IMPATT integrated active microstrip antenna
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An IMPATT diode integrated rectangular patch is theoretically investigated based on the circuit concept in the millimetre range. The various parameters of the antenna are found to depend on the bias voltage and there is marked improvement in the tuning range, radiated power and bandwidth. The antenna exhibits bandwidths of 20% for 1.5:1 VSWR and 35% for 2:1 VSWR. The antenna shows frequency agility for a band of 614 MHz, i.e. 1.7837% band.

1 Introduction
The active antenna has become prominent nowadays in the field of microwave and millimetre wave communications as it offers advantages of enhanced power capability, improved beamwidth, gain, bandwidth, low profile, light weight and easy fabrication. In recent years several workers are concentrating on integration of various active devices such as Gunn diode, MESFET, Tunnel diode, IMPATT diode, etc. with the microstrip patch antenna with a view to improving the antenna performance. However, little efforts have been made to predict the performance of IMPATT diode integrated microstrip antenna. In the present paper, an attempt has been made to develop a theoretical model of IMPATT diode integrated microstrip antenna to predict its performance.

2 Theoretical considerations
An IMPATT diode operates in CW mode in the millimetre wave range (i.e., above 30 GHz). The IMPATT diode employs impact ionization and transit time properties of semiconductor structures to produce negative resistance at microwave frequencies. Owing to negative-resistance property of the IMPATT diode, it can be used as an oscillator.

The basic structure and electric field distribution of an IMPATT diode are given elsewhere. An IMPATT diode can be integrated directly with the patch antenna as shown in Fig. 1(a). The IMPATT diode is mounted between the patch and ground plane (Fig. 1(b)) and biasing is effected by applying d.c. voltage between the patch and ground plane.

The placement of an active device is selected in such a way that the device impedance is matched with the input impedance of the patch. The diode placement location, d, is given by

\[ d = \frac{\lambda_d}{2\pi} \cos^{-1} \left[ 2ZG_1 \left( 1 - \frac{G_m}{G_s} \right) \right]^{1/2} \]  

... (1)

![Fig. 1 — (a) Top view of the IMPATT integrated microstrip patch with location of diode placement and (b) Side view of IMPATT integrated patch antenna](image-url)
where,
\[ G = \left( \frac{W^2}{90A_0^2} \right) \text{ Radiation conductance} \quad \ldots (2) \]
\[ G_m = \text{Mutual conductance of the two edges of the antenna} \]
\[ G_m = 0.32 \]
\[ d = \text{Distance from either antenna edge to the feed point location} \]
\[ Z = \text{Input impedance of the antenna at the diode location, which is equal to the active device resistance} \]
\[ \lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}}}} \text{ Guide wavelength} \]
\[ \varepsilon_{\text{eff}} = \text{Frequency dependent effective relative permittivity} \]

From Fig. 1, the feed location coordinates are given as \((l - d, W/2)\).

The combined equivalent circuit of the IMPATT diode and the patch (i.e. active patch) is shown in Fig. 2.

The parallel combination of \( R, L \) and \( C \) is the equivalent circuit of rectangular microstrip antenna obtained by modal expansion cavity model. The values of \( R, L \) and \( C \) for a rectangular patch can be given as
\[ C = \frac{\varepsilon_{\text{eff}} \varepsilon_0 LW}{2h} \cos^2 \left( \frac{\pi d}{l} \right) \quad \ldots (3) \]
\[ L = \frac{1}{C \omega_i^2} \quad \ldots (4) \]
\[ R = \frac{Q}{\omega_i C} \quad \ldots (5) \]
where,
\[ \varepsilon_{\text{eff}} = \text{Effective dielectric constant} \]
\[ \varepsilon_0 = \text{Dielectric constant of free space} \]
\[ l = \text{Length of patch} \]
\[ W = \text{Width of patch} \]
\[ h = \text{Thickness of substrate} \]
\[ d = \text{Feed location} \]
\[ Q = \text{Quality factor} \]
\[ f_i = \text{Resonance frequency of the patch} \]
\[ \omega_i = 2\pi f_i \]

The total input impedance \( Z_i \) of the active patch can be derived as
\[ Z_i = \left[ R_i + R + \frac{\omega_i^2 R L^2}{(R - \omega_i^2 R L C)^2 + \omega_i^2 L^2} \right] + j \omega_i \left[ \frac{L_i}{(1 - \omega_i^2 L_i C_i)} \right] \quad \ldots (6) \]

To calculate the effective resonance frequency of the active patch, the imaginary part of the input impedance is equated to zero, which gives,
\[ \omega_i = \sqrt{\frac{b \pm m}{2a}} \quad \ldots (7) \]
where,
\[ b = R_i^2 L_i C_i + R_i^2 L L_i (2C_i + C_a) - L_i^2 L_a \]
\[ a = R_i^2 L_i C_i (C + C_a) \]
\[ m = \left[ (R_i^2 L_i C_i + R_i^2 L L_i (2C_i + C_a) - L_i^2 L_a)^2 \right. \]
\[ \left. - 4R_i^2 L_i C_i (C + C_a)(L + L_a) \right]^{1/2} \]

Resonance frequency \( f_i \) is given as
\[ \frac{b \pm m}{2a} \quad \ldots (8) \]

The maximum voltage that can be applied across the diode is given by
\[ V = E \cdot X_d \quad \ldots (9) \]
where, \( E \) is the maximum electric field and \( X_d \) the depletion width. This maximum voltage is limited by the breakdown voltage. Furthermore, the maximum current that can be carried by the diode is also limited by the Avalanche breakdown process.

