Bio-inspired intelligence for minimizing losses in substrate integrated waveguide

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ABSTRACT

This paper presents a study of various types of losses in substrate-integrated waveguides (SIW) using a genetic algorithm. Three main types of losses are considered and examined separately: conductor loss, dielectric loss, and radiation loss. Furthermore, the current analysis allows for a physical understanding of the loss impacts as well as the creation of design guidelines to reduce losses at 10 GHz frequency while keeping the miniaturized size of the SIW. Validation results obtained using the software Ansys HFSS, verify that the attenuation constant of the SIW can be significantly reduced to 0.4 dB/m, the Insertion loss S21 to -0.2 dB and the return loss to -38 dB if the geometric parameters are chosen properly. This study enables us to identify the source of losses in a SIW and, as a result, eliminate any type of dispersion. That demonstrates the usability of SIW technologies in the design of microwave circuits used in Internet of things applications.

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1. INTRODUCTION

Substrate integrated waveguide (SIW) technology is a potential way of constructing microwave and mm-wave circuits [1]. SIW structures are integrated rectangular waveguides fabricated by metalizing both faces of a dielectric substrate with two periodic arrays of metallic vias as shown in Figure 1. Substrate integrated waveguide technology was initially used to power antenna array networks [2], but it is now widely used in various microwave and millimeter-wave components, including cavity filters [3], directional couplers [4], oscillators [5], slot array antennas [6], and circulators [7]. SIW structures provide several advantages: low cost, ease of integration, low mass, and low profile while attaining better performance in terms of high-quality factors and power-handling capabilities. Moreover, the SIW technique permits fabricating a full planar circuit with a typical printed circuit board (PCB) or other planar processing techniques [8].

One of the major issues in the design of SIW components is related to the minimization of losses. Similar to rectangular waveguides, SIW structure is also affected by conductor and dielectric losses, but a new typical aspect of loss in SIW circuits was recently studied due to radiation dispersion [9]. Many conditions and equations in the literature limit the choice of the main parameters of substrate-integrated waveguide design [10]. However, in a region of interest as shown in Figure 2, what are the values that will give less losses and smaller size? This is what this study will go through in depth. Moreover, previous studies have shown design criteria that allow for the reduction of radiation leakage if the ratio of longitudinal spacing *p* to diameter vias is sufficiently tiny: *p/d≤2* [11]. Nevertheless, the evaluation of the several contributions of loss is particularly important in the design of the substrate-integrated waveguides.

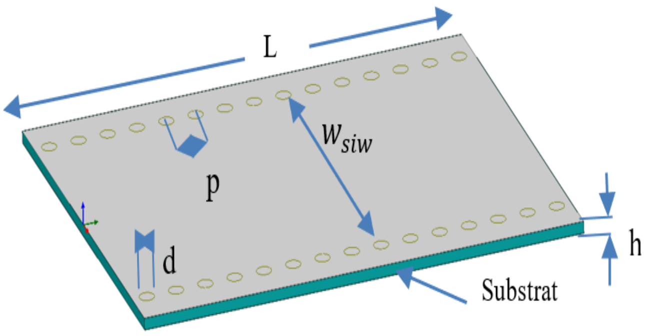

Figure 1. The geometry of SIW

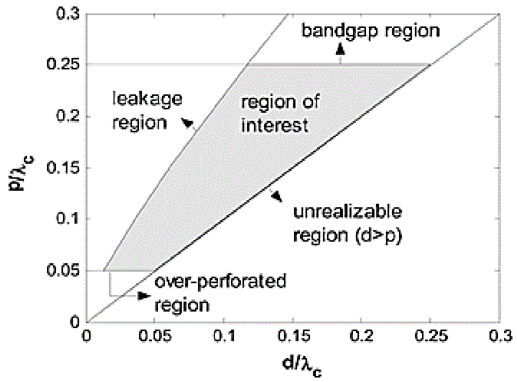

Figure 2. Region of interest in the SIW [10]

In this paper, we present a genetic algorithm (GA) as an efficient and emerging technique for studying and minimizing losses in SIW. It is based on meta-heuristic algorithms which were applied in several electronic fields [12], [13] to the analysis of lossless and to find the optimal design while achieving good performance. The choice of GA is based on its efficient performance, interesting interaction mechanisms between individuals, and its high number of citations as detailed in [14] as shown in Figure 1. This method allows for the quick and accurate determination of geometric parameters corresponding to the good frequency response of SIW circuits.

