REPUBLIC OF TURKEY
YILDIZ TECHNICAL UNIVERSITY
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MICROWAVE CIRCUIT DESIGN USING DIFFERENTIAL EVOLUTION ALGORITHM

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İSTANBUL, 2016

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A thesis submitted by Aysu YILDIRIM in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 26.07.2016 in Department of Electronics and Communication Engineering, Communication Engineering Program.

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ACKNOWLEDGEMENTS

It is a pleasure to thank many people who made this thesis possible.

First and foremost I want to thank my advisors Prof. Dr. Filiz GÜNEŞ, for the contagious joy and enthusiasm she has for researches on Computer Aided Design methods for Microwave circuits which was the main motivation for me and my thesis; and Dr. Peyman MAHOUTI, for supporting me during the possible worst moments of my life. I will not forget his kindness and support, especially his calmness. Whenever something bad happens or a problem occurs he is the one you need. No matter what I write here it would not be enough to thank my mentors for their supports. I should say that it has been an honor to be their Master student and to have a chance to work with them.

A very special thanks goes out to Mehmet Ali BELEN. He provided me with direction, technical support. It was through his, persistence, understanding and kindness that I completed my master’s degree and was encouraged to apply for graduate training. I doubt that I will ever be able to convey my appreciation fully, but I owe him my eternal gratitude.

Finally, I must express my very profound gratitude to my family and to my love for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

July, 2016

Aysu YILDIRIM

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LIST OF SYMBOLS

a	Width of a waveguide
b	Height of a waveguide
c	Speed of light
dB	Decibel
f_o	Center frequency
G_T	Total gain
Gen	Generation
L	Lengths of microstrip lines
RL_{req}	Return loss in the request bandwidth
S_{ij}	S-parameters
S/N	Signal to noise ratio
$\tan\delta$	Tangent loss
W	Widths of microstrip lines
λ_g	Guide wavelength
λ_o	Center frequency wavelength
ε_r	Dielectric constant
l	Waveguide length
t	Thickness
ω_c	Cut off frequency for waveguide

LIST OF ABBREVIATIONS

2-D	Two-Dimensional
3-D	Three-Dimensional
CAD	Computer Aided Design
CST	Computer Simulation Technology
CPW	Coplanar Waveguide
DE	Differential Evolution
DEA	Differential Evolution Algorithm
EA	Evolution Algorithm
EXT	Extrapolation
GP	Genetic Pool
INT	Interpolation
MAE	Mean Absolute Error
PCB	Printed Circuit Board
RF	Radio Frequency
RME	Relative Mean Error
SIW	Substrate Integrated Waveguide
TE	Transverse Electric
TEM	Transverse Electric Magnetic
TM	Transverse Magnetic
VNA	Vector Network Analyzer

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ABSTRACT

MICROWAVE CIRCUIT DESIGN USING DIFFERENTIAL EVOLUTION ALGORITHM

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MSc. Thesis

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In order to achieve a high performance antenna design, firstly novel antenna models are studied and as a result, Substrate integrated waveguide antenna models found to be a promising antenna model for our cause. After the selection of the antenna model, it is very important to obtain the optimal design parameters values for modelling. In this stage the SIW antenna design problem should be converted to an optimization problem to define a cost function for optimization process with respect to the antenna design parameters such as microstrip lines width lengths, number of via's, etc.Then the optimization problem of SIW antenna design will be solved using an efficient novel optimization algorithm named "Differential Evolutionary Algorithm". The obtained optimal SIW antenna design from DEA then will be used to manufactured and its performance are measured and compares to the simulation results. Also for a secondary study case, the proposed DE algorithm is used as an optimization tool for determining the Source and load terminations of a microwave transistor for an ultra-wide band LNA application with respect to both input and output VSWR value.Thus, by this mean an optimization design problem of SIW antennas and performance characterization of a microwave transistorsare carried out by using DEA for modelling of high performance microwave circuit design for many RF applications.

Key words: Microwave, differential evolution, siw antenna, performance characterization, lna, genetic algorithms, neural networks

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ÖZET

DİFERANSİYEL EVRİM ALGORİTMASI KULLANILARAK MİKRODALGA DEVRE TASARIMI

Aysu YILDIRIM

Elektronik ve Haberleşme Mühendisliği Anabilim Dalı
Yüksek Lisans Tezi

Tez Danışmanı: Prof. Dr. Filiz GÜNEŞ
Eş Danışman: Dr.Peyman MAHOUTI

Yüksek performansa sahip anten tasarımı elde etmek için öncelik ile yenilikçi anten modelleri incelenmiş olup, “Substrate integrated waveguide” SIW anten modellerinin bu hedef için uygun olduğu tespit edilmiştir. Anten modelinin seçiminden sonra, modele ait parametrelerin optimal değerlerinin seçimi çok önemli bir husustur. Bu aşamada, SIW anten tasarım probleminin bir maliyet fonksiyonu tanımlanarak bir optimizasyon problemine dönüştürülmesi ve buna bağlı olarak mikroşerit hatların uzunlukları, kalınlıkları, via’ların sayısı gibi parametrelerin optimal değerlerinin belirlenmesi hedeflenmelidir. Daha sonra ise, tasarlanan optimizasyon probleminin etkin ve yenilikçi bir optimizasyon algoritması ile çözümü için “Diferansiyel Evrim Algoritması (DEA) ” kullanılmıştır. DEA tarafından elde edilen optimal tasarım değerleri daha sonra kullanılarak, SIW anten tasarımı gerçekleştirilmiş olup olçum ve simülasyon sonuçları kıyaslanmıştır. Böylelikle ile birçok RF uygulaması için kullanılabilecek yüksek performansı bir anten tasarımı ve optimizasyon problemi, DE algoritmasının ve SIW anten mimarisi ile çözülmüştür.

Anahtar Kelimeler: Mikrodalga, diferansiyel evrim, siw anten, performans analizi, lna, genetik algoritma,sinir ağları

YILDIZ TEKNİK ÜNİVERSİTESİ FEN BİLİMLERİ ENSTİTÜSÜ

CHAPTER 1

INTRODUCTION

1.1 Literature Review

1.1.1 Meta-heuristic Optimization Algorithms

Meta-heuristic algorithm is an advance procedure to form a heuristic that can find a sufficient solution to an optimization problem, especially in case of incomplete or imperfect information. Meta-heuristics may make few assumptions about the optimization problem being solved, and so they may be usable for a variety of problems. Compared to optimization algorithms and iterative methods, Meta-heuristics do not guarantee that a globally optimal solution can be found on some class of problems. By searching over a large set of feasible solutions, Meta-heuristics can often find good solutions with less computational effort than optimization algorithms, iterative methods, or simple heuristics. Several books and survey papers have been published on the subject. Examples for these methods are: methods that inspired from animal and microorganism team behavior, such as particle swarm optimization, artificial immune systems, insect colonies like Ant or Bees. Most of the mentioned methods had been utilized in design optimization of microwave device and antennas [1-6].

1.1.2 Substrate Integrated Waveguide Technology

Waveguides are metallic transmission lines that are used at microwave frequencies, typically to interconnect transmitters and receivers with antennas. Waveguides are better mediums to deliver low-loss signal transmission compare to microstrip transmission lines. However, traditional rectangular waveguides are expensive and have considerable sizes. Substrate integrated waveguide (SIW), is a technology that provides the performance advantages of classic waveguide structures, along with the cost and size benefits of planar PCB designs [7]. The brilliant virtue of substrate integrated waveguide is its ability to integrate all the components, such as active, passive elements, antennas etc., on the same PCB board. SIW also acts as a low-loss feeding network, which enhance the performance of antenna design. There has been increasing interest in implementing SIW technology in active circuits and complete systems, including active integrated antennas [8–14]. A basic SIW structure is presented. SIW technology is essentially a hybrid of microstrip and dielectric-filled waveguide technologies. Surface and ground metal layers of a PCB substrate provide two of the waveguide walls. Then, two parallel rows of via’s can form the side walls of the waveguide.

