International Journal of Renewable Energy Technology Research
Vol. 4, No. 1, January 2015, pp. 1 - 9, ISSN: 2325 - 3924 (Online)
Available online at http://ijretr.org

Review article

Nanoantenna –A Review

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Abstract

In this paper, we discuss the role of nanoantenna system in transforming thermal energy provided by the sun to electricity. Nanoantennas target the mid infrared wavelengths where conventional photo voltaic cells are inefficient. Infrared radiation is an especially rich energy source because it is also generated by industrial process such as coal fire plants. Also objects give off heat as infrared rays, nanoantennas could collect those rays and re-emit energy at harmless wavelengths. The operating principle and production mechanism are illustrated. It also covers advantages, limitations and future research scope. **Copyright © IJRETR, all rights reserved.**

Keywords: nanoantenna, wavelength, radiation, photo voltaic cell, infrared rays.

1.1Introduction

A nanoantenna (nantenna) is a nanoscopic rectifying antenna. It is an electromagnetic collector designed to absorb specific wavelengths that are proportional to the size of the nanoantenna. Idea was first proposed by Robert L. Bailey in 1972 and received a patent in 1973 for an electromagnetic wave converter. The patented device was similar to modern day nanoantenna devices. Alvin M. Marks received a patent in 1984 for a device explicitly stating the use of sub-micron antennas for the direct conversion of light power to electrical power. Marks's device showed substantial improvements in efficiency over Bailey's device. In 1996, Guang H. Lin was the first to report resonant light absorption by a fabricated nanostructure and rectification of light with frequencies in the visible range. Research on nanoantennas is ongoing.

Nanoantennas may prove useful for converting solar radiation to electricity. Sufficient supplies of clean energy are intimately linked with global stability, economic prosperity and quality of life. Finding energy sources to satisfy the world's growing demand is one of the society's challenges for the next half century. The world now uses energy at a rate of approximately $4.1x10^{20}$ J/yr, equivalent to continuous power consumption of 13 trillion watts. Even with considerable conservation and energy efficiency measures , an increase in earth's population to 9 billion people, accompanied by rapid technology development and economic growth worldwide is estimated to produce more than double the demand for energy (to 30 TW) by 2050 and more than triple the demand (to 40 TW) by end of century. As a result of this, increased worldwide energy demands and as a consequence the deleterious effects of hydrocarbon-based power such as global warming, air pollution, acid precipitation, ozone depletion, and forest destruction are increasingly apparent. In order to limit these drawbacks, suitable actions aimed at reducing the dependence on the fossil fuels are needed, and the search for clean and renewable alternative energy resources is one of the most urgent challenges to the sustainable development of human civilization. Our primary source of clean and abundant energy is sun .About 120,000TW of radiations from sun reach earth's surface far exceeding human needs [2][3].

Conversion of solar energy to electricity using photovoltaic cell is most common as shown in figure1. These photovoltaic cells are nothing but traditional pn junction cells. The basic physics of energy absorption and carrier generation are a function of the materials characteristics and corresponding electrical properties (i.e. bandgap). A photon need to have greater energy than that of the band gap in order to excite an electron from the valence band into the conduction band. Earth is composed of photons with energies greater than the band gap of silicon. These higher energy photons will be absorbed by the solar cell, but the difference in energy between these photons and the silicon bandgap is converted into heat (via lattice vibrations — called phonons) rather than into usable electrical energy. For a single-junction cell this sets an upper efficiency of ~20%. The current research path of implementing complex, multi junction PV designs to overcome efficiency limitations does not appear to be a cost-effective solution [7]. Another drawback of PV-based technologies is the fact of being strongly dependent on daylight, which in turn makes them sensitive to the weather conditions [9].

