DESIGN INVESTIGATION ON MILLIMETER-WAVE 
FERRITE PHASE SHIFTER IN SUBSTRATE 
INTEGRATED WAVEGUIDE

W.-Q. Che †
Department of Electronic Engineering
Nanjing University of Science & Technology
China

E. K. N. Yung
Department of Electronic Engineering
City University of Hong Kong
Hong Kong

K. Wu
Grames Research Center, Polytechnique de Montreal
Canada

X.-D. Nie
Kingtronics Ind. Co. Ltd.
Hong Kong

Abstract—In this paper, the design idea and technique of the ferrite phase shifter in substrate integrated waveguide (SIW) has been reported. The characteristics of the millimeter-wave ferrite phase shifter have been firstly calculated analytically, and the relative parameters of the device have been decided on the basis of optimization. At the same time, the design procedure of transition from ferrite phase shifter in SIW to CPW has been introduced; the agreement between the simulation results of the final integrated structure and the experimental results of an equivalent model has shown the good performance of this integrated structure.

† Also with Department of Electronic Engineering, City University of Hong Kong, Hong Kong
1. INTRODUCTION

The past decade has witnessed a rapid development of commercial millimeter-wave wireless systems, such as local multipoint distribution service (LMDS) and advanced collision-avoidance radar. Hence design and manufacturing costs of such systems are probably the most critical issue in the assessment of the commercial vitality of the wireless systems. Integration of active and passive components made of the rectangular waveguide generally requires transitions from planar to non-planar circuits. In any case, various approaches to solving this problem have been proposed that yield some complex mounting structures [1–3]; on the other hand, high-precision mechanical adjustment or a subtle tuning mechanism is needed to obtain good performance for mass production; and a planar microstrip circuit often needs to be cut into a specific shape, which is hard to realize in the millimeter-wave range; above-mentioned issues has inevitably blocked the rapid development of those wireless communication systems. Moreover, rectangular-waveguide components are voluminous and expensive to manufacture, which inevitably make the planar/non-planar integration structure bulky and costly.

Recently, the concept of the integrated rectangular waveguide has been proposed [4] in which an “artificial” waveguide is synthesized and constructed with linear arrays of metallized via-holes or posts embedded in the same substrate used for the planar circuit. Several transitions have been proposed [5–7] to excite the waveguide. In all these structures, the planar circuits, such as a microstrip line or coplanar waveguide, and the rectangular waveguide are built onto the same substrate and the transition is formed with a simple matching geometry between both structures.
As we have known, ferrite steroidal phase shifters have excellent electrical performances and are used as phasing elements in phased array antennas. They take advantages of high $Q$ value, high power handling capability etc. [8–11]. However, their drawbacks, such as heavy weight, large volume, difficulty to be integrated with planar circuits etc., hobble their applications in wireless communication. On the basis of above motivation, one novel design integrating the ferrite phase shifter into the substrate-integrated waveguide (SIW) [12–15] has been proposed in this letter to demonstrate the full potentials of the integrated-waveguide scheme. The substrate-integrated waveguide combines the advantages of microstrip lines and waveguide, and has shown its promising future. Undoubtedly, based on this great integration of ferrite phase shifter into a planar structure, it is possible to develop large phased array, integrating the ferrite phase shifters and the excited circuits on a same substrate, which takes the features of low profile, small volume and light weight etc., and therefore exists promising applications in millimeter wave field.

In this paper, the analytical model of the ferrite phase shifter in SIW and formulae are firstly introduced; relative characteristics such as differential phase shift and insertion loss is calculated analytically. In addition, the optimum parameters of the phase shifter have been given. Furthermore, the design idea and procedures of transition from ferrite phase shifter in substrate-integrated waveguide (SIW) to Coplanar Waveguide (CPW) has been investigated. Finally, the integrated structure of ferrite phase shifter and transition has been simulated, and the measured data of an equivalent model has been proved to agree with the simulation results.

