FACTA UNIVERSITATIS
Series: **Electronics and Energetics** Vol. 27, N° 2, June 2014, pp. 183 - 203
DOI: 10.2298/FUEE1402183J

PLASMONIC ENHANCEMENT OF LIGHT TRAPPING IN PHOTODETECTORS

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Abstract. *We consider the possibility to use plasmonics to enhance light trapping in such semiconductor detectors as solar cells and infrared detectors for night vision. Plasmonic structures can transform propagating electromagnetic waves into evanescent waves with the local density of states vastly increased within subwavelength volumes compared to the free space, thus surpassing the conventional methods for photon management. We show how one may utilize plasmonic nanoparticles both to squeeze the optical field into the active region and to increase the optical path by Mie scattering, apply ordered plasmonic nanocomposites (subwavelength plasmonic crystals or plasmonic metamaterials), or design nanoantennas to maximize absorption within the detector. We show that many approaches used for solar cells can be also utilized in infrared range if different redshifting strategies are applied.*

Key words: *Plasmonics, Metamaterials, Nanoantennas, Solar Cells, Infrared Detectors, Light Trapping*

1. INTRODUCTION

An important requirement posed in photodetector design is to maximize the useful photon flux for a given physical thickness of active region of the device [1]. Probably the most important type of such devices nowadays are solar cells [2-4]. They are basically photovoltaic detectors where an optical signal (radiation of the sun) is converted to voltage and thus to useful energy. Since materials for solar cells are expensive, it is of interest to make their active region as thin as possible. Another important class of the devices are infrared (IR) detectors [5] used in e.g. remote sensing, night vision, etc. Since they are intended for larger wavelengths – typically they operate within the atmospheric windows at (3-5) μm or (8-12) μm – their thickness is usually relatively small compared to the operating wavelength.

Received January 14, 2014
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Actually both the thickness of solar cells and night vision devices may be in subwavelength domain, i.e. smaller than the operating wavelength. A requirement posed to the designers in both situations is how to maximize optical trapping within such thin active regions.

An important aspect of decreasing the thickness in the case of general semiconductor detectors is that it is followed by an increase of the response speed. Thus the basic task in the design of such detectors is to maintain or even improve quantum efficiency in the operating wavelength range while decreasing the thickness as much as possible.

The engineering methods dedicated to maximization of the available optical flux in photodetectors are termed the photon management or the light management [6]. Several general strategies are available for this purpose [7], as shown in Fig. 1.

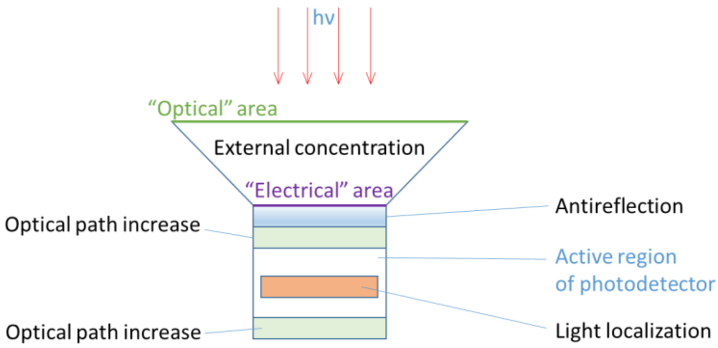


Fig. 1 Strategies for maximization of optical flux in photodetector

First, one may perform external light concentration and collect optical energy from an incident area larger than the physical dimensions of the detector active region itself (photon collector). A typical example of this approach would be the use of concentrating lenses or reflectors that gather irradiation from the so-called optical area and focus it onto the electric area of the detector. Non-imaging collectors can be used to that purpose [8-11].

After the signal has reached the active area of the detector, various antireflection coatings and structures can be used to decrease the reflected component of the incident radiation and to allow as large part of it as possible to enter the active region itself [12]. All of these structures basically match the impedance of the free space/detector environment to that of the detector material.

Once inside the detector, one can increase the optical path through the active region, which can be done by backside reflectors redirecting radiation back to the active region, or by various scattering structures at the front and at the back side of the device which change the path of the beam to make it longer and make use of total internal reflection to return the beam to the active region. It is also possible to utilize resonant structures (resonant cavity enhancement) [13], thus obtaining a narrow-bandwidth response, or to incorporate photodetector in a photonic crystal cavity [14, 15].

