Designing the Width of Substrate Integrated Waveguide Structures

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***Abstract*—A new formula for the effective width design of substrate integrated waveguide (SIW) structures is presented. Contrary to another formulation of similar accuracy, which requires an iterative process or solution of a fifth-order polynomial, the new equation allows the direct design of the SIW's width for a given cutoff frequency. The presented formula is obtained by minimizing the reflections from the junction between the SIW and an all-dielectric waveguide of equivalent width. A mode-matching approach is used to derive the equation which is verified by comparison with μWaveWizard for three SIW examples. Further optimizations in CST Microwave Studio and μWaveWizard demonstrate the robustness of the new formula.**

***Index Terms*—Design equation, effective waveguide width, mode-matching techniques (MMTs), substrate integrated waveguide (SIW).**

I. Introduction

SUBSTRATE integrated waveguide (SIW) technology has proven to be a promising alternative to conventional waveguides for the design of microwave and millimeter-wave circuits. In this technology, relatively low-loss and high-Q waveguide structures are realized in compact size, low-cost, and highly integrated planar structures. As the field pattern inside the SIW is similar to that of rectangular waveguide structures, the design of any SIW structure starts with specifying the waveguide width for the desired frequency band and substrate material. Therefore, the equivalent width of the SIW is of fundamental design importance.

The first and most simple relationship between the SIW width a_{SIW} and its effective waveguide width W_{equi} (cf. Fig. 1) was reported in 2002 [1] when the admittance matrix of a periodic cell of the SIW structure was calculated using the BI-RME method and a formula for the effective waveguide width of the SIW structure reported. The formula was slightly modified empirically in 2005 [2].

In 2004, an experimental formula for the normalized equivalent SIW width was presented [3]. In 2006, the frequency-dependent W_{equi} was obtained from experimental data [4], but a direct design equation is not provided. In [5], a method of moment (MoM) approach was used to calculate a_{SIW} in terms of W_{equi}. Finally, in [6] the unit cell of a via hole and the dielectric space to its neighbor was approximated by electric walls and solved as a rectangular waveguide discontinuity. The SIW's effective waveguide width W_{equi} was then calculated and a correction term was added for more accurate results. These five different models [1]–[3], [5], [6] have been compared in [7] for different ratios of via diameter to via pitch, d/p (Fig. 1). It was found that the accuracies of such formulas vary depending on the d/p ratio. Therefore, the design of an SIW would often proceed using an inferior equivalent-width formula. However, no new design formulas are presented in [7].

For the design engineer, the use of such equations (with the exception of the simplest one in [1]) is not straightforward as the design parameter a_{SIW} is embedded in the computation of equivalent width W_{equi}. For the equation that so far provides the best design based on our investigation [3], an iterative process or the solution of a fifth-order polynomial would be required to design the actual SIW parameter a_{SIW}. Similar complexity is involved using [6]. Only [5] presents a_{SIW} as a function of W_{equi}. However, the approach in [5] is found to be far less accurate than the models presented in [1]–[3], [6].

Therefore, in this letter, we present a new formula based on the mode-matching technique (MMT) for the design of the actual SIW width a_{SIW} in terms of the equivalent waveguide width W_{equi}, which determines the frequency range and bandwidth of the SIW. The formula is based on the reflection from an all-dielectric waveguide of width W_{equi} to an SIW of width a_{SIW}. If that reflection is the lowest, then the actual SIW width is best adjusted to the equivalent waveguide width.

II. Theory

Fig. 1 shows the structural parameters of an SIW structure with width a_{SIW}, consisting of 20 pairs of via holes with diameter d and via pitch p, and with all-dielectric waveguide ports of width W_{equi}. This structure is analyzed with a mode-matching technique (MMT) [8] that uses a circular-to-square via conversion such that the square vias' side lengths are equal to the arithmetic mean of the side lengths of the inscribed and circumscribed squares of the circular via [9]. For details of this technique, the reader is referred to [8], [9], where the theory is fully described, including every formula required to perform the S-parameter calculations. In order to obtain the best value for a_{SIW}, with W_{equi}, d and p given, the input reflection coefficient of the transition is minimized by varying a_{SIW}. Note that during this process, the number of via-hole pairs in Fig. 1 was changed a few times by approximately a quarter wavelength to make certain that the low reflection coefficient was not influenced by the combination of the two (input and output) discontinuities of the structure (cf. Fig. 4).

