

A rigorous modal analysis for substrate integrated waveguide H-plane T-junction diplexer

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Abstract: A rigorous modal analysis for the substrate integrated waveguide (SIW) H-plane T-junction diplexer is presented in this paper. The analysis is based on the classical coupling matrix technique for waveguide T-junction problems. The H-plane T-junction not only connects the two SIW filters together but also acts as a coupling structure between the common port and the first stages of the two SIW filters. The design equations of the H-plane T-junction are first derived, and then a 4-order prototype diplexer working at X-band is designed, fabricated, and measured. The measured centre frequencies of the pass-bands of the diplexer are 9.03 and 9.42 GHz, respectively. Meanwhile, the measured results are in good agreement with the predicted ones.

Key words: Substrate integrated waveguide; H-plane; T-junction; diplexer; SIW filter

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1 Introduction

In recent years, the design of microwave and millimetre-wave (mm-wave) components based on substrate integrated waveguide (SIW) is becoming more and more popular among microwave engineers. Compared with microstrip line and coplanar waveguide (CPW) line, SIW has a high Q-factor and high power handling capacity which are inherited from the conventional waveguide^[1]. Meanwhile, SIW can be mass-produced easily and can be integrated with other planar technologies with a lower cost^[2]. These advantages of SIW make it a promising technology for the implementation and integration of microwave and

mm-wave devices.

Acting as channel separator, diplexer is an important component in microwave transceiver and greatly affects the system's performance. The SIW diplexers were well studied and widely used in wireless communication systems, due to their excellent performances^[3]. In general, diplexers are used to separate or combine two narrow-band frequency channels with guard band. One kind of typical diplexer architectures employs a three-port junction between the two separately designed filters^[4]. By adjusting the length of the branch lines of the T-junction, the two filters share the common port without affecting each other. So far, lots of SIW-diplexer designs have been carried out at different frequency bands, ranging from

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C-band up to 60 GHz, and with different structural configurations. A C-band T-junction SIW diplexer presented in Hao et al^[5] uses complementary split-ring resonators. In Han et al^[6], an X-band diplexer design uses triplet technology, which has input and output ports on opposite sides of the substrate and uses iris filters including a trisection. In Tang et al^[7], a diplexer operating at K-band employs dual-mode SIW filters with circular and elliptic cavities. A Ka-band SIW diplexer using two filters and a circulator is presented in He et al^[8]. In Athanasopoulos et al^[9], a T-junction diplexer with iris filters is presented at 60 GHz. In all diplexers mentioned above, the final steps of the design and optimization of the diplexers are carried out using full-wave simulators, thus can be time consuming.

In this paper, a rigorous modal analysis based on the coupling matrix technique^[10] is introduced for modelling and designing the SIW H-plane T-junction diplexer quickly. The H-plane T-junction acts as a 3-port coupling structure, and the design equations of the H-plane T-junction will be derived. After that, diplexer working at X-band will be presented as an example, which is composed by two 4-order SIW band-pass channel filters. In order to integrate easily with other planar microwave circuits, we choose planar transmission line at the input/output ports of the diplexer. At the common port, a SIW-microstrip transition is applied to connect the diplexer to microstrip line interface. While at the other two ports of the diplexer, SIW-CPWG transitions are applied to connect the diplexer to CPWG interface, which could provide higher channel-to-channel isolation than microstrip line does.

2 SIW diplexer analysis and design

The diplexer consists of two window coupled SIW filters. The two filters are arranged side by side, and share a common port by an H-plane T-junction.

2.1 Modal analysis of H-plane T-junction

The T-junction is a 3-port SIW device that can be used to connect the two filters together in the diplexer^[11].

Fig. 1 presents the simulation structure of the 3-port H-plane T-junction under study. The T-junction acts as a coupling structure as part of the filters.

In our design process, the well-known commercial simulator ANSYS HFSS is used for modal extraction and filter simulation.

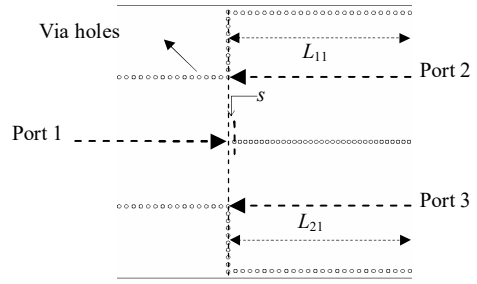


Fig. 1 Simulation structure of the three port H-plane T-junction

At the intersection plane, the T-junction could be represented by a 3-port network as shown in Fig. 2. We can write down the loop equation as follow.

$$v_m = \sum_{n=1}^3 Z_{mn} i_n, \quad m=1,2,3, \quad (1)$$

where v_m denotes the node voltage; i_n is the loop current; and Z_{mn} represents the impedance matrix elements.