Another important approach to detector enhancement after the beam has entered the active region is to perform internal optical concentration (spatial localization), i.e. to fabricate structures that will perform squeezing of the optical space from a larger volume to a smaller one, thus increasing the local density of states of optical energy within the latter.

The last two approaches, i.e. optical path increase and spatial localization belong to the light trapping schemes. The advent of nanostructuring technologies brought an impetus to this field. Various building blocks with nanometer dimensions have been proposed for e.g. solar cell energy harvesting improvement, including nanoparticles, nanowires, different core-shell geometries, colloidal quantum dots, etc. [16, 17].

Recently the use of plasmonics appeared as a novel approach to nanotechnological improvement of photodetector light trapping [18-23].

Basically, plasmonics represents the use of coupled electron oscillations and surface-bound electromagnetic waves called surface plasmons polaritons (SPP). This is achieved through utilization of metal-dielectric nanocomposites that can be designed to obtain almost any desired optical properties and thus almost complete control over electromagnetic propagation in and around such structures [24]. Even the values of optical parameters not ordinarily met in nature can be obtained, like near-zero or even negative values of refractive index [25, 26]. Such ability to engineer optical parameters at will brought to almost complete control over the propagation of electromagnetic waves and resulted in the appearance of transformation optics [27-29], where one optical space is transformed into another. One of the obvious application of plasmonics has been to “squeeze” the optical space to a much smaller volume than that of the free space. In this way high localizations of the electromagnetic field became possible, i.e. local densities of electromagnetic states much larger than those in the free space.

In this paper we consider the use of plasmonics in light trapping in (ultra)thin photodetectors including solar cells and night vision detectors. After considering the fundamental limits to photon management in detectors from the point of view of subwavelength structures, we investigate the basic schemes for light trapping using plasmonics. We analyze the applicability of plasmonic nanoparticles both for field scattering and localization within the detector, the use of subwavelength plasmonic crystals and the possibility to redshift the device response utilizing the designer plasmons. We consider the utilization of dedicated optical antennas (nanoantennas) for detector enhancement. At the end we show how some of the schemes utilized for visible and near infrared radiation can be applied for night vision detectors through the application of different redshifting strategies.

2. FUNDAMENTAL LIMITS TO LIGHT MANAGEMENT IN DETECTORS

We consider a general case of a photodetector as a device that converts optical energy into another form of energy. Most often this energy is electrical signal, although other forms may be used like thermal [30], motion (e.g. cantilever-based detectors) [31], optical signal at another frequency (up- or down-converted) [32, 33] etc. Basically, different light management approaches are intended to improve absorption of light in the detector and ensure a higher degree of this conversion. Obviously, the efficiency of any conversion is limited by basic physical laws. A question is posed what are the fundamental limits of photodetector enhancement through light management.

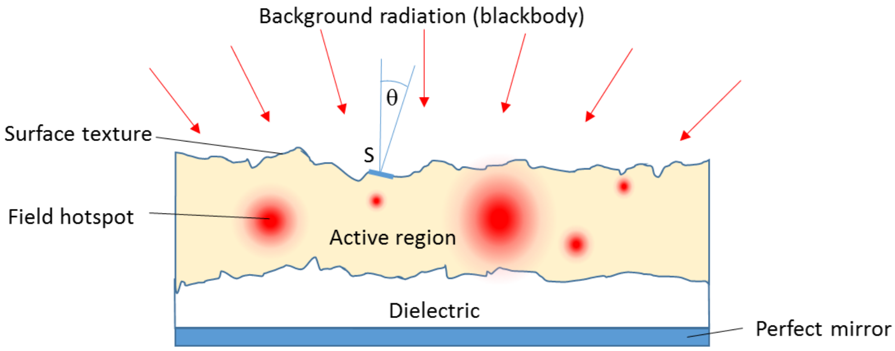


Fig. 2 The structure of the active region of a detector with corrugated surface and ideal backside reflector

A detector system is presented in Fig. 2. A background optical flux is incident to the active area of a photodetector with a thickness d. Both in the case of solar cells and night vision photodetectors the optical flux is blackbody radiation, described by the Planck's law. In a general case the detector material may incorporate nanostructuring that could localize optical field and create hotspots with high density of states. A perfect mirror is placed at the rear side of the device – i.e. it is assumed that the incident light is unidirectional, while the internal radiation is bidirectional.

