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Dual-Polarized Multi-Band Infrared Energy Harvesting Using H-Shaped Metasurface Absorber

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Abstract—We present the design of an infrared metasurface harvester based on the full absorption concept. The metasurface unit cells consist of an H-shaped resonator with the load placed across the gap of the resonator. Different from infrared metamaterial absorber designs, the resonator is capable of not only full absorption but also maximum energy channeling across the load resistance. Numerical simulation demonstrates that 96% of the absorbed energy is dissipated across the load resistance. In addition, cross-polarized H-resonators design is presented, which is capable of harvesting infrared energy using dual polarizations within three frequency bands.

1. INTRODUCTION

The growing demand of electricity around the globe due to population and economic growth coupled with the scarcity and environmental impact of conventional energy resources such as fossil fuels are the main drives for the increasing interest in renewable clean energy. Harvesting solar radiation holds a great promise to solving the current energy crisis due to its abundance at sealevel [1]. Solar radiation spans a wide spectrum including ultraviolet, visible and infrared regimes. The infrared radiation is the chief contributor accounting for 52% of the total solar energy reaching the earth [2].

Photovoltaics are the most commonly used devices to harvest solar radiation [3]. To excite an electron and allow it to jump from the valence band to the conduction band, a photon with energy slightly greater than the band gap energy is required. However, a great portion of the solar spectrum provides energies much greater than the band gap energy of commonly used semiconductor materials. Thus, the solar cell utilizes a portion of the photon energy to create an electron-hole pair and the rest of the energy is lost through lattice vibration [4]. This limits a single-junction solar cell to a maximum theoretical conversion efficiency of $\approx 31\%$ [5]. To overcome this limitation, multi-junction solar cells are used to create multiple bandgaps that respond to different wavelengths providing efficiencies slightly above 40% [6].

As an alternative means to harvest solar energy with higher efficiencies, Bailey theorized the use of nano-scale rectennas operating at optical frequencies [7]. An optical rectenna consists of a nano antenna to capture solar radiation and a rectifier, Metal Insulator Metal (MIM) diode [8], to convert the captured energy to useful DC power. The recent advancements in nanotechnology enabled the possibility to fabricate optical antennas and other terahertz devices [9–11] with a broad range of potential applications [12–16]. The fact that optical rectennas can capture solar energy during the day and night with wideband reception and higher theoretical conversion efficiency make them advantageous over photovoltaic technology. A number of articles demonstrated full rectenna systems operating at optical frequencies [17, 18]. However, the reported efficiencies were less than 1% due to the large mismatch between the MIM diode and the antenna. In a recent article, a novel rectenna design involving an MIM

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diode with a small contact area and a very thin oxide layer is used to offer low zero bias resistance that can be easily matched to the antenna and hence increase the overall rectenna system conversion efficiency [18].

The efficiency of the rectenna system depends on the rectification circuitry but more critically on the electromagnetic collector which is the primary wave-to-signal energy transducer in the system. Most of the articles that presented the design and fabrication of optical antennas focus on enhancing the localized field within the feeding point of the antenna [19]. Such measure is indicative of the ability of the antenna to localize the electric field from an impinging planewave within a small area to create a hot spot. For optical antennas used for electromagnetic energy harvesting, it is more meaningful to analyse the antenna in terms of the power conversion efficiency per unit area of the antenna or energy collecting structure. This quantifies the ability of the antenna to capture and channel the electromagnetic energy to the feeding point of the antenna from an incoming wave, and also facilitates comparison with other systems [20].

In this article, we focus on the first link of the optical rectenna system. We present a metasurface made of electrically-small resonators based on the perfect absorption concept that is capable of capturing the electromagnetic energy from an incoming planewave and channeling the energy to a resistive load. This concept were proven successful in earlier work where a near unity energy harvesting metasurface comprising 13×13 electrically-small resonators was shown to provide 97% microwave-to-AC conversion efficiency at the microwave regime [21]. Here, we show through full-wave numerical simulation that a metamaterial medium operating at the infrared regime can achieve conversion efficiencies higher than 90%.

