SIW-Like Guided Wave Structures and Applications

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SUMMARY   In this paper, the research advances in SIW-like (Substrate Integrated Waveguide-like) guided wave structures and their applications in the State Key Laboratory of Millimeter Waves of China is reviewed. Our work is concerned with the investigations on the propagation characteristics of SIW, half-mode SIW (HMSIW) and the folded HMSIW (FHMSIW) as well as their applications in microwave and millimeter wave filters, diplexers, directional couplers, power dividers, antennas, power combiners, phase shifters and mixers etc. Selected results are presented to show the interesting features and advantages of those new techniques.
key words: Substrate Integrated Waveguide (SIW), Half Mode SIW (HMSIW), Folded HMSIW (FHMSIW), microwave components, antennas, mixers

1.   Introduction

The current design trends of the advanced communication, navigation, radio astronomy and radar systems etc. are oriented towards low cost, low weight, small size and high-density integration without compromise on their performances. Microwave and millimeter-wave transmitter and receiver as well as antenna are fundamental building components and they are usually bulky in these systems. Therefore, the miniaturization of related subsystems becomes crucial to achieve those design goals. It is known that guided-wave structures have been instrumental to the development of microwave and millimeter-wave circuits. Classical guided-wave structures, such as rectangular waveguide, coaxial line and circular waveguide possess the advantages of low insertion loss, high power handling capability and excellent reliability. However, such non-planar structures make them impossible to be integrated with RFICs and other planar circuits in co-planar form. Microstrip, slot-line, coplanar waveguide (CPW) and other planar derivatives are planar guided-wave structures, which can easily be integrated together with RFICs and other microwave and millimeter-wave planar circuits in the planar form. However, they are known to suffer from the high insertion loss, radiation loss, serious crosstalk, lower power handling capability and other problems. Thus, it is natural to search for and explore new guided-wave structures that should si-

multaneously have the advantages of conventional metallic waveguides and microstrip-like planar transmission lines. One conceivable way is to embed the waveguides into a planar substrate so that the integrated waveguide preserve the low loss, high power handling capability and other related advantages of conventional metallic waveguides and the coplanar integration advantage etc. of microstrip-like transmission lines. Since the last decade, researchers have proposed laminated waveguide based on a multilayered LTCC process [1]–[4], post-wall waveguide for feeding slot array antennas [5]–[8], substrate integrated waveguide (SIW) [9]–[50], half-mode SIW (HMSIW) [51]–[57], folded HMSIW (FHMSIW) [58] and folded SIW (FSIW) [59], [60] among others. Those substrate integrated waveguides present a very popular branch of the substrate integrated circuits (SICs) family, which are composed of any planar and non-planar structures integrated within the same planar substrate. Over hundreds papers have been published so far on substrate integrated guided-wave structures, and only research activities in connection with the development and applications of SIW-like guided wave structures within the State Key Laboratory of Millimeter Waves are reviewed and summarized in this paper.

2.   Substrate Integrated Waveguide

2.1   Propagation Characteristics

The configuration of an SIW with transitions to microstrip lines is shown in Fig. 1, where the diameter of metallic vias is d, the spacing between vias is p, the distance between the two rows of metallic vias is designated as W_{siw} which is also defined as the width of SIW, the thickness and permittivity
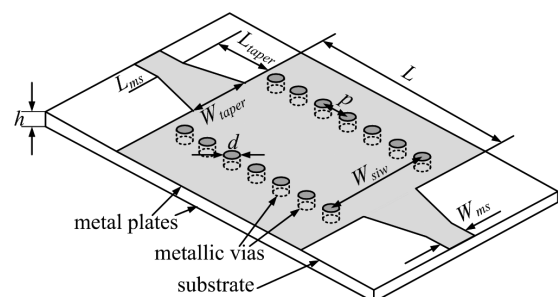
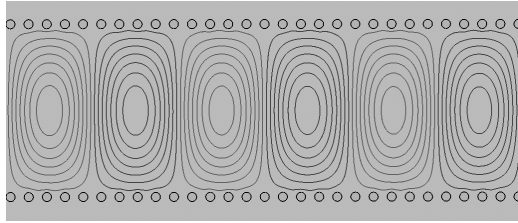**Fig. 1**   Configuration of SIW with transitions to microstrips.

Fig. 2 Quasi-TE$_{10}$ mode in an SIW.

of the dielectric substrate are h and ε_r, respectively, W_{ms} is the width of input and output microstrip lines whose characteristic impedance is generally set to be $50\,\Omega$, L_{taper} and W_{taper} are the length and width of the microstrip tapers made for matching the input/output microstrip lines to the SIW.

A rectangular tunnel is surrounded by the two rows of metallic vias and the top and bottom copper foils of the substrate. The tunnel is then equivalent to a dielectric-filled rectangular waveguide, where the two rows of metallic vias are equivalent to its side walls. If the diameter and spacing of the metallic vias meet some design restrictions, the energy leakage from the gaps between vias could be too weak to be considered. Simulated field distribution of the dominant quasi-TE$_{10}$ mode in the SIW is shown in Fig. 2.

