Parametric Analysis of an Optical Log-Spiral Nano-Antenna for Infrared Energy Harvesting

Abdulrahman Alhomrani [1], Ali Yahyaoui [1,2], Anas Al Hashmi [2], Ameni Mersani [3], Majed Nour [1], Hatem Rmili [1], and Raj Mittra [1,4]

[1] King Abdulaziz University, Electrical and Computer Engineering Department
P.O. Box 80204, Jeddah 21589, Saudi Arabia
hmrmili@kau.edu.sa

[2] Department of Electrical and Electronic Engineering, College of Engineering, University of Jeddah

[3] University of Tunis El Manar, Faculty of Sciences Tunisia, Microwave Electronics Research Laboratory
LR18ES43, 2092 Tunis, Tunisia

[4] Electrical and Computer Engineering Department, University of Central Florida, EMC Lab
Orlando, FL 32816 USA

Abstract – In this paper, we present the design of a spiral nano-antenna dedicated to infrared energy harvesting at 28.3 THz. A comprehensive, detailed parametric study of key parameters such as the initial angle at the origin arm , width of the spiral arms, gap between the two arms, thickness of substrate, length of substrate, thickness of patch and number of turns of the nano-antenna is also presented and discussed in order to harvest maximum electric field in the gap of the spiral antenna in the frequency range of 28 – 29 THz. The maximum electric field is simulated at 28.1, 28.3, 28.5 and 28.7 THz. A variation of the electric field of the antenna for different value of incident wave angle at the resonance frequency 28.3 THz has been simulated. The main advantages of the studied structure are its ability to reach high confined electric field within its gap, its wideband behavior around the operating frequency 28.3 THz, and its insensitivity to polarization of incident electromagnetic waves.

Index Terms –Electric field, harvesting, infrared (IR), optical antenna, spiral antenna, THz.

I. INTRODUCTION

Actually, we still have an important demand for new and innovative electronic devices such as portable sensors, surveillance devices in buildings, global positioning system (GPS), etc. Because these devices are portable, they require a power supply of their own [1]. In most of the aforementioned applications, the power system is still bulky because of the electrical connection cables which also occupy space. In order to overcome this problem, the conventional solution was the use of electrochemical batteries, this solution appeared to be better and it has known notable progress in recent years, but, it remains very limited and has several drawbacks, for example the lifespan of such batteries is really limited. Regular replacement or recharging of the latter is necessary, which can be both costly and burdensome. In addition, 70% of the electricity is produced by combustion from fossil resources (oil, coal, etc.). Two questions arise: the repercussion of these combustions on the environment (pollution, global warming, etc. and the limited stock of these non-renewable resources [2], [3]. Progress in developing perpetually powered systems has led to an optimal solution to limit the use of batteries and ensure the energy autonomy of these systems. It is at this level that energy harvesting takes place, it is a technique that consists in converting the ambient energy available in the environment into electrical energy that will be supplied to electronic systems [4-6]. There are various sources of energy available to be recovered and converted into electricity and, indeed, a lot of work has been presented on generators capable of generating electrical energy from mechanical vibrations, light, thermal gradients, ambient RF, solar energy ... etc. [7-11]. Each energy source has advantages and disadvantages. For example, the most direct and abundant source of energy comes from the sun are solar. However, the energy recovered depends heavily on: ambient conditions, angle of light incidence, the spectral content of light arriving at the surface of the solar cell, the size, the sensitivity of the solar cell, which can result in low variation efficiency [6], [12].

