Comparison on the Coupling Between Substrate Integrated Waveguide and Microstrip Transmission Lines for Antenna Arrays

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***Abstract*—Substrate Integrated Waveguide (SIW) offers a simple and affordable method to implement waveguides in a printed circuit board. This paper presents simulated and measured results on the coupling characteristics between two SIWs and between an SIW and a microstrip transmission line. From the results, the authors conclude that the coupling between the SIW and microstrip transmission line is much less than the SIW to SIW coupling. This could prove useful in antenna designs.**

I. Introduction

Rectangular waveguides have long been a staple of high frequency and high-power RF designs. Although necessary for these types of designs, a rectangular waveguide is typically large, bulky and expensive to manufacture. These factors limit its use to specialized designs where cost and size are not design considerations. Additionally, prototyping any design requiring a rectangular waveguide is usually not possible. Planar microwave structures however, exhibit the opposite characteristics. While poor insertion loss plagues these structures at higher frequencies, their low cost and ease of manufacturing make them common in many printed circuit board (PCB) designs. Additionally, equipment exists which is able to produce these structures rapidly and inexpensively. This makes prototyping designs a possibility.

Following the growing popularity of planar microwave structures, substrate integrated waveguide (SIW), as described in [1] and shown in Figure 1, offers the benefits of a rectangular waveguide in a planar structure. An abundance of literature focuses on SIW design rules, characterization, filters such as the bandpass filter in [2], as well as feeding antenna arrays as in [3] and [4]. However, considerably less literature focuses on the coupling characteristics of SIW. Therefore, this paper investigates these coupling characteristics from an antenna array design point-of-view. In the paper, we look at the coupling between two SIW structures and between an SIW and a microstrip structure. We then compare the performance of both test structures in terms of coupling and insertion loss.

II. Design of the Test Structures

Building upon the work presented in [5], the authors in [6] were one of the first to build an SIW and the associated feed structure using plated vias. While novel, the method still required the use of a waveguide to excite a waveguide mode in the structure. The simple microstrip taper presented in [1] allowed the proliferation of SIW in literature. The ease of feeding an SIW with an end-launch solution greatly increases its utility. With the increasing popularity of SIW, the authors foresee the use of SIW in conjunction with microstrip transmission lines on the same PCB, prompting our research in this paper.

With space constraints present in design criteria, coupling

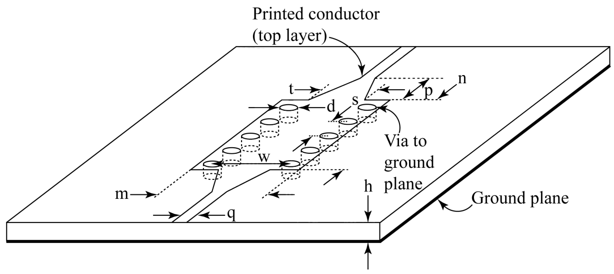


Fig. 1. The SIW structure in this work with labeled dimensions.

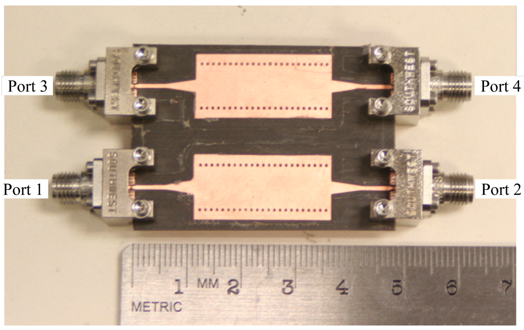


Fig. 2. Test structure for testing two SIW transmission lines. The structures are separated by 7 mm, copper edge to copper edge. The dimensions of the SIW are as defined by the variables in Figure 1: d = 0.6 mm, h = 0.324 mm, l = 2.286 mm, m = 12 mm, n = 25 mm, p = 5.588 mm, q = 0.711 mm, s = 1.05 mm and w = 8.33 mm. The port numbering used for the results in Section III are displayed. This test board is referred to as SIW-SIW in Tables I-IV.

