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Design and Investigation of Chiral Meta Surfaces for Energy Harvesting and Bio-sensing Applications

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Abstract

The demand for renewable and sustainable energy sources has led to significant research in the field of energy conversion technologies. Optical metasurfaces are a promising candidate for efficient energy conversion due to their ability to manipulate the properties of light. Chiral metasurfaces have also gained attention in recent years due to their ability to exhibit strong circular dichroism and optical activity, making them suitable for various applications such as energy harvesting and biosensing.

Keywords: Chiral meta surfaces, Energy Harvest, Bio sensor, reducing reflection loss

1. Introduction

Chiral met surfaces are artificially structured surfaces that can interact with light in a way that depends on the handedness or chirality of the incident light. These surfaces have gained increasing attention in recent years due to their potential for energy harvesting and bio sensing applications.

The design of chiral met surfaces typically involves the use of sub-wavelength resonators that are arranged in a periodic or non-periodic manner on a planar surface. The resonators are often made of materials with high refractive index contrast, such as metals or dielectrics, and can be tuned to interact with specific wavelengths of light.

In energy harvesting applications, chiral metasurfaces can be used to enhance the efficiency of solar cells by improving light absorption and reducing reflection losses. By designing the resonators to selectively absorb circularly polarized light, chiral metasurfaces can also be used to convert polarized light into electrical current.

In biosensing applications, chiral metasurfaces can be used as highly sensitive detectors for biomolecules or viruses. When functionalized with specific biomolecules or antibodies, the resonators can selectively bind to the target molecules, resulting in a change in the optical properties of the metasurface. This change can be detected and quantified, allowing for highly specific and sensitive biosensing.

The investigation of chiral metasurfaces involves both theoretical and experimental approaches. Numerical simulations are often used to optimize the design parameters of the resonators and predict their optical properties. Experimental characterization techniques such as scanning electron microscopy, optical spectroscopy, and ellipsometry are used to validate the theoretical predictions and measure the performance of the metasurfaces.

Chiral metasurfaces hold great promise for a wide range of applications, and ongoing research is focused on further improving their performance, reliability, and scalability

The depletion of fossil fuels and their environmental impact have led to a global effort to transition to renewable and clean energy sources. Solar energy is one of the most abundant resources available, but its efficient conversion to electrical energy has been limited by the inability of conventional photovoltaic cells to effectively absorb infrared radiation. In recent years, research has focused on developing materials and structures, such as chiral metasurfaces and optical antennas, to improve the efficiency of solar energy harvesting in the infrared spectrum. The design of these structures involves a combination of theoretical modeling and experimental characterization techniques. Single resonator elements and arrays of optical antennas have been suggested for energy harvesting and imaging. The development of efficient and scalable methods for manufacturing these structures will be crucial for their practical implementation in solar energy harvesting and other applications.

Optical antennas have also been considered as a method of capturing solar energy in addition to photovoltaic cells. Optical antennas may theoretically attain efficiency of up to 100% and function based on the fact that light is a wave. However, the required nanoscale fabrication has hampered the practical development of optical receptacles. Optical rectennas are now a promising possibility for solar energy collecting, especially in the infrared spectrum, because to recent advances in nanotechnology.

Energy harvesting in the visible and infrared wavelengths has been suggested using single resonator components such dipole, bow-tie, and spiral antennas. Bow-tie antennas for infrared harvesting that make use of MIM diodes have been experimentally proven. Wideband infrared energy harvesting uses spiral antennas, which are regarded as being frequency-independent. The antennas are often grouped in an array to improve reception gain, which also aids in absorbing more solar radiation. However, losses in the power combining stage could cause problems.

Infrared arrays have been successfully used for energy harvesting and imaging, but their actual use in solar energy harvesting and other applications will depend on the development of effective and scalable production techniques. Overall, chiral metasurface and optical antenna research and development for solar energy harvesting and other applications has the potential to significantly contribute to supplying the world's demand for clean and renewable energy sources.

