الجمهورية الجزائرية الديمقراطية الشعبية
REPUBLIQUE ALGERIENNE DEMOCRATIQUE ET POPULAIRE
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كلية التكنلوجيا
Faculté de TECHNOLOGIE

RESUME DE THESE

Préparé pour l’obtention du **grade** de **DOCTEUR EN SCIENCES**

En : Electronique

Spécialité : Electronique

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Sujet

Computational Electromagnetic Characterization of Complex THz Antennas based on MEMS Technology

Soutenue publiquement en 2018, devant le jury composé de :

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Abstract

The very special demand for new integrated antennas with excellent performance for diverse terahertz (THz) frequency ranges grows for the foreseeable future, and requires effective electromagnetic (EM) optimization techniques of enhancing already established designs or developing newly proposed models. Recently, micro-electromechanical system (MEMS) processing has been identified as a very promising technology for revolutionizing a large class of antennas with THz waves by combining silicon-based microelectronics with advanced computer aided design (CAD) techniques to model accurately the physical behaviour of such three dimensional (3D) micro-devices, meet the very specific requirement of reducing the long and expensive development cycles, and reaching interesting characteristics including compact size, good radiation and wide bandwidth.

This research work provides for the THz wireless access systems novel designs of highly miniaturized helix antennas based on MEMS technology with particular emphasis on major optimization challenges facing the device structure complexity. The different antenna geometrical structures are developed using 3D high frequency structure simulator (HFSS) based on efficient computational techniques for modal analysis and active optimization. Each time, the optimization strategy aims to vary the antenna geometric structure and maximize its EM response with a high accuracy for the selective frequency band by training the samples and minimizing the error from Finite Element Method- (FEM) based simulation tool. Excellent antenna performance and high structure precision are finally achieved by modifying and rectifying different parameters embedded in silicon platform including the helix and feeding variables using reliable evolutionary optimizers, effective stochastic solvers and accurate automatic strategists for conceiving high-performance THz MEMS helix antennas.

Key words: Integrated antennas, Terahertz (THz) applications, Micro-electromechanical system (MEMS) technology, computational electromagnetic (EM) optimization, evolutionary/stochastic/automatic strategists.

Summary

As new applications for the electromagnetic THz gap ranging from 0.1 to 10 THz [1] begin to emerge, a great deal of research has been performed to develop functional antennas to manipulate this unique band of waves and incorporate integrated radiators into high frequency systems, especially with the wide wireless technology demand in processing the increasing information capacity in various applications that has revived the usage of integrated antennas on very compact units as essential elements having always been an interesting but difficult subject for designing and modeling. It is now assured that the design of highly miniaturized antennas becomes more critical due to the needs in operating in several frequency bands occupying a large available area [2]. This has attracted the utilization of advanced integrating technologies, and driven requirements for accurate optimization procedures to establish a new class of compact integrated THz antennas to be mainly deployed in high frequency access systems. Micro-electromechanical system technology becomes therefore a very promising technology for revolutionizing such antennas with terahertz waves by combining silicon-based microelectronics with complex computer aided design techniques including evolutionary, stochastic and automatic methodologies to meet the very special demand of novel THz antennas for attractive applications [3].

Many new techniques of MEMS technology have started to gain a great deal of momentum from research, industry and standardization bodies to stimulate interest in the unique THz spectral and help manufacturing integrated antennas, enhancing their performance and achieving precise micro scale. Focused ion beam (FIB) [4] is one of the significant techniques used for designing MEMS THz antennas, especially helix antennas. It consists of implementing silicon platforms as a very good solution for improving the antenna shape and performance. In very specific terms, helix antennas employing silicon-based microelectronics, have achieved over the last decade important characteristics including compact size, good radiation, and wide bandwidth, thus

their implementation into planar forms seems to become easier due to the advanced micromachining techniques [5]. This has marked a major advancing in the field of THz technology, leading to provide new models of THz antennas, especially with the use of accurate computer aided design tools and effective optimization techniques as excellent solutions for improvements in modeling, incorporation of analysis, and execution of repeated electromagnetic simulations until developing existing design models and achieving new design models with a very good accuracy [6]. Three-dimensional high frequency structure simulator [7] presents a good environment for excellent electromagnetic treatment based on evolutionary optimizers, stochastic solvers and automatic strategists to retain a high performance and good accuracy for the antenna structure as compared with finite element modelling, to improve the existing design models or develop new design models, based on reliable and fully functional approximations.

Interestingly, this research work provides for the THz wireless access systems, a novel category of integrated helix antennas based on MEMS technology, and explains the major optimization procedures used to treat the device structure complexity that offer fitness functions for excellent bandwidth learning and fast configuration evaluation. The proposed antenna designs are developed using HFSS software based on fast computational techniques for active electromagnetic investigation and optimization. The research study targets at maximize the antennas' electromagnetic performance for the selective band of frequencies through optimizing their geometrical configurations with a high accuracy based on finite element modeling. Excellent electromagnetic responses and high structure precisions are finally achieved by synthesizing different tunable parameters embedded in the silicon platform divided into the helix form variables and feeding line characteristics. The optimized antennas occupy highly miniaturized volumes of a micro scale having a silicon susbtrate thin very. The proposed MEMS helix antenna designs are validated by demonstrating optimal results in terms of low return loss (RL) properties and excellent voltage standing wave ratios (VSWR) in comparison to the previous structures. This has afforded encouraging results due to the real progress of the different electromagnetic optimization techniques in providing a new class of antennas operating at various THz frequency ranges covering attractive applications for different emerging fields [8-10].

Accordingly, this research work addresses fundamental concerns of newly integrated THz MEMS helix antenna designs and provides relevant representative developments in three chapters that present a balanced approach among various important technical issues pertinent to integrated THz antennas as follows:

1. Integrated Antennas for Modern Wireless Systems

The first chapter describes how antennas have evolved historically, discusses the impact of antennas in various systems, and gives an idea of the range of their applications that include communications, remote sensing, radar, biomedicine, etc. This chapter introduces also the popular types of antennas, presents important advances made in their designs, and offers insight into integrated antennas which are incorporated into different modern wireless systems to transmit, collect and transfer information. Interestingly, understanding how these antennas are employed at different frequencies ranging from radio to terahertz requires a main focus into their design considerations and deep knowledge of the fundamental properties for their operation. Concepts such as efficiency, gain, bandwidth, radiation pattern, and others are covered in an evaluative manner. This introductory chapter offers in fact insight into modern integrated antennas presenting:

1.1. Historical perspective and applications of antennas

Antennas present today an integral part of the daily-life requirements; they are employed to transmit and receive electromagnetic waves for a multitude of purposes; they serve as a transducer that converts guided waves into free-space waves in the transmitting mode, or vice-versa in the receiving mode. All antennas operate on the same basic principles founded by the electromagnetic theory of *J. C. Maxwell*. Numerous antenna designs began to emerge and find important applications over the entire electromagnetic frequency spectrum since 1901, the time of the time of Marconi's first experiments with transmitting electromagnetic waves. Today, antennas provide a very large range of applications in the military, civil and commercial fields. They enjoy extensive use in communication, biomedicine, sensing, imaging, astronomy, spectroscopy, collision avoidance, air traffic control, global positioning systems, pagers, wireless networks, etc., and cover a very wide range of frequencies [11].

1.2. Popular types of antennas

Since the start of radio communications, thousands of antennas have been developed. They can be categorized by various criteria [12]:

- In terms of the bandwidth, antennas can be divided into narrowband and broadband antennas;
- In terms of the polarization, they can be classified as linearly polarized or circularly polarized antennas;
- In terms of the resonance, they can be grouped as resonant or traveling wave antennas;
- In terms of the number of elements, they can be organized as element antennas or antenna arrays.
- In terms of physical structures, they can fall into wire-type antennas and aperture-type antennas.

Different types of antenna exhibit different features and can be analyzed using different methods and techniques. They have distinct characteristics that make them suitable for a variety of applications. Thus, they are very often used in array configurations to improve upon the characteristics of an individual antenna element [13].

Wire-type antennas are made of conducting wires and are generally easy to construct, thus the cost is normally low. The most important examples include: Dipoles, monopoles, loops, and helix antennas. In parallel, aperture-type antennas are not made of metal wires but plates to form certain configurations that radiate and receive electromagnetic energy in an efficient and desired manner according the aperture type. They are often used for higher frequency applications than wire-type antennas. Typical examples include: Reflector antennas, lens antennas, horn antennas and microstrip antennas.

1.3. Integrated Antennas for modern systems

In today's environment of connectivity, wireless devices are ubiquitous. As the radiofrequency electronics technology for these wireless devices continues to decrease in size, there is a corresponding demand for a similar decrease in size for the antenna element. Unfortunately, the performance requirements for the antenna are rarely relaxed with the demand for smaller size. In fact, the performance requirements generally become more complex and more difficult to achieve as the wireless infrastructure evolves but with the deployment of advanced MEMS processes, challenges outperform the significant limitations associated with the design of such radiating structures, and make possible the fabrication of highly miniaturized antennas operating over multiple frequency.

In general, antennas are designed in well-defined environments, over either infinite or large ground planes, however, integrated antenna for modern wireless systems have to operate on an electrically small device, which will cause a distortion of its radiation characteristics. It is thus important to determine how the fact of integrating an antenna in an electrically small device will affect its actual behavior regarding both input and radiation characteristics [14]. Indeed, designing an integrated antenna is not an easy task, as this type of antenna is subject to very stringent specifications. Small size, light weight, compact structure, low profile, robustness, and flexibility are the prime considerations conventionally taken into account in small antenna design. In addition, as modern wireless systems are required to operate at multiple standards, their antennas are expected to grab as much spectrum as possible, so they may provide multiband or broadband operation [15].