Beyond any doubt, one of the most commonly used circuit stages in PCB board technology are microstrip antennas that have a wide range of applications. Also these stages are preferred due to their simple designs, by using SIW technology, it is possible to enhance many advantages of microstrip antennas such as low cost, being small in size, easy integration of antenna stages to circuit etc. Antennas designed with SIW technology have excellent performance because they suppress the propagation of surface waves, increase the bandwidth, and decrease both end-fire radiation and cross-polarization radiation. The cavity-backed structure of antenna design would also overcomes hitches like heat dissipation, unwanted surface wave modes.

1.1.3 Performance Characterization

Nowadays characterization of Low-Noise (LN) microwave transistors and design of the wideband high performance, miniature LN Amplifier (LNA)s are among major interests of microwave electronics with the typical works in [1-8]. Especially most of the receivers are hand-held or battery- operated devices, therefore the very stringent requirements are encountered in the design procedure that are mainly a very low power consumption from a very low supply voltage, high gain G_T, low noise figure F, low input V_{in} and output V_{out} Standing Wave Ratios and the Ultra-Wide Band (UWB).Thus this type of LNA design altogether with these requirements can be considered one of the biggest challenges to the UWB transceiver integrations. Although the cascode configuration is commonly used in the utilization of the high performance LNA designs, since it requires the bigger than 1V supply voltage, it is unsuitable to be used in the miniature LNA with the low-voltage applications. For applications requiring very low supply voltages, a single transistor in the common emitter configuration is typically used.

In fact, LNA design is a highly nonlinear optimization problem in terms of the descriptive parameters of the system. Certainly, within the design optimization process, one can easily embed any desired performance goals without knowing the physical limits and/or compromise relations among the noise, gain and mismatches at the input and output ports. Unfortunately, this process either fails to attain the desired goal or use the transistor under its potential performance. Thus the major challenge in designing a single transistor LNA is to enable the transistor amplify subject to its physical limitations and compromise relations among the noise, gain and mismatches at its input and output ports. Therefore Performance Data Bases (PDB) of a microwave transistor which covers all the trade-off relations between the performance ingredients G_T, F, V_{in}, V_{out} within the device's operation domain of bias condition (V_{DS}, I_{DS}) and frequency f is of primary importance for the LNA design optimization.

1.2 Objective of the Thesis

Communication technology is rapidly developing as a very important area for use of the mankind emerging more and more challenging demands every day. The major demands include high performance, lower size, wider band, lower cost and low energy consumption. Sensitive receiver circuits in telecommunication systems are commonly require high performance RF stages. In this thesis, 2 optimization problem, 1- the design optimization of high performance SIW antennas, 2-performance characterization of a microwave transistor for LNA applications are solved by using differential evolutionary algorithm.

1.3 Hypothesis

In order to achieve a high performance antenna design, firstly novel antenna models are studied and as a result, Substrate integrated waveguide antenna models found to be a promising antenna model for our cause.

After the selection of the antenna model, it is very important to obtain the optimal design parameters values for modelling. In this stage the SIW antenna design problem should be converted to an optimization problem to define a cost function for optimization process with respect to the antenna design parameters such as microstrip lines width, lengths, number of via’s, etc.

Then the optimization problem of SIW antenna design will be solved using an efficient novel optimization algorithm named “Differential Evolutionary Algorithm”. The obtained optimal SIW antenna design from DEA then will be used to manufactured and its performance is measured and compares to the simulation results.

Thus, by this mean an optimum optimization design problem of SIW antennas is carried out by using DEA for modelling of high performance antenna design for many RF applications.

Also for a secondary study case, the proposed DE algorithm is used as an optimization tool for determining the Source and load terminations of a microwave transistor for an ultra-wide band LNA application with respect to both input and output VSWR value. Thus, by this mean an optimization design problem of SIW antennas and performance characterization of a microwave transistors are carried out by using DEA for modelling of high performance microwave circuit design for many RF applications.

CHAPTER 2

SUBSTRATE INTEGRATED WAVEGUIDE ANTENNA

This chapter deals with results of the first aim of this thesis. The main attention is focused on the research of conventional techniques for microstrip patch antennas exploiting SIW technology.

2.1 Introduction

SIWs are planar structures fabricated using two periodic rows of metallic via's (holes) or slots connecting top and bottom metallic ground planes of dielectric substrate. Using SIW technology a non-planar metallic waveguide can be modeled into a SIW, which will be planar in nature and can be fabricated on, as well as integrated to, planar circuits with ease. Like microstrips and coplanar lines SIW components are compact, light, cost effective and easy to fabricate substrate integrated. This makes SIW components more mass producible with small sizes, low weight, and low cost, hence the manufacturing repeatability and reliability are enhanced. In addition, the planar form of the waveguide allows integrating SIW-based components with other passive and active PCB components on the same board. In recent years, SIW technology has gained considerable attention and the SIW structure have been intensively analysed in details [23–28].

In this work, a low cost, small size, high performance antenna design with SIW is aimed for X band applications. For this purpose, a microstrip patch antenna based on SIW technology combined with grounded coplanar waveguide structure is chosen as based model. In the next section the design of two microstrip patch antenna designs with SIW is presented. The simulations results belong to the design are given in third section. Finally the section ends with conclusions.

With the development of new technologies and improvements upon the existing, microwave and RF systems penetrated into many areas of both the daily life and scientific studies. As this rapid development brings higher performance requirements, for the high frequency system designs, being low-cost, high quality, easy to produce and small in size emerges as the essential features. Moreover, the printed circuit board technology has a widespread usage in such systems, because planar structures are preferable in highly integrated designs.

In millimeter-wave technology, waveguides are more advantages relative to planar transmission lines due to their high quality factor and high power handling performances. Furthermore, closed structure of waveguides which provides high isolation and low radiation loss, increase its importance in millimeter-wave systems which suffer from the interactions among the elements. Planar lines have high conductor loss due to the high field density on the conductor edges, while waveguides provide an advantage in this manner by providing low conductor loss. However, high-cost and high-volume constitute significant disadvantages to waveguides. Bulky structure of waveguides is probably the weakest side in system development, because it is difficult to integrate bulky components with planar structures.

Both planar and non-planar structures have significant disadvantages, thus hybrid designs which merge the technologies with the aim of eliminating the drawbacks, have become highly preferable in many applications. Besides this advantage of the hybrid structures, they still have some drawbacks arising from the transition between the planar and non-planar parts, especially in high frequencies.

SIW technology as introduced in [23], makes it possible to implement waveguides as a planar structure. This study states that, side walls of a waveguide can be composed by drilling regularly placed via’s on PCB and using via plating (metallization), while the top and bottom metal plates of the PCB already form the lateral walls of the waveguide as revealed in Figure 2.1. At the end of the process, a non-conventional waveguide structure which is filled with the substrate of the PCB is obtained. The width of this waveguide is the distance between the via arrays and the height is the substrate thickness which is quite low with respect to the width. As long as a waveguide is used in the fundamental mode which is TE_{10} in rectangular waveguides, only parameter for cut-off frequency calculation except the substrate properties is the width of the structure. Thus, this extremely thin waveguide structure has the same spectral characteristics with the conventional rectangular waveguide structures.

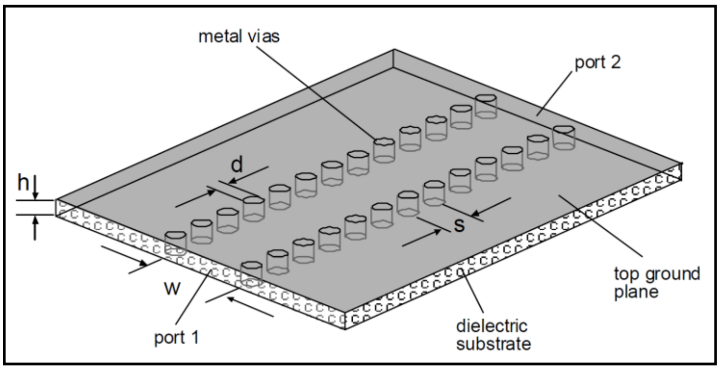


Figure 2.1 Basic SIW structure [17]

2.2 SIW Antenna Design

2.2.1 Design Procedure of SIW Antenna

SIW technology is a promising counterpart of the waveguide cavity [30]–[31]. Because an SIW can be realized on a PCB structure, it can be easily integrated with planar microwave systems. Moreover, when compared with a microstrip line resonator, the SIW resonator has a higher Q factor [32].The SIW is synthesized through the use of arrays of metallized via hole in the substrate (Figure 2.2).

