Abstract In this letter, a novel 3-D empty substrate integrated waveguide (ESIW) phase shifter with equal length has been proposed. The vertical transitions have been introduced into 3-D ESIW phase shifter in the propagation path. Based on it, the different total lengths of phase shifters in the propagation path and the equal total lengths of phase shifters in the external structure are compatible. The phase shifter consists of multi-layer PCB: top layer, interlayer, middle layer, ESIW PCB, and bottom layer. The theory and design process of ESIW phase shifter have been explained and discussed in detail. To demonstrate its feasibility, the 3-D ESIW phase shifters with equal external length are designed, manufactured and measured. Final results show that the phase shifts of 45.2°±3.7° and 89.7°±4.7° can be achieved over the entire Ka-band. Besides, the return losses and the insertion losses are better than 12.5 dB, and 1.9 dB, respectively.

key words: 3-D Empty substrate integrated waveguide (ESIW), phase shifter, vertical transition

1. Introduction

Several microwave and millimeter-wave passive components based on substrate integrated waveguide (SIW) technology have been studied and published, such as power divider, coupler, filter, phase shifter, antenna, etc [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]. The most prominent advantages for SIW are its simple structure, low radiation, low insertion loss, and low cost [11]. Phase shifter is one of the basic components, and has been widely applied in millimeter-wave circuits and systems, especially in phase array [12, 13, 14, 15, 16].

As far as we know, several kinds of SIW phase shifters have been reported [17, 18, 19, 20, 21, 22, 23, 24, 25]. A self-compensating SIW phase shifter combining delay line and equal-length unequal-width has been designed and fabricated [see Fig. 1(a)]. A SIW phase shifter with 5 phase channels and maximum phase range of 60° has been proposed in [19]. In order to reduce complexity and accelerate design process, SIW phase shifters with equal length are needed when a complex feeding network is designed. Recently, phase shifters with an equal length structure based on double dielectric slab-loaded air-filled substrate-integrated waveguide (SIW) are proposed in [20].

Fig. 1. (a) SIW phase shifter in [19], (b) Profile of 3-D SIW phase shifter, (c) Profile details, (d) Interlayer 1, (e) Cross section of interlayer 2, 3 and middle layer, (f) Transition between microstrip and ESIW. Light gray: top and bottom layer. Violet: middle layer. Pink: interlayer 1. Green: interlayer 2. Light blue: interlayer 3. Red: ESIW PCB. Orange: copper metallization on PCB. White: air.

For SIW phase shifter, a fundamental and simple principle was initially presented and derived from equation (6)-(12) in [19]. In fact, almost all SIW phase shifters can be explained by the theories above. The only

---

1School of Electronic Science and Engineering, University of Electronic Science and Technology of China, No.2006, Xiyuan Ave, West Hi-Tech Zone, Chengdu, 611731, China
2School of Electronic Science, National University of Defense Technology, Changsha, 410073, China
3Serioja Ovidiu Tatu is with the Institut National de la Recherche Scientifique, Énergie Matériaux et Télécommunications, Montréal, QC H5A 1K6, Canada.
5School of Information and Communication Engineering, University of Electronic Science and Technology of China No.2006, Xiyuan Ave, West Hi-Tech Zone, Chengdu, 611731, China
a) huanyu_sky@uestc.edu.cn

DOI: 10.1587/elex.16.20190619
Received October 5, 2019
Accepted October 17, 2019
Publicized November 8, 2019

Copyright © 2019 The Institute of Electronics, Information and Communication Engineers
challenge is the existence of unequal lengths, as well as some inconvenient factor for practical case and simplicity of complex feeding networks. Therefore, it can be solved if the different total lengths of phase shifters in the propagation path and the equal total lengths of phase shifters in the external structure are compatible. Recently, a novel vertical transition in empty substrate integrated waveguide (ESIW) has been reported in [26, 27]. It focuses on multilayer compact devices in ESIW with the same height for every dielectric layer. In brief, a 3-D passive component based on ESIW is achieved. According to this idea, a novel 3-D ESIW phase shifter with equal length is represented [see Fig. 1(b-f)]. The length difference ΔL is inserted in the vertical direction instead of horizontal direction. It means that ΔL is really existent and not shown in planar circuits. Compared with the reference [19, 20], an equal length structure can be achieved with acceptable measurement performances.

2. 3-D ESIW phase shifter design and simulation

To design the SIW phase shifters, the first step is to model the reference phase, called 0°. Similar to Fig. 1(a), the width of ESIW is uniform. Therefore, the widths of ws and ws1 in Fig. 1(d) are equal for 0°. To accelerate the design process, the initial parameters for MS-ESIW transition and vertical transition should be chosen firstly, as shown in Table I (similar to [26, 28]).

