

A Potential of Versatile Rectangular Patch with Perturbation Slit Tunnel for Energy Harvesting Device

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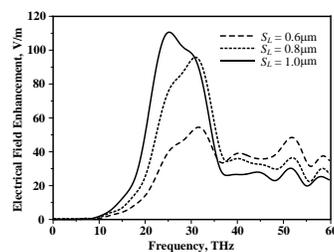
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Graphical abstract



Abstract

Nowadays, numerous devices to manipulate high frequencies for various applications are rapidly being investigated. Among them, nano-antennas for energy harvesting application at thermal radiation spectrum received most attention. A potential of versatile rectangular patch with perturbation slit tunnel that can collect electrical field energy is studied. The antenna performances are defined over field strength and current responses. The electrical field concentrated at the slit junction can be tuned by verifying the perturbation slit parameters. The electrical field amplitude of approximately 110 V/m is achieved with slit length of 1.0 μm . The field then can be guided out through the tunnel with some amplitude degradation in order to be integrated with metal-insulator-metal diode for energy conversion. The diode current obtained inside the insulator layer is compared with published results and it performs outstandingly. It was found that the proposed antenna exhibits promising performances that is suitable as an efficient energy harvesting device.

Keywords: Rectangular; perturbation slit; energy harvesting; metal-insulator-metal

Abstrak

Kebelakangan ini terdapat banyak penyelidikan sedang dijalankan tentang peranti yang memanipulasi frekuensi tinggi bagi pelbagai aplikasi. Antara yang mendapat tumpuan ialah untuk aplikasi penuaian tenaga dari spectra termal radiasi. Antena segiempat tepat dengan alurterganggu serba boleh yang berpotensi mengumpulkan tenaga medan elektrik telah diselidiki. Prestasi antenna dikenalpasti menerusi kekuatan medan dan arus. Medan elektrik yang menumpu pada simpang alur boleh dilaras dengan menentusahkan parameter alurterganggu. Kekuatan medan elektrik bernilai 110 V/m telah dihasilkan apabila panjang alur bernilai 1.0 μm . Medan elektrik ini boleh dipindahkan keluar melalui terowong dengan sedikit pengurangan kekuatan medan untuk digabungkan dengan logam-penebat-logam diod untuk penukaran tenaga. Arus diod yang diperoleh pada lapisan penebat kemudian dibandingkan dengan arus yang telah dilaporkan dalam artikel penerbitan dan didapati menunjukkan prestasi hebat. Hasil kajian menunjukkan bahawa antenna yang dicadangkan memiliki prestasi yang memenuhi spesifikasi. Ini menjadikannya sesuai sebagai peranti penuaian tenaga yang cekap.

Kata kunci: Segiempat tepat; alur terganggu; penuaian tenaga; logam-penebat-logam

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1.0 INTRODUCTION

There are many studies focusing on nano-antennas that can manipulate the electromagnetic energy for various applications. One of the applications that has gained more attention is energy harvesting devices. The traditional method for energy harvesting is photovoltaic which converts solar radiation into usable energy. This method has disadvantages where it can only be operated during daylight. The electromagnetic energy from thermal radiation spectrum which lies from 20 THz to 40 THz can be collected 24 hours a day without being influenced by weather. A

nano or micro scale antenna needs to be designed in order to operate at THz spectrum. Nowadays, a lot of studies have been performed to design devices operating at THz spectrum. The propagation of optical energy for tapered waveguide has been studied whereby the energy tends to propagate towards the tip of the tapered waveguide and caused accumulation of huge energy field at its tip [1]. Furthermore, the field energy can also be focused into the feed gap of an antenna. The studies for dipole antenna have shown that the field energy concentrated at the dipole feed gap is able to produce huge enhancement factor [2-5]. Initial works that study on electrical field enhancement

behavior at higher frequencies have been presented [6-8]. The huge enhancement can be controlled through antenna parameters which are related to the radiating or receiving patch size.

Energy conversion at THz can be done by using metal-insulator-metal (MIM) tunnel diode [9-11]. The MIM diode is able to convert electromagnetic energy at higher frequency into usable energy due to its fast tunneling capability. The proposed antenna is able to provide a location for diode integration. A feed gap is a typical location to place the MIM diode and it has been presented in various works. The MIM diode is placed inside the gap between flared monopole feed and ground plane as reported in [12]. Likewise monopole, the MIM diode is also able to be fit along travelling waveguide where most of the field energy can travel through it from the dipole radiating patch as depicted in Figure 1 [13]. Moreover, there is work that reported regarding the manufacturing process of solar nanostructure electromagnetic collector [14]. An array of antenna-coupled with embedded

rectifier has been modeled and demonstrated successfully as energy collection. This proof of concept is a great motivation for improving and finding a better idea in the future.