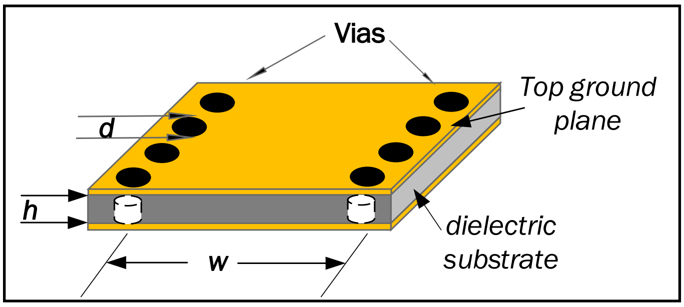


Figure 2.2 Schematic of SIW structure

Those two rows of metallized holes in the substrate create equivalent electrical walls into which electromagnetic waves or field are confined. Surface and ground metal layers of a PCB substrate provide two of the waveguide walls. In the procedure of SIW design there are important parameters that their values should determine wisely.

Substrate's dielectric constant: it affects the bandwidth and radiation efficiency of the antenna, with lower permittivity giving wider impedance bandwidth and reduced surface wave excitation.

Substrate’s thickness: it affects bandwidth and coupling level. A thicker substrate results in wider bandwidth, but less coupling for a given aperture size.

Rectangular patch dimensions: The length of the patch radiator determines the resonant frequency of the antenna. The width of the patch affects the resonant resistance of the antenna, with a wider patch giving a lower resistance.

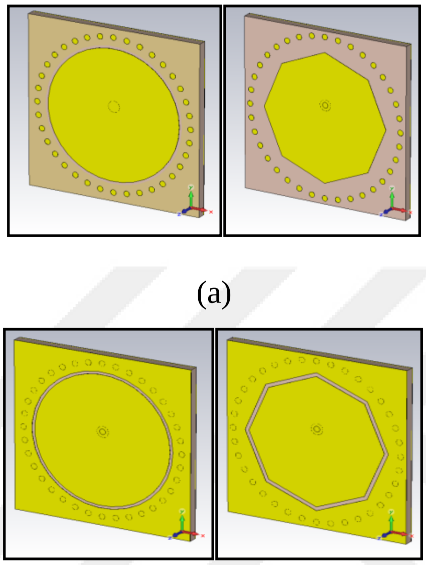
Feed line size: it controls the characteristic impedance of the feed line, and the width of the feed line affects the coupling to the patch antenna.

The proposed dual band SIW antenna model is given in Figure 2.3 alongside of its parametric design layout (Figure 2.4) and parameters value in Table 2.1. The values of parameters given in Table 2.1, are obtained via trial and error alongside of local optimization process of CST studio Environment in order to achieve high performance for X band applications. The proposed antenna is modelled and fabricated on Rogers’s 4350 high performance substrate the simulation and measurement results of the proposed SIW antenna are given in the next section.

2.3 Case Study

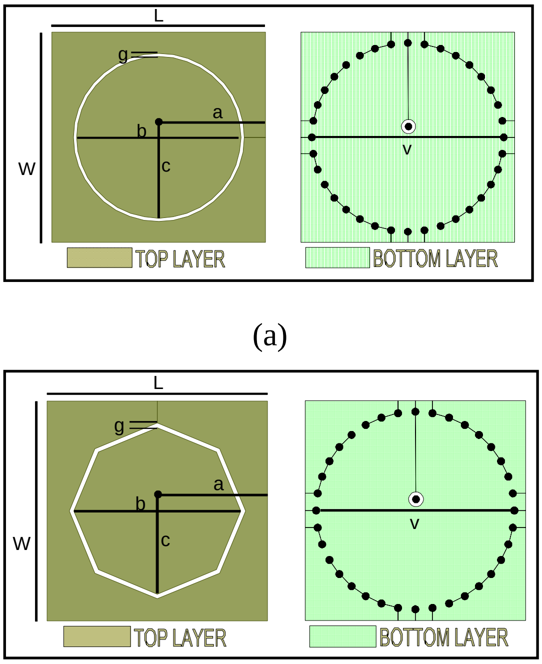
The design of the SIW microstrip patch antenna involves the selection of the properties of both substrates and shape and size of patch. In order to obtain a high performance model, designer should chose the most important parameters of the SIW microstrip antenna; i) dielectric constant of the substrate which affects the bandwidth and radiation efficiency of the antenna, ii) thickness of the substrate which affects bandwidth and coupling level of the designs, iii) shape of the microstrip patch which effects the bandwidth and radiation pattern.

In this work, by using SIW technology it is aimed to design a low cost, small in size and high gain microstrip patch antenna for X band applications. To achieve these goals, Rogers 4350 (relative permittivity 3.66, thickness 1.52mm and loss tangent 0.0035), a high performance dielectric substrate for X band applications is selected for designing the antennas. Also, a circular shaped microstrip patch antenna design based on SIW technology combined with grounded coplanar waveguide structure is chosen. Thus, it would suppress the surface waves, thus obtaining very high isolation from the surroundings, low or negligible coupling, better matching, and wide scan [29]. Via’s were used to construct conventional metal waveguide in a planar substrate to suppress unwanted modes and to form a shielding cavity around the patch element. During the design process it is observed that instead of using circular shape use of octagonal shape Figure 2.3 for the patch of the antenna not only increases the gain but it also reduces the return loss of the antenna. In Figure 2.4 and Table 2.1 the layout and the dimension details of the both design model are given. In the next section the simulation results of the proposed antennas are presented.


(a)

(b)

Figure 2.3 (a) Front, (b) Back view of the proposed SIW antenna models



(a)

(b)

Figure 2.4 Layout of the (a) Circular, (b) Octagonal SIW patch antenna.

Table 2.1 Parameter list

	Model-1	**Model-2**
W (mm)	30	30
L (mm)	30	30
a (mm)	14.9	14.9
b (mm)	23	22.7
c (mm)	16.4	17.3
g (mm)	0.5	0.7
v (mm)	26	26
Number of Vias	36	36

2.3.1 Simulation Results

In this section, the simulation results for both of the proposed antenna models obtained from CST Studio Suite is given. In Figure2.5, the simulated return loss (S_{11}) of the antennas are given, as it seen the octagonal design has a better performance than the circular shape. In Figure 2.6, the simulated gain of the antennas is presented. The octagonal design achieves near 10 dB gain while the circular design achieves 8 dB gain.

A comparison with the similar X band antennas design had been done in Table 2.2. The proposed models are compared with the antenna design in [33-35]. As it seen from Table 2.2 the proposed model is smaller in size and also has a higher gain value compared to the other designs.

