Cubic Spline-Based Genetic Algorithm Optimization for Millimeter and Microwave Integrated Circuits

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Abstract. A clamped cubic spline profile taper of an air-filled substrate integrated waveguide (SIW) transition was optimized to search for the optimal design of taper in this paper. The optimization technique involved a combination of the multi-objective genetic algorithm (MOGA) and full-wave analysis of the waveguide. The data from the return and transmission losses provides a basis for the optimization of the transition tapers design. The simulation results show the efficacy of our proposed strategy, where the optimal taper geometry yields an improvement of the return loss while maintaining its original transmission loss at Ka-band (26–40 GHz) frequencies.

Keywords: Millimeter-wave, air-filled substrate integrated waveguide (SIW), substrate integrated waveguide (SIW), clamped cubic spline method, genetic algorithm optimization, multi-objective genetic algorithm.

1. Introduction

The genetic algorithm (GA) optimization method is widespread in engineering electromagnetics design [1–4]. The electromagnetic optimization problems generally involve several parameters, thus making the design process inefficient and complicated [5]. Meanwhile, spline would be useful for a design process because of the simplicity of their construction, the accuracy of evaluation, and their capacity to approximate complex shapes [6]. Previous studies using the spline optimization approach include optimization of a spline-profile horn with the quasi-Newton method and optimization of microstrip antennas using cubic splines with particle swarm optimization [7, 8]. This paper will develop an optimization procedure based on the combination of GA with the clamped cubic spline. The developed procedure used an air-filled SIW transition design as a case study.

Recently, there has been increasing interest in the manufacturing of millimetre and microwave devices components based on substrate integrated waveguide (SIW) due to the demand for compact, light, flexible, low-cost, and high-performance integrated circuits. Until today, various components based on the SIW technology have been proposed and applied [10, 11]. One of the significant issues with the SIW circuit application in the high-quality microwave millimetre wave component is its losses. Dielectric loss is the primary source of loss in SIW and is significantly larger than the ohmic and radiation losses [9]. Therefore, many efforts had taken to improve the performance of SIW circuits [12–17].

The modified SIW with the dielectric-to air-filled transition taper has been discovered by [16]. The effects of the transition taper geometry on losses were reported in [18]. In parallel, an optimization of the transition taper design of modified SIW also was reported in [15–17]. Therefore, the specific geometry of the transition taper is required to go through to find an optimal design of an air-filled SIW transition taper. Hence, a cubic clamped spline-based genetic algorithm optimization method is applied to re-design the transition taper geometry to minimize the SIW losses in this study.
2. Dielectric-to-air filled SIW transition

The design of the taper for the transition using the characteristic equation is useful in [16]. Based on the full-wave analysis results in [18], the raised cosine taper, as depicted in Figure 1, has an influence on the transition losses compared to others.

By referring to the taper designs in Figure 1, the clamped cubic spline function is applied to define the shape of the transition taper in order to minimize the transition losses further. The \( W_1 \) is the total width in the air-filled region, \( W \) is the width of the dielectric-filled SIW and \( W_2 \) is the width of the air-filled SIW. The width of the taper \( W_2 \) increases along the transition length \( L \) with the initial width \( a \) and the final width \( b \) of the transition taper are constants to ensure the transition continues as presented in Figure 1. All the structural dimensions of the transitions are described in Table 1, with \( L \) being 20 mm, and height \( h \) are 0.508 mm. For our computational experiment, the five fixed number of nodal points are used to form a set of splines that define the taper geometry, as presented in Figure 2. As stated in [16], a transition length of 20 mm is commonly accepted to provide acceptable losses. The dielectric-to air-filled SIW transition is designed for the Roger RT/Duroid 6002 substrate \( \varepsilon_r \) in the Ka-band frequencies.

![Figure 1. Tapered transition with cross-section.](image1)

![Figure 2. Taper profile with clamped cubic splines: \( x \) = length, \( S(x) \) = the clamped cubic spline function](image2)
3. Optimization Procedures

3.1 Taper Design

The first step is to form a spline profile of the taper. The spline profile of transition taper is constructed to have zero slopes at the endpoints. By constructing the equation of the taper with the clamped cubic splines as shown in Figure 2, the internal nodes provide four degrees of freedom \( \{x_1, x_2, x_3, x_4\} \) as the design variables, later, these nodes can serve as a finite number of unknowns to be optimized to find an optimal design of taper. The upper and lower boundaries of each node, i.e., \( x \pm 0.16 \) mm, are also specified so that the optimized variables do not exceed the range for the shape construction. From the geometric construction, a Visual Basic Script (VBS) code is generated for the optimization.