There is a lot of unutilized energy on Earth, most of the sunlight that strikes our planet is absorbed by surfaces, oceans and our atmosphere [2]. Generally heated bodies emit electromagnetic radiation. Stefan-

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Boltzmann law estimates the amount of radiation from a heated perfect black body [13]. This warming leads to a constant leak of infrared radiation, which some estimate to be millions of gigawatts per second. This energy lies in the Infrared Region (IR), i.e., 7-17μm spectral range [6], [14]. Unlike conventional Photovoltaic (PV) technology, which are limited by daylight and climatic conditions, energy from IR heat can be harvested 24 hours a day [15]. The IR band extends from 0.3 to 430 THz with three sub-bands, namely far, mid, and near IR [3], [16], [17]. In [18], Gallo et al. showed that the peak of the earth's emissivity is at 10.6 μm, according to the Stefane-Boltzmann radiation law, therefore the incoming solar radiation being an electromagnetic (EM) wave radiation at terahertz wavelengths and it can be collected using optical antennas which resonates at 10.6 μm, i.e., 28.3 THz. Optical antennas designed to collect the maximum of energy at 28.3 THz (10.6 μm), this method has emerged as a good alternative for the energy harvesting in the infrared region.

Optical antennas are very similar to their Radio Frequency (RF) antennas, but there are crucial differences in their physical properties and scaling behavior. Most of these differences occur, because metals are not perfect conductors at optical frequencies, but rather are highly correlated plasmas described as a free electron gas [19]. The plasmon resonance phenomenon is involved in optics, can be treated from the effects observed on metallic nanoparticles. Surface plasmon modes are electromagnetic modes that are generated by nanoparticles. They have a spectral response dependent on the geometric shape and the size of the particle, in the visible domain. At optical frequencies, the electrons in metals have considerable inertia and cannot react instantly. The average depth of the skin is therefore of the order of tens of nanometers, comparable to the dimensions of the antenna [20-26]. The traditional design rules which prescribe antenna parameters, for radio waves, only in terms of external wavelength λ are therefore no longer valid. Optical nano-antennas can be found in a wide range of applications in the optical and IR ranges such as photo detection, antenna probes for nano-imaging, non-linear signal conversion, clocking and energy harvesting.

Energy harvesting systems require a wave receive antenna connected to a conversion system forming a rectifier antenna or "Rectenna". Recently, several optical nano-antenna with different geometries has been investigated such as dipole [3], bowtie [23], [28], spiral [29] and crescent [30]. In [3], three printed dipoles antennas have different shapes: namely; rectangular, curved bowtie, and elliptical are designed to collect maximum electric field in the gap to operate in the IR region at 28.3 THz. The authors proved that the curved bowtie dipole shape collects a larger electric field than the rectangular and elliptical shapes. In [23], a design of terahertz Bowtie antenna for Infrared Energy harvesting applications is presented. The proposed antenna resonates at 27.4THz with a peak electric field value of 40.934 V/m. The need of establishing communications with higher throughput prompted the use of Ultra Wide Band (UWB) antennas. In fact, they allow the transmission of a large volume of data with a low power density. In this paper, a spiral optical antenna is presented witch resonant at 28.3 THz. In the first section, we present the design of the proposed spiral antenna as well as the design methodology adopted to optimize their performance. The parametric study of different parameters of the antenna at 28.3 THz are presented and commented on section 2. Finally, we detail the results of the optical antenna in infrared band and we will finish with a general conclusion.

II. ANTENNA DESIGN

Antenna is an important element of the IR energy harvesting system. It receives infrared frequency energy and therefore defines the amount of energy supplied to the rectifier [31]. The need to establish communications with higher throughput prompted the use of UWB antennas. In fact, they allow the transmission of a large volume of data with a low power density. UWB antennas are widely used in energy harvesting applications. Among these antennas, there is the spiral antenna. The gradual opening of the slots and arms of the spiral antenna allows for a significant bandwidth. This type of antenna makes it possible to have a circular polarization of the electromagnetic field. The internal radius of the spiral limits the high operating frequency of the antenna while the external radius limits its low frequency which is detailed in [32]. This type of antenna has very favorable characteristics, in terms of gain and polarization, for use in an energy harvesting system.

The general equation of a turn is defined as follows [33]:

$$r_n = r_0 \exp\left(a\left(\alpha+\phi n\right)\right), \tag{1}$$

where n = 1.2, $a = \frac{1}{\tan\delta}$, Φn is the maximum angle of the radius n and α is the initial angle at the origin of the turn. The arm thickness is limited by the two radii r1 and r2. It is equal to the difference of these for a given angle. If we apply this equation, we get two spiral arms which widen according to the angle Φn. Figure 1 shows the prototype simulated antenna. The substrate used in the simulations was quartz ($\varepsilon_r = 3.78$, tan δ = 0.0001) having dimensions of 2.8μm× 3.2μm μm with an initial thickness of 89.1 μm. This antenna uses gold, are the most used because the negative value of their refractive index in the visible, printed on the same substrate.

