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The Concept of Substrate Integrated E-plane Waveguide and Circuits

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The concept of substrate integrated E-plane waveguide and circuits

By

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This thesis has been examined and approved by the following members of the student's committee.

Dr. Xuanhui Wu	Advisor
Dr. Han-Way Huang	Committee Member
Dr. Qun Zhang	Committee Member

Declaration of Authorship

I, Danyang Huang, declare that this thesis titled, "The concept of substrate integrated E-plane waveguide and circuits" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

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Date: 04/06/16

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Abstract

Electrical and Computer Engineering Technology

Master of Science

The concept of substrate integrated E-plane waveguide and circuits

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In this thesis, a new type of substrate integrated waveguide is proposed for implementing E-plane type of waveuguide circuits on printed circuit boards. obviously, these E-plane type of circuits cannot be realized by the conventional substrate integrated waveguide. The so-called substrate integrated E-plane waveguide consists of two circuit boards attached to each other. Two copper strips are inserted in between two circuit boards, where plated through holes are penetrated through them along the transmission direction. The plated through holes and copper strips altogether played as side walls of a conventional waveguide to support longitundinal and vertical currents. Simulation is carried out and the result shows that the proposed waveguide is able to guide horizontally polarized electromagnetic wave. An E-plane inductive septa filter, two one-dimensional E-plane offset waveguide filters, and an air-filled evanescent-mode bandpass filter are proposed as examples to prove that E-plane type of circuits are able to be built based on this new synthesized waveguide structure.

Acknowledgements

First, I would like to thank my advisor, Dr. Xuanhui Wu, for his patience, kindness, and continuous support on my research. He is more than an advisor but a closed friend. Without his guidance, I would have never been able to complete this work.

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I would especially like to thank Yi-Chen Wu, for her company and encouragement. She has provided lots of advice on choice of words and building of sentence of this thesis.

Finally, I would like to thank my family for their support. I really appreciate that they encourage me to study abroad.

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List of Abbreviations

TE	**T**ransverse **E**lectric
TM	**T**ransverse **M**agnetic
TEM	**T**ransverse **E**lectric **M**agnetic
SIW	**S**ubstrate **I**ntegrated **W**aveguide
SIFW	**S**ubstrate **I**ntegrated **F**olded **W**aveguide
HMSIW	**H**alf **M**ode **S**ubstrate **I**ntegrated **W**aveguide
FHMSIW	**F**olded **H**alf **M**ode **S**ubstrate **I**ntegrated **W**aveguide
SISW	**S**ubstrate **I**ntegrated **S**lab **W**aveguide
SIEW	**S**ubstrate **I**ntegrated **E**plane **W**aveguide

Dedicated to my family

1 Introduction

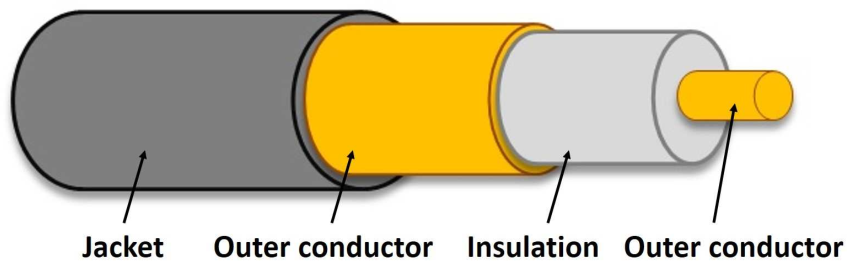
1.1 Transmission lines

In electromagnetics and electrical engineering, a transmission line is generally considered as a pair of electrical conductors designed to carry signal from one place to another in high frequency such as microwave frequency. Coaxial line, stripline, and microstrip line are examples (Fig. 1.1) .

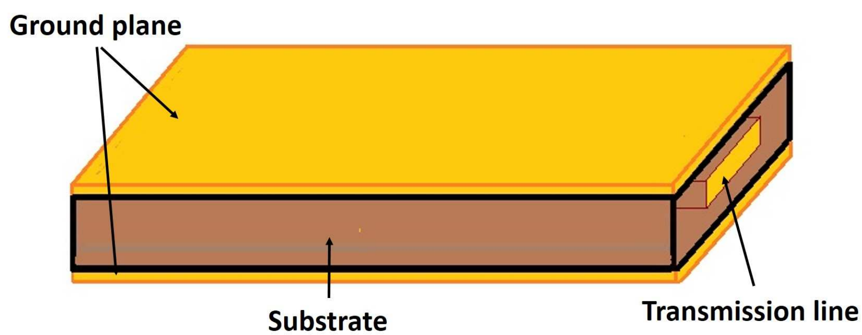
Even though waveguides has quite different characteristics from other two-conductor transmission lines, from the viewpoint of transmitting power in radio frequency, they should be considered as a type of transmission line. Rectangular waveguide shown in Fig. 1.2 is a hollow metal pipe used to carry radio waves mostly at microwave frequencies [1]. Unlike transmission lines mentioned above which support transverse electric magnetic mode (TEM mode), waveguides support transverse electric mode (TE mode) and transverse magnetic mode (TM mode). Among those transmission lines mentioned above, waveguides have the best transmission characteristics because they have no electromagnetic radiation. They are widely used in transmitting high power because compared to other types of transmission lines, they have high quality factor and high power capability [2–5]. However, the bulky size and the presence of the conductive side walls make them difficult to be fit into integrated circuits and in turn has high-cost fabrication and production [6–8].

1.2 Substrate integrated circuits

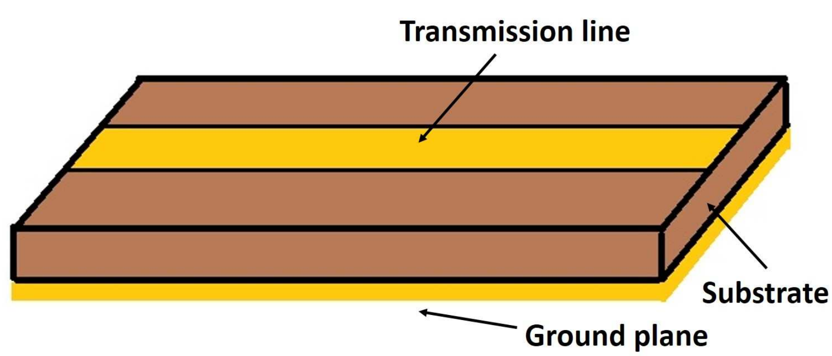
Engineers and researchers have come up a solution called substrate integrated waveguide (SIW) technology [9–13] to overcome above shortcomings. The idea is first developed in 1998, named post-wall waveguide [9] or Laminated Waveguide



(a) Coaxial cable



(b) Stripline



(c) Microstrip line

Figure 1.1: transmission lines

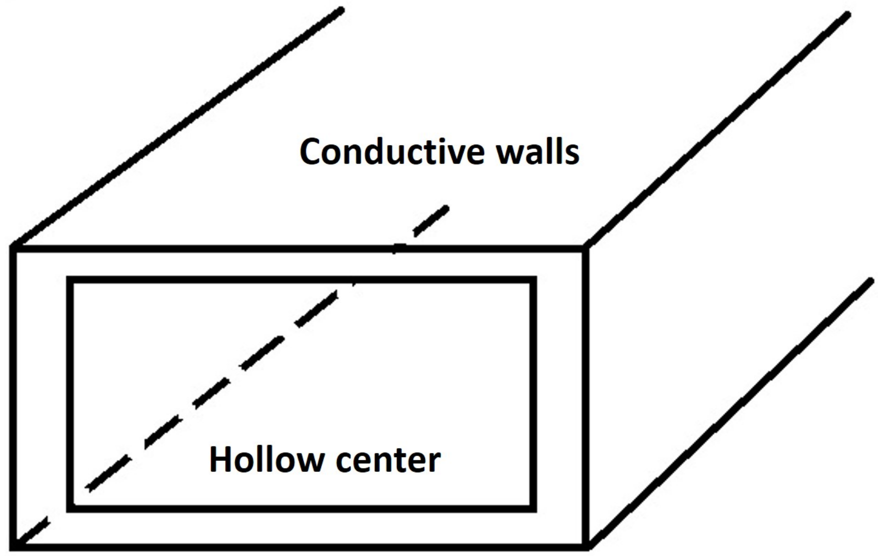


Figure 1.2: Retangular waveguide

[10] for feeding networks in antenna arrays. The so-called post wall waveguide is a dielectric waveguide constructed of two rows of aligned via holes, which function as the vertical side walls of a rectangular waveguide. This post-wall waveguide can support only TE_{n0} modes using vertical walls of the waveguide as E planes, for the reason that such waveguide has no horizontal conductor to support current flow on the side walls, and such current flow is required for TE_{0n} modes. The diagram of laminated waveguide is shown in Fig. 1.3 . The name of laminated waveguide is made due to the reason that it is manufactured using lamination technologies. The geometry of laminated waveguide consists of multiply layers. The top and bottom conductive layers play the role of upper and lower walls of a classical waveguide. In particular, filled via holes and edges of conductive layers at the middle of the waveguide play the role of vertical walls. The dielectric layers are placed in between and filled up the rest of the space of the waveguide. By this way the laminated waveguide provides a promising solution to have waveguide

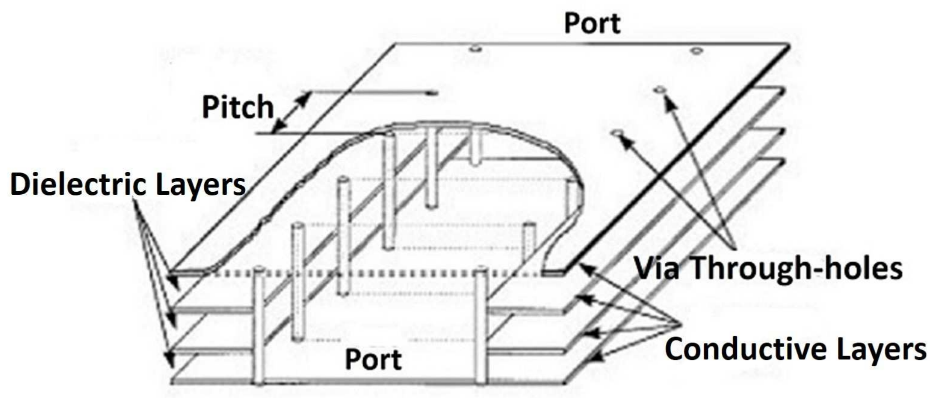


FIGURE 1.3: Laminated waveguide.Reprinted from [10]

components imbedded in circuit boards.

The concept of substrate integrated waveguide is then proposed by Dominic Deslandes and Ke Wu in year 2003 [11]. The geometry of SIW is shown in Fig. 1.4 . They use printed circuit board (PCB) technology in the paper to implant such waveguide-like structure on a printed circuit board. Simply, copper plating of the PCB functions as the top and bottom walls of a waveguide. Two rows of plated through holes embedded along the circuit board to electrically connect the top and bottom surfaces of the PCB function as vertical walls of a waveguide. The idea of substituting conductor walls of a waveguide by plated through holes on the PCB can be proved by Maxwell equations in terms of fields at the interface with a conductor:

$$\hat{n} \cdot \vec{D} = \rho_s \tag{1.1}$$

$$\hat{n} \cdot \vec{B} = 0 \tag{1.2}$$

$$\hat{n} \times \vec{E} = 0 \tag{1.3}$$

$$\hat{n} \times \vec{H} = \vec{J_s} \tag{1.4}$$

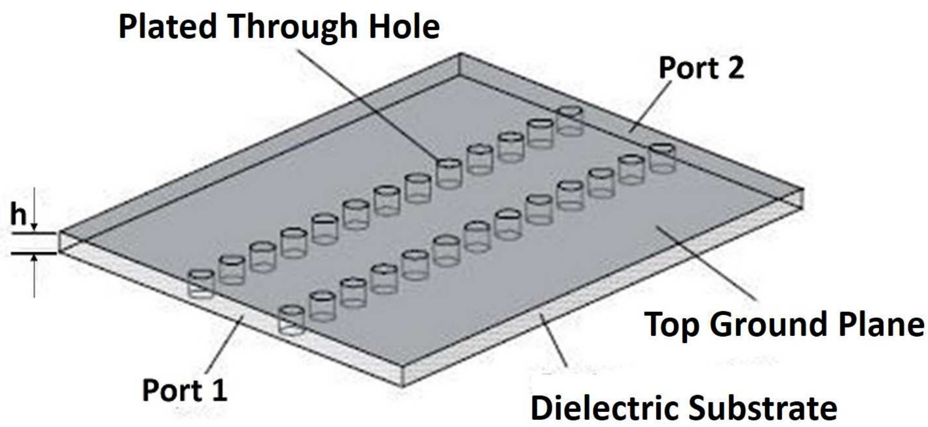
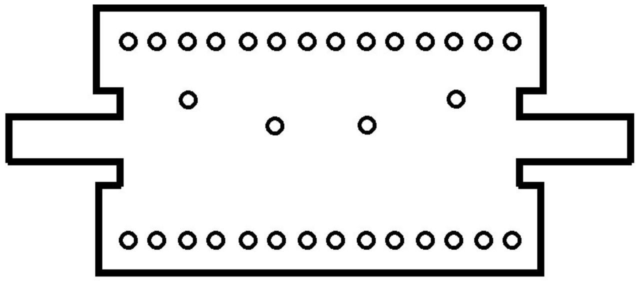


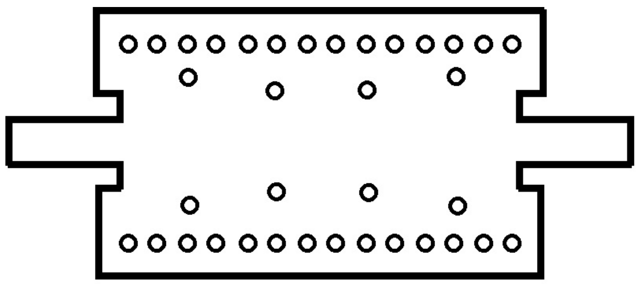
FIGURE 1.4: Substrate integrated waveguide. Reprinted from 'Review of substrate-integrated waveguide circuits and antennas' by M. Bozzi, A. Georgiadis, K. Wu, IET Microwaves, Antennas & Propagation, 2011, 5, (8), pp. 909-920.

