Unloaded quality factor optimization of substrate integrated waveguide resonator using genetic algorithm

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ABSTRACT

The main objective purpose of this paper is to study the enhancement techniques of the unloaded quality factor of substrate integrated waveguide (SIW) resonator, given that the quality of filters depends first on the quality of the resonators that compose it. Performance enhancement is achieved by employing a MATLAB-based genetic algorithm to optimize the geometrical parameters of the SIW resonator by iterative convergence to the target frequency (10 GHz frequency). On the other hand, the Ansys HFSS tool is used to model and optimize the SIW resonator with the suitable transition and plot the S-parameters for a frequency sweep range to validate its property. The results obtained allow increasing the unloaded Q-factor to be more than 1609 and reducing not only insertion and return losses but also reducing the size of the resonator. The proposed SIW resonator with its small size and low loss is directly useful for microwave and millimeter-wave applications.

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1. INTRODUCTION

The application of the substrate integrated circuits (SICs) to high-frequency devices provides an alternate solution to high-performing circuits with complementary advantages of microstrip and waveguide circuits [1]–[3] such as high-quality factor and low loss with an extra advantage of reduced size as in [4]. SICs are based on substrate integrated waveguide (SIW) resonators that emerged in the last decade representing a basic element of a multipole filter or an oscillator circuit [5]–[8]. SIW resonators are made up of double rows of conducting slots immersed in a dielectric substrate that connects two plates on either side of the substrate [9], [10]. As a result, they are affected by conductor, radiation, and dielectric losses [11]–[13] limiting their performance and prompting the need for a quality factor enhancement mechanism.

Previous studies have focused on the choice of the geometry and type of substrate material in SIW structure [14], [15], indicating that the unloaded Q-factor increases with materials of high permittivity and high thickness. Furthermore, dielectric material with a high permittivity increases the insertion losses of the SIW resonator. However, in the presence of a dielectric material with good performance in minimizing losses, is there an impact of additional geometric parameters like the diameter of vias, spacing between two adjacent vias, or the width of SIW on the performance of the entire SIW resonator? Based on the previous study presented above, we will demonstrate in this paper the influence of the full SIW geometry on its unloaded Q-factor increasing. In addition, using a genetic algorithm (GA) and validated by the high-frequency electromagnetic simulation software (HFSS), we will present an optimal design of SIW resonator with high-unloaded Q-factor, low losses, and small size.

2. THEORETICAL FRAMEWORK

2.1. Overview of genetic algorithm

GA is one of the most popular stochastic optimization algorithms often used to solve complex large-scale optimization problems in various fields as illustrated in Scopus database Figure 1. For a given function, the GA is a powerful and efficient method for optimization problems. The basic theory of the GA was proposed by Holland [16], [17], and it is based on a stochastic technique, a population of individuals is created randomly at each generation. The GA mimics natural selection and survival of the fittest in evolution. At each step, it modifies a population of individual solutions and creates a new generation based on the three operators of selection, crossover, and mutation. Figure 2 shows the flowchart of GA optimization.

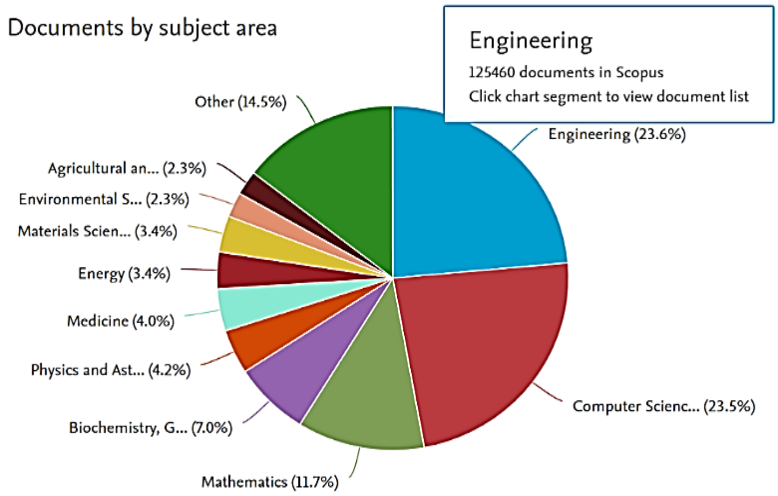

Figure 1. GA documents by subject area [18]

