Progress In Electromagnetics Research M, Vol. 93, 67–76, 2020

Bi-Anisotropic Particles and Chiral Inclusions for Highly-Efficient Electromagnetic Energy Harvesting

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Abstract—We present an analytical analysis of a metasurface-based ambient electromagnetic energy harvesting system in which the bi-anisotropic particles loaded with a resistor are used. The proposed metasurface composed of an array of bi-anisotropic particles referred to as an electromagnetic energy harvester that can capture the ambient incident electromagnetic wave energy with a radiative to AC conversation efficiency of around 100%. The captured energy by metasurface is delivered to the load. The load acts as the input impedance of a rectification circuit in a rectenna system. The derived optimal polarizable inclusions can be applied to design bi-anisotropic metasurfaces which can be used for electromagnetic energy harvesting. Finally, the optimal dimensions of a typical chiral structure have been calculated to achieve maximum efficiency for circularly polarized propagating waves.

1. INTRODUCTION

One of the fundamental challenges in today's daily life is the supply of energy to electronic devices that are expanding significantly. The wireless power supply of electronic devices to overcome the problems caused by constant battery replacement and wired charging, especially for industrial sensors and implantable medical devices, has been a topic of recent research. The idea of wireless power transfer (WPT) goes back to the early 20th century when Tesla invented the first WPT system [1]. Research continues to this day with the development of microwave technology, so that methods for harvesting energy from radio-frequency electromagnetic radiation have received much-renewed interest, and the first wireless radiative power transmission system was introduced by Brown [2]. One of the applications of radiative WPT is the ambient electromagnetic energy harvesting, in which, by using a device called rectenna, the energy of incident radiation fields is captured and delivered to the load [3, 4]. The main element in energy harvesting systems is rectenna. Glasser introduced the idea of utilizing rectennas to harness energy from space known as Space Solar Power (SSP) [5]. In general, a rectenna contains various parts including an antenna, a diode, an RF filter, and a DC rectifier [6]. Interestingly, the reported work in the literature focused on the use of conventional antennas (single antenna or array one) as the primary energy collector, but are challenging to miniaturize because the total footprint of the array is constrained by the physical area of the device and must be comparable to the wavelength [7–10]. Recently, several studies have been done on utilizing metasurface instead of using the antenna in rectenna. Metasurface can be referred to as a two-dimensional counterpart of metamaterial state that exhibits attractive electromagnetic responses that are not found in natural materials [11]. Unlike metasurface-based electromagnetic absorbers [12], in which the power of the captured incident electromagnetic waves is dissipated within the structure as either ohmic or dielectric loss in metasurface energy harvesters, the very low-lossy substrate is used, and the radiation energy is captured through the metasurface-forming resonators and delivered through the optimally positioned vias to the feeding network, and the AC power is transmitted through the feeding network to the final load. The first

Received 1 April 2020, Accepted 20 May 2020, Scheduled 1 June 2020
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metasurface energy harvester was proposed in 2012 in which the split-ring resonator (SRR) formed the metasurface [13]. Subsequently, there were many papers on metasurface energy harvester that showed various capabilities, including polarization-sensitivity [14], multi-band [15], and wideband [16] availability in which ELC resonators were used as metasurface constitutive cells forming the harvester. Recently, a single engineered subwavelength chiral helix has been proposed that can uniformly collect power from all orientations of a polarization state and enables relative robust radiative powering of moving devices [17]. In this paper, the ambient electromagnetic energy harvesting is investigated in which optimal bi-anisotropic particles as energy collectors are found to achieve maximum energy harvesting efficiency. In previous literature, metasurface constitutive resonators located on the ground plane are used where the captured energy is terminated to the grounded load by the vias, but in this paper, bi-anisotropic particles are used as an energy harvester.