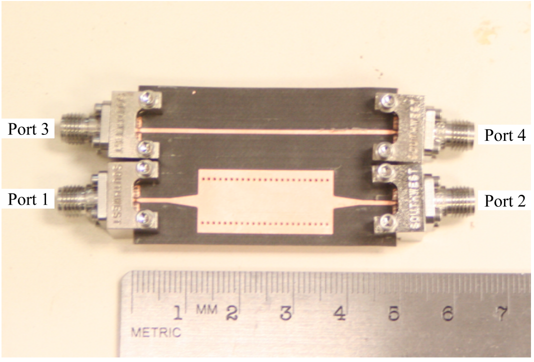


Fig. 3. Test structure for testing an SIW and microstrip transmission line. The port numbering used for the results in Section III are displayed. The dimensions for the SIW in this test board are the same as in Figure 2. This test board is referred to as SIW-MS in Tables I-IV.

between adjacent transmission lines becomes an issue when different signal lines are placed in close proximity. Despite the best efforts of the authors, no current literature found investigated the issue of coupling between SIW and other types of transmission lines. In order to test this issue, the authors decided to create two separate test structures: one testing coupling between two SIW transmission lines, shown in Figure 2, and one testing coupling between an SIW and microstrip transmission line, shown in Figure 3. We decided to use the microstrip taper feed method for all designs as outlined in [1].

The main motivation to test the coupling of SIW stems from its physical structure. Using two parallel, periodically repeating lines of plated via holes, SIW emulates the solid walls of a rectangular waveguide using multiple discrete metal posts; the top and bottom copper planes of the PCB serve as a parallel-plate waveguide. As noted in [7], the discontinuities in two of the waveguide walls present a leakage issue. Besides the issue of increased attenuation, we also see the leakage as a potential coupling issue. The authors of [7] go on to study the mode propagation characteristics of SIW. Through their research, the authors in [7] found that SIW emulates a rectangular waveguide successfully when implemented according to their specified design rules. Referring to the dimensions in Figure 1, to determine the width w of an SIW equivalent rectangular waveguide, the authors in [7] provided the following empirically determined equation.

$$w_{eff} = w - 1.08\frac{d^2}{s} + 0.1\frac{d^2}{w} \qquad (1)$$

In Equation 1, w is the width of a rectangular waveguide, s is the periodic length between posts in the SIW, and d is the diameter of the post. These dimensions are shown graphically in Figure 1.

While the design of the SIW used in this paper is similar to the design in [1], our test equipment only analyzes devices up to 26.5 GHz. We therefore modified the SIW structure in [1] to have a cutoff frequency of 13 GHz. Using the rectangular waveguide design equations in [8], and Equation 1, we found the necessary w to be 8.33 mm. The reference of w with respect to the SIW as well as other critical design dimensions for the SIW in this project can be found in Figure 1. The total length of the SIW line, n, in each test structure is 25 mm. The length of microstrip transmission line from the board edge to the taper has a characteristic impedance of 50 Ω and is 2 mm in length. The microstrip line width was determined using a passive circuit design utility [9]. We manufactured both test structures on Rogers Duroid 5860, with a relative permittivity (ϵ_r) of 2.33, substrate thickness of 0.254 mm and 1 oz. copper. The two test structures are shown in Figures 2 and 3. The SMA connector is from SouthWest Microwave. The connector uses an adjustable clamp, avoiding substrate thickness incompatibilities encountered with fixed metal connectors.