2. LOSS MECHANISM IN SIW

The propagation characteristics of SIW structures are similar to those of traditional rectangular waveguides. The propagation modes of SIW correspond effectively with a selection of rectangular waveguide modes, only TEn0 (n ¼ 1, 2, ...) modes can exist [11] and the fundamental mode is the TE10. Due to this similarity, the two structures exhibit two identical losses, namely conductor losses and dielectric losses. Furthermore, the existence of slots along the side walls of SIW constructions generates another type of loss, particularly radiation loss, due to probable leakage via the gaps [15].

2.1. Conductor loss

Conductor losses in SIW structures are caused by the finite conductivity of metal layers and vias. The same analytical formula (1) [16] can be used for the calculation of the attenuation constant α_C generated by conductor loss in the SIW due to the similarity between SIW and rectangular waveguides, and the width of the rectangular waveguide is replaced with the equivalent with weff of the SIW [1].

$$\alpha_C(f) = \frac{\sqrt{\pi f \varepsilon_0 \varepsilon_r}}{h\sqrt{\sigma_c}} \frac{1+2\left(\frac{f_0}{f}\right)^2 \frac{h}{w_{eff}}}{\sqrt{1-\left(\frac{f_0}{f}\right)^2}} \tag{1}$$

where h is the substrate thickness, ε_r is the dielectric permittivity, f_0 is the cut-off frequency of the SIW, f is the frequency of operation, and σ_c is the metal conductivity.

2.2. Dielectric loss

Dielectric losses are caused by the dielectric substrate's loss tangent $tan\delta$. In this scenario, the analytical formula developed for the rectangular waveguide (2) [16] may also be utilized to calculate the SIW's attenuation constant α_D due to dielectric loss, where c is the speed of light.

$$\alpha_D(f) = \frac{\pi f \sqrt{\varepsilon_r}}{c\sqrt{1-\left(\frac{f_0}{f}\right)^2}} \tan\delta \tag{2}$$

2.3. Radiation loss

The radiation leakage is caused by gaps between metal vias. Radiation in huge gaps causes considerable power loss. A novel method for calculating the attenuation constant α_R owing to radiation loss has recently been established [17], [18]. The resultant formula is (3),

$$\alpha_R = \frac{\frac{1}{w}\left(\frac{d}{w}\right)^{2.84}\left(\frac{s}{d}-1\right)^{6.28}}{4.85\sqrt{\left(\frac{2w}{\lambda}\right)^2-1}} \quad (3)$$

where λ is the wavelength in the dielectric medium at the operation frequency. From (1) to (2) and (3) the attenuation constant of the SIW is calculated as in (4) [16], [19], [20].

$$\alpha_0 = \alpha_C + \alpha_D + \alpha_R \quad (4)$$

3. OPTIMIZATION OF THE ATTENUATION CONSTANT α_0 USING A GENETIC ALGORITHM

3.1. Overview of genetic algorithms (GAs)

GAs are a subclass of evolutionary algorithms known as global search heuristics. They may be used to address a wide range of complicated issues that are difficult to solve using standard methods [21], [22]. A 'chromosome' is a possible solution to the problem. This is further separated into 'genes.' A GA begins with a population of randomly produced chromosomes related to the issue constraints. Then, using repetitive, random, and probabilistic methods governed by the four fundamental operators of parent selection, crossover, replacement, and mutation, new populations are formed and therefore the population distribution can be adequately normalized as shown in Figure 3. The initial population of chromosomes was created at random with the limitations of minimal and maximal values for each of the decision variables, and each chromosome is assessed based on the fitness function value (4). The tournament selection approach was used to reach the parents' selection phase. After then, the crossover operator fuses two chromosomes (parents) to create two new chromosomes (children). Each of these chromosomes was altered by changing the value of one gene at random. The technique was then repeated until the best solution was discovered as shown in Figure 4.