This entire procedure was repeated for the practical range of different d/p ratios which, in order to avoid leakage loss in SIW

Manuscript received May 17, 2013; revised July 05, 2013; accepted July 21, 2013. Date of publication August 30, 2013; date of current version October 03, 2013. This work was supported by the National Science and Engineering Research Council of Canada (NSERC).

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Digital Object Identifier 10.1109/LMWC.2013.2279098

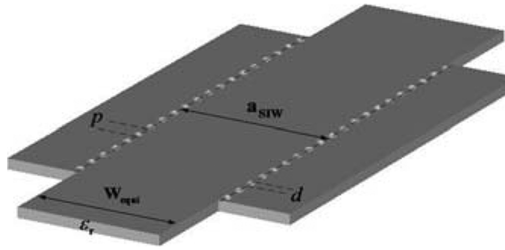

Fig. 1. Structural parameters of the discontinuity between an all dielectric waveguide and the SIW structure.

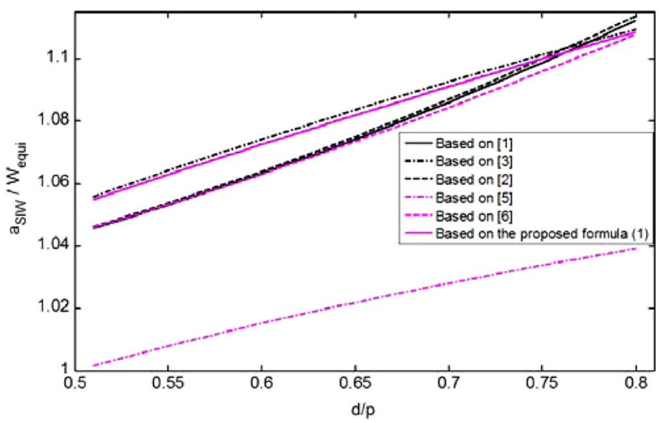

Fig. 2. $a_{\rm SIW}/W_{\rm equi}$ ratios of different formulas reported in the literature for $W_{\rm equi} = 5.828$ mm, $p = 1$ mm on a substrate with $\varepsilon_r = 2.94$.

structures and make fabrication realizable, should lie between 0.5 and 0.8 [10]. Fig. 2 shows the obtained $a_{\rm SIW}/W_{\rm equi}$ ratios versus d/p and compares them to those values found in the literature [1]–[3], [5], [6]. It is observed that our results are closest to that of [3], but the empirical formula in [3] does not allow a *direct* design of $a_{\rm SIW}$. It is also observed that the values reported in [1], [2], and [6] are in relatively close vicinity. However, the results based on [5] are far from the other methods.

Based on the optimum width $a_{\rm SIW}$ obtained from the investigation described in the first paragraph of this section, the nonlinear least squares technique is used to obtain the final formula for the design of $a_{\rm SIW}$

$$a_{\rm SIW} = W_{\rm equi} + p(0.766e^{0.4482d/p} - 1.176e^{-1.214d/p}). \quad (1)$$

The error of this equation is within 1.2×10^{-3} percent of the original data. Note that due to normalization, this formula is independent of the relative permittivity of the substrate and frequency. The applicable range of (1) covers all practical SIW applications for which $0.5 < d/p < 0.8$ [10]. For these limits, $a_{\rm SIW} - W_{\rm equi}$ varies between 0.318 p and 0.651 p which is consistent with fact that $a_{\rm SIW}$ is always larger than $W_{\rm equi}$ and that larger vias require more lateral spacing (Fig. 1) to match the same equivalent waveguide width $W_{\rm equi}$.

