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RESEARCH PAPER

Gunn-mounted active microstrip rectangular patch antenna – revisited

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The microstrip active patch antenna behaves like a resonant circuit/cavity with multiple resonant frequencies; furthermore, depending on the non-linearity of the device, it generates significant amount of second harmonic radiation. The location of the device on the patch that maximizes the fundamental radiated power output is found to be not the position corresponding to the minimum second harmonic content in radiated power. An optimum location of the diode on the patch has been suggested. The paper also discusses the modification of the behavior of the active antenna, which is first an oscillator; and then a radiator, under injection-locked condition. The results are presented with respect to a Gunn-mounted rectangular patch.

Keywords: Rectangular patch antenna, Gunn diode, Second harmonic, Injection locking

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I. INTRODUCTION

Microstrip antennas are increasingly used for their structural simplicity. The radiating microstrip patch may be square, rectangular, circular, and elliptical or of any other configuration [1]. The square, rectangular, and circular patch antennas are common from the standpoint of the ease of their analysis and fabrication. A microstrip patch can be viewed as a parallel-plane transmission line or a parallel-plate waveguide, behaving as a lossy resonant circuit at multiple frequencies [2–4].

The microstrip patch antenna integrated with two-terminal active devices such as the Gunn diode that serves both the purpose of the radiating antenna and the power generator and as such the patch may be called either an active antenna or a quasi-optical transmitter. A number of such patches may be integrated to form an array for generating a high-power main beam that can also be electronically scanned or steered [5, 6]. The number of publications on photonic beam forming [7] and non-mechanical steering [8] for this kind of arrays are increasing day by day.

The main features of developing active antennas are to achieve (1) the highest possible radiated power, (2) the spectral purity of the output, and (3) the stability of the mode of oscillations [9–12]. Perfect matching between the antenna and device is essential to realize the first of these features. This has been done by considering the device–antenna non-linear interaction instead of considering them as independent units. This step is preceded by the design of the antenna itself for the most efficient radiation at the desired frequency. This requires determining the dimensions of the microstrip resonator as well as its frequency response characteristics for ascertaining the purity of the waveform [13]. Thus, it takes care of achieving the second of the above features. The choice of the substrate with a higher dielectric constant improves both amplitude and frequency stability of the patch oscillator though substrate with lower dielectric constant is preferred for radiation efficiency [14] and thus, it can achieve the third of the above features.

The microstrip patch behaves like a resonant circuit/cavity with multiple resonant frequencies, generating significant amount of second harmonic radiation depending on the non-linearity of the device. The location of the device that maximizes fundamental power output is not necessarily the position corresponding to the minimum second harmonic power generated [15–17]. Therefore, an optimum location of the active device, typically the Gunn diode in the patch antenna, has been suggested. An active antenna is basically an oscillator and then a radiator, and its device characteristic under injection-locked condition exhibits an interesting modification [18–26]. An expression for determining the position of the diode in the patch has been proposed (Section II) on the basis of maximum radiated power, which has been found knowing the values of the diode constants (Section II). The results are validated against the available literature [10] and appreciated against the experiments with respect to the different sets of patches (Section III) with due consideration to the harmonic (Section IV) and the injection-locking effects (Section V). Subsequently, the work has been concluded (Section VI).

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II. ACTIVE ANTENNA OUTPUT AND DIODE INTEGRATION

In an active antenna, there are two ways of mounting the Gunn diode on it. The central idea is, obviously, to realize