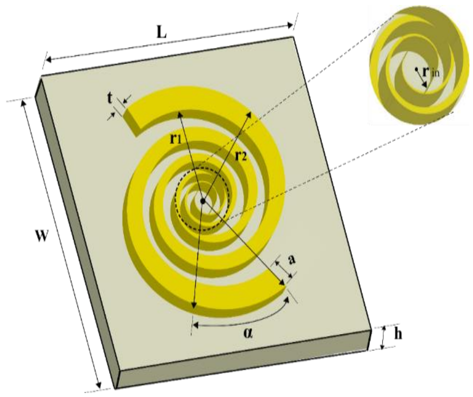


Fig. 1. Spiral nano antenna.

III. PARAMETRIC STUDY

We carried out under Ansys HFSS [34] parametric study on the geometric parameters of the antenna, always with the same objective of maximizing the electric field, with dimensions which remain on the order of a micrometer. We will present results showing the influence of the 7 antenna parameters: the initial angle on the original arm (α), width of the spiral arms (δ), gap between two arms (g), thickness of the substrate (h), length of the substrate (Ls), thickness of the patch (t) and number of turns (N), on the electric field in order to analyze the existing compromises. The range of parameters mentioned before was chosen to achieve the maximum of E-field. We have studied the effect of each parameter on the electric field. The first values that we have started with it, was chosen approximately to satisfy the normal dimensions at this frequencies band then we have started the optimization. The upper and lower limit of each parameter is chosen by covering the maximum range of values without affecting the shape of the proposed antenna. In all the parametric study we present only the important parameters values which give us significant behavior.

A. Effect of Alpha

The electrical field of the antenna versus frequencies for different α is shown in Fig. 2. It is noted that when the initial angle at the origin of the turn (α) = 0.31°, the electric field is important. It is 1010 V/m at 28.3 THz, whereas when α = 0.29°, the electric field is less than 300 V/m. For both α = 0.3° and α = 0.32°, E-field is 550 V/m and 800 V/m respectively at 28.3 THz.

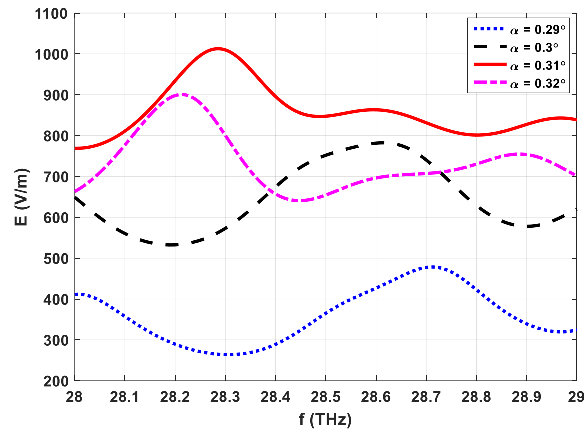


Fig. 2. Effect of Alpha (α) on the electric field.

B. Effect of Delta

The δ parameter is a critical parameter for the antenna. It controls the width of the spiral arms. Figure 3 shows the electrical field of the antenna versus frequencies. The four curves correspond to the δ for four values of δ: {105, 110, 115 and 120} μm. We can observe the influence of the width of the arms on the performance of the antenna. When δ = 105 μm, 110 m and 120 μm, the electric field is around 670 V/m at 28.3 THz. When δ = 115μm, the electrical field is large and is equal to 1010 V/m. The optimum width δ, that which allows operation around 28.3 THz in simulation is equal to 115 μm.