The detector surface is corrugated in order to increase the optical path through the detector. The corrugation may be random or ordered, but in both cases its basic purpose is to change the direction of light incident upon the active surface and to make use of total internal reflection to ensure repeated passing of the beams through the active region. Light can escape if the direction of the internal beam falls within the escape cone, for which according to Snell's law $\sin\theta_{cr} = 1/n$ (θ_{cr} is the critical angle of total reflection, n is the refractive index of the active region).

We first consider the case limited by geometrical optics, which has been established by Yablonovitch [34-37]. In literature it is variably denoted as the conventional limit, the ergodic light trapping limit, the ray-optics limit and the Lambertian limit. It is assumed that the detector active material can be described by an effective absorption coefficient α isotropic throughout the device and that the detector thickness is much larger than the operating wavelength in free space ($d >> \lambda/2n$), so that one considers a bulk process. The absorbance within the photodetector for a single pass across the structure (absorption without enhancement) is

$$A(\omega) = 1 - \exp(-\alpha(\omega)d) \approx \alpha(w)d\ , \qquad (1)$$

i.e. the absorbance is equal to the optical thickness of a photodetector, which is defined as the $\alpha(\omega)d$ product.

Since a bulk case is considered, it is further assumed that interference/diffraction effects can be neglected and that the intensity of light within the detector medium is in equilibrium with external blackbody radiation. The density of states within the medium is proportional to n^2. The next assumptions are that the equipartition theorem is valid (the internal occupation of states is equal to the external one, the internal states are ergodic) and that the surface corrugation performs a full randomization of the incident signal over space. This is not always satisfied, but the assumption holds in a vast majority of cases. A sufficient condition for randomization of light by multiply scattering corrugated surfaces is that these surfaces upon averaging behave as Lambertian. The internal distribution of the light within the medium is then isotropic.

According to the statistical ray optics approach [34] the relation between internal and external intensity of light is

$$I_{\mathrm{int}}(\omega, x) = 2n^2(\omega, x) I_{ext}(\omega) \,. \tag{2}$$

The same result is also obtained according to the principle of detailed balancing of the light [38] applied between the light incident to a small surface element of the detector active area and escaping from that same element through the loss cone and by applying the brightness or radiance theorem (e. g. [39]) stating that the spectral radiance of light cannot be increased by passive optical devices (based on the principle of reversibility).

To determine the enhancement of absorption, one has to consider the loss of light due to various mechanisms. According to Yablonovitch [34, 35] there are three such mechanisms: the escape of light through the light cone, the losses due to imperfect reflection at the surfaces and the absorption in bulk. The absorbance of a photon is the ratio of the rate at which absorption occurs and the sum of the absorption and the photon loss through the escape cone. For the volume absorption in the limiting case when $\alpha(\omega)d \ll 1$ and taking account the angle of the loss cone θ, this expression is

$$A(\omega) = \frac{\alpha(\omega)}{\alpha(\omega) + \dfrac{\sin^2\theta}{4n^2 d}} \,, \tag{3}$$

so that the absorption enhancement limit in the bulk case with internal randomization becomes $4n^2$. For $\theta = \pi/2$ this assumes the more often used simple form

$$A(\omega) = \frac{\alpha(\omega)}{\alpha(\omega) + \dfrac{1}{4n^2 d}} \,. \tag{4}$$

The next case we consider are the devices with plasmonic localization for the enhancement of absorption. In this case many of the above assumptions introduced for ergodic limit are not valid. The crucial points are that the light distribution now is not isotropic (and actually the volumes with a strongly enhanced density of electromagnetic states may be deeply subwavelength) and the thickness of the detector is usually subwavelength.