2. OPTIMAL BI-ANISOTROPIC PARTICLES AND HUYGENS' METASURFACE FOR ELECTROMAGNETIC ENERGY HARVESTING

Figure 1 shows a microscopically structured sheet usually periodic as a metasurface formed by a single two-dimensional periodic array of identical subwavelength electrically and magnetically polarizable inclusions. Assuming electrically small thickness and the period of the structure smaller than the wavelength corresponding to the resonant frequency, we can demonstrate the electromagnetic interaction of the metasurface using the electric and magnetic dipole moments induced in the constituent inclusions. A normally incident plane wave propagating along the z-direction illuminates the metasurface as illustrated in Fig. 1 [18]. The relevance of each inclusion with the incident fields for a thin sheet composite or homogeneous sheet can be described as

$$\begin{pmatrix} \mathbf{P} \\ \mathbf{m} \end{pmatrix} = \begin{pmatrix} \overline{\overline{\hat{\alpha}}}_{ee} & \overline{\overline{\hat{\alpha}}}_{em} \\ \overline{\overline{\hat{\alpha}}}_{me} & \overline{\overline{\hat{\alpha}}}_{mm} \end{pmatrix} \cdot \begin{pmatrix} \mathbf{E} \\ \mathbf{H} \end{pmatrix} \tag{1}$$

where p and m are the induced electric and magnetic dipole moments, respectively, and $\overline{\overline{\hat{\alpha}}}_{ij}$ are the collective polarizability dyadic. The polarizability dyadic of uniaxial bi-anisotropic inclusions can be written as [12]

$$\overline{\overline{\hat{\alpha}}}_{ee} = \hat{\alpha}_{ee}^{co}\overline{\overline{I}}_t + \hat{\alpha}_{ee}^{cr}\overline{\overline{J}}_t \tag{2}$$

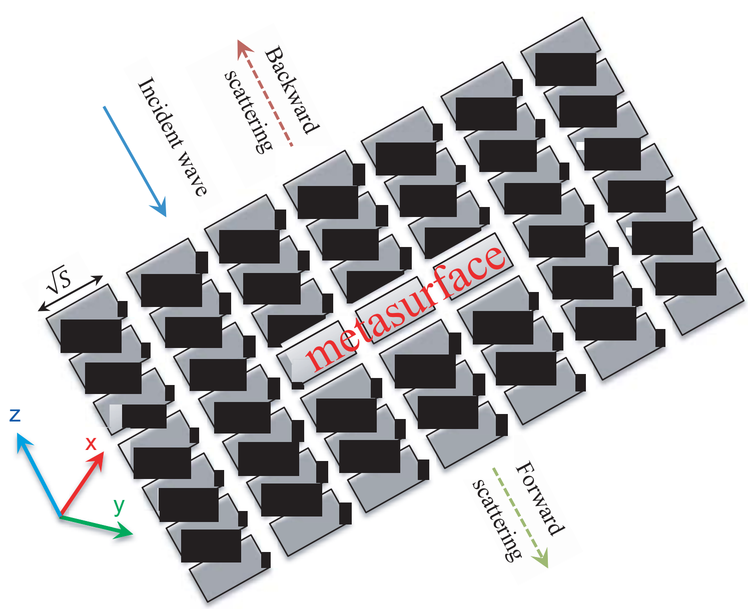


Figure 1. A schematic illustration of a generic, electrically thin metasurface.

$$\overline{\overline{\hat{\alpha}}}_{em} = \hat{\alpha}_{em}^{co}\overline{\overline{I}}_t + \hat{\alpha}_{em}^{cr}\overline{\overline{J}}_t \tag{3}$$

$$\overline{\overline{\hat{\alpha}}}_{me} = \hat{\alpha}_{me}^{co}\overline{\overline{I}}_t + \hat{\alpha}_{me}^{cr}\overline{\overline{J}}_t \tag{4}$$

$$\overline{\overline{\hat{\alpha}}}_{mm} = \hat{\alpha}_{mm}^{co}\overline{\overline{I}}_t + \hat{\alpha}_{mm}^{cr}\overline{\overline{J}}_t \tag{5}$$

where $\overline{\overline{I}}_t = \overline{\overline{I}} - z_0 z_0$ is the two-dimensional unit dyadic, $\overline{\overline{J}}_t = z_0 \times \overline{\overline{I}}_t$, and indices "co" and "cr" specify the symmetric and antisymmetric parts of the dyadic, respectively. For more convenient calculations, the coupling coefficients can be investigated aside for reciprocal and nonreciprocal cases in the form

