

Design of a Dual-Layer Filter-Antenna with Good Frequency Selectivity

Mittameedi Gowthami¹, Nookala Sreeshanth Kumar^{1*}, Pinapala Koonal Jaswanth¹, K.Raghu²

¹ UG Student, Department of ECE, Mahatma Gandhi Institute of Technology, Hyderabad, Telangana, India.

² Assistant Professor, Department of ECE, Mahatma Gandhi Institute of Technology, Hyderabad, Telangana, India.

mgowthami_ece2204a5@mgit.ac.in, nsreeshanth_ece2204b0@mgit.ac.in,
pkoonaljaswanth_ece2204b3@mgit.ac.in

Abstract : This paper presents the design of a dual-layer filter-antenna aimed at achieving good frequency selectivity along with efficient radiation performance. The proposed structure is based on a Substrate Integrated Waveguide (SIW) cavity-backed slot configuration, where a dual-layer arrangement is used to enhance electromagnetic coupling and control radiation characteristics. By introducing a coupling slot and optimizing structural parameters such as slot dimensions and layer interaction, the antenna is able to generate controlled radiation nulls that suppress unwanted frequencies.

The antenna is designed and analyzed using Ansys HFSS. Simulation results show that the antenna operates around 4.3 GHz with good impedance matching and a peak gain of approximately 6 dB. Two distinct radiation nulls are observed on either side of the operating band, indicating strong filtering capability and improved frequency selectivity. The radiation patterns demonstrate stable directional behavior, while field distribution confirms effective energy confinement and radiation through the slot.

Overall, the proposed design successfully integrates filtering and radiation into a single compact structure, reducing system complexity and making it suitable for modern wireless communication applications requiring high selectivity and efficient performance

1. CONFIGURATION

The proposed antenna is based on a dual-layer Substrate Integrated Waveguide (SIW) cavity structure, designed to achieve both radiation and filtering characteristics within a compact form. The SIW cavity is realized by

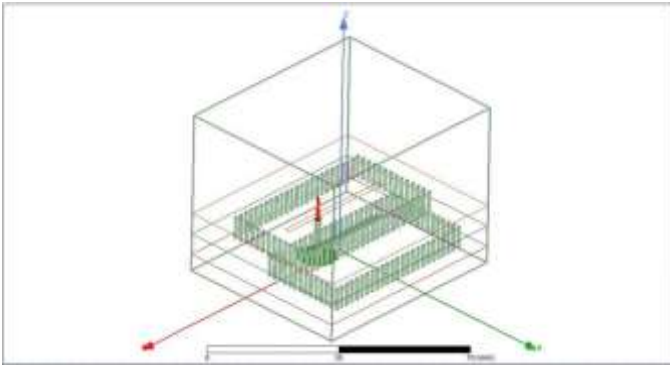
placing periodic metallic vias along the edges of the substrate, which act as sidewalls and confine electromagnetic waves within the structure. The top and bottom metal layers serve as conducting planes, forming a closed waveguide-like configuration.

The antenna consists of two stacked dielectric layers. The bottom layer primarily supports the SIW cavity and guides the electromagnetic energy, while the top layer contains the radiating slot responsible for energy radiation into free space. A coupling slot is introduced between the layers to enable controlled energy transfer from the cavity to the radiating element.

The geometry of the antenna is carefully designed to ensure proper interaction between the cavity modes and the slot. Key structural parameters include the slot length, slot width, via diameter, and via spacing, all of which influence the resonance behavior and radiation characteristics. The dual-layer arrangement enhances coupling between modes, which is essential for generating radiation nulls and achieving frequency selectivity.

Overall, the configuration provides a compact and efficient platform for integrating filtering functionality directly into the antenna structure, eliminating the need for additional filtering components.

2. DESIGN PROCEDURE



The design of the proposed dual-layer filter-antenna is carried out in a systematic manner to achieve the desired resonance, radiation performance, and frequency selectivity. The process begins with the formation of a basic SIW cavity structure, which is realized by placing metallic vias along the edges of the substrate. These vias act as sidewalls, ensuring proper confinement of electromagnetic waves within the cavity.

Initially, the dimensions of the SIW cavity are selected based on the desired operating frequency around 4.3 GHz. The width and length of the cavity are chosen to support the dominant resonant mode. Proper via diameter and spacing are maintained to minimize leakage and to emulate a conventional waveguide structure.

In the next step, a radiating slot is introduced on the top layer of the antenna. The slot acts as the main radiating element, allowing electromagnetic energy from the SIW cavity to radiate into free space. The slot dimensions are carefully optimized to achieve efficient radiation and proper impedance matching.

