

Study of Various Tuning properties and Injection Locking of Resonant-cap IMPATT oscillator

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Abstract - A coherent study of tuning properties of resonant-cap IMPATT oscillator at Ka-band has been carried out by mechanical and electronic means. It is experimentally observed that output power of IMPATT oscillator passes through a maximum, with an optimum combination of cap diameter and cap height. An empirical relation is obtained between cap diameter and wavelength of the optimised resonant cap oscillator, which agrees well with theoretical relation. Electronic tuning is carried out by varying the dc bias current with the optimized cavity parameters. It is observed that the variations of oscillation frequency and power output with dc bias current are characterised by three ranges of bias current. The effect of sliding short tuner position on the performance of the oscillator at optimised condition has also been studied. Finally, the injection locking of the free running oscillator has been studied with a Ka-band signal generator as a reference source. The injection locked IMPATT oscillator shows a good phase noise performance.

Key words: Electronic tuning, Injection locking, Ka-band IMPATT oscillator, Mechanical tuning, Phase noise.

I. INTRODUCTION

IMPact **A**valanche **T**ransit **T**ime (IMPATT) devices based on Silicon have already been established as powerful solid-state sources for generation of high CW and pulsed power at wide range of microwave and millimeter wave frequencies [1], [2]. These devices provide high oscillator output power with high DC to RF conversion efficiency in Silicon Monolithic Millimeter Wave Integrated Circuits (SIMMWIC) [3]. The vast frequency range of operation with high power capability of IMPATT device leads to its application as a highly potential source for meeting the ever increasing demand in mm-wave communication system. IMPATT devices also find useful applications in tracking Radars. The tunable bandwidth of IMPATT oscillator plays an important role on the total system design. The tunable bandwidth of microwave/millimeter wave IMPATT oscillator has been investigated by several researchers and reported in the published literatures [4-11]. Although some research work has been reported in the field of resonant-cap IMPATT oscillators, there remains a lot of scope for research on the detailed and coherent study of their tuning properties specially at Ka-band. Among all the window frequencies, 36 GHz in Ka-band is gaining importance in recent years due to its wide application in civil, industrial, medical and strategic fields. The purpose of this paper is to present a detailed and systematic study of the

mechanical tuning properties of resonant-cap IMPATT oscillator at Ka-band with the variation of cap diameter, cap height and sliding short tuner position and also the electronic tuning properties by varying the dc bias current.

Low phase noise oscillators are in great demand due to the rapid growth of their application in millimeter wave technology for both civilian and defence sectors. The phase noise of IMPATT oscillator is an important parameter to improve the overall system performance. In developing high quality, low cost oscillators, a detailed and accurate study of the phase noise performance of IMPATT oscillators is highly needed for their operation in either a stable amplifier mode or an injection-locked oscillator (ILO) mode [12]. The injection-locked oscillator has the advantage of delivering higher output power with high DC to RF conversion efficiency. These oscillators are not only capable of providing higher gain over a wider bandwidth but also adaptable to power combining. Further they are generally more suitable because of their higher efficiency and power output capability.

II. KA-BAND IMPATT OSCILLATOR

A resonant cap IMPATT oscillator consists of a resonant cap structure under which the diode is embedded and these are mounted in a rectangular wave guide. The cap along with the broad surface of the wave-guide forms a localized radial cavity around the diode. The millimeter wave power generated by the diode is coupled to the main rectangular wave-guide cavity through the vertical open edges of the radial cavity. The resonant cap can be approximated as a radial transmission line which acts like an impedance transformer between the device and the load. The cross sectional view of IMPATT oscillator used in the present study is shown in Fig.1 and the photograph of the same is in Fig. 2 [13]. Experimental studies of the tuning characteristics of resonant-cap oscillators have been carried out by using silicon Ka-band SDR IMPATT diodes having the following specifications: Frequency range = 35 – 42 GHz, Breakdown voltage = 45 Volts (max), Current = 150 mA (max), Power output = 100 mW (max). The block diagram of Ka-band measurement test set up is shown in Fig.3 and a typical spectrum (36.75 GHz) of the oscillator is shown in Fig.4.