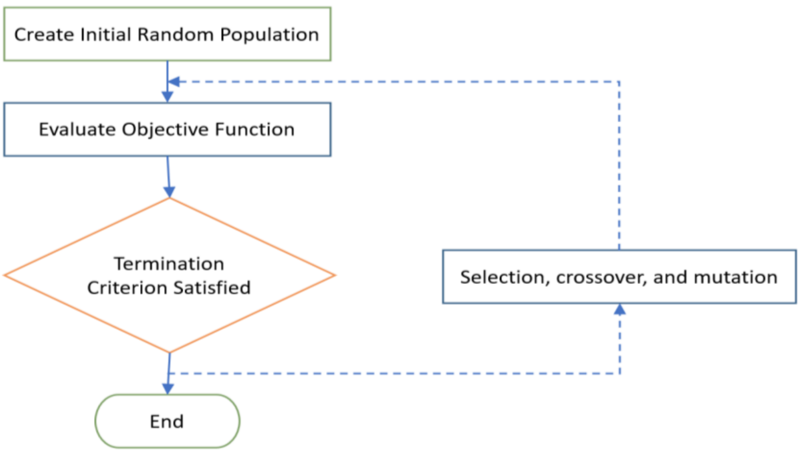

Figure 3. GA optimization flow chart

3.2. Design variables and objective function

A GA was applied for SIW optimization, in which the diameters d, spacing between two adjacent vias p, the height of substrate h, and the width w_{siw} were the variables. We are looking to minimize the attenuation constant α_0 expressed in (4). It is taken as the objective function for optimization problems with linear and non-linear constraints shown below. We have used the current work MATLAB optimization functions to develop the GA algorithm. Constraints applied to the design parameter originated from physical limitations and radiation characteristics. The values of diameter are constrained to the range of (0.8 to 1.2 mm), spacing p constrained to the range of (1.5 to 2 mm), the width constrained to the range of (10 to 11 mm), and the height between (0.9 to 1.2 mm). Once the cutoff frequency f_0 of the SIW is known, the equivalent width weff can be calculated as in [1] so w_{eff}=10 mm.

The optimization problem is as:

- Find: d, p, h, w_{siw}; where: $0.8 \leq d \leq 1.2$; $1.5 \leq p \leq 2$; $0.9 \leq h \leq 1.2$; $10 \leq w_{siw} \leq 11$
- Minimize: attenuation constant α_0
- Subject to

Linear constraints:

$$d < \frac{\lambda_g}{5}; \quad p < 2^* d$$

Nonlinear constraints:

$$w_{eff} = w_{siw} - \frac{d^2}{0.95 * p}$$

with λ_g is the guiding wavelength as in [23]. The substrate integrated waveguide shown in Figure 1 is consisting of a Rogers RT/Duroid 5880 dielectric substrate with a relative permittivity ε_r=2.2, $tan\delta$=0.0009, σ_c=5.8e7 S/m), the height of metal layer h1=0.09 mm, λ=1.78e-3 mm, and w_{eff}=10 mm at 10 GHz frequency.

4. RESULTS AND DISCUSSION

4.1. Optimization results using GA

The genetic algorithm generates the starting population at random. Random numbers are used to perform crossover and mutation. As a result, under identical analytic conditions, the genetic algorithm performs differently for each run. Figure 4 shows how the genetic algorithm improves the objective function through generations. The optimal values of different variables of the circuit are represented in Table 1, and they correspond to a fitness value of 0.14.

Table 1. Parameter ranges and their optimal values

Variable	Minimum (mm)	Maximum (mm)	Optimal value (mm)
d	0.8	1.2	0.8
p	1.5	2	1.6
w_{siw}	10	11	11
h	0.9	1.2	1

