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# Comparative analysis of metaheuristic algorithms (genetic algorithm, artificial bee colony, differential evolution) in the design of substrate integrated waveguide dual bandpass filter

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**ABSTRACT**

A well-optimized substrate integrated waveguide (SIW) filter can significantly enhance the performance of modern technologies, including wireless communication systems, radar, and sensors. The frequencies of 5 and 6 GHz play a crucial role in these applications. Metaheuristic algorithms such as genetic algorithm (GA), artificial bee colony (ABC), and differential evolution (DE) are effective for designing SIW filters specifically tailored to these needs. This paper evaluates the performance of evolutionary optimization techniques in the design of substrate integrated waveguide filters. The optimization focuses on achieving optimal impedance matching within the frequency range of 4 to 8 GHz. The attenuation constant serves as the cost function, guiding the optimization process to ensure reliable and accurate results from each algorithm. The filter parameters derived from the most efficient algorithm are verified using ANSYS HFSS, resulting in two bands with S11=-45 dB and S21=-0.2 dB in the first band, and S11=-28 dB and S21=-0.5 dB in the second band. Additionally, two transmission zeros with rejections of -23 and -12 dB are achieved at 6.4 and 7.08 GHz, respectively. These results highlight the practicality of SIW technologies in designing microwave circuits, particularly for internet of things (IoT) applications.



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## 1. INTRODUCTION

Active phased array antennas must meet strict requirements regarding their sensitivity to interference from nearby radiating systems, particularly in complex environments where the number of sensors and communication systems continues to grow [1]. Radio frequency interference can lead to several problems, including the saturation of the array receiver, which results in reduced sensitivity, missed detections, increased false alarm rates, or diminished channel capacity for telecommunications [2]. To mitigate these performance degradations, frequency-selective functionalities must be incorporated into the antenna panel and radio frequency (RF) front end [3]. One effective approach involves integrating filters into the transmit/receive module of each antenna element. These filters serve to confine the system's operational frequency band, preventing the antenna from transmitting or receiving signals that could interfere with neighboring devices [4].

A major challenge in designing filters for wide-scanning phased arrays is the constraint on available space within a radiating element, which typically occupies an area of only λ/2 × λ/2 (half-wavelength squared) [5]. Developing compact filters that maintain high performance—characterized by low insertion loss and strong rejection—remains an active research topic [6]. Various technological approaches are being explored to achieve the necessary rejection levels. Among these, substrate integrated waveguide (SIW) technology stands out as a promising solution due to its advantages, such as compact structure, cost-effectiveness, and ease of fabrication [7]. This article presents an investigation of innovative solutions aimed at enhancing the performance of miniaturized integrated filters. The main objective is to develop a compact SIW filter that combines high out-of-band rejection and low insertion loss. To achieve this, metaheuristic optimization algorithms are employed in Figure 1 [8]. It was selected over other algorithms due to its simplicity, rapid convergence, capability to address complex optimization challenges, and robustness in exploring a broad solution space while mitigating premature convergence. This method allows for the quick and accurate determination of the geometric parameters corresponding to the desired frequency response of the SIW structure. Furthermore, the study goes beyond this step by comparing three different metaheuristic algorithms widely used in the field: artificial bee colony algorithm (ABC), genetic algorithm (GA), and differential evolution algorithm (DE) to optimize the design. Finally, the obtained results are validated through full-wave electromagnetic simulation using high-frequency structure simulator (HFSS), ensuring the reliability and practical feasibility of the proposed approach.

The structure of the paper is as follows: Section 2 presents a concise overview and references for the algorithms evaluated. Section 3 covers the formulation of the cost function and the dynamic weight allocation for the objectives. Section 4 focuses on the comparison of various optimization algorithms with ABC to achieve optimal performance as well as the validation of obtained results in ANSYS HFSS software. Finally, Section 5 provides a summary of the results.