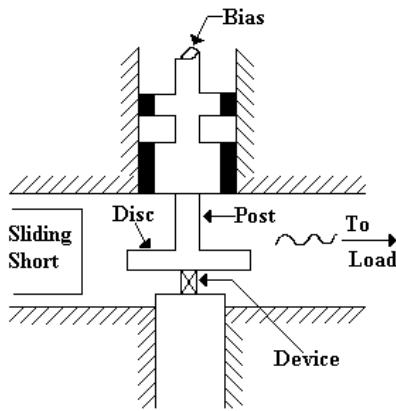


Fig.1. Schematic diagram of a Ka-band resonant cap waveguide cavity

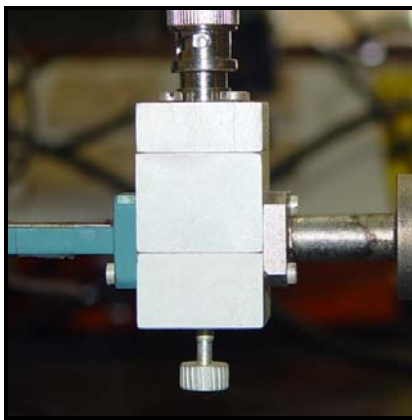


Fig.2. Photograph of resonant cap IMPATT oscillator

III. VARIOUS TUNING

A. Mechanical tuning

Mechanical tuning of a resonant cap IMPATT oscillator is carried out by means of cavity tuning and also by varying sliding short position. The cap diameter and cap height are both varied for tuning the cavity. The variations of both the oscillation frequency and output power with the cap diameter and cap height have been experimentally determined. The results are shown in Fig.5 and Fig. 6 respectively. The cap diameter is varied from 3.4 mm to 4.5 mm and the corresponding cap height from 1 mm to 2.0 mm to optimise the oscillator performance. It is observed that output power attains a maximum value of 90 mw when the cap diameter and cap height are 4.0 mm and 1.6 mm respectively. The oscillation frequency is found to vary from 36.00 GHz to 37.75 GHz during the process of cavity optimisation.

