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

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**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.

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## 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:

$$\coth(k_1 a_1)\left[\frac{k_1 k_d}{\rho}+k_1\coth(k_d a_d)\left(k_f\cot(k_f a_f)\mp\frac{\beta}{\theta}\right)\right] +\frac{b'}{b}\left[-\rho\left(\frac{\beta}{\theta^2}+k_f^2\right)\coth(k_d a_d)+k_3\left(k_f\cot(k_f a_f)\pm\frac{\beta}{\theta}\right)\right]=0 \quad (1)$$

Where

$$k_1 = \sqrt{\beta^2-\omega^2\mu_0\varepsilon_1},$$

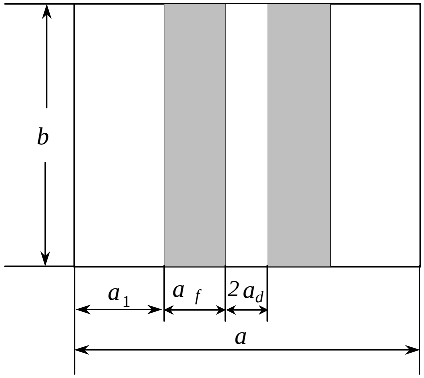


**Figure 1.** Analytical model of the ferrite phase shifter in SIW.

$$\begin{aligned} k_f &= \sqrt{\omega^2 \mu_0 \varepsilon_f \big/ \rho - \beta^2}, \\ k_d &= \sqrt{\beta^2 - \omega^2 \mu_0 \varepsilon_d}, \\ \theta &= \frac{f}{\gamma 4\pi M_r}, \quad \rho = \frac{\theta^2}{\theta^2 - 1} \end{aligned} \tag{2}$$

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:

$$a = 0.373\lambda_0, \quad a_f = 0.0711\lambda_0, \quad a_d = 0.0047\lambda_0, \quad b = 0.1870\lambda_0$$

$$4\pi M_r = 5000.0Gs, \quad \varepsilon_{r1} = 2.0, \quad \varepsilon_{rf} = 15.0, \quad \varepsilon_{rd} = 5.0$$