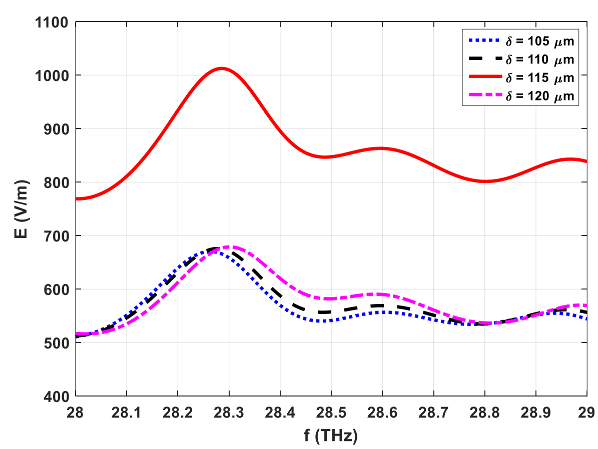


Fig. 3. Effect of Delta (δ) on the electric field.

C. Effect of the Gap

The third critical parameter, carefully studied during the antenna design, is the gap (g) etween the two arms in which the incident electromagnetic wave excites the antenna to generate a localized electric field. In Fig. 4, we show the variation of the electric field vs frequencies for different distances g separating the two arms from the antenna. The result is optimal for a value of g equal to 0.02 µm. the E-field is about 1000 V/m at 28.3 THz.

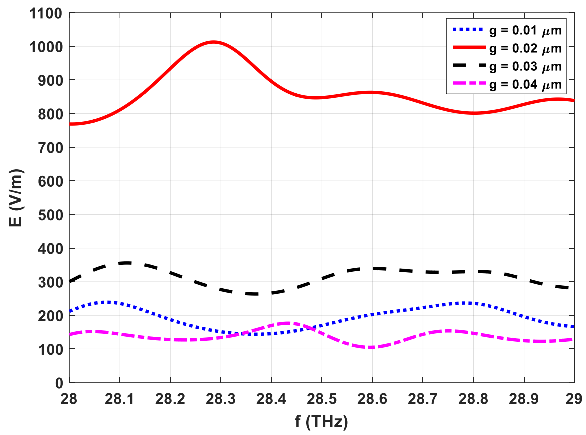


Fig. 4. Effect of the Gap (*g*) on the electric field.

D. Thickness of patch

In order to estimate the effect of the thickness of patch, the performance of the antenna present was studied for different values of thickness "t". Figure 5 shows the evolution of the antenna's electric field for different values of t from 0.042 to 0.072 µm with a step of 0.01. It was noticed that the thickness 0.062 µm offers a high electrical field. It is about 1010 V/m at 28.3 THz.

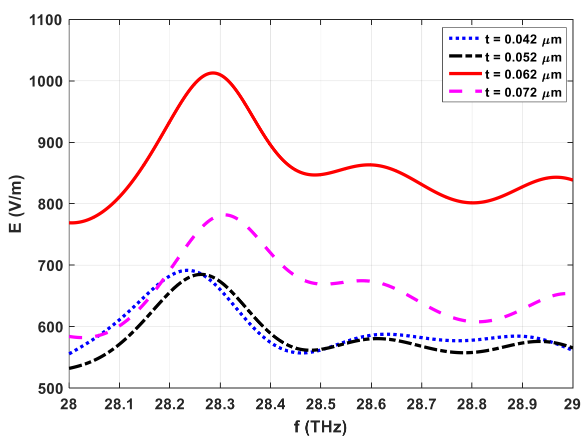


Fig. 5. Effect of thickness of the patch on the electric field.

E. Thickness of the substrate

Another important parameter to study is the effect of substrate thickness on the performance of the spiral antenna. For this study, the parameter noted "h" varies from 89.1 to 119.1 µm with a step of 10 µm, by fixing the other geometric parameters of the antenna.