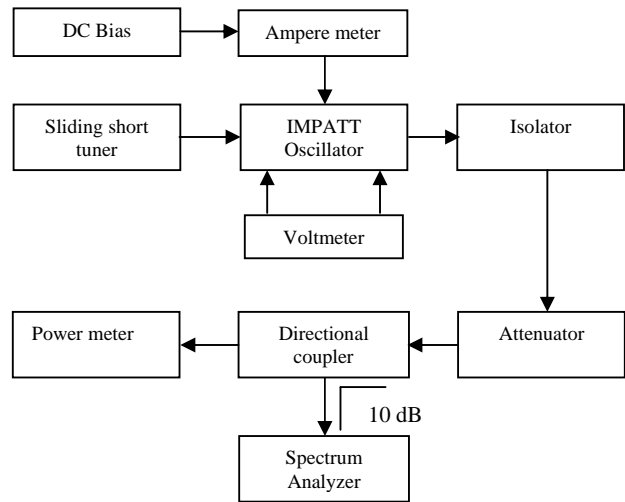


Fig.3. Block diagram of Ka-band measurement test set up

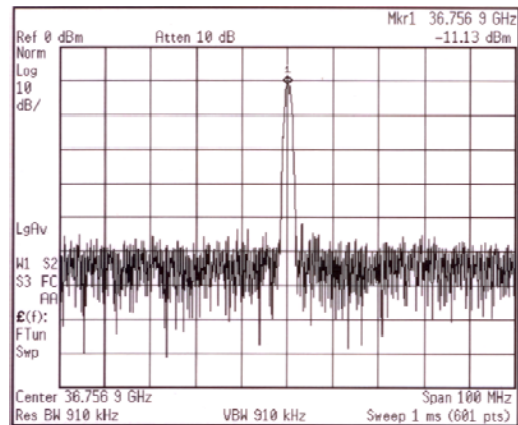


Fig.4. A typical spectrum achieved at Ka-band

For the variation of cap height from 1 mm to 2 mm in steps of 0.2 mm and it is observed that power level increases from 52 mw to a maximum of 88 mw for cap height of 1.6 mm and the same decreases to 72 mw for cap height of 2 mm. The corresponding oscillation frequency varies from 36.00 GHz to 37.5 GHz. The above studies have been carried out at a bias current level of 145 mA and break down voltage of 30.5 Volt. It is observed that the oscillation frequency decreases with the increase of the cap diameter and reverse takes place for the variation of cap height. The rate of decrease of oscillation frequency with the increase of cap diameter for the Ka-band IMPATT oscillator under study is found to be 1.5 GHz/mm. With increasing cap height the oscillation frequency increases at the rate of approximately 1.57 GHz/mm. It is also observed that maximum output power at the desired frequency of 36.5 GHz is obtained when the cap diameter ranges from 3.8 – 4.2 mm and corresponding cap height ranges from 1.4 – 1.8 mm. More precisely a suitable combination of cap diameter and cap height i.e. 4.0 mm and 1.6 mm respectively leads to maximum output power of 90 mw at a desired frequency of 36.5 GHz. Thus the output power delivered by a resonant-cap IMPATT

oscillator passes through a maximum at a particular frequency for a given device with an appropriate combination of cap diameter and cap height.

B. Relation between cap diameter and wavelength

The experimental results for the condition of optimum performance of the resonant cap IMPATT oscillator are related by the following approximate equation.

$$D = \frac{\lambda}{2} \tag{1}$$

Where λ is the operating wavelength and D is the cap diameter. Thus a resonant-cap IMPATT oscillator can be experimentally realised if the cap diameter is designed to be half of the wavelength of desired frequency of oscillation for optimum performance of the oscillator.

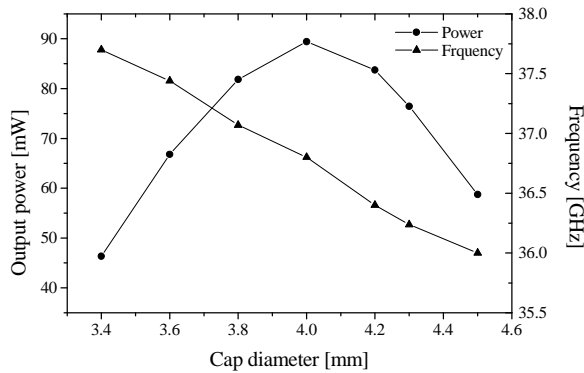


Fig.5. Variation of Output power and Frequency with Cap diameter (Cavity tuning)

The experimental results obtained can be explained by considering the electromagnetic fields within the resonant-cap cavity. The resonant-cap cavity is formed between the disc of the resonant-cap structure and the lower broad face of the waveguide as shown in Fig.7. Such a cavity can be approximately modelled as a cylindrical cavity, bounded at its top and bottom by electric walls and on its sides by a magnetic wall [14-16]. The electric field within the resonant-cap cavity has essentially only a z-component, and the magnetic field has essentially x and y-components. Because $h \ll \lambda_g$ (guided wavelength), the fields do not vary along the z direction, and the component of the current normal to the edge of the cap approaches zero at the edge. This implies that the tangential component of the magnetic field at the edge is vanishingly small. With these assumptions, the resonant cap can be modelled as a cylindrical cavity, bounded at its top and bottom by electric walls and on its sides by a magnetic wall. Thus the fields within the resonant cap cavity, corresponding to TM_{nm} modes, may be determined by solving a cavity problem. The fields corresponding to TM_{nm} modes within the cavity are given by [15].

$$E_z = E_0 J_n(k\rho) \text{Cos}(n\phi) \tag{2.a}$$

$$H_\rho = -\frac{j\omega\epsilon n}{k^2 \rho} E_0 J_n(k\rho) \text{Sin}(n\phi) \tag{2.b}$$

$$H_\phi = -\frac{j\omega\epsilon}{k} E_0 J'_n(k\rho) \text{Cos}(n\phi) \tag{2.c}$$

Where k is the propagation constant, J_n is the Bessel function of the first kind and order n . The open circuited edge condition requires that $J'_n(kr) = 0$, where r is the radius of the disk and the prime indicates differentiation with respect to the argument. Thus for each mode of configuration the disc radius corresponding to zeros of the derivative of the Bessel function can be obtained which will lead to desired resonance condition.