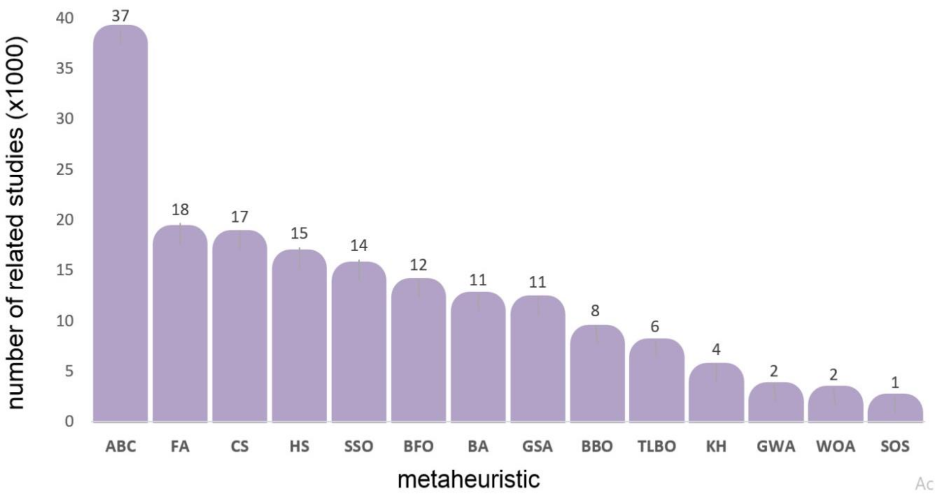


Figure 1. The number of related papers on google scholar for new generation metaheuristics

## 2. PROPOSED METHODOLOGY AND METAHEURISTIC ALGORITHMS

Evolutionary algorithms (EAs) have been developed over the past decade, inspired by Darwin's theory of evolution and natural selection [9]. The study of EAs began in the 1960s, leading to the independent development of three main approaches: genetic algorithms, evolutionary programming, and evolution strategies [10]. These algorithms as illustrated in Figure 2 [11], are widely applied to both single and multi-objective optimization problems.

### 2.1. Artificial bee colony algorithm

The artificial bee colony (ABC) algorithm was developed by Ozturk and Karaboga [12]. Inspired by the foraging behavior of honeybees, the ABC algorithm simulates how bees search for nectar and communicate information about food sources to other members of the colony [13]. The quality of a food source, referred to as its "affinity," is determined by the objective function. Essentially, the optimization process mirrors the bees' search for high-quality food sources, which is analogous to finding optimal solutions to a problem [14]. In the ABC algorithm, each food source is located within a D-dimensional search space and represents a possible solution to the optimization problem. The fitness value of a food source is equivalent to the amount of nectar it contains. Typically, the number of employed bees and spectator bees is equal and matches the number of food sources.

The initial solutions are randomly generated within a defined range of variables $x_i$ (i=1, 2,..,w ) [15]. Each employed bee then identifies new sources, representing half of the total sources. Equation (1) is used to determine a new source [16], where k∈{1,2,..,N} and j∈{1,2,…,D} are randomly selected indices. The value of $k$ is chosen randomly but must differ from $i$, and $\varphi_{ij}$ is a random number between 0 and 1, controlling the generation of neighboring food sources. The bee visually compares two food positions $x_{ij}$. Once a candidate source position $V_{ij}$ is generated, it is evaluated. If its nectar quality is equal to or better than the previous source, it replaces the old one in memory; otherwise, the previous source is retained. Finally, in the next phase, onlooker bees select a food source based on the probability given in (2) [17].

$$V_{ij} = x_{ij} + \varphi_{ij}(x_{ij} - x_{kj}) \quad (1)$$

$$P_i = \frac{fit_i}{\sum_{j=1}^{w_N} fit_j} \quad (2)$$

The adequacy value $fit_i$ of a solution i is proportional to the nectar quantity at a food source and corresponds to the number of employed bees. Scout bees are responsible for random searches within the colony, operating without prior knowledge. They are selected from employed bees based on boundary parameters. If a food source fails to yield a solution after a set number of attempts, it is abandoned, and the associated bee becomes a scout, searching for a new source. The number of attempts before abandonment is determined by the "limit" parameter. The identification of a new source by a scout bee is defined in (3) [18].

$$X_{ij} = X_j^{min} + \left(X_j^{max} - X_j^{min}\right) * rand(0,1) \quad (3)$$

where $X_j^{min}$ and $X_j^{max}$ represent the parameter's optimization limits. The termination criterion in the ABC algorithm is typically based on the number of iterations.