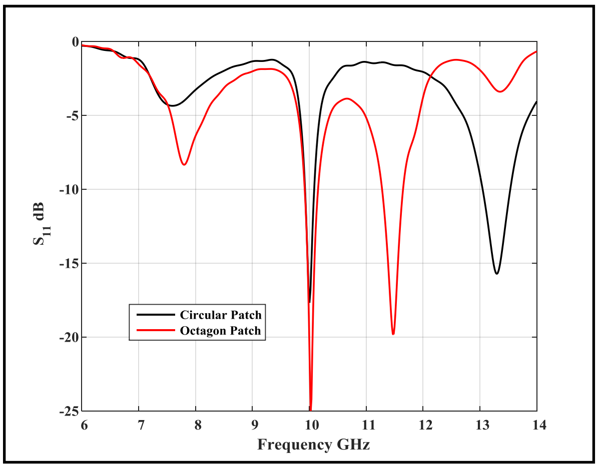


Figure 2.5 Simulated return loss

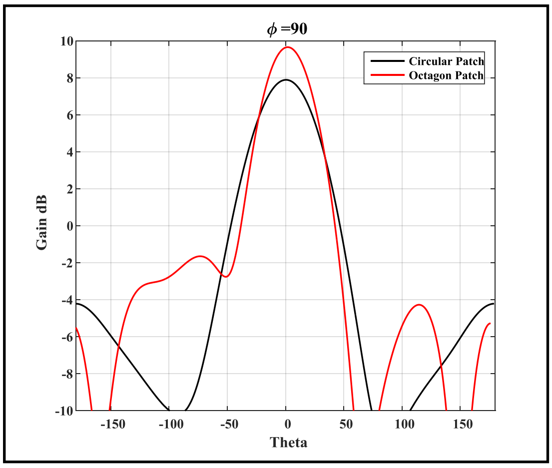


Figure 2.6 Simulated gain

Table 2.2 Benchmarking results of the antennas with literature

	fr **(GHz)**	**S_{11} (dB)**	**Gain (dB)**	**Size (mm)**
Circular Patch	10	~ -17	7.9	30x30
Octagonal Patch	10	~ -25	9.8	30x30
SIW Microstrip Horn Antenna[33]	15	~ -15	~ 7.5	30x70
SIW Fed Microstrip Patch Antenna [34]	10	~-30	~ 7	40x56
SIW Square Ring Slot Antenna [35]	10	~ -27	8.6	34x34

2.4 Conclusion

Design of small size, high performance microstrip antennas with SIW technology for X band application has been proposed in this paper. The models can find wide application in X band radar and remote sensing applications. The models are very simple and development of the prototype is easy in presence of advanced fabrication technology. Also the small size of the designs makes them low cost and easy for integration in modules. For the need of higher gain performance it is possible to use this model as unit cell of an antenna array system.

CHAPTER 3

DIFFERENTIAL EVOLUTION ALGORITHMS

In this chapter we present the DE algorithm for unconstrained global optimization. Before we give a detailed description of the DE algorithm we look at a few general requirements of a global optimization solver and state how the DE algorithm can fulfill these requirements. Depending on the intended use of a global optimization solver, there are many aspects that need to be considered before an appropriate solver is selected. We have imposed the following requirements on the solver:

- Generality: The solver should be insensitive to the underlying problem structure. This will allow it to be applicable to a larger problem set.

- Reliability: The global optimum should be found with a reasonable degree of accuracy.

- Efficiency: The computational complexity of the algorithm should ensure that the algorithm is viable for small to moderate problems e.g. problems with dimensions of up to 100.

- Ease of use: The algorithm should be inherently simple to understand and implement. The number of parameters should also be limited so that too much fine tuning is not required for the algorithm to perform well.

3.1 Description of the DE Algorithms

DE algorithm is originated by Kenneth Price and Rainer M. Storn and first publication of idea of this method was published as a technical report in [36]. Just after inception of this method it has become an attractive field for research and after establishing by Storn in 1997 a website [37] an explosive expansion in differential evolution research took place. Moreover, the current progress in the field of computer computations makes in practice DE a powerful tool for stochastic optimization due to its parallelizable nature from the computational point of view which is used in many optimization problems [38-42]. This situation is caused by the ability to perform calculations on each element of the population separately. DE is a method of multidimensional mathematical optimization which belongs to the class of Evolutionary Algorithm (EA). This meta-heuristic method tries to find optimum of the problem by iteratively improving of the candidate solution with respect to value of the objective function.

3.1.1 Initialization

The first step is to initialize the population. In general, every member of the population is seeded uniformly within a given space. Most problems are considered to be box constrained since the variables are subject to boundary constraints. This leaves us with the following simple initialization formula for each component:

$$x_{i,0}^{j} = l^{j} + rand \times (u^{j} - l^{j}), \quad j = 1, 2, ..., n \tag{3.1}$$

where rand ϵ [0, 1] is a uniformly distributed random value generated for each j and u^j and l^j are the respective upper and lower limits for the jth variable or component. For certain problems, information might be available that would favor exploration in certain areas. In this case the population can be seeded around these areas of interest.

3.1.2 Mutation

The defining characteristic of the DE algorithm is the method via which the new trial points are generated. At every generation g, each member of S ($S=\{x_1,x_2,\cdots, x_N\}$ solution space) is targeted to be replaced with a better trial point. Considering x_{ig} as the target point, the corresponding trial point y_{ig} is created using the target point and a mutated point $\overset{\Delta}{x}_{i,g}$. For the simplest case, a mutated point is created by adding the weighted difference of two population members to a third. However there are various other possible schemes for generating the mutated points. Some possible mutation schemes for the ith target point are given below:

$$\overset{\Delta}{x}_{i,g} = x_{p(1)} + F \times (x_{p(2)} - x_{p(3)}) \tag{3.2}$$

$$\overset{\Delta}{x}_{i,g} = x_b + F \times (x_{p(2)} - x_{p(3)}) \tag{3.3}$$

$$\overset{\Delta}{x}_{i,g} = x_{p(1)} + \lambda \times (x_b - x_{p(1)}) + F \times (x_{p(2)} - x_{p(3)}) \tag{3.4}$$

where F and λ are scaling parameters and x_b is the best point in the current population. $x_{p(1)}$, $x_{p(2)}$ and $x_{p(3)}$ are randomly chosen points such that $p(1) \neq p(2) \neq p(3) = i$ i.e. all points are unique and none of these points corresponds to the target point $x_{i,g}$.

There are other variants to the schemes described by equations (3.2) to (3.4). In order to distinguish between different schemes a standard notation is used to indicate the scheme type: DE*/a/b/c*. The variable "*a"* specifies the base vector used that will be perturbed is chosen. It can which can either be random e.g. $x_{p(1)}$, as is the case for equation (3.2) and (3.4) or the best vector is the population, x_b, as in equation (3.3). The second variable *b* indicates how many vector pairs form the difference vectors. For equations (3.2) and (3.3) the value for *b* is *l* while for equation (3.4) *b* is 2. The variable *c* indicates what type of crossover method is used. Binomial crossover is represented by the abbreviation *b* in and exponential crossover by exp. We will discuss the crossover process below.

3.1.3 Crossover

The target or parent point x_{ig} together with the new mutated points $\overset{\Delta}{x}_{i,g}$ are recombined to create the trial point y_{ig}. There are two popular types of crossover methods used with the DE algorithm, namely binomial and exponential. For the purpose of this thesis we only use the binomial method which will be discussed below.

Binomial recombination starts at the first component of the vector and generates a random number $r^j \epsilon$ [0, 1] for each component. If $r^j < c_r$ then the j^{th} component of y_{ig} is taken from x^j_{ig}, otherwise if $r^j > c_r$ then the component is taken from x_{ig}. This process continues until all components from x_{ig} have been considered. In order to ensure that at least one component in y_{ig} is from x_{ig}, a random integer $I_i \in \{1, 2, ..., n\}$ is generated. The component in y_{ig} corresponding to I_i is taken from x_{ig}. The trial vector can contain components from $x_{i,g}$ at multiple, separated points. Binomial recombination can be mathematically formulated as:

$$y^j_{i,g} = \begin{cases} \overset{\Delta}{x}_{i,g} & if\ r^j \leq c_r \ \ or\ \ j = I_i \end{cases}, \quad y^j_{i,g} = \begin{cases} \overset{\Delta}{x}_{i,g} & Otherwise \end{cases} \tag{3.5}$$

3.1.4 Acceptance

At each iteration the DE algorithm attempts to replace each point in S with a better point. Therefore at each generation *g*, *N* competitions are held to determine the members of *S* for the next iteration. The i^{th} competition is held to replace $x_{\mathrm{i,g}}$ in *S*. This is done by comparing the function values of the trial points $\mathrm{y}_{\mathrm{i,g}}$ to those of $\mathrm{x}_{\mathrm{i,g}}$, the target points. If $f(y_{i,g}) < f(x_{i,g})$ then y_{ig} replaces x_{ig} in *S*, otherwise *S* retains the original $\mathrm{x}_{i,g}$. This can be written mathematically as:

$$x_{i,g}^{j} = \begin{cases} \overset{\Delta}{y}_{i,g} \end{cases} \quad if \quad f(y_{i,g}) < f(x_{i,g}), \quad x_{i,g}^{j} = \begin{cases} \overset{\Delta}{x}_{i,g} \end{cases} \quad Otherwise \tag{3.6}$$

The DE algorithm maintains a greedy selection scheme that ensures that the current generation is equal to or better than the previous generation.