$$\overline{\overline{\hat{\alpha}}}_{em} = (\hat{\chi} + j\hat{\kappa})\overline{\overline{I}}_t + \left(\hat{V} + j\hat{\Omega}\right)\overline{\overline{J}}_t \tag{6}$$

$$\overline{\overline{\hat{\alpha}}}_{me} = (\hat{\chi} - j\hat{\kappa})\overline{\overline{I}}_t + \left(-\hat{V} + j\hat{\Omega}\right)\overline{\overline{J}}_t \tag{7}$$

The magnetoelectric coupling interactions can be classified into two different types using reciprocity and the symmetry of their magnetoelectric coupling dyadic. The first type is reciprocal classes (the parameters $\hat{\kappa}$ and $\hat{\Omega}$ refer to "chiral" and "omega" particles, respectively), and the other is nonreciprocal classes (the parameters $\hat{V}$ and $\hat{\chi}$ refer to "moving" and "Tellegen" particles, respectively). It should be noted that for reciprocal types the electric and magnetic polarizabilities $\overline{\overline{\hat{\alpha}}}_{ee}$ and $\overline{\overline{\hat{\alpha}}}_{mm}$ are symmetric dyadic [19].

2.1. Optimal Particles for Uniaxial Arrays of Reciprocal Bi-Anisotropic Particles for Maximum Electromagnetic Energy Harvesting

Let consider a uniaxial infinite array that all polarizability dyadic are symmetric. The parameters $\hat{\alpha}_{ee}^{cr}$, $\hat{\alpha}_{mm}^{cr}$, and $\hat{\kappa}$ equal zero for a case of reciprocal and polarization-insensitive inclusions as non-chiral metasurface energy harvester. By engineered designing random composite or regular arrays of chiral inclusions over a perfectly conducting ground plane one can form the overall non-chiral structure. The direction of the two-dimensional array in space is defined by the unit vector orthogonal to its plane (z-direction). The electromagnetic fields in the presence of the infinite array can be calculated as [12]

$$\mathbf{E_r} = -\frac{j\omega}{2S}\left(\eta_0\hat{\alpha}_{ee}^{co} \pm 2j\hat{\Omega} - \frac{1}{\eta_0}\hat{\alpha}_{mm}^{co}\right)\cdot\mathbf{E_{inc}} \tag{8}$$

$$\mathbf{E_t} = \left(1 - \frac{j\omega}{2S}\left(\eta_0\hat{\alpha}_{ee}^{co} + \frac{1}{\eta_0}\hat{\alpha}_{mm}^{co}\right)\right)\cdot\mathbf{E_{inc}} \tag{9}$$

where S is the area of a unit cell, and the $\pm$ signs refer to illuminations from the two sides of the metasurface. When the reflection coefficient is the same for illumination from both sides, magnetoelectric coupling in the metasurface is equal to zero ($\hat{\Omega} = 0$). The incident plane wave field defined as

$$\mathbf{E_{inc}} = \hat{x}E_0 e^{jkz} \tag{10}$$

In fact, metasurface-based energy harvester which captures incident fields energy on both sides of the metasurface is simple electrically and magnetically polarizable particles (no bianisotropy). Thin metasurface-based energy harvester which captures incident fields energy only on one side of the metasurface is a bianisotropic metasurface with the antisymmetric coupling dyadic (Omega structures), meaning that only one side of the metasurface is perfectly energy harvesting, while the other side is covered by a surface with an unknown reflection coefficient R_v and reads

$$-\frac{j\omega}{2S}\left(\eta_0\hat{\alpha}_{ee}^{co} - 2j\hat{\Omega} - \frac{1}{\eta_0}\hat{\alpha}_{mm}^{co}\right) = R_v \tag{11}$$