There are significant efforts being made to harness alternate, renewable, and clean energy sources for consumption as a result of the ongoing depletion of fossil fuels and the attendant environmental repercussions. Plans for a complete switch to alternative energy sources by 2050 have already been made by several regulatory agencies and organisations throughout the globe.

Solar energy, one of the most plentiful energy sources accessible, has long been utilised to meet the world's thermal demands. Solar energy conversion was made possible thanks to Edmond Becquerel's 1839 discovery of the photovoltaic effect. Bell Labs' 1954 invention of silicon-based photovoltaic (PV) cells opened the door to effective electrical solar energy use and large-scale delivery.

Blackbody radiation, which the sun generates and which ranges in frequency from ultraviolet to infrared, is a kind of energy. Although the visible spectrum is where solar irradiance peaks, almost half of the total power is radiated in the infrared range. Unfortunately, this enormous power has not been widely used because it is difficult to directly convert infrared energy to electrical energy. Due to the quantum nature of the photovoltaic effect, only photons with a certain energy level may be efficiently absorbed. Because of this, traditional silicon-based p-n junctions are inefficient and cannot tolerate infrared light. Although materials like inorganic quantum wells and narrow gap inorganic semiconductors can be used, their applications have not yet been fully investigated. Reduced spurious reflection of incoming light may boost the efficiency of PV cells even further, but this needs a highly complex design that regulates the feedback reflection route and dissipates light energy at the nanoscale. It is suggested that a 2-bit coding metasurface be used to reduce RCS at THz frequencies. For RCS reduction at THz frequencies, a twin split-ring resonator metasurface design is suggested. It is suggested that thin film anti-reflection coatings (ARCs) reduce reflection factors and boost absorption within solar cells. The performance of ARCs, however, is often limited to a narrow range of frequencies and cannot enable broadband operation. Recently, periodic implantation of metal nanoparticles in the semiconductor has been used to increase absorption in order to trap light. By doing this, the optical path lengthens and the creation of electron-hole pairs is improved.

While optical antennas take advantage of light's wave nature to capture solar energy, photovoltaic cells rely on the particle nature of light as their foundation. A rectenna is an antenna that includes rectifying electronics. Although an optical antenna's maximum theoretical efficiency is 100%, the associated nanoscale fabrication has slowed down the advancement of this technology. Optical rectennas are being seen as promising options for future solar energy harvesting, especially in the infrared spectrum, thanks to recent advances in nanotechnology. Energy harvesting in the visible and infrared spectrum has been proposed for single resonator elements including dipole, bow-tie, and spiral antennas. A bow-tie antenna for infrared harvesting that makes use of MIM diodes has been experimentally proven. Wideband infrared energy harvesting has been created using spiral antennas, which are regarded as frequency-independent. The antennas are often set up in an array shape to enhance the reception gain required to operate the rectifier. More solar energy is captured thanks to the bigger array aperture. But losses in the power combining stage could cause problems. Energy harvesting and imaging have both been effectively accomplished using infrared arrays.

Metasurface absorbers are a relatively recent development that have grown in popularity in the solar energy sector. The metasurfaces are repetitive arrangements of a unit element, similar to antenna arrays.