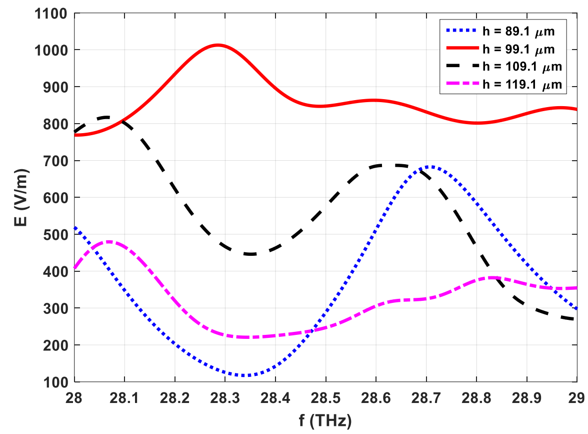


Fig. 6. Effect of substrate thickness (*h*) on the electric field.

The simulated results of this study are presented in Fig. 6. This parameter directly influences the electric field. For values of h = 89.1 µm, h =109.1 µm and h = 119.1 µm, the electric field values are less than 500 V/m at 28.3 THz. While for the value of h = 99.1 µm the E-field is equal to 1010V/m.

F. Length of the substrate

In this part of the study, we try to vary the substrate dimensions in the HFSS tool with a variable marked "Ls" as shown in Fig. 7. According to this study, we find that the electric field is important at Ls= 3.9 µm at IR frequency. It is from the order of 1000 V/m at 28.3 THz however for Ls = 2.9 µm and Ls = 4.9 µm the electric field is less than 250 V/m and when Ls= 5.9 µm, the E-field is about 950 V/m at 28.3 THz.

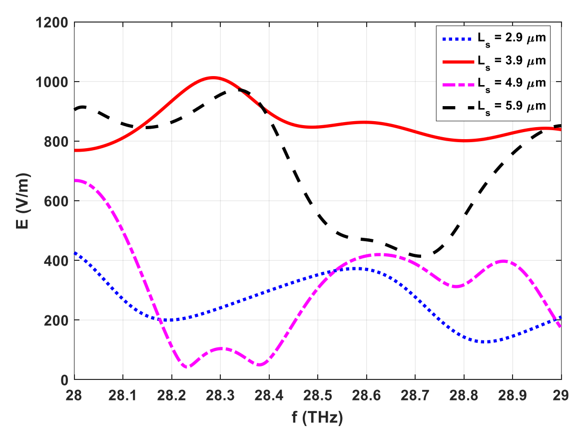


Fig. 7. Effect of length on the electric field.

G. Number of turns

In order to estimate the effect of the number of turns, the performance of the antenna was studied for different values of this geometric parameter noted "N".

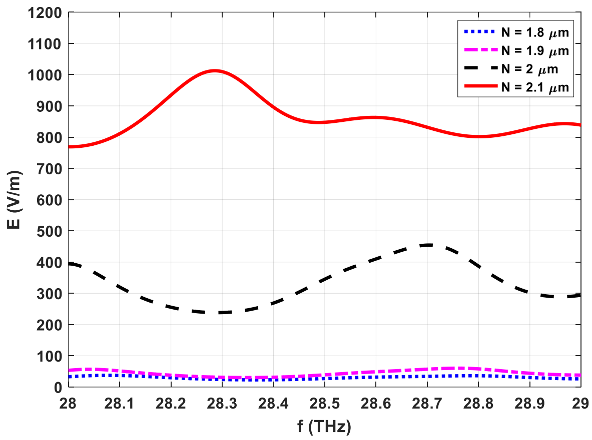


Fig. 8. Effect of the number of turns on the electric field.

A parametric study was carried out on the number of turns to visualize its impact on the value of the electric field. The results of this study are presented in Fig. 8. This figure shows that the electric field is sensitive to the variation in the number of turns .When N = 2.1 μm, the electrical field collected is important. it is equal to 1000 V/m at 28.3 THz while for other values less than 2.1 μm, the electric field is very weak; it is less than 250 V/m.

A complete study of the key parameters of the spiral antenna has been made. We present in Table 1 the main geometrical parameters of the spiral shape. The optimal values obtained for having a significant energy harvesting is listed in Table 1.