Since the infinite array fields are periodically uniform, to calculate the real power dissipated in the unit cell of the array, we can integrate the real part of the Poynting vector dotted with the inward-pointing unit normal vector of a surface that encloses the unit cell. This leads to calculating the power flow into the top side of the enclosing surface owing to the incident field and subtracting the power flow out of the top and bottom sides of the surface owing to the total field incident plus re-radiation. Thus, we can calculate the real power dissipated in the load of the particle in the form [20]

$$P_L = \frac{1}{2}\mathrm{Re}\left\{\overline{E_T} \times \overline{H_T^*}\right\} \cdot \overline{ds} \tag{12}$$

$$P_L = \frac{S}{2\eta_0}|E_0|^2\left(1 - |R|^2 - |T|^2\right) \tag{13}$$

$$P_L = \frac{S}{2\eta_0}|E_0|^2\left(1 - \left|\frac{j\omega}{2S}\left(\eta_0\hat{\alpha}_{ee}^{co} + 2j\hat{\Omega} - \frac{1}{\eta_0}\hat{\alpha}_{mm}^{co}\right)\right|^2 - \left|\left(1 - \frac{j\omega}{2S}\left(\eta_0\hat{\alpha}_{ee}^{co} + \frac{1}{\eta_0}\hat{\alpha}_{mm}^{co}\right)\right)\right|^2\right) \tag{14}$$

Let us recall that at resonant frequency, electric and magnetic polarizabilities are purely imaginary whereas the magnetoelectric coupling is real. To achieve the maximum load power by differentiating concerning the collective polarizabilities $\hat{\alpha}_{ee}^{co}$ and $\hat{\alpha}_{mm}^{co}$ and equal to zero, two linear equations can be obtained as

$$1 - \left(\frac{\omega\eta_0}{S}\right)\mathrm{Im}\left(\hat{\alpha}_{ee}^{co}\right) + \left(\frac{\omega}{S}\right)\hat{\Omega} = 0 \tag{15}$$

$$1 - \left(\frac{\omega}{\eta_0 S}\right)\mathrm{Im}\left(\hat{\alpha}_{mm}^{co}\right) - \left(\frac{\omega}{S}\right)\hat{\Omega} = 0 \tag{16}$$

Substituting Eq. (6) in Eqs. (8) and (9), we find

$$-3\left(\frac{\omega\eta_0}{2S}\right)\mathrm{Im}\left(\hat{\alpha}_{ee}^{co}\right) + \left(\frac{\omega\eta_0}{2S}\right)\mathrm{Im}\left(\hat{\alpha}_{mm}^{co}\right) = R_v - 1 \tag{17}$$

$$-3\left(\frac{\omega}{2\eta_0 S}\right)\mathrm{Im}\left(\hat{\alpha}_{mm}^{co}\right) + \left(\frac{\omega}{2\eta_0 S}\right)\mathrm{Im}\left(\hat{\alpha}_{ee}^{co}\right) = -R_v - 1 \tag{18}$$

Solving the above equations, the optimal polarizabilities can be written as

$$\hat{\alpha}_{ee}^{co} = \left(1 - \frac{R_v}{2}\right)\frac{S}{j\omega\eta_0} \tag{19}$$

$$\hat{\alpha}_{mm}^{co} = \left(1 + \frac{R_v}{2}\right)\frac{\eta_0 S}{j\omega} \tag{20}$$

$$\hat{\Omega} = -\frac{SR_v}{2\omega} \tag{21}$$

When a planar uniaxial bianisotropic layer covers a perfectly conducting surface, the reflection coefficient due to waves propagating along z_0 equals -1. In this case, due to the omega coupling, the induced electric and magnetic surface-current densities are balanced. Realizing the symmetric energy harvesting from both sides of a metasurface, the optimal polarizabilities read

$$\hat{\alpha}_{ee}^{co} = \frac{1}{\eta_0^2}\hat{\alpha}_{mm}^{co} = \frac{S}{j\omega\eta_0} \tag{22}$$