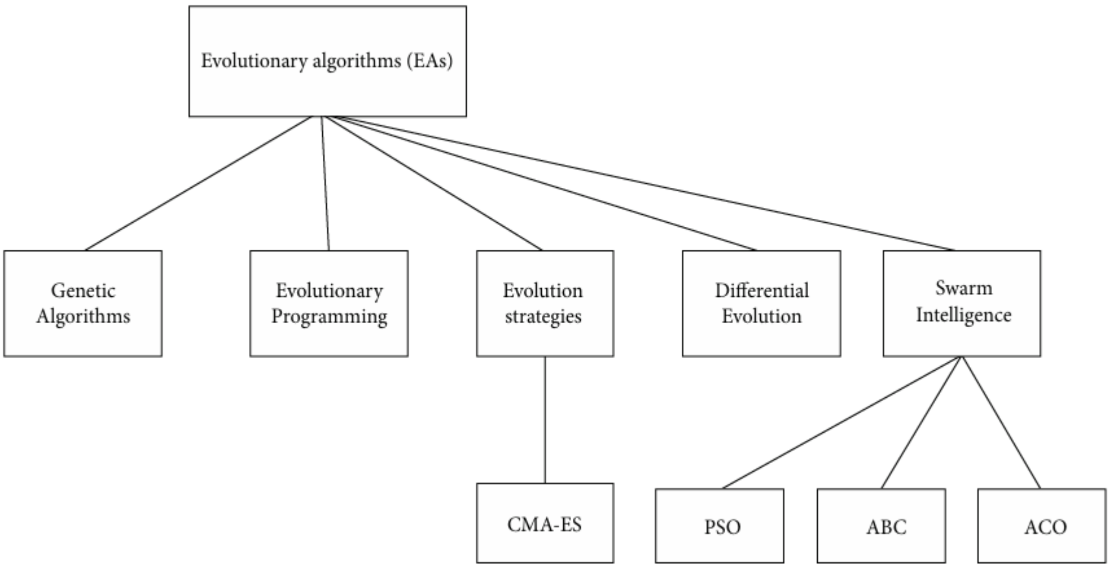


Figure 2. Evolutionary algorithms' main families

## 2.2. Genetic algorithms

GAs, the most popular EAs, are inspired by Darwin's natural selection [9]. The primary operators used in GA are selection, crossover, and mutation. In genetic algorithms (GA), a potential solution is represented as a "chromosome," which is further divided into "genes." The GA begins with an initial population of randomly generated chromosomes, considering problem constraints. Through iterative, probabilistic mechanisms, new populations are created and evaluated using four key operators: selection, crossover, replacement, and mutation.

The objective function is transformed into a fitness function that quantifies the suitability of a chromosome in meeting the optimization goal. The initial population is generated within the predefined minimum and maximum limits for decision variables incorporating both linear and nonlinear constraints. Chromosomes are evaluated based on their fitness values, and an elitism strategy ensures that the best chromosome is preserved to maintain convergence. Parent selection follows the tournament selection method, after which the crossover operator combines two parent chromosomes to generate offspring. Each offspring undergoes mutation, where a gene is randomly altered. This iterative process results in successive populations with improved fitness values.

### 2.3. Differential evolution

The differential evolution (DE) algorithm, introduced by Storn and Price [19], is a population-based evolutionary method designed for optimizing continuous variables in multi-dimensional spaces. Similar to GAs, DE is inspired by Darwin's principles of natural selection and genetic adaptation, later applied to artificial problem-solving by Holland. While DE employs the same evolutionary operators as Gas mutation, crossover, and selection their execution order differs. In DE, mutation and crossover modify parameter vectors before selection, unlike in GAs, where selection occurs first. This approach mitigates the "destructive" impact of mutation seen in GAs, as it is applied at the beginning of each generation instead of the end. Consequently, both the best and average fitness values evolve consistently without requiring additional mechanisms like elitism. Moreover, DE ensures effective exploration of the solution space by treating the entire population as a mating pool. Unlike GAs, it does not favor the fittest individuals; instead, mutant vectors are generated using randomly selected individuals from the population, promoting diversity and broad search coverage.