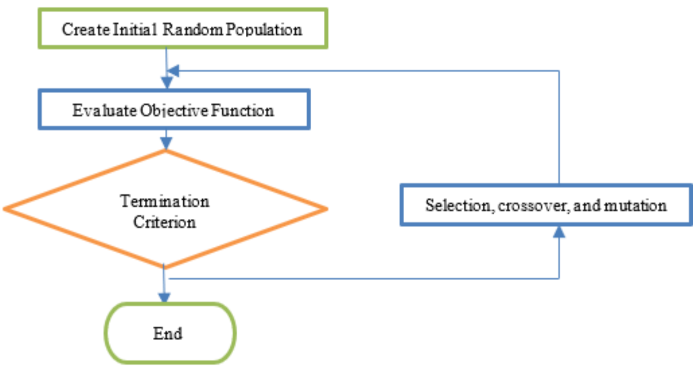

Figure 2. Flowchart of GA optimization

2.2. Design of SIW technology

SIW is built by using top and bottom metal layers on a dielectric substrate, connected by vertical metallization in form of metallic walls or a fence of metalized slots or via holes Figure 3. The main geometric parameters of the SIW cavity are the diameter of metallic vias d, the spacing between two adjacent vias p, and the width of SIW w_{siw}. In the first step, the SIW structure should be designed for the desired frequency by the rules mentioned in (1), where w_{eff} and L_{eff} are respectively the width and the length of equivalent rectangular waveguide Figure 4. The width w_{siw} and the length Lsiw of the SIW cavity are determined from (2) and (3) proposed in [15], [19], c_0 is the speed of light, and (m, p) are the propagation mode numbers.

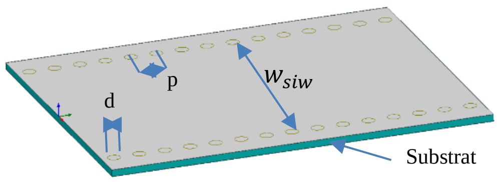

Figure 3. SIW geometry

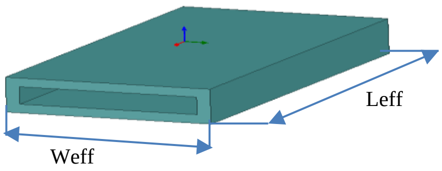

Figure 4. conventional rectangular waveguide

$$f_r(TE_{m0p}) = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{weff}\right)^2 + \left(\frac{p}{L_{eff}}\right)^2} \quad (1)$$

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

$$L_{eff} = L_{siw} - \frac{d^2}{0.95*p} \quad (3)$$

As shown in Figure 5, in the plane of d-p, there is a region where the SIW is equivalent to a traditional rectangular waveguide and has similar guiding properties [9]. This zone is examined in [20] and has the essential specifications. There is no bandgap in its working bandwidth ($p < 0.25\lambda_c$), where λ_c is the TE10 mode's cutoff wavelength. It has negligible leakage loss ($p \leq 2d$). It is physically realizable in ($p > d$) region. For the criterion p>1.2d, an accurate empirical formula with an error of less than 1% has been proposed. As a result, the area may be characterized as $p < 0.25\lambda_c$ and $1.2d < p \leq 2d$.

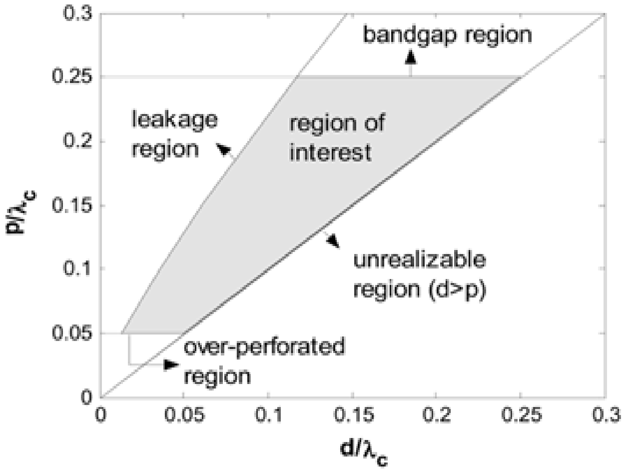

Figure 5. Region of interest of SIW

2.3. SIW unloaded Q-factor

Q-factor determines the performance of any resonant structure and is defined as the ratio of energy stored to the total energy lost. An increase in energy loss results in a low Q-factor, necessitating the use of a Q-enhancement process. Q-factor of SIW resonator is described by (4) as presented in [21].

