Design Equations for Tapered Microstrip-to-Substrate Integrated Waveguide Transitions

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***Abstract* — This paper presents design equations for the microstrip-to-Substrate Integrated Waveguide (SIW) transition. The transition is decomposed in two distinct parts: the microstrip taper and the microstrip-to-SIW step. Analytical equations are used for the microstrip taper. As for the step, the microstrip is modeled by an equivalent transverse electromagnetic (TEM) waveguide. An equation relating the optimum microstrip width to the SIW width is derived using a curve fitting technique. It is shown that when the step is properly sized, it provides a return loss superior to 20 dB. Three design examples are presented using different substrate permittivity and frequency bands between 18 GHz and 75 GHz. An experimental verification is also presented. The presented technique allows to design transitions covering the complete single-mode SIW bandwidth.**

***Index Terms* — Microstrip, substrate integrated waveguide, transition.**

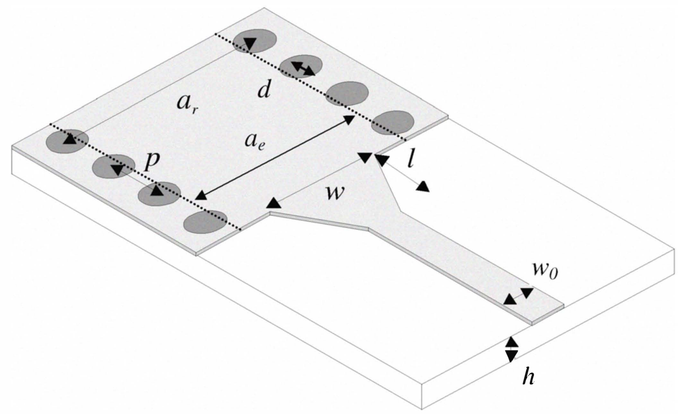

Fig. 1. Configuration of the microstrip-to-SIW transition.

I. Introduction

The Susbtrate Integrated Waveguide (SIW) was proposed ten years ago [1]. In its simplest form, this waveguide is composed of two parallel rows of metallic posts inserted in a plated substrate. If the distance between the posts and their diameter are chosen properly, the energy leaking between consecutive posts is negligible, as demonstrated in [2]. The particularity of this novel transmission line is that it bridges the gap between microstrip lines and metallic waveguides. Microstrip lines are very compact, easy to integrate and low cost but provide a relatively low quality factor, between 50 and 100. Metallic waveguides are, in comparison, bulky and expensive but they provide a high quality factor, between 5,000 and 10,000. The SIW is an intermediate structure. It benefits from the very low production cost of the PCB process and is relatively compact. It can also achieve a high quality factor, in the order of 500 to 1,000. Thus, the SIW is an excellent candidate for the integration of high density millimeter-wave circuits which require a good quality factor.

In the last ten years, several SIW components have been presented, including filters, couplers and antennas. These components, however, must be interconnected with planar structures in order to provide means for measurement and to allow the complete integration of SIW components with active circuits. The tapered microstrip transition [3] has largely been adopted for several reasons: the microstrip line is widely used; the transition covers the complete bandwidth of the SIW and the performances are better when compared to other microstrip transitions [4-7], or coplanar transitions [8-9]. Due to its very simple structure, the transition has very low losses. This comes from the fact that the electromagnetic field in the microstrip matches very well the field distribution in the SIW [3]. Despite that, the design process of this transition requires multiple full-wave simulations, because optimization is the strategy of choice to solve this problem. Indeed, as of yet no analytical equations have been proposed to speed up the design process.

This paper presents design equations for the microstrip-to-SIW transition. With these equations, it is possible to design full bandwidth transitions without optimization or full-wave simulations. They are validated with three examples at different frequencies, using different substrates. An experimental verification is also presented.

II. Design Technique

The microstrip-to-SIW transition is shown in Fig. 1. If the pitch (p) between consecutive posts is inferior or equal to twice the post diameter (d), the leakage losses are negligible [2]. In this case, the SIW can be replaced by a dielectric filled rectangular waveguide. The width is then equal to a_e, and the permittivity is ε_r. This equivalent width can be computed using the method presented in [2]. The SIW is then replaced by an equivalent waveguide in the following design steps.

