Noise considerations in Gunn integrated rectangular microstrip antenna

Anjali Nayak & Babau R Vishvakarma
Department of Electronics Engineering, Institute of Technology, Banaras Hindu University, Varanasi 221 005

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In the present paper, noise behaviour of the active patch antenna (GaAs Gunn integrated patch and InP Gunn integrated patch) has been theoretically investigated and consequently the noise figure, noise temperature and noise power are calculated as a function of bias voltage. The noise performance of InP Gunn integrated patch is found to be much better than that of the GaAs Gunn integrated patch.

1 Introduction

The active microstrip antenna has become prominent, now-a-days, in the field of microwave communication because of their numerous advantages such as low profile, lightweight, low volume, easy fabrication and suitability of mass production. However, the low power capability and narrow bandwidth of the antenna are severe constraints in several practical applications. It has been observed that the active solid-state-device-loaded patch shows improved radiated power and bandwidth.

The patch antenna can be represented by \( R, L, \) and \( C \) circuit where the thermal noise due to the lumped elements can affect the antenna performance. Also the active devices integrated with the microstrip antenna may add additional noise in the system.

In the present paper, an attempt has been made to study the noise behaviour of the active antenna and consequently the noise power, noise figure, noise temperature, etc. have been calculated. The noise in patch antenna as well as Gunn diode for both GaAs and InP (Refs 4-6) have been evaluated separately and then effective noise power, effective noise figure and the effective noise temperature of the Gunn integrated patch have been calculated by considering the diode and patch antenna in cascade.

2 Theoretical considerations

The Gunn diode operates in LSA (limited-space-charge accumulation) relaxation oscillator mode in the X-band frequency range. The equivalent circuit of the patch antenna and Gunn integrated patch antenna are shown in Fig. 1[(a) and (b)].

The patch antenna can be expressed as a parallel combination of \( R, L, \) and \( C \) elements. For a rectangular patch, these elements can be defined as follows:

\[
C = \frac{\varepsilon_r \varepsilon_0}{2} \frac{W}{h} \cos^2 \left( \frac{\pi D}{l} \right) \quad \ldots (1)
\]

\[
L = \frac{1}{\omega_0^2} \quad \ldots (2)
\]

(a)

(b)

\[\begin{align*}
R_1 & \quad L_1 & \quad C_1 \\
R_d & \quad L & \quad C
\end{align*}\]

Fig. 1—Equivalent circuit of (a) patch antenna and (b) Gunn integrated patch antenna
and

\[ R = \frac{Q_r}{\omega r C} \]  \hspace{1cm} ... (3)

where,

- \( l \) = Length of the non-radiating edge
- \( W \) = Length of the radiating edge
- \( D \) = Feed point location
- \( h \) = Thickness of substrate
- \( \omega r \) = Angular frequency = 2\( \pi f \)
- \( f \) = Resonance frequency of patch
- \( Q_r \) = Radiation quality factor

\[ \varepsilon_0 = \text{Free space permittivity} \]
\[ \varepsilon_r = \text{Effective permittivity of the substrate} \]

\[ \varepsilon_0 = \frac{\varepsilon_r + 1 + \varepsilon_r - 1}{2} \left( 1 + \frac{10h}{W} \right)^{-1/2} \]

The frequency of the active patch mainly depends on the bias voltage as well as threshold voltage. The effective resonance frequency of the active patch can be obtained as

\[ f_r = \frac{1}{L} \left( \frac{V_b}{V_T} + 2\pi \sqrt{LC} \right)^{-1} \]  \hspace{1cm} ... (4)

where,

- \( L \) = Inductance of the microstrip patch
- \( C \) = Capacitance of the microstrip patch
- \( R_0 \) = Low-field negative resistance of the device when \( V_b < V_T \)
- \( V_b \) = Bias voltage
- \( V_T \) = Threshold voltage

3 Noise parameters of the rectangular patch antenna

Available noise power of the rectangular patch due to noisy resistor is given by

\[ P_a = k T_a B \]  \hspace{1cm} ... (5)

where,

- \( k \) = Boltzmann's constant
- \( T_a \) = Absolute room temperature = 290 K
- \( B \) = Bandwidth

Effective noise temperature of the patch antenna \( T_a \) can be defined as

\[ T_a = \frac{P_a}{G_a k B} \]  \hspace{1cm} ... (6)

where,

- \( P_a \) = Available noise power
- \( G_a \) = Available power gain

The input conductance of the patch antenna is defined as

\[ G_{in} = G_{rad} + G_{cu} + G_{di} \]  \hspace{1cm} ... (7)

where,

- \( G_{rad} \) = Radiation loss conductance
- \( G_{cu} \) = Copper loss conductance
- \( G_{di} \) = Substrate loss conductance

\[ G_{cu} = \frac{\pi^2 W}{2\omega^2 \mu^2 l h} \]
\[ G_{di} = \omega C \tan \delta \]

The antenna efficiency is given by

\[ \eta = \frac{G_{rad}}{G_{in}} \]  \hspace{1cm} ... (8)
and available power gain of the rectangular patch antenna is calculated as:

\[ G_a = \eta D_w \]  

... (9)

where,

\[ \eta = \text{Efficiency of the antenna} \]

\[ D_w = \text{Directivity of the antenna} \]

Noise figure \( (F_a) \) is defined as the ratio of the input signal-to-noise ratio to output signal-to-noise ratio of the system.