According to the eq. 1.4, to support TE modes where H field is parallel to PCBs, copper plating is necessary on top and bottom surfaces to support both horizontal current and longitudinal current. However, only vertical conductors are needed as the vertical conductor walls of a waveguide for the reason that there is no longitudinal current on the vertical walls. The idea of SIW not only remains the advantage of classical rectangular waveguides with high performance, but also extremely decreases the cost of fabrication and production [12, 13]. Most importantly, SIW technology makes it possible to integrate waveguide circuits with planar circuits on the same circuit board. It is a revolution of transmission lines.

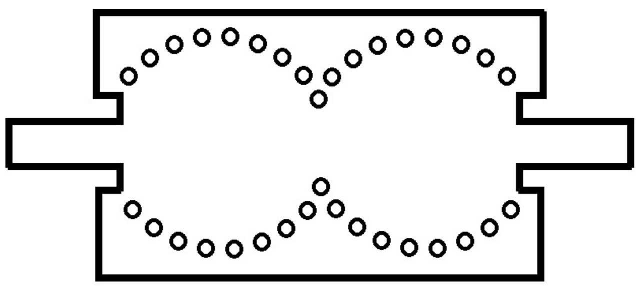
Since SIW technology was presented, many components and related concepts have been proposed based on such technique. The fact that a large quantity of passive and active components including filters (Fig. 1.5) , couplers, oscillators (Fig. 1.6) , amplifiers and even antennas (Fig. 1.7) have been developed by different researchers [11, 14–57] proves that this SIW technology is versatile and talented. Moreover, the transitions between planar transmission lines and SIW structures



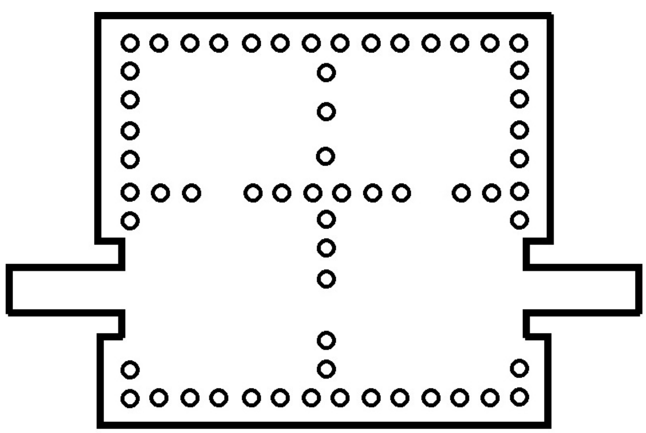
(a) Inductive via-hole filter



(b) Iris windows filter

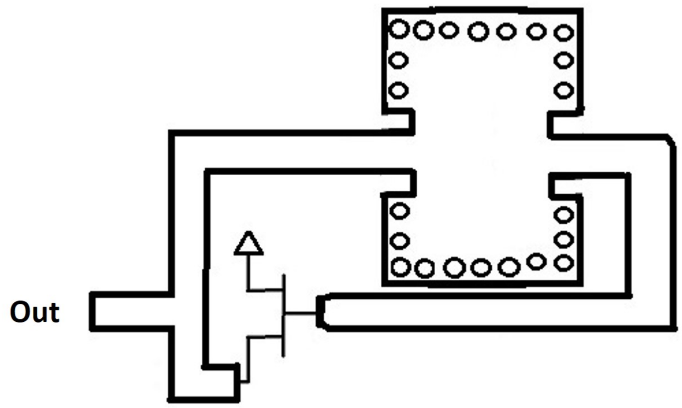


(c) Circular cavities filter

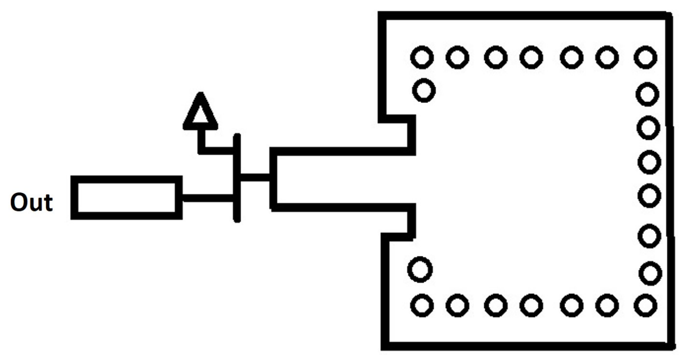


(d) Rectangular cavities and cross-coupling filter

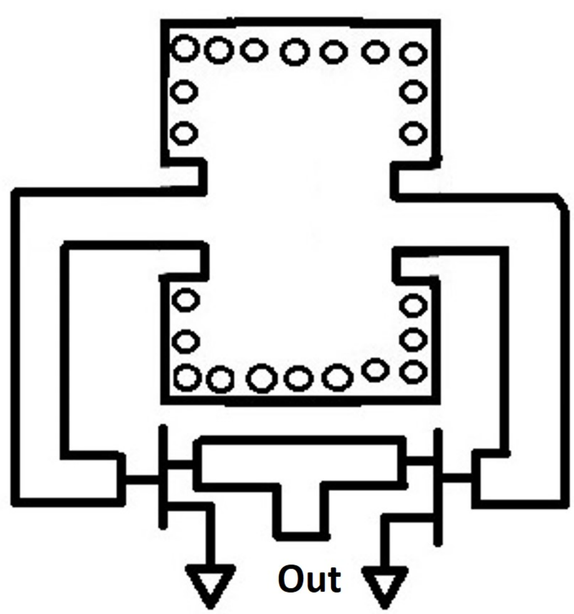
Figure 1.5: Substrate integrated waveguide filters



(a) Feedback oscillator

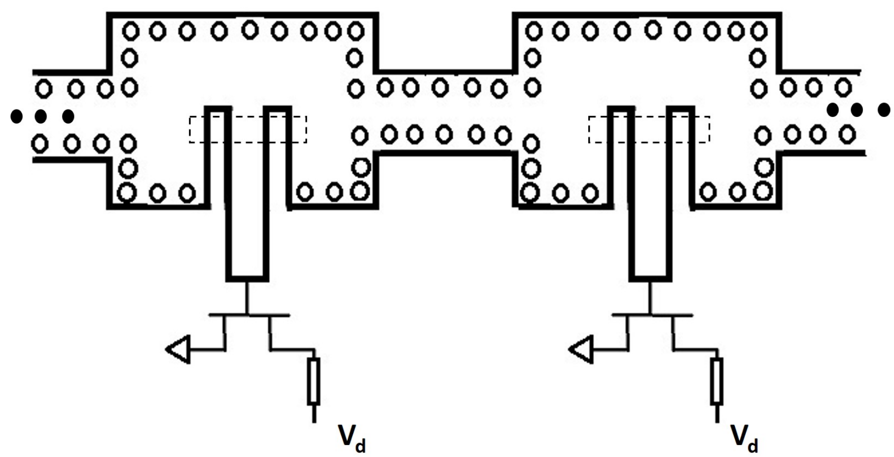


(b) Reflection oscillator

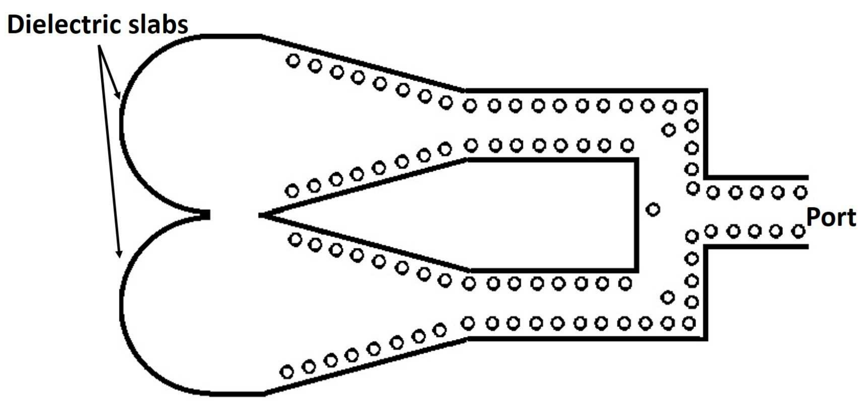


(c) Push-push reflection oscillator

Figure 1.6: Substrate integrated waveguide oscillators



(a) Cavity-backed coupled oscillator antenna array



(b) Horn antenna

Figure 1.7: Substrate integrated waveguide antennas

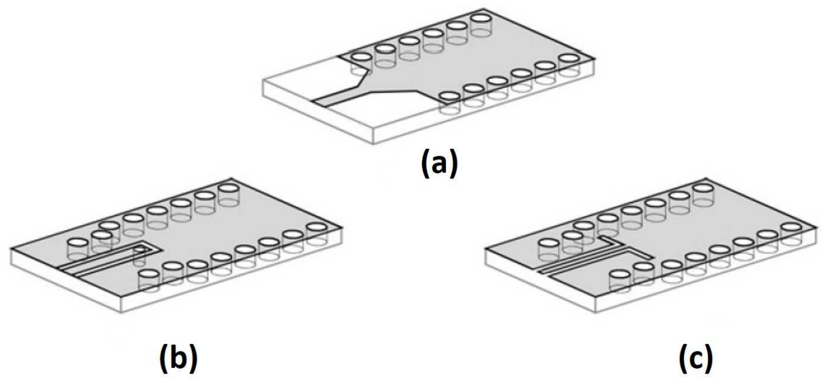


Figure 1.8: Substrate integrated waveguide transitions
(a) Microstrip-to-SIW transition, based on a taper,
(b) Coplanar-to-SIW transition, based on a curren probe,
(c) Coplanar-to-SIW transition, based on a 90° bend. Reprinted from 'Review of substrate-integrated waveguide circuits and antennas' by M. Bozzi, A. Georgiadis, K. Wu, IET Microwaves, Antennas & Propagation, 2011, 5, (8), pp. 909-920.

have also been proposed in [58–63]. Some typical transitions are shown is Fig. 1.8 . In the meanwhile, many SIW topologies such as substrate integrated folded waveguide (SIFW) [64], half-mode substrate integrated waveguide (HMSIW) [65], folded half-mode substrate integrated waveguide (FHMSIW) [66] and substrate integrated slab waveguide (SISW) [67] have also been proposed to decrease the size and improve the performance of SIW.

1.3 Motivation for work

Although many H-plane type of waveguide components in which the electric field is normal to circuit boards can be designed based on this synthesized-waveguide technology, E-plane type of waveguide circuits in which the electric field is parallel to the circuit board are not able to be achieved, due to the nature of vertical walls of SIW: the presence of gaps between through holes makes it unable to support longitudinal current, which is necessary for E-plane type of waveguide-like circuits [68].