For the design of an SIW, the cutoff frequency f_c, substrate permittivity ε_r and d/p ratio $(0.5 < d/p < 0.8)$ are specified. Then the SIW width $a_{\rm SIW}$ is immediately obtained from (1) once the effective waveguide width $W_{\rm equi}$ is calculated from

$$W_{\rm equi} = \frac{c}{2f_c\sqrt{\varepsilon_r}}. \quad (2)$$

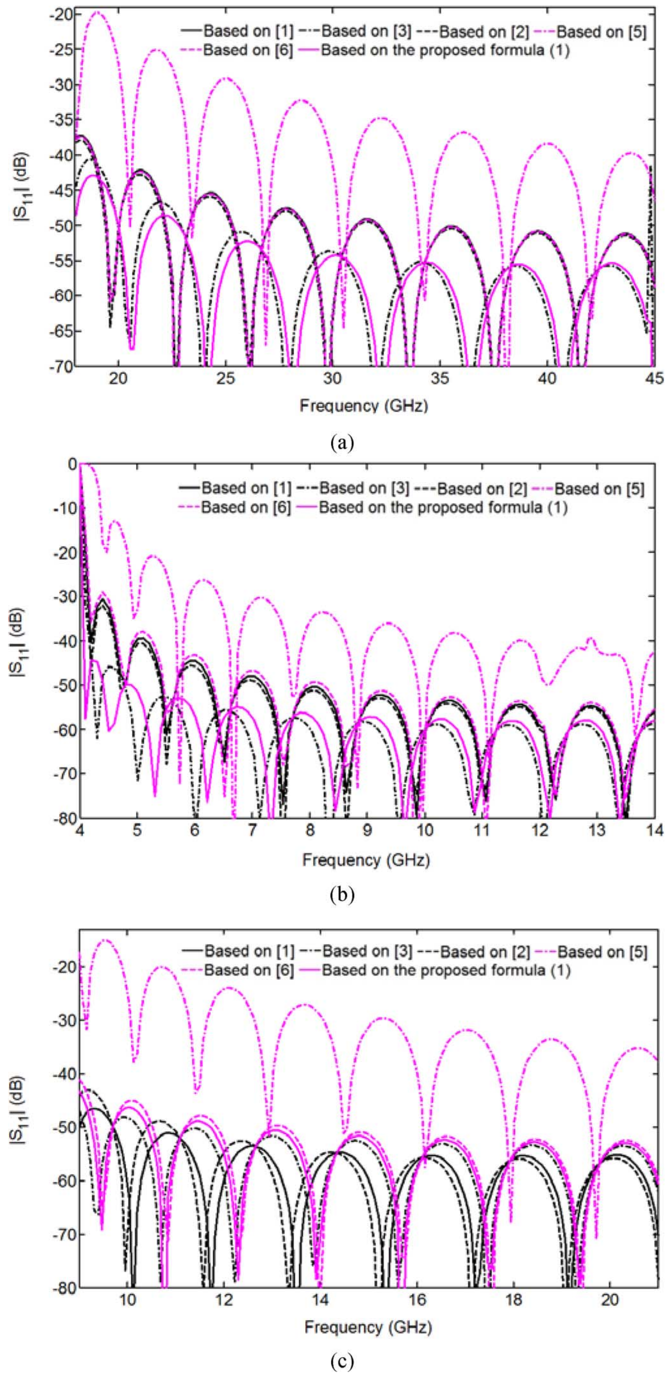

Fig. 3. Return loss investigation of an SIW structure with waveguide ports with μWaveWizard for different formulations. The structural parameters are: (a) RT/duroid 6002 $(\varepsilon_r = 2.94)$, $W_{\rm equi} = 5.828$ mm, $d = 0.55$ mm, $p = 1$ mm; (b) RT/duroid 6010 $(\varepsilon_r = 10.2)$, $W_{\rm equi} = 11.734$ mm, $d = 1.36$ mm, $p = 2$ mm; (c) RT/duroid 6006 $(\varepsilon_r = 6.15)$, $W_{\rm equi} = 8$ mm, $d = 0.96$ mm, $p = 1.2$ mm.

III. Results

Three different design examples illustrate the usefulness of the new formula (1). For different substrates, frequency bands and d/p ratios, the input reflection coefficient of the structure in Fig. 1 is calculated using the μWaveWizard and presented in Fig. 3. In each example, the result based on $a_{\rm SIW}$ of (1) is compared to those of [1]–[3], [5], [6].