Table I. Initial values for MS-ESIW and vertical transitions

| Parameter | Initial | Final |
|-----------|---------|-------|
| ws        | 7.112   | h     |
| ws1       | 0.25    | 0.35  |
| wms       | 4*w    | 4.52  |
| lms       | 1.6     | 2.35  |
| Δms       | 0.55    | 0.12  |
| lti       | 7.112   | 8     |
| Δti       | 2.8     | 2.5   |
| Tanθ      | 16      | 11    |

Seen from circuit and model structures in Fig.1, ESIW phase shifter consists of multi-layer PCB: top layer, interlayer, middle layer, ESIW PCB, and bottom layer. All layers can be fabricated on PCB with the same thickness, except the middle layer. In theory, for different phase differences, the height (h1) is discrete and subtly different. There are two technical ways to achieve the middle layer. The first one is based on the metal structural part, the height (h1) can be arbitrarily selected and fabricated in CNC machining. Besides, it sounds impossible that the second one is to customize PCB of arbitrary thickness. Fortunately, some companies, such as Taizhou WANGLING insulating materials factory [29], can provide related services and products with an acceptable period and cost.

After the dimensional parameters for MS-ESIW transition and vertical transition are optimized, the 3-D ESIW phase shifter will be designed based on the theory in [19]. There are only four optimized dimensional parameters: ΔL, ws1, lms, and Tanθ.

In order to validate the idea in this letter, the 3-D ESIW phase shifter working in Ka-band using Rogers 5880 substrate with the height of 0.381mm have been designed. It is noted that the metal thickness t is 0.04mm from process documents. Based on the parameter sweep and sequential nonlinear programming optimizer in HFSS, the final values (fixed and variable) about 3-D ESIW phase shifter have been shown in Table II. The electric field magnitude distribution at 33 GHz for 3-D ESIW phase shifter is shown in Fig. 2.

Table II. Dimensional values of 3-D ESIW phase shifters

| Parameter | Fixed values (in mm) | Variable values (in mm) |
|-----------|----------------------|-------------------------|
| ws        | 7.112                | 0°                      |
| ws1       | 0.25                 | 45°                     |
| wms       | 4.52                 | 90°                     |
| lms       | 1.6                  | h                       |
| Δms       | 0.55                 | h0                      |
| lti       | 7.112                | Δl                      |
| Δti       | 2.8                  | Δt                      |
| Tanθ      | 16                   | 11                      |

Fig. 2. Electric field magnitude distribution at 33 GHz for 3-D ESIW phase shifter.

3. Manufacturing and measurement

Due to the customized PCB, the manufacturing is based on traditional PCB processing technology. The seven layers, middle layers and one of assembling 3-D ESIW phase shifters are all shown in Fig. 3.

In order to obtain measurement results, which is measured with a PNA network analyzer Agilent E8363B, the end launch connectors and thru–reflect–line (TRL) calibration kits have been adopted. In Fig. 4, the measured results show that the return losses and the insertion losses are better than 12.5 dB, and 1.9 dB, respectively, over the entire Ka-band. Besides, the phase shifts of 45.2±3.7° and 89.7±4.7° have been achieved. For 0°, 45°, and 90°, RMS of insertion losses are 1.24 dB, 1.25 dB, and 1.49 dB, respectively. Besides, RMS of phase errors are 45.2° and 89.8°, respectively.
Table III gives a comparison between the phase shifter manufactured prototypes and assembling one. (a) PCB layers, (b) Middle metal layer and its cross section, (c) Assembling one.

Table III. Comparison Between SIW Phase Shifters

|                  | Δ Total length (mm) | Frequency range (GHz) | S11 (dB) | S21 (dB) | Amplitude imbalance (dB) | Phase shift(°) |
|------------------|---------------------|------------------------|----------|----------|--------------------------|----------------|
| Ref.[19]         | 0.6                 | 27-40                  | < -10.8  | > -1     | 0.28                     | 45±3.5         |
|                  | 1                   | 27-37                  | < -13    | > -1.1   | 0.2                      | 90±2.5         |
| Ref.[20]         | 0                   | 26-40                  | < -12.5  | > -0.52  | 0.23±0.2                 | 43±6           |
| This work        | 0                   | 26-40                  | < -12.5  | > -1.9   | 0.13±0.6                 | 45.2±3.7       |
|                  |                     |                        |          |          | -0.27±0.73               | 89.7±4.7       |