3.2 Optimization Procedure

The second step is setting up the interface code for real-time data transfer between VBS and MATLAB for GA optimization. In order to re-design the transition geometry, the losses along the transition taper need to be optimized. So, GA is run to optimize a spline profile of taper on return \( S_{11} \) and transmission \( S_{21} \) losses. Those losses are indicated by scattering parameters S-parameters. The GA procedure is used for the computation, where it generates the design variables associated with each taper structure. The calculation of fitness values is then evaluated based on the full-wave analysis results. The calculated fitness values are then used in the GA computation for the subsequent iterations to find the optimal geometry. The transition is validated by comparison with an evaluation of a fitness function. If the fitness meets the requirement, the procedure ends. Otherwise, new structures are generated, which are used in the next iteration for full-wave analysis to validate their performance concerning the expectations. A strategy of the analysis is illustrated in Figure 3.

| Band Freq. | Dimension Properties | Parameters | Air-filled SIW | Dielectric-filled SIW |
|------------|----------------------|------------|----------------|---------------------|
| Ka-band    | \( W_1 \)            | 7.05 mm    | –              | –                   |
|            | \( W_2 \)            | 6.034 mm   | –              | –                   |
|            | \( W \)              | –          | 4.11 mm        |                     |
|            | \( \varepsilon_r \)  | 2.94       | 2.94           |                     |
|            | \( h \)              | 0.508 mm   | 0.508 mm       |                     |
|            | \( W \)              | 0.508 mm   | 0.508 mm       |                     |
The transition design goal is to minimize the return and transmission loss by optimizing the tapered design. Since there are two objectives, the multi-objective genetic algorithm (MOGA) was performed. The fitness functions for the multi-objective GA are defined as the average of those $S_{11}$ and $S_{21}$ values over the frequency band of interest as

$$Fitness = \frac{1}{N} \sum_{i=1}^{N} |S_{11}(f_i)| \leq -20 \text{ dB}$$

(1)

$$Fitness = \frac{1}{N} \sum_{i=1}^{N} |S_{21}(f_i)| \geq -0.2 \text{ dB}$$

(2)

where $f_i$ is the sampling frequency, and $N$ is the number of the sample.

4. Results and discussion

The ranges of the optimization parameters to be optimized and the optimal results are displayed in Table 2. The formation of an optimal taper is shown in Figure 4.
In the design specifications, the centre operating frequency is expected to be 33 GHz. In contrast, after the design was simulated, the results displayed that the centre operating frequency is 33 GHz, as shown in Figures 5 and 6. The return loss comparison is depicted in Figure 5. It can be observed that for the Ka-band frequency, the reflection coefficient, $S_{11}$, indicates that the optimal transition taper yields the best performance with a return loss of 20.88 to 52.60 dB at the frequency range from 26 to 40 GHz. However, for the original transition taper the $S_{11}$ of 20.78 to 47.60 dB from 26 to 40 GHz is obtained. The percentage of return loss improvement, $\Delta S_{11}$, of the optimized taper design compared to the original-taper design can be calculated by

$$\Delta S_{11} = \frac{\max S_{11}^p - \max S_{11}^o}{\max S_{11}^o} \times 100\%$$

(3)

where $S_{11}^p$ is the return loss of the optimized taper and $S_{11}^o$ is the return loss of the original taper. From

| Parameters(mm) | $S(x)$ | $S_1$ (1) | $S_2$ (2) | $S_3$ (3) | $S_4$ (4) |
|----------------|--------|-----------|-----------|-----------|-----------|
| **Original value** | | 0.2865 | 1.0365 | 1.9635 | 2.7135 |
| **Optimal value** | | 0.2900 | 1.0187 | 1.8497 | 2.6667 |

Figure 4. Taper geometry with a clamped cubic spline for $L = 20$ mm: $x =$ length, $S(x) =$ the clamped cubic spline function

Table 2. Optimized parameters obtained using MO optimization at Ka-band.
equation (3), the optimal transition taper showed a 17% improvement concerning the return loss.

![Graph showing comparison between MO and RC taper](image)

**Figure 5.** Comparison of the optimized $|S_{11}|$ between MO and RC taper in Ka-band frequency at 33 GHz: RC = original taper, MO = optimal taper.

From figure 6, the transmission loss $S_{21}$ of 0.0745 to 0.14 dB from 26 to 40 GHz are obtained for the optimal transition taper. In comparison, the original transition taper yields the transition loss 0.149 to 0.28 dB at the frequency range from 26 to 40 GHz. The percentage of insertion loss improvement, $\Delta S_{21}$ of the optimized design compared to the original-taper design is calculated as

$$\Delta S_{21} = \frac{\max S_{21}^{\text{MO}} - \max S_{21}^{\text{RC}}}{\max S_{21}^{\text{RC}}} \times 100\%$$  (4)
where $S_{21}^{MO}$ is the transmission loss of the optimized taper and $S_{21}^{RC}$ is the transmission loss of the original taper. Referring to equation (4), the improvement in transmission loss of the optimal taper is 50%.

5. Conclusion
The numerical studies in specific cases of the transition optimization show an improvement of 17% return loss and 50% transmission loss at Ka-band frequencies. Based on the results, the above procedure is viable to find an optimal transition taper, where the new taper transition geometry is shown to be the best choice to minimize the return and transmission losses further. The successful optimization strategy of the present study may be used to the development of the more optimal design of a waveguide component for any frequency band with better performance.

6. References
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