Gunn loaded microstrip antenna with parasitic elements

J A Ansari1,*, Satya Kesh Dubey1, Prabhakar Singh1, Babau R Vishvakarma2,5 & R U Khan2
1Department of Electronics and Communication, University of Allahabad, Allahabad
2Department of Electronics Engineering, I. T. BHU, Varanasi 221 005
E-mail: jaansari@rediffmail.com; brvish@bhu.ac.in

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An analysis of Gunn loaded patch with parasitic elements at radiating edges of the patch has been carried out using equivalent circuit concept for different values of bias voltage and threshold voltage. It is observed that addition of parasitic elements improves the band of operation to 400 MHz (bandwidth 4.48%, center frequency 8.95 GHz) as compared to 297 MHz (bandwidth 3.06%, center frequency 8.90 GHz) for Gunn loaded patch. Antenna also shows tunability of 50 MHz for bias voltage from 8 to 15 V for a given threshold voltage of 4.4 V and exhibits enhanced radiation by 0.5833 dB as compared to patch alone. Various parameters of the antenna are compared with simulated data using IE3D.

Keywords: Microstrip antenna, Gunn diode integrated microstrip antenna, Active antenna, Parasitic elements

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1 Introduction

The rectangular and circular patches are extensively used radiators which have very limited bandwidth. This limits the applications in several practical cases. Active devices can be integrated with patch to improve the antenna performance1-3. Stacked microstrip antenna with different shapes4-6 have been proposed with various method of feeding techniques such as coaxial probe, microstrip lines, slot line and gap coupled7,8. Many researchers have used parasitic elements to achieve the gain9.

In the present paper, a theoretical analysis has been carried out for the symmetrically Gunn diode integrated microstrip antenna with parasitic elements. Figure 1 shows two identical Gunn diode loaded symmetrically on the radiating edge of rectangular microstrip antenna (RMSA). To improve the bandwidth and gain of the antenna, additional coplanar parasitic elements are used. The middle one is Gunn integrated patch and side elements are gap coupled parasitic elements (Fig. 2). The analysis of Gunn integrated RMSA with parasitic elements is based on circuit theory.

2 Theoretical considerations

2.1 Gunn diode loaded active microstrip antenna

Figure 3 shows the current distribution in a symmetrically Gunn integrated microstrip antenna with parasitic elements separated by gap 's'. The equivalent circuit of the microstrip antenna is given as a parallel combination of R, L, and C [Fig. 4(a)] and if the patch is loaded with Gunn diodes then the circuit will be given as in Fig. 4(b). This can also be written as shown in Fig. 4(c), where, R, L and C are defined10.

The input impedance of the patch is given as [Fig. 4(a)]

\[ Z = \frac{1}{\frac{1}{R + j\omega L + j\omega C}} \]  \[ \ldots (1) \]

Fig. 1 — Symmetrically Gunn diode loaded RMSA

Fig. 2 — Symmetrically Gunn loaded RMSA with coplanar parasitic elements
The input impedance of symmetrically Gunn loaded patch can be calculated from Fig. 4(b) as

\[ Z_G = \frac{1}{\frac{2}{R_d} + 2j\omega C_d + \frac{1}{Z}} \]  \hspace{1cm} \ldots (2)

where, \( C_d \) is Gunn diode capacitance; and \( R_d \) is negative resistance of diode.

2.2 Gunn diode loaded active microstrip antenna with coplanar parasitic element

When the parasitic elements are added to the radiating edges of symmetrically Gunn loaded patch [Fig. 5(a)], the equivalent circuit for the gap between patch and parasitic elements can be given as shown in Fig. 5(b), where \( C_s \) and \( C_p \) can be calculated\(^{11}\). The equivalent circuit for parasitic elements can be solved using even and odd mode techniques and hence equivalent circuit for even and odd mode can be given as shown in Fig. 5(c) and 5(d), respectively.