Table 1: Final parameters dimensions

Parameter	Value	Parameter	Value (μm)
α	0.31°	t	0.062
δ	115 μm	h	99.1
Ls	3.9 μm	N	2.1
g	0.02μm		

IV. ANALYSIS AND DISCUSSIONS

A. E-Fields in some frequencies

The absorption of incident electromagnetic energy occurs with maximum values of the electric field through the air gap of the antenna. The maximum electric field of the antenna for different frequencies namely 28.1 THz, 28.3 THz, 28.5 THz and 28.7 THz are presented in Fig. 9. The antenna is illuminated by electric fields in the gap higher than 2100V/m for the 4 frequencies from 28.1 THz to 28.7 THz.

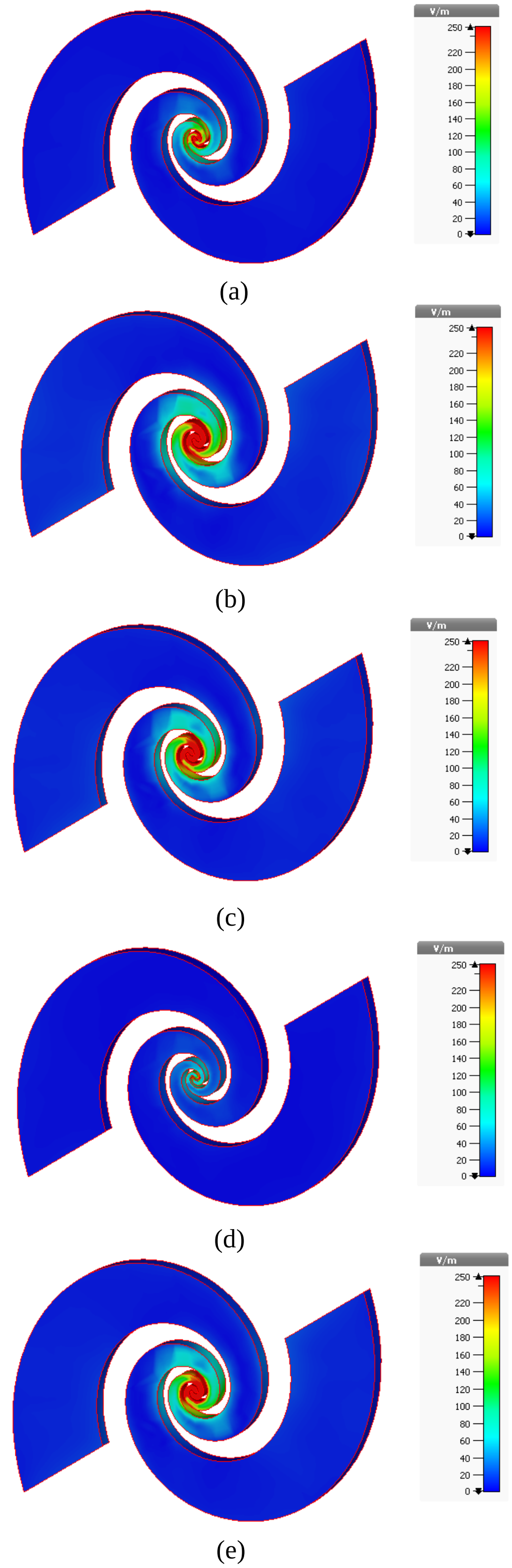
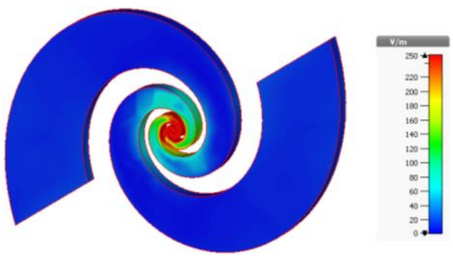


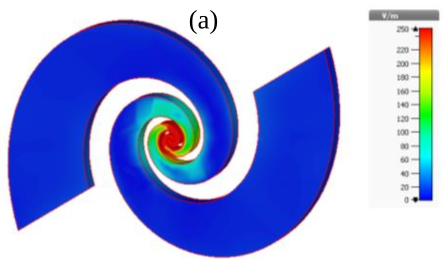
Fig. 9. E-fields at: (a) 28.1 THz, (b) 28.3THz, (c) 28.5 THz, (d) 28.7 THz, and (e) 28.9 THz.