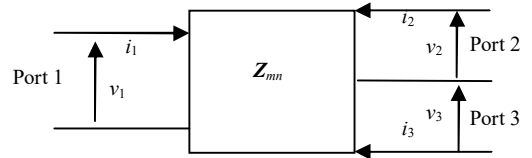


Fig. 2 3-port network of the T-junction voltage, current basic definition

When port 3 is terminated by a short circuit (short circuit is an approximation, in the passband of filter between port 1 and 2, the input impedance of the other filter between port 1 and 3 is approximately equal to a short), the 3-port model circuit is changed to a 2-port circuit, whose impedance matrix $[Z']$ is given by

$$[Z'] = \begin{bmatrix} Z_{11} - \frac{Z_{13}Z_{31}}{Z_3 + Z_{33}} & Z_{12} - \frac{Z_{13}Z_{23}}{Z_3 + Z_{33}} \\ Z_{21} - \frac{Z_{13}Z_{23}}{Z_3 + Z_{33}} & Z_{22} - \frac{Z_{23}Z_{32}}{Z_3 + Z_{33}} \end{bmatrix}, \quad (2)$$

where Z_3 denotes the port characteristic impedance.

Similarly, when port 2 is terminated by a short

circuit, the impedance matrix $[Z'']$ is given by

$$[Z''] = \begin{bmatrix} Z_{11} - \frac{Z_{12}Z_{21}}{Z_2 + Z_{22}} & Z_{13} - \frac{Z_{12}Z_{23}}{Z_2 + Z_{22}} \\ Z_{31} - \frac{Z_{32}Z_{21}}{Z_2 + Z_{22}} & Z_{33} - \frac{Z_{23}Z_{32}}{Z_2 + Z_{22}} \end{bmatrix}. \quad (3)$$

As in Sabri et al^[12-13], the discontinuity of the 2-port microwave network can be equivalent to a T-network. Combined with a section of transmission line whose length is $\varphi/2$ at each side, the T-network acts as a K impedance converter circuit, as shown in Fig. 3.

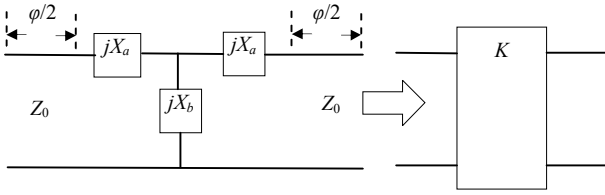


Fig. 3 Equivalent K impedance converter circuit of the 2-port discontinuity

The parameters in Fig. 3 are:

$$X_a = \text{Im}[Z''_{11}] - \text{Im}[Z''_{12}], \quad X_b = \text{Im}[Z''_{11}], \quad (4)$$

$$\varphi = -\tan^{-1}\left(\frac{2X_b}{Z_0} + \frac{X_a}{Z_0}\right) - \tan^{-1}\frac{X_a}{Z_0}, \quad (5)$$

$$K = Z_0 \left| \tan\left(\frac{\varphi}{2} + \tan^{-1}\left(\frac{X_a}{Z_0}\right)\right) \right|, \quad (6)$$

where Z_0 represents the characteristic impedance.

According to the network theory^[13], we can obtain the coupling coefficients, external quality factor, and length of transmission line as:

$$M = \frac{K}{Z_0} \cdot \frac{1}{\frac{\pi}{2} \cdot \left(\frac{\lambda}{\lambda_0}\right)^2}, \quad (7)$$

$$Q_e = \frac{\pi}{2} \left(\frac{\lambda}{\lambda_0}\right)^2 \cdot \frac{Z_0^2}{K^2}, \quad (8)$$

$$\Delta l = \frac{\varphi}{2} \cdot \frac{\lambda}{2\pi}, \quad (9)$$

where λ and λ_0 denote the waveguide wavelength and dielectric wavelength, respectively.

By changing the value of s in Fig. 1 in the HFSS simulation, the curve of the external quality factor and the electric length versus s can be plotted, as shown in Fig. 4.

