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SIW-Like Guided Wave Structures and Applications

Wei HONG†, Ke WÜ†, Hongjun TANG†, Jixin CHEN†, Peng CHEN†, Yujian CHENG†, and Junfeng XU†, Nonmembers

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 simultaneously 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, low 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...
of the dielectric substrate are \( h \) and \( \varepsilon_r \), respectively, \( W_{ms} \) is the width of input and output microstrip lines whose characteristic impedance is generally set to be 50\( \Omega \). \( L_{\text{taper}} \) and \( W_{\text{taper}} \) 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].

\[
p > d, \quad \frac{p}{\lambda_c} < 0.25, \quad \frac{p}{\lambda_c} > 0.05
\]  

(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

\[
a = \frac{W_{RWG}}{W_{SIW}} = \xi_1 + \frac{\xi_2}{p} + \frac{\xi_3 - \xi_1}{d}
\]  

(2)

where

\[
\xi_1 = 1.0198 + \frac{0.3465}{W_{SIW}/p} - 1.0684
\]

\[
\xi_2 = -0.1183 - \frac{1.2729}{W_{SIW}/p} - 1.2010
\]

\[
\xi_3 = 1.0082 - \frac{0.9163}{W_{SIW}/p} + 0.2152
\]

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 the substrate thickness and the equivalent waveguide width \( W_{RWG} = a \cdot W_{SIW} \). 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

\[
\alpha = 10^{\frac{\zeta_1 + \zeta_2}{2.75}}
\]  

(3)

where

\[
\zeta_1 = -4.6 + \frac{26}{W_{SIW}/p} + 4.5
\]

\[
\zeta_2 = -7.7 + \frac{11}{W_{SIW}/p} + 1.1
\]

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
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 pseudocombine resonator and is around 4.5–8.5 for a hairpin-line resonator.
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 \(1 \times 8\) 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\(^\circ\), and that of the H-plane radiation pattern is around 48\(^\circ\). 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]. A \(16 \times 16\) 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 Butler matrix. An SIW array antenna with 24 beams was de-
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-
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].

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
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 TE20 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.

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.
3.4 HMSIW Antennas

By decreasing the WHR of an HMSIW, we can design HMSIW 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
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 FHMSIW 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-


Wei Hong received the B.S. degree from the University of Information Engineering, Zhenzhou, China, in 1982, and the M.S. and Ph.D. degrees from Southeast University, Nanjing, China, in 1985 and 1988, respectively, all in radio engineering. Since 1988, he has been with the State Key Lab. of Millimeter Waves, Southeast University, and is currently a professor of the School of Information Science and Engineering. In 1993, 1995, 1996, 1997 and 1998, he was a short-term Visiting Scholar with the University of California at Berkeley and at Santa Cruz, respectively. He has been engaged in numerical methods for electromagnetic problems, microwave and millimeter wave theory and technology, RF and antenna technology for mobile communications etc. He has authored and co-authored over 200 technical publications, and authored two books of "Principle and Application of the Method of Lines" (in Chinese, Southeast University Press, 1993) and "Domain Decomposition Methods for Electromagnetic Problems" (in Chinese, Science Press, 2005). He twice awarded the first-class Science and Technology Progress Prizes issued by the Ministry of Education of China in 1992 and 1994 respectively, awarded the fourth-class National Natural Science Prize in 1991, and the first-, second- and third-class Science and Technology Progress Prizes of Jiangsu Province. Besides, he also received the Foundations for China Distinguished Young Investigators and for “Innovation Group” issued by NSF of China. Dr. Hong is a senior member of IEEE, senior member of CIE, Vice-Presidents of Microwave Society and Antenna Society of CIE, and served as the reviewer for many technique journals of IEEE Trans., on MTT, on AP, IET Proc.-H, Electron. Lett., etc., and now serve as the associate editor for IEEE Trans. on Microwave Theory and Technique.