2. MEMS Antennas for THz Wireless Systems

The second chapter exposes the characteristics of the electromagnetic THz gap to understand the serious technical challenges on the design of integrated antennas in this unique THz field, and master the use of submillimeter waves which are a fusion between microwaves and optics. Several THz antennas can be successfully integrated in different geometrical configurations using MEMS technology relying on silicon-based microelectronics processing. This has leaded to investigate the silicon-based microelectronics process, and study the fundamentals of THz antennas on electrically thin and thick silicon substrates. Interestingly, this descriptive chapter presents mainly exhaustive illustrations of:

2.1. Electromagnetic THz gap

The electromagnetic THz gap presents a main portion of the electromagnetic frequency spectrum which extends from 0.1 to 10 THz, and shows the ray of hope to the modern wireless systems to meet the future need and carter the exponential growth in the data rates required by such a kind of high performance systems. This presents a potential challenge to the scientific community to increase the operating frequencies, the wireless systems may fetch a high data rate to the target customers.

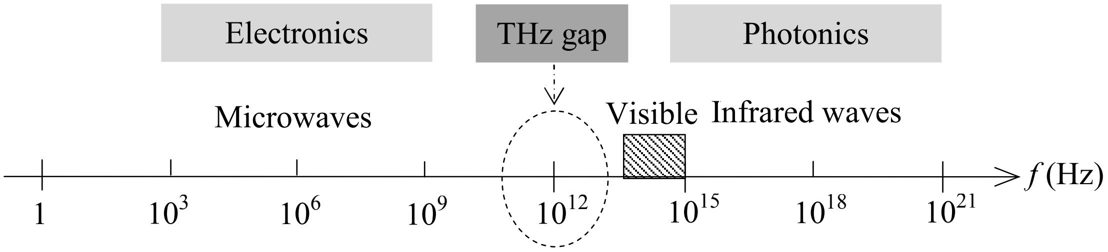


Figure 2.1 – Position of electromagnetic THz gap in the frequency spectrum

This becomes possible with the increasing of operating frequencies to the terahertz band ranging from microwave band to infrared band of the electromagnetic frequency spectrum as illustrated in figure 2.1 [16, 17]. Indeed, due to its unique position, as this gap is situated between these two already well-explored regimes of the spectrum, it is possible to use electronic as well as photonic route to pave the way in the terahertz spectrum. However, with the increase in the operating frequency, the device characteristics changes that needs a thorough analysis of various THz system components, and requires advanced technologies to integrate these components in micro and nanometer scales such as MEMS technology which presents a convincing technology to model functional and high performance devices for diverse THz systems [18-20].

2.2. Integrated antennas for THz systems

To overcome the limitation caused due to the high loss of the signal in THz wireless systems, different hardware parameters need to be optimized. Among them, there is the need of the further research and development in high performance integrated antennas with light profiles to provide low-loss interconnections and inexpensive terahertz wireless systems.

THz has remained a bandgap due to the scarcity of high power devices but with the fast progress in the field of technology, various THz integrated antennas have been reported to be widely used in wireless systems as a valid alternative solution to the photonic devices which need a more complex photomixing techniques in generating the terahertz waves above 1 THz [21], or the excessively large oscillators generating terahertz signals below 1 THz due to the requirement of high magnetic field [22]. Likewise, the role of the THz integrated antenna in modern wireless systems has gradually increased and found relevant applications in different fields especially sensing and imaging systems. The role of the THz integrated antenna in wireless systems is easily understood with the help of *Friis* and Brown analysis [23, 24].

2.3. Micro-electromechanical systems for THz integrated antennas

As the size of radiators is reduced to enhance the performance of THz frequency links, they cannot collect much of the terahertz radiation, and, therefore, the detection of such radiation becomes difficult. MEMS antennas provide in fact efficient radiation elements of large coverage that are highly recommended to manipulate THz waves due to their low profile, excellent electromagnetic response and the fact that they can be softly integrated with electronics. They are realized in a single-crystal silicon substrate and can be fabricated using conventional bulk micromachining relying on available focused ion beam technique, and it is usual practice to integrate the feeding into the dielectric substrate. MEMS antennas have been used in many applications. They have been used in the design of high receivers for astronomical, atmospheric, and imaging arrays. In general, the size of MEMS antennas is comparable to the wavelength of the THz radiation being detected to achieve a fast response. The antenna collects the radiation and supplies an electrical signal to be processed. So far, several antenna geometrical configurations have been used to serve THz wireless systems [25, 26].

Many new processes of silicon-based microelectronics become therefore very useful for designing compact MEMS antennas by implementing silicon wafers to widely preserve the well-known advantages of micromachining technologies such as high precision, high performance, and self consistency [27]. MEMS technology after several years of scaling is approaching a number of fundamental limitations that can only be addressed by the use of silicon-based processes. To meet the challenging MEMS technology requirements as well as staying cost effective, major efforts have been expended to combine the low cost and well-established silicon-based processing attributes, enable performance superior to that achievable with compound semiconductors such as sapphires (SiC, InP, or GaAs), and realize many advantages for silicon substrates.

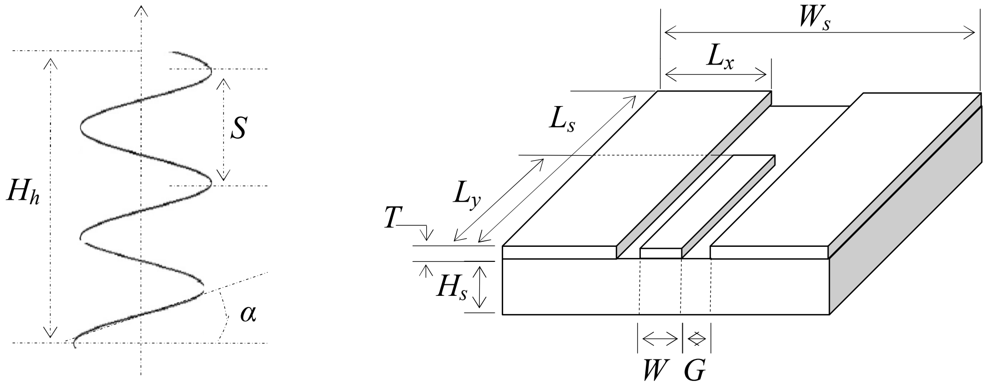
3. Computational Electromagnetic Techniques for Optimizing THz MEMS Helix Antennas

Related to what has been reported in the first two chapters, the third chapter describes for the THz wireless access systems applications a variety of compact helix antenna designs embedded in silicon wafers, presenting a new class of high performance integrated antennas with uniform characteristics and optimal dimensions due to the right exploitation of effective MEMS processes, and sophisticated use of HFSS-based accurate computational electromagnetic optimization techniques. This chapter adds to the knowledge base provided by the previous chapters a particular emphasis on major optimization challenges facing the complex antenna structures developed to efficiently collect terahertz radiation for successful operations. Each time, the optimization strategy aims to vary the antenna geometric structure and maximize its electromagnetic response with a high accuracy for the selective band of frequencies by training the samples and minimizing the error from FEM based simulation tool. Excellent antenna performance and high structure precision are finally achieved by modifying and rectifying different tunable parameters embedded in silicon platform including the helix form parameters, and feeding line variables. This technical chapter therefore presents with details:

3.1. Evolutionary optimizers for developing THz MEMS helix antennas

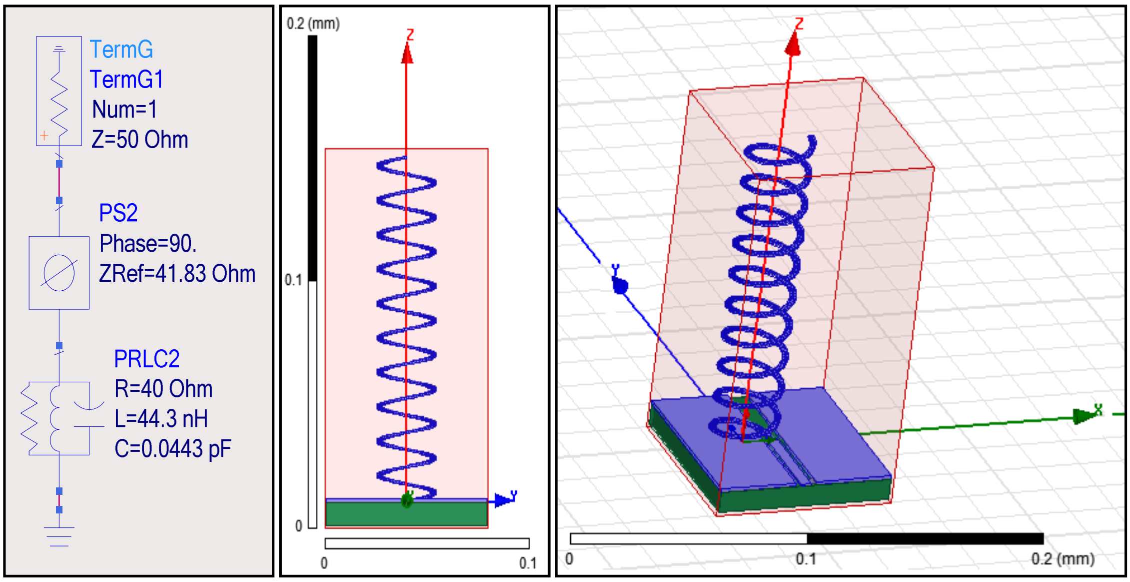
As illustrated in figures 3.1 and 3.2, a novel geometrical configuration of an ultra wideband (UWB) MEMS helix antenna [28] using HFSS software is described. The proposed MEMS antenna is realized in a single-crystal silicon substrate and can be fabricated using conventional bulk micromachining relying on available FIB stress-introducing technique [29]. The optimization procedure relies on Quasi-Newton (Q-N) and Sequential Non Linear Programming (SNLP) algorithms to offer fitness functions for excellent bandwidth learning and fast configuration evaluating. The antenna occupies a very compact volume of

79×80×152 um (0.960 10^{-3} mm^{3}) including the silicon substrate having a thickness of 9.3 um and a dielectric constant of 11.9.



