PERTURBATION SLIT RECTANGULAR PATCH ANTENNA IN TERAHERTZ FOR THERMAL ENERGY HARVESTING

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Dedicated to my family and friends with love and supports.

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ABSTRACT

Research in terahertz (THz) technology is now receiving strong attention worldwide. Devices using this band are predicted to become important in a very wide range of applications. The number of research in this field has increased rapidly in applications such as information and telecommunications, ultrafast computing and energy harvesting technology. Even with such excellent potentials, investigation to explore the properties of devices structure in this band is still lacking. To excite the THz band field response, micro or nano structures are required. In this thesis, a patch structure with enhanced elements are designed and investigated for energy harvesting application at thermal radiation spectrum which lies from 20 THz to 40 THz. A conventional rectangular structure is initially designed to understand the behaviour of performances in THz region. Then a perturbation slit is introduced at the center of the rectangular structure to trap the THz field. Hence, the electrical field is guided into a single collection area named slit tunnel for energy conversion purposes. The relationship between the structure parameters and performances are then analysed and recorded. Through the proposed structure, a broader field bandwidth is achieved which can cover most of the thermal radiation spectrum. Importantly, the amplitude of the electrical field that concentrates on the perturbation slit is increased up to 110.6 V/m with receiving field of 1 V/m which can produce an enhancement factor of 110.6. A promising receiving beamwidth of approximately 85^0 is also achieved where the THz field can be collected from various directions. Next, the proposed structure is integrated with a Metal-Insulator-Metal (MIM) diode to form antenna-coupled diode. The structure integrates well with the MIM diode to produce approximately 0.495 A/m of magnetic field. The performances obtained are suitable for the proposed structure to be energy harvesting device which can collect the abundant thermal radiation and convert it into usable energy.

ABSTRAK

Penyelidikan dalam bidang teknologi terahertz (THz) semakin mendapat perhatian seluruh dunia. Peranti yang beroperasi dalam jalur THz dijangka menjadi keutamaan dalam pelbagai aplikasi. Bilangan penyelidikan dalam bidang ini meningkat dengan pesat seperti dalam aplikasi informasi dan perhubungan, komputer ultra-pantas dan teknologi penuaian tenaga. Disebalik mempunyai potensi besar, penyelidikan lanjut untuk menyelidik sifat-sifat struktur peranti masih lagi kurang mendapat perhatian. Struktur mikro atau nano diperlukan untuk merangsang respon medan dalam jalur THz. Struktur tampal dengan elemen penambahbaikan dibangunkan dan diselidiki dalam tesis ini untuk aplikasi penuaian tenaga pada spectrum radiasi haba yang terletak dalam jalur dari 20 THz hingga 40 THz. Struktur segiempat asas dibangunkan terlebih dahulu untuk memahami perihal prestasi struktur dalam jalur THz. Seterusnya, elemen alur terganggu dimasukkan di tengah struktur segiempat tepat bagi memerangkap medan THz. Jadi medan dipandu ke ruang pengumpulan yang dikenali sebagai simpang alur untuk tujuan penukaran tenaga. Hubungkait antara parameter struktur dengan prestasi dianalisis dan direkodkan. Melalui struktur yang dicadangkan, jalur lebar medan yang besar dapat dihasilkan meliputi hampir keseluruhan jalur spekra radiasi haba. Penemuan penting di sini ialah kekuatan medan elektrik yang tertumpu pada alur terganggu meningkat kepada 110.6 V/m dengan medan penerima sebanyak 1 V/m yang menghasilkan faktor peningkatan bernilai 110.6. Pancaran jalurlebar yang baik juga dapat dihasilkan dengan nilai 85^0 di mana medan elektrik THz dapat dikumpulkan dari pelbagai arah. Selepas itu, struktur yang dicadangkan, digabungkan dengan diod logam-penebat-logam (MIM) untuk menghasilkan diod terganding antena. Didapati bahawa struktur diod MIM tergabung antena menghasilkan medan magnetik bernilai 0.495 A/m. Prestasi yang dihasilkan daripada struktur yang dicadangkan adalah amat berpontensi untuk aplikasi penuaian tenaga di mana ia dapat mengumpulkan radiasi haba terbuang dan menukarkan kepada tenaga yang berguna.

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LIST OF SYMBOLS

$\vec{E}$	-	Electrical field vector
$\vec{H}$	-	Magnetic field vector
V	-	Voltage
I	-	Current
W	-	Rectangular Width
L	-	Rectangular Length
h	-	Substrate thickness
ε_r	-	Relative permittivity
ε_e	-	Effective dielectric constant
ε_1	-	Permittivity of metal 1
ε_2	-	Permittivity of metal 2
ε_m	-	Permittivity of the metal
ε_s	-	Permittivity of dieletric material
ω_p	-	Plasma frequencies
δ	-	Collision frequencies
G	-	Antenna Gain
f_{TLM}	-	Calculated resonant based on transmission line model
f_{THz}	-	Simulated resonant at terahertz
Δf	-	Resonant different
D_L	-	Diode Length
D_W	-	Diode width
S_W	-	Slit Width
Ni_W	-	Nickel width
I_T	-	Insulator thickness
Ni_T	-	Nickel thickness
Au_T	-	Gold thickness