3.1.5 Stop Criteria

Main criteria's

- If the current best cost/Fitness value is reached to the requested value,
- If the maximum iteration limit is reached,

Supportive and optional criteria

- If for the last M iteration the best cost/Fitness value is not changed,

In the next chapter, the DEA is used to determines the optimal design parameters of a SIW antenna for high performance measures such as low input reflection and high gain.

By considering all the above requirements the DE algorithm appears to be one of the most appealing choices as an underlying global optimizer. Next section descript the DE algorithm.

CHAPTER 4

STUDY CASES

4.1 Study Case 1: Dual Band SIW Antenna Design

In this section, the DE algorithm is applied to determine the optimal design parameters of SIW antenna given in Figure 4.1, Table 4.1 and Table 4.2. The parameters given in Table 4.1 are given as optimization variables to DEA alongside of their constraints in Table 4.2. Then the DE algorithm that is work in MATLAB environment send the optimization parameter values to CST suit environment to start an 3D electromagnetic simulation process. Then the simulation results in CST environment will are sent to MATLAB environment in order to evaluate the cost function of the optimization process. The flow chart of the optimization process is given in Figure 4.3.

$$\mathrm{Cost}_i = C_1\left|Gain_{\mathrm{Req}} - Gain_i\right| + C_2 e^{-\left|\frac{RL_i}{10}\right|} \tag{4.1}$$

where, C is weighted constrained determined by user, $Gain_{Req}$ is the requested gain at the requested frequency by user, R_{Li} is the return loss in the requested frequency for the i^{th} element, i: is the index of the current member of DEA population.

In Tables 4.3-4.4 and Figure 4.2 the performance result of DEA algorithm for design of SIW antenna in CST environment is presented according to the cost function defined in Eq (4.1). The performance results are obtained after 10 independent run of optimization process.

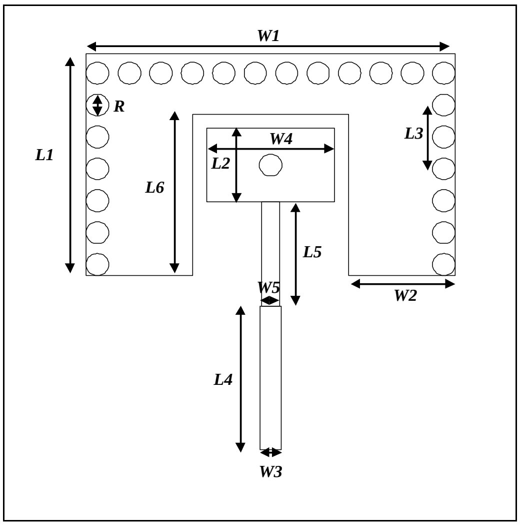


Figure 4.1 Parametric layout of SIW antenna

Table 4.1 Parameter list with optimal values obtained from DEA

W1(mm)	16.4	*L1(mm)*	10.07
W2(mm)	4.8	*L2(mm)*	3.37
**W3(mm)*	1	*L3(mm)*	3
W4(mm)	5.6	**L4(mm)*	6.52
**W5(mm)*	0.8	**L5(mm)*	4.73
**R(mm)*	0.8	*L6(mm)*	7.34

*not taken to the optimization process and had been determined by user.

Table 4.2 Constraints of the optimization variables

Parameter	**Constraint**
W1	10~20
W2	1~10
W4	1~10
L1	5~15
L2	1~5
L3	1~5
L6	1~10

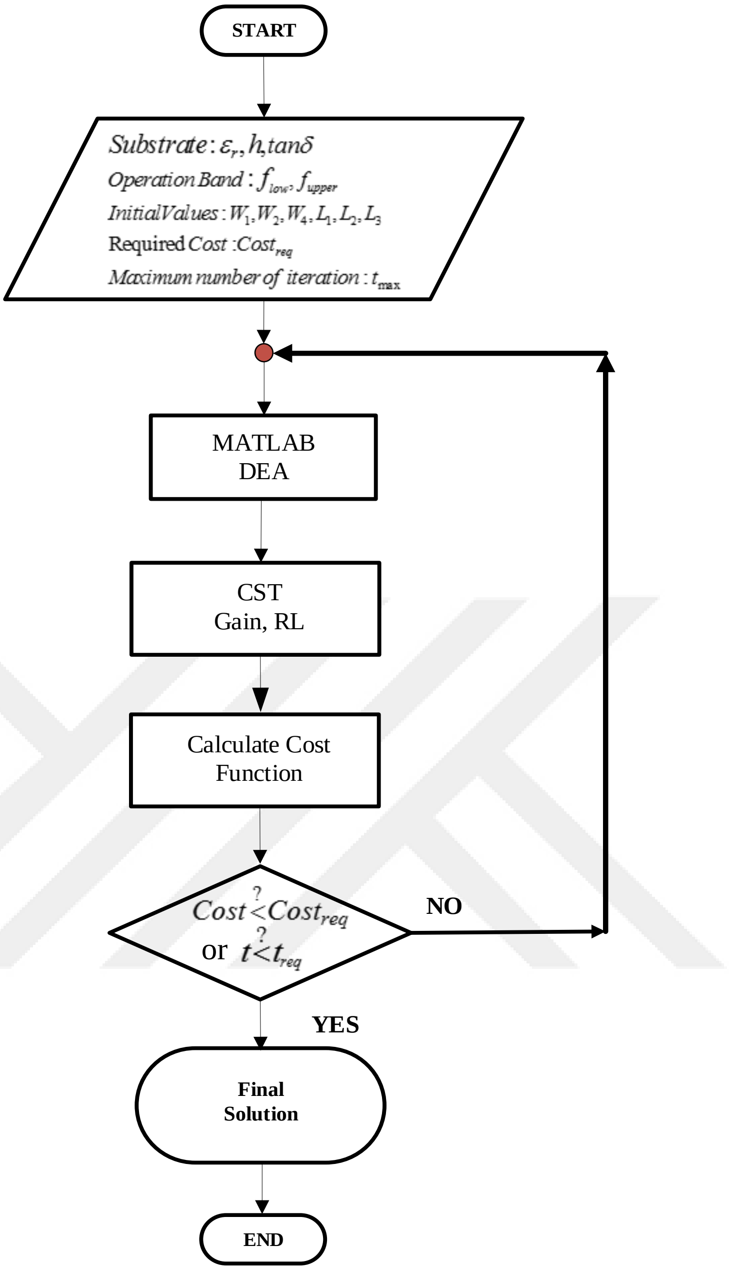


Figure 4.3 Block diagram of design optimization of the SIW antenna with the cost-effective 3D EM-based differential evolution algorithms model

Table 4.3 Performance results of DEA*

Population	**Cost**		
	Maximum	**Minimum**	**Mean**
20	15.54	7.54	8.88
30	10.26	2.94	5.6
50	2.34	0.56	1.313

* Mean results obtain from 10 runs

Table 4.4 Function evaluation results 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 obtain from 10 runs

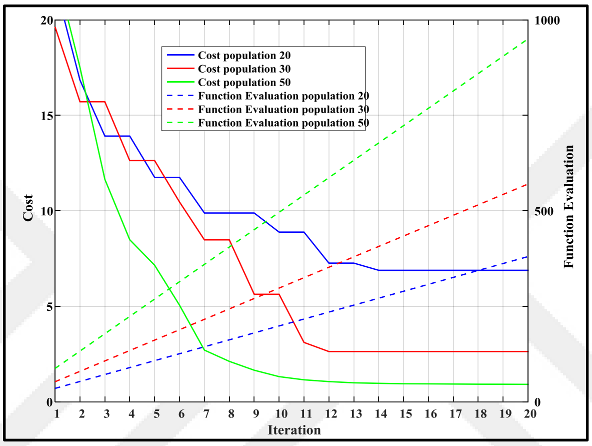


Figure 4.2 Performance evaluations of DEA for the maximum iteration number=20 with different population size