In this case, the metasurface should be non-bianisotropic, and there is no magnetoelectric coupling ($\hat{\Omega} = 0$). Under these conditions, the maximum value of load power can be found as

$$P_L^{\max} = \frac{S}{2\eta_0}|E_0|^2 \tag{23}$$

So the maximum effective aperture area of a unit cell of the uniaxial infinite array reads

$$A_e^{\max} = \frac{P_L^{\max}}{S^{inc}} = S \tag{24}$$

where

$$S^{inc} = \frac{|E_0|^2}{2\eta_0} \tag{25}$$

On the other hand, one can define the ratio of load power to incident power (energy harvesting efficiency) over a unit cell as

$$\eta_{\text{eff}} = \frac{P_L^{max}}{SS^{inc}} = 1 \tag{26}$$

where S is the area of a unit cell. For the convenient design of particle configuration, we can use the relation between individual polarizabilities of the inclusions in free space and the effective ones as [21]

$$\text{Im}\left(\frac{1}{\alpha_{ee}}\right) = \text{Im}\left(\frac{1}{\hat{\alpha}_{ee}^{co}}\right) + \text{Im}(\beta_e) \tag{27}$$

where β_e is the so-called interaction constant which can be calculated analytically for $ka \leq 1.5$ as [22]

$$\text{Im}(\beta_e) = \frac{k}{2\varepsilon_0 a^2} - \frac{k^3}{6\pi\varepsilon_0} \tag{28}$$

where a is the lattice constant. According to the mentioned expressions, the optimal individual polarizabilities of the unit cells of a metasurface energy harvester using the known expression for the interaction constant can be obtained. So at the resonant frequency, the individual polarizability of the particles reads

$$\text{Im}\left(\frac{1}{\alpha_{ee}}\right) = \frac{\omega\eta_0}{S} + \frac{k}{2\varepsilon_0 a^2} - \frac{k^3}{6\pi\varepsilon_0} \tag{29}$$

2.2. Optimal Particles for an Infinite Receiving Huygens' Metasurface over a Ground Plane

In this section, we consider an infinite receiving Huygens' metasurface in the $z = d$ plane loaded over a perfect ground plane in the $z = 0$ plane. Consider the incident field as

$$\mathbf{E_{inc}} = \hat{x}E_0(e^{jkz} - e^{-jkz}) \tag{30}$$

In this case, the real power dissipated in a load of a particle can be found as

$$P_L = \frac{S}{2\eta_0}|E_0|^2\left(1 - \left|-e^{-jkd} + R\left(e^{-jkd} - e^{-j3kd}\right)\right|^2\right) \tag{31}$$

$$P_L = 2\frac{S}{2\eta_0}|E_0|^2\left(1 - \cos(2kd)\right)\left(R - R^2\right) \tag{32}$$

The optimal amplitude coefficient for the scattering field can be found by maximizing the load power as

$$R = \frac{1}{2} \tag{33}$$

The maximum effective aperture area of a unit cell of the infinite receiving array of induced electric dipole moments is

$$A_e^{\max} = \frac{P_L^{\max}}{S^{inc}} \tag{34}$$

where

$$S^{inc} = \frac{|E_0|^2}{2\eta_0} \tag{35}$$

In this case, the energy harvesting efficiency over a single unit cell can be written as

$$\eta_{\text{eff}} = \frac{P_L^{\max}}{SS^{inc}} = \frac{1}{2}\left(1 - \cos(2kd)\right) \tag{36}$$

The above equation shows that for the Salisbury absorber ($d = \lambda/4$) [23] the receive aperture efficiency is 100%. To achieve maximum energy harvesting, the collective polarizabilities can be found as

$$\hat{\alpha}_{ee}^{co} = \frac{1}{\eta_0^2}\hat{\alpha}_{mm}^{co} = \frac{jS}{\omega\eta_0} \tag{37}$$

where S is the area of a unit cell. In this case, the individual polarizabilities of the inclusions read

$$\mathrm{Im}\left(\frac{1}{\alpha_{ee}}\right)=-\frac{\omega\eta_0}{S}+\frac{k}{2\varepsilon_0 a^2}-\frac{k^3}{6\pi\varepsilon_0} \tag{38}$$