## 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

$$d < \lambda_g \big/ 5, \qquad p < 2d$$

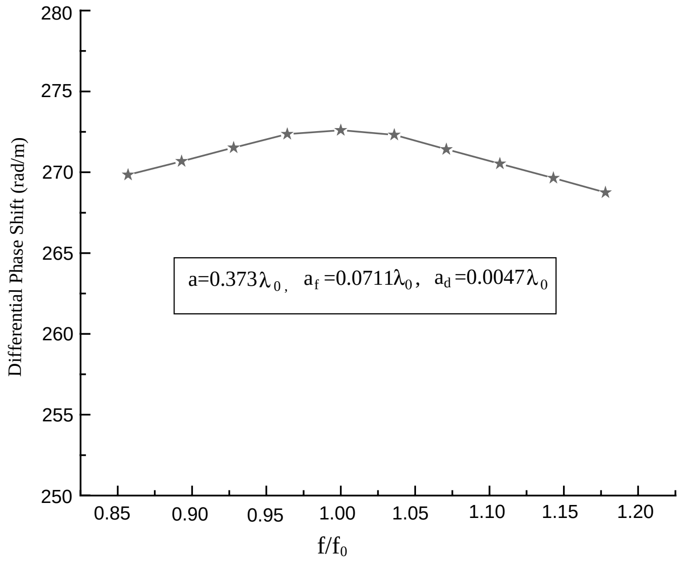


**Figure 2.** Optimized differential phase shift of the MM ferrite phase shifter.

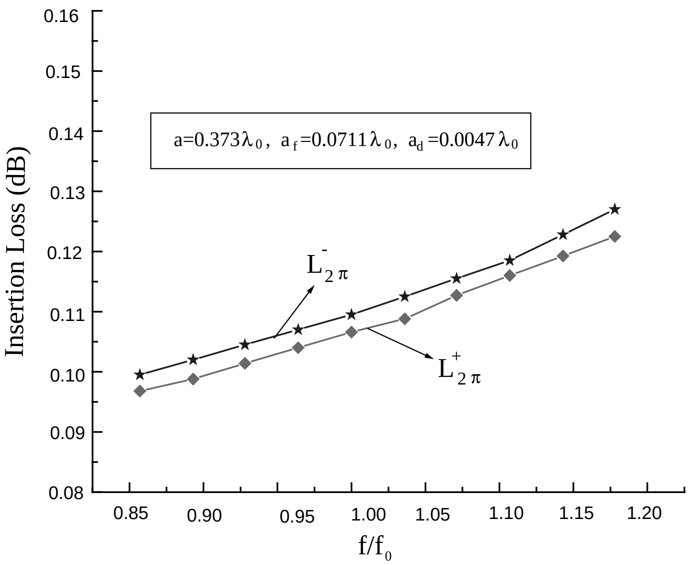


**Figure 3.** Optimized insertion loss of the MM ferrite phase shifter.

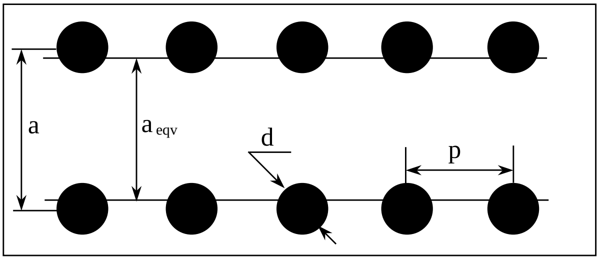


**Figure 4.** The schematic geometry of one SIW section.

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 $a = 0.512\lambda_0$, $d = 30\,\text{mil}$, $p = 60\,\text{mil}$.

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 $p = 60\,\text{mil}$.

## 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-

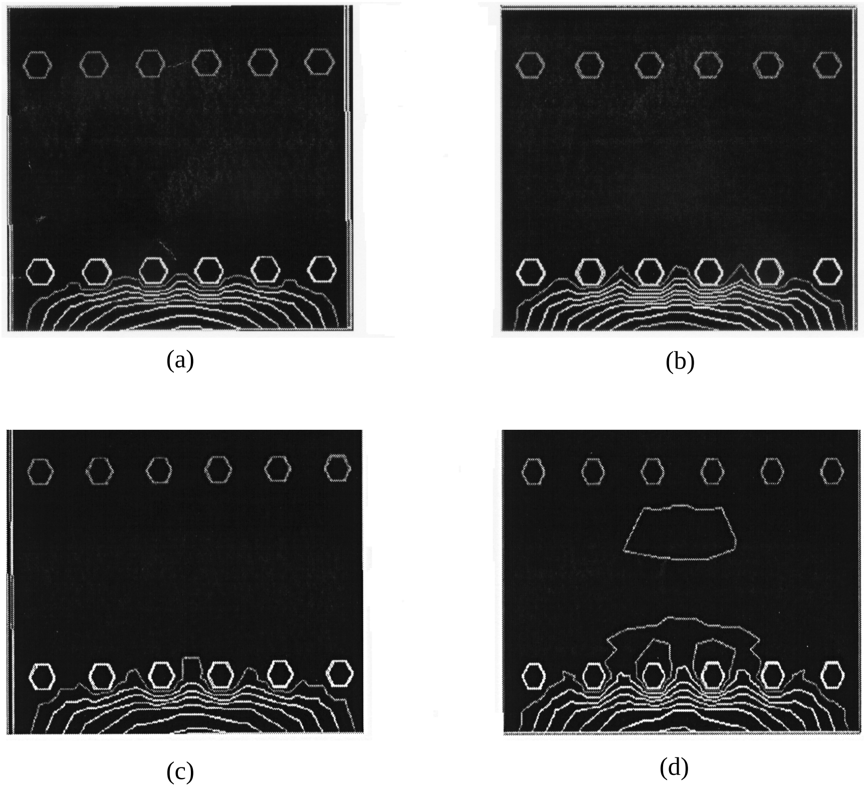


**Figure 5.** (a) the leaky wave coupled into the SIW ($p = 60\,\text{mil}$), (b) the leaky wave coupled into the SIW ($p = 65\,\text{mil}$), (c) the leaky wave coupled into the SIW ($p = 70\,\text{mil}$), (d) the leaky wave coupled into the SIW ($p = 80\,\text{mil}$).