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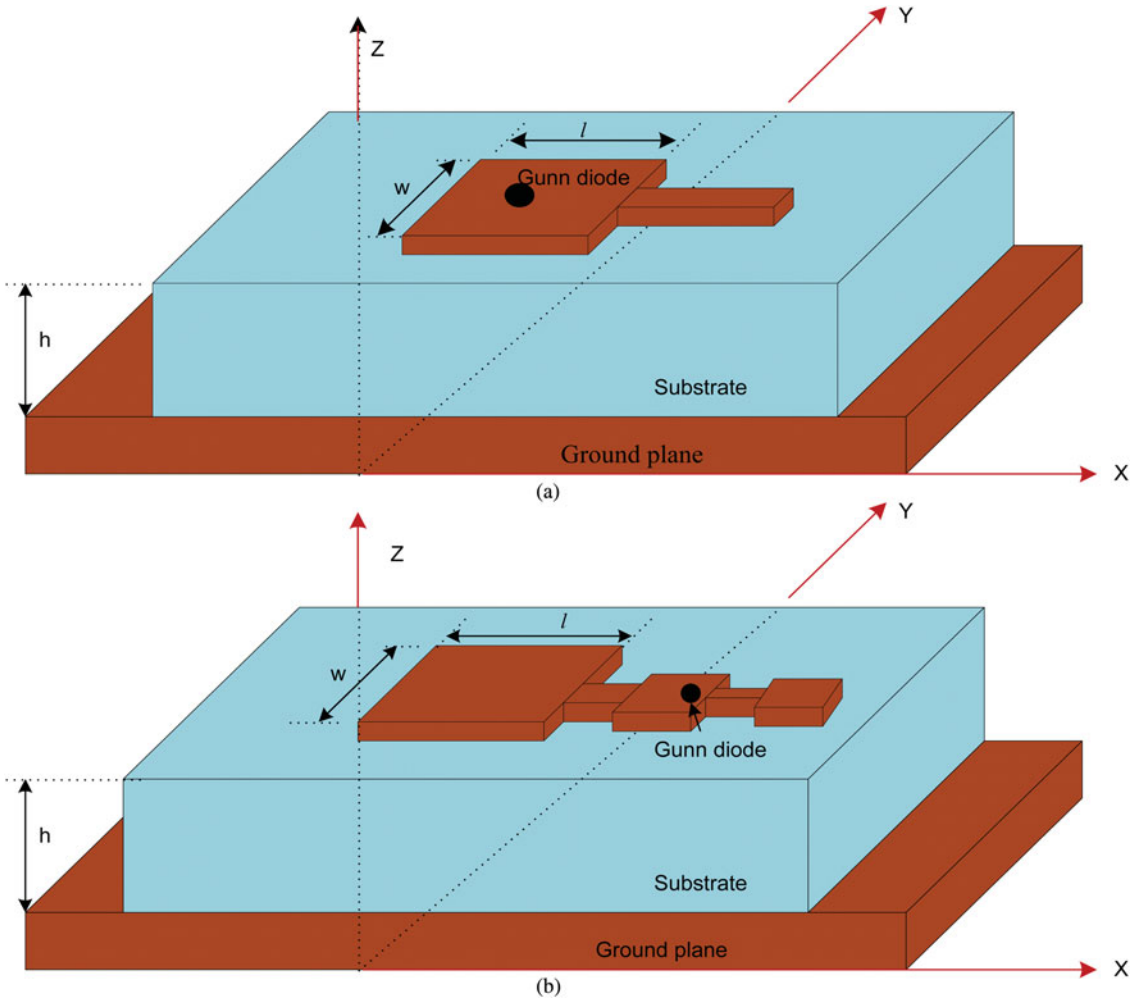


Fig. 1. Rectangular active microstrip patch antenna configuration in which the active device is placed on the patch (a) and is connected to the patch through a microstrip transformer (b).

the maximum radiated power from the antenna. It is not simply the question of finding the condition for maintenance of oscillations and the corresponding amplitude of oscillations. In the first instance (Fig. 1(a)), it is the position of the diode on the patch, where as in the second instance (Fig. 1(b)) it is related with the appropriate design of the microstrip transformer. Figure 1 shows the dimension of the active rectangular patch antenna.

Let the voltage output of the antenna be denoted by

$$v(t) = V(t)\exp j\big(\omega_i t + \psi(t)\big), \tag{1}$$

where $\psi(t)$ is the phase when frequency of oscillation is close to ω_i. Now, the instantaneous frequency as [23]

$$j\omega = \frac{1}{v(t)}\frac{dv(t)}{dt}. \tag{2}$$

Thus, from (1) and (2)

$$\omega = \omega_i + \frac{d\psi}{dt} - \frac{j}{V(t)}\frac{dV(t)}{dt}. \tag{3}$$

The conventional transmission line model of a microstrip patch is shown in Fig. 2. When the dc supply (V) is connected to the Gunn diode, the upper plate of the line acquires a positive charge, whereas the lower plate develops a negative charge. The unlike charges on the upper strip and lower ground plate establish a time-varying electric field between the plates. A closed current path is formed in which the current starts out at the plus terminal (upper strip), traverses the upper strip, short circuited at the wave front by the