Noise output for noisy system = \( G_a k T_B + G_a k T_a B \)

Noise output for noise free system = \( G_a k T_a B \)

Hence, the noise figure \( (F_a) \) of the rectangular patch can be written as:

\[ F_a = \frac{G_a (k T_B + k T_a B)}{G_a k T_a B} = \frac{T_B + T_a}{T_a} \]  

... (10)

where,

\[ T_a = \text{Absolute temperature} \]

\[ T_a = \text{Effective noise temperature of an antenna} \]

4 Noise parameters of Gunn diode

- The expression for the noise voltage of the Gunn diode is given as:

\[ V_d^2 = \frac{8 q D n l B}{A_o \omega^2 e^2} \left( 1 - \frac{\nu}{\omega l} \sin \left( \frac{\omega l}{\nu} \right) \right) \]  

... (11)

where,

\[ \frac{\omega l}{\nu} = \frac{5\pi}{3} \]

\[ A_o = \text{Diode area} \]

\[ D = \text{Diffusion coefficient} \]

\[ n = \text{Electron density} \]

\[ l = \text{Device length} \]

\[ q = \text{Electron charge} \]

Therefore, the available noise power of the Gunn diode is given by

\[ P_d = \frac{V_d^2}{Z_R} \]  

... (12)

where,

\[ V_d = \text{Noise voltage} \]

\[ Z_R = \text{Resistive part of input impedance} \]

Noise figure of the Gunn diode can be calculated using the following relation:

\[ F_d = 1 + \frac{8 q^2 D n l}{k T_C \nu} \left( 1 - \frac{\nu}{\omega l} \sin \left( \frac{\omega l}{\nu} \right) \right) \]  

... (13)

where,

\[ \nu = \text{Average drift velocity} \]

\[ R_{dt} = \text{Density of state ratio} \]

The gain of the Gunn diode can be defined as:

\[ G_d = \frac{Y_o - Y(\omega)}{Y_o + Y(\omega)} \]

... (15)

where,

\[ Y_o = \text{Characteristics admittance of the transmission line} \]

\[ Y(\omega) = \text{Admittance of the Gunn diode} \]

5 Noise parameters of Gunn integrated patch antenna

Total available noise power at the output of the cascade is obtained as:

\[ P_T = G_d G_a \left( T_u + T_d + \frac{T_u}{G_d} \right) B \]  

... (16)

where,
\[ G_a = \text{Gain of the antenna} \]
\[ G_d = \text{Gain of the Gunn diode} \]

The effective noise figure of the antenna is given by
\[ F_T = F_d + \frac{F_a - 1}{G_a} \quad \ldots (17) \]
where,
\[ F_a = \text{Noise figure of the patch antenna} \]
\[ F_d = \text{Noise figure of the Gunn diode} \]

and the effective noise temperature of the system is given by
\[ T = T_d + \frac{T_a}{G_d} \quad \ldots (18) \]
where,
\[ T_a = \text{Noise temperature of the patch antenna} \]
\[ T_d = \text{Noise temperature of the Gunn diode} \]

6 Design considerations

Rectangular microstrip antenna has been designed with the following specifications:

- Substrate material used: RT Duroid 5870
- Loss tangent: 0.0012
- Relative dielectric constant \((\varepsilon_r)\): 2.32
- Centre design frequency: 10 GHz

Specifications of GaAs Gunn diode:
- Type: M/A COM 49104, GaAs n
- DC bias voltage \((V_b)\): (8-15) V
- Threshold voltage \((V_T)\): (2.9-4.4) V
- Oscillating frequency (X-band): (8-12.4) GHz
- Operating mode: LSA relaxation mode
- Device capacitance \((C_d)\): 0.1 pF
- Device length \((l)\): 70 µm
- Diffusion coefficient \((D)\): 207 cm²/sec
- Mobility \((\mu)\): 8500 cm²/Vsec
- Energy bandgap \((\Delta E)\): 0.31 eV
- Density of state ratio \((R)\): 94
- Effective density of states in the conductance band \((N_c)\): \(4.7 \times 10^{17} \) cm⁻³

Specifications of InP Gunn diode:
- Device length \((l)\): 8 µm
- Mobility \((\mu)\): 4600 cm²/Vsec
- Density of state ratio \((R)\): 34.685
- Energy bandgap \((\Delta E)\): 0.53 eV

7 Discussion

Variation of frequency with bias voltage for different values of threshold voltage is shown in Fig. 2. It is observed that resonance frequency decreases with increasing bias voltage for a given value of threshold voltage, whereas resonance frequency increases with increasing threshold voltage for a given bias.

