Design Optimization of a Dual-band Microstrip SIW Antenna using Differential Evolutionary Algorithm for X and K-Band Radar Applications

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Abstract ─ In this work, design optimization and fabrication of a high performance microstrip dual-band antenna are presented using Substrate Integrated Waveguide (SIW) technology with Roger 4350 (ε_r=3.48 and h=1.52mm). Firstly, the SIW antenna design is considered as a multi-objective multi-dimensional optimization problem for a simple microstrip geometry and its geometrical parameters are optimized efficiently using Differential Evolutionary Algorithm (DEA) in the 3D CST Microwave studio environment based on the gain and return loss characteristics at 12 GHz and 24 GHz. In the second step, for justification of the proposed design method, the optimally designed dual band microstrip SIW antenna has been prototyped. Furthermore, the experimental results are compared with the performance measures of other counterpart designs in literature. Thus, based on the obtained results and comparisons, it can be concluded that the proposed microstrip SIW antenna model and its optimization procedure, is a sufficient and low-cost solution for X and K band radar applications.

Index Terms ─ Differential evolutionary algorithm, dual band, microstrip, optimization, substrate integrated waveguide.

I. INTRODUCTION

Substrate-Integrated Waveguide (SIW) is a novel and efficient solution counterpart of the traditionally waveguide designs [1-3]. Since a SIW structure can easily realized on a planar substrate, its integration with other planar microwave systems is possible. In SIW designs, an equivalent electrical walls that can confined EM waves are created via the use of metallized holes where the top and bottom metal layers of PCB substrate would provide the other sides of the waveguide.

The SIW design is a family member of substrate integrated circuits that include other substrate integrated structures such as substrate integrated image guides and substrate integrated non-radiative dielectric guides [1]. SIW components are popular thanks to being easy to design and realized, and have the combined advantages of planar printed circuits and metallic waveguides. Just like microstrip and coplanar transmission lines, SIW components are compact, flexible, and cost efficient. Furthermore, SIW design also have the advantages of conventional metallic waveguides, such as shielding, low-loss, high quality-factor and high-power handling [1]. In this way, the concept of system in Packet (SiP) can be extended to the System on- Substrate (SoS). SoS represents the ideal platform for developing cost-effective, easy-to-fabricate and high performance mm-wave systems.

Recently, especially antenna designs with SIW technology are becoming a trending topic for novel, high performance, low-cost antenna design [4-10]. Antennas designed with SIW technology have excellent performance due to the ability of suppressing surface wave propagation, wider operation band, decreased end-fire radiation and cross-polarization radiation. Typically, in [4-5], the effect of adding SIW structure to the proposed antenna was presented and gain was measured to be enhanced up to 4 dBi.

In this work, SIW technology is applied to design a microstrip dual-band antenna for X and K band radar applications. An antenna model given in Fig. 1 [5] is considered as an efficient antenna model for the aimed operation frequencies. Roger 4350 (ε_r=3.48) with 1.52mm height is used as a low-cost substrate of the SIW. The design optimization process of the proposed SIW antenna model is achieved via the use of Differential Evolutionary Algorithm (DEA) in 3D CST Microwave studio environment. For this purpose, the microstrip SIW antenna design problem is converted to an optimization problem by defining optimization variables and objectives based on the antenna

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performance criteria such as gain and return loss characteristics. Then, in order to prove the success of the design optimization of SIW antenna, a prototype is built with the optimal design parameters obtained from the DEA process and measured its performance. The measurements verify that the proposed microstrip SIW antenna model is a sufficient solution for X and K band radar applications and the DEA algorithm is an efficient algorithm for design optimization of microstrip SIW antennas.

II. DESIGN OPTIMIZATION OF DUAL BAND MICROSTRIP SIW ANTENNA USING DIFFERENTIAL EVOLUTIONARY ALGORITHM

Meta-heuristic algorithm is an advance procedure to form a heuristic that can find an efficient solution to a given problem, especially in case of problems with incomplete or imperfect information. Examples for these methods are: Methods that inspired from the behavior of animal and microorganism, such as particle swarm optimization, artificial immune systems, and insect colonies like Ant or Bees. Most of the mentioned methods have been utilized in design optimization of microwave device and antennas [11-17].