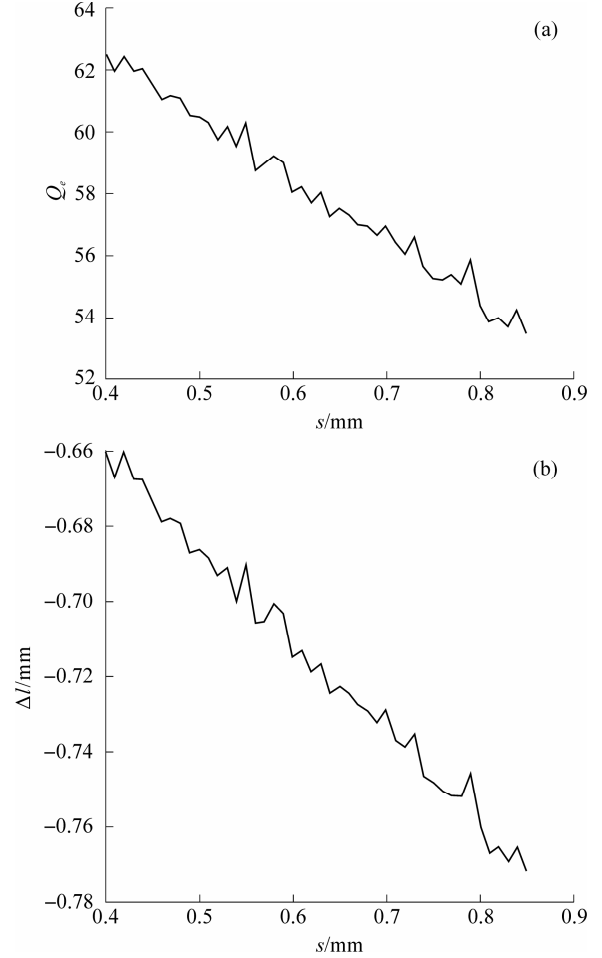


Fig. 4 Change of the external quality factor and the electric length with s

Once Q_e in the coupling matrix of the filter is calculated, the corresponding physical dimension s can be calculated according to the curve in Fig. 4. The other dimensions of the diplexer can be calculated according to the coupling matrix and the model of the coupling windows^[14]. And the equivalent conventional rectangular waveguide for SIW can be obtained from a closed-form formula. Using these models, we designed the SIW inductive window coupled filter. In order to be capable of being integrated with other planar microwave circuits, one SIW-microstrip and two SIW-CPWG transitions are added to the common port of the diplexer and the two separated ports of the diplexer separately. The reason we use CPWG at the two separated ports of the diplexer is that CPWG could provide better isolation performance between the two ports than microstrip line.

2.2 Example of diplexer design

The diplexer design starts with two channel filters. The centre frequencies of these two filters are 9.03 and 9.42 GHz, respectively, and the bandwidths of both filters are 0.1 GHz. The design goal of the return losses for both filters is less than -18 dB in the pass-bands. Fig. 5 shows the block diagram of diplexer. The design procedure of the diplexer based on H-plane T-junction is described in the previous section.

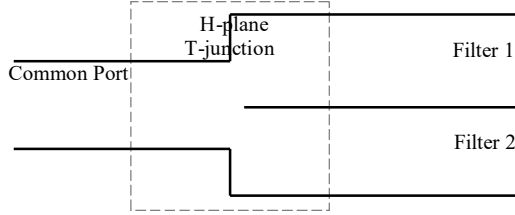


Fig. 5 Design block diagram of diplexer

The substrate is chosen with a relative dielectric constant of 3.0 and thickness of 0.762 mm. The diameters of the plated via hole of SIW are chosen as $R=0.4$ mm and the distance between two adjacent plated via holes is chosen as $d=0.8$ mm. The distance between the centres of two via walls of the waveguide is 14.2 mm. According to the equation in Sabri et al^[12], the effective width of the SIW cavity $a_{SIW}=14.0$ mm. Fig. 6 shows the layout of designed diplexer.

In Fig. 6, the two filters are arranged side by side to realize a compact diplexer structure. On the left hand side of the diplexer, the common port of the diplexer is connected to 50Ω microstrip line through a SIW to microstrip transition^[15]. In order to keep a good isolation performance, on the right hand side of the diplexer, the other two ports of the two filters are connected to the shielded CPWG lines through SIW transition to CPWG line^[16]. The physical dimension of the designed diplexer is listed in Table 1. a_{SIW} is the width of SIW; L_{com} , L_{1i} ($i=1-5$) and L_{2i} ($i=1-5$) are the length of SIW cavities of the common part and the branch parts in filters 1 and 2, respectively; W_{1i} ($i=1-4$) and W_{2i} ($i=1-4$) are the width of SIW coupling windows; R is the diameter of the metallic vias; d is the spacing between the adjacent metallic vias; L_{CPWG1} and L_{CPWG2} are the lengths of

CPWG lines in filters 1 and 2, respectively; W_{CPWG} is the width of CPWG line and W_{50} is the width of 50Ω microstrip line.

