Calculation of Loss Using Full and Surrogate EM Models of Substrate Integrated Waveguide at Ka Band

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***Abstract*—The paper presents the comparison of full substrate integrated waveguide and rectangular waveguide surrogate model when calculating loss at Ka band. The design of the surrogate model itself, the waveguide transition to microstrip line, and the conversion of the surrogate model to the full model have been presented. The influence of the conductor and dielectric losses and the effect of surface roughness have been studied. It has been shown that the surrogate model reduces the numerical complexity of the full model as it requires more than eight times less unknowns which results in more then thirty five times faster simulations without any loss of the accuracy. For all of the cases considered the maximum difference between the loss values calculated using two models was 0.04 dB for a waveguide section of 3.5 wavelength at the middle-band frequency.**

***Index Terms*—Substrate integrated waveguide, surrogate model, loss, EM modeling, Ka band.**

I. Introduction

SUBSTRATE integrated waveguide (SIW) technology offers the alternative approach to realize many different parts of the microwave system traditionally built in rectangular waveguide (RW) technology using well established and cost effective printed circuit process. In SIW circuits, lateral walls of the rectangular waveguide technology are replaced with via walls [1] or grooves [2]. Many examples of SIW passive and active circuits like microwave filters, couplers, antennas and antenna feeding networks, amplifiers, oscillators, etc. have been reported in the literature.

To facilitate the connections of the SIW circuit to the rest of microwave system located on the same printed circuit board (PCB), many transitions have been reported in the literature. Since the microstrip technology is widely used microwave printed circuit technology, the SIW-microstrip transition somehow has the largest significance. The simplest but very versatile and well-performing SIW-microstrip transition is in the form of a tapered microstrip line [2-3].

Electromagnetic (EM) simulators have become the standard design and validation tools in microwave circuit design bringing high level of confidence that fabricated circuit will have the desired performance. SIW structures in particular are very challenging regarding the modeling and computations using EM simulators as dense circular via walls significantly increase the complexity of the structure under investigation. The complexity can result in prohibitively high demand for computer resources, memory and time, required for the simulation. To reduce the complexity, the surrogate model approach has been suggested in [4] where the SIW-microstrip taper transition has been successfully optimized using a surrogate model. By using a reduced-complexity surrogate, the required computer resources can be kept at very low level and simulations are very fast.

Unlike the classic rectangular waveguide technology where the air is mostly used as dielectric to fill the waveguide interior, SIW uses dielectric substrate material. Although the microwave substrates are generally low-loss materials, the loss in SIW structures is larger then in the rectangular waveguide counterparts [5]. To address the merits of using the SIW technology in the particular application, the accurate and numerically efficient calculation of losses is very important, especially at higher microwave frequencies e.g. at Ka band.

In this paper the calculation of SIW loss including the transition to a microstrip line has been carried out using a commercial EM simulator. The influence of dielectric and conductive materials has been examined at Ka band (26-40 GHz) using full and surrogate EM models and the results are compared.

II. SIW and SIW-Microstrip Transition Design

The design procedure of the SIW structure can be similar to the design of a rectangular waveguide [6]. The design will be illustrated for the substrate with dielectric constant ε_r=3.0, dielectric loss tangent $Tan\,\delta$=0.002, and substrate height h=0.127 mm corresponding to the substrate RT6202 available from Rogers Corporation. The conductivity of zero thickness conductors is the one of copper, σ=58 MS. First, the width of the equivalent rectangular waveguide a_r is determined to ensure the propagation of a dominant TE_{10} mode,

$$a_r = \frac{c}{2\, f_c \sqrt{\varepsilon_r}}, \quad (1)$$

where c is the speed of light, f_c is cut-off frequency of the TE_{10} mode, and ε_r is the dielectric constant of the substrate material.

The via diameter d is determined next. The number of vias per SIW wavelength should be greater than 10, but the

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diameter value should also conform with the capabilities of the available via fabrication technology. In this paper, the value d=0.1 mm has been adopted. Via period (distance between the centers of two successive vias) p is determined next. To avoid radiation losses through the via wall a ratio p/d has been set to 2. Finally, the formula from [6] has been used to calculate equivalent SIW width a_e. The length of the SIW section has been taken to be l_w =12.6 mm which corresponds to 62 via in the via wall and to 3.15 wavelengths at the middle-band frequency. The basic SIW design parameters are illustrated in Fig.1.