To enhance the performance and introduce filtering characteristics, a dual-layer configuration is implemented. A coupling mechanism is established between the layers using a slot, which enables interaction between different resonant modes. This interaction is crucial for generating radiation nulls.

Further optimization is carried out by adjusting key parameters such as:

- Slot length
- Slot width
- Slot position
- Coupling strength between layers

The slot length mainly controls the resonant frequency and the position of radiation nulls, while the slot width influences the coupling strength and the depth of the nulls. Parametric analysis is performed to identify the optimal values that provide a balance between radiation efficiency and filtering performance.

Finally, the complete antenna structure is simulated using HFSS over a wide frequency range to evaluate its performance. The design is iteratively refined until the desired results in terms of return loss, gain, and radiation null behavior are achieved.

3. OPERATING PRINCIPLE OF THE PROPOSED ANTENNA

The proposed dual-layer filter-antenna operates based on the principle of electromagnetic wave propagation within a Substrate Integrated Waveguide (SIW) cavity combined with controlled radiation through a slot structure. When an excitation is applied, electromagnetic energy is guided through the SIW cavity formed by metallic vias and conducting layers. The cavity supports resonant modes, allowing energy to be stored and distributed within the structure.

The radiating mechanism is achieved through the slot provided on the top layer, which acts as an aperture for energy to escape into free space. As the electromagnetic waves reach the slot region, fringing fields are generated, resulting in radiation. The efficiency of this radiation depends on the strength of the electric field around the slot and the coupling between the cavity and the radiating layer.

A key feature of the proposed design is the dual-layer configuration, which introduces multiple resonant paths. The coupling slot between layers enables interaction between these modes. At certain frequencies, the fields combine constructively, leading to strong radiation. At other frequencies, the fields become out of phase and cancel each other, resulting in destructive interference.

This destructive interference gives rise to radiation nulls, where the antenna suppresses radiation at specific frequencies. These nulls are responsible for the filtering behavior of the antenna. By carefully designing the structure and controlling the coupling, both radiation and filtering functions are achieved within a single compact system.

Thus, the antenna operates as a combination of a resonant cavity and a radiating element, where the interplay between cavity modes and slot coupling governs the overall performance, including radiation efficiency and frequency selectivity.

4. FREQUENCY CONTROL OF RADIATION NULLS

The radiation nulls in the proposed dual-layer filter-antenna are a key feature that enables its frequency-selective behavior. These nulls occur due to destructive interference between multiple resonant modes generated within the SIW cavity and the coupled layers. By controlling the structural parameters of the antenna, the position and depth of these radiation nulls can be effectively tuned.

Among the various parameters, the slot dimensions play a dominant role in controlling the frequency location of the radiation nulls. The slot length directly affects the electrical path of the current distribution. An increase in slot length results in a shift of both radiation nulls toward lower frequencies, whereas a decrease in slot length shifts them toward higher frequencies. This behavior is due to the change in phase conditions required for destructive interference.

The slot width primarily influences the coupling strength between the SIW cavity and the radiating region. A wider slot enhances the coupling, which can modify the depth and sharpness of the radiation nulls. Stronger coupling typically results in more pronounced nulls, while weaker coupling leads to less distinct suppression. In addition, the position of the slot within the cavity affects the excitation of resonant modes. Placing the slot at regions of high electric field intensity improves radiation efficiency but also alters the balance between constructive and destructive interference, thereby impacting null formation.

Through careful optimization of these parameters, the antenna achieves controlled placement of radiation nulls on either side of the operating frequency. This provides improved frequency selectivity and out-of-band suppression, which are essential for filtering antenna applications.

5. IMPLEMENTATION

The proposed dual-layer SIW cavity-backed slot antenna is designed and analyzed using Ansys High Frequency Structure Simulator (HFSS). The complete antenna structure is modeled by defining the substrate, metallic layers, and via arrays that form the SIW cavity. Proper material properties, including dielectric constant and conductor characteristics, are assigned to accurately represent practical conditions.

The SIW cavity is implemented by placing periodic metallic vias along the edges of the substrate, ensuring effective confinement of electromagnetic waves. The radiating slot is etched on the top layer, and the coupling slot between layers is carefully positioned to achieve the desired interaction between resonant modes.

A wave port excitation is used to feed the antenna, enabling electromagnetic energy to propagate through the SIW cavity. Appropriate boundary conditions are applied to simulate open-space radiation. The simulation is carried out over a frequency range of 3 GHz to 6 GHz to capture the antenna behavior across both operating and non-operating regions.