DEA is a method of multidimensional mathematical optimization which belongs to the class of Evolutionary Algorithm (EA). DEA is originated by Kenneth Price and Rainer M. Storn and first publication of idea of this method was published as a technical report in [18-19].

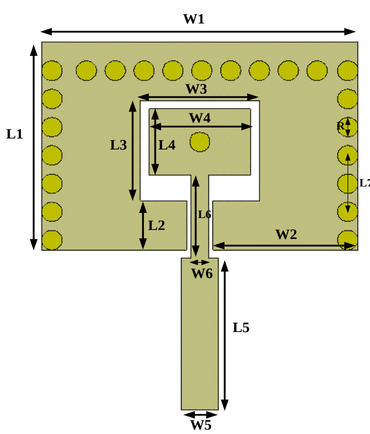


Fig. 1. Parametric layout of SIW antenna.

Roger 4350 (ε_r=3.48) with 1.52mm height is used as substrate of the SIW antenna and the optimization variables are dimensions of the rectangular microstrip patch, feedline size, the total number of metallized via's and their gaps as given with their limitations in Table 1.

The geometrical design parameters can be increased or decreased based on the request of designer, furthermore design parameters such as distance of via's, diameter of via's or other parameters such as dielectric constant or height of substrate can be added. But it should be noted that with the increase in number of optimization variables the search space would become more complex and requires more function evaluations which would drastically decreases the computationally efficiency of the design process. Also it should be taken into consideration that decreasing number of variables might prevent the algorithm to find the optimal solutions in the limited search space.

The flow chart of the optimization process is given in Fig. 2. According to this flow chart, it can be observed the DEA working in MATLAB environment send the optimization parameter values to CST suit environment to start a 3D electromagnetic simulation process. Then the simulation results in CST environment are sent to MATLAB environment in order to evaluate the cost function of the optimization process:

$$\mathrm{Cost}_i = \frac{C_1}{Directivity_i} + \frac{C_2}{\left|S_{11_i}\right|}\,, \qquad (1)$$

where, C is weighted constrained determined by user (Here in C_1=0.9, C_2= 0.3 which is determined with trial and error method), both S_{11} and directivity are only taken into account at the requested operation frequencies, 12 and 24 GHz; ***i*** is the index of the current member of DEA population. The performance results are obtained after 10 independent runs of the optimization process and the specification criteria of the objective function are:

$$S_{11} dB \le -10 \qquad f = 10GHz\ and\ 24GHz\,, \qquad (2)$$

$$Max(Directivity) \qquad f = 10\mathrm{GHz\ and\ 24GHz}\,. \qquad (3)$$

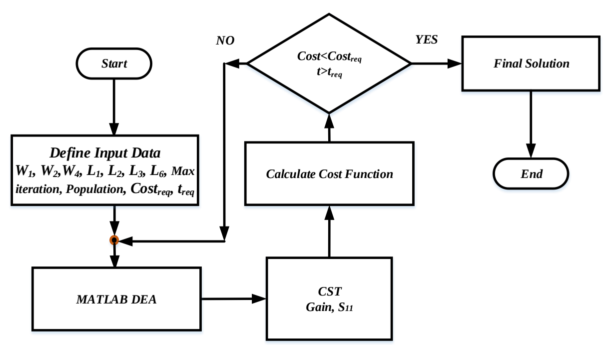


Fig. 2. Flow chart of the SIW antenna design optimization.

In Tables 2-3, the performance results of DEA algorithm for 10 different runs are presented. In Table 2, the best, worst and mean performance results of DEA for these 10 runs are given. As it can be observed, when the population size is taken as 20, the optimization process cannot converge to the required cost value and are trapped in a local minima in the search domain. However when the population size is increased the overall performance of the DEA is also increased. However it should be noted that although the increased number of population might also increases the performance it also would decrease the computationally efficiency of the whole process. This can be observed from Tables 2 and 3, where the minimal cost value obtained from run with 30 population size is reached to the value of 0.307 the run with 50 population size had achieved 0.278. However, even though the mean performance result of 50 population run is much better than the run with 30 population, the required function evaluation for 50 population is much higher than 30 populated run which will drastically decreases the computational efficiency of optimization process.