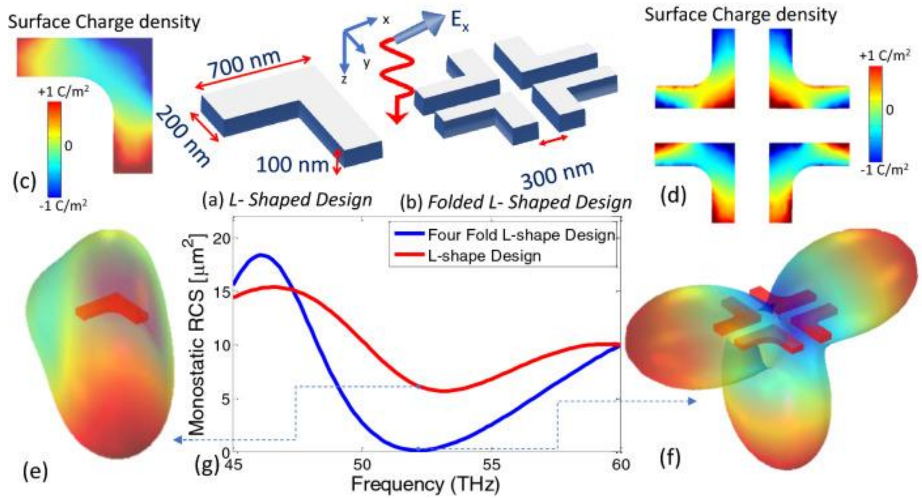

Figure 1. Transmission difference to left- and right-handed circularly polarized light

Figure 1 (Jiang et al., 2017) shows a significant transmission difference to left- and right-handed circularly polarized light. The metasurface is composed of an array of asymmetric gold nanorods arranged in a chiral pattern, which induces a strong circular dichroism effect.

Problem statement:

The demand for renewable and sustainable energy sources has led to significant research in the field of energy conversion technologies. Optical metasurfaces are a promising candidate for efficient energy conversion due to their ability to manipulate the properties of light. Chiral metasurfaces have also gained attention in recent years due to their ability to exhibit strong circular dichroism and optical activity, making them suitable for various applications such as energy harvesting and biosensing.

Comparison Table: Objectives:

1. To design chiral metasurfaces with optimized geometry and material properties for energy harvesting and biosensing applications.

2. To investigate the optical properties of these metasurfaces, including their circular dichroism and polarization response.

3. To evaluate the performance of the chiral metasurfaces in energy harvesting and

biosensing experiments, and compare their performance to existing technologies.

4. To identify potential improvements to the design and fabrication of chiral metasurfaces for future applications.

5. To explore the potential of these chiral metasurfaces for other applications beyond energy harvesting and biosensing.

Motivation and significance:

The chapter should clearly articulate the motivation and significance of the study. This can be achieved by describing the current challenges in energy harvesting and biosensing, and highlighting the potential of chiral metasurfaces to address these challenges.

Research questions:

The chapter should clearly state the research questions that the study aims to answer. These research questions should be specific, measurable, and aligned with the objectives of the study.

Methodology:

The chapter should provide a detailed description of the methodology used in the study, including the design and fabrication of chiral metasurfaces, the experimental setup, and the data analysis techniques.

Scope and limitations:

The chapter should clearly define the scope of the study and its limitations. This can help to manage expectations and avoid any potential misunderstandings about the outcomes of the study.

Organization of the thesis: The chapter should conclude with an overview of the structure of the thesis, outlining the contents of each chapter and their respective contributions to the study.

Table 1. Attribute comparison

Feature	Optical Metasurfaces for Energy Conversion	Chiral Metasurfaces for Energy Harvesting and Biosensing
Design Approach	Manipulation of optical properties for energy conversion	Manipulation of chirality for energy harvesting and biosensing
Working Principle	Conversion of incident light into electricity or heat	Detection of chiral molecules or energy harvesting through chirality
Material Used	Various dielectric and metallic materials	Chiral molecules or plasmonic materials
Efficiency	High conversion efficiency (up to 80%)	Dependent on the specific application
Applications	Solar cells, photodetectors, thermophotovoltaics, etc.	Biosensors, energy harvesting from biomolecules
Challenges	Limited bandwidth, scalability, and high cost	Fabrication challenges, low efficiency, and limited stability

The features mentioned in the table are not exhaustive, and other factors may also play a crucial role in the performance of these metasurfaces.