In order to ensure a neglectable leakage from the gaps between vias, the SIW geometrical parameters of the SIW should satisfy the following relations [11].

$$p > d, \quad \frac{p}{\lambda_c} < 0.25, \quad \frac{p}{\lambda_c} > 0.05 \tag{1}$$

Propagation characteristics of SIW and SINRD (Substrate Integrated Non-Radiative Dielectric Guide) have been investigated by a number of researchers, which have been documented in [12]–[16]. In [13], the propagation characteristics are analyzed by using the Method of Lines (MoL), and the equivalent relationship between the SIW and its dielectric filled rectangular waveguide (RWG) counterpart is given through a defined normalized width

$$\bar{a} = \frac{W_{RWG}}{W_{SIW}} = \xi_1 + \frac{\xi_2}{\dfrac{p}{d} + \dfrac{\xi_1 + \xi_2 - \xi_3}{\xi_3 - \xi_1}} \tag{2}$$
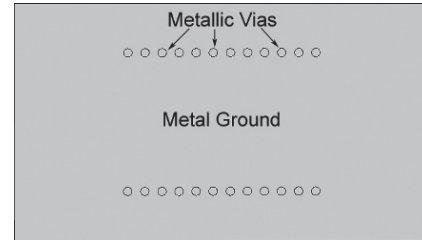
where

$$\xi_1 = 1.0198 + \frac{0.3465}{\dfrac{W_{SIW}}{p} - 1.0684}$$

$$\xi_2 = -0.1183 - \frac{1.2729}{\dfrac{W_{SIW}}{p} - 1.2010}$$

$$\xi_3 = 1.0082 - \frac{0.9163}{\dfrac{W_{SIW}}{p} + 0.2152}$$

The propagation characteristics of an SIW can then be calculated based on the classical formulae for its counterpart of the equivalent dielectric filled RWG with the same height as
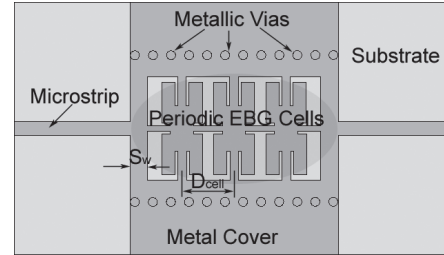
(a) Top surface

(b) Bottom surface

Fig. 3 SIW-PBG wideband filter.

the substrate thickness and the equivalent waveguide width $W_{RWG} = \bar{a} \cdot W_{SIW}$. Using such equivalent relationships would greatly simplify the design procedure of SIW components. We can often start with the well-established design procedures for the equivalent RWG counterpart, and finally generate accurate results by applying full-wave EM simulation software packages directly to the original SIW structures. In [13], an empirical formula for the attenuation constant was also presented as

$$\alpha = 10^{\zeta_1 + \frac{\zeta_2 - \zeta_1}{\frac{p}{d} - 0.75}} \tag{3}$$

where

$$\zeta_1 = -4.6 + \frac{26}{\dfrac{W_{SIW}}{p} + 4.5}, \quad \zeta_2 = -7.7 + \frac{11}{\dfrac{W_{SIW}}{p} + 1.1}$$

2.2 SIW Filters and Diplexers

Filters and diplexers are key components in microwave and millimeter wave systems for frequency selection and suppression of harmonics. Based on SIW technology and normal PCB process, various types of filters [17]–[23] and diplexers [24], [25] were developed in our lab, and some typical filters will be discussed in this paper. Utilizing the cutoff frequency (high-pass) property of SIW and the stopband characteristics of periodic elements etched on the top metallic surface of the SIW, an ultra-wideband bandpass filter was proposed and developed in [17]. The geometrical configuration and frequency responses of the filter are shown in Fig. 3 and Fig. 4, respectively.

A C-band filter of elliptic response with four folded SIW cavities was designed and implemented with a two-layer PCB process [19]. The configuration and response of
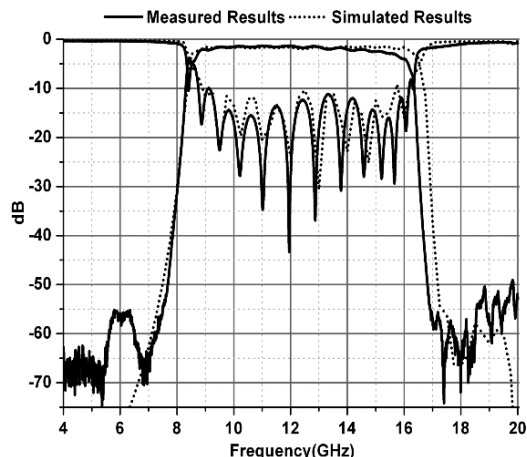
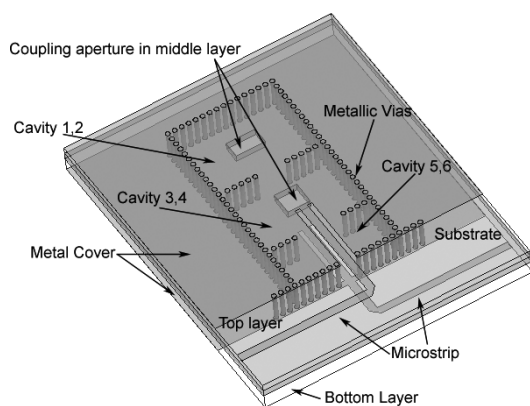**Fig. 4** Measured and simulated results of the filter with eleven cells.

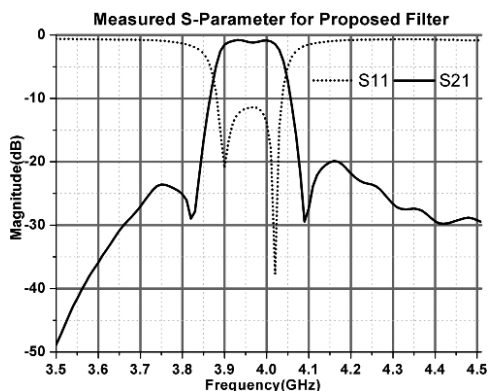**Fig. 5** Configuration of a two-layer folded SIW elliptic filter.

Fig. 6 The measured frequency responses of the folded SIW filter.

Fig. 7 SIW equivalent inductive-post filter.

Fig. 8 Simulated and measured results of a five-pole SIW equivalent inductive-post filter.

the filter are shown in Fig. 5 and Fig. 6, respectively. The center frequency is 3.96 GHz, the measured maximum insertion loss in the passband is about −0.6 dB, and the return loss in the passband is less than −12 dB.