The transition can be broken down into two sections: the tapered microstrip line and the step between the microstrip and the rectangular waveguide. The combination of these two parts must provide a good matching over the complete SIW bandwidth. As for the conventional rectangular waveguide, the bandwidth of the SIW is defined between $1.25f_c$ and $1.9f_c$, where f_c is the cut-off frequency, computed using the equivalent width, a_e.

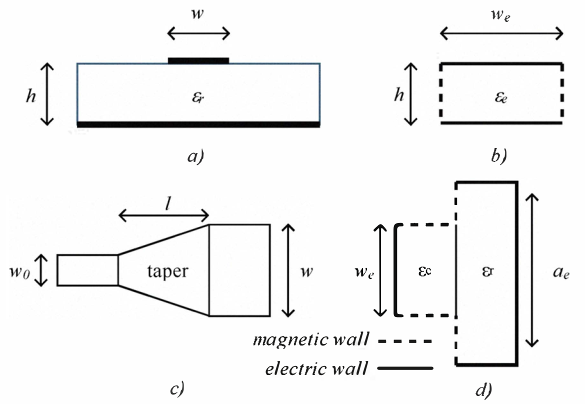

Fig. 2. Equivalent topology for the microstrip-to-SIW transition: a) microstrip line, b) waveguide model of a microstrip line, c) top view of the microstrip taper d) microstrip-to-SIW step.

A. Microstrip to Rectangular Waveguide Step

The microstrip to dielectric-filed rectangular waveguide step has already been analyzed using a mode matching technique [10]. In this paper, the microstrip is modeled by an equivalent TEM waveguide as shown in Fig. 2b). The continuous lines represent electric walls and the dash lines are magnetic walls. The permittivity of the dielectric in the TEM waveguide is equal to the effective permittivity of the microstrip line. Recalling the well-known result [11], we have in a microstrip structure:

$$\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12h/w}}. \quad (1)$$

The width of the TEM waveguide, w_e, is calculated to obtain the same impedance as in the microstrip line. The impedance of the waveguide shown in Fig. 2b) is given by

$$Z_e = \sqrt{\frac{\mu}{\varepsilon_0\varepsilon_e}}\frac{h}{w_e}. \quad (2)$$

Combining with the analytical equation for the impedance of a microstrip line [11], we obtain:

$$Z_e = \sqrt{\frac{\mu}{\varepsilon_0\varepsilon_e}}\frac{h}{w_e} = \begin{cases} \frac{60}{\sqrt{\varepsilon_e}} ln\left(8\frac{h}{w} + 0.25\frac{w}{h}\right) \\ \frac{120\pi}{\sqrt{\varepsilon_e}[w/h+1.393+0.667\ln(w/h+1.444)]} \end{cases}. \quad (3)$$

The first equation is used when $w/h < 1$ and the second, when $w/h > 1$. The model for the step between the microstrip and the SIW is presented in Fig. 2d). Of course, this model is not perfect. The capacitive effects at the end of the SIW in the transition plane are not taken into account, because magnetic walls are used to close the SIW. Also the field distribution in the microstrip model does not perfectly match the real one. However, this model is definitely good enough to accurately predict the amplitude of the scattering parameters. An experimental validation of the model was presented in [10].

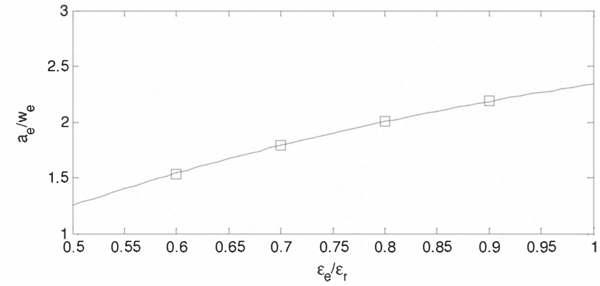

Fig. 3. Optimum dimension for the microstrip-to-SIW discontinuity as a function of the permittivity ratio.

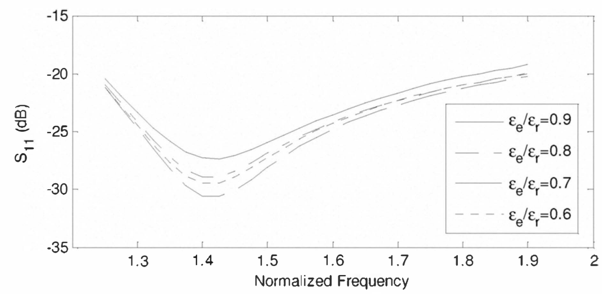

Fig. 4. Return loss for several microstrip-to-SIW discontinuities sized using the proposed desing equation (5).