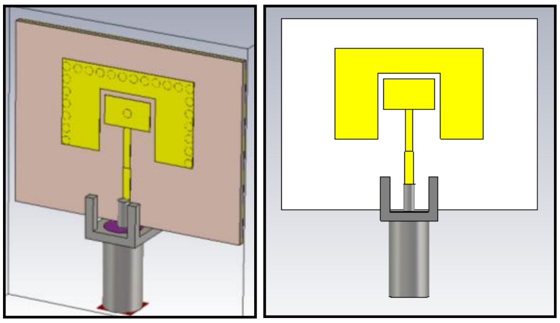
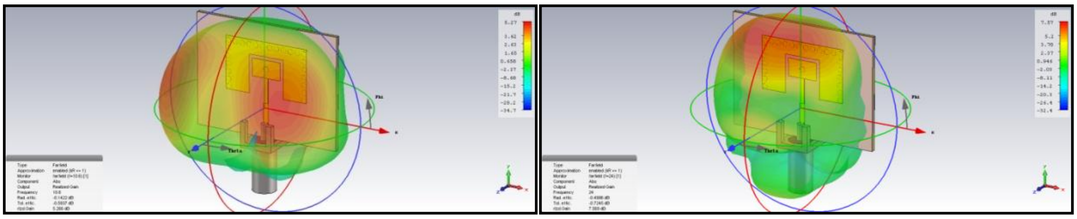


Figure 4.4 Antenna geometry



(a) (b)

Figure 4.5 Simulated gain patterns (a) 10GHz, (b) 24GHz

The obtained optimal design parameters in Table 4.1 are used to manufacturing a SIW antenna. The measurement results are obtained using the measurement setup given in Figure 4.5. The antennas given in [37] and [38] are used for measurements at 1-18 GHz and 18-30 GHz respectively. In Figure 4.4, the prototyped SIW antenna is given. The measurement and simulation results belong to the SIW antenna are given in Figures 4.6-4.8.

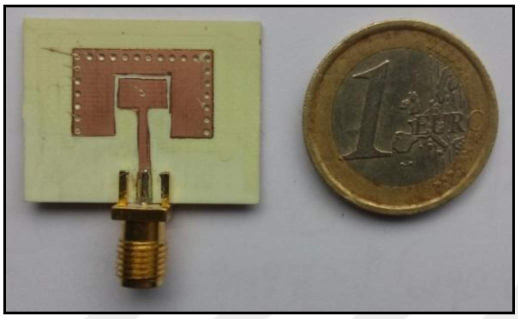


Figure 4.6 Fabricated antenna

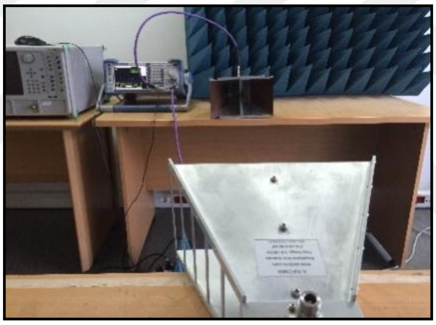


Figure 4.7 Measurement setup for maximum far field gain

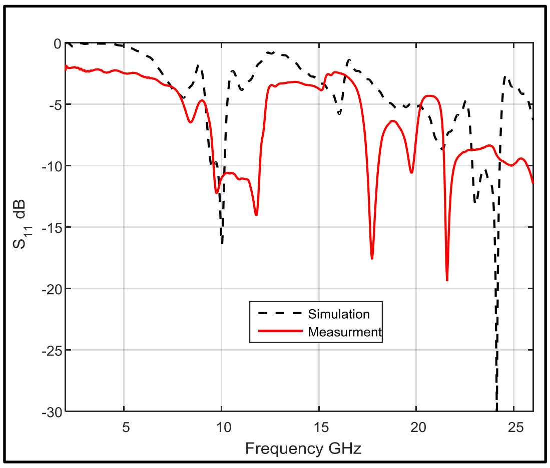
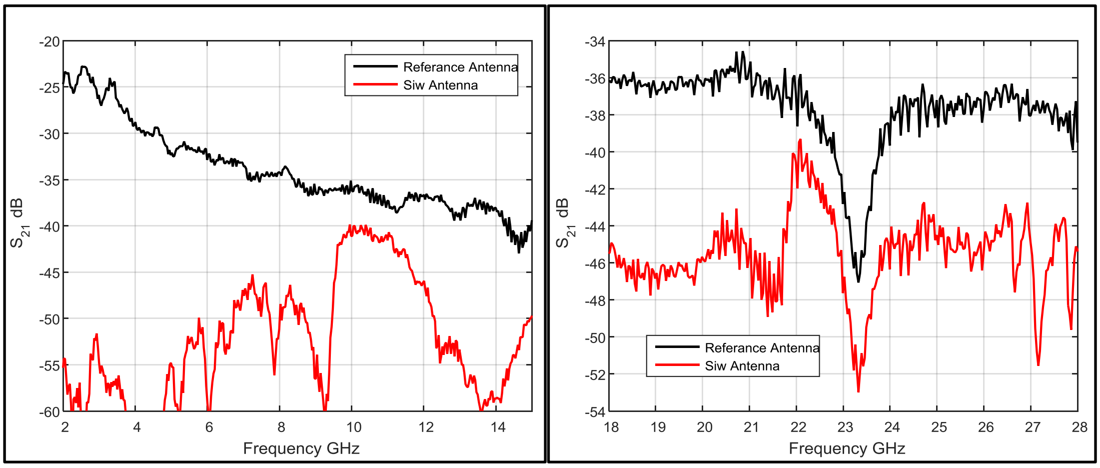
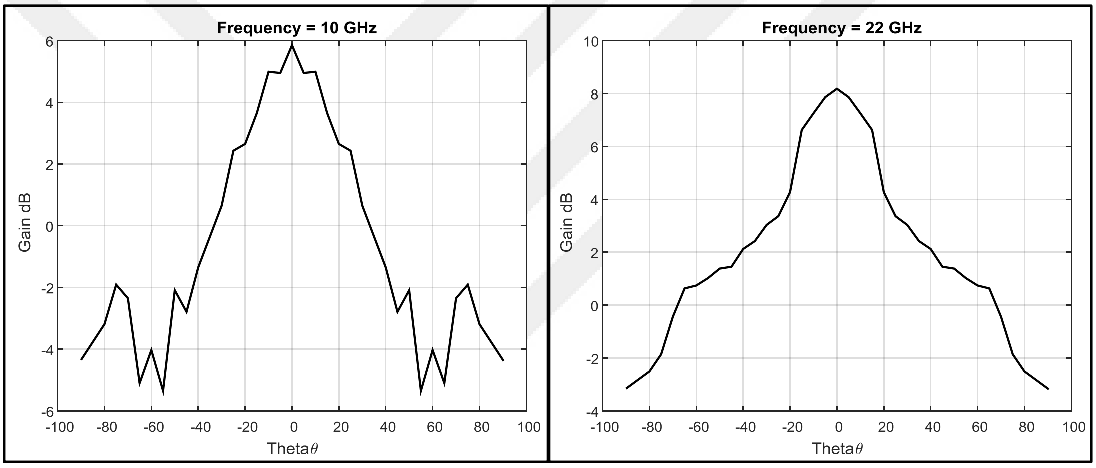


Figure 4.8 Simulated and measured return loss



(a) (b)

Figure 4.9 Transmission characteristics



(a) (b)

Figure 4.10 Maximum gain measurement (a) 10GHz (b) 22GHz

4.2 Study Case 2: Performance Analyze of Microwave Transistors

In this Case Study, we had applied DEA as an optimization tool for determining the Source and load terminations of a microwave transistor for an ultra-wide band LNA application with respect to both input and output VSWR value. In study case, NE350184 is chosen as a fast and high performance microwave transistor for ultra wide band LNA design. The performance characterization of the transistor is analysed for different input and output VSWR values within the frequency range for maximum power delivery and minimum noise figure.