Compared with [19], the lengths of 3-D ESIW phase shifters for different phase shifts are completely equal in this work. Compared with [20], the insertion losses are slightly increased in this work, due to the selected reference planes (shown in Fig. 3(c)) and the possible gaps between each PCB layer. In [20], TRL calibration is used to deembed effects of connectors, CBCPW to SIW transitions, and SIW to air-filled SIW transitions. Besides, the phase shifting accuracy in [20] is slightly worse than it in this letter. Furthermore, the differences of return loss between the simulation and measurement results here can be due to two main reasons: assembly tolerance and machining accuracy, especially for the former. In fact, there is a slight and inevitable displacement in assembly between multi-layer circuit. In summary, compared with the previous ones, return loss and phase shift can be still an acceptable level in this work.
4. Conclusion

In this work, a novel 3-D ESIW phase shifter working in the Ka-band with equal length has been proposed. Shown in Fig. 4, the measured results of insertion loss are slightly greater than simulated ones. It is mainly attributed to power leakage between each PCB layer. The assembly tolerance and machining accuracy (especially for the former) may cause the differences between simulation and measurement results. For a higher frequency band, a contactless air-filled substrate integrated waveguide with artificial magnetic conductor will be considered in [30]. Further investigation is in progress. On the other hand, due to the characteristics of air medium (full of three-dimensional space), SIW (two-dimensional space for PCB) can be applied in 3-D space using ESIW. It is another research direction for ESIW, and will be an excellent candidate in LTCC circuit.

Acknowledgments

This work was supported by the Fundamental Research Funds for the National Natural Science Foundation of China under Grant No. 61701092 and China Postdoctoral Science Foundation under Grant No. 2018M633666.

References

[1] D. Tarek and K. Wu: “Multilayer integration and packaging on substrate integrated waveguide for next generation wireless applications,” 46th European Microwave Conference, (2016) 858 (DOI: 10.1109/EuMC.2016.7824479).
[2] J. Dong, T. Yang, Y. Liu, et al.: “Broadband stripline to rectangular waveguide transition,” IEICE Electronics Express 12 (2015) 20150117 (DOI: 10.1587/elex.12.20150117).
[3] Y. H. Zhou, H. Y. Wang, J. Y. Li, et al.: “A compact high-efficiency power divider/combiner based on quadruple-ridged waveguide,” IEICE Electron. Express 13 (2016) 20160181 (DOI: 10.1587/elex.13.20160181).
[4] K. W. Zuo, Y. Z. Zhu, W. X. Xie, et al.: “A novel miniaturized quarter mode substrate integrate waveguide tunable filter,” IEICE Electron. Express 15 (2018) 20180013 (DOI: 10.1587/elex.15.20180013).
[5] S. Zhang, J. J Cheng, Y. Guo: “A filter design method based on higher-order modes of fan-shaped half-mode substrate integrated waveguide resonator,” IEICE Electron. Express 16 (2019) 20190039 (DOI: 10.1587/elex.16.20190039).
[6] L. B. Sun, Z. P. Qian, W. Q. Cao, et al.: “Higher mode SIW excitation technology and its array application,” IEICE Electron. Express 14 (2017) 20170873 (DOI: 10.1587/elex.14.20170873).
[7] J. Guo, J. Xu, Y. Chen, C. Qian, et al.: “Design of a millimeter-wave third-harmonic mixer using substrate integrated waveguide balun,” IEICE Electron. Express 14 (2017) 20170980 (DOI: 10.1587/elex.14.20170980).
[8] S. Y. Yang, Z. Xu, Y. F. Hou, et al.: “Substrate integrated waveguide filter based on novel coupling-enhanced semicircle slots for 5G applications,” IEICE Electron. Express 16 (2019) 20190125 (DOI: 10.1587/elex.16.20190125).
[9] K. Sato, M. Tamura: “Filter using cylindrical quadruple mode SIW resonator,” IEICE Electron. Express 15 (2018) 20180295 (DOI: 10.1587/elex.15.20180295).
[10] B. R. Zheng, Z. Q. Zhao, and X. Y. Lv: “Improvement of SIW filter upper stopband performance using bypass coupling substrate integrated circular cavity (SICC),” IEICE Electron. Express 8 (2011) 1294 (DOI: 10.1587/elex.8.1294).
[11] D. Deslandes and K. Wu: “Integrated microstrip and rectangular waveguide in planar form,” IEEE Microwave Wireless Component Letter 11 (2001) 68 (DOI: 10.1109/7266.914305).
[12] C. F. Campbell and S. A. Brown: “A compact 5-bit phase-shifter MMIC for K-band satellite communication systems,” IEEE Transactions on Microwave Theory and Techniques 48 (2000) 2652 (DOI: 10.1109/22.899026).
[13] Hain-Ying Wu, et al.: “Electrically tunable room-temperature 2/spi/ liquid crystal terahertz phase shifter,” IEEE Photonics Technology Letters 18 (2006) 1488 (DOI: 10.1109/LPT.2006.877579).
[14] R. Nandi: “Novel current-mode all-pass phase shifter using a current conveyor,” IEEE Transactions on Instrumentation and Measurement 41 (1992) 553 (DOI: 10.1109/19.155925).
[15] G. M. Rebeiz, et al.: “RF MEMS phase shifters: design and applications,” IEEE Microwave Magazine 3 (2002) 72 (DOI: 10.1109/MMW.2002.1004054).
[16] P. Chen, et al.: “Virtual Phase Shifter Array and Its Application on Ku Band Mobile Satellite Reception,” IEEE Transactions on Antennas and Propagation 63 (2015) 1408 (DOI: 10.1109/TAP.2015.2393887).
[17] Hao Peng, et al.: “Slotted substrate integrated waveguide phase shifter,” IEEE Information Technology, Networking, Electronic and Automation Control Conference (2016) 1036 (DOI: 10.1109/ITNEC.2016.7560521).
[18] R. F. Xu, Y. L. Li: “Tunable phase shifter in substrate integrated waveguide,” IEICE Electron. Express 16 (2019) 201904899 (DOI: 10.1587/elex.16.201904899).
[19] Y. J. Cheng, W. Hong, and K. Wu: “Broadband self-compensating phase shifter combining delay line and equal-length unequal-width phase shifter,” IEEE Transaction on Microwave Theory and Techniques 58 (2010) 203 (DOI: 10.1109/TMTT.2010.2045942).
[20] F. Parment, A. Ghioatto, T. P. Vuong, et al.: “Double dielectric slab-loaded air-filled SIW phase shifters for high-performance and low-cost millimeter-wave integration,” IEEE Transaction on Microwave Theory and Techniques 64 (2016) 2833 (DOI: 10.1109/TMTT.2016.2595044).
[21] T. Yang, M. Ettorre, and R. Sauleau: “Novel phase shifter design based on substrate-integrated-waveguide technology,” IEEE Microwave Wireless Component Letter 22 (2012) 518 (DOI: 10.1109/LMWC.2012.2217122).
[22] K. Sellal, L. Talbi, T. A. Denidni, et al.: “Design and implementation of a substrate integrated waveguide phase
[23] K. Sellal, L. Talbi, M. Nedil: “Design and implementation of a controllable phase shifter using substrate integrated waveguide,” IEEE Transactions on Antennas Propagation 6 (2012) 1090 (DOI: 10.1049/iet-map.2011.0380).