(a) **(b)**

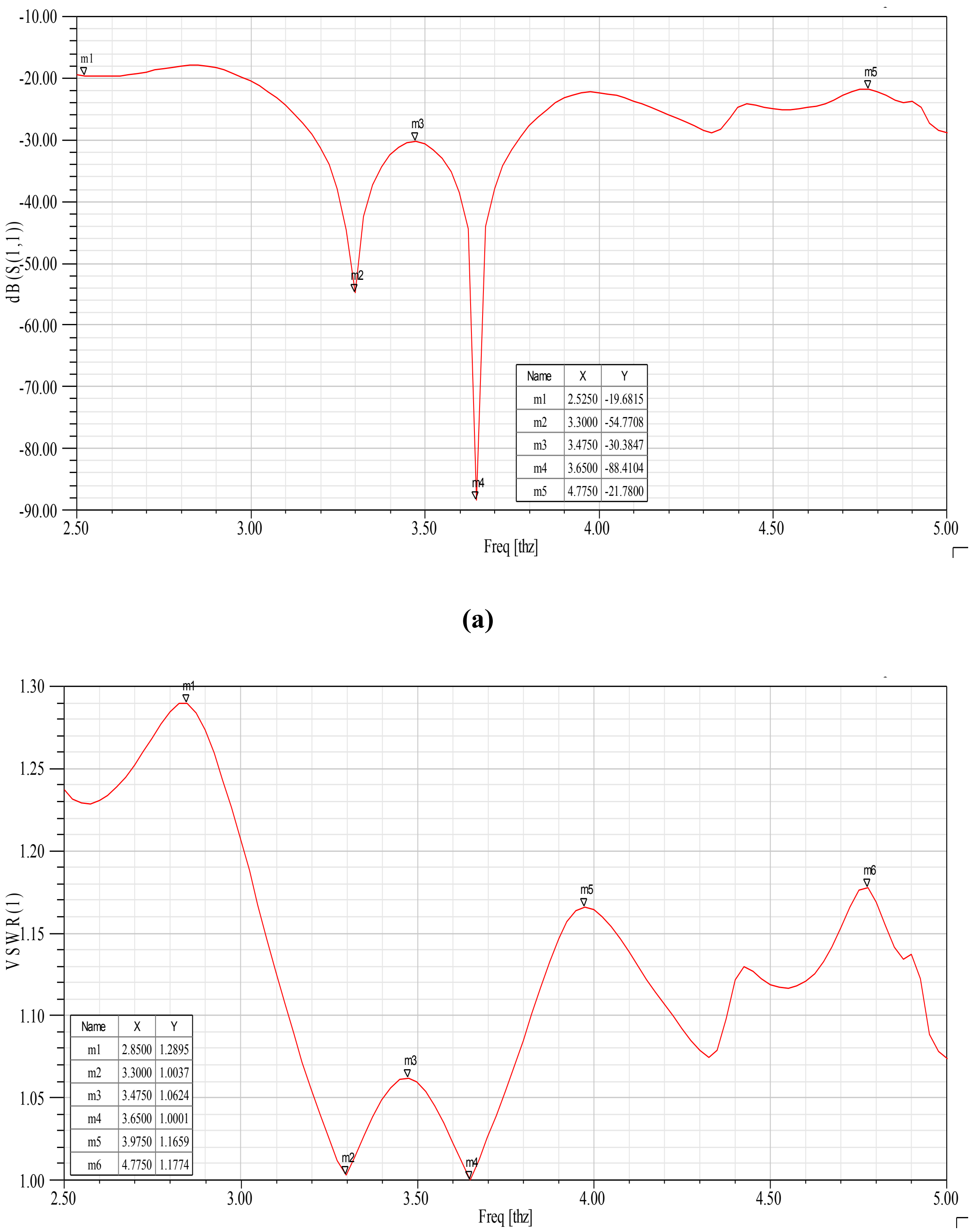
Figure 3.1 - Geometric structure of the THz UWB MEMS helix antenna, (a) schematic diagram of the helix, (b) 3D model of the CPW feeding



(a) **(b)** **(c)**

Figure 3.2 – THz UWB MEMS helix antenna equivalent circuit (a) in ADS, 2D (b) and 3D (c) models in HFSS

The antenna with optimized parameters operates in a wide bandwidth from 2.5 to 5 THz and shows good radiation patterns, very low reflection coefficients with less than -20dB to -88dB, and excellent voltage standing wave ratios of less than 1.15 to 1.00 over the entire bandwidth as shown in figure 3.3.



(a)

(b)

Figure 3.3 – Simulated RL (a) and VSWR (b) graphs of the optimized THz MEMS helix antenna using HFSS-based evolutionary optimizers

The explored MEMS helix antenna design is validated by demonstrating optimal results in terms of return loss properties in comparison to the previous optimized structures [30, 31]. As shown in figure 3.4, it is clearly observed that the new THz MEMS helix antenna geometric characterization developed by HFSS based on efficient electromagnetic optimization comes with very low return losses with closely less than -20dB over the entire frequency band, and less than -30dB over the central frequencies from 3.2 to 3.7 THz, and approximately -55dB and -89dB at 3.20 THz and 3.80 THz respectively.

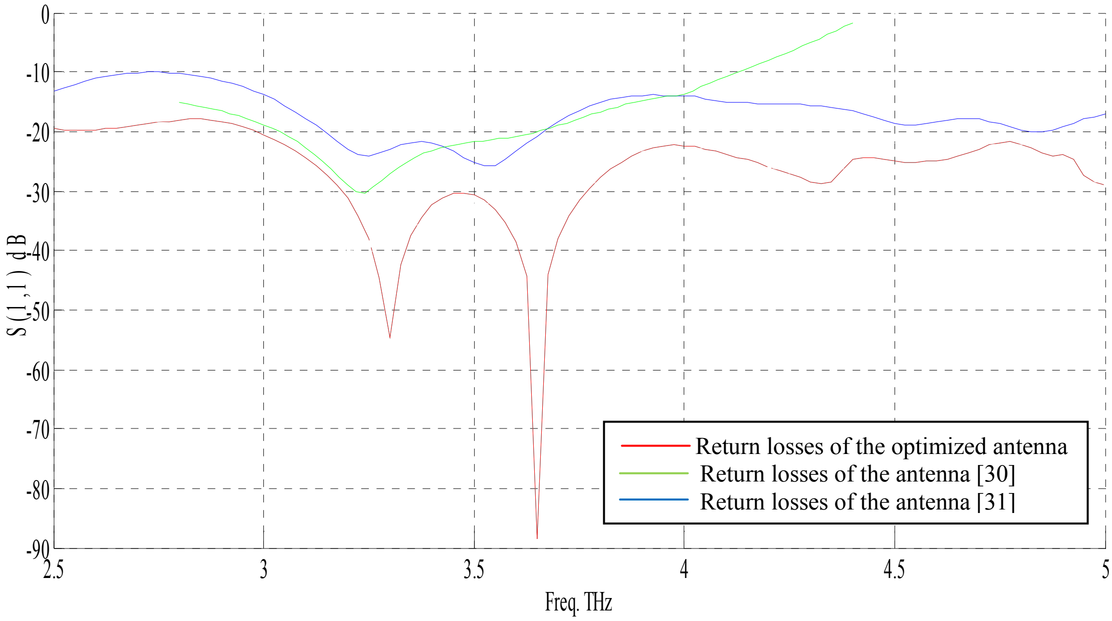


Figure 3.4 - Comparison of RL of the optimized antenna to the antennas [30, 31]

The compact THz helix antenna design optimized using Q-N and SNLP methods has been tested and simulated covering an ultra wide range of frequencies of 8.7 THz extending from 1.2 to 9.9 THz as presented in figure 3.5. The antenna shows very low return losses of closely less than -15dB for the entire bandwidth presenting a great success in finding useful design with very good performance for UWB wireless products. This demonstrates the advantage of HFSS optimization techniques in offering a more degree of freedom in developing new structures, supporting multiple resonance modes distributed across a large THz spectrum, based on the proposed THz UWB MEMS helix antenna design which offers very good applications for an ultra wide range of frequencies covering more than 87.87% of the electromagnetic THz gap that is highly attractive to support several THz systems such as radar, biomedical, sensing, imaging, space, radio astronomy, and spectroscopy systems. Details of geometrical configuration of the THz MEMS helix antenna optimized in HFSS-based evolutionary optimizers are presented in table 3.1.