In this dissertation, the concept of substrate integrated E-plane waveguide (SIEW) is proposed. Compared to SIW, two metal strips are introduced on the mid-layer of the proposed waveguide along the longitudinal direction. They are placed at the middle of two rows of plated through holes, in order to provide paths for currents on the vertical side-walls along longitudinal direction. By this way the proposed SIEW is able to propagate electromagnetic wave with electric field parallel to the circuit board so that it can be applied to develop E-plane type of waveguide circuits on printed circuit boards. In the study, an SIEW is designed to operate at 12-13GHz. As a complemental structure to SIW, the proposed waveguide provides more possibilities and freedom for researchers to implement more designs from conventional rectangular waveguide components on PCBs.

This dissertation is organized as below. The design of substrate integrated E-plane waveguide is proposed in Chapter 2. An E-plane inductive septa filter, two E-plane one-dimensional offset waveguide filter, and an E-plane evanescent mode filter are also presented and operated at around 12.5GHz in Chapter 3. In the end, the conclusion is in Chapter 4.

2 Substrate integrated E-plane waveguide

2.1 Waveguide Geometry

The configuration of a substrate integrated E-plane waveguide is shown in Fig. 2.1 . The waveguide is built by binding two pieces of circuit boards, and both of the boards are made of the same material and with the same thickness of h. The top board has copper plating on the top surface only, while the bottom board has two copper strips on the top surface and copper plating on the bottom. The copper strips are respectively penetrated by two rows of plated through holes, and the holes are closely aligned with spacing p and along the direction of two copper strips. The longitudinal cross-sectional view of the waveguide is shown in Fig. 2.2 . Holes in the waveguide are designed to have diameter d=1mm and spacing p=1.5mm in the case. The plated through holes and two pieces of copper strips at the mid-layer of the waveguide are used to support currents longitudinally and vertically so that they altogether function as the vertical walls of a conventional waveguide. Two pieces of printed circuit boards with dielectric constant of 10.7, loss tangent of 0.0023, and thickness of 2.5mm are chosen in this study, which makes the total thickness of the proposed waveguide 5mm. This is considered as the long dimension of the waveguide since the distance between the two rows of through holes is 3.66mm. In particular, the waveguide supports fundamental mode with electric field parallel to the circuit board, which is similar to the TE_{10} mode of a rectangular waveguide. Consequently, the E-plane of SIEW is parallel to the circuit boards.

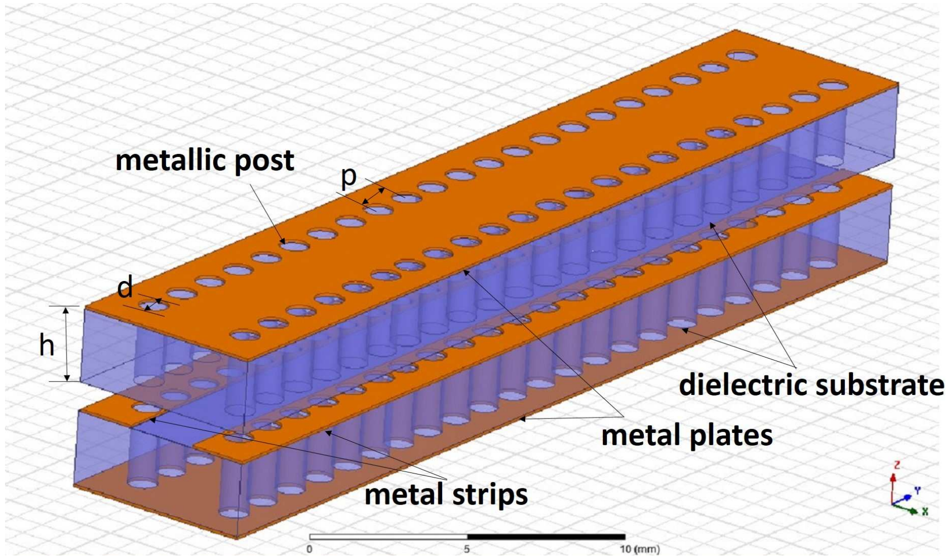


Figure 2.1: Geometry of the substrate integrated E-plane waveguide

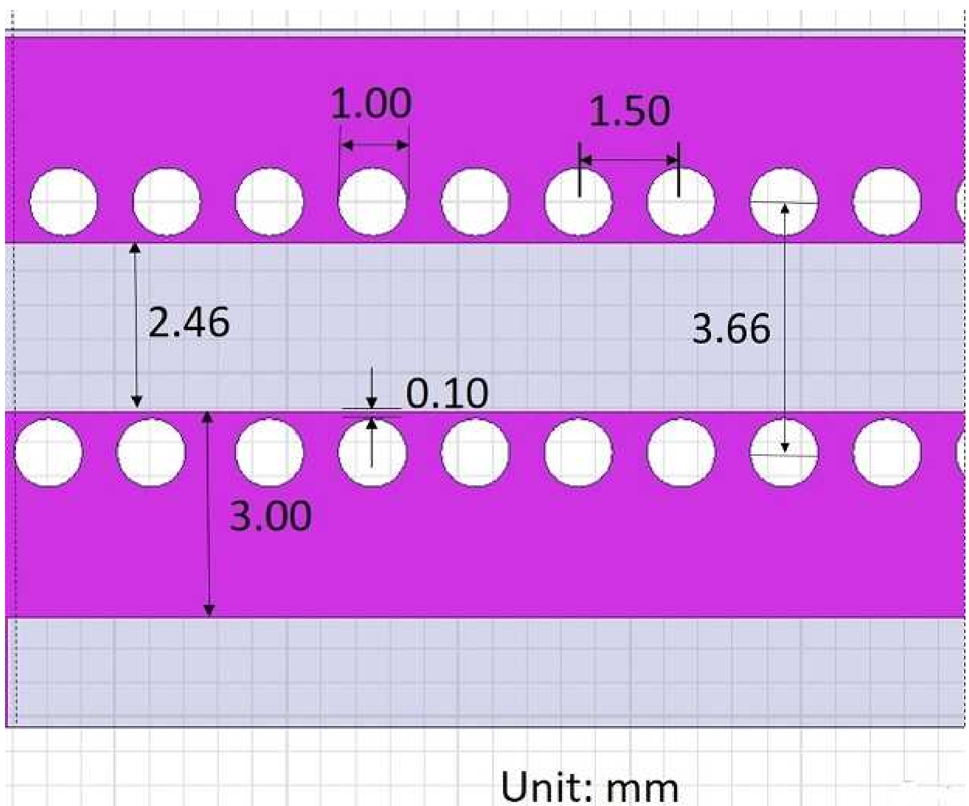


Figure 2.2: The longitudinal cross-sectional view at the middle of the waveguide

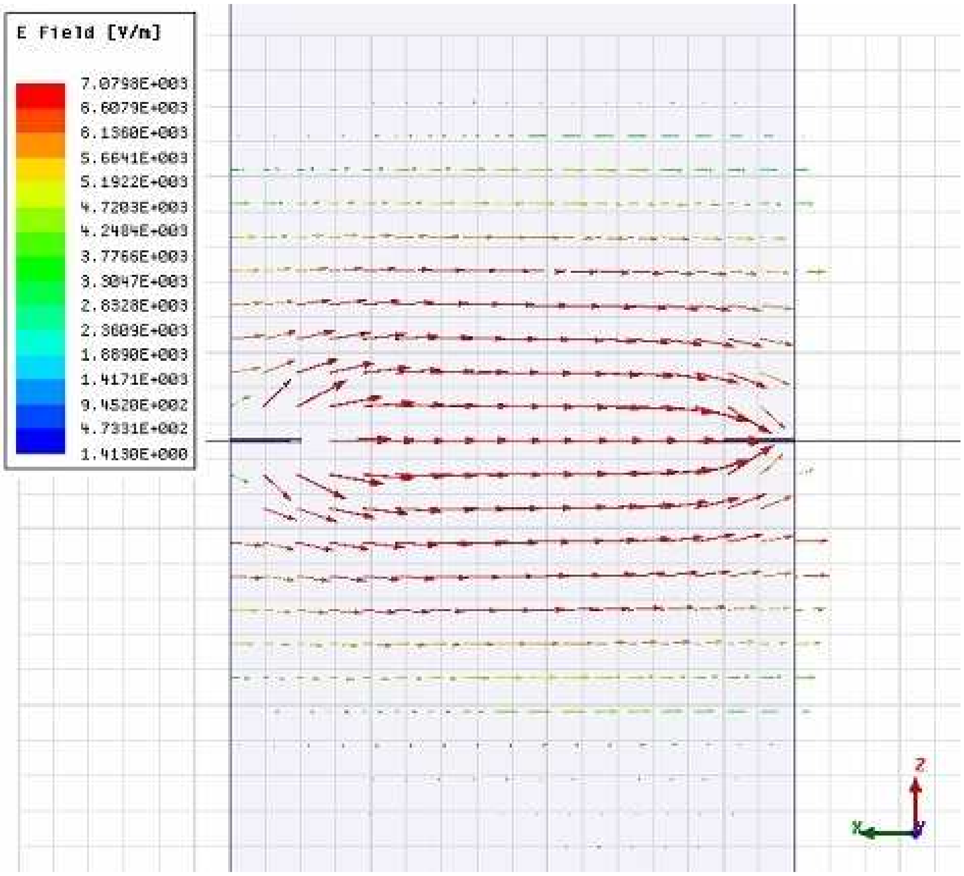


FIGURE 2.3: Electric field distribution in the transverse cross section.

2.2 Waveguide characteristics and performance

In this study, all of the simulation work is carried out using HFSS, a software using finite element method to solve for electromagnetic structure. It is a tool for antenna and other high frequency structure design. In the simulation, the proposed waveguide is excited by horizontally polarized wave, in which the electric field is parallel to the circuit board. The electric field distribution in the transverse cross-section of the waveguide is plotted in Fig. 2.3 . The plot shows that the excited mode inside is similar to the TE_{10} mode of a rectangular waveguide as expected. The electric filed distribution in the longitudinal cross-section is shown in Fig. 2.4 . The graph demonstrates that the electromagnetic energy is confined

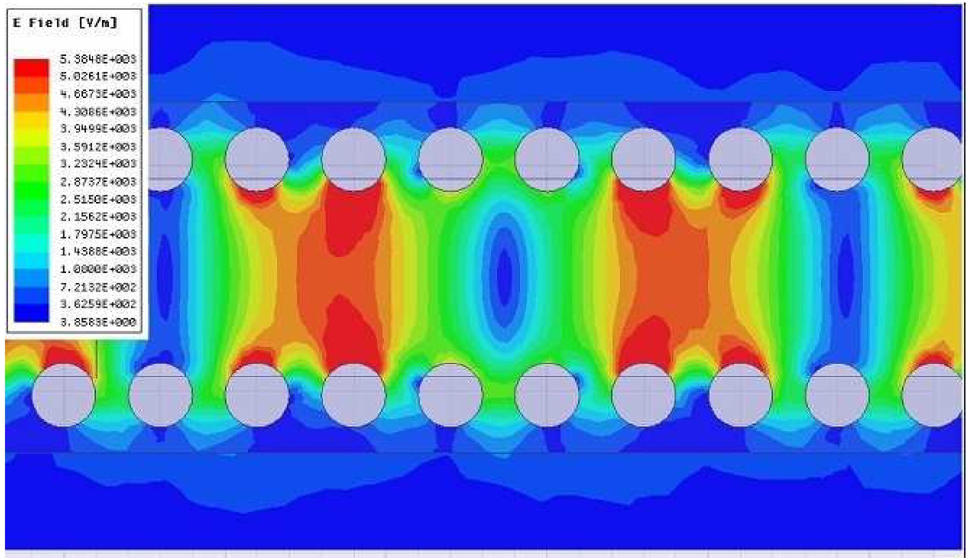


FIGURE 2.4: Electric field distribution inside the SIEW.

and guided inside the proposed structure. The current distribution on the strips is shown in Fig. 2.5 . The plot shows that most energy on the strips is close to the inner edge of the strips and is around the through holes, which demonstrates that the SIEW has little leakage. The simulated S-parameters from 12-13 GHz are shown in Fig. 2.6 . Good impedance matching with return loss at around 40dB and insertion loss close to 0dB can be observed, which demonstrates most energy can be transmitted and guided in the proposed waveguide.