$$Q = 2\pi \frac{Maximum\ Energy\ stored}{energy\ Dissipate\ per\ cycle} \quad (4)$$

Three major losses are related to the SIW: the conductor, dielectric, and radiation losses. Conductor losses are due to the finite conductivity of metal layers and vias, while dielectric losses are due to the loss of tangent of the dielectric substrate. In addition, radiation losses, usually very minimal are due to the gaps in the SIW structure along the walls. Since these are very minimal, they could be ignored in the calculation of the total Q-factor given by (5) as in [21]. The total unloaded Q-factor is defined as (5),

$$Q = \left(\frac{1}{Q_d} + \frac{1}{Q_c} + \frac{1}{Q_R}\right)^{-1} \quad (5)$$

where Q_c depends only on the conduction losses, Q_d depends on dielectric losses, and Q_R depends on radiation losses. So, the unloaded quality factor becomes (6),

$$Q = \left(\frac{1}{Q_d} + \frac{1}{Q_c}\right)^{-1} \quad (6)$$

where $Q_d = \frac{1}{tan\delta}$ and $Q_c = \frac{(K*weff*Leff)^3 h\eta}{2\pi^2 R_s(2hweff^3+2hLeff^3+Leff*weff^3+weff*Leff^3)}$

with $K = \frac{2\pi*f_r(TE_{101})*\sqrt{\epsilon_r}}{c}$; $R_s = \sqrt{\frac{w\mu_0}{2\sigma}}$; $\eta = \frac{377}{\sqrt{\epsilon_r}}$

where K is the wavenumber in the SIW, $tan\delta$ is the dielectric loss tangent, R_s is the surface resistance of the cavity ground planes, and η is the intrinsic impedance.

3. METHOD

In accordance with the SIW design rules discussed in the previous section, we aim to design a SIW resonator operating in f=10 GHz frequency. Based on the analysis already done, the high permittivity reduces the insertion losses of the SIW resonator. In addition, the thickness h of dielectric material increases the unloaded Q-factor. For this reason, in this study, the following parameters are considered: ε_r= 2.08 with $tan\delta$=0.0006, h=1.3 mm, and σ = 6.1 107 S/m is used for the metallization.

3.1. Optimization of SIW using genetic algorithm

3.1.1. Design variables and objective function

GA optimization is applied to the diameter d, width w_{siw}, and the spacing between two adjacent vias p to design a SIW resonator with a high-unloaded Q-factor. We are looking to maximize the unloaded Q-factor: Q, expressed in (6). We will introduce $Q_{op} = -Q$ to transform the problem towards the minimization of Q_{op}. As a result, Q_{op} will be considered as an objective function for our optimization problem:

Subject to:

$0.1 \leq d \leq 0.5$, $0.2 \leq p \leq 1$, $16 \leq w_{siw} \leq 18$.

$d \prec \frac{\lambda_g}{5}$ with $\lambda_g = \frac{2\pi}{\sqrt{\frac{(2\pi*f)^2*\varepsilon_r}{c^2} - \frac{\pi}{weff}}}$ is the guiding wavelength as in [22].

$p \leq 2d$

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

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

We have used in it the current work MATLAB optimization functions to develop the GA algorithm. The optimization process begins with the GA optimizer and continues for multiple iterations. The GA optimization uses a population size of 100, The crossover function is "constraint dependent," the mutation function is "constraint dependent," and 100 generations are chosen. Constraints applied to the design parameter (*d*, *p*, w_{siw}) originally came from physical limitations as well as radiation characteristics. The values of diameter are constrained to the range of (0.1 to 1 mm), spacing *p* constrained to the range of (0.1 to 2 mm), and the width constrained to the range of (16 to 18 mm) while w_{eff}=18 mm, and L_{eff}=20 mm. The computation time for the example described in this work is in the range of a few minutes but optimizing the same instances in full-wave simulation software such as Ansys HFSS takes much longer. A summary of the optimization problem is presented in Figure 6.

