the junction capacitance [7].

The junction capacitance \( C_D \) is given as

\[ C_D = A \left[ \frac{\varepsilon q}{2} \right]^{-1/2} \left[ \frac{n p}{n + p} \right] \left[ V_d - V_b \right]^{1/2} \]  

(5)

The impedance of symmetrically tunnel loaded patch can be given as in Figure 3.

### 2.1. Symmetrically Tunnel Diode Loaded Patch with Parasitic Elements

Figure 4(a) shows two parasitic elements placed at the radiating edges of the RMSA with separation \( s \) and width \( W \). The equivalent circuit of parasitic elements is shown in Figure 4(b). It may be mentioned that such circuit can be analyses using odd and even mode concept and hence equivalent circuit of the odd and even mode can be written as shown in Figures 4(c) and (d) respectively.

Now the combined equivalent circuit of tunnel loaded patch with parasitic elements can be given as shown in Figures 4(a) and (b) for odd and even mode cases.

### 2.2. Operating Frequency

The operating frequency range of the tunnel diode oscillator controlled by self resonance frequency \( (f_r) \).
The input admittance of symmetrically tunnel loaded RMSA with parasitic elements is given by

\begin{align}
\text{Im}[Y] = \frac{a_1 - \omega^2 a_2 + \omega^2 a_3}{a_1 - \omega^2 a_2 + \omega^2 a_3} \left( \frac{\omega^2 b_1 - \omega^2 b_2}{\omega^2 b_1 - \omega^2 b_2} \right) - \left( \frac{\omega^2 c_1 - \omega^2 c_2 - c_3}{\omega^2 c_1 - \omega^2 c_2 - c_3} \right) \left( \frac{d_1 - d_2 \omega^2}{d_1 - d_2 \omega^2} \right)
\end{align}

where

\begin{align}
a_1 &= RL + LR_R + R \left( C_D R^2_v + 2 L_s \right) \\
a_2 &= RLC_D L + RL \left( C + C_D \right) \left( C_D R^2_v + 2 L_s \right) + 2LC_D L_R + L^2 C_D R \\
a_3 &= RLC_D L_R \left( C + C_D \right) \\
b_1 &= L^2 C_D RL \\
b_2 &= RL \left( C_D R^2_v + 2 L_s \right) \\
c_1 &= RLC_D L + 2RR_L \left( C + C_D \right) + L \left( C_D R^2_v + 2 L_s \right) + 2C_D L_R R_s \\
c_2 &= 2C_D L_L R_s RL \left( C + C_D \right) + L C_D L_s \\
c_3 &= R_s R \\
d_1 &= 2R_s RL \\
d_2 &= 2R_s R RL_s
\end{align}

Now the combined equivalent circuit of tunnel loaded patch with parasitic elements can be given as shown in Figures 5(a) and (b) for odd and even mode cases. From Figure 3, the impedance of symmetrically tunnel loaded patch can be given as

\begin{align}
Z = \left[ \left( Z_s + Z_p \right) \| Z_s \right] 
\end{align}

where

\begin{align}
Z_s &= R_s + j \omega L_s \\
Z_p &= \frac{R_D}{j \omega C_D R_D - 1} \\
Z_3 &= Z_s + j \omega L R R_D \\
Z_4 &= j \omega L R R_D \left( R_D - R_s \right) + R_R \left( R_R - R_s \right) + \omega^2 R L s \left( C + C_D \right)
\end{align}

From Figure 5, the equivalent circuit for tunnel loaded patch with parasitic elements can be used to calculate odd and even mode impedances. The odd mode capacitance \( C_o \) and even mode capacitance \( C_e \) can be given as [8].

\begin{align}
C_o &= C_p + 2C_s \\
C_e &= 2C_p 
\end{align}

From Figure 5, the impedances for odd and even mode can be given as

\begin{align}
Z_s &= \left[ Z \| 4X_s \| 2X_p \right] \\
Z_e &= \left[ Z \| 4X_p \right]
\end{align}

where \( X_s \) and \( X_p \) are capacitive impedances of gap and parasitic elements. Total input impedance of the symmetrically tunnel loaded RMSA with parasitic elements is given by

\begin{align}
Z_T = Z_s + Z_e
\end{align}

The different antenna parameters can be calculated as Reflection coefficient

\begin{align}
\rho = \frac{Z_T - Z_s}{Z_T + Z_e}
\end{align}
where $Z_c$ is the characteristic impedance of the coaxial feed ($50 \, \Omega$).
\[
VSWR = \frac{1 + \rho}{1 - \rho}
\]
(17)

Return loss = $10 \log \frac{1}{\rho^2}$ (18)

The radiation pattern for tunnel loaded RMSA with parasitic elements can be calculated as
\[
E_{\theta}(\theta) = AF \times E_s(\theta)
\]
(19)

\[
E_{\phi}(\phi) = AF \times E_s(\phi)
\]
(20)

where $AF$ is array factor and given by [10].

