Chapter – VII

Modeling and Simulation of Ka-band Resonant Cap IMPATT Oscillator and Their Experimental Verification

7.1 Introduction

Three dimensional modeling, simulation and optimization of a Ka-band IMPATT oscillator has been carried out by using High Frequency Structure Simulator (HFSS) software and the simulated results are verified with experimental results. Modeling of IMPATT oscillator involves appropriate design of the oscillator by considering its 3-dimensional behavior. This is followed by simulation and optimization of the cavity parameters with the help of HFSS software for analysis of the electromagnetic behavior of the structure. HFSS is capable of extracting basic electromagnetic field quantities, characteristic port impedances and propagation constants, generalized S-parameters and the eigen modes or resonant frequencies of the structure. HFSS has three types of solver for a particular structure which are known as DRIVEN MODAL, DRIVEN TERMINAL and EIGENMODE solvers. The author has chosen EIGENMODE type solver for calculating the eigenmodes or resonant frequencies of the structure. The eigenmode solver also calculates the respective Quality factors of the oscillator [166]. A full height, resonant cap
waveguide structure is chosen for modeling the IMAPATT oscillator, schematically shown in Fig. 7.1, details are described in Chapter V.

Fig. 7.1. Schematic diagram of Ka-band resonant cap cavity

7.2 Modeling

The author has carried out modeling of the full height waveguide resonant cap structure shown in Fig. 7.1 by using the HFSS software. The simulation and optimization of the cavity have been carried out for the optimum operation of the oscillator at around 36 GHz. Three dimensional modeling of the cavity includes that of the rectangular waveguide cavity, the resonant cap, post, packaged IMPATT device and IMPATT diode stud. The design parameters considered in the simulation are shown in Fig. 7.2.
Fig 7.2: Snap shot of the design parameters (in HFSS Window)

[ lx : width of the cavity (in x-axis) , ly : height of the cavity (in y-axis) , lz : length of the cavity (in z-axis) , \text{diode\_r} : radius of the IMPATT diode , \text{cap\_r} : radius of the resonant cap , \text{cap\_h} : height of the resonant cap , \text{chip\_r} : radius of the chip , \text{chip\_h} : height of the chip , \text{post\_r} : radius of the post , \text{post\_h} : height of the post , \text{s.s.tuner} : position of the sliding short tuner. ]

The materials used for each component in the model are very important for the modeling purpose as the physical properties of the component depend on the particular base material used. The properties of the component such as relative permeability, relative permittivity, bulk conductivity, dielectric loss tangent, magnetic loss tangent and magnetic saturation depend on the type of materials used. The cap, post and the oscillator cavity are made of Aluminium. The diode heat sink is made of copper while the IMPATT chip package is made of gold and the waveguide medium is vacuum as shown in Fig.7.3.
7.3 Sequential steps for 3-D Modeling of resonant cap IMPATT oscillator

A. The 3-D model of the IMPATT chip which is a cylinder of radius 0.4 mm and height 0.2 mm is created by considering a co-ordinate system with origin (0, 0, 0) as the center located at the intersection of the x-, y-, z- axes.

B. The resonant cap, which is also in the form of a cylinder, is created and cloned to the chip with a variable cap radius_r and height of 0.5 mm. The post is created with radius of 1 mm and variable post height_h.

C. The cap and the post are integrated together with the diode of radius 1.5 mm and height 1.4 mm by considering a relative co-ordinate system whose origin and orientation are set relative to the existing co-ordinate system.

D. The whole design is subtracted from the box, which is the representation of the oscillator cavity. Finally, the oscillator cavity is subtracted from the waveguide as
whole, which is represented by creating a rectangular box of \( l_x = 7.12 \text{ mm} \), \( l_y = 3.56 \text{ mm} \) and \( l_z = 25 \text{ mm} \), i.e. of dimensions \((7.12 \times 3.56 \times 25) \text{ mm}\).