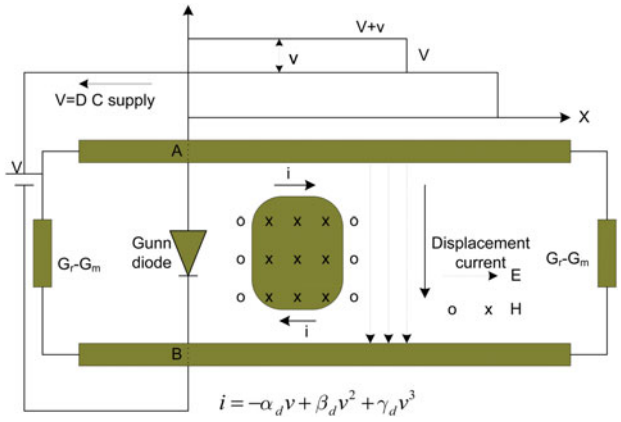


Fig. 2. Transmission line model of active patch antenna.

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displacement current through the dielectric and returns through the ground plate to the anode terminal via the cathode terminal. Each time the transient current (i) flows through the diode in opposition to the dc direction, it develops a transient voltage $v = i/\alpha_d$. Here, α_d is magnitude of the incremental negative conductance of the diode. The transient voltage will build up provided the intrinsic losses of the transmission line as well as the loss due to radiation through the ends of the transmission line are made by the negative conductance of the diode. This growth will be limited by the limiting-type non-linearity of the Gunn diode. Thus, after a while, the transient voltage will reach its limiting value. Once this limiting value is reached, the voltage will start discharging through the dielectric. As soon as this happens, the displacement current will start flowing in the opposite direction and the process will continue till the voltage attains the maximum negative value. Here, G_r represents the radiation conductance and G_m denotes the conductance due to mutual coupling between the opposite ends of the patch.

Propagation constant of a low loss transmission line is

$$\gamma = \alpha_j + j\beta_j = \sqrt{(R_1 + j\omega L)(G_j + j\omega C)}, \tag{4}$$

where R_1 is the series intrinsic resistance. Now, G_j the equivalent shunt conductance of a line of length l_j can be written as

$$G_j = G_i + 2G/l_j.$$

Here, G is the total antenna conductance and G_i is the intrinsic conductance; L and C are the inductance and capacitance per unit length of the transmission line, respectively. The input admittance at a point AB (Fig. 2) where the Gunn diode is connected is given by (considering $\beta_1 = \beta_2 = \beta = \omega\sqrt{LC}$)

$$Y_{in} = G_{in} + jY_o \times \left\{ \tan\beta l_1 + \tan\beta l_2 + \sqrt{LC}\frac{d\psi}{dt}\left(l_1 \sec^2\beta l_1 + l_2 \sec^2\beta l_2\right)\right\}. \tag{5}$$

At the steady state, Y_{in} becomes [3]

$$\begin{aligned} Y_{in} &= G_{in} + jY_o(\tan\beta l_1 + \tan\beta l_2) \\ &= G_{in} + \frac{jY_o}{\cos^2\beta_r l_1}(\omega - \omega_r)\sqrt{LC}\, l. \end{aligned} \tag{6}$$

Here, G_{in} is the input shunt conductance per unit length, Y_o is the output admittance, and β is the propagation constant. In (6), β is assumed to be nearly equal to $\beta_r\ (=\omega_r\sqrt{LC})$.

Equating (6) with dynamic impedance of diode and using (3), we obtain

$$-\left(\frac{I}{V}\right)_{diode} = G_{in} + \frac{Cl}{\cos^2\beta_r l_1}\left[j\left(\omega_i - \omega_r + \frac{d\psi}{dt}\right) + \frac{1}{V}\frac{dV}{dt}\right]. \tag{7}$$

Representing the diode current–voltage relation as [15]

$$i = -\alpha_d v + \beta_d v^2 + \gamma_d v^3,$$

where, α_d, β_d and γ_d are diode constants with values of 0.0252, −0.01087 (at 9.5 V) and 0.0265, respectively.

From (7), we find that

$$-\left(\frac{I}{V}\right)_{diode} = \left(-\alpha_d + \frac{3}{4}\gamma_d V^2\right).$$

Equating real and imaginary parts of equation (7) we can write the amplitude and phase equations of the antenna

$$\frac{dV}{dt} = \left(\frac{V}{Cl}\right)\left[\left(\alpha_d - G_{in} - \frac{3}{4}\gamma_d V^2\right)\cos^2\beta_r l_1\right], \tag{8}$$

and

$$\frac{d\psi}{dt} = \omega_r - \omega_i. \tag{9}$$

Combining expression (8) and (9) we obtain the steady-state output from an antenna as

$$V_s^2 = \frac{4}{3}\frac{\alpha_d - G_{in}}{\gamma_d}. \tag{10}$$

Power radiated

$$P_r = \frac{4}{3}\frac{\alpha_d - G_{in}}{\gamma_d}2G_r. \tag{11}$$

Maximum power radiated is found by putting, $dP_r/dG_r = 0$, which gives

$$\alpha_d = \left[4G_r - 2G_m + 0.5\left(G_i + R_1 Y_o^2\right) l\right]\sec^2\left(\beta_i l_1\right). \tag{12}$$