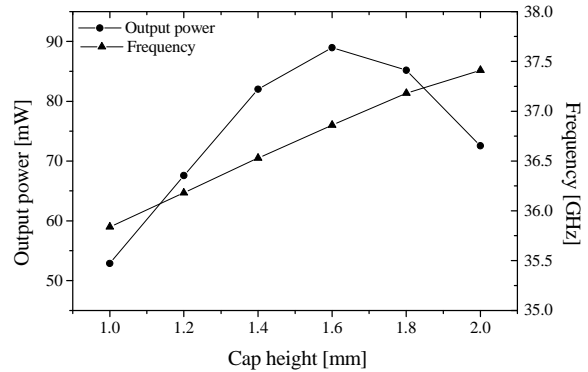


Fig.6. Variation of output power and Frequency with Cap height (Cavity tuning)

For any given frequency, the dominant mode has $n = m = 1$ and it corresponds to the minimum radius of the disc for resonance. The root of $J'_n(kr) = 0$ for dominant mode is $kr = 1.841$. But $k = \frac{2\pi}{\lambda}$ and $2r = D$. The diameter of the disc is obtained from the relation

$$\frac{D}{\lambda} = 0.58 \tag{3}$$

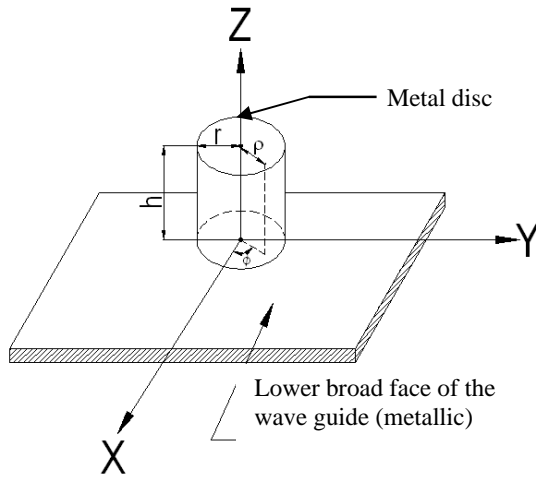


Fig.7. Resonant-cap cavity between the resonant-cap and the lower broad face of the wave guide.

The theoretical relation (3) shows that the operating wavelength λ and the disc diameter D of the resonant-cap are directly proportional and the constant of proportionality is 0.58. The empirical relation (1) derived from our experimental results has a form similar to the theoretical relation (3) which is found to be a close approximation to the results published in [5], [8] and [17].

C. Tuning by Sliding Short

The dependence of the oscillation frequency and output power on the sliding tuning short position has been studied and the results are shown in Fig.8. Sliding tuning short position has been varied from 0 to 9.7 mm in steps of 0.5 mm. It is observed that RF power output varies from 0 mw to 88 mw and frequency varies from 34.50 GHz to 37.75 GHz. It is also observed that the mechanical tuning is characterised by an initial frequency jump followed by a sharp fall with a subsequent rise of output power. A smooth mechanical tuning range of 3.15 GHz with a centre frequency of 36 GHz is obtained for a change of sliding short position over a range of $\frac{\lambda}{2}$. It is further observed that frequency jumps by 3 GHz approximately. Also a sudden power gain of 70 mw is achieved nearly at distances $\frac{\lambda}{2}$ and λ between the sliding short position and the diode plane. This experimental observation agrees well with the reported results [5] and [7].

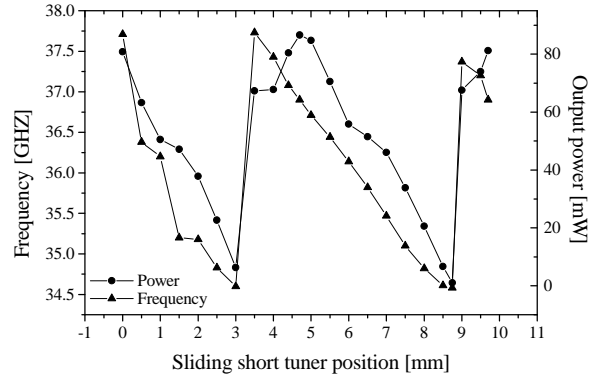


Fig.8. Variation of Frequency and output power with sliding short tuner position (Mechanical tuning)