In this study, a rectangular patch with perturbation slit antenna suitable for energy harvesting application is proposed. Through some variations, the perturbation slit gap is able to concentrate its high field which fits to place a diode for energy conversion. In principle, the electromagnetic energy emitted from thermal radiation spectrum will be captured at the frequency operation of the proposed antenna. An alternating current generated through free electrons from the electromagnetic energy interaction will be converted into direct current using MIM diode. Figure 2 shows the potential equivalent circuit of rectangular patch with perturbation slit tunnel for energy harvesting device. The block diagram for an overall process of energy harvesting device is depicted in Figure 3.

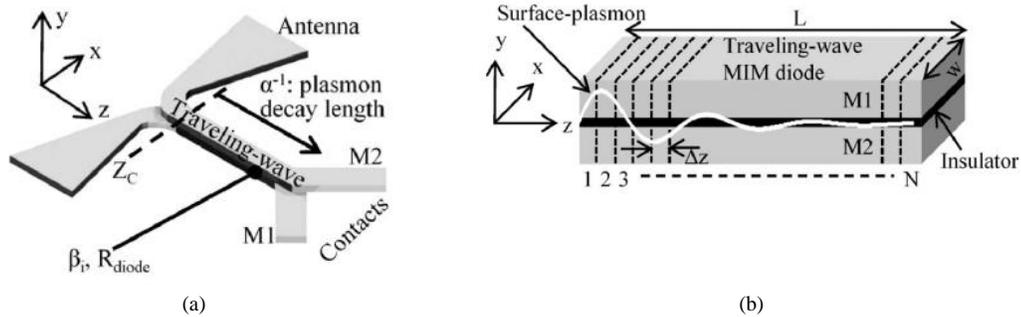


Figure 1 (a) The dipole patch antenna attached to a parallel plate waveguide consisting of thin insulator layer between metals M1 and M2, and (b) 3-D view of a traveling wave MIM diode [13]

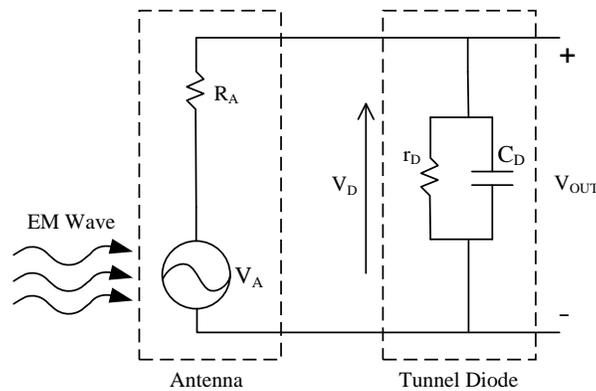


Figure 2 Equivalent circuit of rectangular patch with perturbation slit tunnel for energy harvesting device

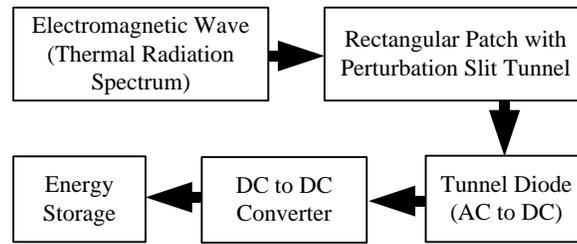


Figure 3 Block diagram of energy harvesting device with a rectangular patch having perturbation slit tunnel at the front end

2.0 DESIGN METHODOLOGY

Figure 4a shows the geometry of a rectangular patch with perturbation slit tunnel. There are no specific equations to calculate the dimensions of a rectangular patch size at THz spectrum have been reported in the literature. Due to that, the effective wavelength scaling method is employed. The effective wavelength with the substrate is given as [15]

$$\lambda = \frac{\lambda_0}{\sqrt{\frac{\epsilon_r + 1}{2}}} \quad (1)$$

Where λ_0 is the wavelength in a vacuum. Based on equation (1), the dimension of a rectangular patch is scaled to the center frequency of 30 THz. The rectangular patch antenna dimensions of length, L and width, W are obtained with values of $1.8 \mu\text{m}$ and $1.2 \mu\text{m}$, respectively. The thickness of the rectangular patch layer, t is $0.5 \mu\text{m}$.