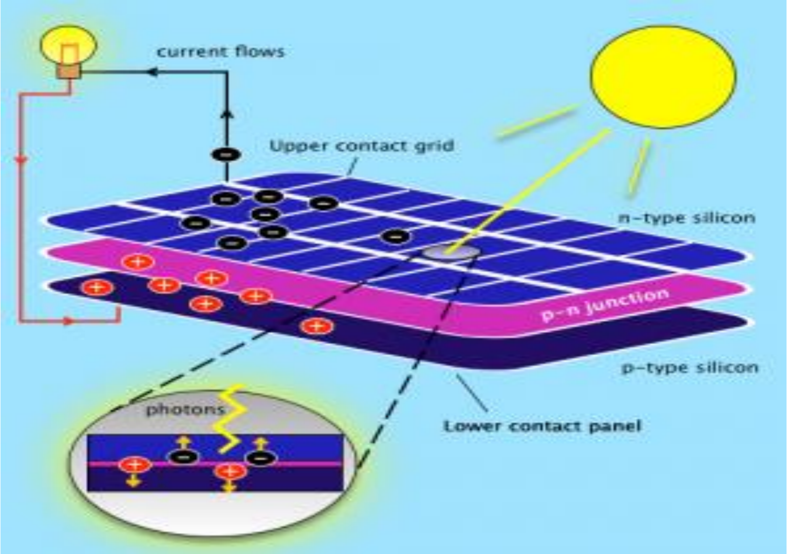

Figure 1: Photovoltaic cell

An energy harvesting approach based on nantennas is an alternative to PV Cells. In contrast to PV, which are quantum devices and limited by material bandgaps, antennas rely on natural resonance and bandwidth of operation as a function of physical antenna geometries. Efficient collection of the incident radiation is dependent upon proper design of antenna resonance and antenna impedance matching. Recent advances in nanotechnology have provided a pathway for large-scale fabrication of nanoantennas.

1.2 Operating principle

The theory behind nanoantennas is essentially the same for rectifying antennas. Incident light on the antenna causes electrons in the antenna to move back and forth at the same frequency as the incoming light. This is caused by the oscillating electric field of the incoming electromagnetic wave. The movement of electrons is an alternating current in the antenna circuit. To convert this into direct current, the AC must be rectified, which is typically done with some kind of diode. The resulting DC current can then be used to power an external load. The resonant frequency of antennas (frequency which results in lowest impedance and thus highest efficiency) scales linearly with the physical dimensions of the antenna according to simple microwave antenna theory. The wavelengths in the solar spectrum range from approximately 0.3-2.0 µm. Thus, in order for a rectifying antenna to be an efficient electromagnetic collector in the solar spectrum, it needs to be on the order of hundreds of nm in size. This can be achieved by shrinking the dimensions of the antenna to the scale of the wavelength. To this aim, nantennas are an alternative approach used to scale the microwave theory down to the IR regions of the electromagnetic spectrum in figure2 [4].