The value of α_d is chosen to be the dynamic conductance of the diode. From this relation the value of l_1 i.e., location of the diode to obtain maximum radiated power is determined as

$$l_1 = \frac{l}{\pi}\cos^{-1}\sqrt{R_d\left\{4G_r - 2G_m + 0.5\left(G_i + R_1 Y_o^2\right) l\right\}}. \tag{13}$$

The value of l_1 as given in [10] is presented as

$$l_1 = \frac{l}{\pi}\cos^{-1}\sqrt{R_d(G_r - G_m)}, \tag{14}$$

where $R_d = \dfrac{1}{\alpha_d}$.

Now, maximum power becomes

$$[P_r]_{\max} = \frac{16G_r^2}{3\gamma_d}\sec^2\left(\pi\frac{l_1}{l}\right). \tag{15}$$

This indicates that the maximum power radiated is a function of the radiation conductance, non-linearity, and location of the diode.

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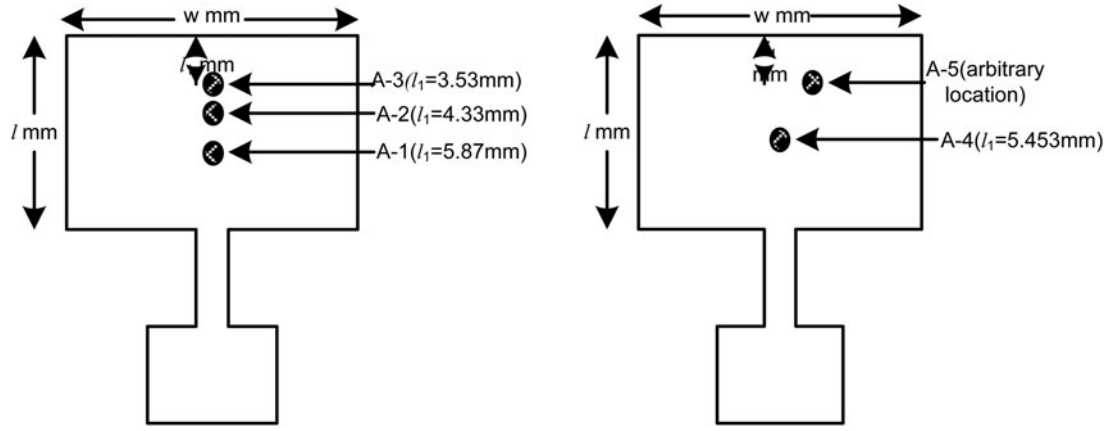


Fig. 3. Antenna configuration with diode at different positions.

III. COMPARISON OF DIFFERENT SETS OF PATCHES: EXPERIMENTAL RESULTS

An active patch working at 9.5 GHz has been designed and fabricated with the help of photo-etching by using 0.787-mm thick Takonic TLY-5-0310-CH/CH substrate with $\varepsilon_r = 2.2$. The conducting material has 0.502/sq ft copper metallization with a metal thickness of 0.018 mm. The antenna is supported from the other side by a thick aluminum plate, which serves the purpose of heat sink as well as provides mechanical support for experimental observation. Two sets of five patches have been fabricated at two spot frequencies (f_r) of 9.0 and 9.5 GHz by using 0.787-mm thick Takonic TLY-5-0310-CH/CH substrate with $\varepsilon_r = 2.2$. The entire scheme is shown in Fig. 3, where the diode positions have been measured from the top edge of the patches. For patches A-2 to A-4, the diodes have been placed at points (w/2, l_1), while the position of the diode on the patch A-1 is at ($w/2$, l–l_1). For the patch (A-5), the position of the diode on the patch is arbitrary (x, y). A screw-type low-power MA/COM-49104 Gunn diode has been used for the five patches to obtain a comparative picture. Radiation patterns are measured for three patches namely A-3, A-5, and a passive patch and are shown in Fig. 4. Table 1 lists the operational parameters of the antennas like frequency power etc. Power values have been calculated by using passive antenna gain to be 7.97 dBi. It is found from Table 1 that patch A-3 ($l_1 = 3.53$ mm) gives highest radiated power although the position of the diode on the patch should be A-2 ($l_1 = 4.33$ mm). When the diode is placed further up ($l_1 < 3.53$ mm), the radiated power is found to decrease along with significant deviation in operating frequency [21].