One of the considerations in the proposed waveguide is the electrical connectivity between the plated through holes and the middle strips, since such connection cannot be always guaranteed during fabrication. Thus, the effects of such disconnectivity is investigated. As shown in Fig. 2.7 , the investigation is carried out between two situations, one with the through hole plating connected to the middle strips and one with them disconnected. The simulated results of both are plotted and compared in Fig. 2.8 . The results show that the disconnectivity between the through holes and the two middle strips has little effect on the waveguide performance, due to the reason that the plated through holes only support vertical

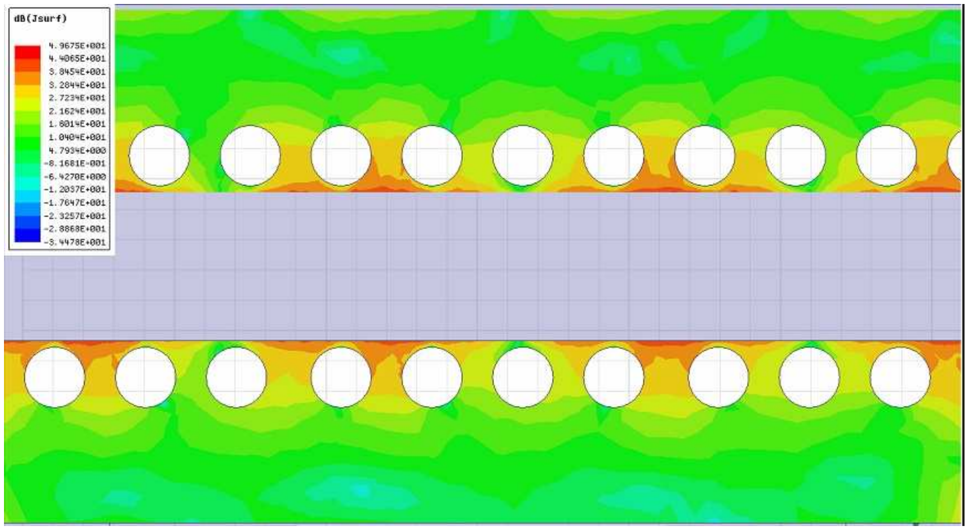


Figure 2.5: Surface current on the middle strips

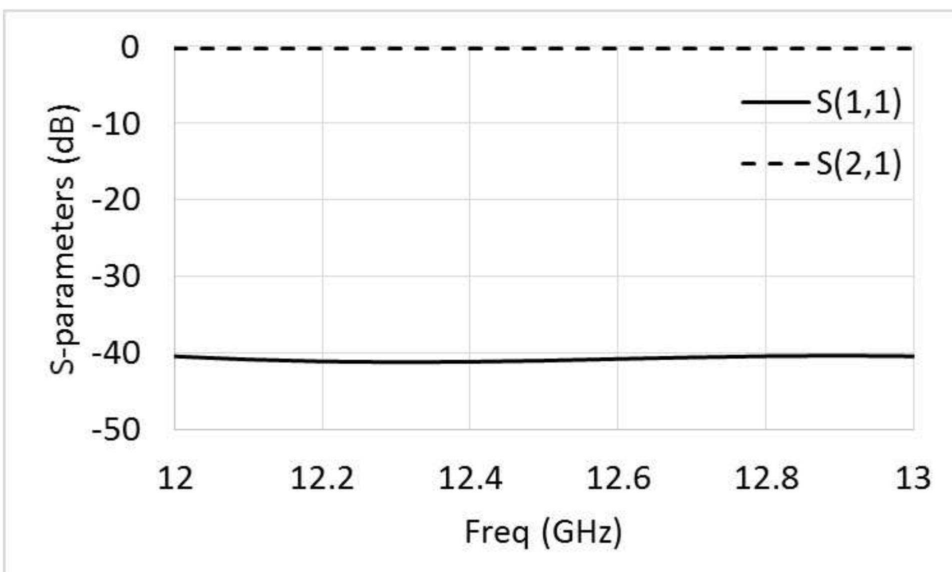


Figure 2.6: S-parameters of the SIEW

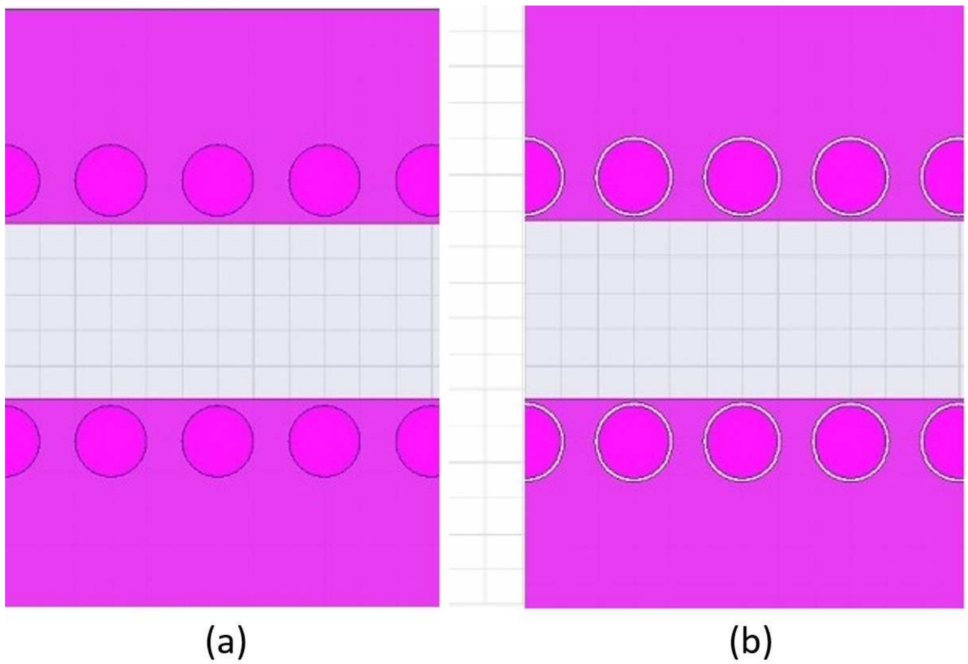


Figure 2.7: SIEW with middle strips and plated through holes (a) connected and (b) disconnected

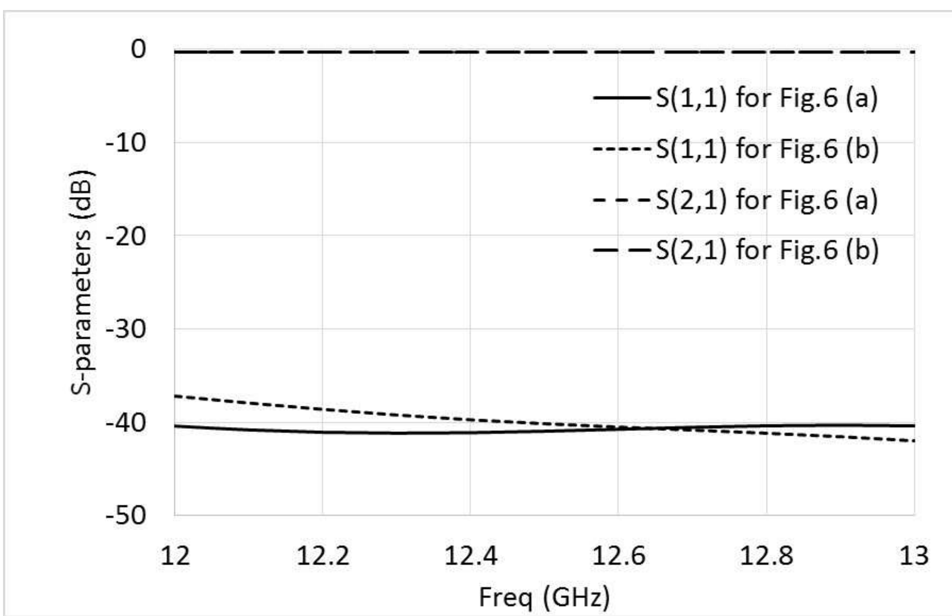


Figure 2.8: Effects of the disconnectivity of the middle strips and the plated through holes

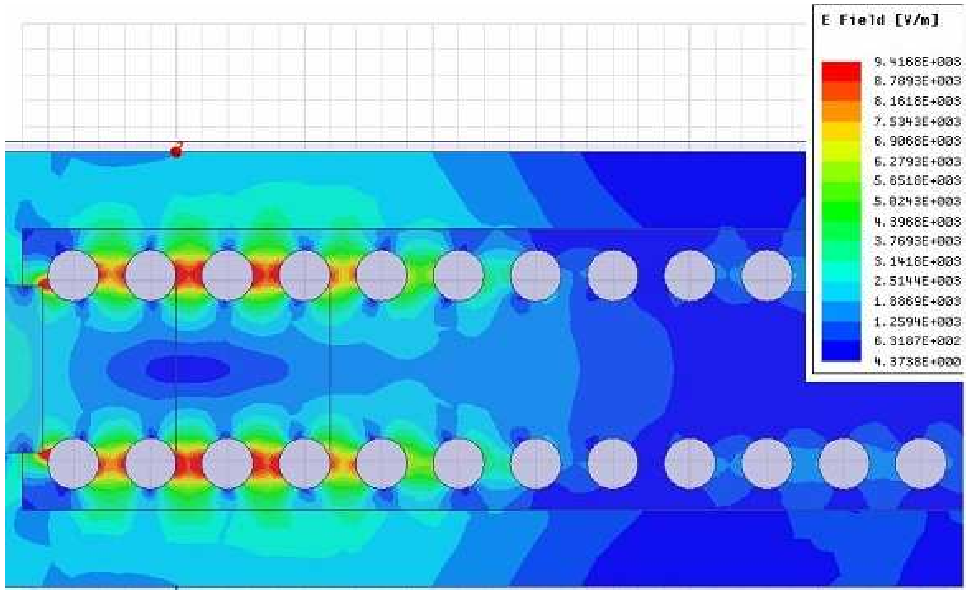


Figure 2.9: Electric field distribution in a conventional SIW

current on the side walls of the waveguide-like structure, and the middle strips only support longitudinal current. Those two types of currents are orthogonal to each other and neither relies on the electrical connectivity between the through holes and the middle strips.

As mentioned above the geometry of SIW and SIEW are mostly the same except that two middle strips are inserted purposely in SIEW. To confirm the significance of two middle strips when propagating horizontally polarized wave, a conventional SIW is simulated as well. All the dimensions of SIW are the same as the proposed SIEW in Fig. 2.2, except that the two strips are removed. With the SIW is also excited by a horizontally polarized electric field, the electric filed distribution inside the waveguide is simulated and illustrated in Fig. 2.9 . As can be seen in the plot, the electromagnetic energy is radiated in all directions instead of being guided by the waveguide. It is obvious that the SIW is not able to guide the wave with electric field parallel to the waveguide without conductor to support longitudinal current on the side walls. The resulting S-parameters are simulated

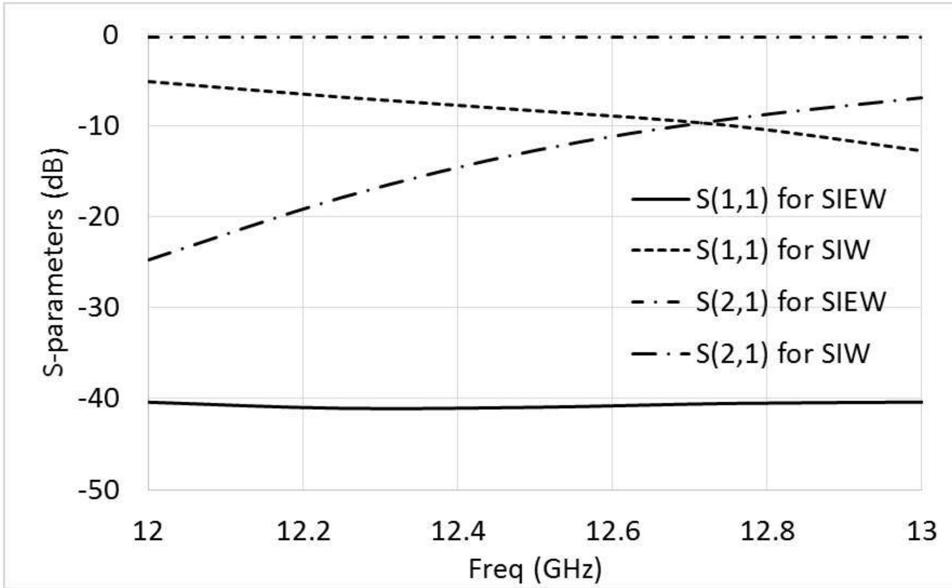


Figure 2.10: S-parameters of SIEW and SIW

and compared to that of the SIEW in Fig. 2.10 . The comparison shows that the SIW is very lossy when propagating horizontally polarized wave due to the radiation loss between the through holes.