To investigate various parametric performances of the proposed antenna, perturbation slit length, S_L is varied from $0.6 \mu\text{m}$ to $1.0 \mu\text{m}$ and slit width, S_W is fixed for $0.1 \mu\text{m}$. Moreover, the performances of the proposed antenna with the presence of slit tunnel are analyzed. A variation of slit tunnel length, T_L of $0.05 \mu\text{m}$ and $0.1 \mu\text{m}$ are performed.

Next, the slit is attached with a tunnel where it can be incorporated with MIM diode. The MIM diode is then

constructed inside the slit tunnel which is made from a combination of gold-nickel oxide-nickel (Au-NiO-Ni) layer. The diode length, D_L is designed to have $0.05 \mu\text{m}$ in order to construct a contact pad size of $0.005 \mu\text{m}^2$ ($D_L \times S_W$) as presented in [10]. The NiO layer of 3 nm is sandwiched between the lower gold tunnel layer and nickel at the upper layer. The cross sectional view of a MIM diode is depicted in Fig. 4b.

The performances of the proposed antenna are simulated using numerical simulation software CST Microwave Studio based on finite integration technique. The Drude model is used to explain the relative dielectric constant for the gold patch. The Drude model is given as [16]

$$\epsilon_r = 1 - \frac{\omega_p^2}{\omega(\omega + i\delta)} \quad (2)$$

where ω_p and δ are the plasma frequency and collision frequency, respectively. The value of $\omega_p = 3.22 \times 10^{16} \text{Hz}$ and $\delta = 1.19 \times 10^{14} \text{Hz}$. The substrate layer is made from silicon oxide with dielectric constant of 3.57.

The antenna is excited by a plane wave with amplitude of 1 V/m perpendicular to the antenna patch along z-axis. The electrical field probe is located at the open slit edge.

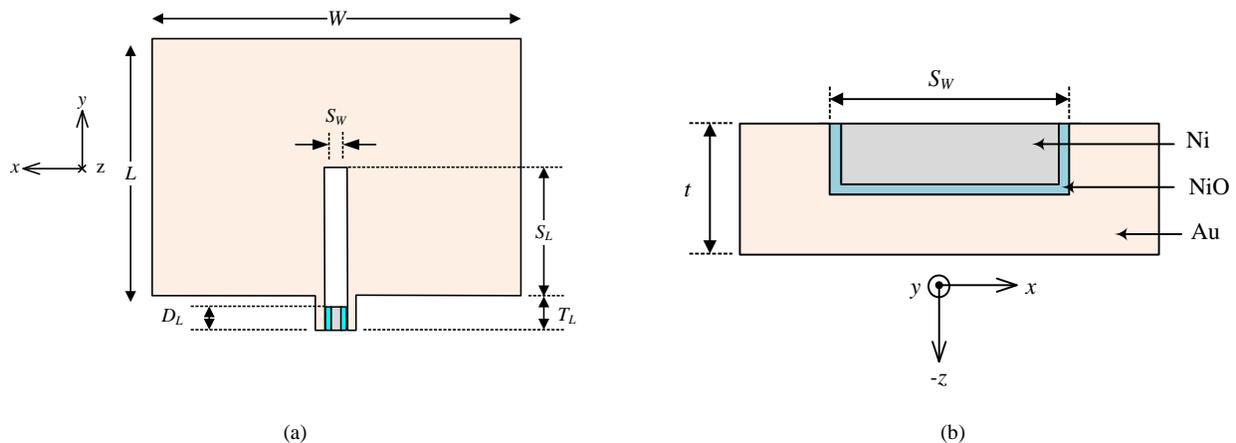


Figure 4 (a) Geometry of a rectangular antenna with perturbation slit tunnel and (b) Cross sectional view of a MIM diode

3.0 RESULTS AND DISCUSSION

The analysis begins with the rectangular patch having perturbation slit. An interesting result can be observed as depicted

in Figure 5, where the electrical field is enhanced when S_L is increased. The amplitude of electrical field raises up to approximately 110 V/m for $S_L = 1.0 \mu\text{m}$, where it is almost the length of a rectangular patch $L = 1.2 \mu\text{m}$. This happened due to

the fringing fields of the rectangular patch move towards the slit and concentrated at the larger slit cavity to form maximum field enhancement.