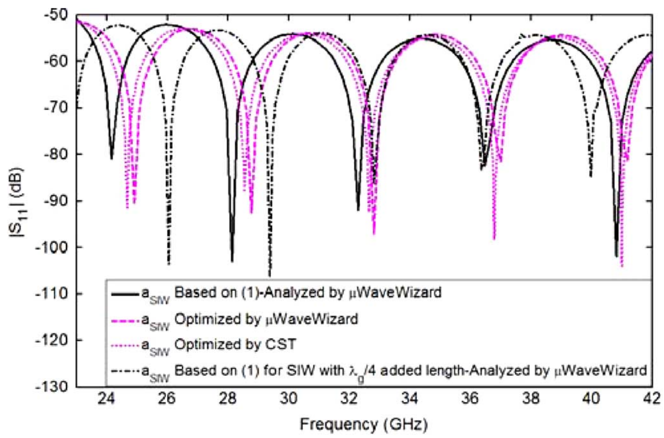

Fig. 4. Comparison between reflection coefficients of an SIW structure with waveguide ports, for three different values of $a_{\rm SIW}$: $a_{\rm SIW}$ based on (1) (solid line—analyzed by μWaveWizard), $a_{\rm SIW}$ based on (1) for SIW with quarter of wavelength added line (dashed-dotted line—analyzed by μWave-Wizard), optimized $a_{\rm SIW}$ with μWaveWizard (dashed line) and CST (dotted line). The structural parameters are: RT/duroid 6002 ($\varepsilon_r = 2.94$), $W_{\rm equi} = 5.828$ mm, $d = 0.55$ mm, $p = 1$ mm.

First we are considering an RT/duroid 6002 substrate with $\varepsilon_r = 2.94$, height $h = 0.508$ mm and $f_c = 15$ GHz, resulting in $W_{\rm equi} = 5.828$ mm according to (2). The via pitch is chosen such that we have at least twelve vias per wavelength. Thus $p = 1$ mm and $d = 0.55$ mm are chosen $(d/p = 0.55)$. Fig. 3(a) shows input reflection results for different $a_{\rm SIW}$ obtained from different formulas reported in the literature and in (1). It is observed that the $a_{\rm SIW}$ calculated with the proposed formula (1) yields the minimum return loss. (Note that due to symmetry reasons, the theoretical bandwidth is extended to $3f_c$).

As the second example, we are using RT/duroid 6010 with $\varepsilon_r = 10.2$ and height $h = 1.27$ mm. We are interested to work in the C-band so that (2) yields $W_{\rm equi} = 11.7336$ mm for $f_c = 4$ GHz. $p = 2$ mm and $d = 1.36$ mm are chosen so that $d/p = 0.68$. Fig. 3(b) shows the reflection coefficients for different $a_{\rm SIW}$ obtained from the literature and from (1). As it can be seen, the calculated $a_{\rm SIW}$ based on the proposed formula (1) yields the minimum return loss when the entire frequency band is considered.

The third example uses RT/duroid 6006 with $\varepsilon_r = 6.15$ and substrate height $h = 0.508$ mm. The frequency range is X-band, and we obtain $W_{\rm equi} = 8$ mm for $f_c = 7.56$ GHz. The via dimensions are selected as $p = 1.2$ mm and $d = 0.96$ mm $(d/p = 0.8)$. Fig. 3(c) shows the input reflection coefficients for different $a_{\rm SIW}$ obtained from [1]–[3], [5], [6] and from (1). As can be expected from Fig. 2 $(d/p = 0.8)$, the calculated $a_{\rm SIW}$ based on the different formulas (except for [5]) are really close which is confirmed in Fig. 3(c). Note that at such a high d/p ratio, which is not often used in practice, the simplest formula [1] provides slightly better results.