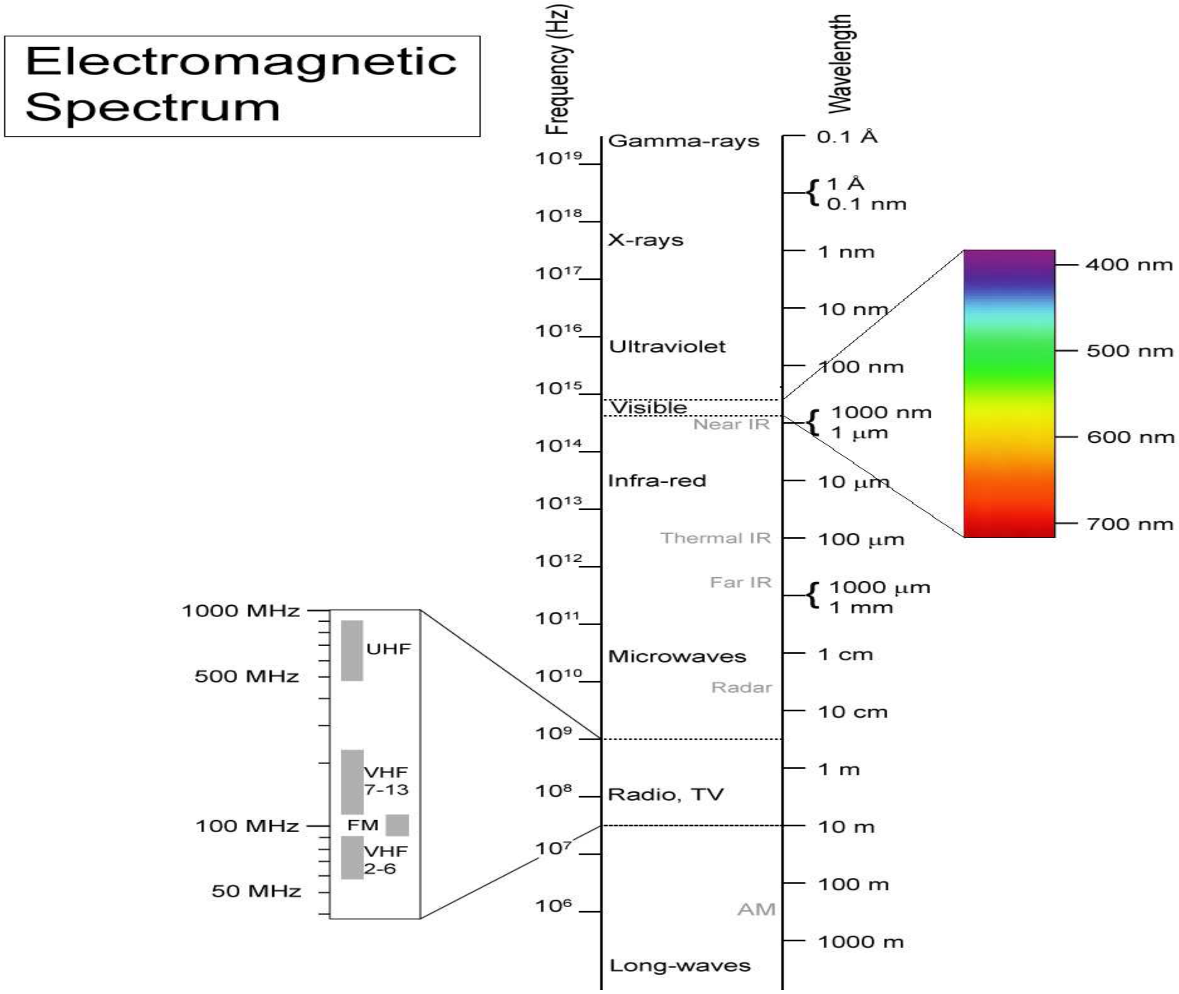

Figure 2: Electromagnetic spectrum

When an antenna is excited into a resonance mode it induces a cyclic plasma movement of free electrons from the metal antenna. The electrons freely flow along the antenna generating alternating current at the same frequency as the resonance. The current flow is toward the antenna feedpoint. In a balanced antenna, the feedpoint is located at the point of lowest impedance as in figure3. The e-field is clearly concentrated at the center feedpoint. This provides a convenience point to collect energy and transport it to other circuitry for conversion.

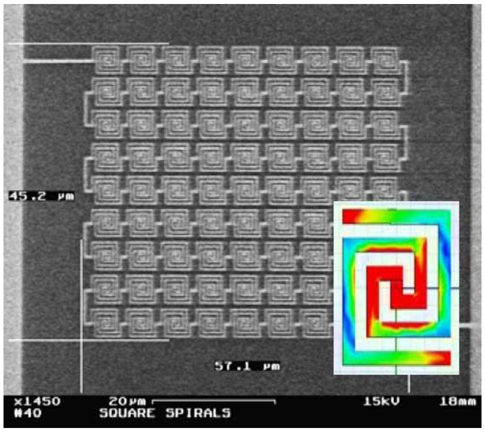

Figure 3: Array of loop nanoantennas, (inset) Flow of T Hz current to feed point of antenna. Red represents highest concentrated E-field.