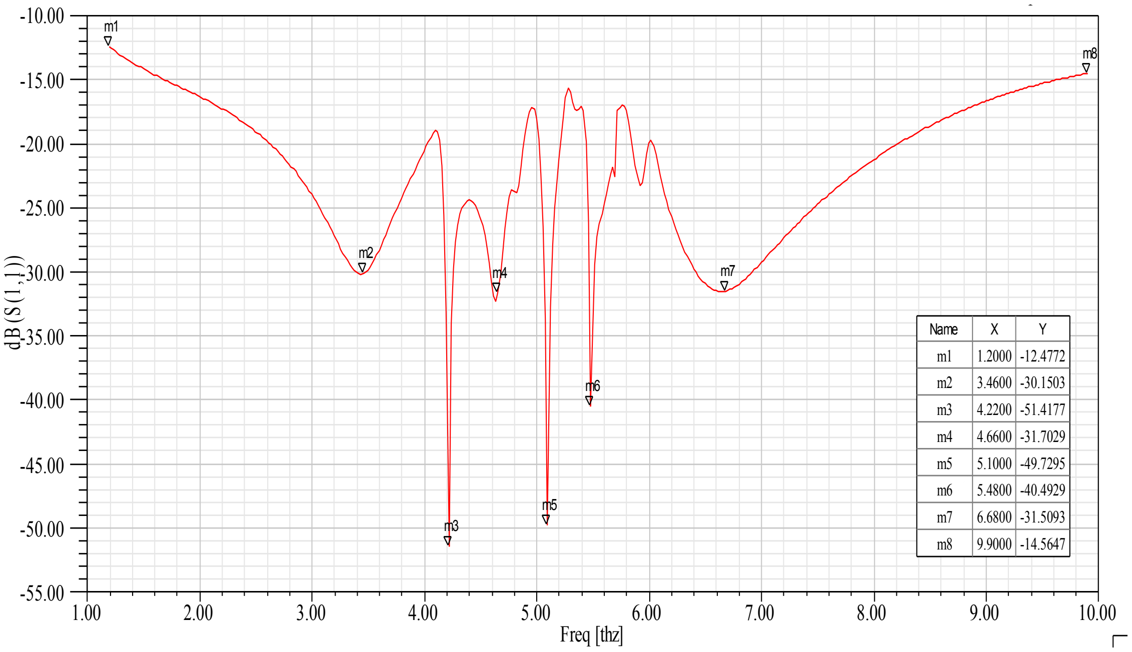


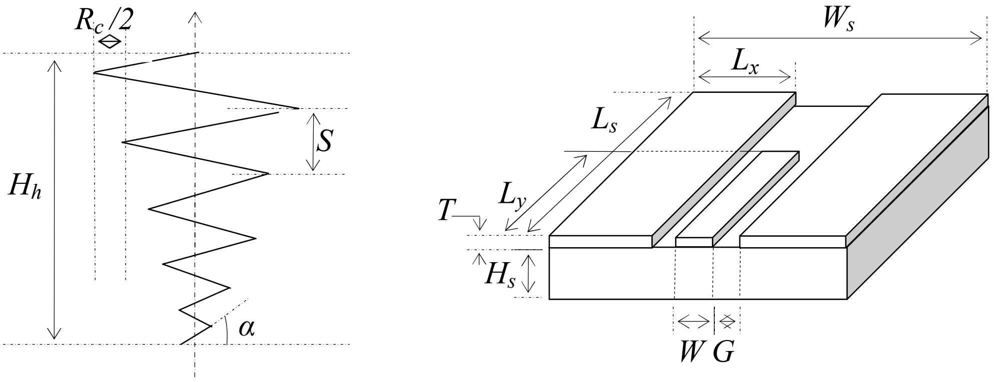
Figure 3.5 – Simulated RL graph of the proposed UWB MEMS helix antenna optimized by HFSS-based evolutionary optimizers in 1.2 to 9.9 THz

Table 3.1 - Characterization of the THz UWB MEMS helix antenna optimized in HFSS using evolutionary optimizers

Section	Parameter	Value (um)	Specification
Helix form	Diameter (*D*)	27.3661	Q-N optimization
	Pitch (*S*)	14.1409	SNLP optimization
	Turn number (*N*)	10	SNLP optimization
	Slent angle (α)	9.340°	$S = \pi.D.\tan\alpha$
	Height (H_h)	141.4090	$H_h = S.N$
CPW feeding	Width (*W*)	4.8659	Q-N optimization
	Gap (*G*)	2.0937	SNLP optimization
	Width (L_x)	35	/
	Longer (L_y)	40	/
	Thickness (*T*)	1.5674	SNLP optimization
Silicon platform	Thickness (H_s)	9.2952	Q-N optimization
	Longer (L_s)	80	/
	Width (W_s)	79.0533	$W_s = W + 2(L_x + G)$
Antenna	Height (H_A)	152.2721	$H_A = H_s + T + H_h$

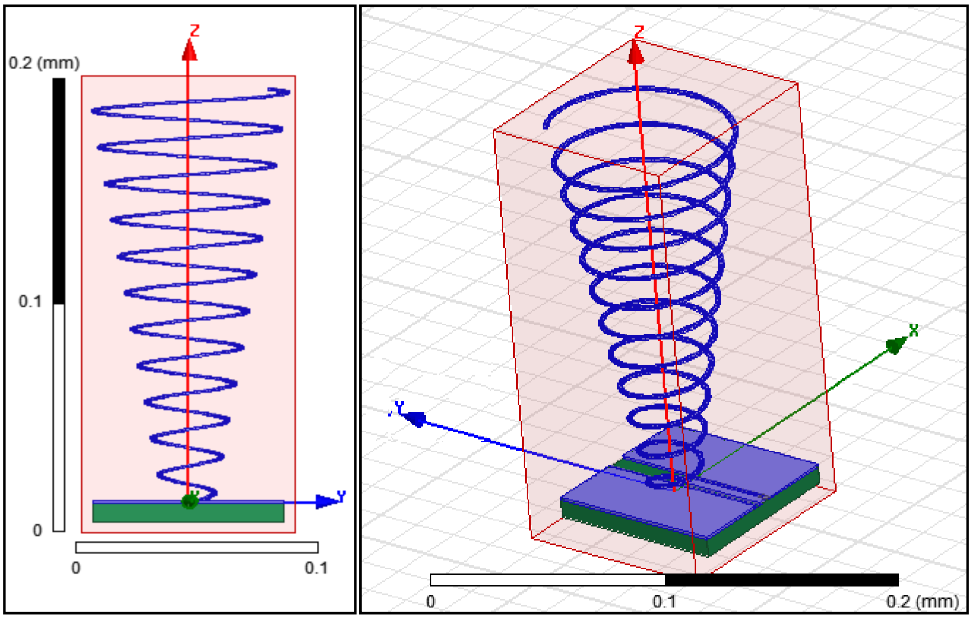
3.2. Stochastic solvers for designing THz MEMS helix antennas

Based on the optimized THz UWB MEMS helix antenna design developed using evolutionary optimizers in section 3.1, the second section describes in the fisrt stage a new design of a MEMS horn-shaped helix antenna. The antenna geometry is optimized using Genetic Algorithms (GA) technique for excellent bandwidth learning and fast configuration evaluating.



(a) **(b)**

Figure 3.6 – THz MEMS horn-shaped helix antenna geometric structure, (a) schematic diagram of the helix, (b) 3D model of the CPW feeding



(a) **(b)**

Figure 3.7 - 2D (a) and 3D (b) HFSS models of the optimized THz MEMS horn-shaped helix antenna

Figures 3.6 and 3.7 present respectively the geometrical structure and the HFSS models of the novel MEMS antenna developed by GA solvers. The MEMS antenna occupies a very compact volume of 79×80×188 um ($1.1881\ 10^{-3}\ mm^3$) including the silicon substrate having a thickness of 8.5 um and a dielectric constant of 11.9.

In Genetic Algorithms optimization [32] as illustrated in figure 3.8, the random selection of evaluations to proceed to the next generation has the advantage of allowing the optimizer to jump out of a local minima at the expense of many random solutions which do not provide improvement toward the optimization goal. GA optimizer performs the search via a population to population presenting an iterative process that goes through a number of generations to vary the values of the antenna parameters initially selected for the optimization on the basis of finding a minimum or maximum of a cost function parameters to overall simulation goals.