B. E-fields (variation of incident wave angle)

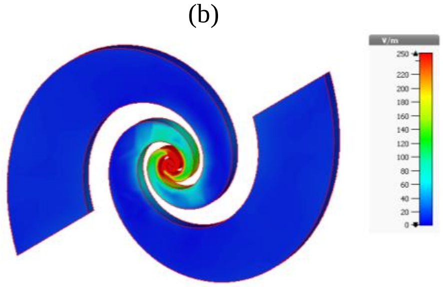
Figure 10 shows the variation of electric field of the spiral antenna for different value of incident wave angle at 28.3 THz. For α=0°, α=20°, α=40° and α=60°, E-field remains virtually unchanged. Recall that an application of environmental energy harvesting suggests that the direction of propagation of incident waves, nor their polarizations are unknown in advance. It is therefore not possible to predict the orientation of the antenna which will encourage the maximum reception of the waves. The use of an omnidirectional circular polarization antenna overcomes this difficulty. Indeed, such an antenna will be able to capture the waves in all directions and for several polarizations. The antenna was able to function whatever its orientation and wave polarization without the need to replace or maintain it.



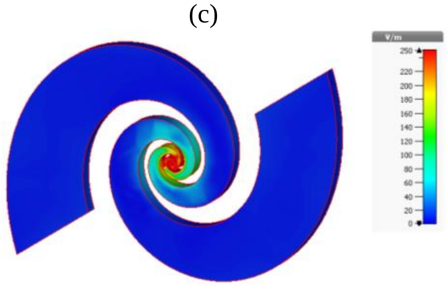
(a)



(b)



(c)



(d)

Fig. 10. E-Fields (variation of incident wave angle): (a) α= 0, (b) α= 20, (c) α= 40, and (d) α=60.

V. CONCLUSION

A nano-antenna for infrared energy harvesting system has been studied in this article. A spiral antenna was chosen to collect a maximum IR electromagnetic radiation at 28.3 THz. a parametric study is presented on the effect of the initial angle on the origin arm, width of the spiral arms, gap between two arms, thickness of the substrate, length of the substrate, thickness of the patch and number of turns. The spiral antenna has a circular polarization which allows it to capture infrared waves from different polarization.

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Abdulrahman G. Al-Hamrani was born in Jeddah, November 1991. He received the B.E. degree in Electrical Engineering from King Abdulaziz University, Jeddah, KSA, in 2014. He is currently working toward the M.Sc. degree in Electronic/Communication Engineering with the Department of Electrical Engineering, King Abdulaziz University, Jeddah Saudi Arabia, from 2016. His Research interests include Renewable energy, Nanotechnology, green power generation including rectifying antennas.

Ali Yahyaoui received the Master degree in Electronics from the University of Tunis El Manar, Tunisia, in 2012. He received the Ph.D. degree in Communication Systems from the National Engineering College of Tunis (ENIT), University of Tunis El Manar, Tunisia, in 2018. He has been employed by University of Jeddah, Saudi Arabia, since 2014. His research interests focuced on RF and microwaves antennas, Terahertz and optical antennas, terahertz photo-conductive antennas for infrared energy harvesting, UWB nano-rectennas for collection of solar energy, metamaterials and metasurfaces.

Anas Al Hashmi was born in Saudi Arabia, and graduated from the University of Nottingham, UK in 2011 (B.Eng. (Hons) Electrical and Electronic Engineering with Mathematics). In 2012 he completed the M.Sc. course in Electronic and Ultrasonic Instrumentation and Ph.D. in Electrical and Electronics Engineering in 2017 from the same university. He has been employed by Jeddah University, Saudi Arabia since 2014. He had been in the Optics and Photonics Group in the University of Nottingham, UK. His research focuses on the development of inexpensive differential ultrasonic calorimeter for accurate measurement of heat loss in machinery. He is currently holding a position of assistant professor at the University of Jeddah, he was promoted as the Head of Electrical and Electronic Engineering Department at the same university.