The Source and Load (Z_S, Z_L) termination couple guarantees a corresponding compatible performance ($F \geq F_{min}$, G_T, $V_{in} \geq 1$, $V_{out} \geq 1$) quadrate. In other words they are a simultaneous solution set of the following highly nonlinear performance equations under the physical realization conditions:

$$F = \frac{(SignalPower/NoisePower)_{input}}{(SignalPower/NoisePower)_{output}} = F(Z_S) = F_{\min} + \frac{R_n \left| Z_S - Z_{opt} \right|^2}{\left| Z_{opt} \right|^2 R_S} \tag{4.2}$$

$$G_T = \frac{\text{Power delivered into the Load}}{\text{Maximum Source Power}} = G_T(Z_S, Z_L) = \frac{4R_S R_L \left| z_{11} \right|^2}{\left| (z_{11} + Z_S)(z_{22} + Z_L) - z_{12} z_{21} \right|^2} \tag{4.3}$$

$$V_{in} = V_{in}(Z_S, Z_L) = \frac{1+\rho_{in}}{1-\rho_{in}},\ where\ \rho_{in}^2 = \frac{\text{Reflected Power at the input Port}}{\text{Input Power}} = \left| \frac{Z_{in} - Z_S^*}{Z_{in} + Z_S} \right|^2 \le 1 \tag{4.4}$$

$$V_{out} = V_{out}(Z_S, Z_L) = \frac{1+\rho_{out}}{1-\rho_{out}},\ where\ \rho_{out}^2 = \frac{\text{Reflected Power at the Load}}{\text{Load Power}} = \left| \frac{Z_{out} - Z_L^*}{Z_{out} + Z_L} \right|^2 \le 1 \tag{4.5}$$

The physical realization conditions can be given as

$$\Re e\{Z_{in}\} = \Re e\left\{ z_{11} - \frac{z_{12} z_{21}}{z_{22} + Z_L} \right\} > 0 \tag{4.6}$$

$$\Re e\{Z_{out}\} = \Re e\left\{ z_{22} - \frac{z_{12} z_{21}}{z_{11} + Z_S} \right\} > 0 \tag{4.7}$$

$$F \ge F_{\min},\ V_{in} \ge 1,\ V_{out} \ge 1,\ G_{T\min} < G_T \le G_{T\max} \tag{4.8}$$

where the conditions given by (4.6) and (4.7) ensure the stable operation of the active device, while the inequalities in (4.8) guaranties the performance ingredients to remain within the physical limitations of the device.

The optimization objective is to find out transducer gain G_T and the source Z_S and load Z_L terminations for the required noise F_{req}, and mismatching's at input V_{inreq} and output V_{outreq} ports of the LNA. This objective is expressed in two different cases. The first case is to follow a similar logic to the analytical method in [39], the optimization problem is studied in two stages: Since the noise figure depends only the source termination Z_S as can be seen from Eq. (4.2); the first stage is to obtain the source terminations Z_S to satisfy simultaneously the required noise figure F and the maximum transducer gain G_T. In the second stage, the load termination Z_L is utilized as an instrument to realize mismatching requirements at input V_{inreq} and output V_{outreq} ports Eqs (4.4-4.5) using the $\overline{Z_S}$ termination obtained from stage 1 as a source impedance. The objective belongs to the Case1 is given in Eqs (4.9-4.10)

$$\mathrm{Cos}t_1 = f(R_S, X_S, Z_L = Z^*_{Out}) = a\left|F - F_{req}\right| + e^{-\frac{G_T}{b}} \tag{4.9}$$

$$\mathrm{Cos}t_2 = g(\overline{Z_S}, R_L, X_L) = c\left|V_{Out} - V_{Out\,\mathrm{Req}}\right| + d\left|V_{inopt}\right| \tag{4.10}$$

Where *F* is function of (R$_S$, X$_S$), G$_T$, V$_{in}$ and V$_{out}$ are functions of (R$_S$, X$_S$, R$_L$, X$_L$) are given by Eqs. (4.2-4.5) respectively; F$_{req}$, and V$_{outreq}$ are the required noise figure, output VSWR values, respectively. a, b, c and d are the user-defined weighting constants. Eq. (4.10) is arranged to obtain the optimum input mismatching for the corresponding to the requested output mismatching V$_{outreq}$. If Z$_L$ is wanted for the required (V$_{outreq}$, V$_{inreq}$) couple the Eq. 4.11 can be re-arranged as follows:

$$\mathrm{Cos}t_2 = g(\overline{Z_S}, R_L, X_L) = c\left|V_{Out} - V_{Out\,\mathrm{Req}}\right| + d\left|V_{in} - V_{in\,\mathrm{Req}}\right| \tag{4.11}$$

In the Case 2, all the requirements is picked up in a single objective where the optimization problem becomes a 4- dimensioned problem with 4-objective nonlinear optimization problem.

$$\mathrm{Cos}t_3 = f(R_S, X_S, R_L, X_L) = a\left|F - F_{req}\right| + c\left\|V_{out} - V_{out\,\mathrm{Req}}\right\| + e^{-\frac{G_T}{b}} + d\left|V_{in} - V_{in\,\mathrm{Req}}\right| \tag{4.12}$$

Table 4.5 Performance results of DEA for cost 1

Population		Max	Min	Mean
30	**Cost 1**	2.37	0.27	1.37
	FEN	1633	1656	1651.7
50	**Cost 1**	1.25	0.18	1.09
	FEN	2743	2752	2759.5
100	**Cost 1**	1.02	0.15	0.48
	FEN	5499	5488	5501.5

Table 4.6 Performance results of DEA for cost 2

Population		Max	Min	Mean
30	**Cost 2**	0.322	0.303	0.307
	FEN	1630	1627	1649.6
50	**Cost 2**	0.315	0.302	0.304
	FEN	2752	2749	2758.5
100	**Cost 2**	0.311	0.302	0.303
	FEN	5478	5497	5486.5

Table 4.7 Performance results of DEA for cost 3

Population		Max	Min	Mean
30	**Cost 3**	4.40	0.67	1.72
	FEN	1641	1634	1649.4
50	**Cost 3**	2.02	0.66	1.25
	FEN	2757	2748	2748
100	**Cost 3**	1.41	0.63	0.894
	FEN	5474	5505	5499.2

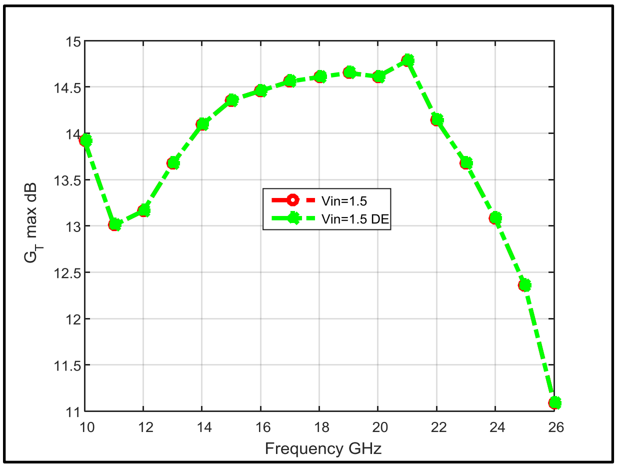


Figure 4.11 Gain performance results of DEA for Vin at 2V, 20mA, Vi =1.5 [Freq = Fmin ,Voutreq=1.5, GTreq = GTmax (f)]

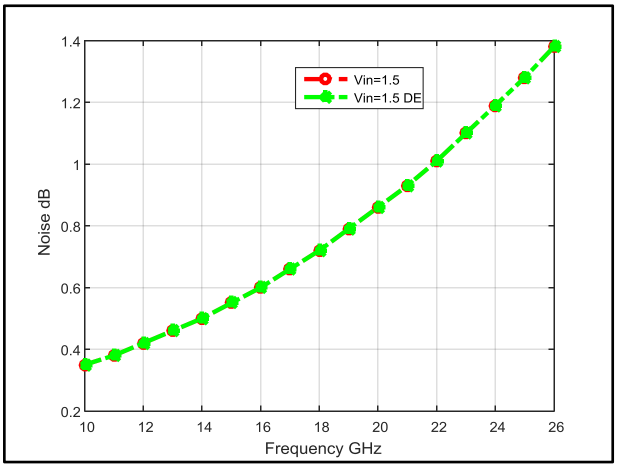


Figure 4.12 Noise performance results of DEA for Vin at 2V, 20mA, Vi =1.5 [Freq = Fmin ,Voutreq=1.5, GTreq = GTmax (f)]