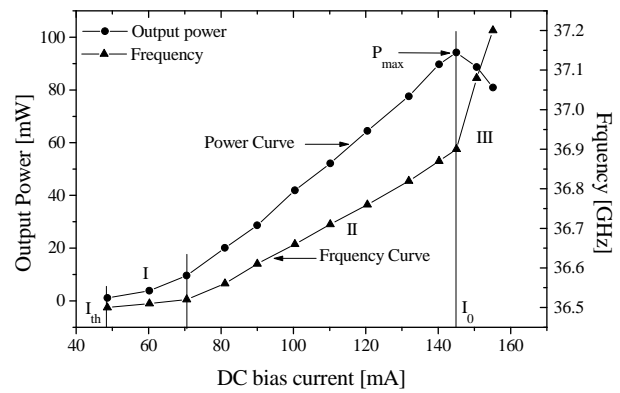


Fig.9. DC bias current Vs Output power and Frequency (Electronic tuning)

D. Electronic tuning

Electronic tuning of the oscillator with the optimized cavity parameters i.e. $D = 4.0\text{mm}$ and $h = 1.6\text{mm}$ is carried out by varying the DC bias current. DC bias current has been pushed upto 160 mA keeping other parameters fixed. The variations of output power and frequency with DC bias current are shown in Fig.9. It is observed that the variations of oscillation frequency and power output with dc bias current are characterised by three ranges of bias current. In the first range I, starting from threshold dc bias current for oscillation I_{th} , both the output power and frequency increase very slowly with dc bias current. This is followed by a second range II of dc bias current where the output power increases sharply to a maximum value P_{max} but the oscillation frequency increases with dc bias current in an approximate linear nature. In the third range III of dc bias current exceeding the current I_0 corresponding to P_{max} the power begins to fall gradually from its maximum value but the frequency increases more sharply compared to the second range, called burn out zone. The

results agree well with the findings of Roy et al [11]. The useful linear frequency range is approximately 34 MHz corresponding to a change of dc bias current of 64 mA in the second range II of dc bias current. The third range III of DC bias current should normally be avoided to prevent the electronic burn out phenomenon.

IV. INJECTION LOCKED IMPATT OSCILLATOR

A. Injection Locking Model

The phenomenon of injection phase-locking may be used to synchronize one or more oscillators to a lower power master or reference oscillator and also to reduce some part of the resultant FM noise power spectrum. The cavity oscillator has been represented as a tank circuit where C_0 is the equivalent capacitance of the cavity oscillator, L_0 its equivalent inductance, $+G$ the conductance of the load, and $-G$ the equivalent negative conductance of the oscillator, equal in magnitude to the conductance G of the load in the steady-state condition [18]. The basic injection phase locked oscillator model is shown in Fig.10 and the injection locking has been done by a “reference” oscillator having good phase noise performance.

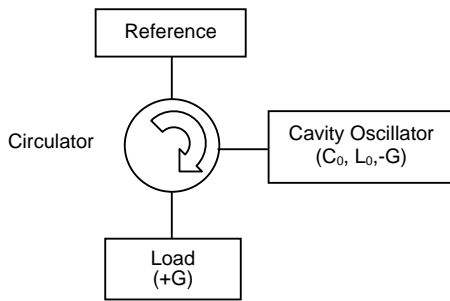


Fig.10. Basic injection phase-lock circuit diagram

B. Injection Locking of IMPATT Oscillator

The indigenously developed Ka-band CW IMPATT oscillator [13] is used as a free running oscillator with power output 0 dBm and a Ka-band signal generator has been used as a reference source. An injection signal from the signal generator of very low power – 40 dBm is used to lock the free running oscillator. Fig.11 shows a schematic of injection locked Ka-band IMPATT oscillator. Using the same configuration the phase noise of Ka-band IMPATT oscillator has been measured under injection locked condition. A snap shot of the phase noise at different offset frequency has been shown in Fig.12 by using a phase noise measurement system. The measured values are tabulated in Table. 1 at various offset frequencies.