t_p	-	Thickness of top patch
t_g	-	Thickness of bottom patch
T_L	-	Tunnel length
S_L	-	Slit length
T_W	-	Tunnel width
λ	-	Wavelength
λ_{eff}	-	Effective wavelength
λ_o	-	Wavelength in vacuum
k	-	Wave vector
k_x	-	Wave vector in x-axis direction
k_{sp}	-	Wave vector that present the surface plasmon at the interface between two slit surface metal and substrate
f_1	-	Lower frequency for fractional bandwidth
f_2	-	Upper frequency for fractional bandwidth
ω	-	Frequency of the wave
c	-	Speed of light in a vacuum
T	-	Temperature
J	-	Energy
m	-	Meter

LIST OF ABBREVIATIONS

THz	-	Terahertz
RF	-	Radio frequency
FIT	-	Finite integration technique
SiO_2	-	Silicon dioxide
TLM	-	Transmission Line Model
MIM	-	Metal-Insulator-Metal
FOM	-	Figure of merit
HFSB	-	Half-field Strength Bandwidth
FBW	-	Fractional Bandwidth
HPBW	-	Half-power beam width
RSL01	-	Rectangular antenna with perturbation slit length of 0.1 µm
RSL02	-	Rectangular antenna with perturbation slit length of 0.2 µm
RSL03	-	Rectangular antenna with perturbation slit length of 0.3 µm
RSL04	-	Rectangular antenna with perturbation slit length of 0.4 µm
RSL05	-	Rectangular antenna with perturbation slit length of 0.5 µm
RSL06	-	Rectangular antenna with perturbation slit length of 0.6 µm
RSL07	-	Rectangular antenna with perturbation slit length of 0.7 µm
RSL08	-	Rectangular antenna with perturbation slit length of 0.8 µm
RSL09	-	Rectangular antenna with perturbation slit length of 0.9 µm
RSL10	-	Rectangular antenna with perturbation slit length of 1.0 µm
RST05	-	Rectangular antenna with perturbation slit tunnel of 0.5 µm
RST10	-	Rectangular antenna with perturbation slit tunnel of 1.0 µm
RST15	-	Rectangular antenna with perturbation slit tunnel of 1.5 µm

CHAPTER 1

INTRODUCTION

1.1 Back Ground

In this thesis, the development of a new structure for energy harvesting at Terahertz (THz) region is presented. The new structure performs a high field enhancement factor with good radiation properties for better energy conversion. It is designed using established radio frequency (RF)/microwave design analogy and modelling. Fresh relationship between the geometrical structure and performances is successfully developed that adds new knowledge to improve the design methodology.

Terahertz (THz) technology has received a lot of attention around the world. The devices manipulating this waveband are set to become increasingly important in a very broad range of applications. However, today's technology is still far away from enabling the terahertz devices for commercial use. THz technology is finding usage in many sectors such as information and communications technology, satellite communications, global environmental monitoring and astronomy. Despite such a great potential, the analytical means to describe the properties of THz devices is still lacking and hence calls for thorough investigations to be performed. Towards that, the studies to translate establish RF/microwave device theories into the terahertz region are rapidly increased.

In RF and microwave regions, an antenna is an electrical device which converts electric currents into radio or microwave, and vice versa. In THz region, it is defined as a device that converts freely propagating THz radiation into localized energy, and vice versa. The devices that are working at THz region is primarily associated with their small scale size which lie in the range of micro-meter and nano-meter. The devices normally require fabrication accuracies of a few nano meters. Although many properties and parameters of THz devices are similar to their radio wave and microwave counterparts, they have important differences due to their small size and resonant properties of metal nanostructure.

Throughout the thesis, the antenna device operating at THz band is the main subject to be discussed. In 1985, John Wessel proposed for the first time that a gold particle can function as an antenna [1]. The first experimental demonstration of this is followed in 1995 by Dieter Pohl and Ulrich Fischer who used gold-coated polystyrene particle [2]. The studies continued, and since then, various infrared antenna geometries have been systematically investigated for various ranges of applications.

1.2 Problem Statement

This research intends to investigate and improve the performance of energy harvesting application by using modified transmission-line model (TLM). Nowadays, not many modeling have been established in THz band especially for energy collector applications. The implementation of TLM into THz for thermal harvesting energy has a great potential due to its simplicity. However, the use of TLM for rectangular patch into THZ band cannot be applied directly and its invites new studies to be carried out. The use of established TLM into THz design is expected to simplify the demanding design modelling in THz technology

An electrical field enhancement factor is vital characteristic that needs to be considered for thermal harvesting energy applications. An electrical field enhancement factor greater than 70 is acceptable value for thermal energy harvesting applications for more energy collection. Furthermore, the field enhancement excitation is a concerning collection location. The biggest challenge of this work is to provide a convenient location from which it collects energy and transport it to other rectifier circuitry for conversion. An appropriate design modification and techniques are required to drive all excited field into a single location. The field enhancement excitation larger than 70 which concentrated at a single location is proposed to be design in this work.