The proposed metamaterial infrared energy harvester design is inspired by the concept of perfect absorption. Infrared metasurface perfect absorbers consist of an array of sub-wavelength unit cells that is capable of absorbing all the energy from an incoming wave [22–27]. This is achievable by simultaneously minimizing the reflectivity and transmissivity from and through the medium. By tailoring the effective μ and ϵ, the metasurface impedance can be matched to the free space impedance, thus minimizing reflections. Wave transmission through the surface can be minimized by placing a backed ground plane thicker than the skin depth of the incoming wave. In addition, a lossy substrate can be used to dissipate the absorbed energy; therefore, all the energy from an impinged plane wave is absorbed and consumed within the medium. This fact is the initial impetus to use such a medium as infrared energy harvesters. However, it was shown in reported metasurface absorbers that a lossy substrate is the main component responsible for consuming the absorbed energy [28]. A metamaterial harvester consisting of split-ring resonators arranged in symmetric and asymmetric configurations were used to capture infrared energy at around 500 GHz [29]. In this work, we present the design of a metamaterial absorber such that the absorbed energy is channelled and delivered to a resistive load, hence it can be used to energize a load instead of being lost in the dielectric substrate.

2. RESULTS AND DISCUSSION

The proposed metasurface harvester composed of H-shaped electrically-small resonators is shown in Fig. 1. A number of H-shaped resonators with various configurations were introduced in the literature as a building block for metamaterial media [30, 31]. However, the proposed H-shaped cell is modified to fit the targeted application. The resonator was designed to operate at 30 THz with dimensions of $L = 0.9\,\mu\text{m}$, $w = 0.14\,\mu\text{m}$, $g = 0.13\,\mu\text{m}$, $s = 0.6\,\mu\text{m}$, $t1 = 0.07\,\mu\text{m}$ and a unit cell size of $d = 1.5\,\mu\text{m}$. The resonator was placed on top of a silicon substrate with a height of $h = 3.55\,\mu\text{m}$ and a dielectric constant of $\epsilon_r = 11.9$. The silicon substrate was chosen to minimize dielectric loss as it experiences low energy absorption at the operating frequency since the bandgap energy of silicon is much higher than the photon energy at infrared regime. The unit cell is baked by a ground plane having a thickness of $t2 = 0.07\,\mu\text{m}$ to minimize energy transmission through the medium. Both the H-resonator and the ground plane were made of sliver due to its low conductive loss at the resonance frequency. The frequency of the H-resonator was designed to capture energy during day and night. In addition, to the energy absorption from the sun radiation, the earth re-emits a large amount of infrared energy when it cools off at night. This re-radiated energy peaks at around 30THz, hence the design frequency chosen in this work.