For the dimensional choices in our test structures, we found motivation in both [1] and [7]. The taper dimensions result from the work in [1]. From simulation, we deemed these dimensions suitable for the SIW in this work, even with a lower cutoff frequency (resulting in a larger w). While our choice for a thin substrate, given by h (not including copper thicknesses) in Figure 1 does increase conductor losses, it will decrease radiation losses from the microstrip sections [1]. The thin substrate will also not effect mode propagation, since only TE_{n0} modes will be present [7]. Observing Figure 1, our choices for d and s were motivated by equipment capabilities and the results from [7]. These results recommended keeping the ratio of $\frac{s}{d}$ and $\frac{d}{w}$ as small as possible, in order to decrease attenuation and maintain dispersion characteristics. For the test structures in Figures 2 and 3, the coupling distance measured from copper edge to copper edge of each line is 7 mm.

III. Measurement and Simulation Results

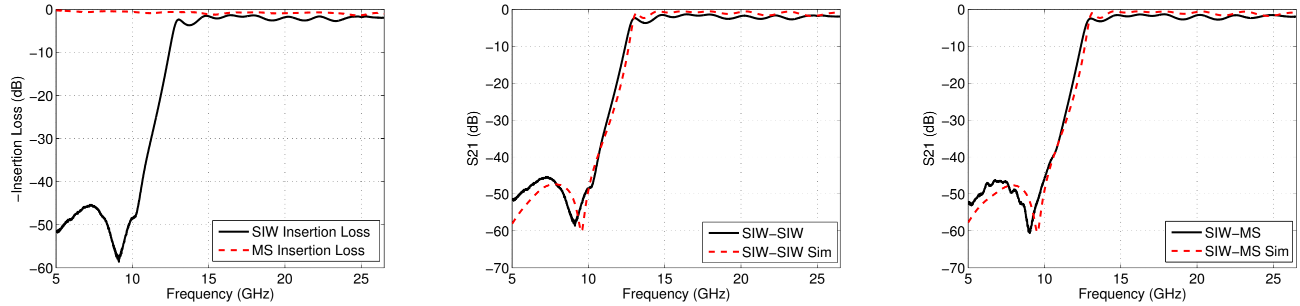
Each test structure was modeled and simulated in a Finite-Element method simulation software package [10]. After simulation, each structure was manufactured and tested using a PNA network analyzer, rated between 10 MHz and 26.5 GHz. The S-parameters for each test structure, along with individual simulation and measured data comparisons are given in Figures 4-6. Additionally, Tables I, II and III give the absolute error between simulated and measured results, the mean and standard of deviation for the measured results and an insertion loss comparison, respectively, above the waveguide cutoff frequency. The data in Table IV gives measured and simulated results below the waveguide cutoff frequency.

A. S21 / Insertion Loss

S21 and insertion loss data is shown in Figure 4 and given numerically in Table II. Measured and simulation data correlated well, observing the data in Table I. The 13 GHz waveguide cutoff frequency is evident in Figures 4a, 4b and 4c. The increased insertion loss present in the measured data, compared to simulation data, results from connector losses and launch mismatch, which were not simulated. Comparing the insertion loss of SIW to microstrip in Figure 4a, it is apparent that SIW exhibits greater insertion loss. This is numerically compared in Table III.

B. S31 & S41

S31 data is shown in Figure 5 and S41 data is shown in Figure 6. Measured and simulation data again correlated well observing the data in Table I. Since the cutoff frequency of the SIW is 13 GHz, we did not consider the coupling