In order to calculate the value of frequency in Table 2 the following relation [3] is used:

$$f_r = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left[\left(\frac{m}{l}\right)^2 + \left(\frac{n}{w}\right)^2\right]}.$$

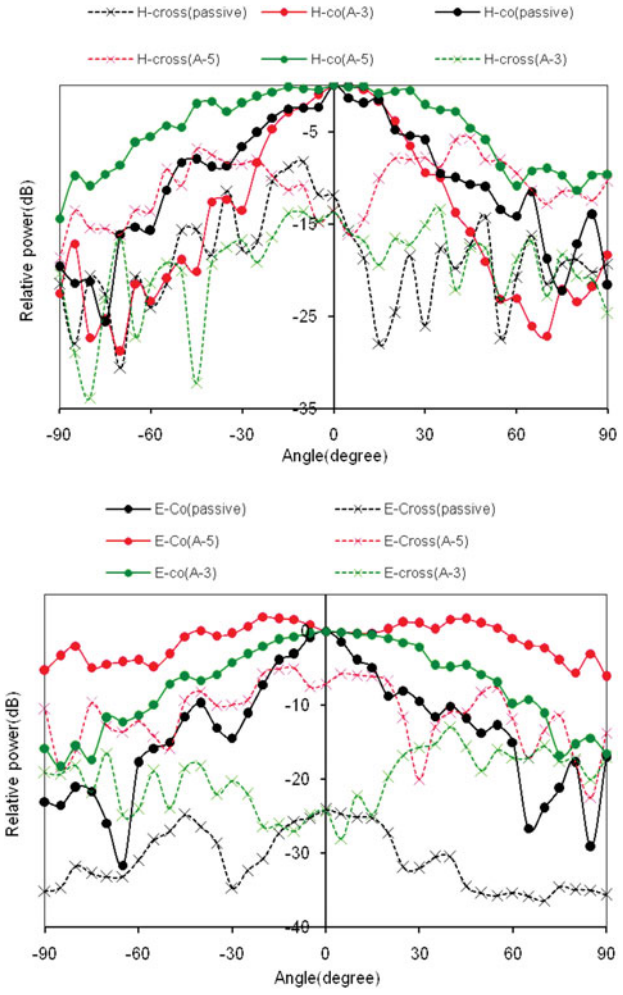


Fig. 4. Radiation pattern (co- and cross-polarization) of microstrip rectangular patch antenna.

IV. HARMONICS IN ACTIVE MICROSTRIP PATCH ANTENNA

An active microstrip patch antenna combines the function of radio frequency (RF) generation and radiation in the same antenna element. However, it is beset with the problems of harmonic generation and to some extent spurious radiation [16]. These adversely affect its operating efficiency and electromagnetic compatibility (EMC) implications. These problems are common to both the Field-effect transistor (FET) and Gunn/Impatt integrated microstrip patch antennas.

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Table 1. Measured active antenna power and efficiency at the operating frequencies.

Antenna	Operating frequency (GHz)	Bias voltage (V)/ Current (mA)	RF Power (mW)		EIRP (mW)	DC–RF conversion efficiency	
			In Patch	In w/g Cavity		In w/g cavity	In patch
A-1	9.77	12.64/381	29.8	64.10	186.83	1.42	0.62
A-2	9.76	11.90/390	35.9	50.35	225.10	1.17	0.77
A-3	9.646	11.10/420	64.33	63.10	403.6	1.55	1.38
A-4	9.036	11.00/303	1.0	55.60	6.14	1.42	0.03
A-5	9.82	10.70/322	2.57	47.21	16.10	1.18	0.075

An active antenna can be represented by a large number of parallel resonant circuits. Experimental observation on the radiated field shows the presence of second harmonic component. Therefore in our analysis, the microstrip patch is represented by a series combination of two parallel resonant circuits: one is resonant at fundamental and other is at the second harmonic frequency. An active antenna (integrated with Gunn diode) basically operates on the principle of distributed parameter oscillator with the patch as distributed parameter circuit element and the diode as a non-linear negative resistance device. Owing to the non-linear current voltage characteristics of the Gunn diode and the harmonic resonant character of the microstrip patch, the system undergoes harmonic oscillations. The multiple resonant characteristic of the patch antenna can be easily explained with the help of cavity model as well as transmission line model. The system equations are written as [17]

$$C_1\frac{dv_1}{dt}+\frac{1}{L_1}\int v_1 dt+G_1v_1+\left(-\alpha_d v_1+\beta_d v_1^2+\gamma_d v_1^2\right)=0, \tag{16}$$

where, $v_1 = V_1 \cos(\omega t + \psi)$ current–voltage relation of a Gunn diode has been used [17].