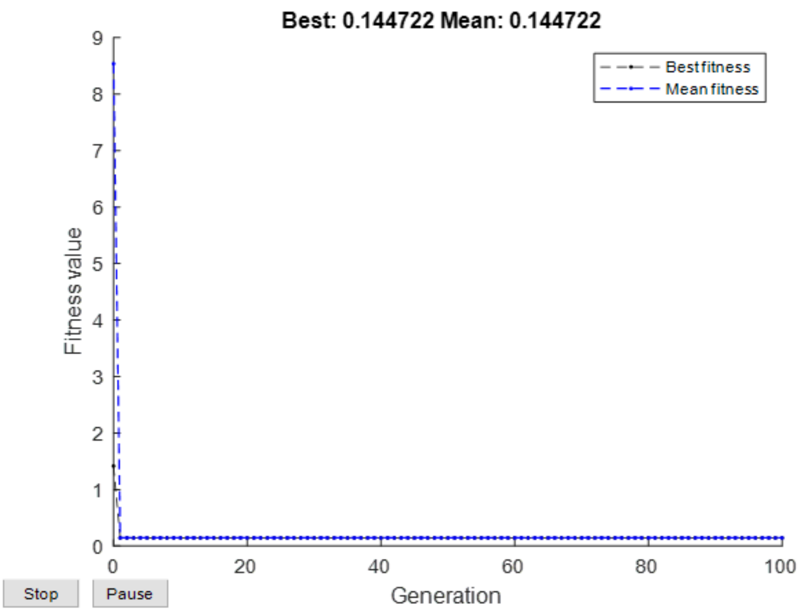

Figure 4. Objective function versus iterations

4.2. Validation results using HFSS

In order to better appreciate the accuracy of the proposed GA method and to verify the validity of the optimal values generated by the GA, a detail of the scattering parameters as well as the variation of the attenuation constant α_0 using Ansys HFSS software are shown in Figures 5 and 6. It can be clear from Figure 6 that the attenuation constant α_0 at the target frequency (10 GHz) is 0.42 dB/m is approximately near to the fitness value obtained by GAs. In addition, the scattering parameters of the Substrate integrated waveguide are $S11 = -38$ dB and $S21 = -0.2\ dB$ as shown in Figure 4 which indicates that simulation results are in good agreement with those obtained using GA techniques.