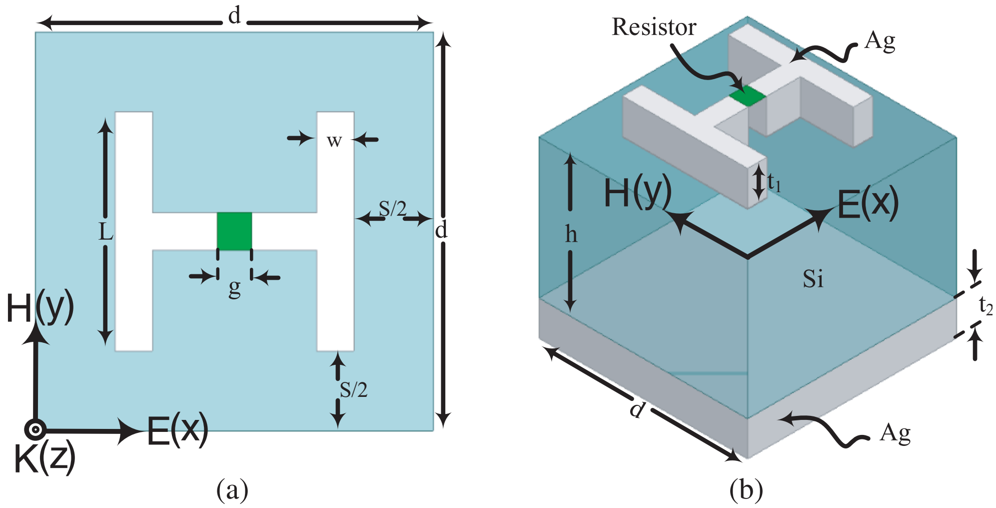


Figure 1. A schematic showing the proposed H-shaped metamaterial harvester. (a) Top view and (b) prospective view.

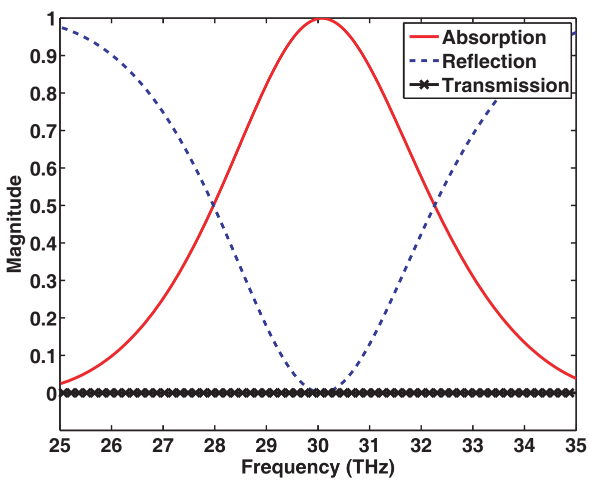


Figure 2. Simulation results showing the absorption, reflection and transmission for a single H-resonator unit cell.

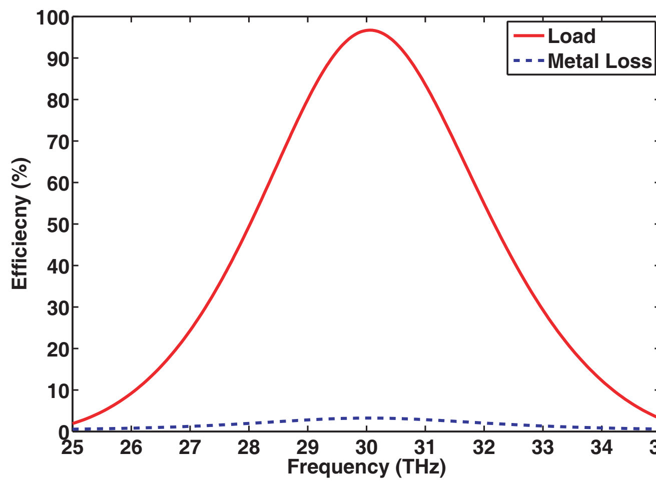
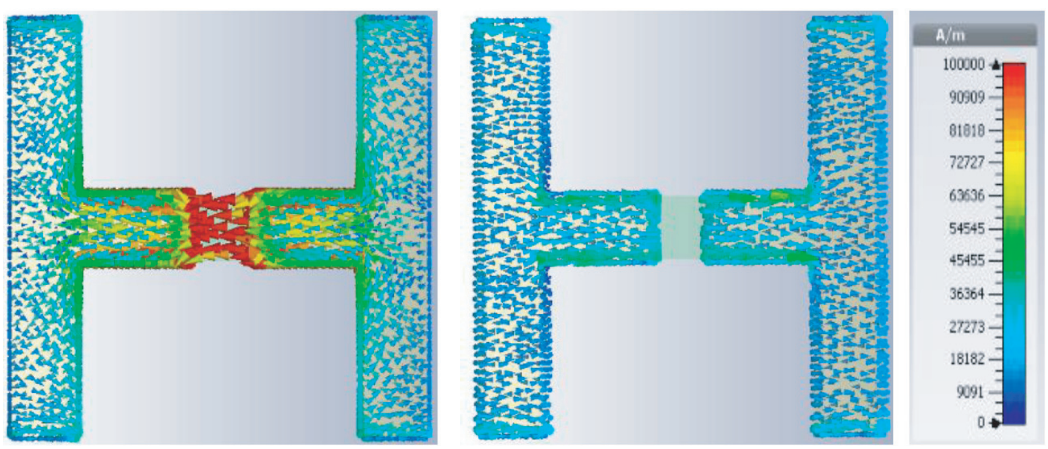