Now the equivalent circuit of symmetrically Gunn loaded microstrip antenna with parasitic elements can be given as shown in Fig. 6. The input impedance of the symmetrically Gunn loaded microstrip antenna with parasitic elements can be calculated using even mode and odd mode impedances which are given as

\[ Z_{even} = Z_G | 4X_p \]  \hspace{1cm} \ldots (3)

and

\[ Z_{odd} = Z_G | 2X_p | 4X_s \]  \hspace{1cm} \ldots (4)

where, \( X_s \) and \( X_p \) are capacitive impedances of gap and parasitic elements; and \( Z_G \) is the impedance of symmetrically Gunn loaded patch. Hence, total input impedance can be given as

\[ Z_{in} = Z_{odd} + Z_{even} \]  \hspace{1cm} \ldots (5)

Using Eq. (5), one can calculate several antenna parameters such as reflection coefficient, VSWR and return loss.

3 Operating frequency

The Gunn diode operates in limited charge accumulation (LSA) mode\(^{12}\). It may be mentioned that when bias voltage \( V_b \) is less than threshold voltage \( V_{th} \), the diode is in ohmic region with relatively small parallel capacitance and current is exponentially limited by \( \frac{L}{R_0} \) time constant. Thus, the time period \( T_1 \) can be written as\(^{12}\):

\[ T_1 = \frac{L}{R_0 \frac{V_b}{V_{th}}} \]  \hspace{1cm} \ldots (6)

where, \( R_0 \) is the low field resistance when \( V_b < V_{th} \) and \( L \) is the inductance of microstrip patch.

The resonance frequency of the microstrip antenna is also controlled by \( L \) and \( C \) parameters of the patch and hence time period \( T_2 \) for the patch can be written as

\[ \text{Fig. 3 — Vector current distribution on fed patch and parasitic patch} \]

\[ \text{Fig. 4(a) — Equivalent circuit of the RMSA} \]

\[ \text{Fig. 4(b) — Equivalent circuit of symmetrically Gunn loaded RMSA} \]

\[ \text{Fig. 4(c) — Modified circuit of symmetrically Gunn loaded RMSA} \]
Therefore, the total time period $T$ for the Gunn integrated microstrip antenna can be given by

$$T = T_1 + T_2$$

$$T = \frac{L}{R_0 \frac{V_b}{V_{th}}} + 2\pi\sqrt{LC}$$

Hence, the operating frequency of the Gunn integrated antenna is given by

$$f = \frac{1}{LV_{th} \frac{1}{R_0 V_b} + 2\pi\sqrt{LC}}$$

3.1 Radiation pattern

The radiation pattern for Gunn loaded active microstrip antenna is given as

$$E(\theta) = -jk_o W e^{-jk_o r} \cos(kh \cos \theta) \frac{\sin \left( \frac{k_o W}{2} \sin \theta \sin \phi \right)}{\pi r} \cos(kh \cos \theta) \frac{k_o W}{2} \sin \theta \sin \phi \times \cos \left( \frac{k_o l}{2} \sin \theta \sin \phi \right) \cos \phi \quad (0\leq \theta \leq \pi/2) \quad \ldots (10)$$

$$E(\phi) = -jk_o W e^{-jk_o r} \cos(kh \cos \theta) \frac{\sin \left( \frac{k_o W}{2} \sin \theta \sin \phi \right)}{\pi r} \cos(kh \cos \theta) \frac{k_o W}{2} \sin \theta \sin \phi \times \cos \left( \frac{k_o l}{2} \sin \theta \sin \phi \right) \cos \phi \sin \phi \quad (0\leq \theta \leq \pi/2) \quad \ldots (11)$$

where, $V_b$ is radiating edge voltage; $r$, is the distance of an arbitrary point;

$$k = k_o \sqrt{\varepsilon_r}$$

$$k_o = \frac{2\pi}{\lambda}$$

$$E_r(\theta) = AF \times E(\theta)$$

$$E_r(\phi) = AF \times E(\phi)$$

Where, $AF$, is array factor and given by

$$AF = \frac{1}{3} \sin \left( \frac{3\psi}{2} \right) \frac{\sin \left( \psi \right)}{2}$$

4 Design specifications

The design specifications of the microstrip patch and Gunn diode are given in Tables 1 and 2, respectively.