The maximum current is given by
\[ I = \frac{v_d \varepsilon_i E A}{X_d} \quad \ldots (10) \]

Combining Eqs (9) and (10), one gets the relation between total current and reverse d.c. voltage as,
\[ I = \frac{v_d \varepsilon_i V A}{X_d^2} \quad \ldots (11) \]
where,
\[ v_d = \text{Carrier drift velocity} \]
\[ \varepsilon_i = \text{Semiconductor permittivity} \]
\[ A = \text{Diode cross-section} \]
\[ X_d = \text{Length of the drift space charge region} \]
The IMPATT diode mainly consists of three regions namely, Avalanche region, drift region and inactive region. The Avalanche region behaves as an inductance-capacitance parallel circuit, where the inductance $L_a$ and capacitance $C_a$ vary with respect to current and width of Avalanche region, respectively. They are given as:

$$L_a = \frac{X_s}{21\alpha v_a}.$$  ... (12)

and

$$C_a = \frac{E_a A}{X_s}.$$  ... (13)

where,

$X_s =$ Width of an Avalanche region

$$\alpha = \frac{A h}{E^2}$$

$A_1 = 1.55 \times 10^7 \text{ cm}^{-1}$

$I =$ Total d.c. current

The space charge resistance ($R_d$) in the drift region is given by

$$R_d = \frac{(D - X_s)^2}{2A\varepsilon_x v_a}.$$  ... (14)

where,

$D =$ Total depletion width

and

$(D - X_s) =$ Width of drift region

The inactive region resistance ($R_i$) is constant.

Six IMPATT diodes in parallel are connected in series with the microstrip resonant patch\(^6\), which are identical in total depletion width having different Avalanche widths $\left( \frac{X_s}{D} = \frac{1}{10} \cdot \frac{1}{3} \cdot \frac{1}{2} \cdot \frac{1}{3} \cdot \frac{9}{10} \right)$. During operation, one diode can be selected in the circuit.

The bandwidth (BW) can be mathematically defined as

$$\text{BW} = \frac{s - 1}{Q_T \sqrt{s}}.$$  ... (15)

where,

$Q_T =$ Total quality factor

$$Q_T = \frac{c\sqrt{E_r}}{4f_r h} \left( 1 + \frac{2R_{DL}}{R_i} \right).$$  ... (16)

$R_D =$ Dielectric loss resistance

$$R_D = \frac{90\lambda_0^2}{W^2} \tan \delta.$$  ... (18)

$\tan \delta =$ Loss tangent of substrate material

The VSWR of an active patch can be calculated using the following relation:

$$\rho = \frac{1 + \rho}{1 - \rho}.$$  ... (19)

where,

$\rho =$ Reflection coefficient

### 3 Radiation pattern

The theoretical E-plane radiation patterns for the microstrip patch can be calculated using the following relations\(^5\):

$$E_y = \frac{jV_0 k_0 W e^{-jkr}}{\pi r} \left[ \cos(kh\cos\theta) \right]$$

$$\times \left[ \frac{\sin(k_0 W/2) \sin\theta \sin\phi}{(kW/2) \sin\theta \sin\phi} \right]$$

$$\times \left[ \cos(k_0 W/2) \cos\theta \sin\phi \right] \cos\theta \sin\phi; \left( 0 \leq \theta \leq \frac{\pi}{2} \right)$$

and

$$E_y = \frac{jV_0 k_0 W e^{-jkr}}{\pi r} \left[ \cos(kh\cos\theta) \right]$$

$$\times \left[ \frac{\sin(k_0 W/2) \sin\theta \sin\phi}{(k_0 W/2) \sin\theta \sin\phi} \right]$$

$$\times \left[ \cos(k_0 W/2) \sin\theta \cos\phi \right] \cos\theta \sin\phi; \left( 0 \leq \theta \leq \frac{\pi}{2} \right)$$

where,

$V_0 =$ Radiating edge voltage

$r =$ Distance of any arbitrary point

$k = k_0 \sqrt{E_r} = \left( \frac{2\pi}{\lambda} \right) \sqrt{E_r}$

### 4 Design considerations

An active rectangular microstrip patch antenna has been designed with the following specifications:

Substrate material \quad = \quad \text{RT Duroid 5870}
Relative dielectric constant ($\varepsilon_r$) = 2.32
Thickness of substrate material ($h$) = 1.524 mm
Loss tangent (tan $\delta$) = 0.0012
Centre design frequency ($f$) = 34 GHz
Resistance of patch ($R$) = 30.246 $\Omega$
Inductance of patch ($L$) = 70.604 pH
Capacitance of patch ($C$) = 0.3107 pH

The specifications for IMPATT diode are as follows:

- Type: Si (n type)
- DC resistance ($Z$) = 1.5 $\Omega$
- Oscillating frequency = (30-300) GHz
- Operating mode = Continuous wave mode
- Passive resistance of the inactive region ($R_5$) = 1.5 $\Omega$
- Breakdown voltage ($V_b$) = 94.1 V
- DC reverse bias voltage ($V$) = (55-80) V
- Diode cross-section ($A$) = $10^8$ m$^2$
- Derivative of ionization coefficient with electric field ($\alpha$) = 3.059
- Carrier drift velocity ($v_d$) = $2 \times 10^5$ m/s
- Semiconductor permittivity ($\varepsilon_r$) = $11.8 \times 8.857 \times 10^{-12}$ F/m
- Electric field ($E$) = $4 \times 10^7$ V/m

The sides of a rectangular patch (length and width) were calculated using the design equations:

At resonance, the resistance of the rectangular microstrip patch is given by:

$$ R_R = \frac{1}{2G} $$

where,

$$ G = \frac{\pi W}{2 \eta_0 \lambda_0} \left[ 1 - \left( \frac{k h}{2} \right)^2 \right] $$

$$ \eta_0 = 120 \pi $$

$$ k = \frac{\lambda}{\lambda_0} $$

Diode radiation conductance and diode location were calculated using Eqs (1) and (2).

The design parameters of an active patch antenna are given as follows:

- Width of the patch ($W$) = 3.42419 mm
- Length of the patch ($l$) = 1.800792 mm
- Patch resistance at resonance ($R_0$) = 157.94 $\Omega$
- Diode radiation conductance ($G_0$) = 0.00167 mho
- Diode feed location ($d$) = 1.22065 mm

**5 Calculations**

In order to design the active antenna, calculations were made for various parameters such as width, length, radiation conductance and feed-location using Eqs (1) and (2). The values of equivalent $R$, $L$ and $C$ for rectangular patch were calculated using Eqs [(3)-(5)] and the IMPATT diode parameters were also calculated using Eqs [(9)-(14)]. The values of various parameters such as input impedance, resonance frequency, bandwidth and VSWR were calculated using Eqs [(6)-(8), (15)-(19)] as a function of reverse bias voltage. The data thus obtained are shown in Figs 3-5.

The E-plane radiation patterns for different reverse bias voltages were calculated using Eqs [(20) and (21)], which are shown in Fig. 6.

**6 Discussion**

Examination of Fig. 3 indicates that the resonance frequency of IMPATT loaded patch antenna increases almost linearly with reverse bias voltage. This is in accordance with the fact that increasing bias voltage increases the current in the device [Eq. (11)] resulting in enhancement in the resonance frequency. It is also evident that the antenna can work for the frequency range 34.105 - 34.719 GHz by changing the reverse bias voltage. Figure 3 also shows the variation of real and imaginary part of the input impedance of
It is observed that the reactive part of the input impedance is almost zero at all the values of reverse bias voltage indicating that the circuit may resonate at any bias voltage. However, the real part of the input impedance decreases with increasing reverse bias of the IMPATT loaded patch. This further reveals that such an antenna may work satisfactorily for the feed impedance ranging from 31.53 to 101.54 ohms.

The variation of input VSWR with reverse bias voltage (Fig. 4) shows that the IMPATT loaded patch antenna exhibits lowest value of VSWR (1.06:1) at reverse bias voltage of 65 V. This is justified because of the fact that the antenna is connected to the 50 Ω feed line and the real part of input impedance at 65 V bias shows the value of 50 Ω, which gives rise to the best matching of the device. This is further corroborated from the return-loss which is −30.18 dB at 65 V.

The variations of bandwidth with reverse bias voltage are shown in Fig. 5. It is observed that the bandwidth of the antenna maintains almost a constant value with reverse bias voltage. This is justified because the total quality factor of the antenna does not vary significantly with the bias voltage. Further, the value of quality factor is very low. Since the bandwidth is inversely proportional to the quality
factor, the low value of the quality factor makes the bandwidth of the IMPATT loaded patch quite high. Typically the bandwidth is around 20% for VSWR 1.5:1 and around 35% for VSWR 2:1.

The examination of radiation pattern (Fig. 6) of IMPATT loaded antenna indicates that the radiated power depends inversely on the reverse bias voltage. The beamwidth of the antenna also increases very minutely with the decreasing bias voltage.

7 Conclusions
From the study it may be concluded that the resonant frequency, radiated power and beamwidth of the IMPATT loaded microstrip patch antenna depends on reverse bias voltage applied to the device. Such antenna can provide frequency agility from 34.105 to 34.7192 GHz just by controlling the reverse bias voltage.

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References