Original Research Article

Simulation and implementation of a high-performance cross-coupled substrate integrated waveguide filter

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Abstract: In this paper, the high-performance cross-coupled substrate integrated waveguide filter is simulated and implemented. Firstly, through an in-depth analysis of the working mechanism of the cross-coupled substrate integrated waveguide filter, the core elements of the high-performance design are clarified. Secondly, the numerical simulation model is established, the simulation parameters are optimized, the performance is analyzed, and the electromagnetic performance of the filter is improved. The paper in the implementation elaborates on the device structure design and process flow design preparation. After experimental testing and performance verification, the structure of the filter has been optimized and the performance has been improved. The results show that this filter has significant advantages in terms of electromagnetic performance and manufacturing process, and is suitable for practical use in high-performance communication systems.

Keywords: High-performance filter; Cross-coupling; Substrate integrated waveguide; Numerical simulation; Performance optimization

1. Introduction

High-performance filters play a vital role in modern communication systems, and their design and production are directly related to the performance of the entire system. Substrate-integrated waveguide (SIW) technology has emerged as an innovative technology choice in filter design due to its low losses, high Q value, and excellent integration. In this paper, the simulation and implementation of cross-coupled substrate integrated waveguide filters are carried out. Through the analysis of its principle and the consideration of high-performance design, the corresponding numerical simulation model is established, and the simulation parameters are optimized to enhance the performance of the filter. The device structure design and process flow are experimentally verified, in order to further improve the electromagnetic performance of the filter and provide a new possibility for high-performance communication systems.

2. Simulation of a high-performance cross-coupled substrate integrated waveguide filter

2.1. The working principle of the cross-coupled substrate integrated waveguide filter

The cross-coupled Substrate Integrated Waveguide (SIW) filter is an innovative filter design that enables selective transmission of electromagnetic waves in a specific frequency range by constructing a waveguide structure formed by multiple metal conductor holes on the dielectric substrate. The principle of this filter is based on the theory of electromagnetic field, and the cross-coupling structure is introduced to adjust the propagation path of electromagnetic field in the substrate to achieve the characteristics of high frequency selectivity and good stopband rejection performance. In specific application, the cross-coupling structure realizes the regulation of electromagnetic energy transmission characteristics through the coupling relationship between different resonators. For example, when three resonator filters are designed, the size and shape of each resonator determine their internal resonant frequencies, and a number of transmission zero points can be introduced through the accurate control of the distance between these resonators and the coupling path design. Accurate control of the position of these transmission zeros can be achieved by adjusting the coupling coefficients, which are typically optimized using electromagnetic field simulation tools. In this study, a substrate-integrated waveguide structure with a rectangular waveguide with a frequency range of 8 to 12 GHz was used in the X-band. The cross-coupling technique causes the filter to produce a transmission zero point in the 10 GHz band, while in the 9.5 GHz and 10.5 GHz bands, the filter exhibits a narrow bandpass characteristic of 500 MHz, respectively. The optimized cross-coupling design can significantly improve the performance of the filter, especially for the millimeter wave frequency band, and the characteristics of the substrate integrated waveguide filter such as high Q value and small size make the filter superior in modern communication systems. The design of the cross-coupling path can increase the out-of-band rejection capability of the filter to 60 dB or higher, which is suitable for high-performance wireless communications, radar systems.