![Fig. 5(a) — Parallel gap coupled microstrip lines](image)

![Fig. 5(b) — Equivalent circuit of gap coupled lines](image)

![Fig. 5(c) — Even mode](image)

![Fig. 5 (d) — Odd mode](image)

![Fig. 6 — Equivalent circuit of symmetrically Gunn diode loaded RMSA with parasitic elements: (a) Even mode; (b) Odd mode](image)
5 Results and discussion

The input impedance of symmetrically Gunn loaded microstrip antenna with parasitic elements were calculated using Eq. (12) and resulting data for real and imaginary parts of impedance are plotted as a function of frequency with simulated result in Fig. 7 for s=1 mm (V_b=15 V and V_th=4.9 V). Variation of return loss as a function of frequency is shown in Fig. 8 along with simulated results for s=1 mm. It is evidently clear that proposed theoretical and simulated results are in good agreement. However, variation of return loss with frequency for different values of ‘s’ is shown in Fig. 9. It is observed that when gap length is increased beyond 12 mm, antenna behaves as a symmetrically Gunn loaded patch and the effect of parasitic elements ceases to exist. This is because of the fact that for separation beyond 12 mm, the coupling between radiating edge of the patch and parasitic elements become negligibly insignificant.

Further, it may be noted that Gunn loaded patch with parasitic elements exhibits an increased band of 400 MHz (bandwidth of 4.48%) for s=1 mm as compared to the Gunn loaded patch (band 297 MHz, bandwidth 3.06%). Similar results were also reported by Kumar & Gupta7 and Gautam & Vishvakarma3 which justify the veracity of the proposed method. Variation of bandwidth with gap separation ‘s’ is shown in Fig. 10. It is observed that the increase of gap separation between patch and parasitic elements degrades the bandwidth. Typically increase of gap ‘s’ beyond 12 mm renders the patch to behave as a Gunn loaded patch. However, the antenna shows maximum

<table>
<thead>
<tr>
<th>Table 1 — Design specifications of microstrip patch</th>
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<tbody>
<tr>
<td>Substrate material used</td>
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<tr>
<td>Relative permittivity of the substrate (ε_r)</td>
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<tr>
<td>Thickness of the dielectric substrate (h)</td>
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<tr>
<td>Length of the patch (l)</td>
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<tr>
<td>Width of the patch (W)</td>
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<td>Design frequency (f)</td>
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<th>Table 2 — Design specifications of Gunn diode</th>
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<tr>
<td>Type</td>
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<tr>
<td>Threshold voltage (V_th)</td>
</tr>
<tr>
<td>Operating point</td>
</tr>
<tr>
<td>Oscillation frequency</td>
</tr>
<tr>
<td>D C resistance</td>
</tr>
<tr>
<td>Operating mode</td>
</tr>
<tr>
<td>Out put power (mW)</td>
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<tr>
<td>Conversion efficiency</td>
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<td>Device capacitance (Cd)</td>
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<td>Packaging capacitance</td>
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<tr>
<td>Series inductance (Ls)</td>
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<tr>
<td>Typical value of low resistance (-R_0)</td>
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<tr>
<td>Typical value of device resistance (-R_d)</td>
</tr>
<tr>
<td>D C bias voltage (V_b)</td>
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Fig. 7 — Variation of real and imaginary part of impedance with frequency

Fig. 8 — Variation of return loss with frequency for a given gap s = 1 mm (V_b=15 V, V_th=4.4 V)
Fig. 9 — Variation of return loss with frequency for different gap ($V_b=15$ V, $V_{th}=4.4$ V)

Variation of bandwidth with gap ‘s’ bandwidth for s=1 mm. The bandwidth remains lowest and invariant with the gap beyond 12 mm. It may be noted that the amount of excitation in the parasitic elements decreases with separation between the patch and parasitic elements. Thus, the effect of parasitic elements on the antenna performance becomes negligibly small beyond a certain value (s=12 mm). Variation of operating frequency with bias voltage is shown in Fig. 11 for different values of $V_{th}$. It is also found that the operating frequency decreases with increasing bias voltage for all the values of threshold voltage considered, however, the operating frequency is higher for higher threshold voltage.

In order to obtain the radiation pattern of the patch with two parasitic elements at the radiating edges, the current distribution were obtained using IE3D (Fig. 3). It is observed that the patch with parasitic elements exhibits enhanced radiated power by 0.5833 dB as compared to patch alone. It is further observed that the radiated power of the patch with parasitic elements decreases with increasing value of separation ‘s’ (Fig. 12). Typically when s=12 mm, the effect of parasitic element ceases to exist.

Fig. 11 — Variation of operating frequency with bias voltage

Fig. 10 — Variation of bandwidth with gap ‘s’

Fig. 12 — Radiation pattern
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