As far as S_L is concerned, the slit junction is engaged with the tunnel for easy integration with the MIM diode. The tunnel is required to provide a typical overlap area for a MIM diode of approximately $0.005 \mu\text{m}^2$ [12]. According to this value, the slit tunnel is designed and simulated with several tunnel lengths, T_L 0.05 μm and 0.1 μm . The tunnel fits well with the perturbation slit and its field performances are depicted in Figure 6. By having the slit tunnel, the amplitude of electrical field is slightly decreased. The decrement of the field by having small increment of tunnel length is very small as shown in Figure 6. The field amplitude of approximately 100 V/m is achieved for a slit tunnel length, T_L of 0.05 μm . This is a worthy performance where the field enhancement factor of 100 can be achieved with an excitation wave of 1 V/m.

Finally, by integrating a MIM diode with diode length, D_L of 0.05 μm inside the tunnel, the electrical field is well confined inside 3 nm insulator region. Then, the diode current is defined

using Ampere's law by integrating the magnetic field around the insulator-metal interface as depicted in Figure 7. The diode current I_D of approximately 0.4 A/m is achieved at the middle of the insulator. The current distribution pattern achieved for the proposed antenna is similar compared with published results [13] while the current amplitude is better.

4.0 CONCLUSION

A rectangular patch with perturbation slit tunnel at the center of a rectangular patch can offer versatile performances for energy harvesting applications, which is defined in terms of electrical field enhancement. There is not much difference between having a tunnel or no tunnel for electrical field enhancement. The results obtained have been proved and agree well with the published work. In addition, these promising performances are able to provide an efficient energy conversion device and have a lot more improving characteristics to be discovered.

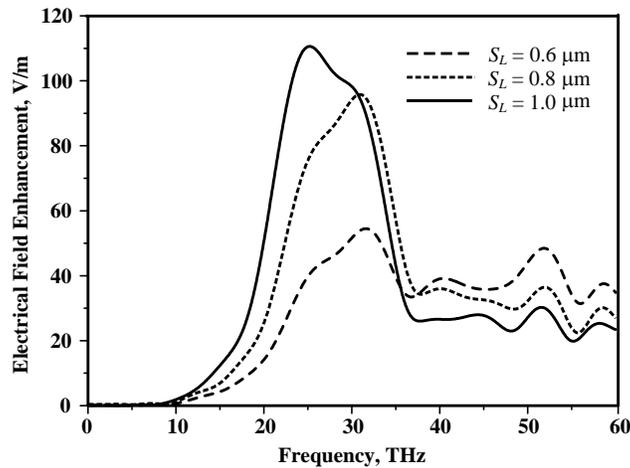


Figure 5 Electrical field distribution for a rectangular patch with perturbation slit

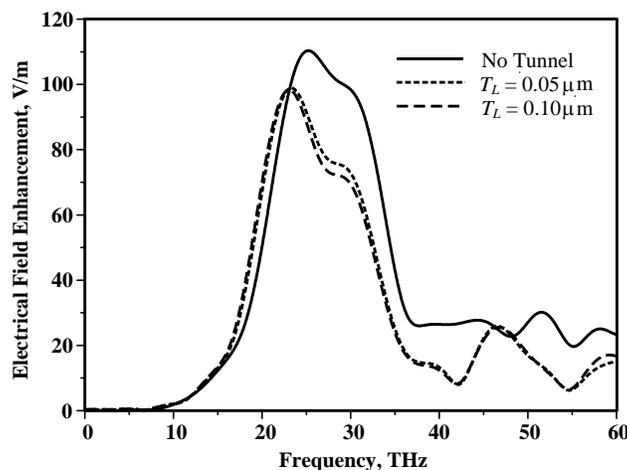


Figure 6 Electrical field distribution for a rectangular patch with perturbation slit attached with the tunnel

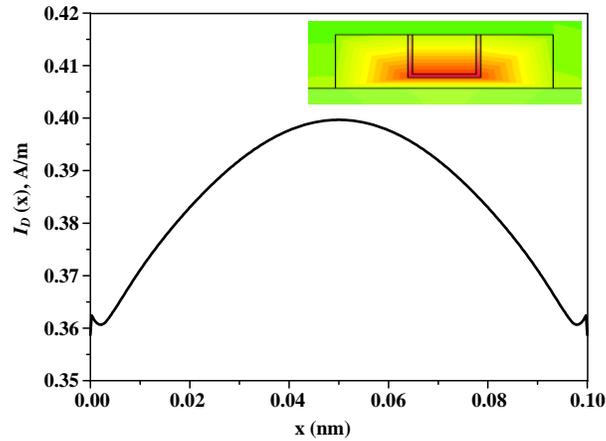


Figure 7 Current distribution responses inside the insulator layer of a MIM diode

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