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

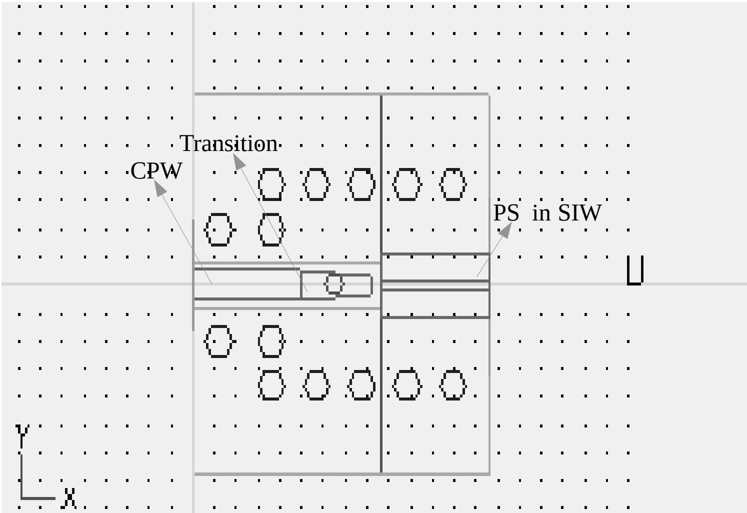


**Figure 6.** Geometrical structure of the transition from ferrite PS in SIW to CPW.

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 $f = 10\,\mathrm{GHz}$,

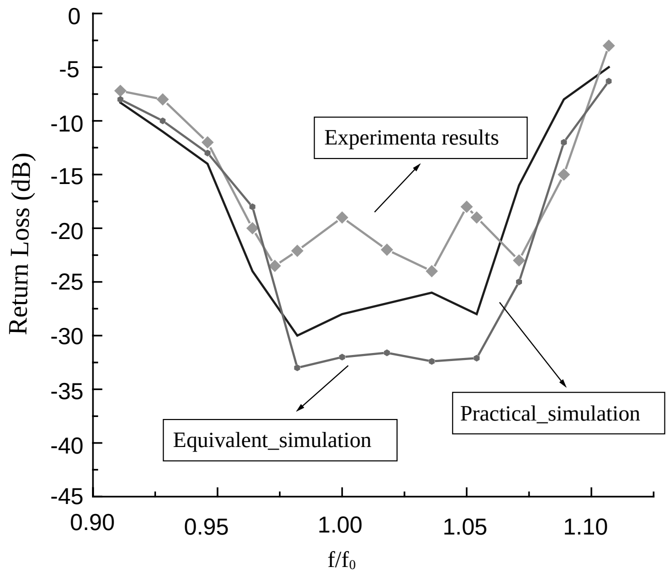


**Figure 7.** The return loss of the integrated structure.

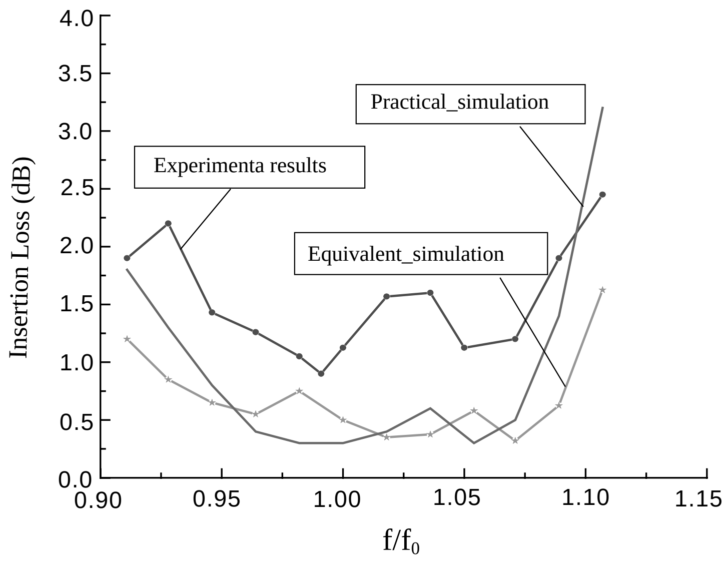


**Figure 8.** The insertion loss of the integrated structure.

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 torpid 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.

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