A novel equivalent inductive-post SIW filter was proposed in [23], in which the diameter of equivalent inductive posts can be changed continuously and then we can obtain the optimal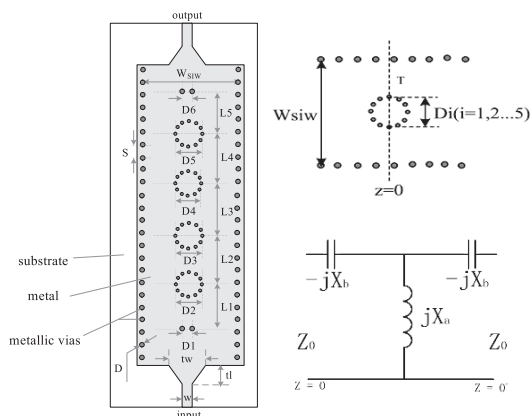 solution. The configuration of the filter, the equivalent inductive posts and their equivalent circuits are shown in Fig. 7. The measured response of a design example is shown in Fig. 8.
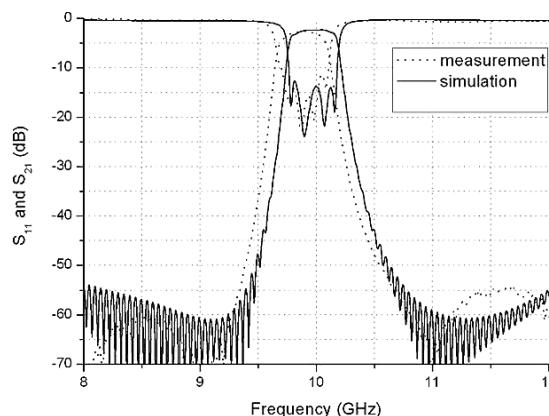
It is known that the upper side response of a filter with circular cavity is relatively steep while the lower side steep response of a filter can be achieved with elliptic cavities. Based on this complementary character of SIW dual-mode filters with circular and elliptic cavities, a high performance millimeter-wave diplexer was designed and implemented in [25], which has successfully made a tradeoff between the isolation, insertion loss and selectivity. The configuration and measured responses are shown in Fig. 9 and Fig. 10, respectively. The measured insertion losses are 2.09 dB and 1.95 dB in the upper and lower pass bands centered at 26 GHz and 25 GHz with fractional bandwidths of 5.2% and 5.4%, respectively, and the isolation is better than 50 dB.

The good performance of SIW filters is mainly profited from high quality factor (Q-factor) characteristic of SIW cavities. The Q-factor (roughly 200~500) and external Q-factors (roughly 10~50) of SIW cavities (rectangular, circular, elliptic etc.) are usually several times higher than that of microstrip-like resonators [18],[25]. The external Q-factor reported in [61] is around 4.5–16 for a pseudocombline resonator and is around 4.5–8.5 for a hairpin-line resonator.
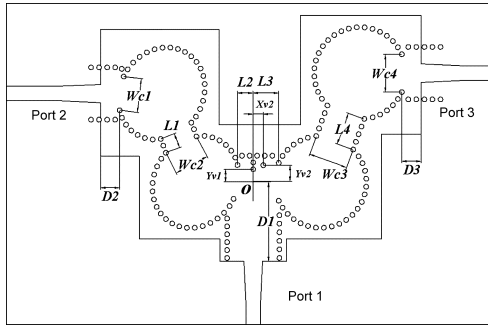
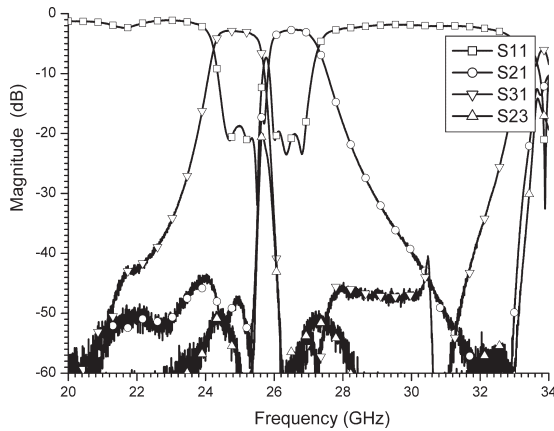**Fig. 9**   SIW diplexer with circular and elliptic dual-mode cavities.

Fig. 11   SIW fed ATLSA array.
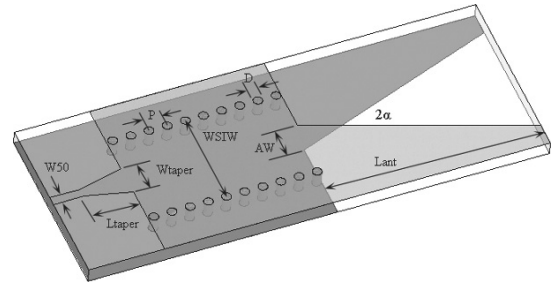

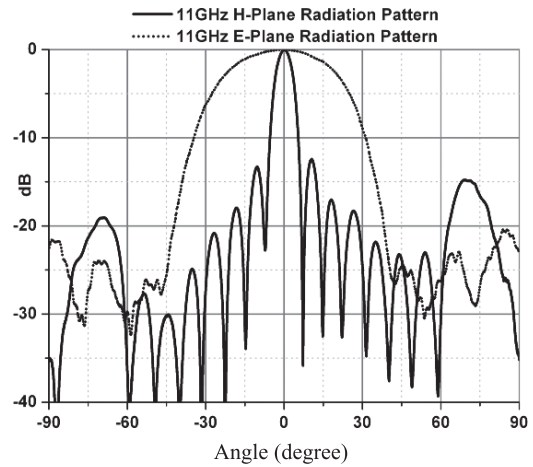**Fig. 10**   Measured responses of the SIW diplexer.

Fig. 12   Measured radiation patterns of SIW fed 1×8 ATLSA array.