Figure 3. Simulation results showing the power distribution of the absorbed energy within a single H-resonator unit cell.

Using CST MICROWAVE STUDIO, [32] the unit cell was numerically excited by a waveguide having perfect magnetic (x-z plane) and perfect electric (y-z plane) boundaries to ensure TEM mode excitation as shown in Fig. 1. Both the H-resonator and the ground plane were modeled as silver using a Drude model having a plasma frequency of 2174 THz and damping frequency of 4.35 THz [33]. A resistive load was placed within the gap of the resonator to mimic a full rectification circuitry. The resistance of the load was selected such that it equals to the input resistance of the resonator when looking from the port of the gap. It was found from the simulation results that the resonator absorb maximum energy when terminated by a resistance of 90 Ω. The scattering parameters of the resonator is extracted when the resonator is terminated by the optimal load resistance. Plots of the absorption, reflection and transmission (Fig. 2) show that the resonator experiences full absorption at the operating frequency of 30 THz. Although full energy absorption by the resonator is achieved, it is critical to analyse the energy distribution within the resonator as this energy can be dissipated anywhere within the unit cell.

The energy consumed within the unit cell is analyzed as shown in Fig. 3. From the figure, we can observe that 96% of the energy is dissipated by the terminated load impedance. This is different from the power distribution within the reported infrared metasurface absorbers where the energy was mostly consumed within the dielectric host material [28]. This is due to the fact that silicon is a poor absorber at the operating frequency and it was used as a dielectric substrate to minimize dielectric loss. In addition, the inserted load resistance created a different means to dissipate the absorbed energy within the unit cell. By placing a resistive load across the gap of the resonator, a path for the current is created to flow from one arm of the resonator to the other. This can be clearly seen from the surface current distribution plot shown in Fig. 4(a) where high concentration of surface current is flowing across the connected load. However, when the load resistance is not present, the maximum magnitude of the surface current within the arms of the resonator reduces by half as shown in Fig. 4(b). In addition to the high absorption efficiency of the proposed metasurface harvester, the optimal load impedance connected across the gap can be tuned to match the desired rectification circuitry. The optimal load impedance strongly depends on the resonator dimensions and most critically on the periodicity of the cell denoted by d in Fig. 1. Therefore, by varying the resonator dimensions along with the periodicity of the cell one can tune the resonator to the desired load resistance. This can be critical when a low input impedance MIM diode is connected across the gap of the resonator such as the diode presented in [18]. It is critical to note here that unlike metamaterial absorbers, the proposed metamaterial harvester not only absorb the energy within the medium, but also utilize a load resistor to channel the absorbed energy to a load. In previous metamaterial absorber designs [22–24, 28], the absorbed energy is dissipated mostly within the lossy substrate used to host the metasurface resonators. In the proposed metasurface harvester, a low loss substrate was used, and the energy was trapped across a resistive load placed at the gap of the resonator instead of the substrate host material. This way, the energy from each resonator can be channelled to a single load or a diode for energy rectification from AC to DC power more efficiently.