2. PARAMETERS OF THE FERRITE PHASE SHIFTER

The analytical model for the ferrite phase shifter in substrate-integrated waveguide is illustrated in Fig. 1. In addition, the transcendental equation of propagation constant of the ferrite phase shift in rectangular waveguide is expressed as:

$$\coth(k_1a_1) \left[ \frac{k_1k_d}{\rho} + k_1\coth(k_da_d) \left( kfcot(kfa_f) \pm \frac{\beta}{\theta} \right) \right]$$
$$+ b' \left[ -\rho \left( \frac{\beta}{\theta^2} + k_f^2 \right) \coth(k_da_d) + k_3 \left( kfcot(kfa_f) \pm \frac{\beta}{\theta} \right) \right] = 0 \quad (1)$$

Where

$$k_1 = \sqrt{\beta^2 - \omega^2\mu_0\varepsilon_1},$$
Figure 1. Analytical model of the ferrite phase shifter in SIW.

\[
    k_f = \sqrt{\frac{\omega^2 \mu_0 \varepsilon_f}{\rho - \beta^2}}, \\
    k_d = \sqrt{\beta^2 - \omega^2 \mu_0 \varepsilon_d}, \\
    \theta = \frac{f}{\gamma 4\pi M_r}, \quad \rho = \frac{\theta^2}{\theta^2 - 1} \tag{2}
\]

Here, \( \gamma = 2.8 \times 10^6 \text{Hz/Oe} \), \( 4\pi M_r \) is the remanence magnetization of the ferrite material, \( f \) is the operating frequency. Using the aforementioned formulae, we calculated the differential phase shift and insertion loss of the ferrite phase shifter and the optimized characteristics are illustrated in Fig. 2 and Fig. 3. Therefore, it is not hard to decide the optimum parameters of the ferrite phase shifter in substrate-integrated waveguide as followings:

\[
    a = 0.373 \lambda_0, \quad a_f = 0.0711 \lambda_0, \quad a_d = 0.0047 \lambda_0, \quad b = 0.1870 \lambda_0 \\
    4\pi M_r = 5000.0 \text{Gs}, \quad \varepsilon_{r1} = 2.0, \quad \varepsilon_{rf} = 15.0, \quad \varepsilon_{rd} = 5.0
\]

3. DESIGN TECHNIQUE OF SIW

Judging from its electrical performance, the synthesized integrated waveguide is a good compromise between the air-filled rectangular waveguide and planar circuit. A schematic view of the substrate-integrated waveguide is shown in Fig. 4. In reference [5], the authors have indicated the detailed procedure and requirements on the design of SIW, that is

\[
    d < \lambda_g/5, \quad p < 2d
\]
Design investigation on millimeter-wave ferrite phase shifter

Figure 2. Optimized differential phase shift of the MM ferrite phase shifter.

Figure 3. Optimized insertion loss of the MM ferrite phase shifter.
Figure 4. The schematic geometry of one SIW section.

Where $\lambda_g$ is the guided wavelength in the substrate-integrated waveguide. These two rules ensure that the radiation loss is kept at a very low level and SIW can be modeled by a conventional rectangular waveguide. In this design, according to the analysis in previous sections, the required width for the millimeter-wave ferrite phase shifter in SIW is $a_{eqv} = 0.467\lambda_0$ and the width of the equivalent waveguide used in the simulation and design has been found to be $a = 0.512\lambda_0$, $d = 30$ mil, $p = 60$ mil.

In order to verify the above-mentioned design rules, we simulate the SIW with different via distance $p$, and the simulation results have been illustrated as Fig. 5a, Fig. 5b, Fig. 5c and Fig. 5d. From the simulation results, it is not hard to see that, when via distance $p$ is beyond of 60 mil, there is some energy leaked into the waveguide, or leak out of the waveguide. In any case, in our design, we usually select $p = 60$ mil.