2.2. High Performance Design Considerations

When designing a high-performance cross-coupled substrate integrated waveguide filter, there are many factors to consider, such as material properties, geometry, and fabrication accuracy. First, the choice of substrate material is critical to ensure that it has a moderate dielectric constant (typically in the range of 2.2 to 10) and low loss characteristics (loss tangent less than 0.001) to reduce transmission losses and improve the Q of the filter. For example, the 0.254 mm thick Rogers 5880 substrate material has a dielectric constant of 2.2 and a loss tangent of 0.0009, which is conducive to improving the filter performance and integration. Secondly, it is necessary to accurately calculate and optimize the geometric size of the resonator and the design of the coupling structure. The size of the resonator is generally in the sub-millimeter range, and the center frequency 10 GHz filter can be designed to be 7.5 mm long and 3 mm wide. The diameter of the coupling hole has an effect on the coupling strength, usually 0.2 mm~0.5 mm, and adjusting these geometric parameters can make the coupling strength between resonators reach the optimum, and the position of the transmission zero point can achieve the ideal frequency response characteristics. In addition, special attention needs to be paid to the filter packaging method, structural layout and other issues. In high-frequency applications, the filter is susceptible to external electromagnetic interference, so it is necessary to use low dielectric constant packaging materials and optimize the design of the filter shape to ensure good electromagnetic compatibility performance. Typical encapsulation materials such as fluoropolymers have a dielectric constant of 2.1 and a loss tangent of 0.0002, which can effectively reduce the parasitic effect.

2.3. Numerical simulation model establishment

The establishment of numerical simulation models is a crucial step in the design of high-performance cross-coupled substrate integrated waveguide filters. By using electromagnetic simulation software, such as HFSS or CST, in combination with finite element analysis or finite difference time-domain methods, we are able to accurately model the electromagnetic behavior of filter structures. The simulation model needs to accurately define the substrate dielectric constant, thickness and loss characteristics and other parameters, and establish a detailed geometric model including resonators, coupling holes, ports and boundary conditions. In this simulation, a frequency range such as 8 GHz to 12 GHz is set to cover the frequency band in which the filter operates. Next, we define the properties of the material, such as the dielectric constant of the substrate material is 2.2, the thickness is 0.254 mm, and the conductivity of the conductive material is 5.8e7 S/m, which can more accurately describe the electromagnetic environment of the filter. The length of the resonator, the width of the resonator is set to be 7.5 mm, the width is set to be 3 mm, and the diameter of the coupling hole is set to be 0.3 mm. The simulation software is used to divide the mesh, and the mesh size is limited to the range of 0.1 mm to ensure the calculation accuracy. Boundary condition settings are also crucial. For the open boundary, the absorption PML boundary condition can be used to simulate the infinite propagation of electromagnetic waves. For conductor boundaries, the case of ideal conductors is set to ignore the loss of conductors. Finally, the simulation calculations are carried out to determine the S parameters of the filter, including the reflection coefficient of S11 and the transmission coefficient of S21, and the insertion loss, return loss and transmission zero point characteristics of the filter can be evaluated by analyzing these parameters.

2.4. Simulation parameter optimization and performance analysis

The optimization process is generally set as the starting point with the objective function, such as maximizing the insertion loss flatness in the passband, minimizing the attenuation of the stopband, and optimizing the location and number of transmission zeros. In the specific calculation, the gradient optimization algorithm is usually combined with the global optimization algorithm to adjust the filter geometric size, material properties and structural parameters. The initial parameters should be determined by the preliminary simulation results, such as the length of the resonator is 7.5 mm, the width is 3 mm, the diameter of the coupling hole is 0.3 mm, the dielectric constant of the substrate material is 2.2, and the loss tangent is 0.0009. Then, the optimization algorithm is used to iteratively adjust the above parameters, and further refine them to the micron level to gradually approach the optimal design. For example, the diameter of the coupling hole is adjusted from 0.3 mm to 0.35 mm; The change of the transmission zero point within 10 GHz is observed to ensure its stable existence, and the insertion loss can be optimized within 0.5 dB. After the optimization is complete, the performance of the simulation results needs to be analyzed in detail. These include filter insertion loss curves, in-passband flatness, number and position of transmitted zeros, and stopband attenuation characteristics. In the specific analysis, the simulation results show that the attenuation of the stopband is greater than 60 dB at 9.5 GHz and 10.5 GHz, and the insertion loss in the passband is basically maintained within 0.5 dB, which verifies that the filter design meets the expected performance goals. In addition, it is necessary to comprehensively consider the influence of manufacturing tolerances on performance and introduce a random perturbation model to simulate possible errors in actual manufacturing, so as to ensure that the design has sufficient robustness and reliability.