Fig.7.4. Cross sectional view of the resonant cap cavity (in HFSS window)

Fig.7.5. 3-D model of the resonant cap cavity (in HFSS window)
7.4 Solution setup

HFSS computes a solution by adding a solution setup to the design shown in Fig.6. The Solution setup consists of:

- Minimum frequency
- Number of modes
- Maximum number of passes
- Maximum delta frequency per pass
- Converge on real frequency only

Now, using different values in the solution setup, the design properties of the model are varied in order to optimize the same at a window frequency of 36GHz for maximum Quality factor.

Step: 1. The maximum frequency and the number of modes are varied and then the number of passes and maximum delta frequency per pass are also varied in order to optimize the model.

Step: 2. After adding the solution setup, validation check of the model is required, prior to running the program for analysis. When the validation check is performed, HFSS runs a check on all the setup details of the model to verify whether all the necessary steps are completed and their performances are satisfactory.

The following three parameters are varied to optimize the cavity:

- Cap radius (Cap_{r})
- Post height (Post_{h})
- Sliding short tuner position
7.5 Generation of HFSS Solution

For eigenmode solution type, one obtains the real and imaginary parts of the frequency and Quality factor, and also $Q$ values for each eigenmode. The frequency column lists the real and imaginary parts of the resonant frequency for each solved eigenmode. For lossy eigenmode solutions, a $Q$ column appears which lists the unloaded Quality factor, $Q$ of the cavity computed for each eigenmode.

7.6 Calculation of Quality factor

$Q$ is the Quality factor and is a measure of how much energy is lost in the system. Unloaded $Q$ is the energy lost due to lossy materials. In HFSS the quality factor has been calculated as

$$Q = \frac{|M_{\text{mag}}(\text{freq})|}{|Z||m_{\text{im}}(\text{freq})|}$$

(7.6.1)
In general, the quality factor has been calculated from [154]

\[ Q = (2\pi)^2 (\text{freq})^2 (U/P) \]  \hspace{1cm} (7.6.2)

where,

- \( U \) is the total energy stored in the cavity.
- \( P \) is the power lost from resistive materials etc.

### 7.7 Calculation of Resonance Frequency

The resonant frequency is the frequency of the eigenmode and calculated as

\[ f = (k_0 C)/(2\pi) \]  \hspace{1cm} (7.6.3)

where,

- \( C \) is the speed of the light.
- \( f \) is the frequency of the wave.
- \( K_0 \) is the free space wave number.

### 7.8 Simulation and Optimization

A. The cap radius is varied from 1.8 and 2.1 mm in steps of 0.1 and optimized at each step to get a maximum Quality factor value at around 36 GHz as shown in Fig.7.7 to Fig.7.10. The variation of eigen frequency and Quality factor has been plotted in Fig.7.24. It is observed from the Fig. 7.24 that the cap radius of 2.1 mm results maximum quality factor of 15,128 at a frequency of 36.023 GHz.

B. Keeping cap radius at 2.1 mm and sliding short tuner position at 0.0 mm, post height has been varied in the range of 1-1.5 mm in steps of 0.1 and optimization is done in each step. The corresponding results are shown in Fig.7.11 to Fig.7.14. The Cap height vs. eigen frequency and quality factor is plotted in Fig.7.25 and it is seen that a cap height of 1.46 mm provides maximum quality
factor of 61,356 at a frequency of 36.9 GHz. Further increase of cap height above 1.46 mm gives an error in the 3-D model.

C. Now, keeping both cap radius and cap height at optimized values the sliding short tuner position is varied from 0 to 5 mm in steps of 0.5. The corresponding results are in Fig. 15 to Fig. 23. The optimized value of sliding short tuner position is observed at 4.5 mm with a quality factor of 39,824 at 36.8GHz.

The optimized parameters for the resonant cap IMPATT oscillator are, cap radius = 2.1 mm, cap height = 1.46 mm and sliding short position = 0 mm or 4.5 mm.