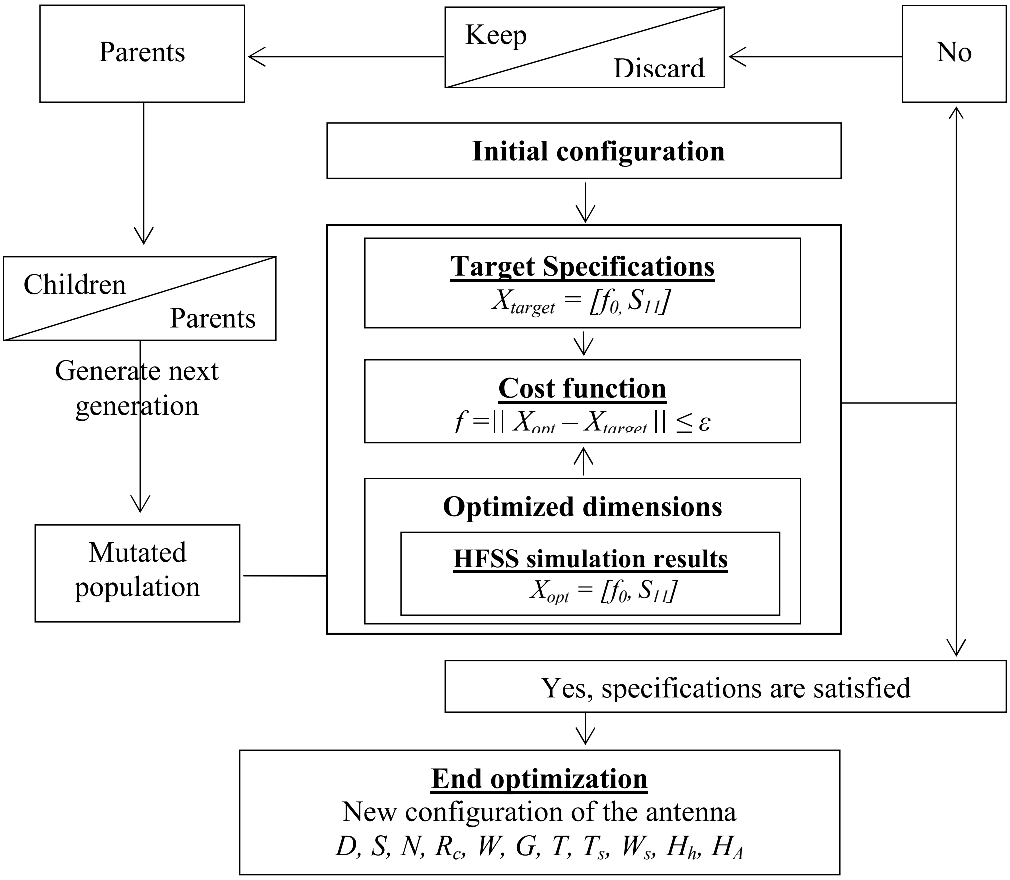


Figure 3.8 - Adaptive GA optimization process

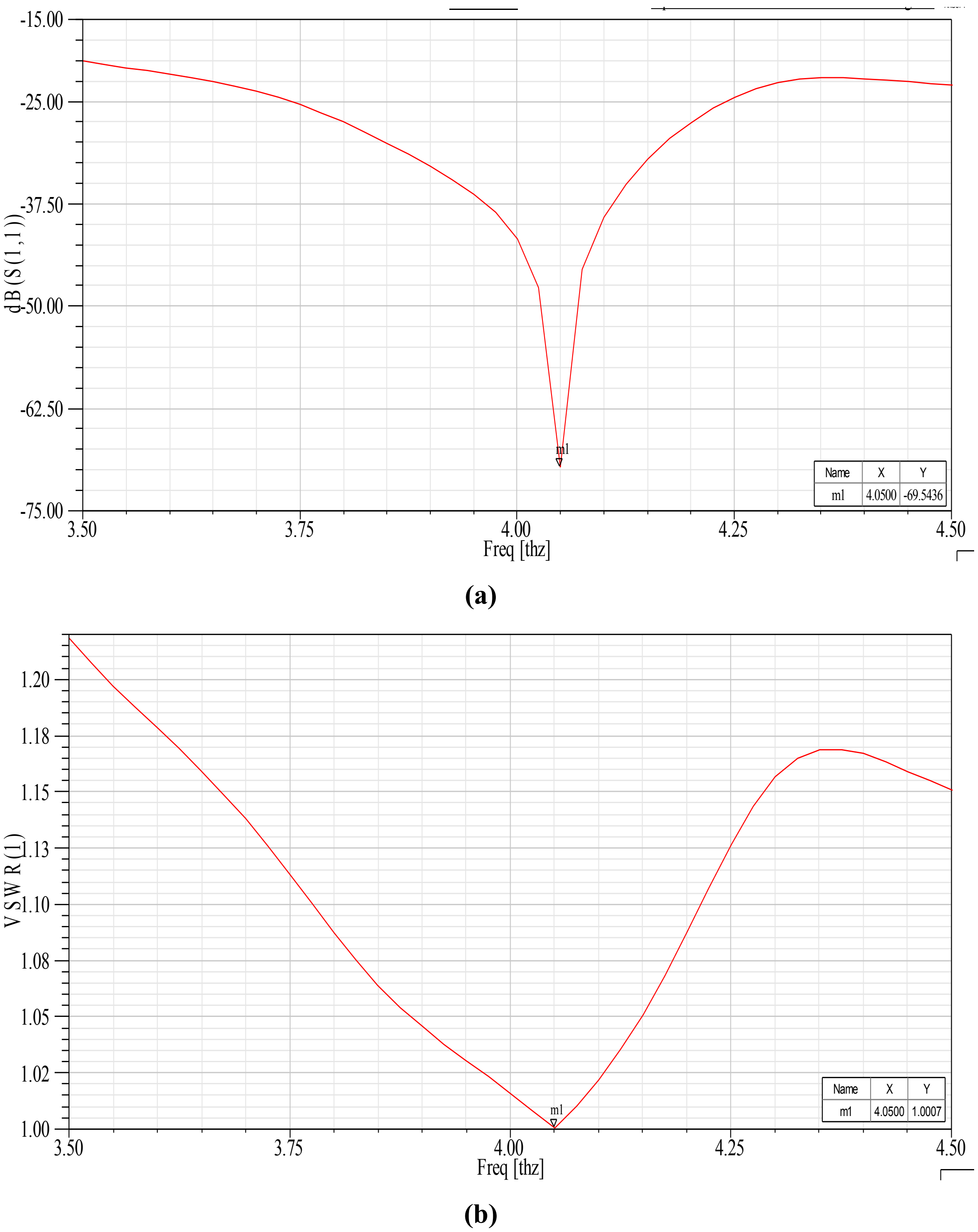


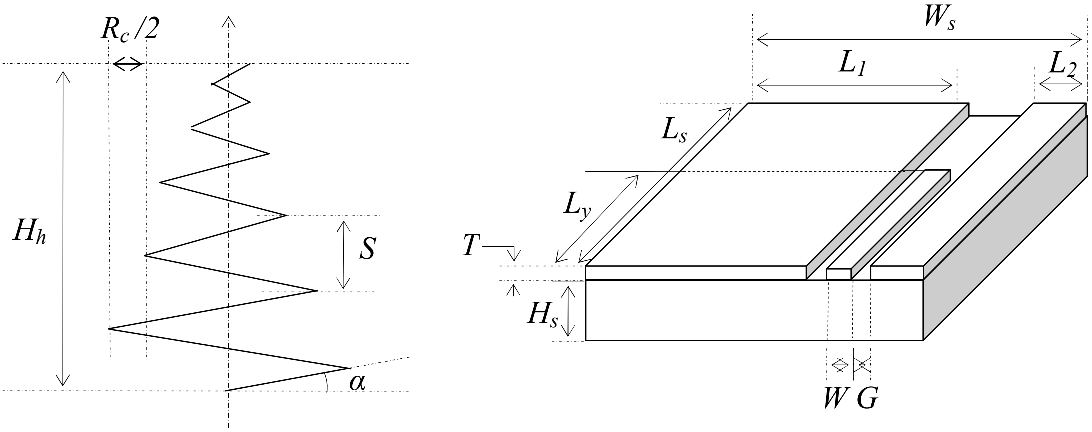
Figure 3.9 - Simulated RL (a) and VSWR (b) graphs of the optimized THz MEMS horn-shaped helix antenna using HFSS-based stochastic solvers

As presented in figure 3.9, the optimized horn-shaped helix antenna design based on MEMS technology has been found to resonate at 4.05 THz and show very low return losses less than -20dB to -70dB and excellent voltage standing wave ratios of closely less than 1.20 to 1.00 for a wide frequency band ranging from 3.5 to 4.5 THz, resulting in excellent electromagnetic response and good directivity due to the high geometrical accuracy achieved using effective stochastic solvers in rectifying the antenna parameters. It is very important to mention that the size of the helix aperture (pitch S, and radius change R_c) presents a very significant parameter in improving the helix antenna performance and making it very beneficial to the THz applications. The optimized antenna design presents in fact a potential candidate for THz wireless products due to GA optimization technique presenting a global search technique that is particularly very effective in a high-dimension multimodal function due to their versatility and ease of implementation [33]. Details of the geometric configuration of the new MEMS horn-shaped helix antenna optimized in HFSS-based Genetic Algorithms are presented in Table 3.2.

Table 3.2 - Characterization of the THz MEMS horn-shaped helix antenna optimized in HFSS using stochastic solvers

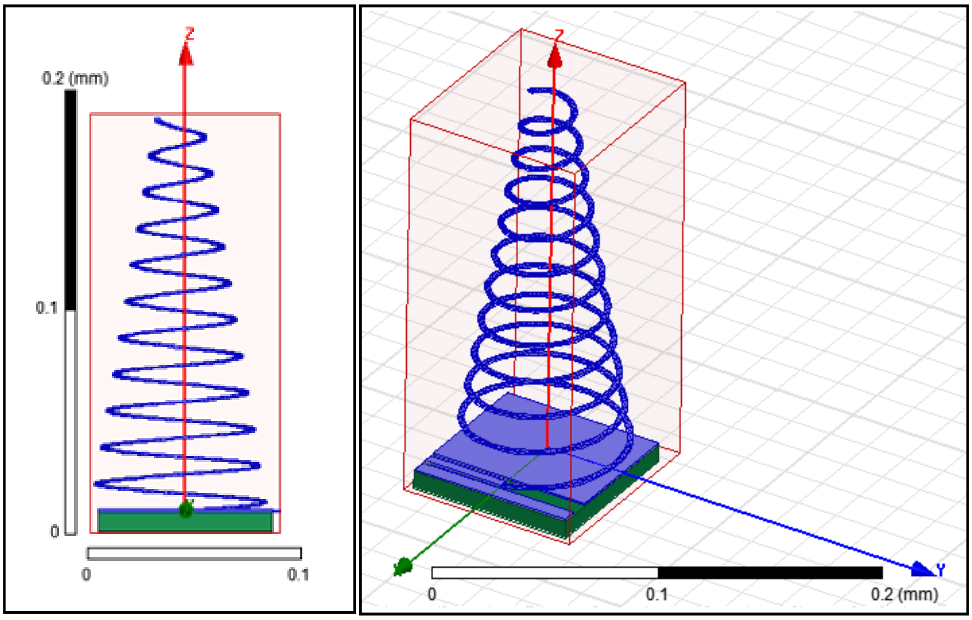
Section	Parameter	Value (um)
Helix form	Diameter (D)	20.4166
	Pitch (S)	16.3062
	Turn number (N)	11.3403
	Radius Change (R_c)	2.7798
	Slent angle (α)	14.2638°
	Height (H_h)	184.9171
CPW feeding	Width (W)	4.8946
	Gap (G)	2.3860
	Thickness (T)	1.1895
Silicon platform	Thickness (H_s)	8.4954
	Width (W_s)	79.6666
Antenna	Height (H_A)	194.6020

In the second stage, a novel design of a compact MEMS pyramidal helix antenna [34] is proposed for the wireless access systems using for modal electromagnetic analysis Genetic Algorithms as automatic stochastic solvers (figures 3.10 and 3.11). In this case, the antenna occupies a highly miniaturized volume of 80×80×217 um (1.3888 10^{-3} mm^3) including the silicon substrate having a thickness of 8.14 um, and a dielectric constant of 11.9.