Antennas have electromagnetic radiation patterns, which allow them to exhibit gain and directionality and effectively collect and concentrate energy, as illustrated in figure 4. The nanoantenna radiation pattern displays angular reception characteristics, resulting in a wider angle of incidence exposure to thermal radiation than typical PV. Any flux from the sun that falls within the radial beam pattern of the antenna is collected. This property is a critical antenna characteristic that optimizes energy collection from the sun as it moves throughout the horizon. Antennas by themselves do not provide a means of converting the collected energy. This will need to be accomplished by associated circuitry such as rectifiers. As illustrated in figure 4, the electrical size of the antenna (comprised of radiation beam pattern) is much larger than the physical size of the antenna. The virtual large surface area antenna focuses the electromagnetic energy onto the nano-sized energy conversion material fabricated at the antenna feedpoint. Theoretical efficiency is improved by the enhanced radiation capture area of the antenna.

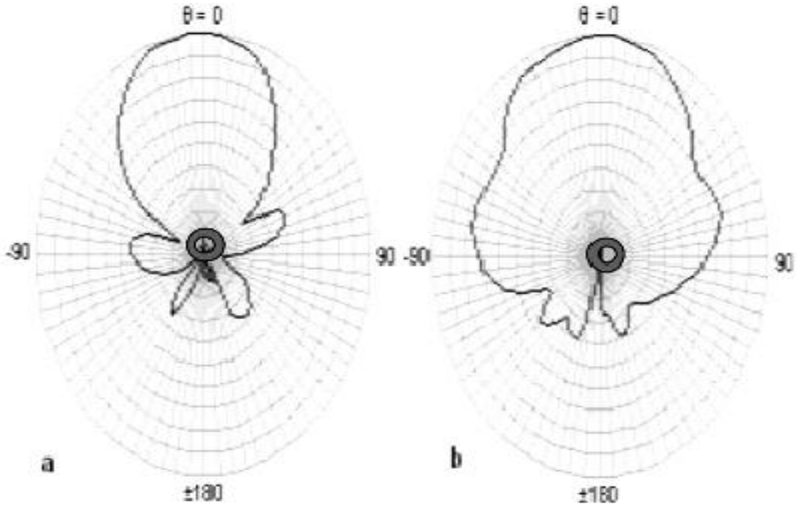

Figure 4: Typical electromagnetic radiation pattern of antenna. The physical size of the antenna is represented by the ring and the effective electrical size of the antenna is the radiation pattern.

1.2.1 Analytical model –RLC Circuit

RLC circuit analog of array of square loop antennas is shown in Figure 5. The electrical behavior of the structure is described as follows. The metal loops give inductance to the nanoantenna as thermally-excited radiation induces current. The gaps between the metallic loops and the gap within the loop compose capacitors with a dielectric fill. A resistance is present because the antenna is composed of lossy metallic elements on a dielectric substrate. The resulting RLC circuit has a resonance tuned filter behavior [11]. It is evident that the proper selection of element and substrate material is important and contributes to the RLC parameters. The electro-optical characteristics of the nanoantenna circuit and the surrounding media have the effect of shaping and optimizing the spectral response.