A number of treatises is dedicated to the situations in which the ray optics limit is exceeded and optical modes are confined at subwavelength scale [40-42]. However, until now no generally valid solution has been given for the extension of the ray optics limit [43].

3. PLASMONICS FOR LIGHT TRAPPING

Surface plasmons polaritons (SPP) are oscillations of free electrons in conductive material near an interface with dielectric coherently coupled with electromagnetic radiation at the interface. The conductive material can be characterized by negative value of dielectric permittivity, while that in dielectric is positive. Typically the conductive material is metal (most often used being gold and silver, although other metals are used like chromium, copper, various alloys, alkali metals, etc.), however other materials are used too, for instance transparent conductive oxides like indium tin oxide, zinc oxide, tin oxide, etc. (in near infrared), different semiconductors like silicon carbide, gallium arsenide (mid infrared), intermetallics, graphene and some other materials, all being denoted as plasmonic materials [44-46]. The SPP is related with electromagnetic waves that are confined to the interface between positive and negative permittivity materials and are evanescent in perpendicular direction, i.e. they exponentially decay away from the interface. SPPs can be propagating along the interface, or they can be nonpropagating, i.e. spatially confined to e.g. a metal nanoparticle (localized surface plasmons polaritons). Generally, the rapidly expanding field of research and application of SPP-based phenomena is denoted as plasmonics [24, 47-49].

The field of plasmonics is dedicated to the use of SPPs in a similar way electrons are used in electronics. This is achieved via engineering of nano-composites that combine materials with positive and with negative values of dielectric permittivity in a certain frequency range. Plasmonic nanocomposites can be one-dimensional (1D) like planar metal-dielectric superlattices, two-dimensional (2D) like cylindrical metallic nanowires, or three-dimensional (3D) like spherical metallic nanoparticles embedded in dielectrics. These structures can be periodic, quasiperiodic [50], aperiodic [51] or fully random [52]. The building blocks of these functions themselves may have different shapes, from simple to complex and from regular to irregular [53].

Even in their simplest version, SPPs at the plane boundary between two semi-infinite media with opposite signs of dielectric permittivity are inhomogeneous electromagnetic waves (i.e. not plane waves) that propagate along the interface, and whose energy is concentrated in the narrow region near the boundary plane. This is possible only in a frequency range where the absolute value of the negative dielectric permittivity on one side is greater than the positive value on the other side of the interface. SPPs are strongly TM (transverse-magnetic) polarized, and because of that they are called *polaritons*. In other words, magnetic field and wavevector of the SPP lay in the plane of interface, while electric field of the wave has both perpendicular and parallel to the wavevector components. Therefore, SPPs are neither longitudinal nor transversal waves. It should be noted that TE polarized component of electromagnetic field cannot satisfy the Maxwell equations with standard boundary conditions, in the form of surface wave.

Plasmonic nanocomposites with two or more metal-dielectric interfaces within distances less than, or comparable to the plasmonic material skin depth (~25 nm for Au or Ag) produce strong coupling of neighbouring SPPs, and highly pronounced nonlocal effects. A plethora of new modes and possible novel effects may appear in such structures [54, 55]. Sophisticated theoretical and numerical methods are necessary in order to achieve desired nanocomposite design levels.

An important disadvantage of SPPs is their resonant nature, which causes a narrow bandwidth of operation. Another one is their large wave damping due to collisions of free carriers in the epsilon-negative material, which leads to shorter SPPs lifetimes and/or propagation lengths and high absorption of incident radiation.

The relative dielectric permittivity of plasmonic materials is negative below plasma frequency, and its dispersion is well-described by electron resonance model of Drude [56], also denoted as Drude-Sommerfeld model

$$\varepsilon = \varepsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\Gamma)}, \tag{5}$$

where ω_p is the plasma frequency, Γ denotes damping factor describing losses (i.e. defines the imaginary part of the complex dielectric permittivity), while ε_∞ is the asymptotic relative dielectric permittivity.

The plasma frequency is determined by the properties of free carriers as

$$\omega_p^2 = \frac{n_e e^2}{m^* \varepsilon_0}, \tag{6}$$

where n_e is electron concentration, e is the free electron charge ($1.6 \cdot 10^{-19}$ C), ε_0 is the free space (vacuum) permittivity ($8.854 \cdot 10^{-12}$ F/m), and m^* is the electron effective mass.