(a) **(b)**

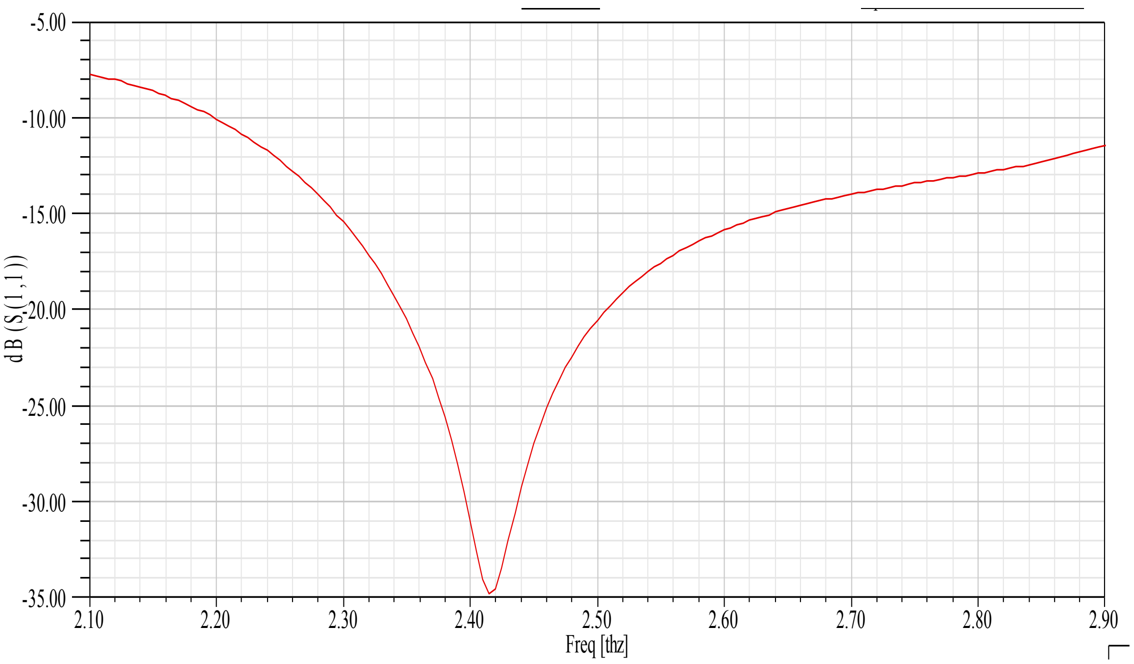
Figure 3.10 – THz MEMS pyramidal helix antenna geometric structure, (a) schematic diagram of the helix, (b) 3D model of the CPW feeding



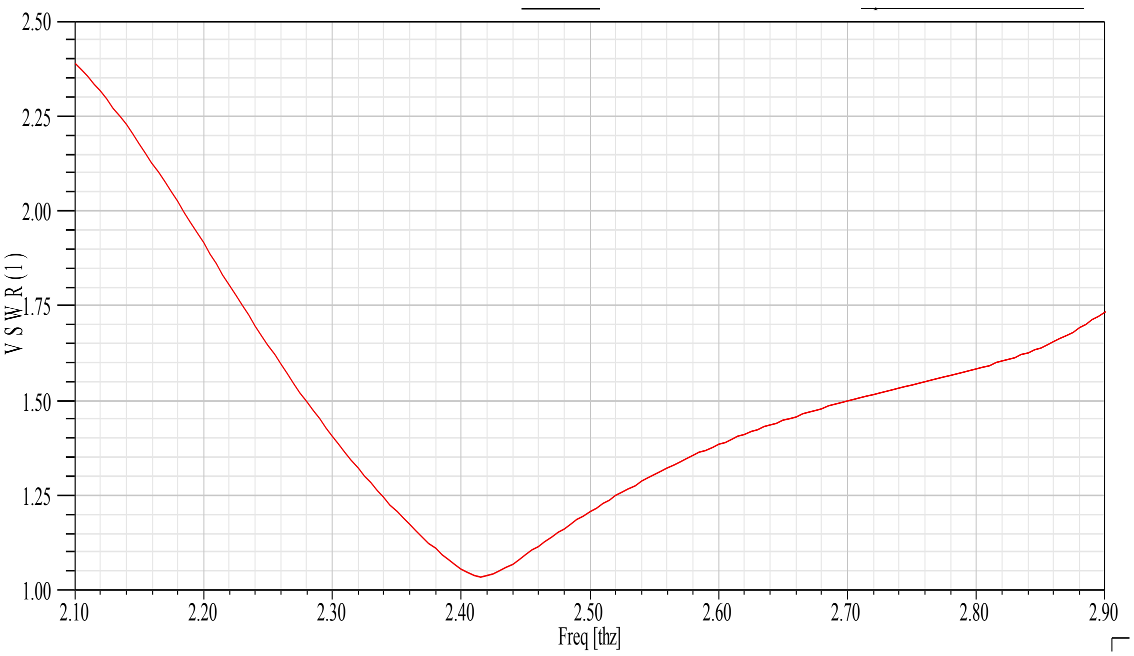
(a) **(b)**

Figure 3.11 - 2D (a) and 3D (b) HFSS models of the THz MEMS pyramidal helix antenna

The explored MEMS pyramidal helix antenna design shows good radiation patterns, low return losses with closely less than -15dB to -35dB, and excellent voltage standing wave ratios of less than 1.20 to 1.03 (figure 3.12). The antenna demonstrates very good performance for a wide range of frequencies covering more than 150 GHz presenting a large area for wireless applications.



(a)



(b)

Figure 3.12 - Simulated RL (a) and VSWR (b) graphs of the optimized THz MEMS pyramidal helix antenna using HFSS-based stochastic solvers

The novel MEMS pyramidal helix antenna geometric characterization developed by HFSS based on high automatic GA solvers comes with very low return losses with closely less than -20dB over the central frequencies to achieve less than -34dB at f_0 = 2.41 THz. The voltage standing wave ratios present also excellent values of less than 1.25 from 2.34 to 2.52 THz to achieve the value of 1.03 at the resonate frequency f_0 = 2.41 THz. HFSS software constitutes therefore relevant device for the improvement of THz technology due to its efficient optimization techniques. Details of geometrical configuration of the novel MEMS pyramidal helix antenna optimized in HFSS based on effective stochastic solvers are presented in Table 3.3.

Table 3.3 - Characterization of the THz MEMS pyramidal antenna optimized in HFSS using stochastic solvers

Section	Parameter	Value (um)
Helix form	Diameter (D)	19.3601
	Pitch (S)	16.0064
	Turn number (N)	10.7333
	Radius Change (R_A)	-2.5327
	Slent angle (α)	14.7442°
	Height (H_h)	171.8014
CPW feeding	Width (W)	4.9644
	Width (L_1)	63
	Width (L_2)	7
	Gap (G)	2.6110
	Thickness (T)	1.1821
Silicon platform	Thickness (H_s)	8.1415
	Width (W_s)	80.1864
Antenna	Height (H_A)	181.1250

3.3. Automatic strategists for modeling THz MEMS helix antennas

Based on the set of antennas developed using stochastic solvers, the final section describes first a new compact geometric configuration of a MEMS horn-shaped helix antenna [35] using Artificial Neural Networks (ANN) which are employed for the modeling of antenna design problems to obtain a surrogate based model instead of a computationally intensive three dimensional electromagnetic simulation in design.

Geometrical parameters of the proposed MEMS helix antenna have been optimized by introducing an accurate ANN model using MATLAB programming [36, 37], in order to enhance the accuracy of the existing structure - already developed by stochastic solvers in the section 3.2 (figures 3.6 and 3.7 - MEMS horn-shaped helix antenna) through an automated data training process having the ability to capture multi-dimensional arbitrary nonlinear relationships in a very fast way to finally provide an efficient high-level antenna design.