2.3   SIW Antennas and Arrays

The miniaturization of antennas and arrays is an important issue for reducing the size of wireless systems. SIW antennas and arrays present numerous electrical and mechanical advantages, namely, low-profile, low-cost, mass-producible and planar integration with other planar circuits. Many kinds of SIW antennas have been investigated and some of the authors' works on SIW antennas and arrays [26]–[37] are reviewed in this section.

In view of the equivalence between RWG and SIW, the RWG slot array antennas could be naturally replicated in the form of SIW slot array antennas [26] but with planar form. The unbalanced microstrip is transformed into a balanced feeding structure for antipodal linearly tapered slotted antenna (ATLSA) simply through a section of SIW [27] as shown in Fig. 11. The measured radiation patterns of a 1×8 SIW fed ATLSA array is shown in Fig. 12. Since there are eight elements in the E-Plane, the 3 dB beam-width of E-plane radiation pattern is around $5°$, and that of the H-plane radiation pattern is around $48°$. The measured gain at 11 GHz for this antenna is around 19 dBi. This kind of antenna array was also applied to the design of a rectenna.

With the high fabrication precision of PCB process, SIW low sidelobe slot array antenna can easily be realized in a similar way to the conventional RWG case [29], [30].
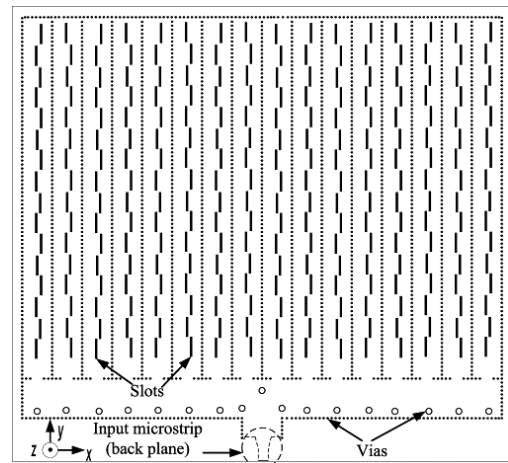

Fig. 13   A 16×16 SIW low sidelobe slot array antenna.

A 16×16 low sidelobe level SIW slot array antenna was designed and implemented with normal PCB process, the layout of the antenna is shown in Fig. 13, its measured and simulated radiation patterns are shown in Fig. 14, where the sidelobe level is lower than -30 dB.

For the purpose of developing a multi-input and multi-output (MIMO) communication application, a multi-beam SIW slot array antenna was proposed in [31] with an SIW Bulter matrix. An SIW array antenna with 24 beams was de-
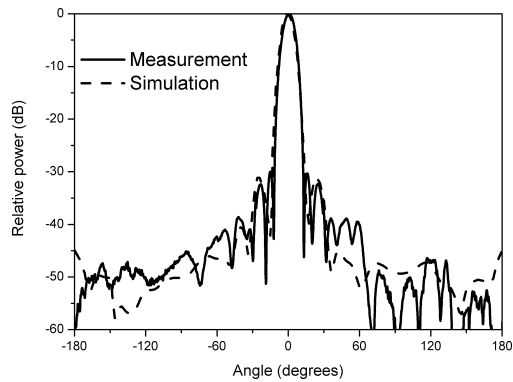
(a) H-plane
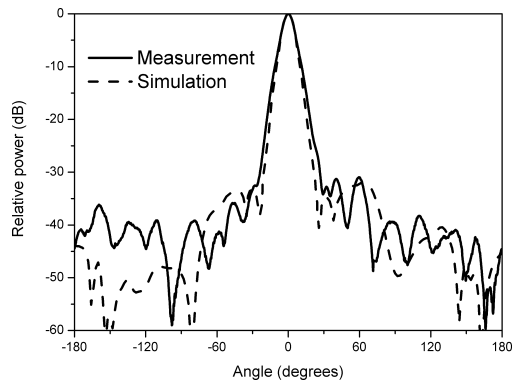
(b) E-plane

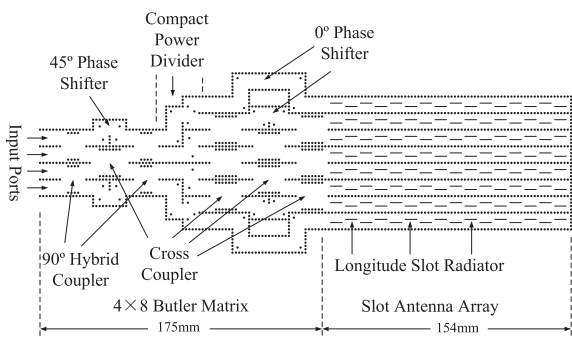**Fig. 14** Measured and simulated radiation patterns at 10 GHz.

Fig. 15 SIW multi-beam slot array antenna with Bulter matrix.

Fig. 16 Measured E-plane patterns of the 24-beams antenna at 16 GHz.

Fig. 17 The PCB of SIW multi-beam antenna based on the parabolic reflector principle. (1. SIW parabolic reflector, 2. SIW slot antenna array, 3. feeding network).
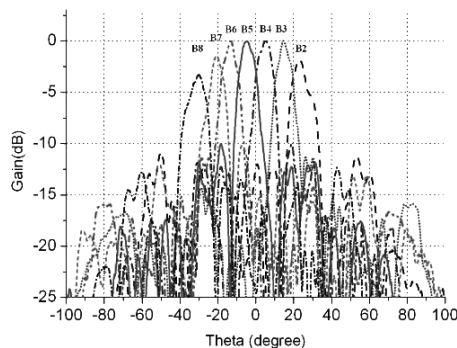
Fig. 18 The measured E-plane radiation patterns of the SIW multi-beam antenna at 37.5 GHz frequency corresponding to each exciting port.

signed, which consists of 6 elements and each of the element (shown in Fig. 15) can generate 4-beams corresponding to 4 input ports of the Bulter matrix. The measured 24 beams are shown in Fig. 16.

Some quasi-optical antennas can also be implemented in a substrate based on the SIW technology [32], [33]. We can even design conformal multi-beam antennas utilizing the flexible property of SIW [32] as shown in Fig. 17, the measured multi-beams are shown in Fig. 18.