In the structure shown in Fig. 2d), the scattering parameters are independent of the waveguide heights. The scattering parameters are then only dependant of: a_e, w_e, ε_e and ε_r. Waveguide structures are scalable: if the structure is reduced by half, we will get exactly the same S-parameters at twice the frequency. It is then possible to normalize the frequency of operation; the S-parameters are consequently related to the ratio a_e/w_e. Also, if we maintain the same ratio between the effective permittivity in the microstrip model and the permittivity in the SIW, the S-parameters, at the normalized frequency, will be unchanged. With these observations, we see that the scattering parameters, in the normalized frequency band, are only dependant of the ratios a_e/w_e and $\varepsilon_e/\varepsilon_r$.

We are interested in finding the optimal width that will minimize the return loss over the full waveguide bandwidth. For substrates with a permittivity between 1 and 20, and conventional microstrip structures, we have $0.5 < \varepsilon_e/\varepsilon_r < 1$. Several microstrip-to-SIW steps, using the model in Fig. 2d), have been optimized to find the optimum a_e/w_e for a given $\varepsilon_e/\varepsilon_r$ ratio. The results for these optimum values are shown in Fig. 3. Curve fitting techniques have been used to find the relation between permittivity and width ratios, and we found:

$$\frac{a_e}{w_e} = 4.38e^{-0.627\frac{\varepsilon_r}{\varepsilon_e}}. \quad (5)$$

It is generally possible to obtain a return loss lower than -20 dB over the full waveguide bandwidth, as shown in Fig. 4. The curves in Fig. 4 are the return loss results for the full-wave simulations for the dimensions shown by the markers in Fig. 3. We this in mind, we can now write the final design equations. Rewriting (3) and combining (1) and (5) we obtain:

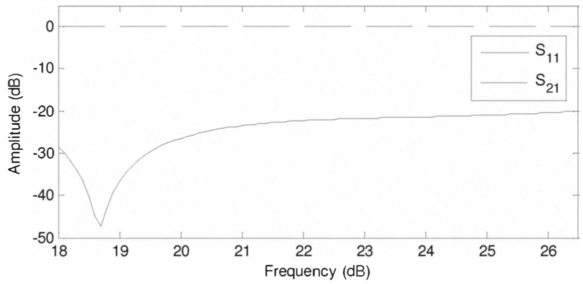

Fig. 5. Simulation results for the first design example.

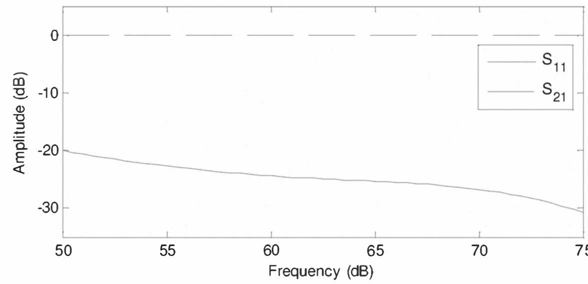

Fig. 6. Simulation results for the second design example.

$$\frac{1}{w_e} = \begin{cases} \frac{60}{\eta h} ln\left(8\frac{h}{w} + 0.25\frac{w}{h}\right) \\ \frac{120\pi}{\eta h[w/h+1.393+0.667\ln(w/h+1.444)]} \end{cases}, \quad (6a)$$

$$\frac{1}{w_e} = \frac{4.38}{a_e} e^{-0.627\frac{\varepsilon_r}{\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12h/w}}}}, \quad (6b)$$

where $\eta = (\mu_0/\varepsilon_0)^{1/2}$. For a given substrate (h and ε_r) and SIW width (a_e), we can equate (6a) and (6b) and solve it to find w, which is the optimum taper width.

B. Microstrip Taper

The microstrip taper is used to adapt the optimum width found in the previous section, w, to the input impedance of the microstrip line, w_0, as shown in Fig. 2c). A large difference between these two widths will require a long taper. In the millimeter frequency range and for a substrate with a permittivity comprised between 2 and 10, the widths w and w_0 are usually close and a quarter wavelength taper is sufficient to obtain a good return loss. In any case, taper lengths must be chosen as a multiple of a quarter of a wavelength in order to minimize the return loss. The transmission parameters of a linear tapered TEM transmission line are already known analytically [12]. These equations are used to verify the return loss of the taper over the full bandwidth.