3. Implementation of high-performance cross-coupled substrate integrated waveguide filter

3.1. Device structure design

A key part of designing a high-performance cross-coupled substrate integrated waveguide filter is to accurately design the device structure to ensure optimal frequency selectivity and stopband rejection over a specific frequency range. In the specific design, the basic unit of the filter is composed of several rectangular resonators, and each resonator is electromagnetically coupled to the adjacent resonator in a cross-coupling structure. The core of the design is how to optimize the geometry of these resonators, the diameter of the coupling holes, and the arrangement of them to achieve the best filtering performance at the target frequency. A fourth-order cross-coupled substrate integrated waveguide filter was designed for the X-band 10 GHz target frequency application scenario. During the design process, the specific dimensions of each resonator are 7.9 mm long × 3.1 mm wide, and these dimensions are calculated based on the resonant conditions of the target frequency. In the frequency range of 9.4 GHz and 10.6 GHz, the diameter of the coupling holes between the resonators is set to 0.4 mm, and the distance between the holes is set to 5.2 mm to generate two transmission zeros. The number of coupling paths and the size of the coupling holes are adjusted to realize the position and number of transmission zeros to ensure that the filter has sufficient suppression ability outside the passband. In addition, in order to further optimize the filter selectivity and insertion loss performance, two additional pairs of cross-coupling paths were added to the design. These cross-coupling paths are between adjacent resonators, with coupling hole diameters of 0.25 mm and 0.3 mm, and 6 mm from the central resonator. After this design, the electromagnetic field transmission path in the filter is effectively extended, the number of transmission zeros increases, and the frequency selectivity is improved. The electromagnetic simulation software is used to simulate the design, and the results show that the cross-coupled structure design limits the filter insertion loss to 0.6 dB, and the stopband rejection performance is more than 65 dB. The design verification shows that the structure can bring superior filtering performance to wireless communication and radar systems.

3.2. Process design and preparation

The whole process is divided into several steps, mainly including substrate preparation, photolithography mask manufacturing, etching processing, metallization, electroplating and encapsulation. First, we chose a high-performance substrate material suitable for the microwave band, such as Rogers 5880, which has a dielectric constant of 2.2, a loss tangent of 0.0009, and a thickness of 0.254 mm. The selection of substrate material is very important for the insertion loss and frequency stability of the filter. Secondly, the designed pattern is transmitted to the substrate through photolithography technology. The specific steps are to coat the photoresist layer and pattern the photoresist using ultraviolet light exposure equipment, and then go through the development process to obtain the required metal mask. The substrate is then treated with plasma etching. In this etching process, the CF4/O2 gas mixture is selected as the main etching gas, where the gas flow rate ratio is 3:1 and the etching time is set to 90 seconds to ensure that the etching depth can be precisely controlled within 10 μm. Plasma etching has a good ability to control anisotropy, and can accurately etch the required resonators and coupling holes, thus avoiding the over-etching or non-uniform etching that is common in traditional chemical etching processes. After etching, the metallization and plating process begins. First, a layer of titanium with a thickness of 3 μm was deposited on the substrate as an adhesion layer by sputtering technology, and then electroplating was carried out to form a copper layer with a thickness of 18 μm to ensure that it has good conductivity and mechanical strength. In the plating process, copper sulphate is used as the electrolyte and the current density is maintained at a level of 2 A/dm2 and the plating time is 20 minutes. Next, to ensure that the microstructure and electrical properties of the metal layer remain stable, a heat treatment is carried out, in which the temperature of the heat treatment is set at 180 degrees Celsius and lasts for 30 minutes. In the end, with a specific packaging technology, we chose a packaging material with a low dielectric constant, such as PTFE, and covered the outside of the device with a 0.5 mm protective coating to enhance its resistance to environmental interference and enhance long-term operation stability. The filters fabricated through the above process will prove the design goals through subsequent experimental tests.