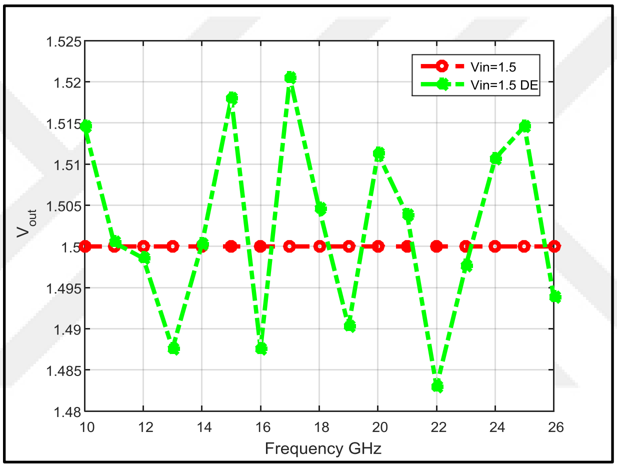


Figure 4.13 Vout performance results of DEA for Vin at 2V, 20mA, Vi =1.5 [Freq = Fmin ,Voutreq=1.5, GTreq = GTmax (f)]

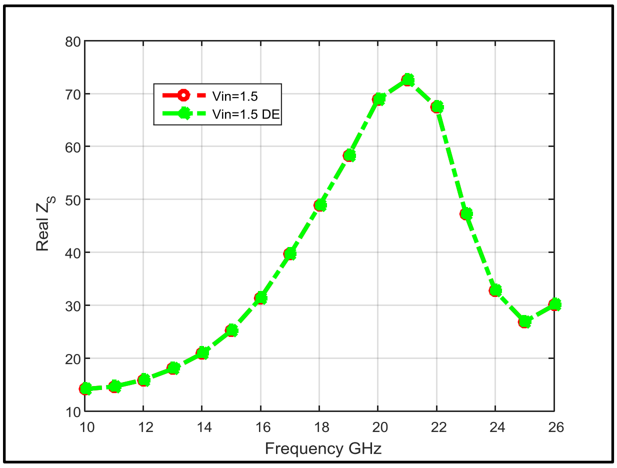


Figure 4.14 Correspond RS Values for Vin at 2V, 20mA [Freq = Fmin ,Voutreq=1.5, GTreq = GTmax (f)]

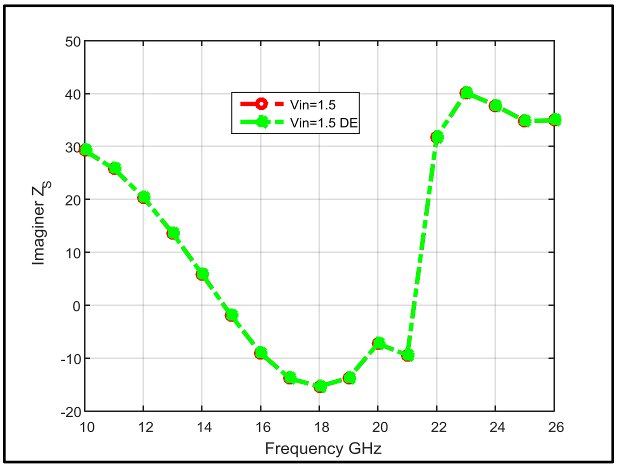


Figure 4.15 Correspond XS Values for Vin at 2V, 20mA [Freq = Fmin ,Voutreq=1.5, GTreq = GTmax (f)]

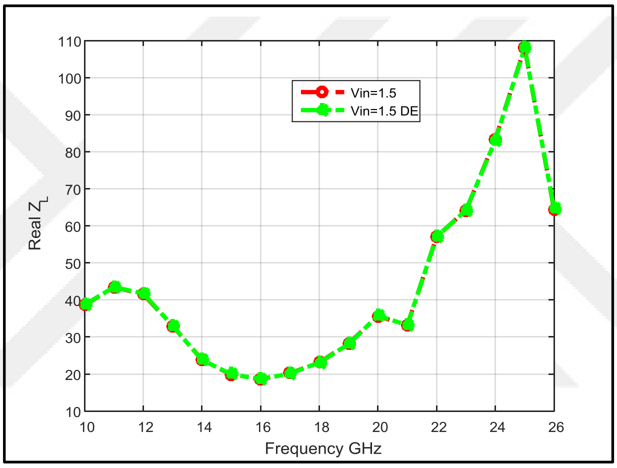


Figure 4.16 Correspond RL Values for Vin at 2V, 20mA [Freq = Fmin ,Voutreq=1.5, GTreq = GTmax (f)]

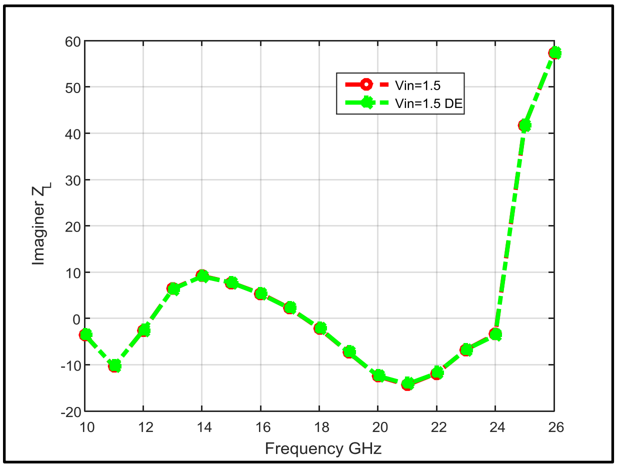


Figure 4.17 Correspond XL Values for Vin at 2V, 20mA [Freq = Fmin ,Voutreq=1.5, GTreq = GTmax (f)]

As it seen from figures by using DE algorithm, the performance characterization problem of a single transistor LNA design is solved accurately as a novel 4-objective optimization problem without any need for expertise microwave device, circuit and noise theory. Thus, the proposed DE algorithm can also be used as a fast and effective optimization tool for solving performance characterization problem of a microwave transistor.

CHAPTER 5

RESULTS AND DISCUSSION

In this thesis, firstly substrate integrated waveguide technology which is a novel high performance design structures for microwave circuits are studied. Then the methodology of a high performance, fast and efficient optimization algorithm "Differential Evolutionary" optimization algorithm is investigated. Thus, a novel design optimization procedure for design of high-gain planar antenna was proposed for X and Ka band applications are proposed. By using, differential evolutionary optimization algorithms and SIW technology on microstrip patch antenna structures an easy and cost-effective design optimization procedure is achieved. The obtained results from optimization and simulation processes are then verified by measurement and experimental results. The obtained results suggest that the proposed methodology is a suitable candidate for RADAR application that requires an enhanced-gain performance.

Also in the secondary study case, the proposed DE algorithm is used as an optimization tool for determining the Source and load terminations of a microwave transistor for an ultra-wide band LNA application with respect to both input and output VSWR value.As it can be seen from the results, the proposed algorithm is highly effective and successful for determining the optimal values of the source and load termination for the requested performance criteria's.

In future works, it is possible to extend the limit of the optimization problem for far more complex antenna designs or other microwave circuit stages such as filters, power dividers matching networks etc.

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PUBLISHMENTS

Conference Papers

1. Belen M.A.,Gunes F., Caliskan A., Mahouti P., Demirel S., Yıldırım A., (2016).“Microstrip SIW Patch Antenna Design for X Band Application”, MIKON 2016 - 21st International Conference on Microwaves, Radar and Wireless Communications, May 9-11, Krakow, Poland.

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