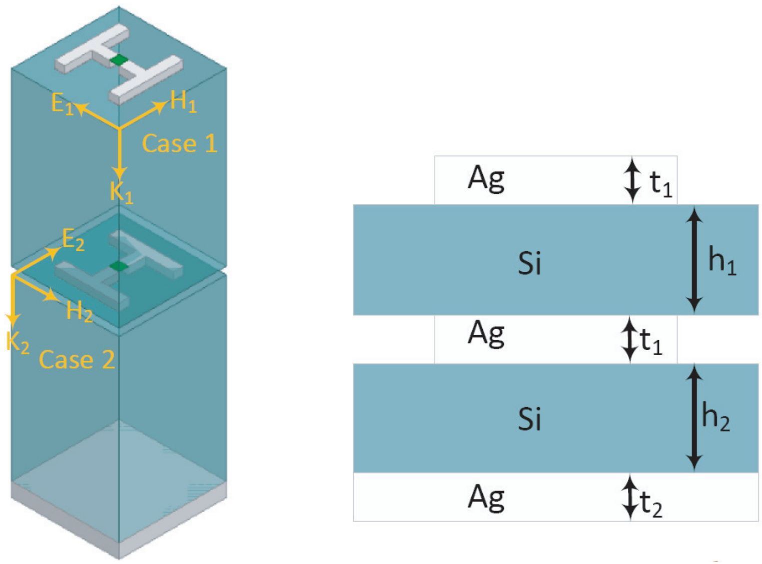


(a) (b)

Figure 4. Surface current density on the H-resonator (a) with a load and (b) without a load. Dark blue corresponds to 0 A/m and dark red corresponds to 10000 A/m.

The design was extended to provide energy reception from two orthogonal polarizations. The sun emits energy that is randomly polarized in addition to the fact that the angle of maximum solar radiation intensity changes with time. In addition, the remitted infrared energy from the earth surface during the earth cooling period at night ranges in wavelength between approximately 7 µm–14 µm [17]. Hence, it is critical to maximize energy reception within this frequency range from different angles.

Two cross polarized H-resonators with identical dimension and material to the one presented above was designed as shown in Fig. 5(a). The top and bottom resonators were hosted on a silicon substrate of heights $h1 = 4.54$ µm and $h2 = 4.63$ µm, respectively. The metasurface harvester was backed by a ground plane with a thickness of $t2 = 0.07$ µm as shown in Fig. 5(b). The 5-layer unit cell was excited



(a) (b)

Figure 5. A schematic showing the proposed dual-polarized H-shaped metamaterial harvester. (a) Prospective view and (b) side view.

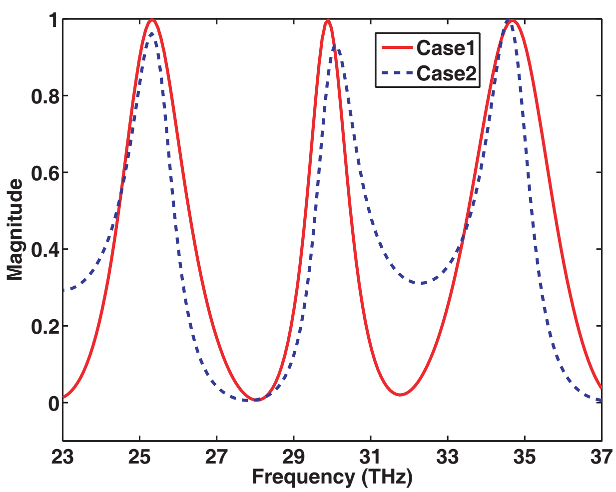


Figure 6. Simulation results showing the absorption of the two proposed polarization cases.