The damping factor can be calculated from the material scattering data as

$$\Gamma = \frac{e}{\mu m^*} \tag{7}$$

where μ is mobility of free carriers.

If interband transitions from the valence to the conduction bands exist, dielectric permittivity is described by the Lorentz model [57]

$$\varepsilon = \varepsilon_\infty + \frac{\omega'^2_p}{(\omega_0^2 - \omega^2) - i\Gamma'\omega}, \tag{8}$$

where ω_0 is the resonant frequency of electron oscillator, while the apostrophe in plasma frequency ω'_p and damping factor Γ' denotes that these values are related with the concentration of bound electrons taking part in the interband transitions.

Since one is able to tailor a plasmonic nanostructure, this means that dispersion relations could be designed within it, even enabling the optical behavior that surpasses that of natural materials. The structures thus obtained are known as plasmonic metamaterials [25]. In that case one can obtain modes with superluminal group velocities (“fast light”), near-zero (“slow light”) or even negative (“left-handed light,” propagating in the direction opposite to that of the phase velocity) [58]. The possibility to obtain an arbitrary frequency dispersion gives a possibility to convert propagating far field modes into spatially localized near-field modes, thus obtaining strongly increased density of states. The same energy is compacted into a much smaller space, thus ensuring much higher energy densities. This ensures highly enhanced interaction of optical radiation with photodetector material. This kind of engineering of optical absorption ensures its maximization in the active area, leading to vastly increased photodetector response and sensitivity compared to other light trapping schemes.

A drawback of the use of plasmonics in photodetection are large absorption losses in metal, which result in a large part of energy being converted to heat instead of the useful signal. This topic is a field of active investigation, and various schemes are used to avoid it [59]. One of the approaches is the use of alternative plasmonic materials, like for instance transparent conductive oxides like tin oxide, indium tin oxide or zinc oxide [60] which are routinely used in solar cells because of their transparency at visible wavelengths. Another such material for solar cell enhancement is graphene [45].

The applicability of plasmonics for photodetector enhancement has been recognized very early, in the period 1970-1980-ties, and actually some of the first proposed applications of surface plasmons polaritons were in photodetection [61, 62].

A large body of papers has been published on various methods of plasmonic enhancement in solar cells [19, 59]. Surface plasmon polariton-mediated light trapping schemes may be roughly divided into the following groups according to the particular mechanism used (and bearing in mind that a single trapping scheme may include more than one of these):

- Enhanced Mie scattering on plasmonic nanoparticles or nanovoids through plasmonic enlargement of effective cross-section [63].
- Coupling into guided modes (which may be propagating or SPP modes) [19]
- Field localization and generation of hotspots near the surface of plasmonic material (using embedded nanoparticles, nanoantennas, metamaterials) [20]
- Use of plasmon-based singular optics (optical vortices, i.e. circular flow of field in a corkscrew fashion around phase singularities in the optical near field around plasmonic nanostructures) [59]
- Use of metamaterial-based transformation optics to map the optical space into a desired shape and with an increased density of states (optical superconcentrators and superabsorbers, optical black holes) [64]
- Plasmon-enhanced up-conversion media (reverse of luminescent materials used for down-conversion) [65]

The plasmonic structures to be used for one or more of the above purposes include the following:

- Nanoparticles and nanovoids – used as scatterers and as nanoantennas for field coupling and localization. May be arranged in an ordered fashion (pattern) or disordered)
- Diffractive structures (gratings, lattices) – used for field coupling into guided modes; may be ordered or disordered.
- Subwavelength plasmonic crystals (SPC) – used for field coupling and localization. May be periodic [66] or quasiperiodic [67] in 1D, 2D or 3D.

Plasmonic structures may be used as resonant enhancers, in which case they offer a narrow-bandwidth operation, or may be nonresonant, with a wide-bandwidth operation [68].

4. Plasmonic Nanoparticles as Mie Scatterers

The scattering cross-section of a plasmonic nanoparticle is greatly enhanced due to plasma resonance compared to non-plasmonic ones. The effective cross-section may be an order of magnitude larger than the geometrical cross-section. Thus a 10% surface coverage would suffice for practically 100% efficiency of conversion from incident propagating modes into surface plasmons polaritons.