## 3. FORMULATION OF THE OPTIMIZATION PROBLEM

The artificial bee colony algorithm was utilized to optimize the design of the substrate integrated waveguide structure. In this optimization process, key design parameters include the via diameter (d), the spacing between adjacent vias (p), the substrate height (h), and the SIW width $w_{siw}$ as presented in Figure 3. The objective is to minimize the attenuation constant alpha0 (4), which directly affects the waveguide's performance and it summarizes the total loss in SIW: conductive loss $\alpha_C$ (5) dielectric loss $\alpha_D$ (6) and radiation loss $\alpha_R$ (7) [20].

$$\alpha_0 = \alpha_C + \alpha_D + \alpha_R \tag{4}$$

$$\alpha_C(f) = \frac{\sqrt{\pi f \varepsilon_0 \varepsilon_r}}{h\sqrt{\sigma_C}} \frac{1+2\left(\frac{f_0}{f}\right)^2 \frac{h}{w_{eff}}}{\sqrt{1-\left(\frac{f_0}{f}\right)^2}} \tag{5}$$

$$\alpha_D(f) = \frac{\pi f \sqrt{\varepsilon_r}}{c\sqrt{1-\left(\frac{f_0}{f}\right)^2}} \tan\delta \tag{6}$$

$$\alpha_R = \frac{\frac{1}{w}\left(\frac{d}{w}\right)^{2.84}\left(\frac{s}{d}-1\right)^{6.28}}{4.85\sqrt{\left(\frac{2w}{\lambda}\right)^2-1}} \tag{7}$$

The ABC algorithm, inspired by the foraging behavior of honeybee colonies, was implemented in MATLAB, leveraging its robust global search capabilities. The optimization process consists of three main phases: employed bees explore the search space and share information, onlooker bees evaluate the potential solutions, and scout bees introduce diversity by replacing stagnating solutions. Constraints imposed on the design parameters stem from physical manufacturing limitations and electromagnetic radiation characteristics. Specifically, the via diameter is constrained within the range of 0.8–1.2 mm, the spacing (p) is set between 1.5–2 mm, the width varies from 10–11 mm, and the substrate height is limited to 0.9–1.2 mm. The conductivity of metal is σ=5.8×107S/m and the metal layer have a height of h1=0.09 mm, a surface roughness of 1.78×10−3 mm. Through iterative optimization, the ABC algorithm effectively identifies an optimal set of design parameters that minimize attenuation while satisfying all imposed constraints.

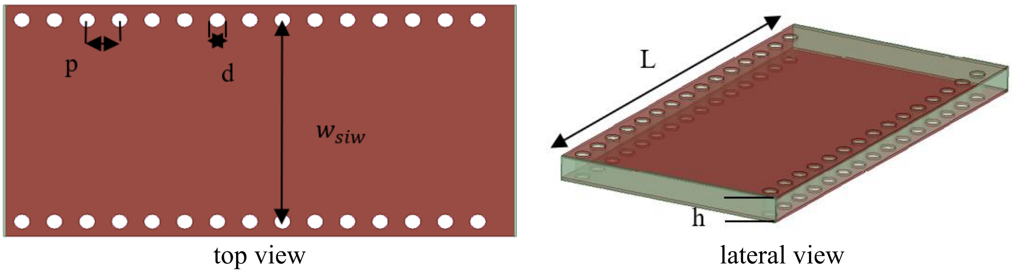


Figure 3. Geometric parameters of the SIW structure

## 4. RESULTS AND DISCUSSION

When the algorithm reaches convergence, it identifies the best possible solution, as illustrated in Figure 4. At this stage, the optimization process has explored and refined the search space, ultimately selecting the most efficient parameter set. The attenuation constant, a key performance metric, was obtained through simulation using the ABC algorithm. The results indicate that at a frequency of approximately 10 GHz, the optimized SIW structure achieves an attenuation constant of 0.139 dB/m, demonstrating the effectiveness of the ABC method in minimizing transmission losses.