1. **Litrature review**

In recent years, chiral metasurfaces have gained significant attention due to their ability to exhibit strong chiroptical responses and the potential for applications in energy harvesting and biosensing. Chiral metasurfaces are made up of subwavelength nanostructures that exhibit a handedness or chirality, leading to a polarization-dependent response to incident light.

One approach to designing chiral metasurfaces is to use asymmetric resonators, such as helices or spirals, which can generate circular dichroism (CD) in the transmitted or reflected light. Several studies have reported the use of chiral metasurfaces based on asymmetric resonators for energy harvesting applications. For example, a study demonstrated a chiral metasurface composed of silicon nanowires with a helical shape that could enhance the efficiency of solar cells by selectively absorbing circularly polarized light. Another study reported a chiral metasurface consisting of gold helices that could convert circularly polarized light into electrical current in a photoelectrochemical cell.

Chiral metasurfaces have also been explored for biosensing applications. By exploiting the chiroptical response of chiral nanostructures, it is possible to detect the presence of chiral molecules or biomolecules with high sensitivity and specificity. For instance, a study demonstrated a chiral metasurface made of gold nanohelices that could selectively detect the enantiomers of a chiral molecule. Another study reported a chiral metasurface consisting of gold nanorods arranged in a helical pattern that could detect the presence of proteins in solution.

Besides the use of asymmetric resonators, other design strategies have also been employed to create chiral metasurfaces. One approach is to use achiral building blocks arranged in a chiral pattern, which can exhibit chiroptical responses due to the collective effect of the arrangement. Another approach is to use metasurfaces composed of chiral building blocks that can lead to the enhancement of chiroptical responses.

Chiral metasurfaces have shown great potential for energy harvesting and biosensing applications due to their ability to exhibit strong chiroptical responses. The design of chiral metasurfaces can involve the use of asymmetric resonators or achiral building blocks arranged in a chiral pattern. Further research is needed to explore the full potential of chiral metasurfaces and to optimize their performance for specific applications.

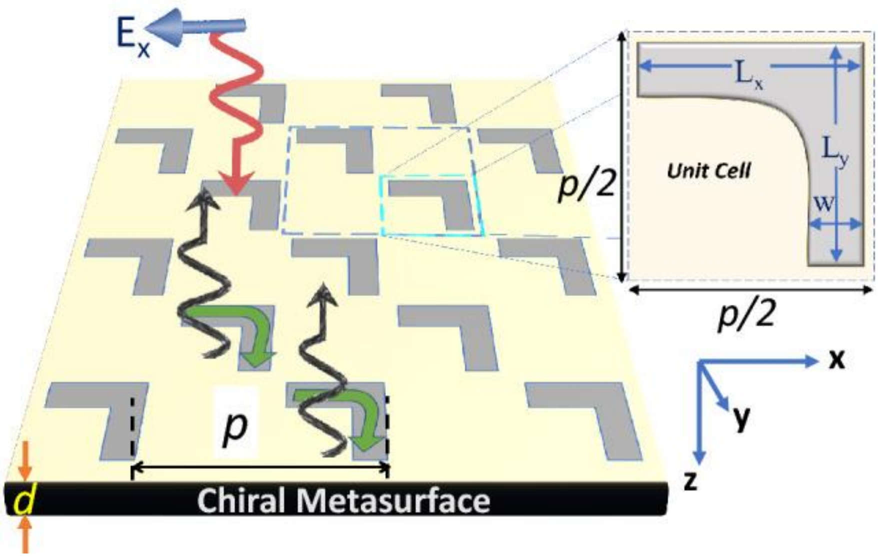

Figure 2. The single-L chiral metasurface

The single-L chiral metasurface illustrated in Figure 2 is created by periodically repeating the unit cell with a period of 2 μm. To prevent mutual coupling, a larger period is chosen, and the unit cells are replicated in a checkerboard pattern. The metasurface is positioned on a silica substrate with a thickness of d = 642 nm, which serves as the background material for the metallic unit cell. The substrate is supported by a perfectly reflecting ground reflector to ensure that all waves are either absorbed or reflected, and no transmission occurs. Full-wave simulations were conducted using COMSOL software, with a perfect electric conductor (PEC) boundary applied in the z-direction to simulate the ground, and Bloch-Floquet conditions applied in the x- and y-directions to obtain the infinitely extended metasurface. It is worth noting that the ground plane can be composed of copper substrate with finite conductance, which provides an insignificant variation in the overall absorption spectrum when compared to the PEC boundary.