Optimization problem:

Solve for:
d, p, w_{siw}

Minimize:
$Qop = -Q$

Variable bounds:
0.1< d <0.5
0.2< p <1
14< w_{siw} <18

Constraints:

linear constraints:	Nonlinear constraints
d<0.5	$w_{eff} = w_{siw} - \frac{d^2}{0.95*p}$
p<2*d	$L_{eff} = L_{siw} - \frac{d^2}{0.95*p}$

Figure 6. Summary of optimization problem

3.1.2. GA procedure

The possible solution to the problem in GA is defined as a 'chromosome' and then subdivided into 'genes'. A GA starts with an initial population of randomly generated chromosomes concerning the problem constraints. Then, new populations are generated and evaluated through iterative, random, and probabilistic mechanisms ruled by the four fundamental operators of parent: selection, crossover, replacement, and mutation. Using the GA approach, the objective function (Qop) is translated into a positive fitness function that measures the suitability of a chromosome and its performance to satisfy the objective of the problem to be optimized. The initial population of chromosomes was randomly generated under the constraints of minimal and maximal values for each of the decision variables (d, p, w_{siw}) while taking into consideration linear and nonlinear design constraints. Each chromosome is evaluated based on the value of the fitness function (Qop). The elitism of one chromosome rule was then used to ensure algorithm convergence by preventing the fittest chromosome from departing through crossover and mutation operations. The parents' selection phase was obtained based on the tournament selection method. The crossover operator then combines two chromosomes (parents) to produce two new chromosomes (children). Each of these chromosomes was modified by randomly altering the value of one gene. With the above procedure, the successive population contained chromosomes with higher fitness values. The procedure was then repeated until the criterion of convergence was reached, i.e., the optimal solution is obtained Figure 7.

3.1.3. Optimization result

The best fitness value in each generation is plotted in Figure 7. The convergence rate is relatively fast. After 10 generations, the design goal is achieved. Optimal geometric parameters are shown in Table 1 as best individuals. Result optimization is summarized in Table 1.

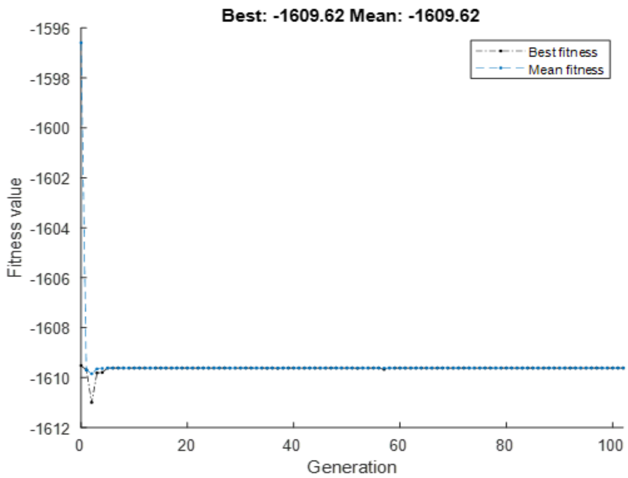

Figure 7. Objective function versus number of generations

Table 1. Parameter ranges and their optimal values

Variable	Minimum (mm)	Maximum (mm)	Optimal value (mm)
d	0.1	0.5	0.1
p	0.1	1	0.2
w_{siw}	14	18	18

3.2. Optimization of SIW using Ansys-HFSS

Poorly designed transitions can make higher-order modes propagate along the SIW, which deteriorates the signal integrity and reduce the effective channel bandwidth. For that reason, the size of a SIW resonator as well as the transition shown in Figure 8 has been optimized to be reduced at 10 GHz frequency. Furthermore, the length Lt, the width W0, and Wt of the transition taper have been significantly reduced while maintaining an optimal quality of signal transmission in the transition, optimal transition results are Wt=8 mm, W0=1 mm, and Lt= 3 mm. Figure 9 shows the generated scattering parameters of the SIW resonator designed.