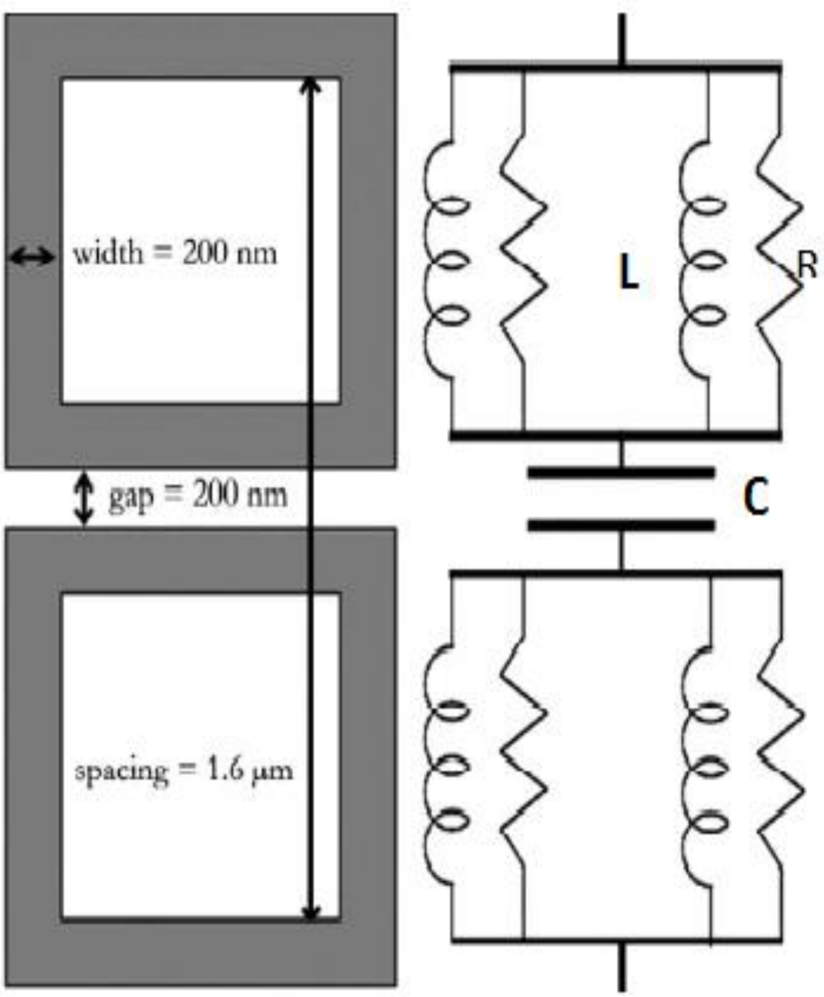

Figure 5: Analog RLC equivalent circuit of frequency selective element.

Nanoantenna structure incorporates an antenna layer, a dielectric standoff layer, and a ground plane as in figure 6. The standoff layer serves as an optical resonance cavity. The nanoantenna to ground plane separation acts as a transmission line that enhances resonance. The thickness of the standoff layer is selected to be a ¼ wavelength to insure proper phasing of the electromagnetic energy.

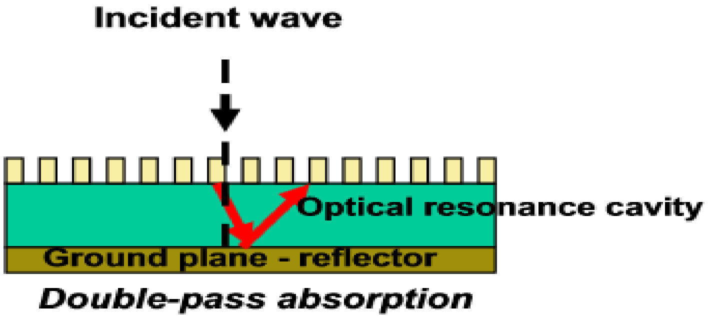

Figure 6: Side walls of nanoantenna showing path of incidence of wave.