Moreover, the field bandwidth causes the success of receiving thermal energy from full radiation spectrum which lies from 20 THz to 40 THz. The energy harvesting antenna that can generate field bandwidth over thermal radiation spectrum is critical to be designed. The parametric studies need to be performed in order to find the relationships which control the field bandwidth performances.

In addition, an efficient rectification circuit needs to be designed for optimum energy conversion at thermal radiation spectrum. The lack of design and method for designing THz rectification circuit required a lot of effort and challenge to the proposed antenna design. To date, the dipole and the flare monopole are among the designs that were published to convert the electrical field energy into current at 30 THz. Those designs use a metal-insulator-metal (MIM) diode for energy conversion where it can be integrated with the antenna structure to form antenna coupled rectifier. The integration between antenna and MIM diode is very difficult and required a very intense research work. The size area that locates higher field is needed to be design accordingly with diode contact size to produce optimum energy conversion.

1.3` Research Objective

The objective of the research is to design parametric modelling of perturbation slit at terahertz rectangular patch antenna for thermal energy harvesting. The proposed antenna shall deliver higher than 70 field enhancement factor and field bandwidth that cover thermal radiation spectrum which lies from 20 THz to 40 THz for optimum thermal energy conversion.

1.4 Research Scope

The scope of the research is outlined as below:

i. Study and understand the concept of antenna structure for thermal energy harvesting, the theory and design of transmission line mode and review the usage of materials in THz antenna.
ii. Design, simulate and optimize a rectangular patch antenna at THz band.
iii. Design, simulate and optimize a perturbation slit rectangular patch antenna for field enhancement.
iv. Design, simulate and optimize a perturbation slit rectangular patch antenna integrated with metal-insulator-metal diode for energy conversion.
v. Finalize the optimum design, pile up reports and publish regional and international conference and journal papers.

1.5 Significant Contributions to New Knowledge

There is an urgent need to contribute in pursuing RF/microwave design analogy and modeling into the THz region that is able to support and simplify structure design development. Exploration into higher frequency region is needed due to high technology demands where the lower frequency technologies are saturated. The possible contributions are as follows:

(a) Modified Transmission Line model – The Transmission Line model cannot be used directly in THz band. This resulted from different values of effective dielectric and wave penetration effect into the antenna patch metal layer. A modified Transmission Line model for rectangular antenna is proposed. The model is designed to operate between 5 THz to 60 THz that covers thermal radiation spectrum which lies between 20 THz to 40 THz.

(b) Rectangular antenna with perturbation slit - The configuration exhibits electrical field being excited at the perturbation slit with enhancement factor that is higher than that of a dipole structure. Strong electrical field intensity is targetted to cover most of the thermal radiation spectrum and it offers broad half-field strength bandwidth (HFSB) that is controllable. The proposed structure is a potential candidate for energy harvesting devices that requires high electrical field and broader electrical field bandwidth for efficient energy conversion.

(c) Rectangular antenna with perturbation slit tunnel - By introducing a tunnel at the slit edge, the electrical field intensity is guided out through the tunnel. Hence, the proposed structure is a potential candidate for energy harvesting devices.

(d) Rectangular antenna with perturbation slit integrated with MIM diode – The configuration allows simple but practical conversion of the electrical field into usable energy. Verification results provided show that this design analogy is able to add a new foundation of knowledge for future development of energy harvesting devices.

1.6 Thesis Organisation

The thesis comprises of seven chapters. The remaining chapters are organised as described. In Chapter 2, related literatures studied intensely are reviewed. The basic theories of designing an antenna structure at THz region which focuses on establishing an RF/microwave design analogy is discussed in this chapter. Initially, the basic of dipole structure is discussed before involving a complex structure. Then, the critical and important aspects of designing a structure that operates in THz region are investigated. It is important to note that the application can be applied to benefit the mankind.

The design of dipole structure is first discussed in Chapter 3. Then, the enhancement technique for field enhancement is proposed. The performance between basic dipole structure and with enhancement technique is compared and discussed. The important factor for the design has been studied and reported. Furthermore, the performances of field enhancement are analysed and discussed.

The transmission line model for designing a rectangular structure is discussed in Chapter 4. The effect of using transmission line model at THz range is discussed further in this chapter. In addition, the transmission line model is then modified to consider the effect of antenna at THz frequency and related formula is plotted and discussed.

In Chapter 5, the rectangular antenna patch with perturbation slit is discussed in details. The performance results by inserting perturbation slit have been analysed and compared with published design to show the significant improvement of the proposed design. The required performance for energy harvesting application is achieved. Meanwhile, all the results involved are deliberated and explained for future reference.

A variation of diode platform for energy conversion is proposed and discussed in Chapter 6. The platform is arranged from the perturbation slit parameters to examine the energy conversion performances. The optimum performances are discussed in depth.

The final chapter concludes the thesis and suggestions for future work are proposed. The advantages and originality of the design are also discussed.

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