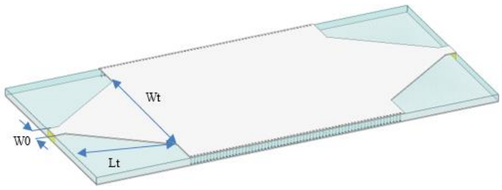

Figure 8. Design of SIW cavity and the optimal tapered transition

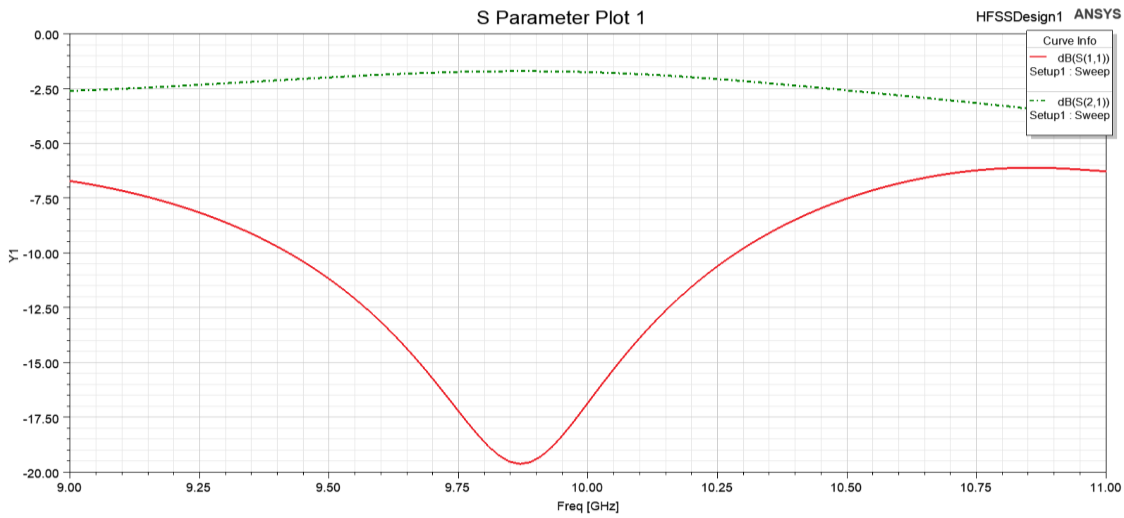

Figure 9. Return loss (S11) and insertion loss (S21)

4. RESULTS AND DISCUSSION

The SIW resonator has been modeled in the finite element method (FEM) based Electromagnetic Tool HFSS. The scattering parameter plots of the SIW generated are shown in Figure 9. The transmission coefficient is approximately -1.5 dB, and the reflection coefficient is near -19.5 dB, which means that most of the energy is transferred in this cavity. In order to verify the results obtained by the GA, the SIW resonator has been realized under the HFSS software, and a simulation in Eigenmode (free oscillation) has been carried out. The value of the Eigenmode quality factor calculated by HFSS is approximately 1663 as shown in Figure 10, which is comparatively consistent with the results obtained by the GA.

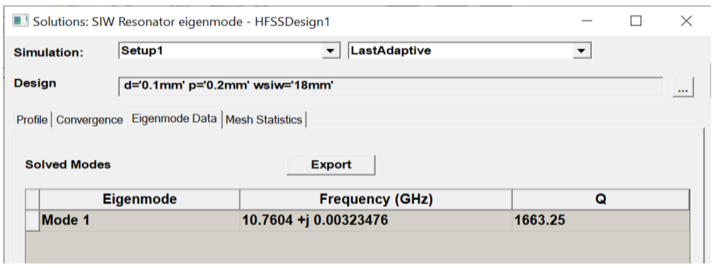

Figure 10. Unloaded Q-factor in Eigen mode using HFSS

Q is the unloaded quality factor and is a measure of how much energy is lost in the resonator due to lossy materials. HFSS uses (7) to calculate the approximate unloaded quality factor.

$$Q = \frac{Mag(freq)}{2*Im(freq)} \quad (7)$$

The analysis and simulation illustrated in previous sections have indicated the optimal geometric parameters of SIW, firstly using a GA and then using Ansys HFSS we have found that the optimal physical values around the desired frequency (10GHz) are [d=0.1 mm, p=0.2 mm, w_{siw}=18 mm] with the unloaded quality factor more than 1609, and lower losses (RL=-19.5 dB, IL=-1.5 dB). These results present additional advantages compared with other studies [5], [6] which have shown that the unloaded Q-factor is 373 and 540 respectively. The new generation of metaheuristic techniques like artificial bee colony and particle swarm optimization algorithms are introduced recently in the design of electronic circuits [23]–[25], This is what we intend to accomplish in the near future; to find the optimal metaheuristics to design a compact SIW filter that gives more interesting interaction mechanisms between individuals and additional advantages in term of efficient performance.

5. CONCLUSION

The design of SIW structure based SIW technology can benefit a lot from the use of this optimization project provided by combining the merits of GA and HFSS. An example is used here, showing that the Unloaded Q-factor can arrive at more than 1,609, insertion loss equal to -1.5 dB, and return loss is approximately -19.5 dB while keeping the small size of the SIW resonator. Moreover, these design parameters can be considered the key parameters in the design of an SIW resonator which represents a basic element of a multipole filter or an oscillator circuit. In future work, we aim to introduce new-generation metaheuristics in the program to improve the convergence rate and the ability to find an optimal design of SIW filters intended for IoT applications.

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