2.3 Geometry of SMA adaptor for SIEW and performance

In order to realize the proposed waveguide and measure it in practice, transition between the SIEW and the SMA connector is necessary. As a result, a coplanar-to-SIEW transition is introduced in this section to connect the SMA connector with the SIEW for measurement. The geometry of the proposed waveguide with the transition section called SMA adaptor is shown in Fig. 2.11 . As can be seen in the figure, a current probe is inserted between the two middle strips on the top surface of the lower circuit board. On the upper circuit board, a notch is cut so that the inner conductor of the SMA connector can be plugged in and connect to the current probe. A 90° bend is designed between the SMA adaptor section and waveguide section, so that when connected to the SMA connector and excited by generator, the current through the current probe generates a magnetic field, which

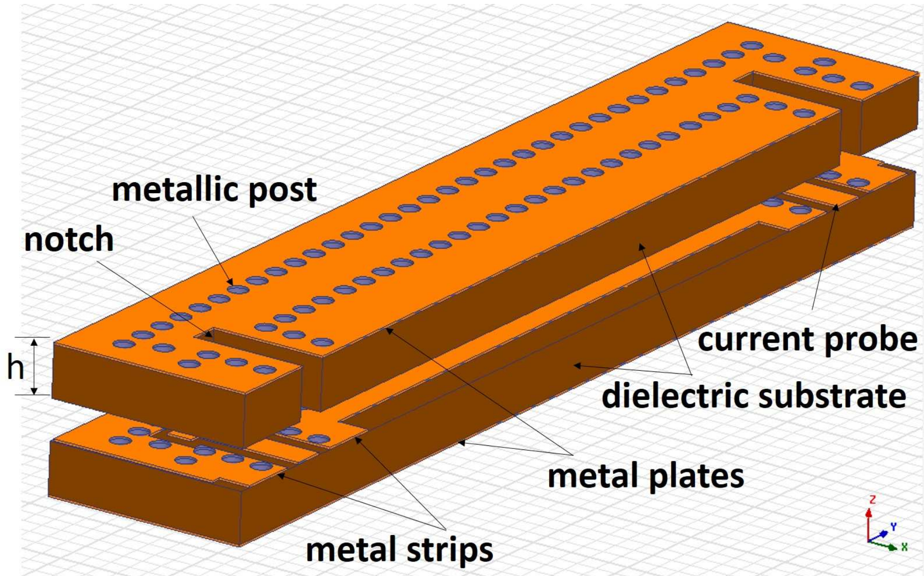


Figure 2.11: Geometry of SIEW with SMA adaptors

matches with the magnetic field inside the proposed waveguide. The longitudinal cross-sectional view at the middle of the SMA adaptor is shown in Fig. 2.12 . The length of the current probe is designed to be 5.29mm, and step is introduced at the end of the probe for the impedance matching. The gaps between the middle strips and the current probe is 0.85mm. In order to consider the impedance matching between the proposed waveguide and the SMA connector in simulation, a SMA connector is built in this project. Fig. 2.13 shows that the geometry of the SMA adaptor section of the proposed SIEW connected to the SMA connector in HFSS. Good impedance matching can be observed in the result shown in Fig. 2.14 , where return loss of the geometry shown in the figure is lower than 20dB and insertion loss of it is close to 0dB.

To finally confirm the performance of the waveguide, a geometry of it including the waveguide section and the SMA adaptor connected to two SMA connectors is built in HFSS and is shown in Fig. 2.15 . In Fig. 2.16 , the simulated S-parameters with return loss at around 20dB and insertion loss close to 0dB shows that good

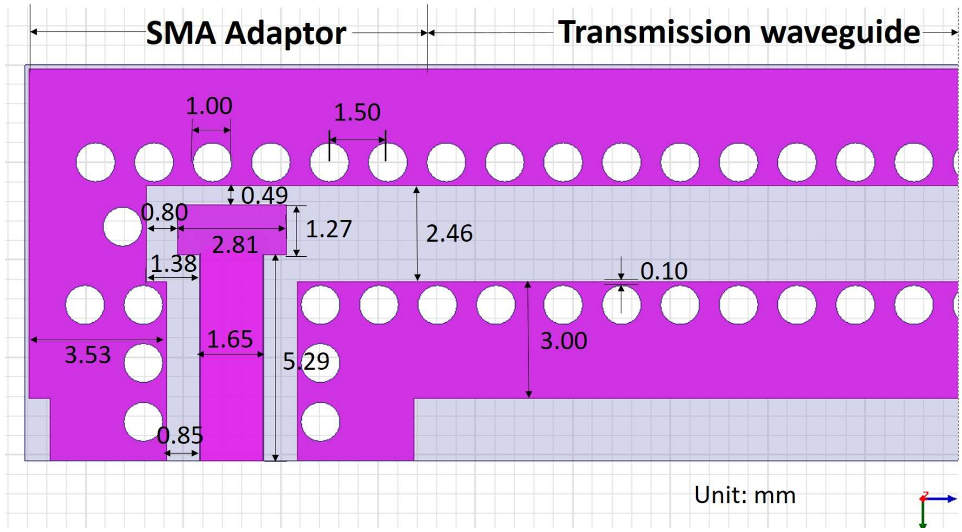


FIGURE 2.12: The longitudinal cross-sectional view of SIEW with the SMA adaptor

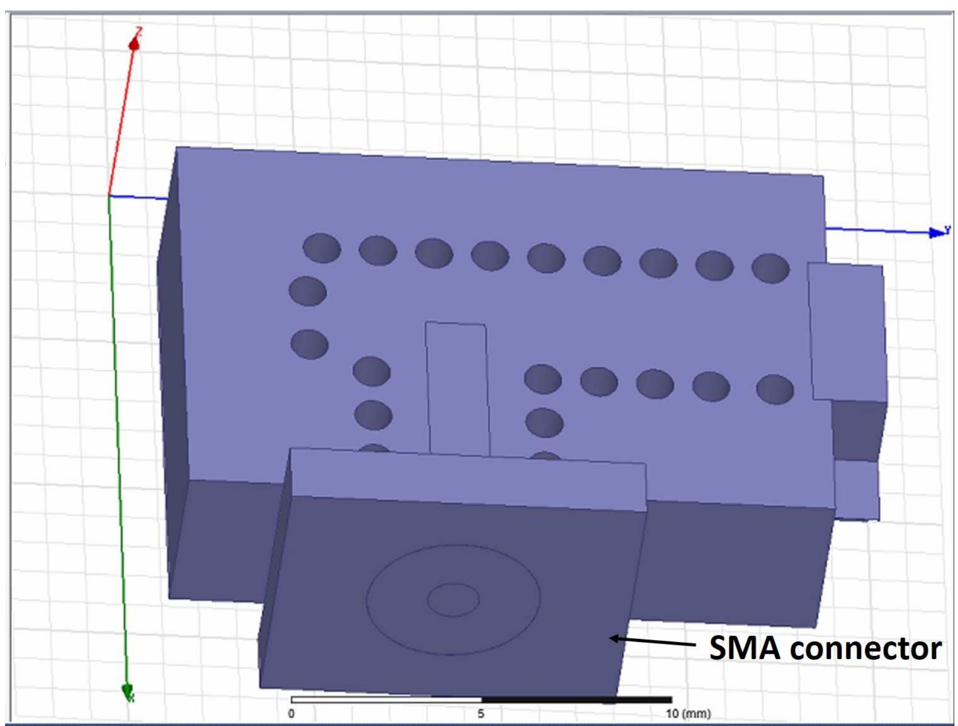


FIGURE 2.13: Geometry of SIEW SMA adaptor with SMA connector

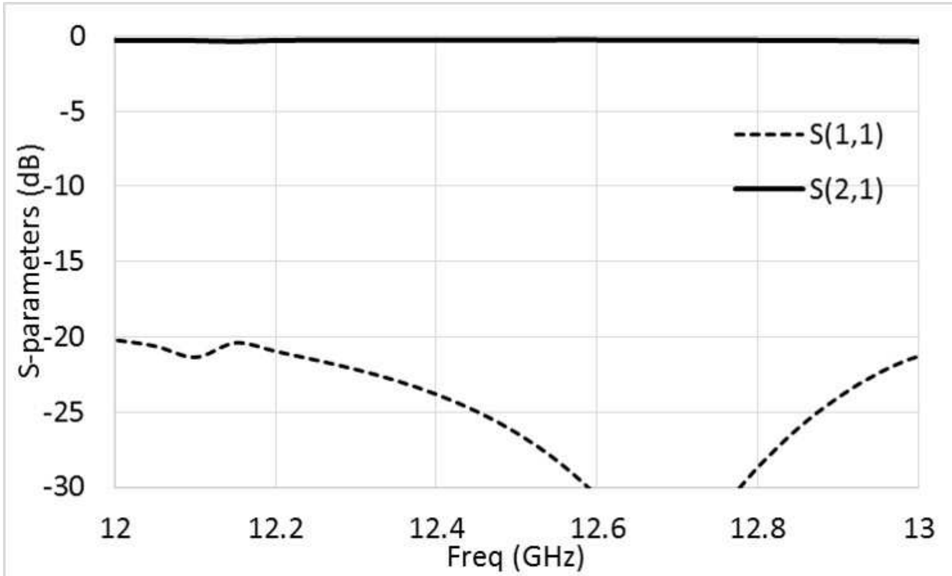


Figure 2.14: Simulated S-parameters of SIEW SMA adaptor with SMA connector

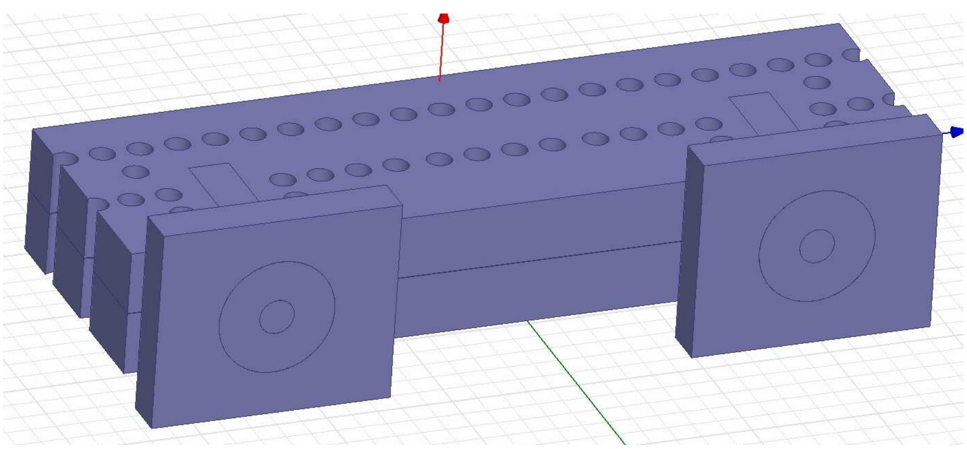


Figure 2.15: Geometry of SIEW with two SMA connectors

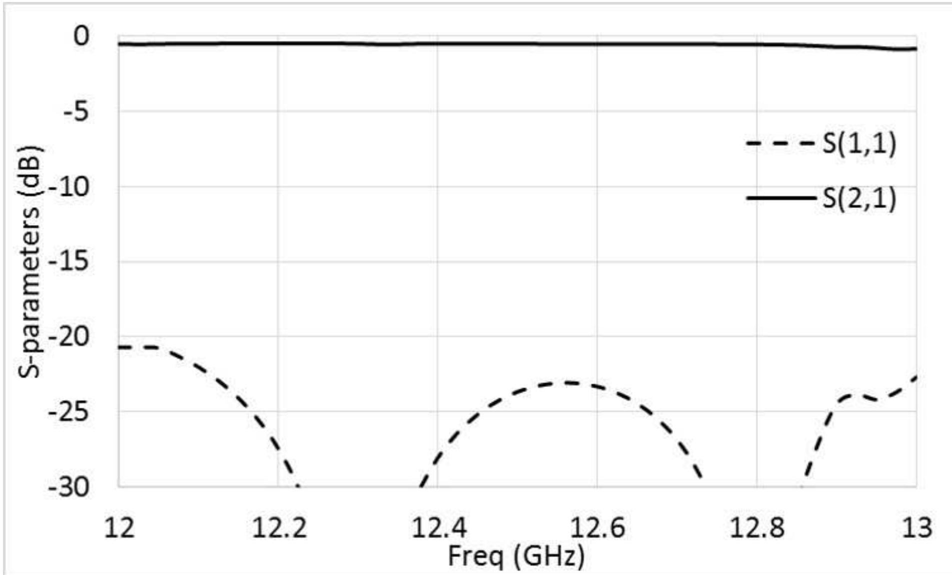


Figure 2.16: S-parameters of SIEW with two SMA connectors

impedance matching between each part can be expected in practice.