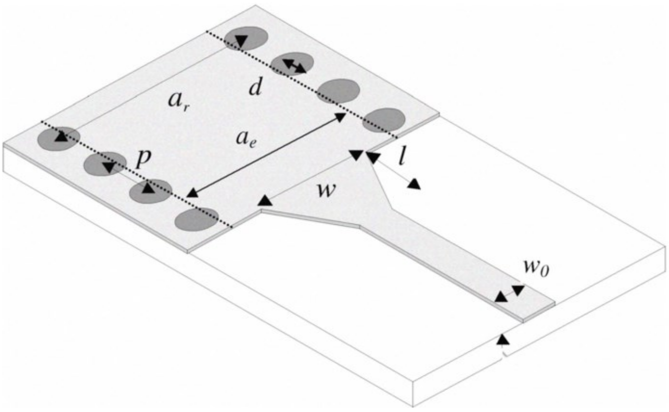

Fig. 1. SIW-microstrip transition. Dimensions and other parameters are listed in Table I.

TABLE I
EQUIVALENT RECTANGULAR WAVEGUIDE, SUBSTRATE INTEGRATED WAVEGUIDE AND MICROSTRIP PARAMETERS

RW-SIW-Microstrip parameter	Value
ε_r	3.0
$Tan\ \delta$	0.002
h	0.127 mm
σ	58 MS
a_r	4 mm
d	0.1 mm
p	0.2 mm
a_e	4.06 mm
l_w	12.6 mm
w	1.0 mm
l	1.8 mm
w_0	0.33 mm

In the same figure microstrip-SIW transition is shown with taper width w and taper length l. Although there are some closed-form expressions for the taper dimension calculation available in the literature, in this paper taper dimensions have been determined through EM simulations. The criterion to select the particular value for l was to minimize the return loss in the whole Ka band. The width of a 50 Ω microstrip line has been designated as w_0. The values of substrate, material and dimensional parameters are listed in Table I.

III. EM MODELS OF SIW STRUCTURE

The structure of the SIW-microstrip transition has been modeled in WIPL-D Pro full wave 3D electromagnetic simulator [7]. To design the transition, rectangular waveguide model, which is the surrogate model of the full SIW structure, has been used. The optimized transition has then been replicated with the full SIW model. The hardware used for simulation was the standard desk top computer with Intel i7-950 CPU running at 3.06 GHz and 8 GB RAM under 64-bit Windows 7 operating system.

A. Rectangular Waveguide Model of SIW (Surrogate Model)

The surrogate model is illustrated in Fig. 2. The lateral wall is modeled as a metal sheet and is shown as an inset in the same picture. The symmetry has been exploited to include only one half of the structure in the model, therefore halving the number of unknowns. The meshing of the model has been performed at 60 GHz resulting in total of 1192 unknowns and requiring only 62 s to complete the simulations for 15 frequency points at Ka band.

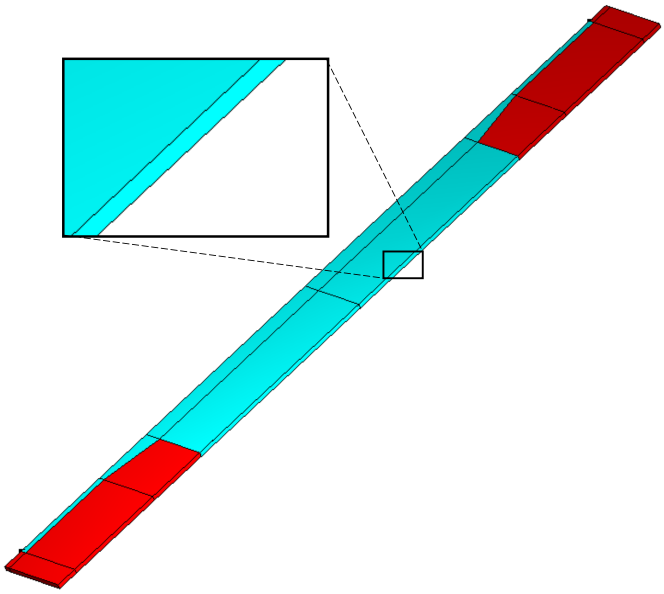

Fig. 2. Surrogate model of SIW-microstrip transition. Symmetry has been used to reduce the model complexity. Dimensions and other parameters are listed in Table I.

B. Square Via Wall Model of SIW (Full Model)

The full model of the SIW structure is built with the via walls at lateral sides. The model is illustrated in Fig. 3. As in the case of surrogate model, the symmetry has been used to reduce the model size. The vias are of square shape, as presented in the inset in the same picture. The side length of the square has been set equal to d. It has been confirmed that this via model is adequate for the accurate modeling, as similar results has been obtained if regular, twelve-sides polygon has been used to approximate circular via geometry. The meshing frequency of the model has been again set to 60 GHz. For the full model, the number of unknowns was 10462, which is more than 8 times larger then the number of unknowns obtained for the surrogate model. The increased number of unknowns requires 2334 s to complete the simulations (more than 35 times slower comparing to the surrogate model case).