Circular polarization (CP) antennas are widely used in satellite communication etc. Based on SIW technology, we have designed and implemented an SIW CP array antenna with 30 dBi gain and −20 dB sidelobe level. The prototype, measured radiation patterns and Axial Ratio (AR) are shown
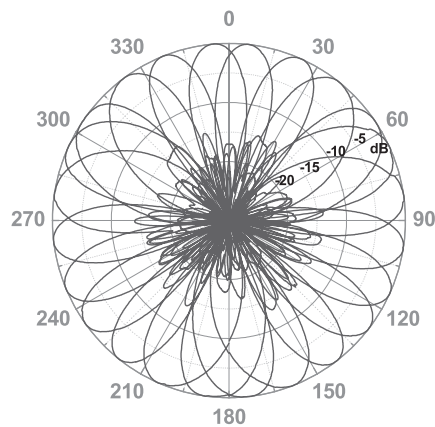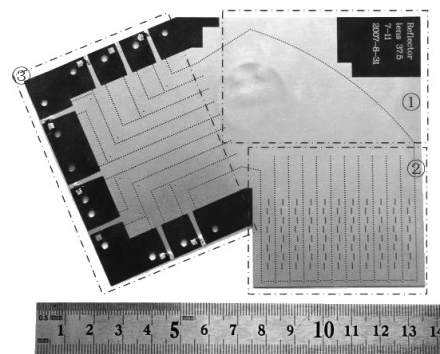
in Fig. 19, Fig. 20 and Fig. 21, respectively. The results for a CP linear SIW slot array antenna were reported in [34].

2.4 SIW Frequency Selective Surface

As a sort of spatial filter, frequency selective surface (FSS) has been widely used in satellite communications and radar radome. It is known that the selectivity of an FSS is mainly determined by the quality factor (Q) of periodic resonant elements. Based on the high-Q property of SIW cavities, sev-

Fig. 19   Prototype of SIW circular polarized planar array.

Fig. 20   Measured radiation patterns at 16.1 GHz.
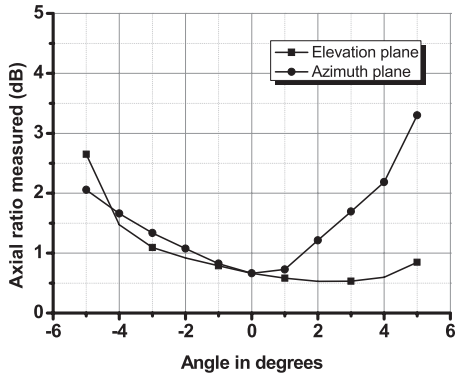
Fig. 21   Measured AR at 16.1 GHz.

Fig. 22   SIW FSS and the periodic element.

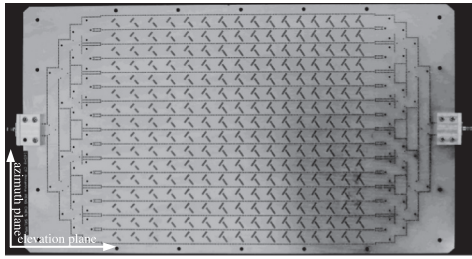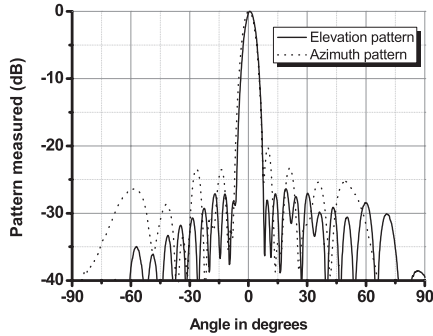

Fig. 23   Simulated and experiment results at normal incidence. (1) **E** perpendicular to y-z plane. (2) **E** perpendicular to x-z plane.
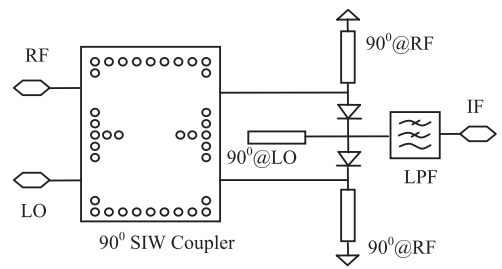
Fig. 24   Configuration of the SIW mixer.
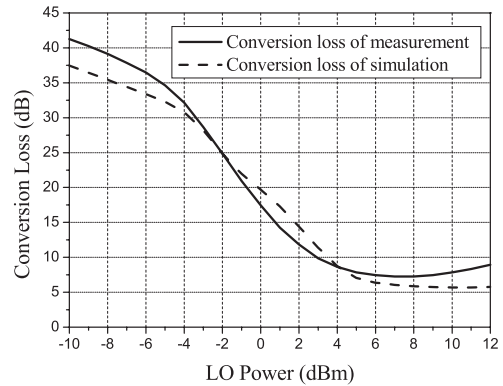
Fig. 25   Conversion loss vs. LO power.

2.5   SIW Active Circuits

SIW technology can also be applied in the design of active microwave and millimeter wave circuits [47]–[50]. Using an SIW directional coupler, an 8.5–12 GHz balanced mixer as shown in Fig. 24 was developed in [47], the measured and simulated conversion losses with respect to LO is shown in Fig. 25.