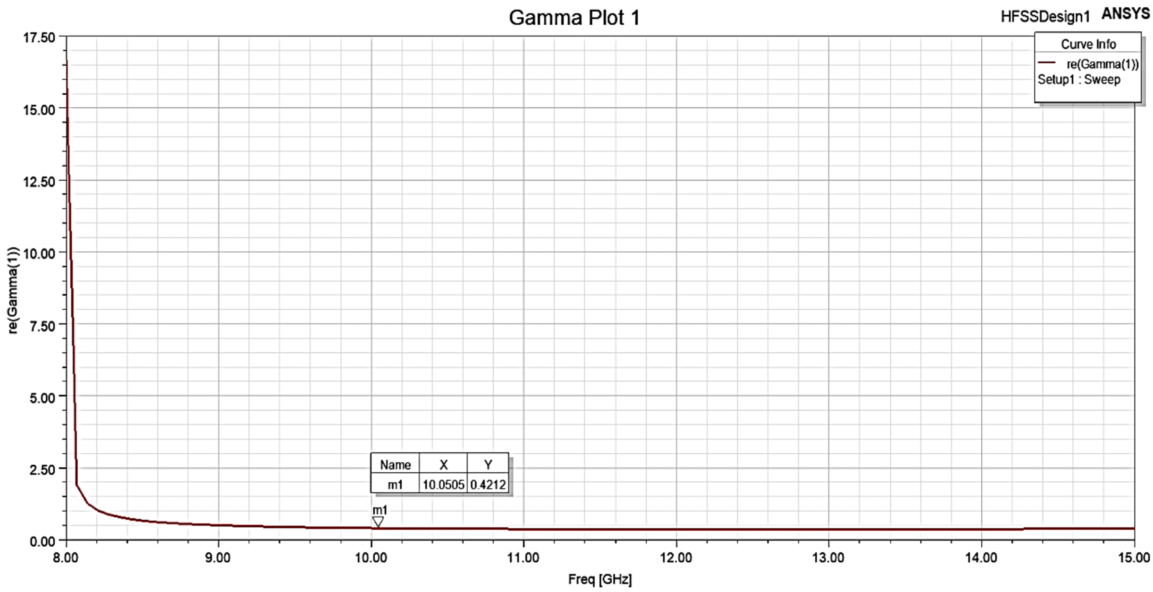

Figure 5. The Attenuation constant α_0 versus frequency

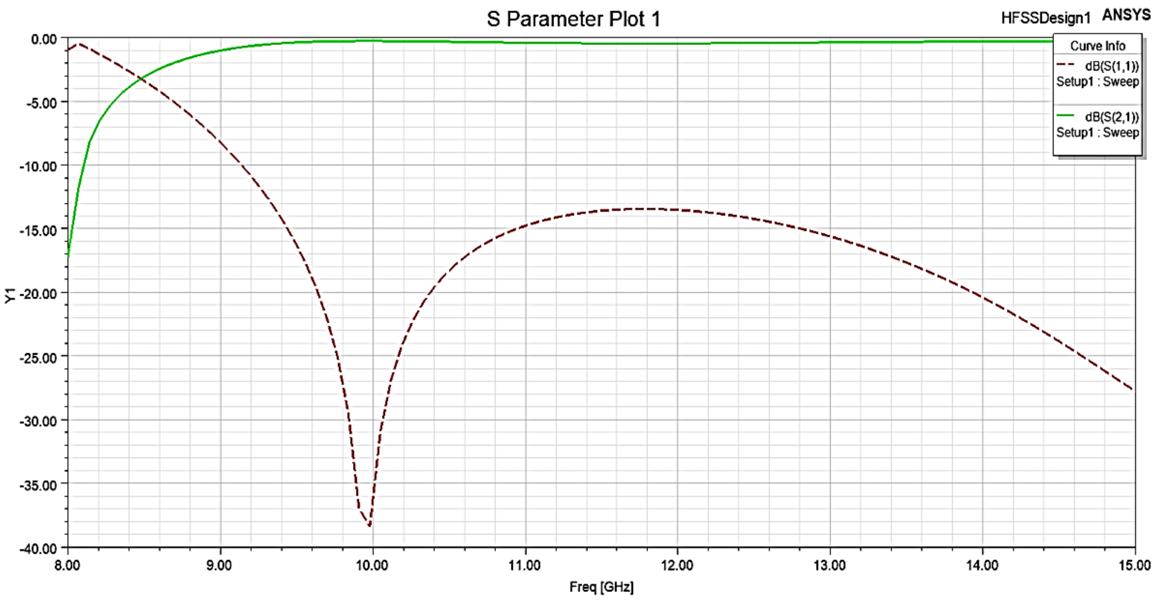

Figure 6. Return loss S11 and Insertion loss S21 of SIW at the optimal value.

4.3. Study of the impact of the geometric parameters on the attenuation constant

First of all, we begin by illustrating the variation of different losses of SIW with the optimal values as shown in Table 1. It results that radiation loss is very low and nearly constant versus frequency, whereas conductor and dielectric losses are typically greater near the cutoff frequency and tend to remain stable throughout the graph. From Figure 7, we can conclude also that dielectric losses are the main cause of attenuation in the SIW, that is why researchers are opting for the choice of SIW dielectric substrate to affect the total losses in the SIW since the dielectric losses depend only on tangent loss $tan\delta$ as in (2).

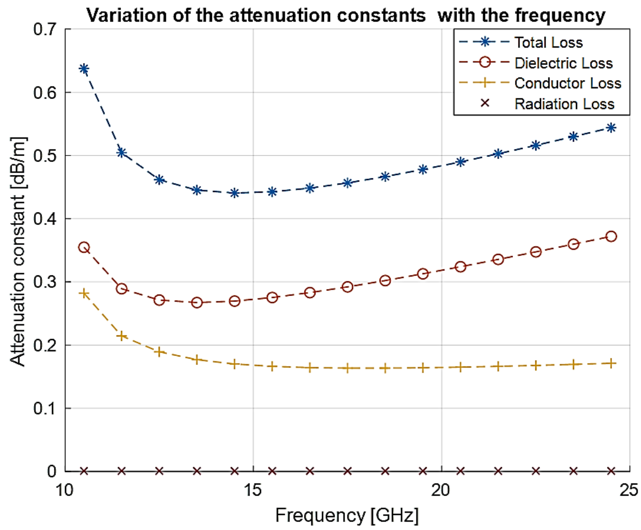

Figure 7. Different contributions of losses in the SIW: total loss, conductor losses, dielectric losses, and radiation losses