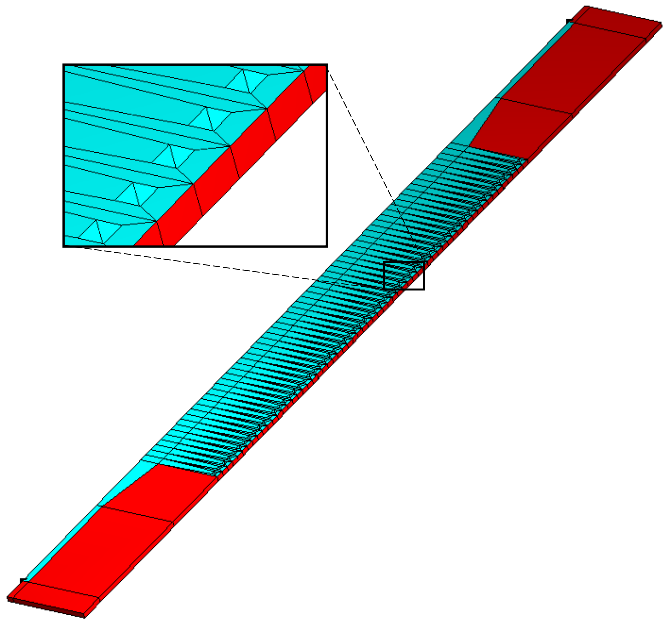

Fig. 3. Full model of SIW-microstrip transition. Symmetry has been used to reduce the model complexity. Dimensions and other parameters are listed in Table I.

IV. Simulation Results and Comments

Both of the models have been simulated in the frequency range 26-40 GHz. To investigate the loss mechanism, several cases have been considered for each of the model. The lossless case, i.e. lossless dielectric and metal has been analyzed to establish the baseline for any radiation losses. Next, lossy substrate and lossy metal have been taken into consideration and simulated in separate projects, and then together in the subsequent simulations. The effect of excess loss in via walls has been addressed next. Finally, the effect of surface roughness, which is modeled as triple reduction of the conductivity, has been analyzed. The simulated S parameters are presented in Fig. 4 to Fig. 7.

Comparing the S_{11} parameters presented in Fig. 4 and Fig 6, it can be concluded that for most of the Ka band the return loss is below 15 dB which indicates that the transition is very well designed. It can be also concluded that the surrogate model resembles very well the full model performance regarding the return loss. Therefore, the surrogate model can be used from the very start to design the transition in a numerically efficient way. As indicated earlier, the changeover from RW surrogate to full SIW model in this paper is performed using equivalent width formula from [6] which immediately produces very good agreement between the two models. This is more efficient approach then the one described in [4] where, starting from given SIW structure, the width of the equivalent RW surrogate has been found through repeated simulations of the surrogate. For both of the models, the influence of the loss to S_{11} parameter is negligible.

The insertion losses, corresponding to S_{21} parameters, are shown in Fig. 5 and Fig. 7. Comparing the figures with the graphs of S_{11} parameter, it can be noticed that the ripply form of the insertion loss closely resembles the shape of the return loss i.e. a portion of the insertion loss is due to the imperfect matching. In the frequency range 32-36 GHz, where the return loss is below the value of 25 dB, the insertion loss is smooth which allows us to draw the important conclusions.

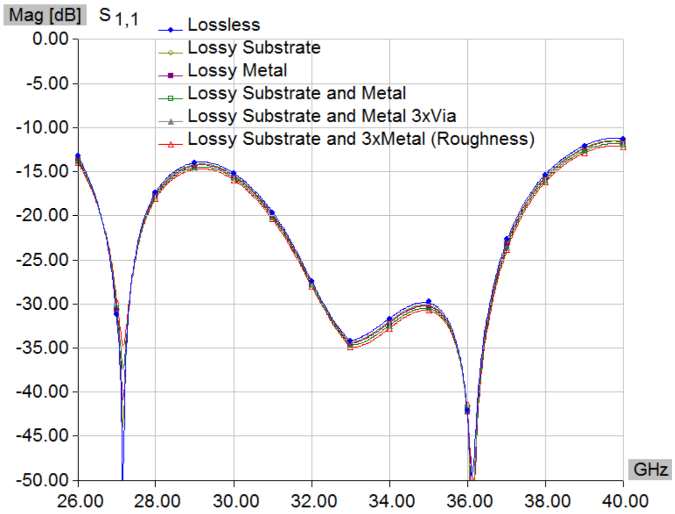

Fig. 4. S_{11} parameter of the surrogate RW model presented in Fig. 2. The curves are presented for six loss mechanisms that are described in the legend.