To achieve optimal performance, a series of parametric analyses are performed by varying key design parameters such as slot length, slot width, and coupling position. This iterative process helps in fine-tuning the antenna for improved impedance matching, gain, and radiation null control.

The implementation also includes extraction of key performance metrics such as S-parameters (S11), gain, radiation patterns, and electric field distribution. These results are used to validate the design objectives and ensure that the antenna meets the required performance criteria.

Overall, the implementation confirms that the proposed design can be effectively realized using standard simulation tools and fabrication-compatible structures, making it suitable for practical wireless communication applications.

6. RESULTS

The performance of the proposed dual-layer SIW cavity-backed slot antenna is evaluated through simulation using HFSS. The results are analyzed in terms of

radiation pattern, S-parameters, gain characteristics, and field distribution to validate the design objectives.

A. Radiation Pattern Analysis

The radiation characteristics of the antenna are examined using both azimuth and elevation plane polar plots. The antenna exhibits a directional radiation pattern, with maximum radiation observed around the 90° direction. The pattern is smooth and stable, indicating proper excitation of the radiating slot.

The elevation plane shows a broad main lobe, suggesting that the antenna radiates over a wide angular region. Reduced radiation in the backward direction is observed due to the SIW cavity structure, which confines electromagnetic energy and minimizes backward leakage.

B. S-Parameter (Return Loss) Analysis

The impedance matching performance of the antenna is evaluated using the S11 parameter. A clear resonance is observed at approximately 4.33 GHz, where the return loss reaches around -14.5 dB.

The antenna satisfies the -10 dB bandwidth condition over a narrow frequency range, indicating efficient operation at the desired frequency. This confirms that most of the input power is radiated rather than reflected.

C. Gain and Radiation Null Analysis

The gain response of the antenna shows a peak value of approximately 6 dB near the operating frequency, indicating good radiation efficiency.

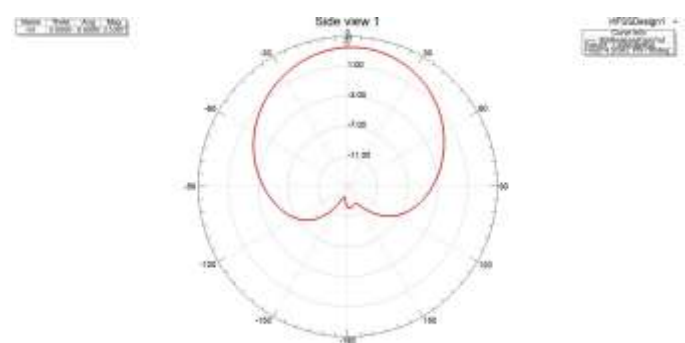
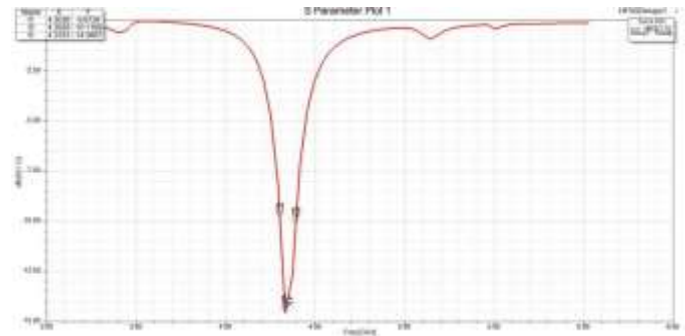
Two distinct radiation nulls are observed:

- RN1 $\approx$ 3.6 GHz
- RN2 $\approx$ 5.1 GHz

At these frequencies, the gain drops significantly, indicating strong suppression of radiation. These nulls are a result of destructive interference between resonant modes and confirm the filtering capability of the antenna.

D. Electric Field Distribution

The electric field distribution is analyzed to understand the radiation mechanism. Strong field concentration is observed near the slot region, confirming that it acts as the primary radiating element.



The SIW cavity effectively confines the electromagnetic energy, ensuring proper wave propagation. The field distribution also indicates strong coupling between layers, which contributes to both radiation and null generation.

E. Overall Performance Evaluation

The obtained results demonstrate that the proposed antenna successfully achieves:

- Good impedance matching at the operating frequency
- Efficient radiation with moderate gain
- Controlled bandwidth
- Effective suppression of unwanted frequencies through radiation nulls

These results confirm that the antenna integrates both radiation and filtering functions within a compact structure, making it suitable for practical wireless communication applications.