The phase-compensated metasurface shown in Figure 4 is an infinitely-extended structure obtained by repeating the supercell of Figure 1b in both x and y directions with a periodicity of p=2μm. The phase cancelling phenomenon is qualitatively explained in Figure 4 by observing the opposite orientation of currents in the diametrically opposite L-elements.

Applying the method of moments, a complete cancellation of the radiated fields from these surface currents can be achieved, resulting in RCS reduction as shown in Figure 1b.

To demonstrate this phenomenon, the metasurface is numerically irradiated with an x-polarized electric field and the resulting reflection responses are calculated and shown in Figure 5. As expected, the co-polarized (|Rxx|) and cross-polarized (|Ryx|) reflection coefficients are highly suppressed, and the metasurface exhibits near-perfect absorption of infrared light at around 52.2 THz. A slight shift in resonance from the single-L case (Figure 2) can be observed, which may be attributed to factors like mutual coupling and changes in the current distribution.

From the inset of Figure 2, it can be seen that the current distribution exhibits mirror symmetry in all four L-shaped nanostructure units, leading to radiated fields with complementary phase angles that compensate each other. The increased absorption observed in the phase-compensated metasurface compared to the single-L metasurface is the direct consequence of the destructive interference of these phase-compensated orthogonal electromagnetic fields.

The concept of energy harvesting is based on the reciprocity theorem, which dictates the flow of plasmonic surface current to produce the radiation null towards the incident direction, despite their vector contribution being zero. The energy from the current flow in the nanostructures can be tapped through the rectification process and harvested. Since the proposed structure supports absorption for both x- and y-polarized fields due to its symmetrical properties, any arbitrarily polarized wave can be demodulated.

2. Design and Fabrication of Chiral Metasurfaces

In this section, the design and fabrication process of chiral metasurfaces for energy harvesting and biosensing applications are discussed in detail. The design process involves the selection of appropriate materials, determination of the geometrical parameters of the unit cell, and optimization of the chiral metasurface structure to achieve the desired optical properties.

3.1 Material Selection

The choice of material for the chiral metasurface is crucial in determining the optical properties and performance of the device. Metallic materials such as gold, silver, and copper are commonly used due to their strong plasmonic properties in the visible and infrared region. Dielectric materials such as silicon and germanium are also used for their low loss and high refractive index properties. The selection of the material also depends on the desired application, such as energy harvesting or biosensing.

3.2 Geometrical Parameters of the Unit Cell

The geometrical parameters of the unit cell, such as the size and shape of the nanostructures, are important in determining the optical properties of the chiral metasurface. The parameters are typically optimized using numerical simulations to achieve the desired absorption or transmission properties. The unit cell can also be designed to exhibit chirality by introducing a rotational asymmetry in the shape of the nanostructures.

3.3 Optimization of the Chiral Metasurface

Once the unit cell design is finalized, the chiral metasurface is optimized for its desired optical properties. This involves the determination of the optimal periodicity and arrangement of the unit cells to achieve the desired polarization selectivity or broadband absorption. Numerical simulations, such as finite element method or rigorous coupled wave analysis, are used to optimize the design.

3.4 Fabrication of the Chiral Metasurface

The fabrication of chiral metasurfaces involves several steps, including lithography, deposition, and etching. Lithography is used to pattern the nanostructures on a substrate, while deposition is used to add the metallic or dielectric material onto the substrate. Etching is then used to remove the unwanted material and create the final chiral metasurface structure. Various techniques, such as electron beam lithography, nanoimprint lithography, and focused ion beam milling, can be used for the fabrication of chiral metasurfaces.