Ameni Mersani received the B.S. degree in Electronics, Computer and Information Science from the University Tunis El Manar, Tunisia in 2009 and the Master thesis in Electronics from the Faculty of Science of Tunis, Tunisia in 2012. She received the Ph.D. in Engineering Sciences (Electronics) from the University of Tunis El Manar, 2018. From September 2018, she was a Research Assistant in ISET'COM (Department of Telecommunication). From December 2019, she was a Post-Doctoral Researcher with King Abdulaziz University, Saudi Arabia. Her research mainly focuses on the development of design of wearable antennas for wireless applications, metamaterial, reconfigurable antennas and Energy Harvesting.

Majed Nour received the Ph.D. in Electronics Engineering (Biomedical) from the Royal Melbourne Institute of Technology (RMIT), Australia since 2014 and his Master degree in Biomedical Engineering from La Trobe University, Australia since 2010. His Bachelor in Electrical Engineering (Biomedical) from King Abdul Aziz University since 2007. He is an Assistant Professor at KAU and an active researcher in the field of Nanotechnology, Biomedical Engineering and Sensors with several highly cited publications. He is keen in Hospital design, medical equipment acquisition and commissioning, medical equipment regulation and standards. He is a Medical equipment and hospital design consultant. He is a member of the Saudi Scientific Society for Biomedical Engineering, and the Saudi Society for Quality.

Hatem Rmili received the B.S. degree in General Physics from the Science Faculty of Monastir, Tunisia in 1995, and the DEA diploma from the Science Faculty of Tunis, Tunisia, in Quantum Mechanics, in 1999. He received the Ph.D. degree in Physics (Electronics) from both the University of Tunis, Tunisia, and the University of Bordeaux 1, France, in 2004. From December 2004 to March, 2005, he was a Research Assistant in the PIOM laboratory at the University of Bordeaux 1. During March 2005 to March 2007, he was a Postdoctoral Fellow at the Rennes Institute of Electronics and Telecommunications, France. From March to September 2007, he was a Postdoctoral Fellow at the ESEO Engineering School, Angers, France. From September 2007 to August 2012, he was an Associate Professor with the Mahdia Institute of Applied Science and Technology (ISSAT), Department of Electronics and Telecomm-unications, Tunisia. Actually, he is Full Professor with the Electrical and Computer Engineering Department, Faculty of Engineering, King Abdulaziz University, Jeddah, Saudi Arabia.

Rmili's research interests concern applied electromagnetic applications involving antennas, metamaterials and métasurfaces. The main targeted applications are reconfigurable antennas for multi-standard wireless communications systems, security of chipless RFID systems with fractal tags, terahertz photoconductive antennas for infra-red energy harvesting, UWB nano rectennas for collection of solar energy, phase shifters for low-cost 5G communication systems, and microwave absorbing materials for stealth technologies.

Raj Mittra is a Professor in the Department of Electrical & Computer Science of the University of Central Florida in Orlando, FL., where he is the Director of the Electromagnetic Communication Laboratory. Prior to joining the University of Central Florida, he worked at Penn State as a Professor in the Electrical and Computer Engineering from 1996 through June, 2015. He also worked as a Professor in the Electrical and Computer Engineering at the University of Illinois in Urbana Champaign from 1957 through 1996, when he moved to the Penn State University. Currently, he also holds the position of Hi-Ci Professor at King Abdulaziz University in Saudi Arabia.

He is a Life Fellow of the IEEE, a Past-President of AP-S, and he has served as the Editor of the Transactions of the Antennas and Propagation Society. He won the Guggenheim Fellowship Award in 1965, the IEEE Centennial Medal in 1984, and the IEEE Millennium medal in 2000. Other honors include the IEEE/AP-S Distinguished Achievement Award in 2002, the Chen-To Tai Education Award in 2004 and the IEEE Electromagnetics Award in 2006, and the IEEE James H. Mulligan Award in 2011.

Mittra is a Principal Scientist and President of RM Associates, a consulting company founded in 1980, which provides services to industrial and governmental organizations, both in the U.S. and abroad.