Several geometrical variables, including substrate thickness, SIW width, metal via diameter, and longitudinal spacing p, can be adjusted to minimize the various forms of losses in a substrate-integrated waveguide. The dielectric substrate thickness is critical: Figure 8 displays the various contributions to the attenuation constant vs thickness h while keeping all other geometrical dimensions constant. As a result, increasing h reduces conductor loss significantly but has no effect on dielectric loss. In this scenario, radiation loss is almost non-existent, and it is unaffected by substrate thickness in general. The conductor loss's behavior is not surprising given that it depends on 1/h as seen in (1).

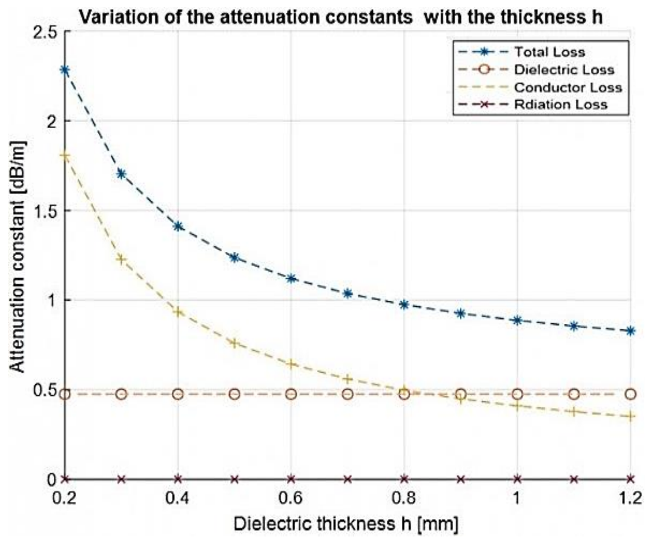

Figure 8. Attenuation constant versus thickness h

The diameter of the metal vias is another essential geometrical parameter. Figure 9 illustrates the various contributions of losses against the diameter d while holding all other geometrical dimensions unchanged. As a result, the attenuation constant increases significantly for $d \geq 0.8$ mm, mainly due to conductor and dielectric losses, because the attenuation constant practically depends on the condition $p/d \leq 2$ reported in [24]. We conclude that α_0 increases when increasing the diameter d of the vias because the design rules that permit minimizing loss are not respected.

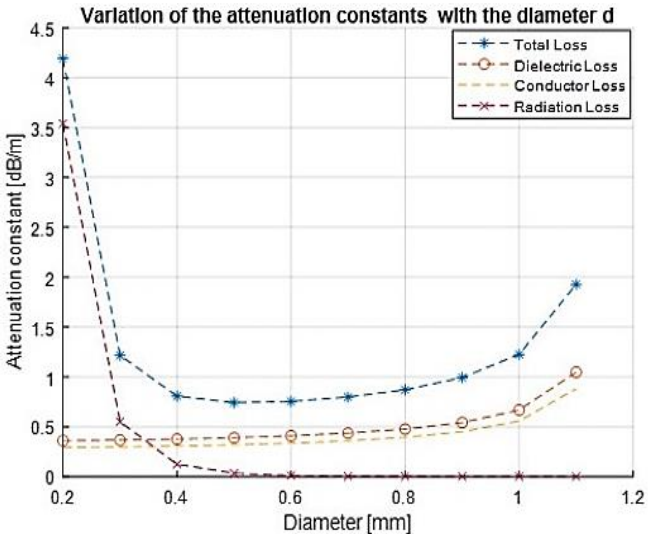

Figure 9. Attenuation constant versus diameter d

Similarly, the result seen while varying the longitudinal pitch p is shown in Figure 10 depicts the varied contributions of losses versus p while maintaining all other parameters at their optimal values. It results that starting from p=1.6 mm radiation loss increases for large values due to radiation leakage under the condition $p/d \geq 2.5$ reported in [16].