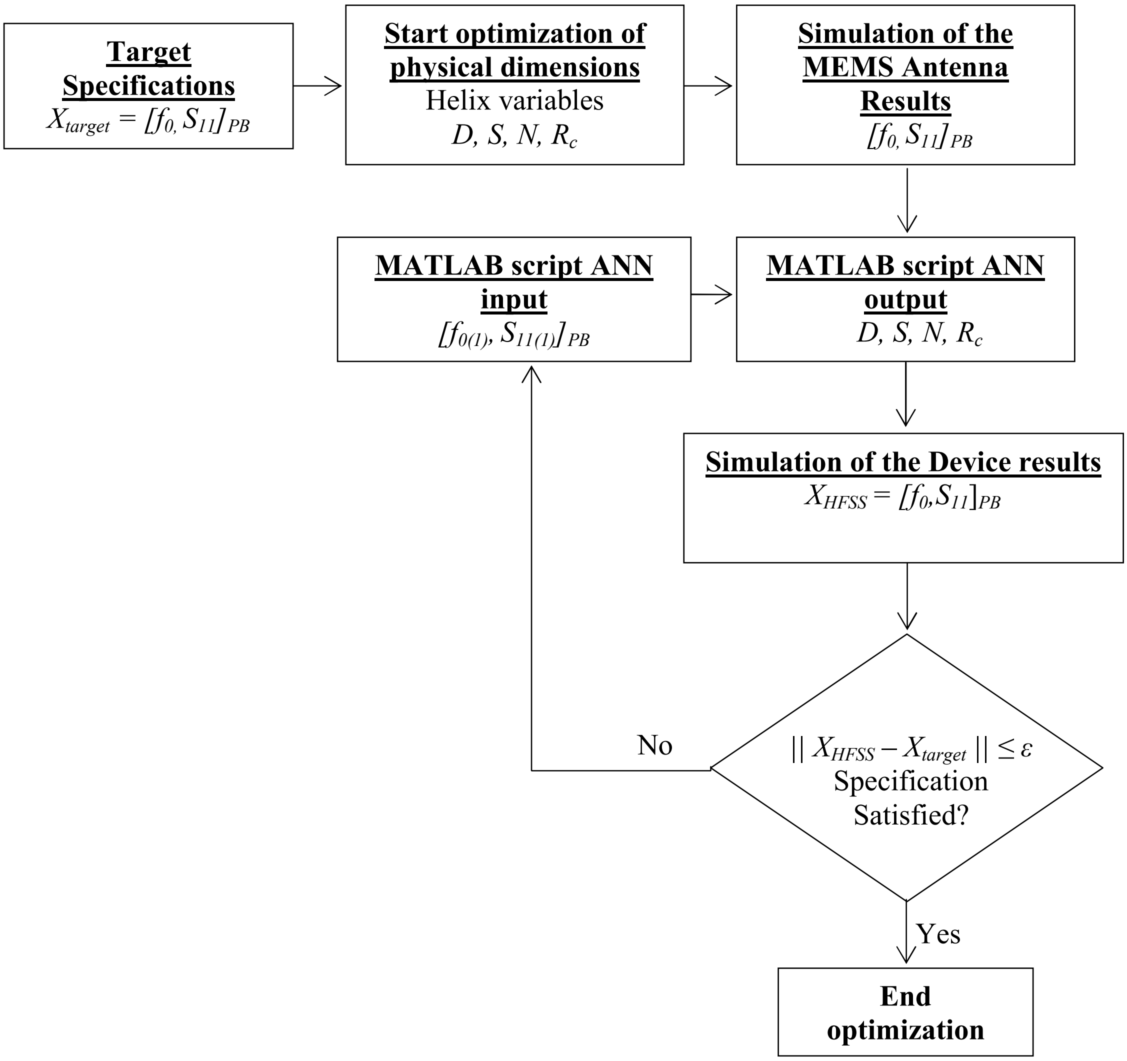
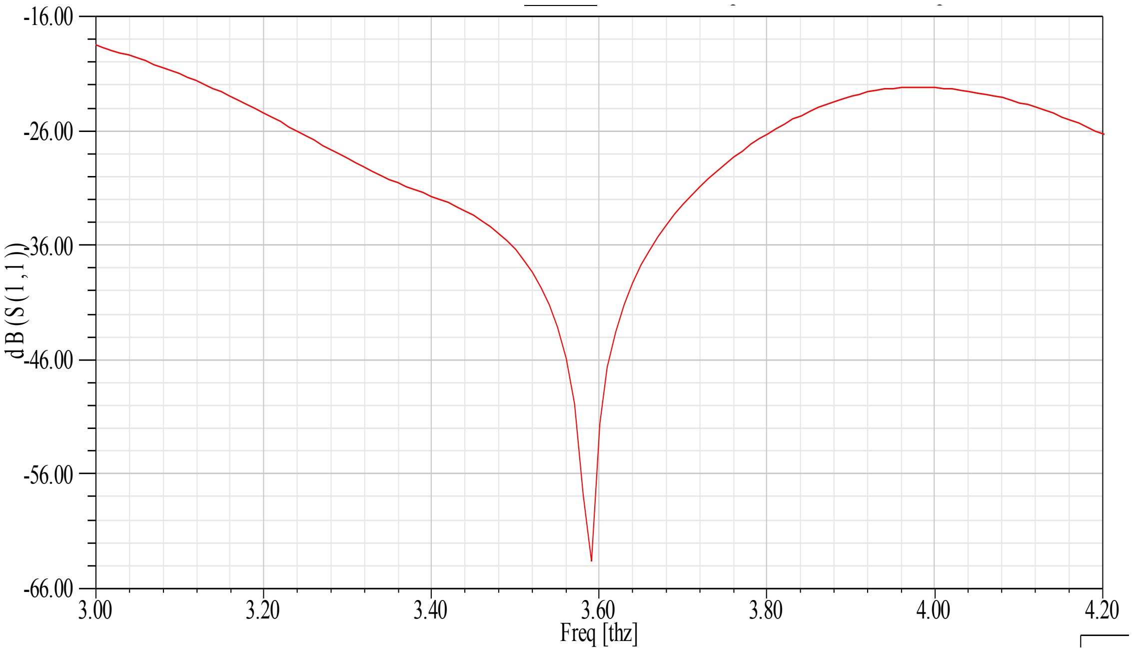
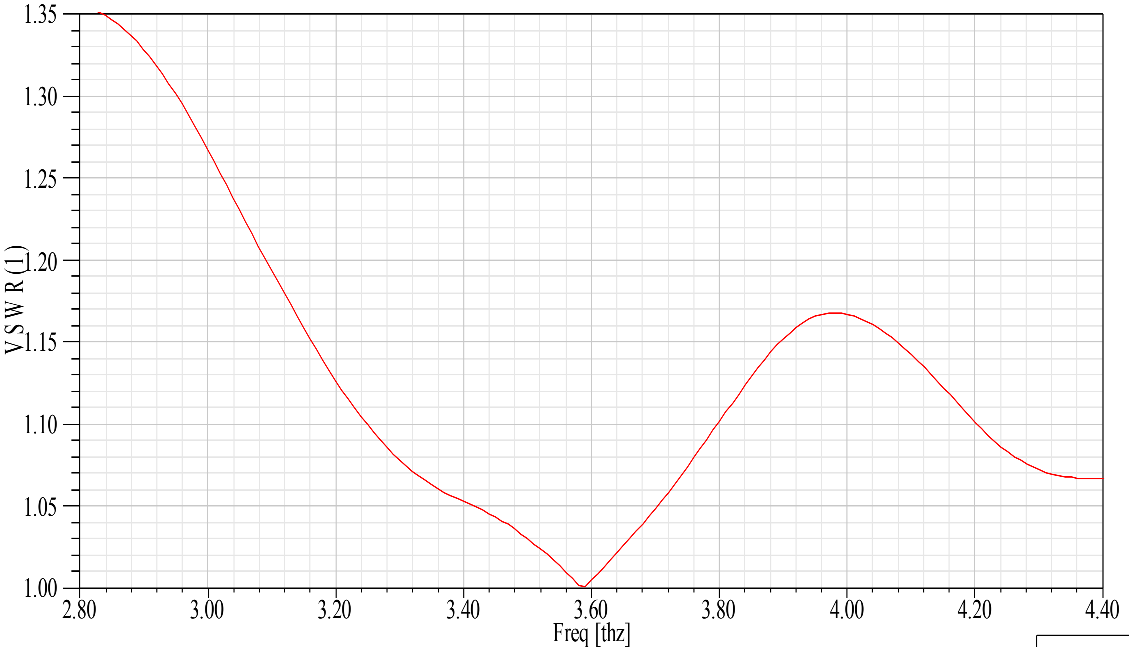


Figure 3.13 - Adaptive CAD procedure for the ANN optimization process

The optimization operation is launched aiming to determine a new configuration of the MEMS helix providing simulation results (X_{HFSS}) close to the target design specifications (X_{target}) initially proposed. The key technique used in this adaptive CAD procedure is explained in details in figure 3.13 which presents the design process steps.



(a)



(b)

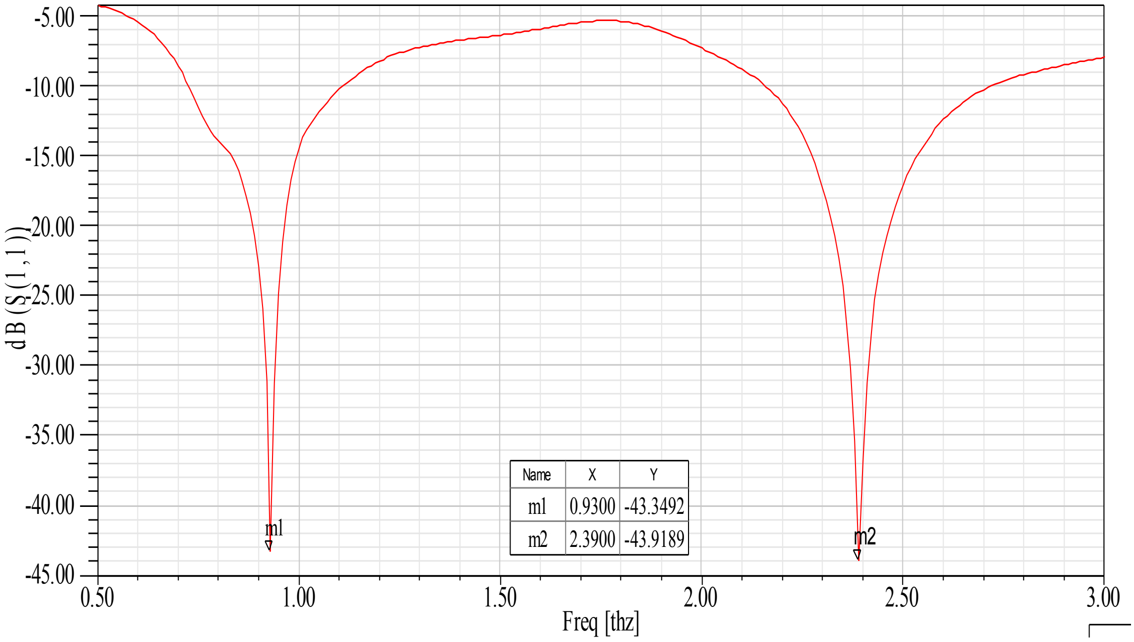
Figure 3.14 - Simulated RL (a) and VSWR (b) graphs of the optimized THz MEMS horn-shaped helix antenna using HFSS-based ANN modeling

The optimized antenna occupies a very compact volume of 79×80×162 um (1.02×10^{-3} mm^3), including the silicon substrate having a thickness of 9.3 um and a dielectric constant of 11.9. The proposed MEMS helix antenna design is validated by demonstrating optimal results in terms of low return loss properties and voltage standing wave ratios (figure 3.14). The antenna has been also found to resonate at 3.59 THz and operate in a wide bandwidth from 3.12 to 4 THz with very low reflection coefficients with less than -17dB to -63dB, and excellent voltage standing wave ratios from 1.35 to 1.00. Table 3.4 shows the final geometric configuration reported from the 8th iteration, selected for the MEMS horn-shaped helix antenna design after optimization.