Figures 3 and 4 show the variation of noise figure with bias voltage for a given threshold voltage which indicate that the noise figure decreases with increasing bias voltage for a given threshold voltage for GaAs Gunn diode as well as GaAs Gunn loaded patch antenna. The noise contribution by the GaAs Gunn diode is very high (12.422 dB to 15.175 dB) as compared to the patch antenna (0.804 dB), which enhances the overall noise figure of the GaAs Gunn integrated patch antenna (12.547 dB to 15.242 dB). The decrease in the noise figure with increasing bias voltage in Gunn diode is attributed to the fact that

![Graph showing variation of frequency with bias voltage at different threshold voltages](image-url)
increasing bias voltage raises the value of average drift velocity \( (v) \), which reduces the noise figure of the Gunn diode [Eq. (17)]. The calculated value of noise figure of GaAs Gunn diode is in good agreement with the earlier reported data in which the noise figure was reported\(^1\) to be between 12 dB and 15 dB.

The noise figure in the InP Gunn diode and InP Gunn integrated patch is also found decreasing with increasing bias voltage for a given threshold voltage (Fig. 5). However, the noise contribution of the InP Gunn diode is almost half (4.895 dB to 7.029 dB) the GaAs Gunn diode (12.547 dB to 15.175 dB). This indicates that InP Gunn diode is preferable over the GaAs Gunn diode so far as the noise performance of the active antenna is concerned. The calculated value of InP Gunn diode is in good agreement with the earlier reported data in which the noise figure was reported\(^2\) to be between 6 dB and 10 dB.

Variations of noise temperature with bias voltage for GaAs Gunn diode and InP Gunn diode are shown in Figs 6 and 7, respectively. It is observed that the noise temperature decreases with increasing bias voltage for both active antennas for a given threshold voltage. The contribution of the noise temperature by GaAs Gunn diode (7652.24 K-3806 K)
K) is almost ten times to that of InP Gunn diode (716.582 K-229.153 K).

As such the noise contribution by the patch antenna (Fig. 8) is quite low (-107.5427 dB) which is constant for the entire range of bias voltage. The contribution of the noise by GaAs Gunn diode is (-92.944 dB to -93.035 dB) which is almost constant with the bias voltage for a given value of threshold voltage. However, the effective noise power of the GaAs Gunn integrated patch is found decreasing with increasing bias voltage for a given value of threshold voltage. This is because of the fact that resonance frequency decreases with increasing bias voltage, which reduces the gain of the antenna. The overall noise power of the GaAs Gunn integrated patch is found to be between -85.67 dB and -88.47 dB.

The noise contribution by the InP Gunn diode is relatively low (-99.63 dB to -99.723 dB) as compared to noise in GaAs Gunn diode (-92.944 dB to -93.035 dB) and this is why the overall noise power of the InP Gunn loaded patch (-94.123 dB to -96.509 dB) is 9 dB lower than that of GaAs Gunn integrated patch (-85.67 dB to -88.475 dB).

![Fig. 6—Variation of noise temperature with bias voltage at different threshold voltage for GaAs Gunn diode and GaAs Gunn loaded patch antenna (variations for patch antenna are also shown.)](image1)

![Fig. 7—Variation of noise temperature with bias voltage at different threshold voltage for InP Gunn diode and InP Gunn loaded patch antenna (variations for patch antenna are also shown.)](image2)

![Fig. 8—Variation of noise power with bias voltage at different threshold voltage for different antennas](image3)
8 Summary and conclusion

It has been found that the resonance frequency of the Gunn loaded microstrip antenna depends on bias voltage and threshold voltage. The resonance frequency depends inversely on bias voltage for a given threshold voltage and directly on the threshold voltage for a given bias voltage. The noise contribution by GaAs Gunn diode is very high (12.547 dB-15.175 dB) which is almost double the noise in the InP Gunn diode. The noise data obtained by the proposed method are in good agreement with reported data both for GaAs and InP Gunn diode. The noise temperature contribution by GaAs Gunn diode is almost ten times to that of InP Gunn diode. It is, therefore, concluded that the noise performance of the InP Gunn loaded patch is much better than the GaAs Gunn loaded patch.

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References