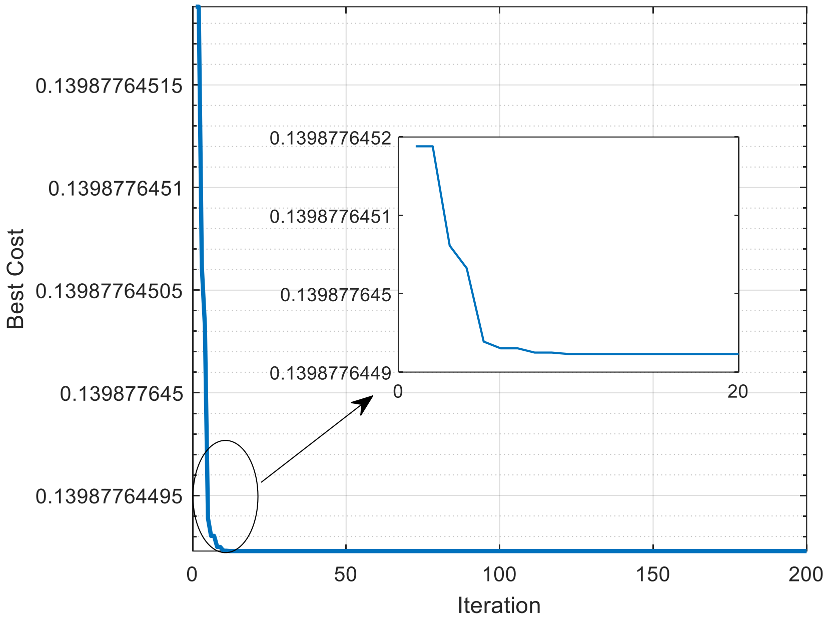


Figure 4. Objective function (attenuation constant) versus iterations

The optimized parameters identified by the ABC algorithm are then applied to construct the final SIW design, ensuring that the structure meets the required specifications for performance and efficiency. These optimized values define critical dimensions such as substrate thickness, via hole diameter, and spacing, which directly impacts the waveguide's behavior and overall filter performance. Table 1 presents the final set of optimal dimensions obtained using the ABC method, highlighting its capability to fine-tune design parameters for improved attenuation and signal integrity.

Table 1. Parameter ranges and their optimal values

| Variable | Minimum (mm) | Maximum (mm) | Optimal value (mm) |
|---|---|---|---|
| d | 0.8 | 1.2 | 0.8 |
| p | 1.6 | 2.2 | 1.64 |
| $w_{siw}$ | 18 | 20 | 20 |
| h | 0.9 | 1.2 | 1.2 |

### 4.1. Performance comparison of ABC, GA, and DE algorithms

New generations of metaheuristic techniques, such as GA [21], [22], and DE [23], [24], have recently been introduced in electronic circuit design. In this context, our study explores alternative metaheuristics for designing a compact SIW filter, leveraging more sophisticated interaction mechanisms between individuals and offering additional performance benefits.

To compare the ABC algorithm with other stochastic approaches, we selected two widely used evolutionary algorithms: GA and DE. GA was chosen due to its well-established role in optimization problems, particularly in engineering applications, where it effectively explores large search spaces through selection, crossover, and mutation. DE, on the other hand, was selected for its strong exploitation capabilities and its ability to handle continuous optimization problems efficiently. By comparing ABC with these two approaches, we aimed to evaluate how well each algorithm balances exploration and exploitation while optimizing the same objective function α0 within a common framework.

Figure 5 presents the results of cost function evolution as a function of the number of iterations. The findings clearly show that the ABC algorithm achieves the best optimal solution, outperforming the other algorithms in terms of convergence speed and accuracy. This superiority can be attributed to its ability to effectively balance exploration and exploitation of the search space, as well as its robustness against local minima. In comparison, while GA and DE also demonstrated respectable performance, they exhibited limitations in convergence speed and final accuracy. These observations confirm the relevance of ABC as an optimization tool for designing compact and high-performance SIW filters.