Table 1: Constraints of the variables in (mm)

Parameter	Constraint	Parameter	Constraint
W_1	10~20	L_1	5~15
W_2	1~10	L_2	1~10
W_4	1~10	L_3	1~10
		L_6	1~10

Table 2: Performance results of DEA*

Population	Cost		
	Maximum	Minimum	Mean
20	7.54	2.54	3.88
30	2.26	0.307	0.916
50	1.34	0.278	0.613

*Mean results obtained from 10 different runs at 20 iteration.

Table 3: Number of function evaluations of DEA*

Population	Iteration			
	5	10	15	20
20	107	198	289	380
30	161	297	433	570
50	268	495	722	950

*Mean results obtained from 10 different runs.

Table 4: Optimal parameter list in (mm)

W_1	15.4	L_1	10.7
W_2	7	L_2	2.5
W_3	5.75	L_3	5.1
W_4	4.95	L_4	3.4
W_5	$2xW_6$	L_5	7.8
W_6	0.85	L_6	4.2
R	0.8	L_7	3.35

The parameters given in Table 4 are obtained via DEA with 50 population size after a 20 iteration where the minimal cost was found as 0.278 with respect to the limitations given in Table 1 and Eq. 1.

The simulated and measured results of the prototyped SIW antenna design (Fig. 3) are presented in Figs. 4-6. The measurement results are obtained using the measurement setup given [20]. The simulated radiation pattern of the optimally designed SIW antenna are given in Fig. 4 where the designed antenna achieves a simulated gain level of 7 and 7.13 dBi at 12 and 24 GHz respectively.

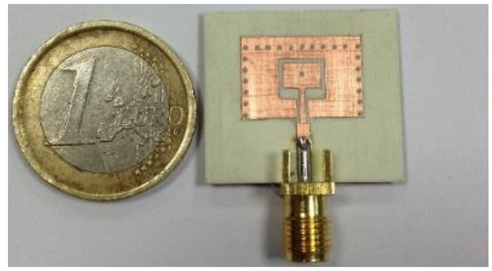
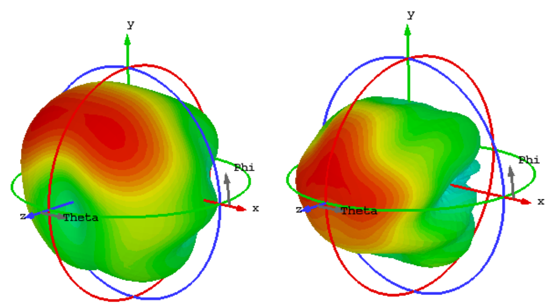


Fig. 3. Fabricated antenna.



(a) (b)

Fig. 4. Simulated gain patterns (a) 12GHz and (b) 24 GHz.

For further investigation of the effect of SIW structure on the performance results of antenna designs two additionally simulation cases had been added. (i) An antenna design similar in Fig. 1 which does not have any SIW structure with the same geometrical design parameters in Table 4 (NO SIW design), (ii) the same No SIW antenna design that is optimized via the DEA (NO SIW OPT). In Fig. 5, the simulated performance of antenna design with and without SIW structure had been presented alongside of both simulated and measured performance of the optimally design SIW antenna. Here it should be noted that optimized antenna not only is have resonance frequency in 12 and 24 GHz but also is resonated in middle frequencies. This can be prevented by simply adding these frequencies to the cost function or it is also possible to make the antenna has better performance measures in these frequencies by adding them to the cost function. However in this work simply only performance measures at 12 and 24 GHz are provided to the cost function and optimization process for design optimization of a dual band antenna.