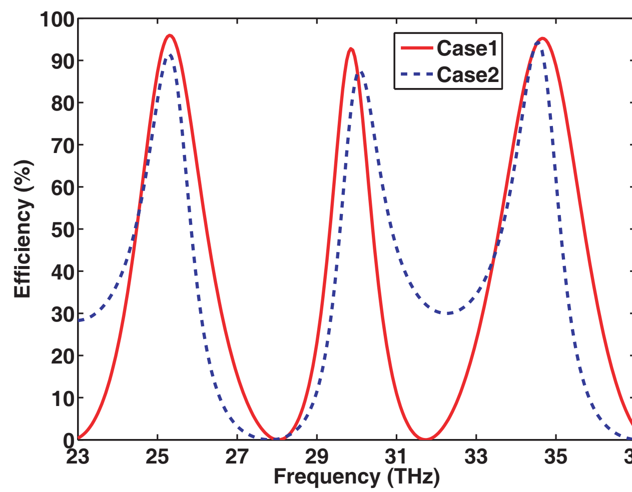


Figure 7. Simulation results showing the power distribution of the absorbed energy within the dual-polarized 5-layer H-resonator unit cell.

by a waveguide with two different polarizations to test the ability of the resonators to capture infrared energy from various angles. The polarization of the two excitation cases are shown in Fig. 5(a). For each case, the scattering parameters were extracted to plot the energy absorption within the unit cell. Fig. 6 shows that the unit cell experiences full energy absorption at both polarization cases. In addition, full absorption occurs at multiple bands in particular 25 THz, 30 THz, and 34 THz. All the 3 operating bands were carefully designed to lie within the range of the earth emitted infrared energy at night time. If different bands were desired, one can change the resonator size, substrate thickness and the periodicity of the unit cell to operate at different frequency bands.

The power distribution of the absorbed energy within the 5-layer energy harvester is shown in Fig. 7. For the polarization of case I, the unit cell dissipated more than 92% of the absorbed energy across the load resistance. The top resonator is the main contributor to the absorbed energy at the polarization of case I. For case II, the unit cell consumed more than 88% of the absorbed energy across the load of the bottom resonator. In both cases, the unit cell showed energy absorption and channelling to the connected load at the same three bands. This can be attributed to the multi-resonances of the unit cell due to the presence of two substrate materials having different heights. Such features are very critical to maximize energy harvesting in the infrared regime.

Although the terminated load in both polarization cases for the two resonators was $90\,\Omega$, the proposed design possesses a wideband impedance response having appreciable electromagnetic energy