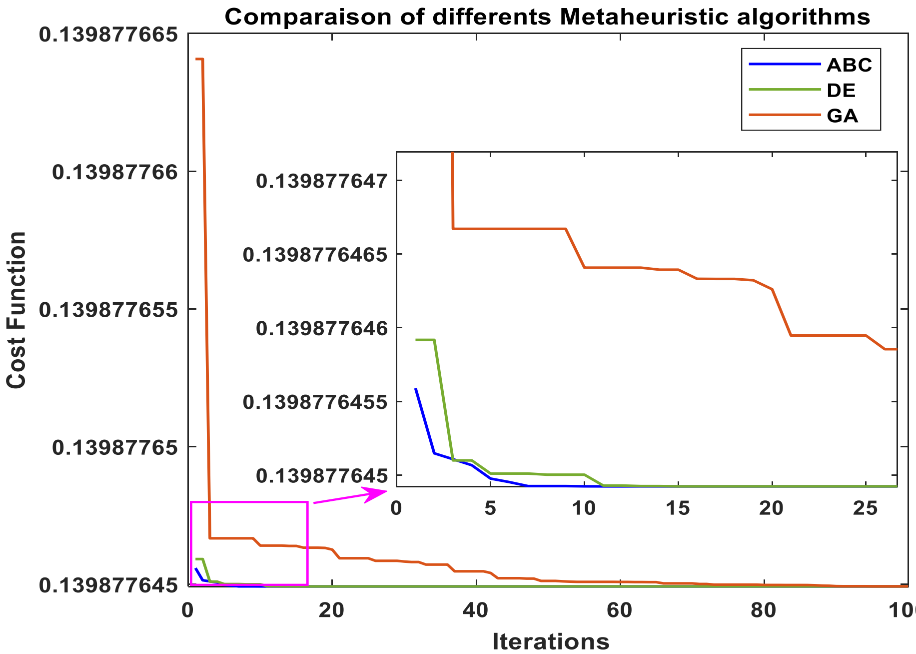


Figure 5. Objective function vs number of iterations

### 4.2. Validation using ANSYS HFSS simulation

In this study, a dual-band filter is designed using a topology based on three centrally positioned inductive posts in Figure 6(a) with d1=1.6 mm, d2=3.2 mm, and y=6.25 mm. The filter is constructed on a diamond substrate with a relative permittivity of 16.5, and a length of 25 mm. The copper plate has a thickness of 0.099 mm. The vias have a diameter of 0.8 mm, with a spacing of 1.6 mm between adjacent vias, and the total width is 20 mm, and a thickness substrate is 1.2 mm.

To ensure proper integration between SIW and microstrip technologies, SIW-microstrip transitions are essential. The tapered transition, depicted in Figure 6(b), has been optimized using HFSS, with the best taper dimensions found to be wt=7.1 mm and Lt=3 mm. The microstrip line has dimensions of w50=1 mm and L50=1 mm. This transition consists of a tapered microstrip section connecting a 50-ohm microstrip line to the substrate-integrated waveguide. The taper is designed to facilitate the conversion of the microstrip line's quasi-TEM mode into the waveguide's TE10 mode.

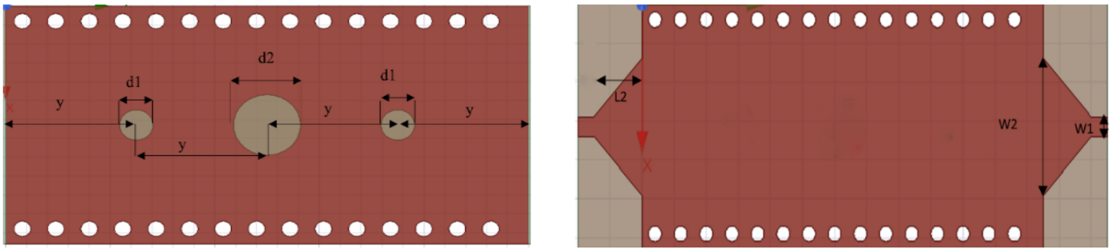


Figure 6. Geometry of SIW filter (a) in SIW + taper transition, and (b) with circular inductive posts

The simulation results demonstrate excellent performance in terms of S-parameters in Figure 7. The SIW filter offers key advantages, including compatibility with planar technologies, low insertion loss, good impedance matching, compactness, and robustness. It operates efficiently in two frequency bands: at 6.00 GHz with a return loss of -45 dB and an insertion loss of -0.24 dB, and at 7.00 GHz with a return loss of -28.12 dB and an insertion loss of -0.56 dB, ensuring optimal signal transmission. Additionally, transmission zeros at 6.50 and 7.50 GHz significantly attenuate unwanted signals with -23 and -12 dB rejection respectively, enhancing filter selectivity, reducing interference, and improving overall performance compared with related work as presented in Table 2. The comparative results demonstrate that the proposed design achieves superior performance in terms of insertion loss and return loss compared to previous works. Although the out-of-band rejection of the proposed filter (–23 dB at 6.4 GHz and –12 dB at 7 GHz) is moderate compared to the high rejections achieved in [25] and [26], the overall combination of low insertion loss and excellent impedance matching highlights the effectiveness of the design for applications requiring minimal signal attenuation and good selectivity. These results confirm the SIW filter’s effectiveness in dual-band applications, making it a strong candidate for RF and microwave systems.