3. OPTIMAL CHIRAL PARTICLE ILLUMINATED BY A CIRCULARLY POLARIZED PROPAGATING WAVE

Let consider a metasurface formed by identical subwavelength electrically and magnetically polarizable inclusions which are illuminated by a circularly polarized incident field where $E_y=\pm jE_x$. For the axially incident waves, both chiral and moving inclusion coupling terms are required, and the extracted power by the particle follows as [24]

$$P_{ext}=\frac{\omega}{2}|\mathbf{E_{inc}}|^2\mathrm{Im}\left(\hat{\alpha}_{ee}^{co}-\frac{2}{\eta_0}\left(\hat{V}\mp\hat{\kappa}\right)+\frac{1}{\eta_0^2}\hat{\alpha}_{mm}^{co}\pm\left(\hat{\alpha}_{ee}^{co}+\frac{1}{\eta_0^2}\hat{\alpha}_{mm}^{cr}\right)\right) \tag{39}$$

where

$$j\hat{\kappa}\overline{\overline{I}}_t=\overline{\overline{\hat{\alpha}}}_{em}=-\overline{\overline{\hat{\alpha}}}_{me} \tag{40}$$

Assuming that the particles are reciprocal which means that parameter $\hat{V}$ equals zero. Thus the real power dissipated in the dipole load of a particle can be written as

$$P_L=\frac{S}{2\eta_0}|E_0|^2\left(1-|R|^2-|T|^2\right) \tag{41}$$

$$P_L=\frac{S}{2\eta_0}|E_0|^2\left(1-\left|\frac{j\omega}{2S}\left(\eta_0\hat{\alpha}_{ee}^{co}-\frac{1}{\eta_0}\hat{\alpha}_{mm}^{co}\right)\right|^2-\left|\left(1-\frac{j\omega}{2S}\left(\eta_0\hat{\alpha}_{ee}^{co}+\frac{1}{\eta_0}\hat{\alpha}_{mm}^{co}\right)\right)\pm j\frac{\omega}{S}\hat{\kappa}\right|^2\right) \tag{42}$$

So the energy harvesting efficiency over a single unit cell is

$$\eta_{\mathrm{eff}}=\frac{P_L^{\max}}{SS^{inc}}=1-\left|\frac{j\omega}{2S}\left(\eta_0\hat{\alpha}_{ee}^{co}-\frac{1}{\eta_0}\hat{\alpha}_{mm}^{co}\right)\right|^2-\left|\left(1-\frac{j\omega}{2S}\left(\eta_0\hat{\alpha}_{ee}^{co}+\frac{1}{\eta_0}\hat{\alpha}_{mm}^{co}\right)\right)\pm j\frac{\omega}{S}\hat{\kappa}\right|^2 \tag{43}$$

For the most general linear particle we can use the inverse polarizability in the form

$$\frac{1}{\hat{\alpha}_{ee}^{co}}=\hat{\xi} \tag{44}$$

where $\hat{\xi}=\hat{\xi}'+j\hat{\xi}''$ depends on the configuration, material, and resonant frequency of the particle. $\hat{\xi}'=0$ is corresponding to the resonant frequency of the particle. So at the resonant frequency, we can write for the inverse polarizability using

$$\hat{\alpha}_{ee}^{co}=\frac{1}{j\hat{\xi}''}=\frac{1}{j\mathrm{Im}\left(\frac{1}{\hat{\alpha}_{ee}^{co}}\right)} \tag{45}$$

Under this condition, the ratio of load power to incident power (energy harvesting efficiency) over a single unit cell can be calculated as

$$\eta_{\mathrm{eff}}=1-\left(\frac{\omega\eta_0}{2S}\left(\frac{1}{\mathrm{Im}\left(\frac{1}{\hat{\alpha}_{ee}^{co}}\right)}-\frac{1}{\eta_0^2}\frac{1}{\mathrm{Im}\left(\frac{1}{\hat{\alpha}_{mm}^{co}}\right)}\right)\right)^2-\left(1-\frac{\omega\eta_0}{2S}\left(\frac{1}{\mathrm{Im}\left(\frac{1}{\hat{\alpha}_{ee}^{co}}\right)}+\frac{1}{\eta_0^2}\frac{1}{\mathrm{Im}\left(\frac{1}{\hat{\alpha}_{mm}^{co}}\right)}\right)\pm\frac{\omega}{S}\mathrm{Im}\left(\hat{\kappa}\right)\right)^2 \tag{46}$$