3 Substrate integrated E-plane waveguide related designs

3.1 SIEW E-plane filters

In microwave engineering, bandpass filters are used to transmit an incoming signal with low loss in a specified frequency range and to suppress the remaining spectrum in other frequency. Among them,bandpass filters realized in dominant-mode rectangular waveguide receive particular attention due to their simple geometry and fabulous performance. These filters are made in rectangular waveguide by introducing discontinuities in between. Various types of rectangular waveguide H-plane bandpass filters have been realized in substrate integrated waveguide structure and discussed in the first chapter of this paper. Waveguide E-plane bandpass filters, however, have not been investigated because of the nature limitation of the SIW. In other words, E-plane type of circuits cannot be realized without longitudinal currents on side-walls. In this section, an E-plane inductive septa filter, two one-dimensional E-plane offset waveguide filters, and an air-filled evanescent-mode bandpass filter are realized based on the SIEW structure, and the simulation results are also shown in it.

3.2 E-plane inductive septa filter design

The simplest way to realize bandpass filter in waveguides is to introduce obstacles with small longitudinal dimensions. Those obstacles include posts, windows, and metal septa. A third-order E-plane inductive septa filter based on the SIEW structure is proposed and its geometry is shown in Fig. 3.1 . As can be seen in the figure, five pieces of copper septa are inserted at the same layer as the middle strips inside of the substrate. The simulated S-parameters are plotted in Fig. 3.2 , where the return loss is better than 20dB in the pass-band of 12.4-12.7GHz and

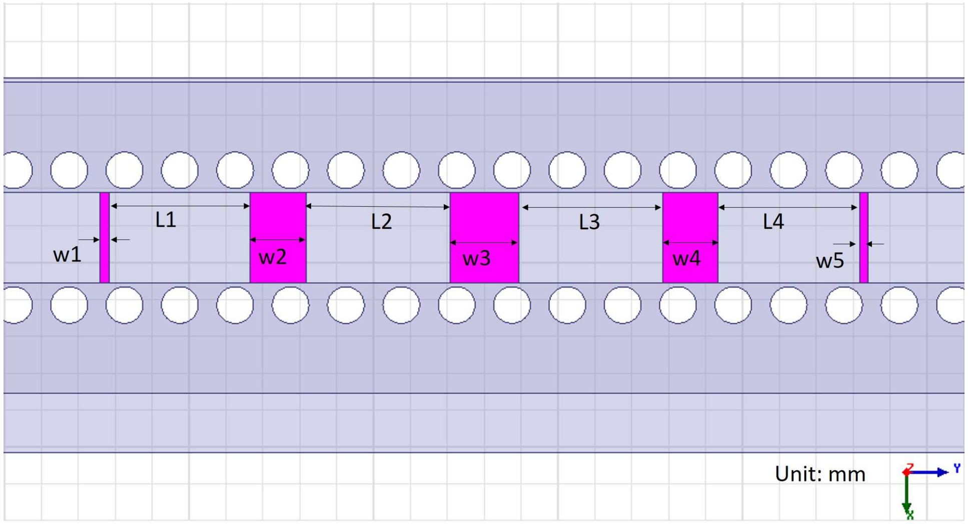


FIGURE 3.1: the longitudinal cross-sectional view of the proposed inductive septa filter

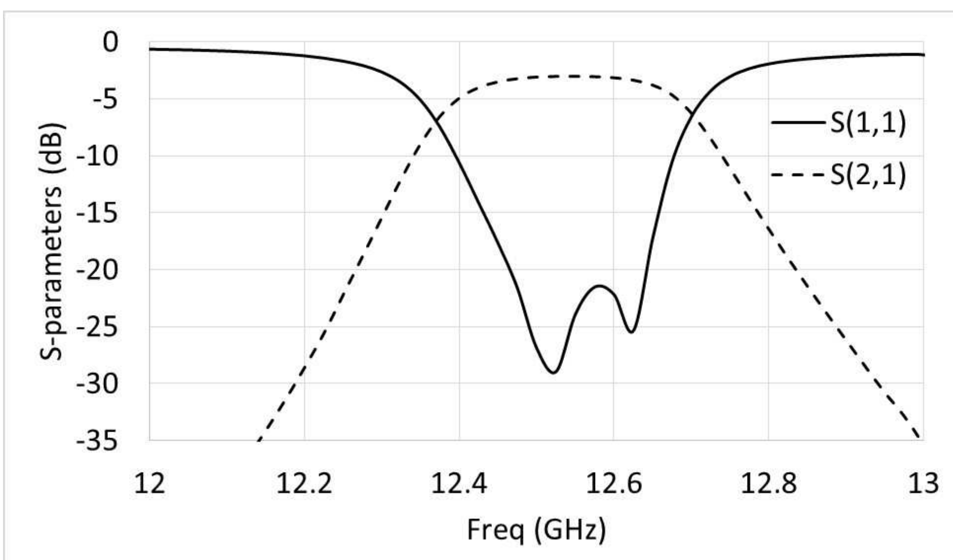


FIGURE 3.2: S-parameters of the proposed inductive septa filter

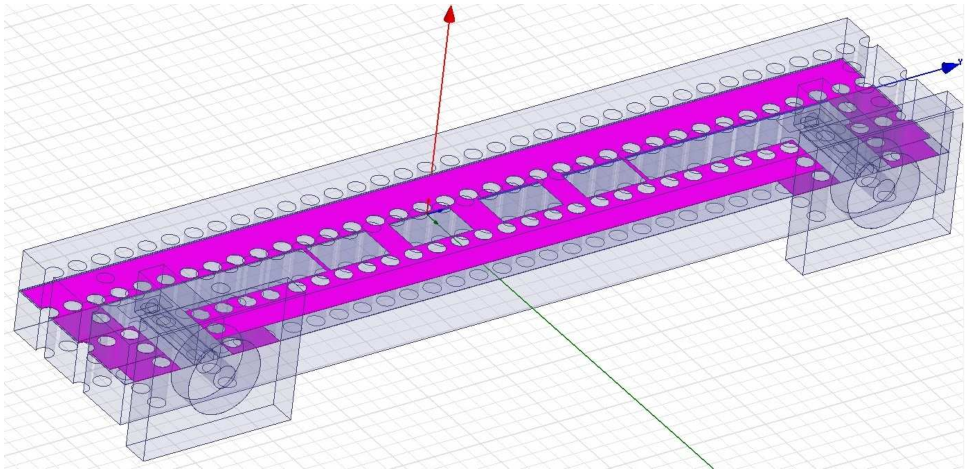


FIGURE 3.3: Geometry of the proposed inductive septa filter with SMA adaptors

the insertion loss is at around 3dB in the pass-band. The insertion loss is mainly due to the dielectric loss of the substrate. Fig. 3.3 shows the proposed filter with SMA adaptors in HFSS software. Two SMA connectors are also included in this project. The simulated result in Fig. 3.4 shows that the return loss is lower than 15dB and the insertion loss is around 3dB in the pass band.

3.3 One-dimensional E-plane offset waveguide filter design

The waveguide bandpass filters realized by inserting obstacles have acceptable performance in the computer-design aid, however, unnecessary loss caused by the thickness effect has to be considered in practice especially in higher frequency. To overcome this shortcoming, the bandpass filters made inside of the rectangular waveguide with one-dimensional offsets have been proposed by E. Kuhn in 1978 [69]. Design equations for direct-coupled type of one-dimensional E-plane offset filter in the rectangular waveguide are proposed by E. Kuhn in [69] and shown below, and the length of each offset can be found in the table in the paper mentioned above based on the equations:

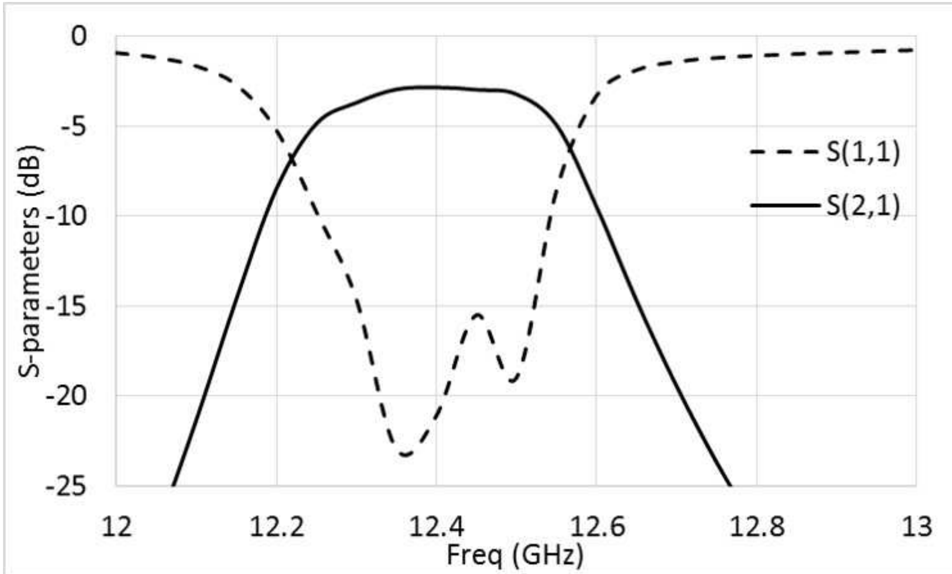


FIGURE 3.4: S-parameters of the proposed inductive septa filter with SMA adaptors

$$|\frac{X_{i0}}{Z}| = \frac{x_i}{1 - x_i^2} \tag{3.1}$$

$$x_i = \begin{cases} \sqrt{(q+1)\frac{\pi}{2}\frac{w_\lambda}{g_{i-1}g_i}} & i = 1, (n+1) \\ (q+1)\frac{\pi}{2}\frac{w_\lambda}{\sqrt{g_{i-1}g_i}} & i = 2, 3, \ldots, n \end{cases} \tag{3.2}$$

$$l_i = \frac{\lambda_{g0}}{2\pi}[(q+1)\pi + \frac{\varphi_i + \varphi_{i+1}}{2}] \quad i = 1, 2, \ldots, n \tag{3.3}$$

$$\varphi_i = -\arctan\frac{2\frac{X_{i0}}{Z} + \tan\frac{2\pi d_{i0}}{\lambda_{g0}}}{1 - 2\frac{X_{i0}}{Z}\tan\frac{2\pi d_{i0}}{\lambda_{g0}}} \tag{3.4}$$

$$d_{i0} = 0 \quad \text{E-plane offsets} \tag{3.5}$$

In this section, a one-dimensional E-plane offset waveguide filter is designed and realized based on the SIEW structure. The configuration of proposed filter is shown in Fig. 3.5 . Four offsets along E-plane in the SIEW are introduced so that resonances are formed in between. The simulated S-parameters of the proposed filter are shown in Fig. 3.6 , where the return loss is at around 20dB

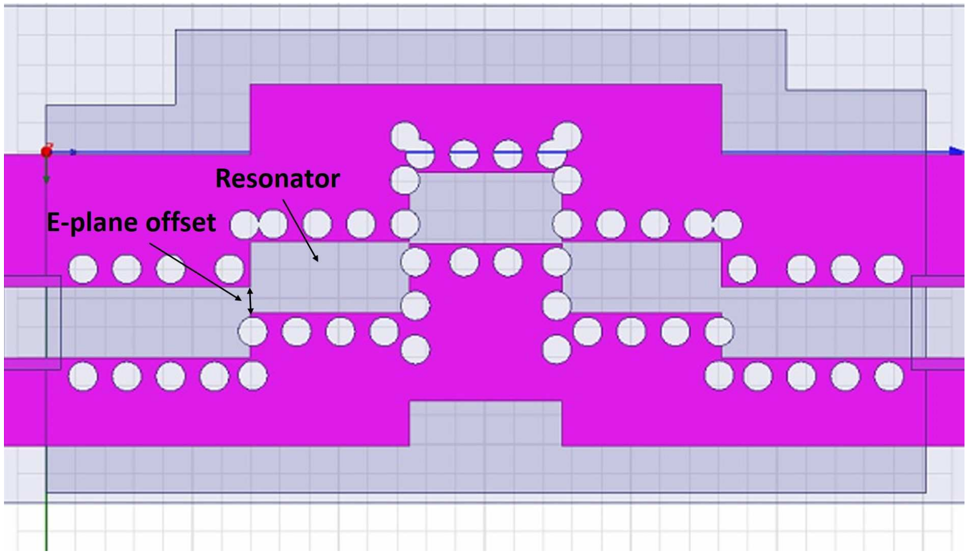


Figure 3.5: Longitudinal cross-sectional view of the proposed E-plane 1-d offset filter