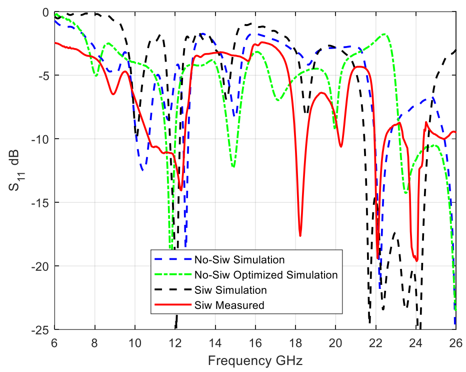


Fig. 5. Simulated and measured return losses.

In Table 5 and Fig. 6, the simulated and measured gain performance results of the antenna designs are presented. As it can be seen, the best gain performance results obtained from the design without SIW structure, even though an optimization process is applied, is around 6 dB for the selected operation frequencies while after the application of SIW design the gain is increased almost 2 dB. Furthermore, for extending the performance enhancement of SIW structure a comparison analysis with recently published works with SIW designs in literature [21-26] is presented in Table 6. As it can be seen from Table 6, the proposed design optimization process has achieved an antenna model that not only have better or similar performance results (Gain and S_{11}), but also have realized this performance measure with smaller size compared to counterpart designs even though one of its operation band is at 12 GHz.

Table 5: Comparison of the realized gains

Model		Realized Gain (dB)		Die Size in (mm)
		12GHz	24GHz	
SIW Measured		6.7	7	25.5x22.5
Simulated	**SIW DEA**	7.01	7.13	25.38x22.45
	No SIW	4.8	5.8	25.38x22.45
	No SIW DEA	5.1	6.2	23.85x22.45

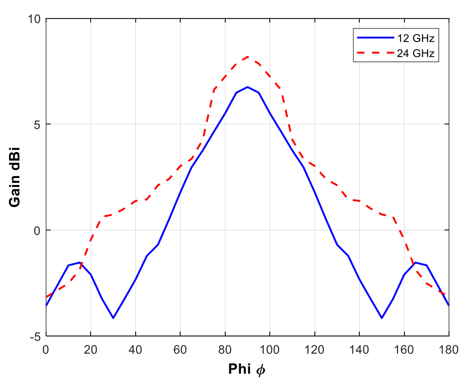


Fig. 6. Measured far field gain.

Table 6: Comparison of antenna with literature

Models	***f* (GHz)**	**S_{11} (dB)**	**Realized Gain dB**	**Substrate**	**Die Size (mm)**
Here	12 / 24	-10 / -19	6.7 / 7	Roger 4350	25.5x22.5
[6]	10	-25	9.8		30x30
[21]	15	-15	7.5	---	30x30
[22]	25	-20	---	Arlon 25N	15x27
[23]	10 / 12	-30 /-30	8 / 9	Taconic TLY	40x56
[24]	18.2-23.8	<-15	9.5	Droid 5880	20x25
[25]	25.8-31.5	<-15	>6	RT/Duroid 5880	---
[26]	8-15	<-17	>6	Arlon IsoClad 917	55 × 46.8

V. CONCLUSION

In this work, a high performance, miniature, novel antenna is designed and fabricated on a low-cost substrate for X and K band radar applications. For this purpose, design optimization and fabrication of a high performance microstrip dual band antenna using Substrate Integrated Waveguide technology is worked out. Thus firstly, an efficient design optimization of a microstrip SIW antenna has been carried out on a low-cost substrate Roger 4350 with a possible simple geometry as a multi-objective, multi-dimensional optimization problem using the Differential Evolutionary Algorithm (DEA) within 3-D CST Microwave studio environment. At the same time, effects of the SIW structures are investigated on the radiation and return loss characteristics of the antenna design by simulation in different cases and optimized using DEA. In simulated results, the optimized antenna with SIW structure achieves the simulated gain level of 7 and 7.13 dB at 12 and 24 GHz respectively, while other two cases of antenna design without SIW design can only achieves 6 dB at most. In the second step, for justification of the proposed design method, the optimally designed dual band SIW antenna has been prototyped. Finally it has been reached a conclusion that the competitive performance has been achieved with this miniature, simple microstrip SIW antenna design as compared with the counterpart designs in the literature.

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