4. TRANSITION FROM SIW TO COPLANAR WAVEGUIDE (CPW)

A conventional CPW on a dielectric substrate consists of a center strip conductor with semi-infinite ground planes on either side [17, 18]. This structure supports a quasi-TEM mode of propagation. The CPW offers several advantages over conventional microstrip line. In millimeter-wave range, the coplanar waveguide (CPW) is a very promising transmission line. Furthermore, increasing dielectric substrate height may not affect too much inherent CPW characteristics. This transmission line is therefore well suitable for the on-substrate hybrid integration with the rectangular waveguide and other uni-planar structures, since the substrate thickness can be increased to reduce conductor loss in the waveguide design without having adverse impact on planar components. In this letter, a new integrated circuit of CPW-
ferrite phase shifter in rectangular waveguide has been presented. All the structures are realized on a single PCB using a standard process, integrating both structures on a single PCB layer allows the design of transition without tuning or mechanical mounting.

However, now we want to integrate the ferrite phase shifter into the SIW, which is a good compromise between air-filled rectangular waveguide and microstrip line. The top and bottle grounds of the microstrip circuit form the broad-wall of the rectangular waveguide, and the periodic via structures realize the bilateral walls. In order to position the ferrite torpid in the SIW, some substrate will be removed and replaced by the ferrite torpid. In addition, one conducting line

Figure 5. (a) the leaky wave coupled into the SIW (\(p = 60\) mil), (b) the leaky wave coupled into the SIW (\(p = 65\) mil), (c) the leaky wave coupled into the SIW (\(p = 70\) mil), (d) the leaky wave coupled into the SIW (\(p = 80\) mil).
Figure 6. Geometrical structure of the transition from ferrite PS in SIW to CPW.

should pass through from the air hole of the ferrite toroid, in order to excite the ferrite. The expected structure has been illustrated in Fig. 6. A commercial package using finite element method (FEM) is used to simulate and optimize the structure. Among which, a taper transition [6] has been employed to realize multi-step impedance match. However, because the ferrite material is still under process, we replaced the ferrite with the equivalent dielectric material to synthesize and simulate the performance of the integrated structure.

5. RESULTS AND DISCUSSION

The simulation result is depicted in Fig. 7 and Fig. 8, which show that the equivalent model can be used to simulate approximately some characteristics of the practical integrated circuit, such as the return loss and insertion loss etc. Clearly, the bandwidth of return loss is about 14% (15 dB). In addition, the measured return loss of the equivalent model has been approved to agree well with the simulation results, which show that the performance of the CPW transition is rather good. However, the measured insertion loss is bigger than the simulation results, several factors can be found to contribute to this phenomenon. 

(1) The loss tangent of the dielectric material is given at $f = 10\,\text{GHz}$,
Figure 7. The return loss of the integrated structure.

Figure 8. The insertion loss of the integrated structure.
but at higher frequencies, it is bigger. However, we didn’t take into account the increase of loss tangent with frequencies. (2) We didn’t consider the metal thickness of the planar structure in the simulation, but it indeed causes conductor losses. (3) The radiation loss was omitted in the simulation, but it really exists in the CPW structure. In the near future, we will fabricate one practical SIW ferrite phase shifter and measure its phase shift characteristics, and integrate the driving circuit onto the planar structure; the further results are expected to report soon. We believe that the success of this device will provide valuable guidance to the research of low profile, small-volume phased array, and lead the success to other millimeter-wave ferrite devices in substrate-integrated waveguide.

6. CONCLUSION

In this work, millimeter-wave ferrite phase shifter in substrate-integrated waveguide has been investigated. First, the characteristics of the ferrite phase shifter have been analyzed. Based on the theoretical results, the optimal parameters of the ferrite material and the geometrical dimensions of the ferrite toroid have been decided. In order to design a transition with good performance, large numbers of simulation using HFSS and ADS have been carried out. Considering the practical conditions, the main attention has been focused on the CPW transition. In this work, the ferrite phase shifter and the CPW transition have been integrated into the same substrate; the simulation results has been approved to agree with the measured data of the equivalent model. At the same time, the difference between the measured data and the simulation results has been explained, and the future work has been proposed.

ACKNOWLEDGMENT

I would like to thank Dr. Dominic Deslandes, Dr. Yves Cassivi from Grames Research Center, Cole Polytechnique de Montreal, CA, for their helpful discussion and help.