III. DESIGN EXAMPLE

In order to validate the proposed design techniques, three transitions were designed in different frequency bands using several substrates. The design steps used to obtain the microstrip-to-SIW transitions are as follow:

1. Compute the equivalent width of the SIW (a_e). This width is computed using the technique presented in [2].
2. Compute the width of the microstrip taper (w). Equation (6) is solved for w.
3. Compute the taper length (l). The analytical equations presented in [12] are applied to find the length which minimizes the return loss over the full bandwidth.

The performances of the transition are finally evaluated using full-wave simulations.

A. First Design Example

The specifications for the first design example are:

- Frequency band : 18 to 26.5 GHz
- Substrate : Alumina (ε_r = 9.9, h = 0.254 mm)

The diameter of the post is 0.254 mm and the pitch between posts is 0.5 mm. The distance between the two rows of posts is equal to 3.55 mm. The equivalent width of the SIW is found to be: a_e = 3.39 mm. Solving (6) we have w = 1.44 mm. The taper length required to match this width to a 50 Ω microstrip line is equal to 5.5 mm, which represented three quarters of a wavelength. The design is now completed and the frequency response is verified with a full-wave simulation using *Ansoft HFSS*. The results are presented in Fig. 5. The return loss is better than 20 dB over the full bandwidth.

B. Second Design Example

The specifications for the second design example are:

- Frequency band : 50 to 75 GHz
- Substrate : Liquide Crystal Polymer (ε_r = 3.15, h = 150 μm)

The post diameter is 200 μm and the pitch between posts is 400 μm. The distance between the two rows of posts is selected as 2.24 mm. The equivalent width of the SIW is then equal to 2.12 mm. Solving (6) for the optimum microstrip width, we find w = 770 μm. The taper length required to match the output to a microstrip line of width equal to 370 μm is found to be 1.57 mm. The return loss in this case is below -25 dB for the taper. The full-wave simulation results for the complete transition are presented in Fig. 6. Return loss better than 20 dB is again achieved in the complete bandwidth.

C. Third Design Example

The specifications for the third design example are:

- Frequency Band : 24 to 38 GHz
- Substrate : Duroid (ε_r = 2.2, h = 0.508 mm)

The dimensions related to the SIW are: d = 0.77 mm, p = 1.52 mm and a_r = 5.57 mm. The equivalent width of the SIW is equal to: a_e = 5.08 mm. Solving (6) we find w = 1.55 mm. The taper length required to match this width to a microstrip line of width equal to 0.76 mm is 1.57 mm. Excellent results are also obtained for this transition, as shown in Dig. 7.

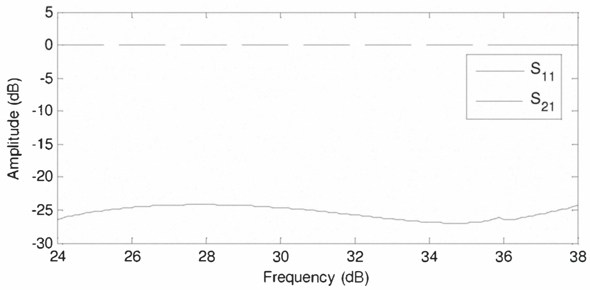

Fig. 7. Simulation results for the third design example.

IV. Experimental Validation

The third design example presented in the last section has been fabricated and measured. The measured structure involves two transitions separated with a 9.9 mm section of SIW. The simulated and measured results of the complete structure are presented in Fig. 8. Two back-to-back transitions give a global return loss superior to 18 dB over the whole bandwidth and a global insertion loss lower than 0.45 dB. There is a good agreement between the full-wave simulation and the measured results.

VII. Discussion

The proposed technique allows to design microstrip-to-SIW transitions without the need for any full-wave simulations. Analytical equations, derived using curve fitting techniques, are used to evaluate the optimum width at the output of the taper. The taper length, which should be a multiple of quarter-wavelength, is selected using the analytical equation for linear tapered transmission lines. This design does not take into account the parasitic reactance at the end of the SIW or does it benefit from the cancellations that could occur due to multiple reflections. Nevertheless, it guaranty very good performances over the full SIW bandwidth, without any tuning or optimization. Some applications may require better matching in a narrow band. In these cases, the proposed techniques can very well be used to find a starting point that can further be optimized. In this way, the optimization process will converge easily as the starting point will be close to the optimum value.