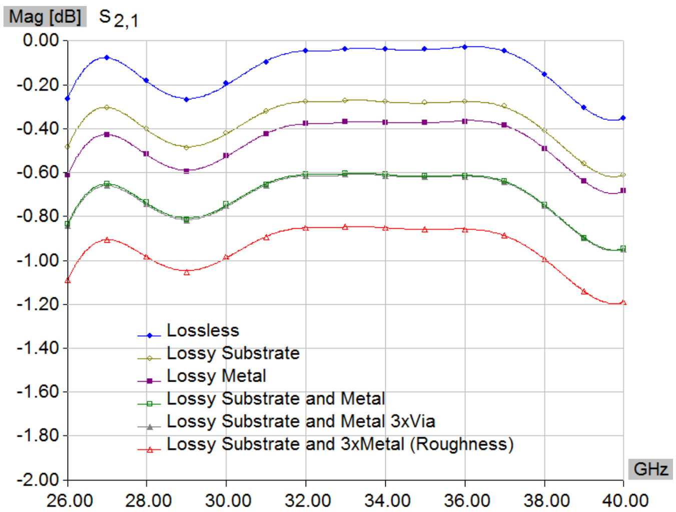

Fig. 5. S_{21} parameter of the surrogate RW model presented in Fig. 2. The curves are presented for six loss mechanisms that are described in the legend.

The conclusions will be drawn simultaneously for both of the models simulated. In the reduced frequency band, a very small but noticeable loss (0.03 dB at 33 GHz) exists even for the case where the lateral walls are modeled as metal sheets and the materials are lossless (blue trace). This indicates the presence of radiation losses. It has been confirmed that the radiation occurs at the edges of the SIW structure where the microstrip transitions are attached. Although the radiated power is very small, it perhaps may have significance in some practical cases. Furthermore, to confirm good agreement between the results, the insertion loss of the "lossless" case must be taken into account. For example, to add the effects of individually calculated contributions of substrate and metal losses (yellow and magenta curves respectively) and obtain the good agreement with the value of loss calculated with simultaneous presence of both of the loss mechanism (green curve), the values from the blue curve should be subtracted from the remaining three curves.

The values along yellow and magenta traces indicate that, for this particular case considered in this paper, loss due to finite conductivity of the conductors exceeds the substrate loss. Adding extra loss to via metal does not change noticeably the overall loss as green and gray curves almost coincide for both of the structures. Finally, reducing the conductivity to emulate surface roughness adds approximately 0.2 dB to the loss value (red curve).

Neglecting the loss of the microstrip portion of the circuit, the attenuation per unit length *a* and attenuation per wavelength a_λ can be calculated based on simulated insertion loss values. The results for the full model are listed in Table II. The attenuation values are calculated at the middle-band frequency of 33 GHz where the SIW length of 12.6 mm corresponds to 3.15 wavelengths.

TABLE II
CALCULATED ATTENUATION PER UNIT LENGTH AND ATTENUATION PER WAVELENGTH (SIW FULL MODEL) AT 33 GHZ

Loss source	Insertion loss [dB]	*a* [dB/m]	a_λ [dB/λ]
Lossless	0.03	/	/
Lossy substrate	0.28	19.8	0.08
Lossy metal	0.41	30.2	0.12
Lossy substrate and metal	0.66	50.0	0.2
Lossy substrate and 3x metal	0.88	67.5	0.27

Relying on calculated attenuation per wavelength values, it should be straightforward to estimate the value of the ohmic losses in a circuit if the approximate electrical length is known. For example, the ohmic loss of a filter containing five half wavelength sections should be in the range of 0.68 dB if surface roughness is taken into account.

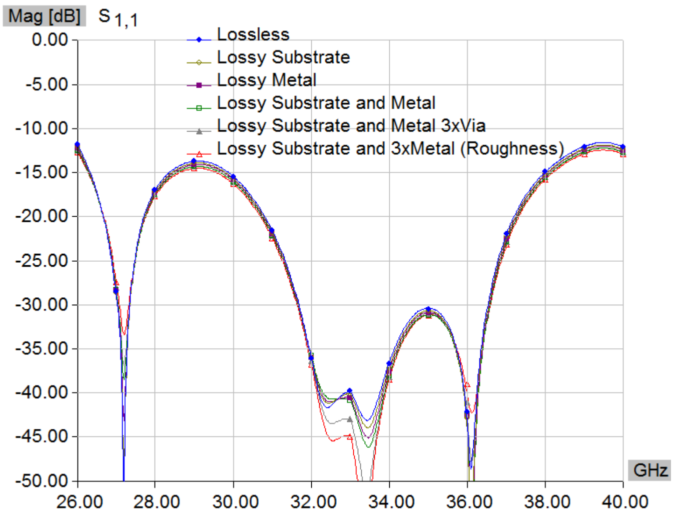

Fig. 6. S_{11} parameter of the full SIW model presented in Fig. 3. The curves are presented for six loss mechanisms that are described in the legend