From the plots presented in Fig. 3, the reflection coefficient of the SIW structure with all-dielectric waveguide ports with SIW width based on [5] are between -20 dB to -30 dB for all three cases. Those based on [1], [2], and [6] are between -40 dB to -50 dB. The best return loss of the structure for $d/p < 0.75$ is obtained with the empirical width from [3] and the width proposed in this work (1)—with a few dB improvement compared to [3]. However, in order to calculate $a_{\rm SIW}$ according to [3], the roots of a fifth-order polynomial need to be calculated. In all different structures, the SIW widths calculated based on these two formulations, lead to the return loss between -50 dB and -60 dB. For $d/p > 0.75$, all different formulations (except for [5]) result in almost the same value for $a_{\rm SIW}$, as it can be seen in Fig. 2.

In Fig. 4, we are demonstrating that once $a_{\rm SIW}$ is obtained from (1), further attempts by optimization to find an $a_{\rm SIW}$, which might provide better return loss than that given by (1), either in μWaveWizard or in CST, will not result in better performance. This confirms the robustness of the formula presented in (1). Note that in this and previous figures, the ripples are related to the length of 20 via-hole pairs between the two discontinuities at the input and output [Fig. 1]. Of course, the number of minima changes with the SIW length or number of via-hole pairs. It is important to observe though that the levels of the maxima do not change; in other words, the level of reflection is independent of the interaction between the input and output discontinuities. This is demonstrated in Fig. 4 by adding three SIW pairs which corresponds to an additional line length of approximately a quarter-wavelength.

IV. Conclusion

A new formula for the design of SIW components is presented. It allows the design engineer to directly obtain the optimum SIW width without solving more complicated formulas presented in the literature. The validity and usefulness of the new formula is demonstrated for three design examples spanning a large variety of frequency ranges, substrates and d/p ratios. Moreover, it is demonstrated that further optimization of the SIW width does not improve the excellent performance obtained with the new formula.

References

[1] Y. Cassivi, L. Perregrini, P. Arcioni, M. Bressan, K. Wu, and G. Conciauro, “Dispersion characteristics of substrate integrated rectangular waveguide,” *IEEE Microw. Wireless Compon. Lett.*, vol. 12, no. 9, pp. 333–335, Sep. 2002.

[2] F. Xu and K. Wu, “Guided-wave and leakage characteristics of substrate integrated waveguide,” *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 1, pp. 66–73, Jan. 2005.

[3] L. Yan, W. Hong, G. Hua, J. Chen, and K. Wu, “Simulation and experiment on SIW slot array antennas,” *IEEE Microw. Wireless Compon. Lett.*, vol. 14, no. 9, pp. 446–448, Sep. 2004.

[4] C. Tseng and T. Chu, “Measurement of frequency-dependent equivalent width of substrate integrated waveguide,” *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 4, pp. 1431–1437, Apr. 2006.

[5] W. Che, K. Deng, D. Wang, and Y. L. Chow, “Analytical equivalence between substrate-integrated waveguide and rectangular waveguide,” *IET Microw. Antennas Propag.*, vol. 2, no. 1, pp. 35–41, Feb. 2008.

[6] M. Salehi and E. Mehrshahi, “A closed-form formula for dispersion characteristics of fundamental SIW mode,” *IEEE Microw. Wireless Compon. Lett.*, vol. 21, no. 1, pp. 4–6, Jan. 2011.

[7] F. Taringou and J. Bornemann, “Return-loss investigation of the equivalent width of substrate-integrated waveguide circuits,” in *Proc. IEEE MTT-S Int. Microw. Workshop Series Millim. Wave Integr. Technol.*, 2011, pp. 140–143.

[8] J. Bornemann, F. Taringou, and Z. Kordiboroujeni, “A mode-matching approach for the analysis and design of substrate-integrated waveguide components,” *Freq.—J. RF/Microw. Engr. Photon., Commun.*, vol. 65, pp. 287–292, Sep. 2011.

[9] Z. Kordiboroujeni, J. Bornemann, and T. Sieverding, “Mode-matching design of substrate-integrated waveguide couplers,” in *Proc. Asia-Pacific Int. Symp. Electromag. Compat.*, Singapore, May 2012, pp. 701–704.

[10] D. Deslandes and K. Wu, “Accurate modeling, wave mechanisms, and design considerations of a substrate integrated waveguide,” *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 6, pp. 2516–2526, Jun. 2006.