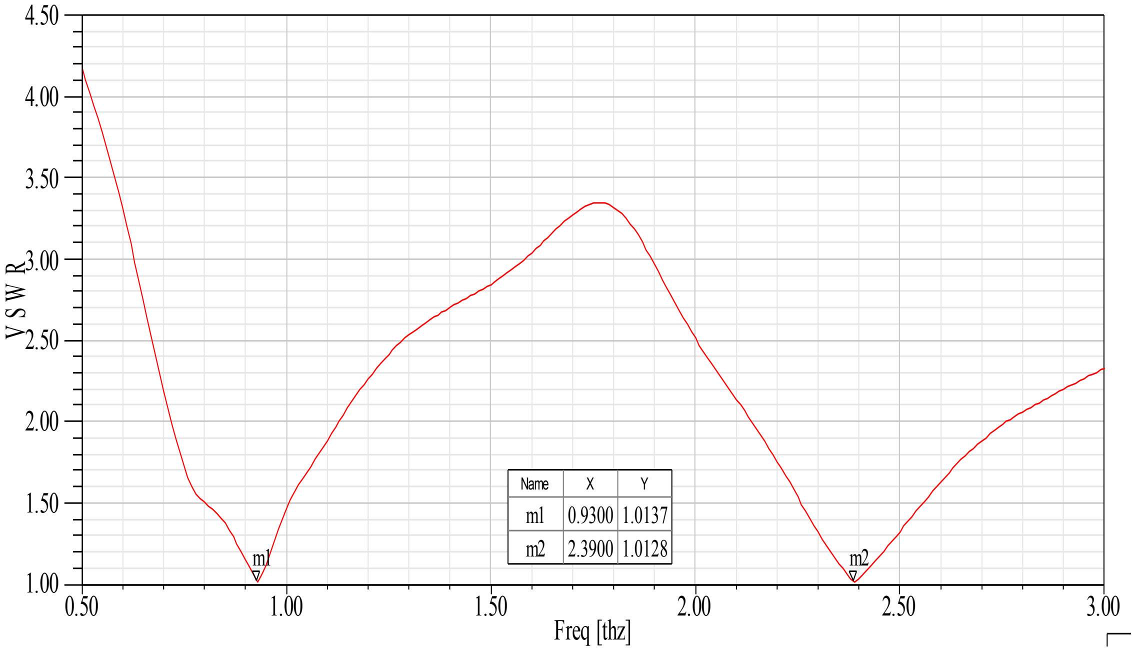
Table 3.4 - Characterization of the THz MEMS horn-shaped helix antenna optimized in HFSS using ANN modeling

Section	Parameter	Value (um)
Helix form	Diameter (D)	25.4565
	Pitch (S)	14.3676
	Turn number (N)	10.5738
	Radius Change (R_c)	2.6483
	Slent angle (α)	10.184°
	Height (H_h)	151.9201
Antenna	Height (H_A)	161.6050

Second, a novel design of MEMS pyramidal helix antenna [38] using accurate Artificial Neural Networks model is proposed for dualband wireless applications based on the THz MEMS pyramidal helix antenna design already established using GA technique in section 3.2 (figures 3.10 and 3.11). An efficient multilayer perceptron (MLP) network is employed for the automated data training process relying on back propagation algorithms in which neurons are grouped into: input neurons including down and upper return losses (S_{11D} and S_{11U}), and down and upper resonance frequencies (f_D and f_U). The output neurons contain the helix diameter, pitch, turn number, and change radius (D, S, N and R_A). The optimized MEMS pyaramidal helix antenna occupies a highly miniaturized volume of 79×80×189 um (1.1944 10^{-3} mm^3) including the silicon substrate having a thickness of 9.3 um and a dielectric constant of 11.9. The antenna geometry is optimized in a way it resonates at 0.93 THz and 2.39 THz and shows excellent performance.



(a)



(b)

Figure 3.15 - Simulated RL (a) and VSWR (b) graphs of the optimized THz MEMS pyramidal helix antenna using HFSS-based ANN modeling

The new MEMS antenna design is validated by presenting optimal results in terms of low return losses of closely less than -15dB to -43dB, and excellent simulated voltage standing wave ratios of less than 1.5 to 1.01 for the down and upper frequency bands ranging from 0.8 to 1 THz and from 2.3 to 2.5 THz respectively (figure 3.15). Details of the geometrical configuration of the new MEMS pyramidal helix antenna optimized in HFSS based on ANN modeling are presented in table 3.5.

Table 3.5 - Characterization of the THz MEMS pyramidal helix antenna optimized in HFSS using ANN modeling

Section	Parameter	Value (um)
Helix form	Diameter (D)	17.2656
	Pitch (S)	16.0382
	Turn number (N)	11.1280
	Radius Change (R_A)	-2.5217
	Slent angle (α)	16.471^o
	Height (H_h)	178.4730
Antenna	Height (H_A)	187.7966

ANN model developed for the optimization offers the advantage of superior computational ability to provide optimal geometric configurations due to its high efficiency and interconnectivity to solve design problems. Therefore, it is very important to mention that global-function approximation capability and greater generalization capability of ANN technique facilitate the modeling phenomenon and can avoid the limitation encountered for objective-function formulation in the GA optimization [39].

Finally, this research study attempts at the analysis and development of novel integrated antenna designs linking the well-known advantages of MEMS processing to the modular properties of the electromagnetic THz frequency field. It is the hope of this study to find in it the necessary prototypes and mechanisms that can help in manufacturing such a kind of antennas and realizing new wireless applications in the future research works.

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Abstract

This research work provides for the THz wireless access systems novel designs of highly miniaturized helix antennas based on MEMS technology with particular emphasis on major optimization challenges facing the device structure complexity. The different antenna geometrical structures are developed using 3D high frequency structure simulator (HFSS) based on efficient computational techniques for modal analysis and active optimization. Each time, the optimization strategy aims to vary the antenna geometric structure and maximize its EM response with a high accuracy for the selective frequency band by training the samples and minimizing the error from Finite Element Method- (FEM) based simulation tool. Excellent antenna performance and high structure precision are finally achieved by modifying and rectifying different parameters embedded in silicon platform including the helix and feeding variables using reliable evolutionary optimizers, effective stochastic solvers and accurate automatic strategists for conceiving high-performance THz MEMS helix antennas.

Key words: Integrated antennas, Terahertz (THz) applications, Micro-electromechanical system (MEMS) technology, computational electromagnetic (EM) optimization, evolutionary/stochastic/automatic strategists.

ملخص

يقدم هذا البحث لأنظمة تيراهيرتز اللاسلكية تصميمات مبتكرة عالية الدقة لهوائيات حلزونية (لولبية) باستعمال تكنولوجيا الأنظمة الكهروميكانيكية الجزئية و التركيز على تحديات التحسين الأساسية التي تواجه هيكلة الجهاز المعقدة، مختلف الهياكل الهندسية للهوائيات تم تصميمها باستخدام برنامج ثلاثي الأبعاد لمحاكاة الهياكل عالية التردد اعتمادا على تقنيات حوسبة كهرومغناطيسية فعالة من أ جل تحليل نشط و تحسين أمثل، في كل مرة، تهدف إستراتيجية التحسين المتبعة لتغيير بنية الهوائي الهندسية وزيادة استجابته الكهرومغناطيسية بدقة عالية حسب نطاق التردد المختار من خلال تدريب العينات وتقليل الأخطاء باستعمال طريقة العناصر المحددة، و في الأخير تم الحصول على أداء ممتاز ودقة بنية عالية للهوائي عن طريق تعديل وتصحيح عدة أبعاد مختلفة متضمنة في قاعدة السليكون بما في ذلك مقاييس اللولب و الإمداد باستخدام أدوات تحسين تطورية، معالجات ستوكاستيكية فعالة، و استراتيجيات أوتوماتيكية دقيقة

الكلمات المفتاحية: الهوائيات المتكاملة، تطبيقات تيراهيرتز، تكنولوجيا الأنظمة الكهروميكانيكية الجزئية، التحسين الكهرومغناطيسي الحاسوبية، لاستراتيجيات التطورية / الستوكاستيكية / الأوتوماتيكية.

Résumé

Ce travail de recherche fournit aux systèmes d'accès sans fil térahertz de nouveaux modèles d'antennes hélicoïdales hautement miniaturisées basées sur la technologie MEMS, avec un accent particulier sur les principaux défis d'optimisation face à la complexité de la structure du dispositif. Les différentes structures géométriques d'antennes ont été développées en utilisant un 3D simulateur de structure haute fréquence (SSHF) basé sur des techniques de calcul efficaces pour une analyse modale et une optimisation active. A chaque fois, la stratégie d'optimisation vise à faire varier la structure géométrique de l'antenne et à maximiser sa réponse électromagnétique avec une grande précision pour la bande de fréquences sélective en entraînant les échantillons et en minimisant l'erreur par l'utilisation de la méthode des éléments finis. Une excellente performance et une grande précision de structure pour l'antenne sont finalement obtenues en modifiant et rectifiant plusieurs paramètres intégrés dans la plate-forme de silicium y compris les variables d'alimentation et d'hélice en utilisant des optimiseurs évolutionnaires fiables, des solveurs stochastiques efficaces et des stratèges automatiques précis pour concevoir des antennes hélices MEMS térahertz à haute performance.

Mots clés: Antennes intégrées, Applications térahertz (THz), Technologie des systèmes micro-électromécaniques (SMEM), Optimisation électromagnétique (EM), Stratégistes évolutionnaire/stochastiques/automatiques.