3.   Half-Mode SIW

It is known that when an SIW works only in the dominant mode, the symmetrical plane can be equivalent to a perfect magnetic wall. On this idea, we can bisect the SIW with a fictitious magnetic wall along its symmetrical plane, and
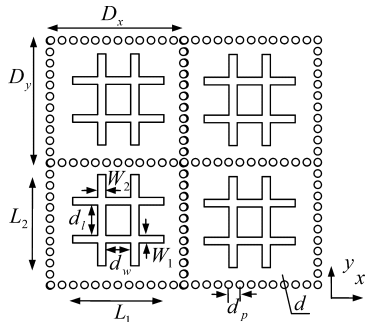
eral types of FSS were deigned and implemented [38]–[45]. A typical FSS with SIW cavity and slot apertures is shown in Fig. 22, and its measured response is shown in Fig. 23 [38].
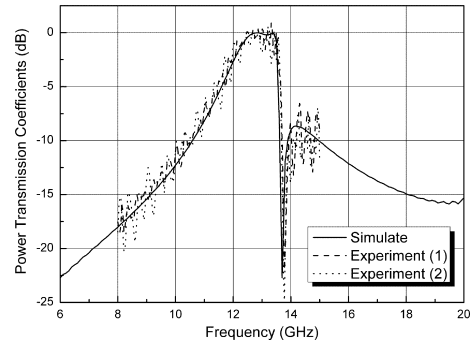
Fig. 26 Dominant mode field distribution in HMSIW and SIW.

each half of the SIW becomes an HMSIW structure [51], which can almost keep the original field distribution in its own part and be considered to support the half guided wave modes. Both simulation and experiment results show that the energy leakage from the open side of an HMSIW could be neglected if the width to height ratio (WHR) is larger than 10. The configurations and dominant mode distributions of HMSIW and SIW are shown in Fig. 26. It can be seen that the size of HMSIW is only around half the size of the original SIW, which may also result in the decrease of conducting and dielectric losses. Besides, since HMSIW cannot support TE_{20} mode as in an SIW, it will possess wider dominant operation bandwidth than SIW.

Similar to the SIW, we can also design and implement various kinds of microwave and millimeter wave components based on HMSIW technology [52]–[57].

3.1 Propagation Characteristics
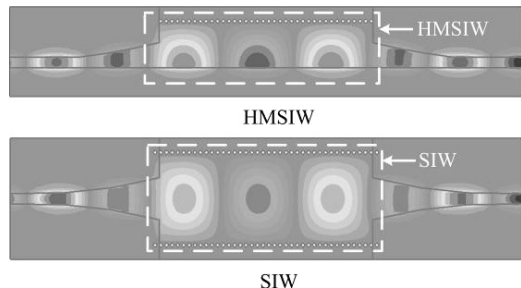
Based on multi-line calibration principle and measurement, the attenuation characteristics of SIW and HMSIW are investigated, and the results within 20–40 GHz are shown in Fig. 27, where the curves corresponding to "loss" are the transmission losses (for 17.1 mm length) calibrated from the transmission losses corresponding to different lengths (28 mm and 45.1 mm). It can be seen from the figures that the loss of HMSIW is better than that of the original SIW in 20–35 GHz, but worse over the band of 35–40 GHz. The reason is the conducting loss and dielectric loss of HMSIW are smaller than that of SIW for lower frequency band, the leakage from the open side of the HMSIW will increase for higher frequency band. In order to keep the low loss property, we should use thin substrate for HMSIW to increase the WHR, thus decreasing the leakage from the open side for the high frequency band.

3.2 HMSIW Directional Couplers

Figure 28 shows the layouts of both HMSIW and SIW 90° 3 dB directional couplers [52]. It can be seen that the size of the HMSIW one is around half the size of the SIW coupler. Measured amplitude and phase responses of the HMSIW coupler are shown in Fig. 29.
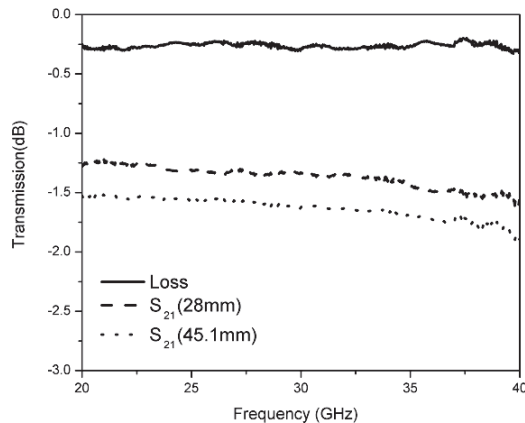
(a) Attenuation of a section of SIW
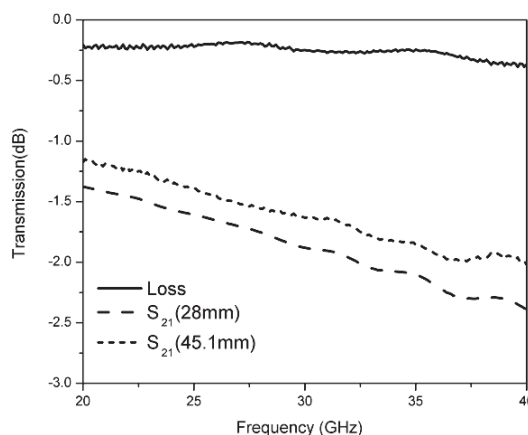
(b) Attenuation of a section of HMSIW

Fig. 27 Attenuation of SIW and HMSIW.

Fig. 28 HMSIW and SIW 3 dB couplers.

3.3 HMSIW Filters

Several kinds of HMSIW filters with inductive windows, transverse resonant slots and periodic CPW elements etc. were designed and fabricated using normal PCB process [55]. Figure 30 shows the configuration of an HMSIW filter with transverse resonant slots. Measured response of this filter is shown in Fig. 31. Its size is around the half size of an SIW filter.