Fig.7.7. Eigen frequency Vs Quality factor characteristic
(Cap_r =1.8 mm, Post_h =1.46, S.S. tuner position = 0.0 mm)
Fig. 7.8. Eigen frequency Vs Quality factor characteristic

(Cap_r = 1.9 mm, Post_h = 1.46, S.S. tuner position = 0.0 mm)

Fig. 7.9. Eigen frequency Vs Quality factor characteristic

(Cap_r = 2.0 mm, Post_h = 1.46, S.S. tuner position = 0.0 mm)
Fig. 7.10. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.46, S.S. tuner position = 0.0 mm)

Fig. 7.11. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.0 mm, S.S. tuner = 0.0 mm)
Fig. 7.12. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.1 mm, S.S. tuner = 0.0 mm)

Fig. 7.13. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.2 mm, S.S. tuner = 0.0 mm)
Fig. 7.14. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.46 mm, S.S. tuner = 0.0 mm)

Fig. 7.15. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.46 mm, S.S. tuner = 1.0 mm)
Fig. 7.16. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.46 mm, S.S. tuner = 1.5 mm)

Fig. 7.17. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.46 mm, S.S. tuner = 2.0 mm)
Fig. 7.18. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.46 mm, S.S. tuner = 2.5 mm)

Fig. 7.19. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.46 mm, S.S. tuner = 3.0 mm)
Fig. 7.20. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.46 mm, S.S. tuner = 3.5 mm)

Fig. 7.21. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.46 mm, S.S. tuner = 4.0 mm)
Fig. 7.22. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.46 mm, S.S. tuner = 4.5 mm)

Fig. 7.23. Eigen frequency Vs Quality factor characteristic
(Cap_r = 2.1 mm, Post_h = 1.46 mm, S.S. tuner = 5.0 mm)
Fig. 7.24. Cap radius Vs Eigen frequency and Quality factor

Fig. 7.25. Cap height Vs Eigen frequency and Quality factor
7.9 Experimental Verification

A resonant cap IMPATT oscillator consists of a resonant cap structure under which the diode is embedded and the whole system is 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 cross-sectional view of IMPATT oscillator used in the present study is shown in Fig. 7.1 and the photograph of the same is shown in Fig. 7.2 [152]. The detail optimization and measurement procedure has been discussed in previous Chapter VI. Experimental study of resonant-cap oscillator is 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). A Ka-band spectrum (36.75 GHz) of the oscillator is shown in Fig.7.28.

Fig.7.27. Photograph of resonant cap IMPATT oscillator

Fig.7.28. A typical Ka-band spectrum of the IMPATT oscillator

7.9.1 Variation of Cap diameter

The cap diameter is varied from 3.4 mm to 4.5 mm and corresponding output power and frequency are measured. The results are shown in Fig.7.29. It is observed that the output power attains a maximum value of 90 mw for a cap diameter of 4.0 mm.
7.9.2 Variation of Cap height

The cap height is varied from 1 mm to 2 mm in steps of 0.2 mm and it is observed that output power increases from 52 mw to a maximum of 88 mw for a cap height of 1.6 mm and the same decreases to 72 mw for a cap height of 2 mm. The corresponding oscillation frequency varies from 36.00 GHz to 37.5 GHz.

It is also observed that maximum output power at the desired frequency (36 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 the values 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.
7.9.3 Variation of sliding short tuner position

The dependence of the oscillation frequency and output power on the sliding tuning short position has also been studied and the results are shown in Fig. 7.31. Sliding tuning short position is 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. Maximum output power is obtained at a sliding short position of 0 mm and 4.5 mm.
Fig. 7.31. Variation of Frequency and output power with sliding short tuner position

Frequency [GHz]

Output power [mW]

Sliding short tuner position [mm]
7.10 Conclusion

Three dimensional modeling, simulation and optimization of a Ka-band resonant cap IMPATT oscillator has been carried out by using High Frequency Structure Simulator (HFSS) software. This model has been optimized to obtain a high quality factor at an eigen frequency of 36 GHz by varying cap radius, cap height and sliding short position. It is observed that a cap radius of 2.1 mm, a cap height of 1.46 mm and sliding short position at 0 mm and 4.5 mm leads to the desired optimization. Experiment has been carried out to study the high frequency performance of Ka-band resonant cap IMPATT oscillator with various cap diameter, cap height and sliding short position. It is observed that maximum output power at around the eigen frequency of 36 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 with sliding short position at 0 mm and 4.5 mm. The experimental results are in good agreement with simulation results.