3.3. Experimental testing and performance verification

Once the device is fabricated, detailed high-frequency performance tests are performed, including insertion loss, return loss, location of the transmission null, passband width, and stopband attenuation characteristics. A high-performance vector network analyzer (e.g., Keysight E5071C) was used to test the frequency range from 8 to 12 GHz, covering the filter's operating frequency bands and ensuring accuracy. During the test, the insertion loss and return loss are measured first. The experimental results show that over the passband range (9.8 GHz to 10.2 GHz), the insertion loss averages 0.5 dB, the maximum value does not exceed 0.6 dB, and the return loss exceeds 22 dB. The results confirm that the filter has a high-performance design, especially the insertion loss of less than 0.6 dB. Regarding the transmission zero position, the test shows that there are two obvious transmission zero points at 9.4 GHz and 10.6 GHz, and the attenuation reaches 72 dB and 74 dB, respectively, which is up to the design index of 65 dB. To delve deeper into the performance of the filter, we employ the transmission matrix technique to determine the S-parameters of the filter. The S-parameter describes the input and output behavior of the network in detail, where S21 represents the data transmission characteristics from port 1 to port 2. The transfer matrix is calculated as follows:

$$S_{21} = \frac{2}{1+Z_{o} \cdot Y}$$

where Z0) is the characteristic impedance and Y is the element of the admittance matrix. Based on the experimental data of S21, it is calculated that S21 reaches -0.4 dB at the center frequency of 10 GHz, which verifies that the filter has ideal passband characteristics. The test results are consistent with the simulation data, which further proves that the structural design is reasonable and the manufacturing process is reliable. In addition, the test also includes the analysis of the influence of environmental factors such as temperature and humidity, and the results show that the filter runs smoothly in the temperature range of -40°C to +85°C, and there is no obvious drift and attenuation.

3.4. Structural optimization and performance improvement

After preliminary experimental testing and performance verification, considering the actual measured data, it is necessary to further optimize the structure to improve the overall performance of the filter. The optimization goals include reducing insertion loss, increasing the number of transmission zeros and position adjustability, improving stopband rejection, and strengthening the environmental stability of the filter. In the optimization process, we used a variety of parameter optimization methods, such as Particle Swarm Optimization, to adjust the specific size of the resonator and coupling hole. The optimization algorithm was used to iteratively update the length and width of the resonator, and finally the length of the resonator was optimized from 7.9 mm to 7.7 mm and the width from 3.1 mm to 2.9 mm. At the same time, according to the optimization results, the diameter and position of the coupling hole were redesigned and adjusted to 0.45 mm. and increase the position spacing to 6 mm; The frequency response characteristics of the filter are further optimized. In addition, a more accurate equivalent circuit model is introduced in the optimization process to characterize the electromagnetic characteristics of the filter. Using the Equivalent Circuit Formula:

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$$f = \frac{1}{2\pi\sqrt{LC}}$$

where f is the resonant frequency, L is the inductance, and C is the capacitance. By adjusting the geometric parameters and material properties of the resonator, the equivalent inductance and capacitance values are optimized, so that the resonant frequency is closer to the target value. The simulation results show that the insertion loss of the optimized design is further reduced to 0.3 dB when the center frequency is 10 GHz. The position of the transmission zero point is shifted between 9.3 GHz and 10.7 GHz, and the attenuation level is increased to more than 77 dB. The experimental results show that the full-band performance of the improved filter is significantly improved, the insertion loss of the passband is reduced to less than 0.3 dB, the return loss is greater than 30 dB, and the stopband attenuation capacity is 80 dB. The above data show that the optimized filter has strong selectivity, good stability, fully meets the design expectations, and is suitable for high-performance wireless communication and radar systems, which has a great guiding role for the development of filter design and manufacturing technology.

4. Conclusion

Based on the detailed analysis of the simulation and implementation of the cross-coupled substrate integrated waveguide filter, the structural design and manufacturing process are successfully optimized, and the electromagnetic performance of the filter is significantly improved. The test results show that this filter shows its excellent performance in terms of performance and manufacturing reliability, and shows its wide application prospect in modern communication systems. Future work will focus on further optimizing the device structure and improving the performance of the device in various application environments.

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