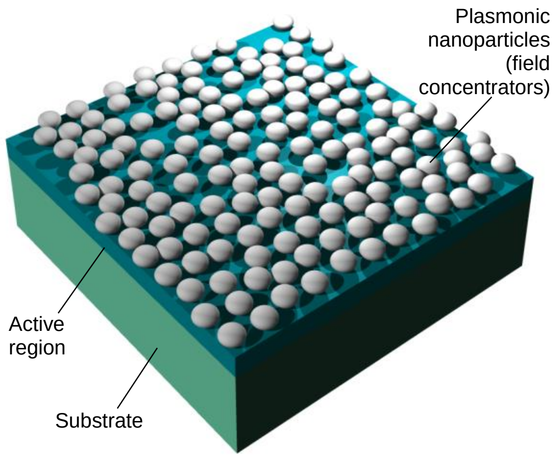


Fig. 3 Light trapping utilizing plasmonic nanoparticles stochastically placed on the detector surface

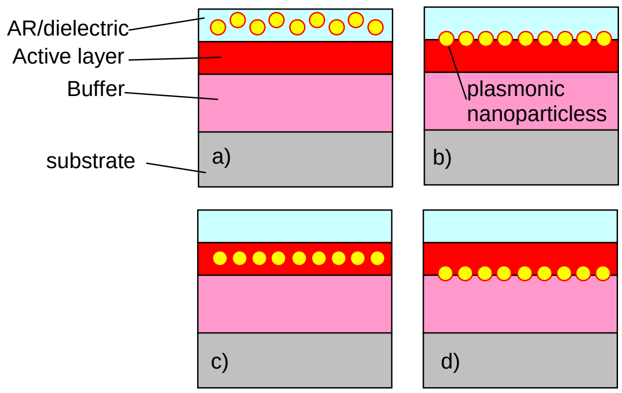


Fig. 4 Geometries for plasmonic scatterers for light trapping within photodetector. a) nanoparticles embedded in top dielectric; b) nanoparticles on top of the active region; nanoparticles embedded within the active region; d) nanoparticles on the back side

Usually the conventional Mie theory is utilized for the calculation of effective cross-sections for absorption and scattering on nanoparticles [69]. Mie theory is valid for noninteracting nanoparticles (i.e. those where the interparticle distance is large enough to prevent their electromagnetic coupling). In nanoparticles interacting through near-field coupling or far-field dipole interactions various additional phenomena appear like splitting of plasmon resonances and their shifting.

The simplest case is scattering on a spherical plasmonic nanoparticle that can be considered as an electric dipole. Its scattering cross-section at a wavelength λ can be calculated as [70, 71]

$$C_{scat} = \frac{8}{3\pi}\alpha^2\left[\frac{\pi}{\lambda}\right]^4, \tag{9}$$

where

$$\alpha = 3V\left(\frac{\varepsilon_{np}}{\varepsilon_d} - 1\right) \Big/ \left(\frac{\varepsilon_{np}}{\varepsilon_d} + 2\right). \tag{10}$$

Here ε_{np} is the complex and wavelength-dispersive relative dielectric permittivity of the plasmonic nanoparticles, ε_d is the permittivity of the surrounding dielectric medium and V is the geometrical volume of the nanoparticle. The plasmon resonance and the maximum scattering cross-section are achieved at $\varepsilon_{np} = -2\ \varepsilon_d$.

The absorption cross-section is determined as

$$C_{abs} = \frac{2\pi}{\lambda}\mathrm{Im}(\alpha)\ . \tag{11}$$

Elongated ellipse may be taken as a generalization of the case of sphere and corresponds to a single wire nanorod antenna. This structure is actually the basic building block, out of which more complex forms are built. Again the Mie theory is applicable to this case, in a somewhat modified form. The dipole moment induced by an external field in an elongated ellipsoid is

$$\mu = \varepsilon_0 V \frac{\varepsilon - \varepsilon_e}{\varepsilon P_j + \varepsilon_e(1 - P_j)}, \tag{12}$$

and its resonant frequency

$$\omega_{res} = \frac{\omega_p}{\sqrt{2}}\frac{r}{R}, \tag{13}$$

where r is short radius of the ellipsoid, and $R/2$ its longer radius.