[24] M. Ebrahimpouri, S. Nikmehr, A. Pourziad: “Broadband Compact SIW Phase Shifter Using Omega Particles,” IEEE Microwave and Wireless Components Letters 24 (2014) 1 (DOI: 10.1109/LMWC.2014.2350692).

[25] F. Yang, H. X. Yu, B. Zhang, et al.: “Substrate integrated waveguide phase shifter,” 2011 International Conference on Electronics, Communications and Control, (2011) 3966 (DOI: 10.1109/ICECC.2011.6066655).

[26] J. A. Ballesteros, M. D. Fernandez, A. Belenguer, et al.: “Versatile transition for multilayer compact devices in empty substrate integrated waveguide,” IEEE Microwave Wireless Component Letter 28 (2018) 482 (DOI: 10.1109/LMWC.2018.2825653).

[27] A. Belenguer, M. D. Fernandez, J. A. Ballesteros, et al.: “Compact multilayer filter in empty substrate integrated waveguide with transmission zeros,” IEEE Transaction on Microwave Theory and Techniques 66 (2018) 2993 (DOI: 10.1109/TMTT.2018.2823306).

[28] H. Esteban, A. Belenguer, J. R. Sánchez, et al.: “Improved low reflection transition from microstrip line to empty substrate-integrated waveguide,” IEEE Microwave Wireless Component Letter 27 (2017) 685 (DOI: 10.1109/LMWC.2017.2724011).

[29] Taizhou WANGLING insulating materials factory: http://www.wang-ling.com.cn/EN/index.asp.

[30] B. M. Nima, and A. A. Kishk: “Contactless air-filled substrate integrated waveguide,” IEEE Transaction on Microwave Theory and Techniques 66 (2018) 2928 (DOI: 10.1109/TMTT.2018.2818137).