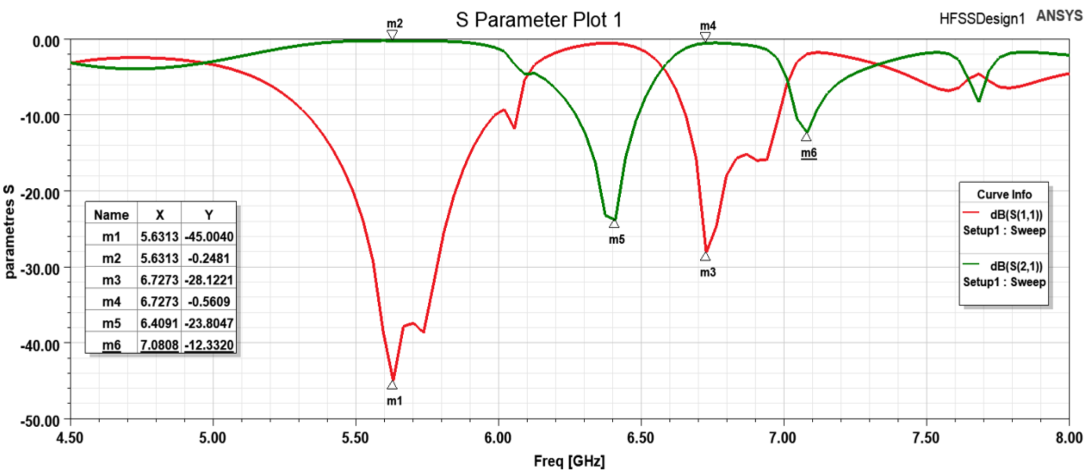


Figure 7. S11 and S21 of proposed filter (return loss and insertion loss)

Table 2. Performance comparison

| References | Freq (GHz) | Insertion loss (dB) | Return loss (dB) | Rejection |
|---|---|---|---|---|
| [27] | 6.8/10.3 | -1.7/-1.9 | -24/-22 | -16 dB at 7.4 GHz and -19 dB at 14.8 GHz |
| [26] | 5.57/7.84 | -1.8/-2 | -27/-20 | -43dB at 10.5 GHz |
| [25] | 1.9/4.8 | -1.2/-2.6 | -15/-16 | -55 dB at 3 GHz and -25 dB at 5 GHz |
| [28] | 1.5/4.96 | -0.85/-0.9 | -20/-23 | -48 dB at 3.4 GHz and -58 dB at 7.5 GHz |
| This work | 5.6/6.7 | -0.2/-0.5 | -45/-28 | -23 dB at 6.4 GHz and -12 dB at 7 GHz |

## 5. CONCLUSION

The 5.6 and 6.7 GHz frequencies are crucial for many modern applications, including wireless communications, radar, and sensor systems. For these frequencies, an optimized SIW filter can play a key role in improving the performance of entire communication and detection systems. Metaheuristics such as GA, ABC, and DE can be used to design efficient SIW filters tailored to these applications. In this article, the designed SIW filter offers significant advantages, including low insertion loss, excellent impedance matching, and high selectivity due to transmission zeros. The results demonstrate efficient operation in two frequency bands (around 6.00 and 7.00 GHz), ensuring optimal performance in terms of transmission and reflection. Transmission zeros play a crucial role in enhancing selectivity and rejecting unwanted signals, making this filter an ideal solution for demanding RF/microwave applications. In future work, we aim to focus on multi-objective optimization by combining three functions: quality factor, bandwidth, and insertion loss simultaneously.


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## CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

## DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author SA on request.

## AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

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## BIOGRAPHIES OF AUTHORS

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