(a) Amplitude

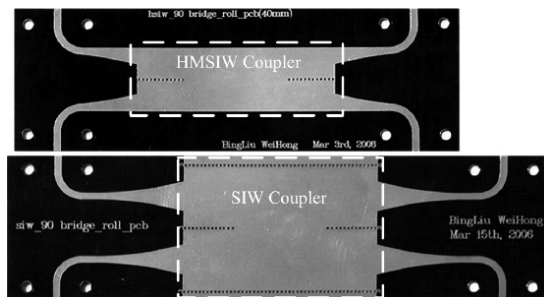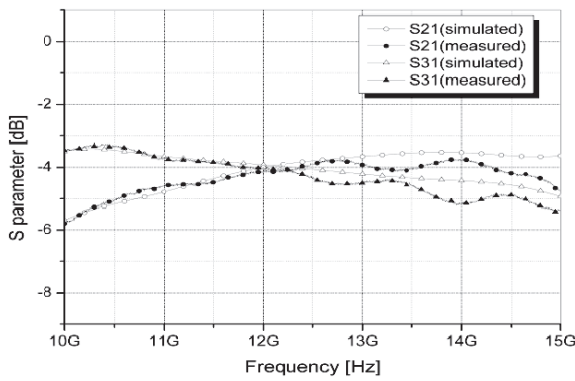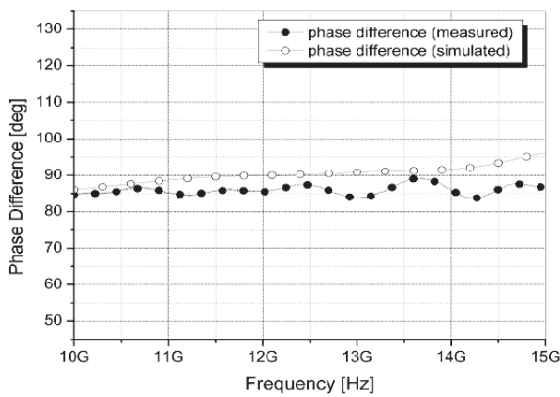(b) Phase difference

Fig. 29 Measured amplitude and phase responses.
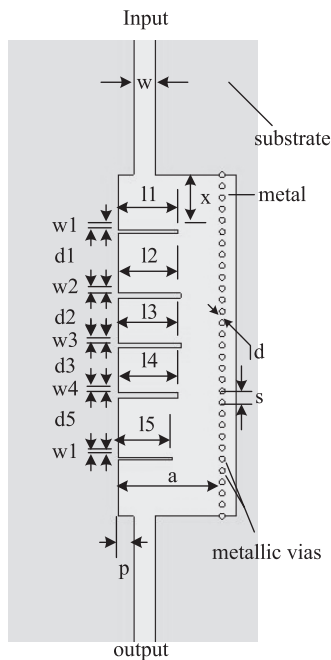
Fig. 30 HMSIW filter with transverse resonant slots.
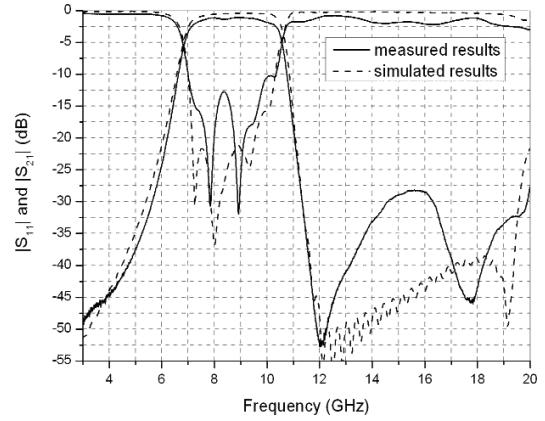
Fig. 31 Measured and simulated responses of the HMSIW filter.
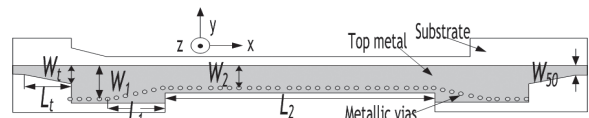
Fig. 32 HMSIW leaky wave antenna.

3.4 HMSIW Antennas

By decreasing the WHR of an HMSIW, we can design HM-SIW leaky wave antenna using the energy leakage from the open side of the HMSIW [56]. The configuration and radiation patterns are shown in Fig. 32 and Fig. 33, respectively.

Recently, more and more attention is being paid to the development of ultra-wideband (UWB) antennas with multiple frequency band-notched characteristics for suppressing potential interferences between UWB wireless communication systems and other narrow band wireless communication systems, such as the Wireless Local Area Network (WLAN) operated at 2.4 GHz and 5.8 GHz, Worldwide Interoperability for Microwave Access (WiMAX) system working on the frequency bands of 2.5 GHz (2500–2690 MHz), 3.5 GHz (3400–3690 MHz) and 5.8 GHz (5250–5825 MHz) etc. Using the multi-modes of HMSIW cavities, an UWB antenna with four frequency notches was developed in [57]. The configuration is shown in Fig. 34, and measured VSWR of the antenna is shown in Fig. 35. The antenna consists of a planar UWB monopole antenna and one HMSIW cavity which can generate multiple stopbands through a proper arrangement. Planar antennas with dual, triple and quadruple notched bands are designed and implemented. The notched frequencies and their bandwidths can be adjusted according to specifications by altering the cavities and feed lines independently. The antenna was fabricated with a two-layer PCB process. High quality band rejection, narrow frequency notches have been achieved.