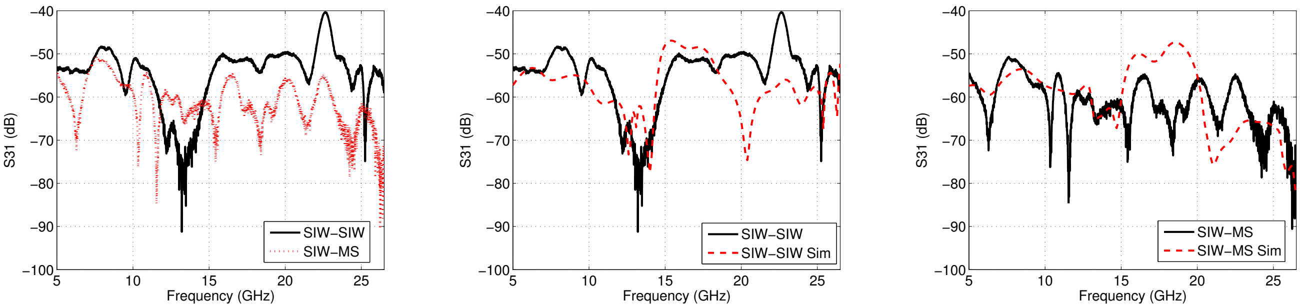


(a) Comparison of measured insertion loss for SIW to microstrip.

(b) Comparison of measured S21 to simulation data for the 2 SIW test structure shown in Figure 2.

(c) Comparison of measured S21 to simulation data for the SIW and microstrip test structure shown in Figure 3.

Fig. 4. Simulated and measured data for insertion loss / S21.



(a) Comparison of S31 experimental data.

(b) Comparison of measured S31 to simulation data for the 2 SIW test structure shown in Figure 2.

(c) Comparison of measured S31 to simulation data for the SIW and microstrip test structure shown in Figure 3.

Fig. 5. Simulated and measured data for S31.

TABLE I. SIMULATED AND MEASURED RESULTS ARE COMPARED BETWEEN 13 GHZ AND 26.5 GHZ. MEAN ABSOLUTE ERROR AND THE STANDARD OF DEVIATION IS PRESENTED.

Test Board	Measurement	Mean Error (dB)	Stdev (dB)
SIW-SIW	S21	1.02	0.47
SIW-SIW	S31	7.04	5.29
SIW-SIW	S41	7.46	6.01
SIW-MS	S21	0.97	0.38
SIW-MS	S31	7.43	5.30
SIW-MS	S41	8.25	6.58

TABLE II. MEAN OF THE SIMULATED AND MEASURED RESULTS ARE COMPARED BETWEEN 13 GHZ AND 26.5 GHZ.

Test Board	Measurement	Simulate Mean (dB)	Measured Mean (dB)
SIW-SIW	S21	-1.07	-2.08
SIW-SIW	S31	-57.42	-54.49
SIW-SIW	S41	-56.56	-54.37
SIW-MS	S21	-1.06	-2.02
SIW-MS	S31	-61.62	-63.05
SIW-MS	S41	-60.97	-62.90

in any structure containing SIW below that frequency point. Observing Figures 5a and 6a, as well as Table II, it is evident that greater coupling exists between the transmission lines of the 2 SIW test board shown in Figure 2 than the SIW to microstrip test board shown in Figure 3.

TABLE III. MEAN OF THE MEASURED RESULTS FOR INSERTION LOSS BETWEEN 13 GHZ AND 26.5 GHZ.

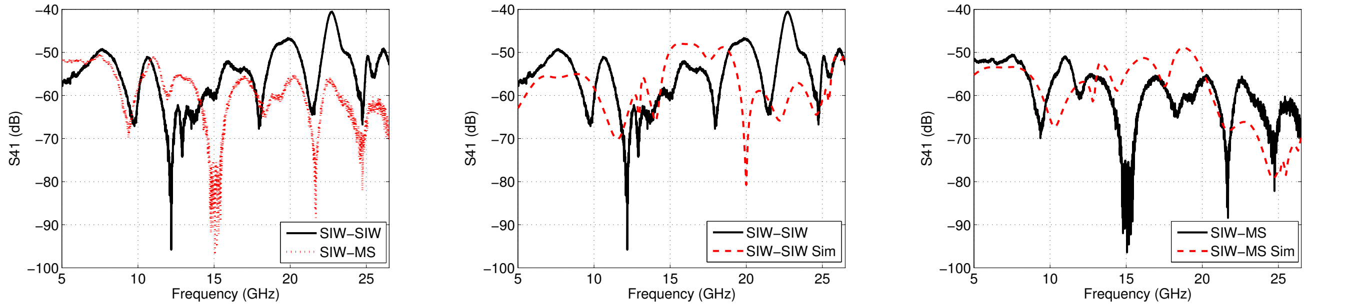
Test Board	Measurement	Measured Mean (dB)
SIW-SIW	S21	-2.08
SIW-MS	S21	-2.02
SIW-MS	S43	-0.89

TABLE IV. MEAN OF THE SIMULATED AND MEASURED RESULTS ARE COMPARED BETWEEN 5 GHZ AND 13 GHZ.