And

$$C_2\frac{dv_2}{dt}+\frac{1}{L_2}\int v_2 dt+G_2v_2+\left(-\alpha_d v_2+\beta_d v_2^2+\gamma_d v_2^3\right)=0, \tag{17}$$

$$v_2 = V_2\cos(2\omega t+\theta),$$

where v_1, v_2 is the output voltage across the fundamental and the second resonant circuit. G_1 and G_2 are the equivalent input conductance of a patch working at ω and 2ω, respectively, and are given by

$$G_1=\left[2(G_r-G_m)+0.5\left(R_1Y_o^2+G_i\right)l\right]\sec^2(\beta l_1),$$

$$G_2=\left[2\left(G_r'-G_m'\right)+0.5\left(R_1'Y_o^2+G_i'\right)l\right]\sec^2(2\beta l_1),$$

where un-primed and primed quantities are the corresponding parameters for a patch working at ω and 2ω, respectively. Variation of the fundamental and the second harmonic power with the position of the diode (l_1) is obtained through computer simulation. The result is plotted in Fig. 5. Simulation results indicate that the value of l_1 (at which fundamental Power is the maximum) is very close to the value where the second harmonic power is maximum. Theoretical exercise is based on the assumption that the diode is a point source. In practice, it is not so, e.g. for an MA/COM 49104 diode, dimension is 0.15 × 0.15 mm. Therefore, the suggested equation for locating diode is

$$l_1=[l_1]^{max}-\frac{\text{diode diameter}}{2}. \tag{18}$$

V. INJECTION LOCKING

Active antenna acts as a transmitter as well as a receiver and for its faithful operation it is necessary to generate near noise-free oscillations. Improvements of the oscillator phase jitter and oscillator stability, thus, are important consideration. Techniques such as injection-locking dielectric resonators, tuned cavities, etc. are usually used to improve frequency stability and phase noise characteristics. In this section, a combination of injection and phase locking through bias control has been proposed. The arrangement is shown in Fig. 8. It consists of a rectangular active patch antenna, a balanced mixer-type phase-sensing device, and a bias control arrangement. A sinusoidal signal of frequency ω_1 acting on a nearly sinusoidal oscillator of frequency ω_o affects its behavior in many respects depending on the strength and frequency of the forcing signal. A forcing signal when injected into an oscillator modifies its properties in many ways. The analytical equivalent circuit of an oscillator under the influence of a forcing signal is represented in Fig. 6. Within the

Table 2. Calculated and measured operating frequencies for two set of five-patch antennas.

Antenna	Length l (mm)	Width w (mm)	l_1 (mm)	Calculated f_r (GHz)	Measured f_r (GHz)	% Error in frequency
A-1	10.202	12.483	5.87	9.5	9.77	2.84
A-2	10.202	12.483	4.33	9.5	9.76	2.74
A-3	10.202	12.483	3.5	9.5	9.646	1.54
A-4	10.798	13.176	5.453	9.0	9.036	0.34
A-5	10.798	13.176	Arbitrary location	9.0	9.82	9.11

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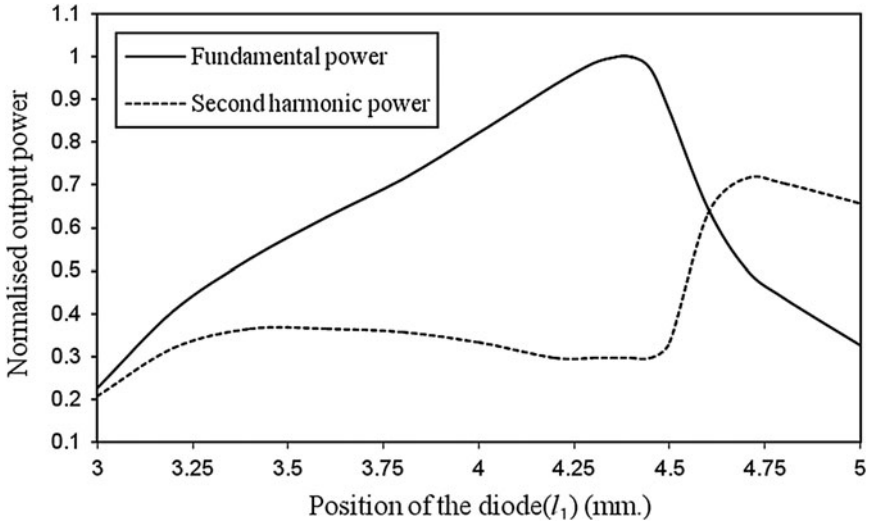