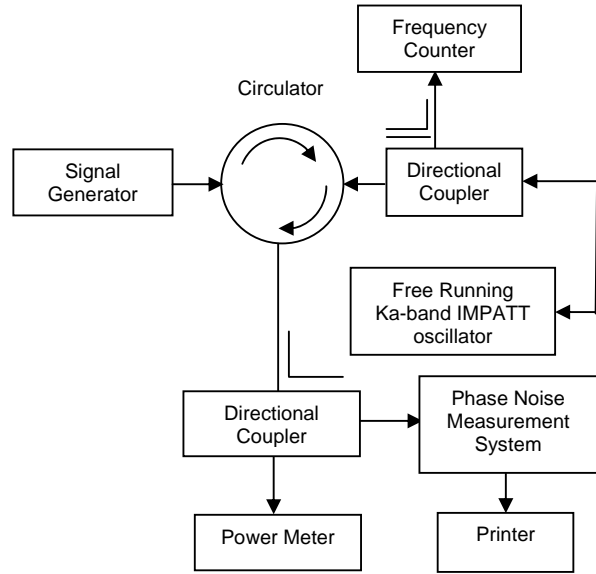


Fig.11. Injection locked IMPATT Oscillator and Phase noise measurement set up

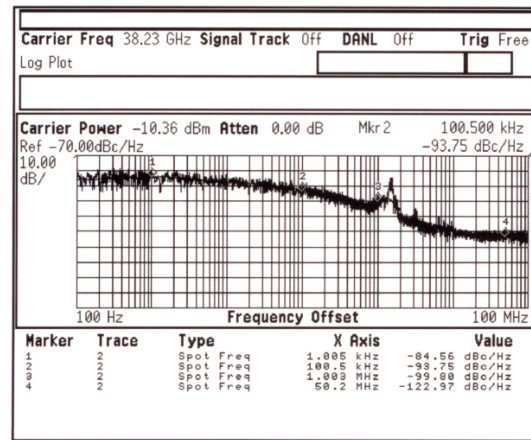


Fig.12. Snap shot of Phase Noise at different offset frequency (using phase noise measurement system)

Table: 1
Phase noise at different offset frequency

Offset Frequency	Phase noise (Phase noise measurement system)
1 KHz	-84.56 dBc / Hz
100 KHz	-93.75 dBc / Hz
1 MHz	-99.80 dBc / Hz

V. CONCLUSION

In this paper the authors have used three different methods of mechanical tuning of wave guide mounted resonant-cap Ka-band IMPATT oscillator. A wide tunable range of 3.15 GHz is achieved by sliding short and tunable ranges of 1.75 GHz and 1.5 GHz are obtained by varying cap diameter and cap height respectively around the centre frequency of 36 GHz

at Ka-band. For the design and development of millimeter wave (Ka-band) IMPATT oscillator using resonant-cap wave guide structure, the values of cap-diameter and cap height are important parameters in deciding the output power as well as the frequency. The authors have obtained an approximate relation between cap diameter and wavelength under

optimised condition i.e., $D = \frac{\lambda}{2}$ which is very close to the

theoretical relation $D/\lambda = 0.58$. The dependence of output power and frequency with the sliding short position has been demonstrated. In order to achieve the optimum condition the sliding short position is to be tuned to a distance which are

multiples of $\frac{\lambda}{2}$. In course of tuning by sliding short, sudden

frequency jump occurs at certain positions with high power gain. Utmost care is to be taken for tuning the oscillator by sliding short.

The authors have carried out electronic tuning by varying the dc bias current and taking into account the values of the optimized cavity parameters, i. e. cap diameter $D = 4.0$ mm and cap height $h = 1.6$ mm. It is observed that the variation of oscillation frequency and power output with dc bias current is characterised by three ranges of bias current. In the first range I, both the output power and frequency increases slowly, in the second range II, both the output power and frequency increase sharply. In the third range III, the output power decreases where as frequency increases. The operating bias current of the oscillator in the third range III, should normally be avoided to prevent the burn out phenomenon of IMPATT diode which occurs very frequently while tuning the IMPATT oscillator.

Finally, the authors have demonstrated the injection locking of IMPATT oscillator by using a signal generator as a reference source with the corresponding phase noise measurement. A phase noise of -84.56 dBc / Hz @ 1 KHz has been realised from the Ka-band injection locked IMPATT oscillator.

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