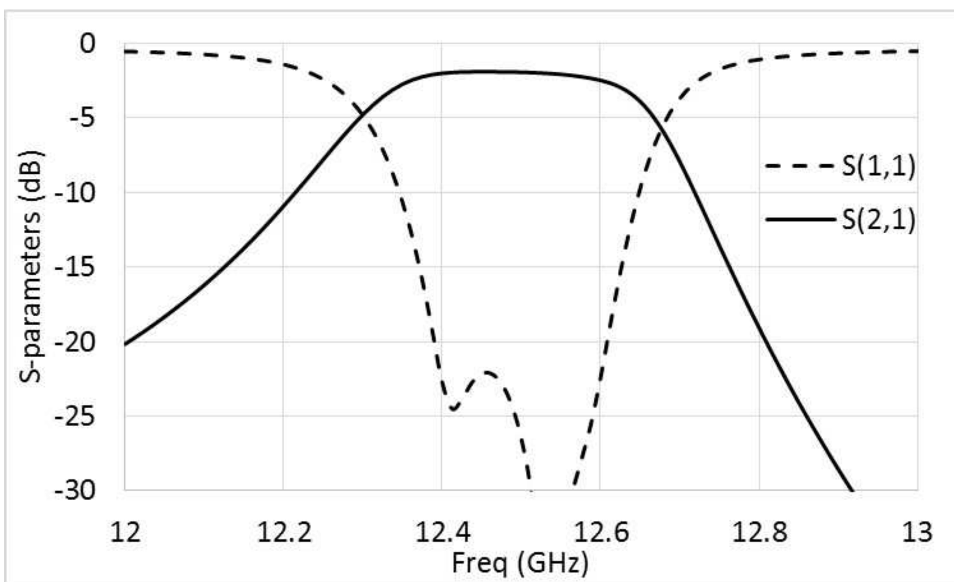


Figure 3.6: S-parameters of the proposed E-plane 1-d offset filter

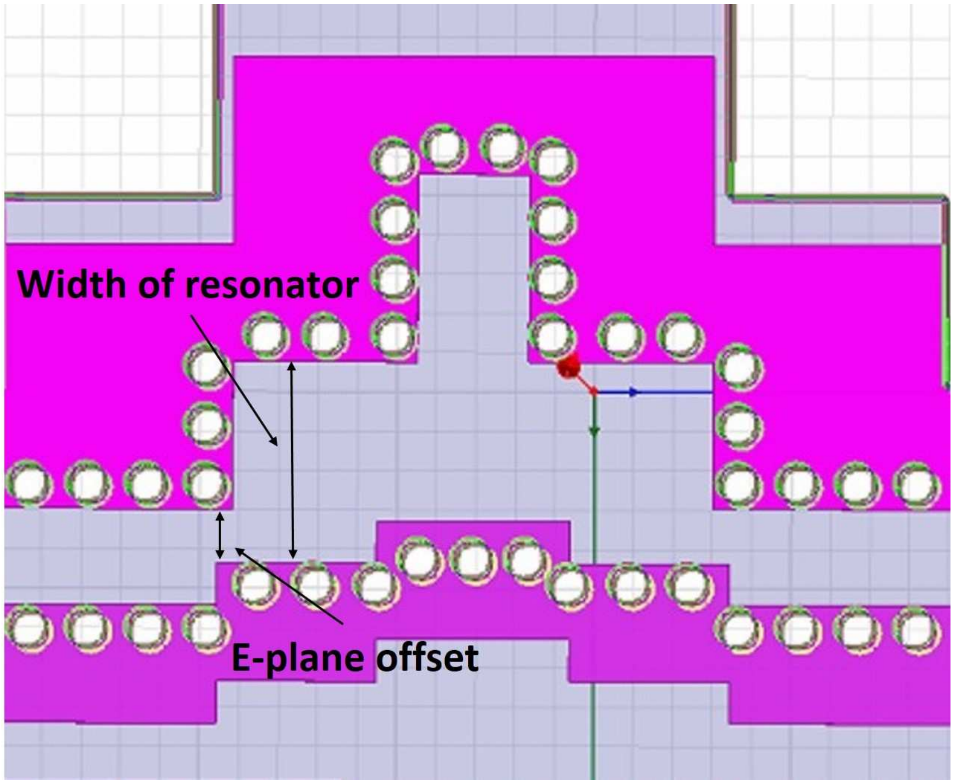


Figure 3.7: Geometry of the second E-plane 1-d offset filter

in the pass-band of 12.3-12.7GHz and the insertion loss is at around 2dB in the pass-band.

Another one-dimensional E-plane offset waveguide filter is designed by optimization method by HFSS. The longitudinal cross-sectional view of proposed design is shown in Fig. 3.7 . In order to have more freedom in the design process, the width of resonances in the SIEW are considered as parameters in the optimization. As a result, the width of three resonances are different in the design. By this way, the opening between two resonators can be wider so that it can be easier to realize in practice. The S-parameters of the design is shown in Fig. 3.8 . The result shows that the return loss is at around 15dB in the pass-band of 12.3-12.7GHz and the insertion loss is at around 2dB in the pass-band.

The geometry of the filter with connection to SMA adaptors is drawn in Fig.

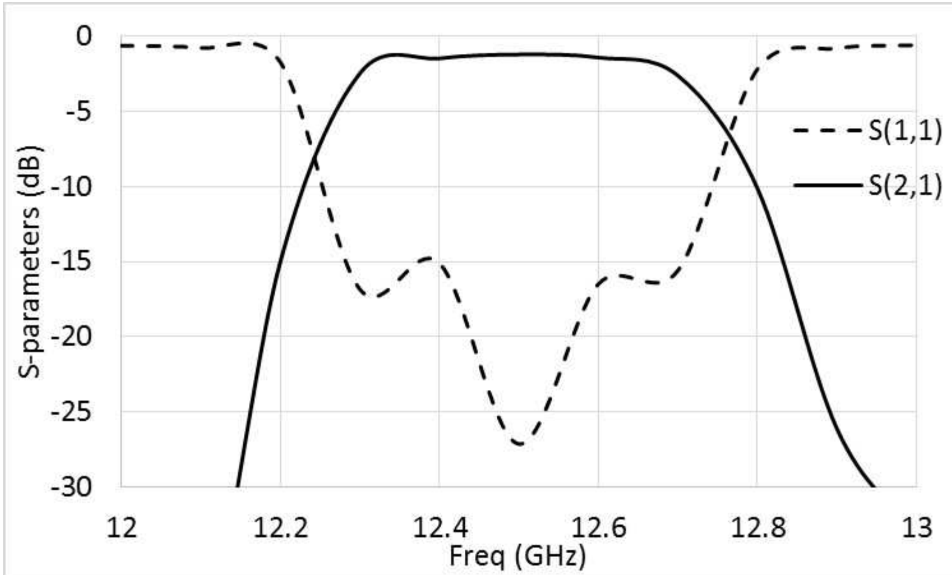


FIGURE 3.8: S-parameters of the second E-plane 1-d offset filter

3.9 , and the simulation result of it is plotted in Fig. 3.10 . When two SMA connectors are also included in the project, the performance in terms of return loss improves to be around 20dB, which is acceptable and can be fabricated in the future.

3.4 Air-filled evanescent-mode bandpass filter design

Considering the insertion loss caused by dielectric loss of the substrate, another third-order air-filled evanescent-mode bandpass filter is designed based on the SIEW structure. The configuration of the proposed filter is illustrated in Fig. 3.11 . As can be seen in the figure, five different size of cuboid areas are hollowed out inside of the waveguide. The size of the hollow areas are carefully designed so that only the electromagnetic wave in specific frequency range can pass through the waveguide. The wave in other frequency points will be in evanescent mode due to the dielectric constant difference between air-filled area and substrate of the printed circuit board. The size and position of these air-filled blocks is pinpointed in the longitudinally cross-sectional view of proposed filter in Fig. 3.12 . In par-

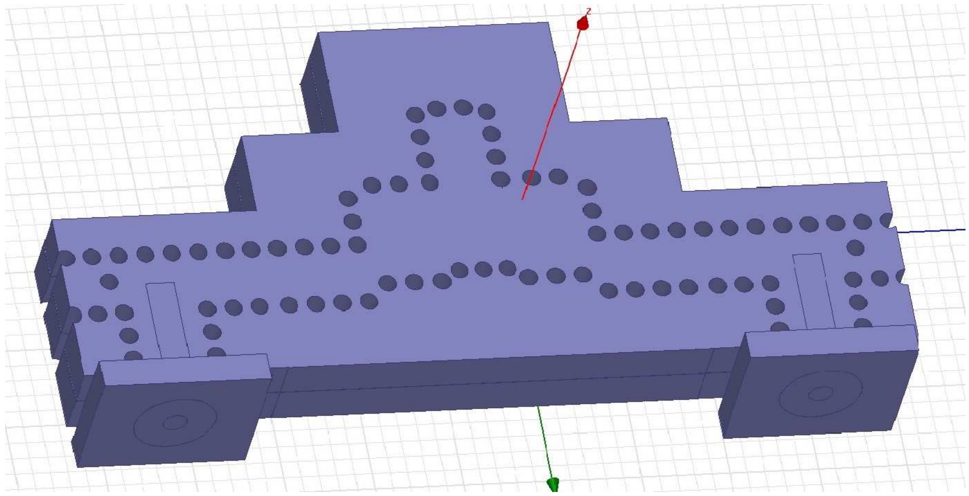


Figure 3.9: Geometry of the second E-plane 1-d offset filter with SMA adaptors

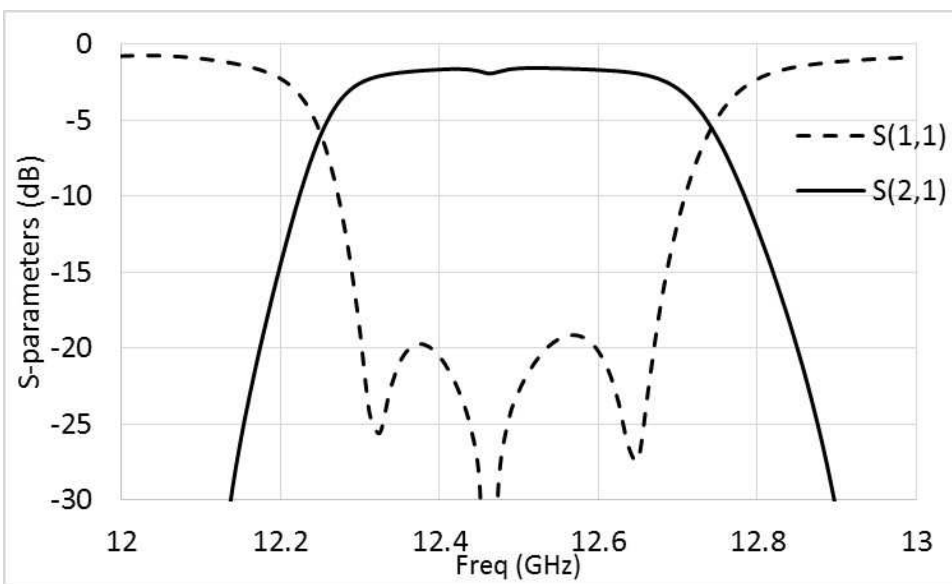


Figure 3.10: S-parameters of the second E-plane 1-d offset filter with SMA adaptors