Fig. 5. Variation of relative fundamental and second harmonic power with the position of diode along the length of a rectangular active patch designed to oscillate at 9.5 GHz.

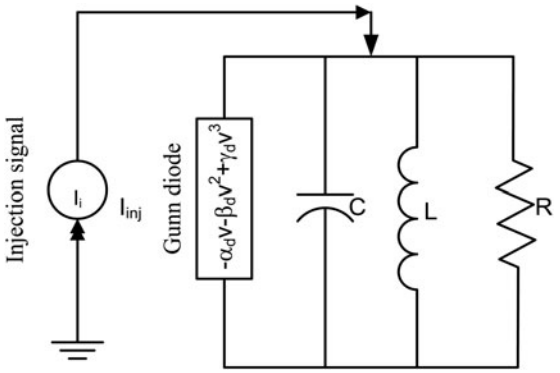


Fig. 6. Equivalent circuit of an ILO.

synchronization range the locked oscillator loses its identity and obeys commands from the forcing signal, and the oscillator is said to be injection locked (phase locked) to the synchronization signal. Injection-locked oscillators (ILOs) find many uses in practice. It can be used (1) to reduce the depth of modulation of an amplitude modulation (AM) signal, (2) as frequency modulation (FM)–AM converter, (3) as an amplifier for angle-modulated signals, etc. An active microstrip patch integrated with a Gunn diode can be used as an injection-locked Gunn oscillator (ILGO). Detection of an information signal in the presence of co-channel interference has been performed in this section. Injection-locking technique is efficient to demodulate the signal [22].

A parallel equivalent circuit of a Gunn oscillator in the presence of an injection-locking signal is shown in Fig. 6. Let

$$I_{inj} = I\cos(\omega_c t + \theta), \tag{19}$$

where $\theta = m\sin(\omega_m t)$, represents an FM signal at X-band shining on the active antenna. The equation of a negative resistance oscillator in the presence of injected microwave FM signal can be written as [9]

$$\frac{1}{L}\int v(t)dt + C\frac{dv(t)}{dt} + G_1 v(t) - \alpha_d v(t) + \gamma_d v(t)^3 = I_{inj}, \tag{20}$$

where L, C, G_1 are inductance, capacitance and conductance of the parallel tuned circuit, respectively; α_d, γ_d are constants of Gunn diode; and I is the current strength of the carrier signal.

Suppose that the carrier frequency of the injected FM signal is close to the free running frequency of the oscillator. Output of the locked antenna is assumed to be of the form

$$v(t) = V(t)\cos(\omega_o t + \theta_o(t)), \tag{21}$$

$$\varphi = \theta - \theta_o. \tag{22}$$

V is the voltage amplitude of the locked antenna and ϕ is the phase error. Substituting (21) and (22) into (20) and applying the principle of harmonic balance, we obtain the

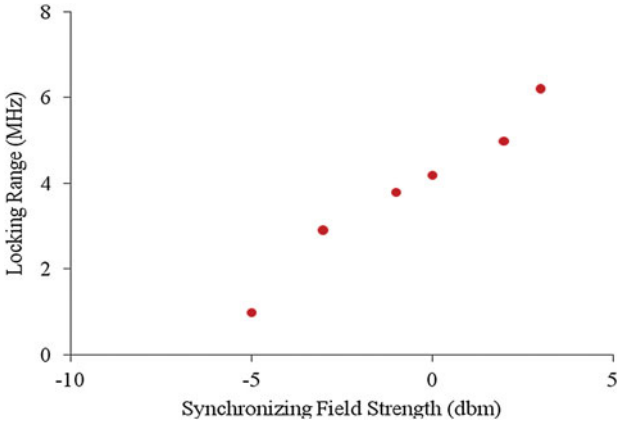


Fig. 7. Experimental value for locking range with synchronized field strength.