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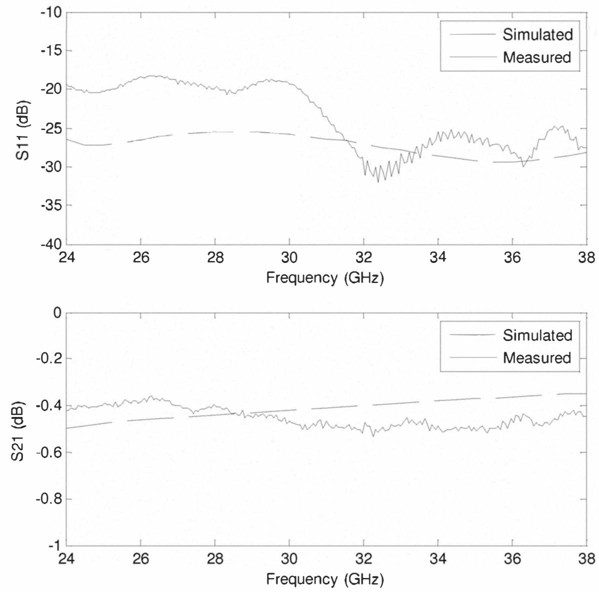

Fig. 8. Simulated and measured resulted for the manufactured prototype.

References

[1] J. Hirokawa and M. Ando, "Single-layer feed waveguide consisting of posts for plane TEM wave excitation in parallel plates," *IEEE Trans. Microwave Theory & Tech.*, vol. 46, no. 5, pp. 625–630, May 1998.

[2] D. Deslandes and K. Wu, "Accurate modeling, wave mechanism, and design consideration of a substrate integrated waveguide," *IEEE Trans. Microwave Theory & Tech.*, vol. 54, no. 6, pp. 2516–2526, Jun. 2006.

[3] D. Deslandes and K.Wu, "Integrated microstrip and rectangular waveguide in planar form," *IEEE Microwave Wireless Compon. Lett.*, vol. 11, no. 2, pp. 68–70, Feb. 2001.

[4] N. Jain and N. Kinayman, "A novel microstrip mode to waveguide mode transformer and its applications," *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, 2001, pp. 623–626.

[5] T. H. Yang, C. F. Chen, T. Y. Huang, C. L. Wang, and R. B. Wu, "A 60GHz LTCC transition between microstrip line and substrate integrated waveguide," *Proc. APMC*, vol. 1, pp. 4-7, Dec. 2005.

[6] M. Abdolhamidi, A. Enayati, M. Shahabadi and R. Faraji-Dana, "Wideband single-layer DC-decoupled Substrate Integrated Waveguide (SIW)-to-microstrip transition using an interdigital configuration," *Asia-Pacific Microwave Conference*, Dec. 2007.

[7] C.-K. Yau, T.-Y. Huang, T.-M. Shen, H.-Y. Chien and R.-B. Wu, "Design of 30GHz transition between microstrip line and substrate integrated waveguide," *Asia-Pacific Microwave Conference*, Dec. 2007.

[8] D. Deslandes and K. Wu, "Integrated transition of coplanar to rectangular waveguides," *IEEE MTT-S Int. Microwave Symp. Dig.*, May 2001, pp. 619–622.

[9] D. Deslandes and K. Wu, "Analysis and design of current probe transition from grounded coplanar to substrate integrated rectangular waveguides," *IEEE Trans. Microwave Theory & Tech.*, vol. 53, pp. 2487-2494, Aug. 2005.

[10] G. Kompa, "About the frequency-dependent characteristics of a microstrip-waveguide transiton," *AEÜ*, vol 35, 1981, pp. 69-71.

[11] D. M. Pozar, *Microwave Engineering*, 2nd Ed., Toronto: John Wiley & Sons, 1998, pp. 144-145.

[12] K. Lu, "An efficient method for analysis of arbitary nonuniform transmission lines," *IEEE Trans. Microwave Theory & Tech.*, vol. 45, pp. 9–14, Jan. 1997.