2.3. Design Specifications for Microstrip Patch Antenna

The designed frequency of the rectangular patch antenna is 1 GHz. The dimension of the rectangular patch is calculated by [6]. The detail design specifications are given in Table 1 and Table 2.

3. Result and Discussion

Variation of return loss for single patch, tunnel diode loaded patch and tunnel loaded patch with parasitic elements are shown in Figure 6, for different values of bias voltages. It is observed that the resonance occurs for tunnel loaded patch at lower value as compared to single patch and it is still lower for parasitic loaded patch for all the values of bias voltage.

From Figure 7, it is also observed that the bandwidth of the patch improves by loading the patch with tunnel diodes. However, by loading the tunnel loaded patch with parasitic elements the bandwidth further improves as compared to patch. Typically it may be noted that maximum bandwidth is achieved for tunnel loaded patch with parasitic element having $s = 3.6 \, \text{cm}$. When the value of $(s)$ increases bandwidth decreases. At $s = 9.9 \, \text{cm}$, the antenna behaves as a tunnel loaded patch and the effect of parasitic elements ceases to exist. This is because of the fact that when $(s)$ is more than 9.6 cm. there is no coupling between patch and parasitic elements. Variation of resonance frequency with bias voltage is shown in Figure 8. It is found that the resonance frequency increases minutely with bias voltage. The result is in good

<table>
<thead>
<tr>
<th>Components</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>GaAs</td>
</tr>
<tr>
<td>Series resistance ($R_s$)</td>
<td>3.5 ($\Omega$)</td>
</tr>
<tr>
<td>Series inductance ($L_s$)</td>
<td>8.02 (nH)</td>
</tr>
<tr>
<td>Negative resistance ($R_D$)</td>
<td>$-152$ ($\Omega$)</td>
</tr>
<tr>
<td>Self resonance frequency ($f_s$)</td>
<td>0.678 (GHz)</td>
</tr>
<tr>
<td>Resistive cut off frequency ($f_r$)</td>
<td>1.046 (GHz)</td>
</tr>
<tr>
<td>Bias voltage ($V_b$)</td>
<td>250 - 550 (mV)</td>
</tr>
<tr>
<td>Charge concentration</td>
<td>$2.01 \times 10^{19}$ (cm$^{-3}$)</td>
</tr>
<tr>
<td>Junction area ($A$)</td>
<td>$2.9 \times 10^{-10}$ (cm$^2$)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Components</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate material used</td>
<td>Bakelite</td>
</tr>
<tr>
<td>Relative dielectric constant ($\varepsilon_r$)</td>
<td>4.78</td>
</tr>
<tr>
<td>Thickness of the substrate ($h$)</td>
<td>0.159 (cm)</td>
</tr>
<tr>
<td>Design frequency ($f$)</td>
<td>1.0 (GHz)</td>
</tr>
<tr>
<td>Length of the patch ($l$)</td>
<td>6.8108 (cm)</td>
</tr>
<tr>
<td>Width of the patch ($W$)</td>
<td>8.8083 (cm)</td>
</tr>
</tbody>
</table>

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agreement with the reported data [10]. The radiation pattern of the antenna is shown in Figure 9. It is observed that tunnel loaded patch with parasitic elements for \( s = 3.6 \) cm shows maximum radiated power which is 0.5647 dB higher as compared to patch alone. It is further noted that the radiation pattern is invariant with the bias voltage.

4. Conclusion

It is concluded from the above analysis that the bandwidth of the tunnel loaded patch antenna with parasitic elements is improved and it is found maximum for the patch size \( s = 3.6 \) cm. Further, an increase in gap \( s \) (beyond \( s = 9.9 \) cm) reduces the bandwidth. It means the effect of tunnel loaded patch and the parasitic elements ceases to exist or at this state the effective mutual interaction between patch and parasitic elements is stopped. In this way the performance of tunnel diode loaded microstrip antenna can be enhanced by using parasitic elements of optimum gap \( s \).

REFERENCES