Test Board	Measurement	Simulate Mean (dB)	Measured Mean (dB)
SIW-SIW	S21	-42.91	-40.77
SIW-SIW	S31	-57.84	-55.52
SIW-SIW	S41	-59.63	-57.52
SIW-MS	S21	-43.02	-40.94
SIW-MS	S31	-57.04	-58.61
SIW-MS	S41	-57.39	-55.16

IV. DISCUSSION

From the simulation data and the measured data, several conclusions can be made. First, observing Table III, the microstrip transmission line exhibits less insertion loss than the SIW, in excess of 1 dB. The S43 measurement in Table III is the insertion loss through the microstrip transmission line for the test board shown in Figure 3. The other two results for S21 are the insertion loss through the SIW on both test boards. Both test structures shown in Figures 2 and 3 are



(a) Comparison of measured S41 data.

(b) Comparison of measured S41 to simulation data for the 2 SIW test structure shown in Figure 2.

(c) Comparison of measured S41 to simulation data for the SIW and microstrip test structure shown in Figure 3.

Fig. 6. Simulated and measured data for S41.

the same overall length. We speculate that the cause for this is mismatch in the taper transition or leakage through the discontinuous SIW walls formed by vias. Another possible cause is the need for another pair of via holes at each end of the SIW segments, capping off the waveguide. Observing Figure 6 in [2], it appears an extreme edge via is present. This possibly is a fix for leakage resulting from the taper to SIW junction.

The importance of the S31 and S41 results is the direct correlation to coupling. The higher S31, as well as S41, the greater the coupling between a pair of transmission lines on the test structure. Observing both Figures 5a and 6a, SIW to SIW coupling is notably higher than SIW to microstrip coupling. Table II puts the increase at 8.56 dB and 8.53 dB for S31 and S41, respectively. The data in Table II is taken between 13 GHz and 26.5 GHz. This is where a TE mode is propagating through the SIW. Observing Table IV, these results show more equal coupling for both test boards when the frequency is below the cutoff of the SIW. These observations suggest that the increase in coupling is a direct result of leakage through the SIW section of transmission line, not from the microstrip taper section. The fact that the SIW walls are discontinuous along with additional leakage from not having vias on the extreme edge, may serve as an explanation for this behavior.

The increased insertion loss of SIW is in direct conflict to the stated advantages of using waveguide. Considering only insertion loss, microstrip exhibits an advantage over SIW. Considering the coupling data, if two transmission lines need to be placed near each other, it is better to use an SIW and a microstrip, versus two SIW lines. From a manufacturing and layout aspect, microstrip is at an advantage as well. Compared to SIW, microstrip does not need plated via holes, lowering the overall cost and complexity of the PCB. Microstrip also consumes much less board space, with a width nearly 12 times smaller than a suitable SIW line, for the design in this work.

V. Conclusion

In this paper, the authors completed a coupling and insertion loss performance comparison of SIW and microstrip transmission lines. Microstrip transmission line displayed the least insertion loss when compared to SIW. Additionally, the coupling between two SIW lines was over 8 dB greater than the coupling between an SIW and a microstrip transmission line for the designs in this work. Besides this, microstrip line is easier to manufacture and has a smaller PCB footprint than SIW.

Acknowledgements

The authors would like to thank Michael T. Reich from the Center for Nanoscale Science and Engineering for their invaluable support and the use of prototyping and test equipment.

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