In the most general case, the shapes of the nanoparticles widely vary and may assume different complex forms (e.g. various convex and concave polyhedra, including stellated and other forms [72]. This reflects strongly in their plasmonic response [19], since in principle sharper forms will cause larger field localizations. Mie theory has been generalized to some of the more complex forms, but in the most general case the response is calculated numerically.

5. Diffractive Plasmonic Couplers

An obvious approach to light trapping using plasmonics is to integrate the detector structure with a diffractive plasmonic structure (diffractive optical element, DOE) [73] and generally with a corrugated metal layer to act as a coupler with propagating modes. The simplest DOE is the conventional diffractive grating.

A parameter of a general diffractive optical element (DOE) that determines the degree of coupling with propagating modes is its diffraction efficiency. The diffraction efficiency is dependent on geometrical and material parameters of the plasmonic DOE, i.e. the complex refractive index of the plasmonic material (for instance, transparent conductive oxides will generally have lower losses and longer resonant wavelengths than metals), the dimensions of the DOE features (in the case of plasmonic diffractive gratings the parameters of influence will be the lattice constant (the grating element spacing), the shape and height of the grating ridges. Thus its value can be tailored and optimized by a proper choice of the quoted parameters.

The guided modes into which propagating modes are coupled by a DOE can be propagating optical modes (the conventional waveguide modes) and surface plasmon polariton modes. In an ideal case for a photodetector, all propagating modes will be converted to plasmonic ones.

Figure 5 shows two different geometries for incorporation of DOE into thin photodetectors: a) back-side DOE, b) top-side DOE. The configuration shown in Fig. 5a is more common of the two [74]. However, the second one (Fig. 5b can perform an additional function as light collector.

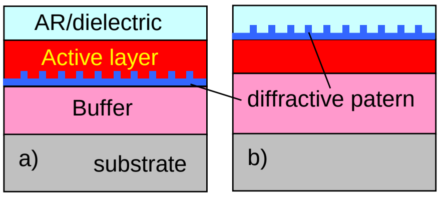


Fig. 5 Two geometries for incorporation of plasmonic DOE into a photodetector. a) bottom DOE, b) top DOE

Depending on the structure of the DOE coupler, the propagation lengths of the SPP modes may be shorter or longer [75]. Besides its function as a light trapping structure, a DOE can also serve as a light collector by its virtue of functioning as a non-imaging light concentrator [76]. In addition to that, a DOE may perform impedance matching between free space and photodetector material, thus behaving basically as a diffractive antireflection structure. For instance, 1D metallic gratings (i.e. metal surface with an array of parallel slits) have been proved to act as such impedance-matching structures [77]. This means that such grating exhibit wideband extraordinary transmission. Since this is a non-resonant phenomenon, it ensures a wide bandwidth and a broad range of incident angles.

The diffractive structure may have a form of conventional diffractive grating with parallel ridges of metal, or may be more complex (e.g. a lattice/fishnet, etc.) In a most general case it will have a form of a holographic optical element with fully tailorable properties that can be computer generated [78].

Plasmonic DOE may function in narrow-bandwidth mode near resonance, but also as non-resonant elements with wide bandwidth. A built-in plasmonic DOE in photodetector may simultaneously perform its function as a coupler and an electromagnetic field concentrator, but it may be also built to perform as a plasmonic waveguide [79, 80].

6. Subwavelength Plasmonic Crystals and Designer Plasmons

Further generalization of diffractive plasmonic structures is that to subwavelength plasmonic crystals (SPC) [81]. A SPC may be defined as a 1D, 2D or 3D plasmonic structure with its period much smaller than the operating wavelength (a rule of thumb is that the periodicity is at least ten times smaller than the operating wavelength). Thus the details of the structure are not "seen" by the incident light and it behaves as an effective medium with its optical parameters dependent on its design, thus ensuring engineering of frequency dispersion of such materials.