It is found that right shape, materials and size the simulated nanoantennas could harvest upto 92% of energy at infrared wavelength. Different efforts are made to improve the nanoantenna performance. The total efficiency of nano-rectennas consists of two parts. The first part is the efficiency by which the light is captured by the nanoantenna and brought to its terminals. The second part is the efficiency by which the captured light is transformed into low frequency electrical power by the rectifier. The radiation efficiency of IR for five different conducting materials silver, gold, aluminum, copper, and chromium, respectively, are reported in vacuum. Chromium is not suited at all for energy harvesting since maximum efficiency is in the order of 20%. Copper reaches efficiencies in the order of 60–70%, but the bandwidth is rather limited. This is reflected in the total efficiency which reaches a maximal value of about 30% for a dipole length of 300 nm. The same is observed for gold, the material most used in this area. Its efficiencies are a bit higher than for copper, in the order of 70–80%, but the total efficiency reaches a maximum of about 35% for a dipole length also of 300 nm. Aluminum performs quite well and reaches efficiencies of 60–70% around 500–600 THz, yielding total efficiency values of about 50% for a whole range of dipole lengths. The highest values are obtained for silver. In the lower region of the band considered, silver is by far superior over all other metals. It reaches efficiencies over 80–90% in a remarkably wide band. The maximal total harvesting efficiency reached by silver is 65.4% at a dipole length of 200 nm [5]. Also according to recent advances in technology, rectennas formed from nanodipole antennas terminated by plasmonic metal–insulator–metal (MIM) travelling wave transmission line rectifiers are developed for ambient thermal energy harvesting at 30 THz [6].

1.3 Methods of production of nanoantenna

The nanoantenna consists of three main parts: the ground plane, the optical resonance cavity, and the antenna. The antenna absorbs the electromagnetic wave, the ground plane reflects the light back towards the antenna, and the optical resonance cavity bends and concentrates the light back. Because the size of nanoantennas is in the range from a few hundred nanometers to a few microns, the technological limits did not allow their realization until a few years ago. However, thanks to the development of electron beam lithography and similar techniques the required level of miniaturization for the realization and demonstration of nanoantennas has been obtained [8].

1.3.1 Lithography method

A metallic ground plane is deposited on a bare silicon wafer, followed by a sputter deposited amorphous silicon layer. The depth of the deposited layer is about a quarter of a wavelength. A thin manganese film along with a gold frequency selective surface (to filter wanted frequency) was deposited to act as the antenna. Resist was applied and patterned via electron beam lithography. The gold film was selectively etched and the resist is removed.

Idaho Nationals Labs used this method to fabricate their nantenna arrays. Currently, they have designed a nantenna to absorb wavelengths in the range of 3–15 µm. These wavelengths correspond to photon energies of 0.08-0.4 eV. Based on antenna theory, a nantenna can absorb any wavelength of light efficiently provided that the size of the nantenna is optimized for that specific wavelength. Ideally, nantennas would be used to absorb light at wavelengths between 0.4–1.6 µm because these wavelengths have higher energy than far-infrared (longer wavelengths) and make up about 85% of the solar radiation spectrum.

1.3.2 Roll-to-roll manufacturing

In moving up to a greater production scale, laboratory processing steps such as the use of e-beam lithography are slow and expensive. Therefore a roll-to-roll manufacturing method was devised using a new manufacturing technique based on a master pattern. This master pattern in effect mechanically “stamps” the precision pattern onto an inexpensive flexible substrate and thereby creates the metallic loop elements seen in the laboratory processing steps.

The master template fabricated by Idaho National Laboratories consists of approximately 10 billion antenna elements on an 8-inch round silicon wafer. Using this semi-automated process, Idaho National Labs has produced a number of 4-inch square coupons. These coupons were combined to form a broad flexible sheet of nantenna arrays.

1.4 Advantages

One of the biggest claimed advantages of nantennas is their high theoretical efficiency. When compared to the theoretical efficiency of single junction solar cells (30%), nantennas appear to have a significant advantage. The most apparent advantage nantennas have over semiconductor photovoltaics is that nantenna arrays can be designed to absorb any frequency of light. The resonant frequency of a nantenna can be selected by varying its length. This is an advantage over semiconductor photovoltaics, because in order to absorb different wavelengths of light, different band gaps are needed. In order to vary the band gap, the semiconductor must be alloyed or a different semiconductor must be used altogether. Also nantennas exhibit potential advantages in terms of polarization, tunability, and rapid time response. In fact, they have (i) a very small detection area, they (ii) allow the electromagnetic field localization beyond the diffraction limit, (iii) they very efficiently release radiation from localized sources into the far field, (iv) they make possible the tailoring of the interaction of electromagnetic field at the nanoscale, and (v) they can be tuned to a specific wavelength [10].