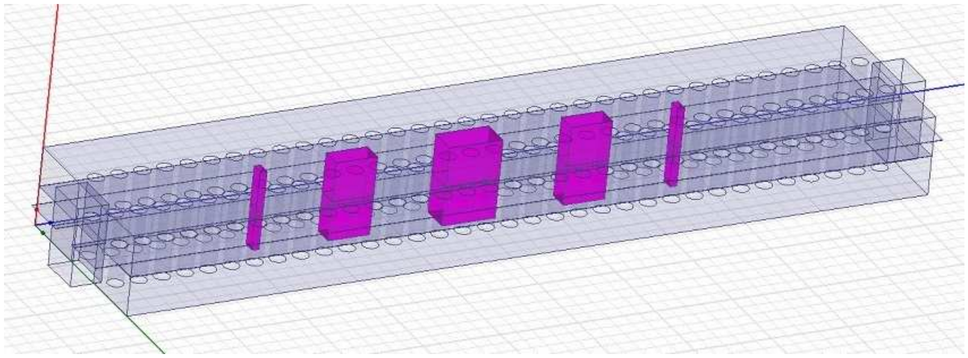


FIGURE 3.11: Geometry of the air-filled evanescent-mode bandpass filter

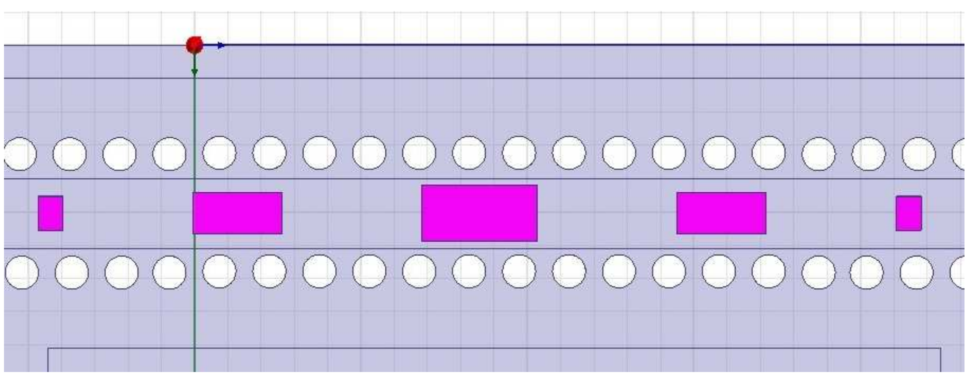


FIGURE 3.12: The longitudinally cross-sectional view of the air-filled evanescent-mode bandpass filter

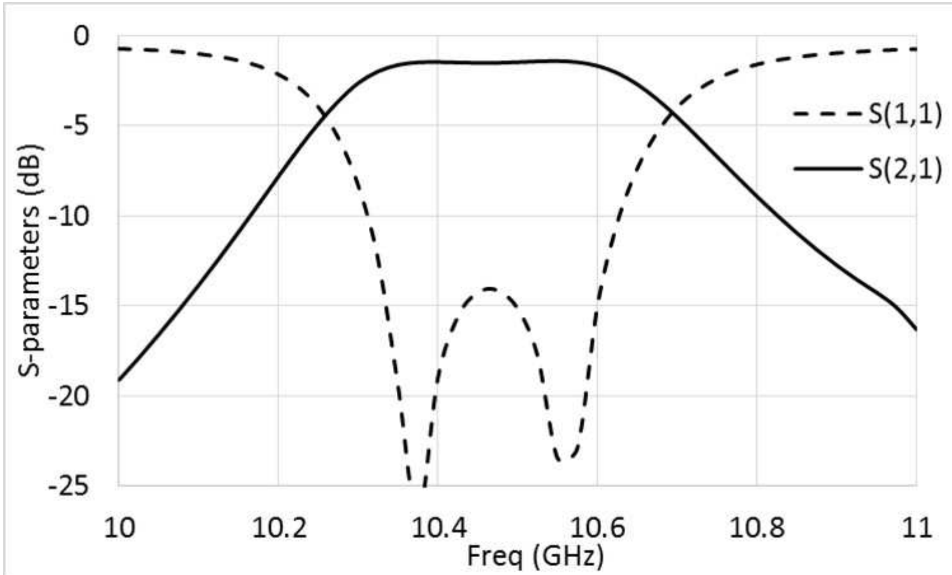


FIGURE 3.13: S-parameters of the air-filled evanescent-mode band-pass filter

ticular, the thickness of all air blocks is designed to be 5.08mm the same as the thickness of the proposed waveguide. The top surface and bottom surface of those air blocks are covered by copper sheets, so that energy cannot radiate out from the circuit. The simulated S-parameters of the proposed filter are shown in Fig. 3.13 , where the return loss is better than 15dB in the pass-band of 10.3-10.7GHz and the insertion loss is at around 2dB in the pass-band.

The geometry of such evanescent-mode filter connected to SMA adaptors is also simulated in HFSS and drawn in Fig. 3.14 . When two SMA connectors are combined with the filter, the simulated result of it in Fig. 3.15 shows that the return loss improves to 20dB, and the insertion loss remains the same as 2dB.

Considering the difficulty of cutting a right angle inside the material in practice, all the rectangular air-filled blocks are changed to fillet angles, and the radius of which is according to American wire gauge (AWG). The longitudinal cross-sectional view of the modified filter and the size of those blocks after optimization is shown in Fig. 3.16 . The smallest blocks are directly changed to cylindrical

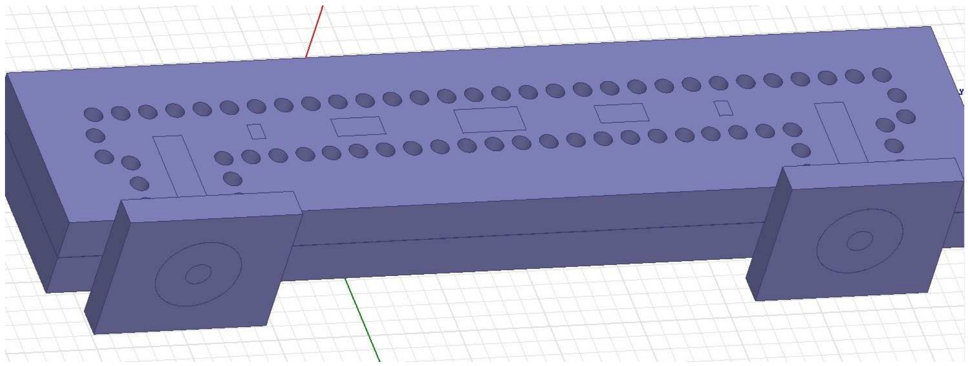


Figure 3.14: Geometry of the air-filled evanescent-mode bandpass filter with SMA adaptors

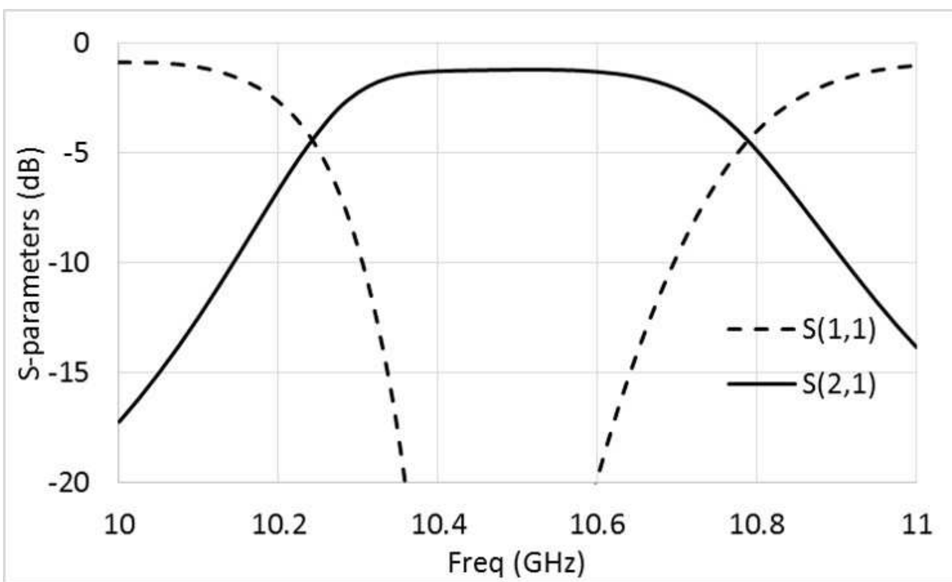


Figure 3.15: S-parameters of the air-filled evanescent-mode bandpass filter with SMA adaptors

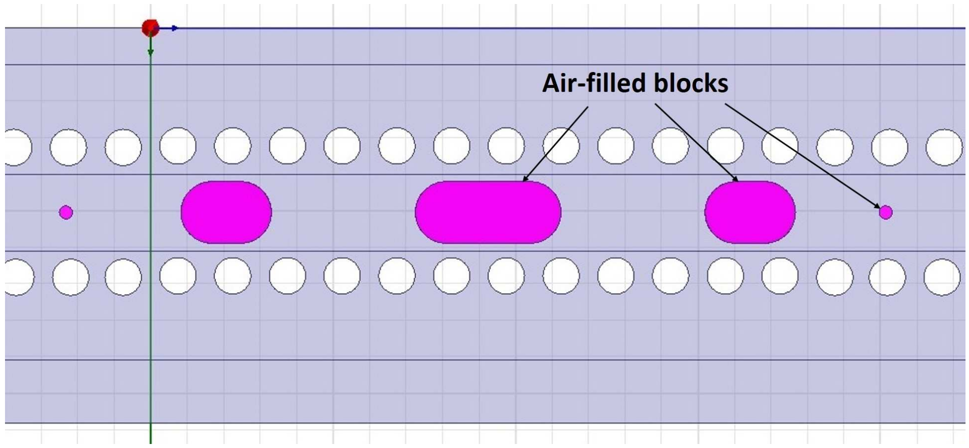


Figure 3.16: The longitudinal cross-sectional view of the fillet air-filled evanescent-mode bandpass filter

blocks. The simulated S-parameters of the filter connected to the SMA adaptors and SMA connectors are illustrated in Fig. 3.17 . The result shows that the return loss is around 18dB in the pass band and the insertion loss is around 1.5dB.

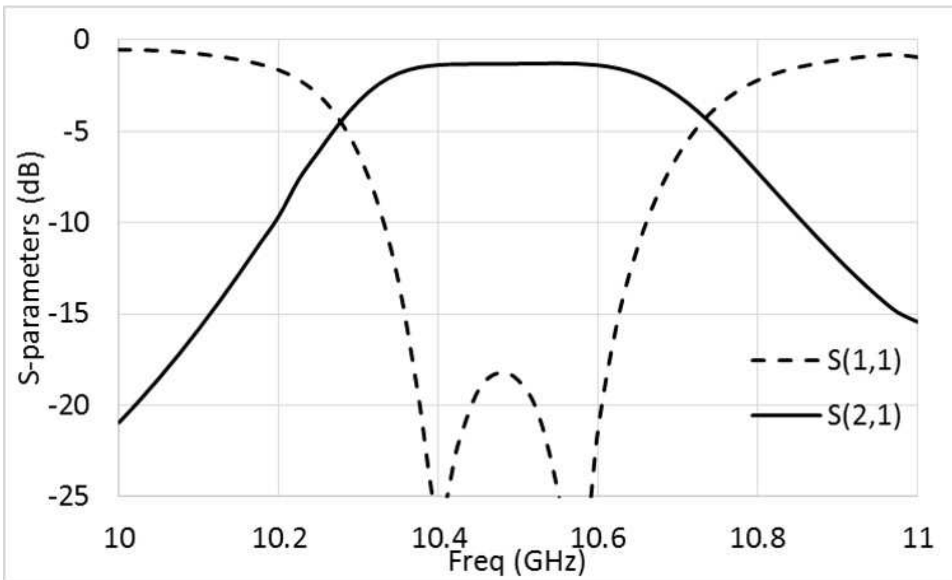


FIGURE 3.17: S-parameter of the fillet air-filled evanescent-mode bandpass filter

4 Conclusion

In this paper, the concept of substrate integrated E-plane waveguide is proposed. The novel waveguide structure is built by attaching two printed circuit boards. Two copper strips are sandwiched between the two boards with two rows of plated through holes penetrating through the strips. The waveguide supports the propagation of wave with the circuit boards serving as E-plane, which cannot be achieved by using the substrate integrated waveguide structure due to the leakage between via holes. An substrate integrated E-plane waveguide is designed in this work for frequency range from 12 to 13GHz. Simulation shows good return loss at 40dB and insertion loss close to 0dB. Further more, to prove that the waveguide can be fabricated and measured, an SMA adaptor is designed in order to connect the SMA connector. The simulated return loss of 20dB and insertion loss of 0dB can be observed, which is acceptable for wave transmission. In order to prove that the proposed waveguide is applicable for rectangular E-plane waveguide designs, an inductive septa filter, two different types of one-dimensional E-plane offset waveguide filter, and an air-filled evanescent-mode filter are designed based on the substrate integrated E-plane waveguide. Acceptable results can be observed on all the designs when connected to SMA adaptors. It is expected that all of them can be realized in practice. It is also expected that other E-plane type of rectangular waveguide circuits can be implemented on printed circuit boards using this novel PCB based E-plane waveguide structure.

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