Ke Wu is a Professor of electrical engineering, and Tier-I Canada Research Chair in RF and millimeter-wave engineering at the Ecole Polytechnique, University of Montreal, Montreal, QC, Canada. He also holds the first Cheung Kong endowed chair professorship (visiting) at the Southeast University, Nanjing, China, the first Sir Yue-Kong Pao chair professorship (visiting) at the Ningbo University, and an honorary professorship at the Nanjing University of Science and Technology, and the City University of Hong Kong, China. He has been the Director of the Poly-Grames Research Center. He is Director of the newly established Center for Radiofrequency Electronics Research of Quebec — Centre de recherche en électronique radiofréquence (CREER). He has authored or coauthored over 660 refereed papers, and a number of books/book chapters and patents. His current research interests involve substrate integrated circuits (SICs), antenna arrays, advanced CAD and modeling techniques, and development of low-cost RF and millimeter-wave transceivers and sensors for wireless systems and biomedical applications. He is also interested in the modeling and design of microwave photonic circuits and systems. Dr. Wu is a member of Electromagnetics Academy, the Sigma Xi Honorary Society, and the URSI. He has held key positions in and has served on various panels and international committees including the chair of technical program committees, international steering committees and international conferences/symposia. In particular, he will be the general chair of the 2012 IEEE MTT-S International Microwave Symposium. He has served on the editorial/review boards of many technical journals, transactions, and letters as well as scientific encyclopedia including editors and guest editors. He is currently the chair of the joint IEEE chapters of MTT/S/APS/LEOS in Montreal. He is an elected IEEE MTT-S AdCom member for 2006–2012 and serves as the chair of the IEEE MTT-S Transnational Committee. He was the recipient of many awards and prizes including the first IEEE MTT-S Outstanding Young Engineer Award and the 2004 Fessenden Medal of the IEEE Canada. He is Fellow of the IEEE, Fellow of the Canadian Academy of Engineering (CAE) and Fellow of the Royal Society of Canada (The Canadian Academy of the Sciences and Humanities).

Hongjun Tang received the B.S. degree in radio engineering from the Sichuan Institute of Light Industry and Chemical Technology, Zigong, China, in 1992, the M.S. degree in circuits and system from the University of Electronic Science and Technology of China, Chengdu, China, in 2000, and the Ph.D. degree in electromagnetic field and microwave technology from the Southeast University, Nanjing, China, in 2007. From 1992 to 2002 he worked in the Sichuan Institute of Light Industry and Chemical Technology. He is currently with the state key lab. of millimeter waves, school of information science and technology of Southeast University since 2007. His research interests include microwave and millimeter wave components, circuits and system.
Jixin Chen was born in Jiangsu Province, P.R. China, in 1976. He received the B.S., M.S. and Ph.D. degrees from Southeast University, Nanjing, China, in 1998, 2002 and 2006, respectively. Since 1998, he has been with State Key Lab. of Millimeter Waves, Southeast University, and is currently a associate professor of the School of Information Science and Engineering. His current research interests include microwave and millimeter-wave circuit and system design.

Peng Chen was born in Nanjing, Jiangsu Province, P.R. China, in 1982. He received the B.S. degree in electrical engineering from Southeast University, Nanjing, China, in 2004, and is currently working toward the Ph.D. degree in electromagnetic field and microwave technology with the School of Information Science and Engineering, Southeast University. His current research interests include beam-forming networks, multi-beam antennas, phased array antennas and antenna tracking systems for satellite and mobile communications.

Yujian Cheng was born in Sichuan Province, P.R. China, on April, 1983. He received the B.S. degree in the school of Electric Engineering from University of electronic Science and Technology of China, in 2005 and is currently working toward the Ph.D. degree in electromagnetic field and microwave technology with the School of Information Science and Engineering, Southeast University, Nanjing, China. His current research interests include microwave and millimeter-wave passive circuits, antennas. He served as the reviewer for IEEE Microwave and Wireless Components Letters, IEEE Transaction on Electromagnetism, and IEEE/ASME Journal of Microelectromechanical Systems.

Junfeng Xu received the B.S. degree and the M.S. degrees from Southeast University, Nanjing, China, in 2003 and 2006, respectively, all in school of information science and engineering. He is currently pursuing the Ph.D. degree at Southeast University, Nanjing, China. He was a short-term Visiting Student with the Institute of Inforcomm Research, Singapore, in 2008. His main research interests include substrate integrated antennas and arrays for microwave and millimeter-wave applications.