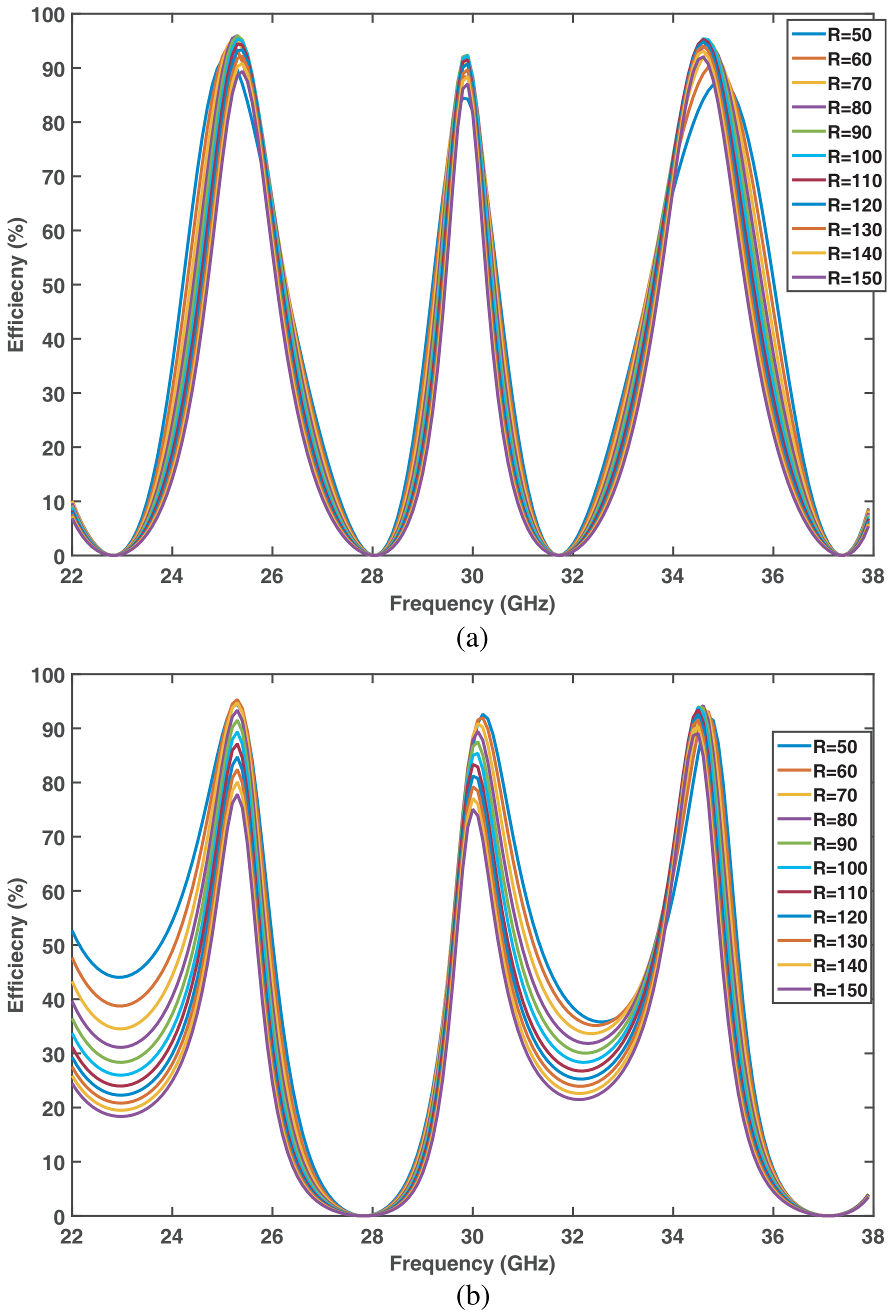


Figure 8. Simulation results showing the efficiency of the harvester as a function of frequency with various resistive loads for (a) case 1 and (b) case 2 as described in the text.

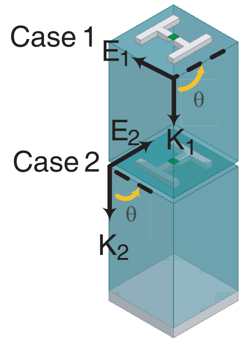


Figure 9. A schematic of the 5 layer harvester showing the two polarizations with the direction of the oblique incident angle.