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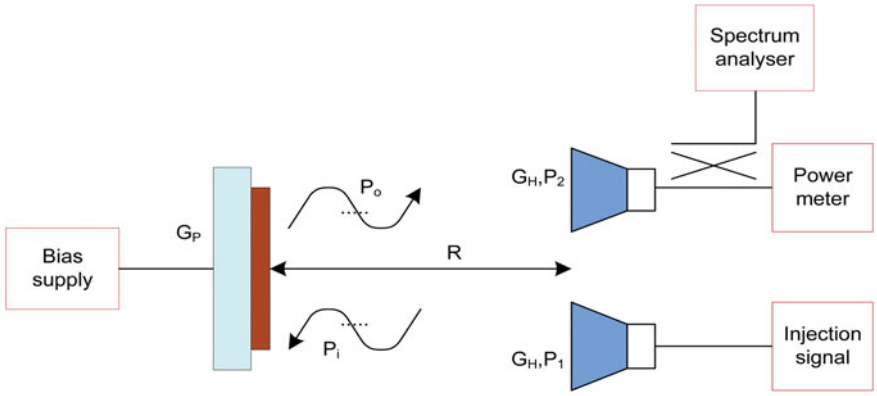


Fig. 8. Injection-locking arrangement.

following amplitude and phase equations of the ILGO:

$$\frac{dV}{dt} = \frac{\omega_o V}{2Q}\left(\alpha_k - \frac{3}{4}\gamma_k V^2\right) + \frac{\omega_o}{2Q}E\cos\phi, \tag{23}$$

$$\frac{d\phi}{dt} = \frac{\omega_o}{2}\left(\frac{\omega_c}{\omega_o} - \frac{\omega_o}{\omega_c}\right) - \frac{\omega_o}{2Q}\left(\frac{E}{V}\right)\sin\phi + \frac{d\theta}{dt}, \tag{24}$$

where $-R(\alpha_d - G_1) = \alpha_k$ and $R\gamma_d = \gamma_k$ m and ω_m are the modulating index and modulating frequency of the FM signal, ω_o is resonance frequency of the oscillator, Q is the quality factor of the oscillator; and E is the strength of the injection.

Now, locking range of the ILO can be expressed as

$$k = \frac{\omega_o}{2Q}\frac{E}{V}, \tag{25}$$

It is revealed by (25) that the lock range is directly proportional to the strength of the injection signal and inversely proportional to the quality factor of the Inductance and Capacitance (LC) tank. Increasing the amplitude of injection signal E, although increasing the lock range, is at the cost of power consumption. Figure 7 shows the variation of locking range with synchronized field strength obtained using the experimental arrangement as depicted in Fig. 8. Figure 7 supported the theoretical finding.

VI. CONCLUSION

An expression (13) for determining the position of the diode within the rectangular patch has been proposed in this paper on the basis of maximum radiated power. The result was compared with the available literature [10] given in (14). Knowing the values of diode constants, one can easily find out the maximum radiated power (15). It is further observed that the location of the diode at which the fundamental power is maximum, is not the position of minimum second harmonic generation [16, 17]. Moreover, a commercially available diode has a finite dimension, not a point source. When the diode is placed at the point where the fundamental power is maximum it infringes into the susceptible zone of second harmonic oscillations. Therefore, the diode has been placed so as to avoid the susceptible zone of second harmonic oscillations. Fortunately, it has been found that in doing so, the generation of fundamental power is not much affected. Expression (13) has therefore been modified to (18), so that the power output and EMC conditions are optimum. With this arrangement, power output from an active antenna designed to operate at 9.5 GHz was 64.33 mW (Effective Isotropic Radiated Power (EIRP) ~403.6) almost equal to waveguide tuned oscillator. The frequency error is 1.54%, which also confirmed the proper design of the patch. Conversion efficiency (DC to RF) achieved was 1.38% in contrast to 1.55% when the diode has been placed in a waveguide. Owing to the perfect matching between the device and antenna a large Q value has been realized (~156). Bias-tuning bandwidth of such a rectangular patch is only 2.16% which is very low and is one of the disadvantages of active microstrip patch antenna. A 10.198 × 12.283 mm^2 rectangular patch exhibited a locking gain of 25 dB, a locking range 3.6 MHz at 9.799 GHz. As the injection lock power decreases, there is a corresponding decrease in obtainable bandwidth. A notable improvement in signal quality has been observed even in the free running mode in comparison to others [14, 19].

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