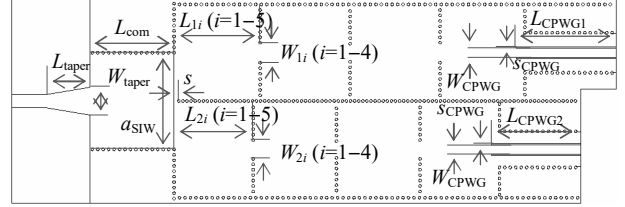


Fig. 6 Configuration for the designed diplexer based on H-plane T-junction

Table 1 Dimensions of SIW diplexer mm

Items	Values	Items	Values	Items	Values
a_{SIW}	14.2	R	0.40	d	0.80
L_{11}	12.64	L_{21}	11.6	s	0.69
L_{12}	13.2	L_{22}	12.24	L_{com}	12.3
L_{13}	13.2	L_{23}	12.24	L_{taper}	6.52
L_{14}	12.44	L_{24}	11.65	W_{taper}	4.10
L_{15}	13.44	L_{25}	11.93	L_{CPWG1}	14.7
W_{11}	2.943	W_{21}	2.75	L_{CPWG2}	13.06
W_{12}	2.66	W_{22}	2.44	s_{CPWG}	0.20
W_{13}	2.94	W_{23}	2.75	W_{CPWG}	1.34
W_{14}	5.87	W_{24}	5.29	W_{50}	1.91

3 Experimental results

The designed X-band SIW diplexer has been fabricated with standard PCB technology, as shown in Fig. 7. For facile measurement, the diplexer is mounted into the shielding box and connected to coaxial connectors. When measuring the S -parameters of the diplexer, one port is matched with a standard 50Ω load, and the other two ports are connected to a vector network analyzer (Agilent E8361C). The simulated and the measured S -parameters are shown in Fig. 8, including the effect of coaxial to planar transmission line transitions. The measured results show that the centre frequencies of the pass-bands of the diplexer are 9.03 and 9.42 GHz, respectively; the insertion losses of diplexer is 6.5 dB for the lower band and 6.3 dB for the upper band; the return losses are less than -18 dB in the

two passbands and the isolation of the diplexer is around 60 dB. The measured results agree with the simulated ones.



Fig. 7 Photograph of the fabricated diplexer

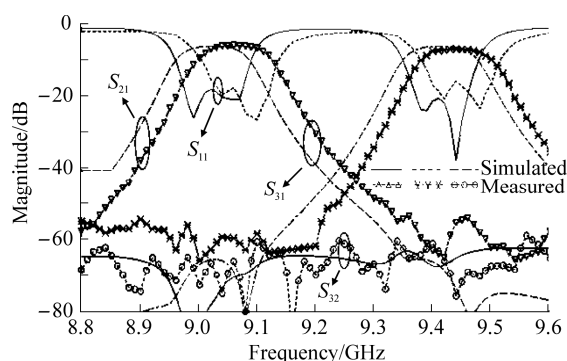


Fig. 8 Measured S -parameters performance of the designed diplexer compared with simulated ones

4 Conclusion

SIW diplexer based on H-plane T-junction has been proposed, by using H-plane T-junction as the coupling structure between the two first-stage resonators of two filters and the common port. The design equations of external quality of the T-junction have been derived based on the 3-port network parameter of the H-plane T-junction. Based on the derived equations for the T-junctions, the design of diplexer based on coupling matrix is simple and straightforward. A 4-order prototype diplexer working at X-band has been designed and the measured results agree with the predicted ones. As the whole structure of the SIW diplexer is made by metallic vias on a planar substrate with standard PCB technology, the proposed SIW diplexer structure merits low cost, small size and light weight, and can be easily fabricated and conveniently integrated into microwave and millimeter-wave integrated circuits.

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基片集成波导 H 面 T 型双工器严格模态分析

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摘要: 本文介绍了基板集成波导(SIW)H 平面 T 型双工器的严格模态分析. 该分析基于用于波导 T 型结问题的经典耦合矩阵技术. H 平面 T 型结不仅将两个 SIW 滤波器连接在一起, 而且还用作两个 SIW 滤波器的公共端口和第一级之间的耦合结构. 首先推导了 H 平面 T 型的设计方程, 然后设计, 加工并测试了一个工作在 X 波段的 4 阶原型双工器. 双工器的实测通带中心频率分别为 9.03 和 9.42 GHz. 同时, 测试结果与预测结果具有很好的一致性.

关键词: 基片集成波导; H 面; T 型结; 双工器; 基片集成波导滤波器

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