1.5 Disadvantages

One of the major limitations of nantennas is the frequency at which they operate. The high frequency of light in the ideal range of wavelengths makes the use of typical Schottky diodes impractical. Although MIM diodes show promising features for use in nantennas, more advances are necessary to operate efficiently at higher frequencies. Another disadvantage is that current nantennas are produced using electron beam (e- beam) lithography. This process is slow and relatively expensive because parallel processing is not possible with e-beam lithography. Typically, e-beam lithography is only used for research purposes when extremely fine resolutions are needed for minimum feature size (typically, on the order of nanometers).However, photolithographic techniques have advanced to where it is possible to have minimum feature sizes on the order of tens of nanometers, making it possible to produce nantennas by means of photolithography.

1.6 Applications

Applications for this technology are very diverse. It is conceivable that nanoantenna collectors, combined with appropriate rectifying elements, could be integrated into the “skin” of consumer electronic devices to continuously charge their batteries. Economical large-scale fabrication would support applications, such as, coating the roofs of buildings and supplementing the power grid. They can be optimized for collection of discrete bands of electromagnetic energy. Double-sided panels could absorb a broad spectrum of energy from the sun during the day, while the other side might be designed to take in the narrow frequency of energy produced from the earth's radiated heat or potentially residual heat from electronic devices. Another application of the nanoantennas is to create more compact, faster circuits and computers that use packets of light, instead of electrons for carrying signals. Such photonic circuits could be used for a new type of sensitive sensors which detect tiny traces of chemicals and biological materials, making them useful for applications including analyzing a patient's DNA for medical diagnostics, monitoring air quality for pollution control and detecting dangerous substances for homeland security.

This technology may also support several emerging applications, including passive energy management products, such as building insulation, window coatings, and heat dissipation in small electronic consumer products, such as, computers. The nantennas are broadband collectors of energy. This in effect generates a frequency selective distribution of energy. This potentially will collect unwanted energy (residual or incident heat) and redistribute it at other innocuous wavelengths.

1.7 Future scope for research

The researchers are still fine-tuning the device, getting the nanoantennas and the diodes to “talk” to each other.

Because the nanoantennas have the ability to collect energy from the infrared spectrum, the next step will be to tweak the technology to harvest industrial waste heat. As such, nanoantennas will be complementary to photovoltaics, offering increased energy efficiencies through thermal harvesting when compared to existing solar PV collection devices.

Efficiencies are proportional to the change in temperature. We could potentially harvest waste heat from an aluminum smelting operation with greater than 60 percent efficiency, the hotter the better for harvesting infrared energy from waste heat. Speculated that the nanoantennas might be integrated into building materials or electronics. “They potentially could be used in electric vehicles, and there may be no need for a battery in a car, charge cell phones and even cool homes”.

Currently, the largest problem is not with the antenna device, but with the rectifier. Present-day diodes are unable to efficiently rectify at frequencies which correspond to high-infrared and visible light. Therefore, a rectifier must be designed that can properly turn the absorbed light into usable energy. Researchers currently hope to create a rectifier which can convert around 50% of the antenna's absorption into energy. Another focus of research will be how to properly upscale the process to mass-market production. New materials will need to be chosen and tested that will easily comply with a roll-to-roll manufacturing process.

1.8 Conclusions

The progress and challenges of nanoantenna has been reviewed. Capturing energy from light using tiny antennas could be a way to produce solar energy at a lower cost, and capture and reuse waste heat from industrial processes. The research is at an intermediate stage and may take years to bring to fruition and market. The advances made in research have shown that some early barriers of this alternative PV concept have been crossed and has a potential to be a enabling technology.

“It’s what nations need to proceed: renewable resources with well-thought out manufacturing and scale-up. That’s our goal: a quality product that is inexpensive enough to be accessible to all people.”

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