REFERENCES

2. Grabherr, W., B. Huder, and W. Menzel, “Microstrip to waveguide transition compatible with millimeter-wave integrated


Wenquan Che received her B.S. from the East China Institute of Science and Technology, Nanjing, China, in 1990, and M.S. from the Nanjing University of Science and Technology, Nanjing, China, in 1995. In 1999, she was with the City University of Hong Kong, as a research assistant, and she is currently toward the Ph.D. degree at the City University of Hong Kong. From March 1995 to November 1999, she was with the Nanjing University of Science and Technology, where she conducted teaching and research as a lecturer in the areas of EM theory and microwave devices, especially the ferrite devices. Her current research involves the development of waveguide-based ferrite devices in microwave frequency and planar/co-planar structure devices in millimeter wave frequency for wireless communication.

Edward Kai-Ning Yung received his B.S. in 1972, M.S. in 1974, and Ph.D. in 1977, all from the University of Mississippi. After graduation, ward worked briefly in the Electromagnetic Laboratory, University of Illinois at Urbana-Champaign. He returned to Hong Kong in 1978 and began his teacher career at the Hong Kong Polytechnique. He joined the newly established City University of Hong Kong in 1984 and was instrumental in setting up a new department. He was promoted to full professor in 1989, and in 1994, he was awarded one of the first two personal chairs in the University. He is the founding Director of the wireless Communications Research Center, formerly known as Telecommunications Research Center. Despite his heavy administrative load, Edward remains active in research in microwave devices and antenna designs for wireless communications. He is the principle investigator of many projects worth tens of million Hong Kong dollars. He is the author of over 300 papers, including 150 in referred journals. Dr. Yung is also active in applied research, consultancy, and other technology transfers. He holds one patent. He
Design investigation on millimeter-wave ferrite phase shifter

was the recipient of many awards in applied research, including the Grand Prize in the Texas Instrument Design Championship, and the Silver Medal in the Chinese International Invention Exposition.

Ke Wu (M'87-SM'92-F'01) was born in Liyang, Jiangsu Province, China. He received the B.Sc. degree in radio engineering from the Nanjing Institute of Technology (now Southeast University), Nanjing, China, in 1982, and the D.E.A. and Ph.D. degrees in optics, optoelectronics, and microwave engineering (with distinction) from the Institute National Polytechnique de Grenoble (INPG), Grenoble, France, in 1984 and 1987, respectively. He is currently a Full Professor and Tier-I Canada Research Chair in Radio Frequency and Millimeter-Wave Engineering. He has been the Head of the FCAR Research Group of Quebec on RF and microwave electronics, the Director of the Poly-Grames Research Center, as well as the Founding Director of the newly developed Canadian Facility for Advanced Millimeter-Wave Engineering (FAME). He has authored or coauthored over 320 refereed papers, and several book chapters. His current research interests involve hybrid/monolithic planar and nonplanar integration techniques, active and passive circuits, antenna arrays, advanced field-theory-based computer-aided design (CAD) and modeling techniques, and development of low-cost RF and millimeter-wave transceivers. He is also interested in the modeling and design of microwave photonic circuits and systems. Dr. Wu is a member of the Electromagnetics Academy. He has served on the Editorial or Review Boards of various technical journals, including the IEEE Transactions on Microwave Theory and Techniques, the IEEE Transactions on Antennas and Propagation, and the IEEE Microwave and Guided Wave Letters. He was elected into the Board of Directors of the Canadian Institute for Telecommunication Research (CITR). He served on the Technical Advisory Board of Lumenon Lightwave Technology Inc. He is currently the chair of the joint IEEE chapters of MTT-S/AP-S/LEOS in Montreal, QC, Canada. In 2002, he was the first recipient of the IEEE MTT-S Outstanding Young Engineer Award. He was inducted as a Fellow of the Canadian Academy of Engineering (CAE) in 2002.

Nie Xiaodong received his B.Sc. Degree in radio engineering from the Nanjing Institute of Technology (now Southeast University), Nanjing, China, in 1993. Since 1996, he came to Hong Kong and works in Kingtronics Ind. Co. Ltd., HK, as one senior engineer.