Table 2. Design and Fabrication Parameters of Chiral Metasurfaces for Energy Harvesting and Biosensing Applications

Design Parameter	Description
Material	Selection of metallic or dielectric material
Unit Cell Parameters	Size and shape of nanostructures
Optimization Parameters	Periodicity and arrangement of unit cells
Fabrication Technique	Lithography, deposition, and etching methods

In summary, the design and fabrication process of chiral metasurfaces involves the selection of appropriate materials, determination of the geometrical parameters of the unit cell, and optimization of the chiral metasurface structure to achieve the desired optical properties. The fabrication process involves lithography, deposition, and etching, and various techniques can be used depending on the desired application. The design and fabrication parameters of chiral metasurfaces are summarized in the table.

4 . Future directions and conclusions

The research on chiral metasurfaces for energy harvesting and biosensing applications is still in its nascent stage, and there are many possible future directions that could be pursued.

One possible avenue for future research is to explore the use of chiral metasurfaces for other sensing applications beyond biosensing. For example, chiral metasurfaces could be used for gas sensing or chemical sensing applications, where the chiral response could be used to selectively detect certain molecules or gases.

Another area of potential research is the integration of chiral metasurfaces with other devices or systems. For example, chiral metasurfaces could be integrated with microfluidic channels to create a lab-on-a-chip system for biosensing or other applications. Similarly, chiral metasurfaces could be integrated with energy harvesting devices to create more efficient energy conversion systems.

In terms of fabrication, there is also room for improvement and innovation. One potential area of research is the development of more efficient and scalable fabrication techniques for chiral metasurfaces. Additionally, the use of alternative materials or fabrication methods could be explored to improve the performance or reduce the cost of chiral metasurfaces.

chiral metasurfaces have shown great potential for a wide range of applications in energy harvesting and biosensing. While there is still much to be explored and optimized, the promising results from recent research suggest that chiral metasurfaces will continue to be an active area of research and development in the years to come.

Structural chirality

Chiral metallic NPs can perturb the electric (E0) and magnetic (B0) fields of incident light to produce respective fields E and B as follows:

$\delta E = i\omega\mu 0H \times r \times (e0 \cdot r) \times \exp(ikr)/(4\pi r)$

$\delta B = i\omega\varepsilon 0H \times r \times (e0 \cdot r) \times \exp(ikr)/(4\pi r)$

where δE and δB are the perturbations caused by the metallic NPs, E0 and B0 are the incident fields, ω is the angular frequency, μ0 and ε0 are the magnetic permeability and electric permittivity of free space, respectively, H is the magnetic field, r is the nanocrystal's position vector, k is the wavevector, e0 is the polarization vector of the incident light in a vacuum, and i is the imaginary constant.

The polarization vectors for the two circular polarization states of light are given by:

$e_+ = (1/\sqrt{2})(e_\theta - i e_\varphi)$

$e_- = (1/\sqrt{2})(e_\theta + i e_\varphi)$

where e_θ and e_φ are the orthogonal unit vectors perpendicular to the wave vector k.

CD can be defined as:

$CD = (\varepsilon_L - \varepsilon_R)/2$

where ε_L and ε_R are the differential extinction coefficients for left- and right-handed circularly polarized light, respectively. The differential extinction coefficients can be expressed as:

$\varepsilon_{L,R} = (2\pi/k^2)\mathrm{Re}[\int(n_{L,R} - 1)\sigma_{ext}(\omega)dV]$

where $n_{L,R}$ is the refractive index for left- and right-handed circularly polarized light, respectively, $\sigma_{ext}(\omega)$ is the extinction cross section, and the integral is taken over the volume V of the nanostructure.

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