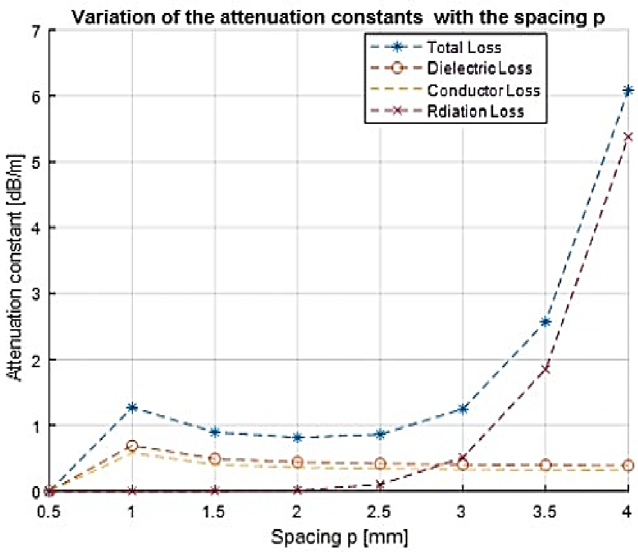

Figure 10. Attenuation constant versus spacing p

The last parameter is the width w_{siw}, the behavior observed when varying the width w_{siw} while keeping all other parameters in optimal values is shown in Figure 11. The remarkable losses, in this case, are the dielectric and conductor losses, α_C and α_D increase when increasing the width w_{siw}, which is also mentioned in the relationship (1), (2).

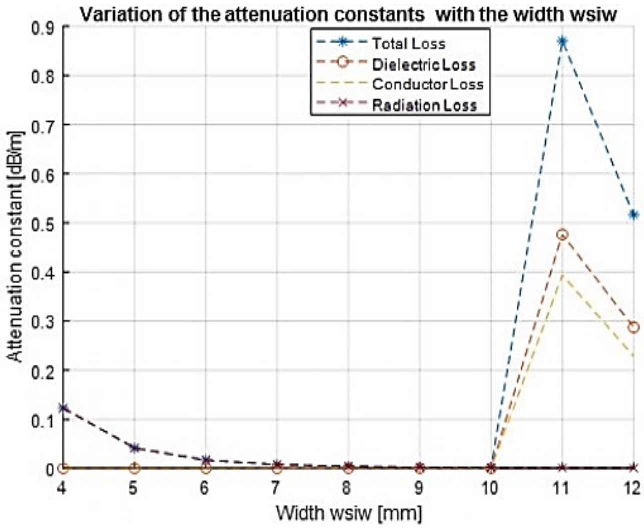

Figure 11. Attenuation constant versus the width w_{siw}

Summing up the results, it can be concluded that, the conductor loss can be reduced by increasing the thickness h of the substrate, while the usage of low-loss laminates (with minimal $tan\delta$) is necessary to minimize the dielectric loss. The pitch between two vias holes controls the quantity of leaking field, and it has been demonstrated that minimal loss may be attained when this pitch is used as $p \leq 2.5 * d$. Simulation results obtained using Genetic algorithms in MATLAB programing language and Ansys HFSS software show good agreement, especially compared with previous work [24]–[27].

5. CONCLUSION

This work identifies and discusses the various contributions of losses in the substrate-integrated waveguide, as well as the impact of several fundamental geometrical factors on the attenuation constant. In summary, dielectric losses are the primary source of attenuation in the SIW. GA presents good results compared with boundary integral-resonant mode expansion (BI-RME) used in the design of SIW, GA returns that the attenuation constant of the SIW can be reduced significantly if the width, diameter, pacing, and height of the SIW are chosen properly. The attenuation constant is 0.14 dB/m at the optimal dimensions, the insertion loss S21 is -0.2 dB, and the return loss is -38 dB. It was shown that both size miniaturization and lower loss can be achieved simultaneously. This is therefore an optimal method for fabricating microwave components based on SIW technology and evaluating their physical, electronic, and electromagnetic properties to respond to the huge demand for very small and portable components for the internet of things applications. In future work, we aim to focus on the choice of the dielectric substrate in order to reduce the dielectric losses as much as possible, but this time, using new generation metaheuristics like artificial bee colony optimization.

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