4. Folded HMSIW

As described above, the HMSIW reduced nearly half the

(a) H-plane

(b) E-Plane
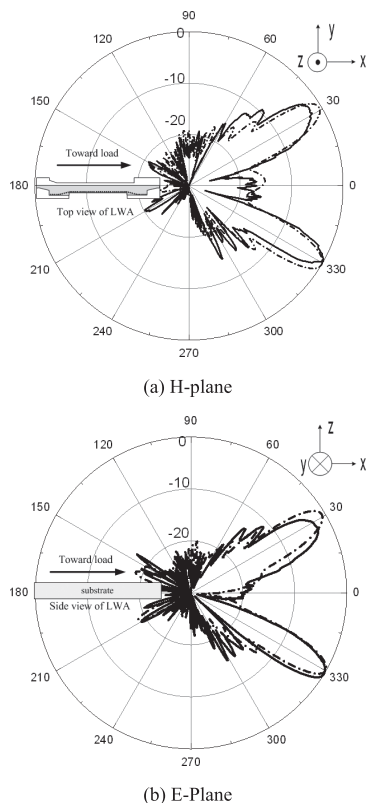
Fig. 33 Radiation patterns of the HMSIW leaky wave antenna at 28 GHz.
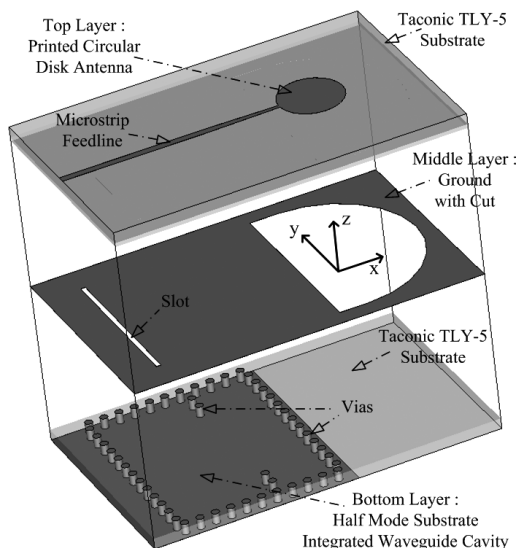
Fig. 34 Structure of the UWB antenna with multiple frequency notches.

size compared with SIW. Grigoropoulos and his co-workers proposed another way to reduce the SIW size, i.e., the folded SIW (FSIW) [59], [60] with two-layer PCB process, which can also reduce nearly half the size. In order to further reduce the size, we proposed a folded half mode substrate integrated waveguide (FHMSIW), it can reduce the size to around 25% of the original SIW structure. Compact FHM-
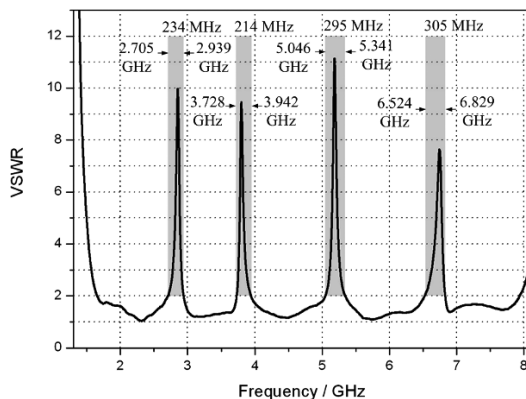
Fig. 35 Measured VSWR of the UWB antenna with quadruple frequency notches generated by the HMSIW cavity.
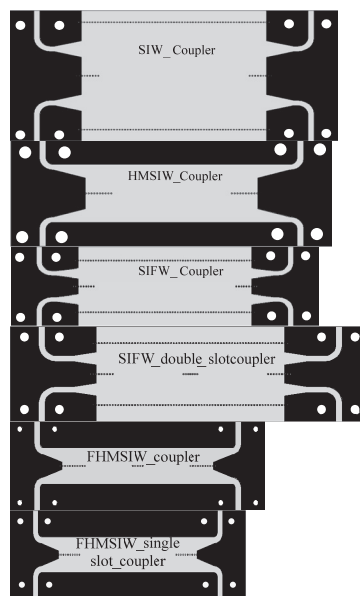
Fig. 36 Layouts of SIW, HMSIW, FSIW and FHMSIW couplers.

SIW 3 dB couplers were developed in [58]. For comparison, SIW, HMSIW, FSIW and FHMSIW couplers are shown in the same Fig. 36, it can be seen that the FHMSIW coupler is the smallest one. The measured amplitude and phase responses of the FHMSIW with double slots are shown in Fig. 37.

5. Conclusions

SIW-like guided wave structures simultaneously possess the advantages of low loss, high power handling capability etc. of a conventional metallic waveguide as well as the advantages of planar integration, low cost and easy fabrication etc. of microstrip-like planar transmission lines. In this paper, the research advance in the propagation characteristics of SIW-like guided wave structures (SIW, HMSIW and FHMSIW etc.) and their applications in filters, power dividers, couplers and antennas etc. in the State Key Labora-
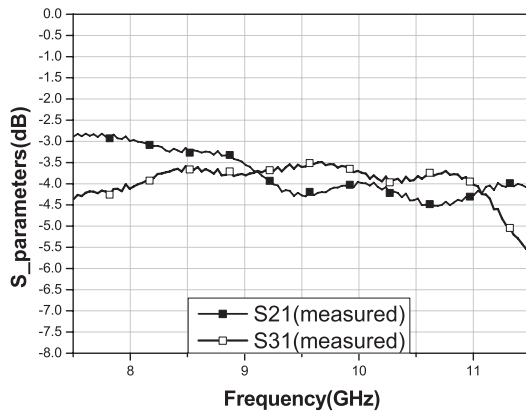
(a) Amplitudes of the output signals at through and coupled ports
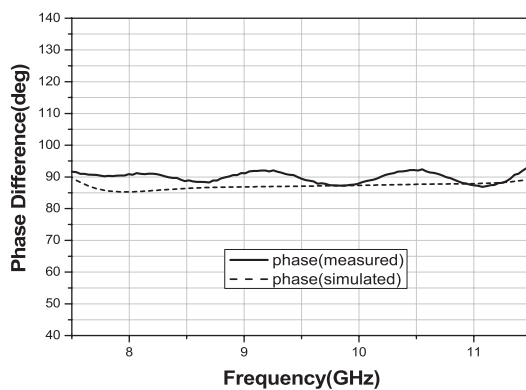
(b) Phase difference between through and coupled ports

Fig. 37 Amplitude and phase responses of the FHMSIW coupler.

tory of Millimeter Waves, Southeast University, China, are reviewed. It is expected to give a brief introduction to these kinds of new transmissions and their applications.

Acknowledgments

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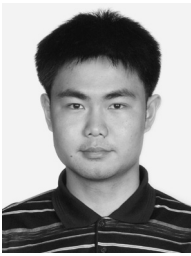
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