where

$$\mathrm{Im}\left(\frac{1}{\hat{\alpha}_{ee}^{co}}\right)=\mathrm{Im}\left(\frac{1}{\alpha_{ee}}\right)-\mathrm{Im}(\beta_e) \tag{47}$$

$$\mathrm{Im}\left(\frac{1}{\hat{\alpha}_{mm}^{co}}\right)=\mathrm{Im}\left(\frac{1}{\alpha_{mm}}\right)-\mathrm{Im}(\beta_m) \tag{48}$$

and

$$\beta_m = \beta_e/\eta_0^2 \tag{49}$$

To achieve the maximum energy harvesting efficiency, all the collective polarizabilities of optimal chiral particles should be equal as

$$\eta_0\hat{\alpha}_{ee}^{co} = \pm\hat{\kappa} = \frac{1}{\eta_0}\hat{\alpha}_{mm}^{co} = \frac{S}{2j\omega} \tag{50}$$

Using these obtained equations, we can find optimal chiral particles for interactions with propagating circularly polarized waves. In the following, we consider a specific example of a small chiral particle as a well-known metal canonical particle illustrated in Fig. 2(a).

This particle is formed by two small wire antennas including a short electric dipole antenna of length $2l \ll \lambda$ and a small loop antenna with the radius $b \ll \lambda$. The analytical expressions for its polarizabilities along the x-direction in terms of the parameters of the two electric and magnetic dipoles forming the particle follows as [25]

$$\alpha_{ee} = -j\frac{l^2}{\omega Z_t} \tag{51}$$

$$\alpha_{mm} = \alpha_{ee}\left(\eta_0\frac{kA}{l}\right)^2 \tag{52}$$

$$\alpha_{em} = j\kappa = \pm j\alpha_{ee}\eta_0\frac{kA}{l} \tag{53}$$

where Z_t is the total impedance of the particle so that it is the sum of the input impedance of the loop and electric dipole antennas and resistive load, $A = b\pi^2$ the loop area, and η_0 the impedance of free space. At the resonance of the particle $Z_t = R_t + jX_t$ is a real number, and its imaginary part equals zero. Due to the anyway present scattering losses, this value is nonzero even in the absence of absorption in the particle. For particles without absorption loss and due to the scattering loss, R_t can be written as [26]

$$R_t = 2R_{rad} = \frac{\eta_0}{3\pi}\left(k^2l^2 + k^4A^2\right) \tag{54}$$

where R_{rad} is the radiation resistance of the particle. To deliver the maximum power to the load, R_{load} must be equal to R_{rad}. At the fundamental resonance frequency, the total length of the antenna constituent wire $2l + 2\pi b$ is approximately $\lambda/2$, and imaginary part of the impedance of the particle is zero. Under these conditions and using Eq. (50), we can write

$$\mathrm{Im}\left(\frac{1}{\hat{\alpha}_{ee}^{co}}\right) = \eta_0^2\mathrm{Im}\left(\frac{1}{\hat{\alpha}_{mm}^{co}}\right) \tag{55}$$

Substituting Eqs. (47) and (48) in the above equation

$$\mathrm{Im}\left(\frac{1}{\alpha_{ee}}\right) - \mathrm{Im}\beta_e = \eta_0^2\left(\mathrm{Im}\left(\frac{1}{\alpha_{mm}}\right) - \frac{1}{\eta_0^2}\mathrm{Im}(\beta_e)\right) \tag{56}$$

Solving Eq. (56) and using Eqs. (51) and (52), we can calculate optimal dimensions as:

$$l_{opt} = \left(2 - \sqrt{3}\right)\frac{\lambda}{4} \tag{57}$$

$$b_{opt} = \left(\frac{\sqrt{3}-1}{\pi}\right)\frac{\lambda}{4} \tag{58}$$

that is consistent with the proven results presented in [24].