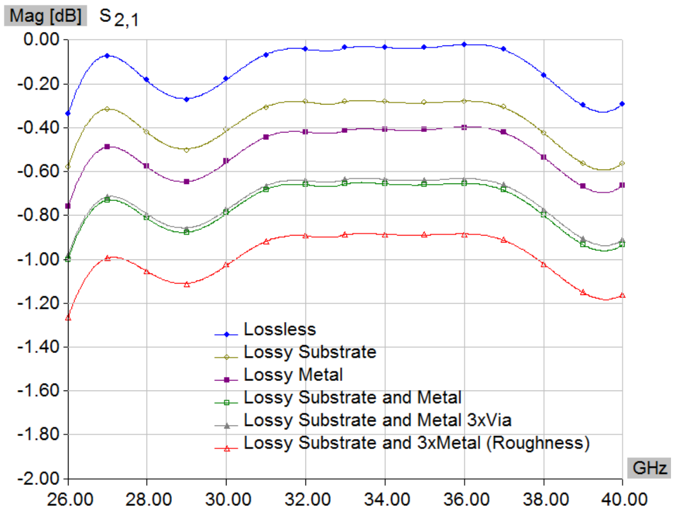

Fig. 7. S_{21} parameter of the full SIW model presented in Fig. 3. The curves are presented for six loss mechanisms that are described in the legend.

Although the figures Fig. 4 - Fig. 7 already suggest good agreement between the two models, all of the relevant insertion loss results have been put together in Fig. 8 in order to quantify the differences. The agreement between the results is very good. For the case of lossless materials, and for the case where only the substrate is lossy, the results obtained using two models practically coincide. For other three cases, where the lossy metal has been introduced, the maximum difference between the two curves was in the range of 0.04 dB, which is negligible for most practical applications. Therefore, the surrogate model can be confidently used to predict the SIW loss with significantly increased numerical efficiency compared to the full model.

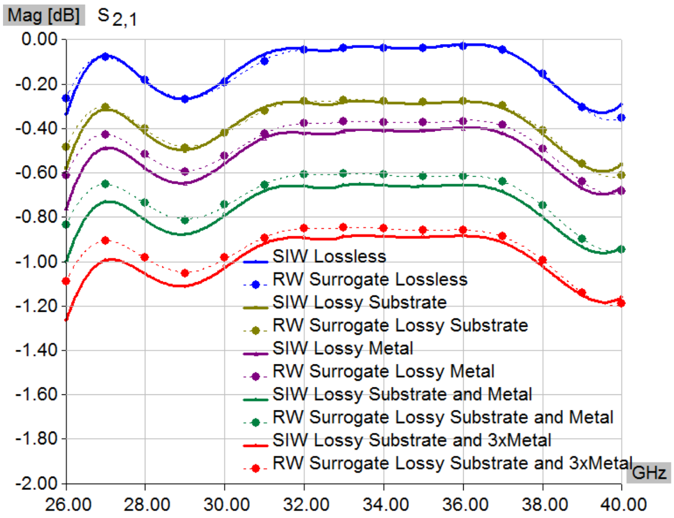

Fig. 8. Comparison of the S_{21} parameter of the surrogate RW model and full SIW model. The curves are presented for five loss mechanisms that are described in the legend.

V. Conclusion

The comparison between surrogate RW and full SIW model when calculating loss at Ka band has been presented. It has been demonstrated that the design of the SIW and the SIW-microstrip transition can start from the surrogate model and a simple analytical formula from the literature can be used to convert the surrogate model to full SIW model. The obtained results for loss indicate that the surrogate model is sufficiently accurate and can be used in the simulations with high confidence. Utilization of the surrogate model significantly increases the numerical efficiency as it requires eight times less unknowns and the simulations are thirty five times faster than the full model.

The future work should include the analysis of the loss contribution of dielectric and metal SIW parts for the cases where the substrate thickness is altered, where the realistic conductor thickness is introduced as a parameter and where the via period is different from the one considered in the paper.

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