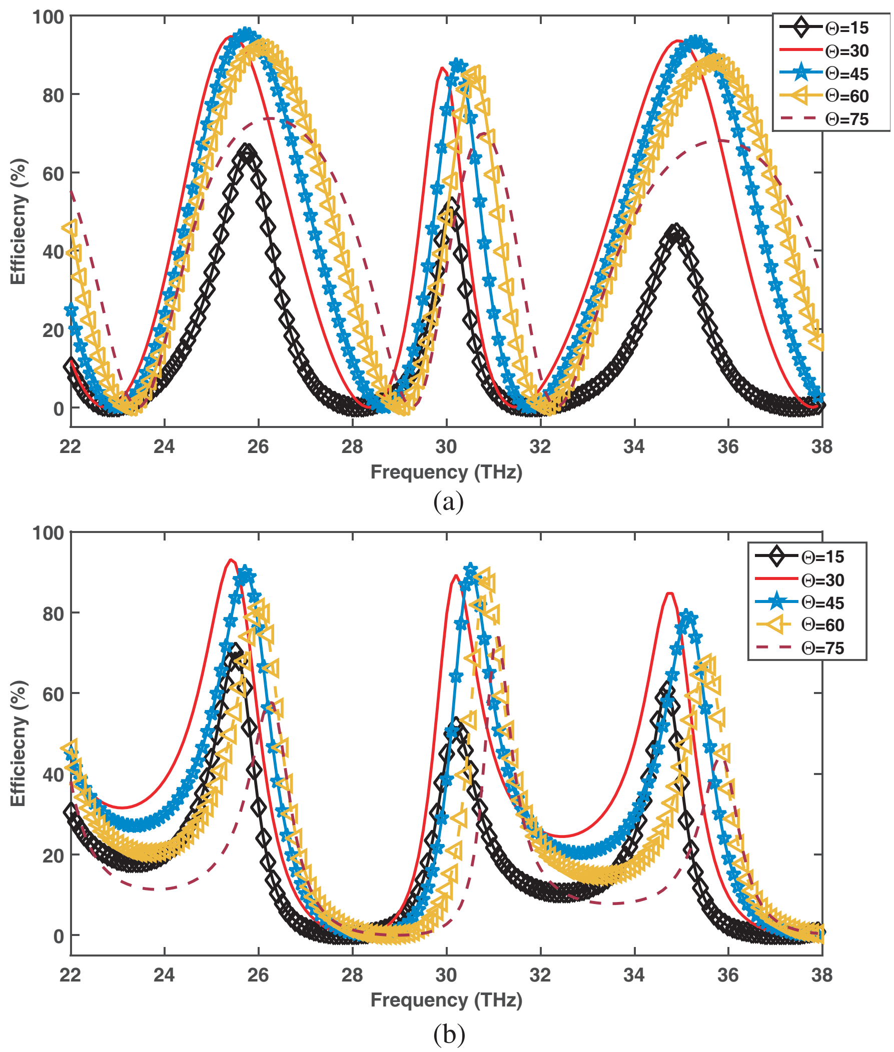


Figure 10. Simulation results showing the efficiency of the harvester as a function of frequency with various oblique incident angles for (a) case 1 and (b) case 2 as illustrated in Fig. 9.

absorption at resistances higher and lower than the load resistance used above. To illustrate this feature, the resistance values across the gap of both resonators were varied simultaneously while being excited by the two proposed polarizations. Figs. 8(a) and (b) show the efficiency of the harvester with a sweep of resistances ranging from $50\,\Omega$ to $150\,\Omega$ for both polarizations respectively. It is clear from the curves that a range of resistances can be used to achieve appreciable energy harvesting efficiency (higher than 80%) which provides design flexibility when a diode is to be connected across the gap instead of a resistor.

Since the polarization and direction of the electromagnetic wave at the infrared regime is arbitrary, it is critical for the harvester to capture the energy from as much angles as possible to maximize the total energy harvested. Therefore, the harvester was tested for various oblique angles for two E-field polarizations as shown in Fig. 9. The incident angle was varied from 15° to 75° with 15° steps for both E-field polarizations as shown in Fig. 9. The efficiency as a function of frequency for the two E-field polarizations is shown in Figs. 10(a) and (b), respectively. From the results, it is interesting to see that the harvester can capture the infrared energy with relatively wide angle of the incident wave. In all the proposed angles with the two polarizations, the efficiency of the harvester was at least 50% or higher which is a critical feature for infrared energy harvesting.

It is important to note here that a full and practical realization of the H-resonator metasurface collector/antenna requires termination by an MIM diode placed within each gap resonator. Then the energy collected from each cell is combined through power combining network. Although high efficiencies were achieved in both the single and dual-polarized unit cells, the silver metallic layers consumed 4% and 12% of the absorbed energy for the single and dual-polarized unit cells, respectively. This can be significant loss especially if the mismatch between the diode and the antenna is high. Therefore, low loss metallic materials can be used to minimize the energy dissipated within the resonator and ground layers.

3. CONCLUSION

We presented a numerical study of an infrared metasurface harvester inspired by the perfect absorption concept. The metasurface unit cell was capable of channeling 96% of the absorbed power to a resistive load connected across the gap of the resonator. In addition, a 5-layer unit cell was introduced to provide dual polarizations with multiple reception bands. The frequency of operation is selected such that the harvester receives infrared energy throughout the day.

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