In the next step, we obtain the optimal lattice constant using Eqs. (50), (51), and (54). After some simple algebraic calculations, the following equations can be obtained as

$$\mathrm{Im}\left(\frac{1}{\hat{\alpha}_{ee}^{co}}\right) = \frac{2\eta_0\omega}{S} \tag{59}$$

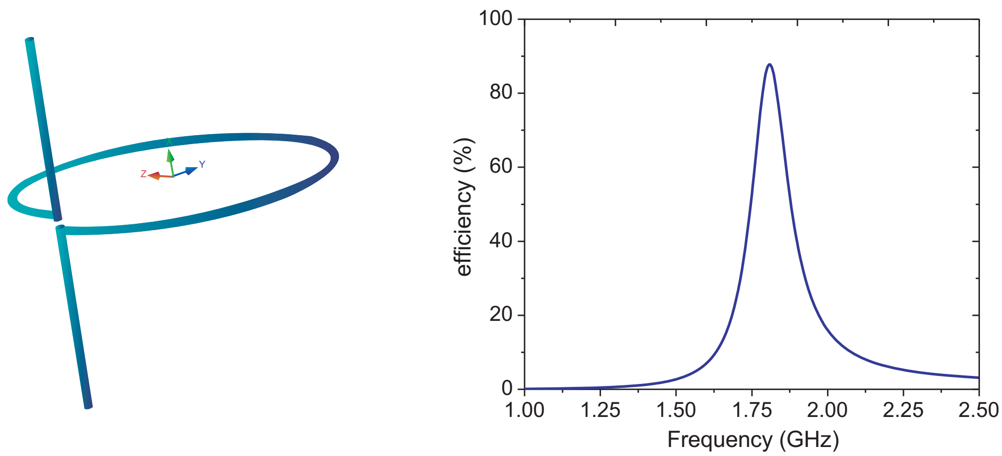
$$\frac{k^2\left(l^2 + \frac{k^2}{\pi^2}\left(\frac{\lambda}{4} - l\right)\right)}{3\pi l^2} - \frac{1}{2a^2} + \frac{k^2}{6\pi} = \frac{2}{S} \tag{60}$$

Substituting Eq. (57) in the above equation, the optimal lattice constant leading to maximum possible efficiency can be found as

$$a^2 = \frac{1}{\dfrac{20\pi}{3\lambda^2} - \dfrac{4}{S}} \tag{61}$$

This expression is the trade-off between the cell area and the lattice constant. By defining the optimum dimensions of the desired sub-wavelength polarizable inclusions, the lattice constant can be determined using the above expression so that the maximum possible efficiency will be achieved in bi-anisotropic metasurface design.

In order to validate the proposed theory with full-wave results, a metasurface energy harvester composed of chiral particles as collectors is designed, and its electromagnetic response is simulated by CST Microwave Studio using the unit cell boundary condition. Using Equations (59), (60), and (61) as well as the CST Microwave Studio optimization tool, the dimensions and the lattice constant are obtained. In fact, the proven analytical expressions can be useful for the initial design of the proposed energy harvester formed by the chiral particles. The energy harvesting efficiency for this configuration is shown in Fig. 2(b). As can be seen from the figure, maximum efficiency of 90% is obtained at the resonant frequency for the proposed array of proposed inclusions.



(a) (b)

Figure 2. (a) A canonical chiral particle along axis x, and (b) energy harvesting efficiency for the proposed metasurface harvster composing chiral particles with optimized dimension of $l = 10.05\,\text{mm}$, $b = 8.74\,\text{mm}$, and lattice constant $a = 26.61\,\text{mm}$.

4. CONCLUSION

In this paper, we have obtained optimal bi-anisotropic particles to achieve 100% efficiency of an energy harvesting system. In this section, we show that the optimum bi-anisotropic particles can capture the energy of the ambient electromagnetic radiation waves and deliver it to the load. Finally, we investigate a canonical chiral particle and calculate its optimum dimensions to satisfy the maximum efficiency (ratio of radiation power to AC power). The proposed system was previously used as a perfect electromagnetic absorber, which we have introduced in this paper by adding a resistive load to the particle structure as a metasurface energy harvester.

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