The number different possible kinds of SPC is virtually limitless. Plasmonic metamaterials may be regarded a special class of the SPC and are defined as the structures possessing electromagnetic properties that are not readily found in nature [25], the most often researched among such properties being the possibility to reach negative values of effective refractive index [82].

The SPC structures ensure light localization and can be therefore straightforwardly utilized to enhance optical absorption in photodetectors. In addition to that, owing to a large number of possible modes in such structures [boba], it is possible to utilize them at the same time to match the impedance between the free space and the photodetector, effectively behaving as an antireflective diffraction structure.

As an example of SPC for the enhancement of solar cells, Fan et al [83] fabricated an ordered 2D array or metal cubes (or rather cuboids) on semiconductor surface to improve light trapping.

Among SPC structures within the context of photodetection, one of the more frequently encountered ones are 2D arrays of nanoapertures in opaque metal films. Such structures first drew attention for their ability to transmit light in spite of the dimensions of nanoapertues being much smaller than the operating wavelength and were denoted as extraordinary optical transmission (EOT) arrays [84]. This behavior is a consequence of resonant excitation of SPP at their surface that forces the passage of electromagnetic waves incident to the whole surface through the apertures. Since such behavior effectively corresponds to impedance matching between propagating waves and the perforated metal film, the EOT arrays thus act as efficient antireflective structures. However, there is another useful application of the EOT arrays in photodetection (and generally structured metal-dielectric surfaces) and it is based on the properties of the surface waves that propagate along them.

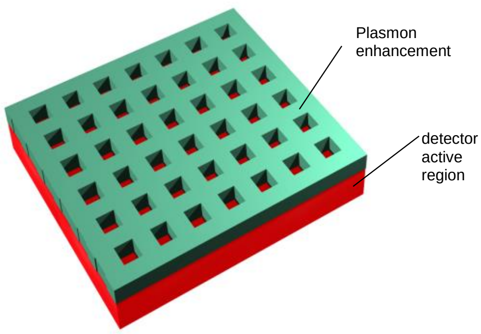


Fig. 6 Metallodielectric EOT structure introducing "designer" plasmons with structurally tunable plasma frequency

Pendry et al [85] have shown that for a surface wave that propagates along a perforated metal film one is able to introduce an effective permittivity with a form

$$\varepsilon_{in-plane} = \frac{\varepsilon_{hole}\pi^2 d^2}{8a^2}\left(1 - \frac{\pi^2 c^2}{a^2\omega^2\varepsilon_{hole}\mu_{hole}}\right) \tag{14}$$

where ε_{hole} is the permittivity of the material within the holes, a is the hole side length (in the case of square holes, as shown in Fig. 6) , and k_0 is the wavevector in vacuum. The effective plasma frequency of such material is

$$\omega_p = \frac{\pi c}{a\sqrt{\varepsilon_{hole}\mu_{hole}}} \tag{15}$$

In other words, the effective dielectric permittivity of an EOT array has the form identical to that of plasmonic materials. Such surface waves that mimic SPP were denoted by Pendry the designer plasmons, and are also known as "spoof" plasmons. Their main advantage is that one is able to tune the effective plasma frequency by a proper choice of geometry and material parameters and thus to shift it at will. An obvious application of this approach was for infrared detectors and structures tuned to the range of 8-10 μm have been reported [86].

A paragidm that appeared in the wake of metamaterials is the transformation optics [27-29, 87], the use of conformal mapping to transform one optical space into another, thus ensuring bending of light at will and tailoring of the density of states within a given volume. In a general state this is ensured through the use of gradient index metamaterials [88, 89]. Probably the best known example of transformation optics are the so-called cloaking devices [29, 90], but from the point of view of photodetection much more interesting concepts are met in superfocusing and superconcentrators [91], superabsorbers [92, 93] including optical black holes [94], superscatterers [95], etc . In their 2011 paper Aubry et al [64] proposed the use of transformation optics to ensure broadband light harvesting.

7. Nanoantennas for Photodetection Enhancement

Nanoantenna or optical antenna [68, 96-98] is a plasmonic structure redirecting propagating waves into evanescent field (and vice versa), where propagating and spatially localized modes are linked in a highly efficient manner. The amount of localization itself can be tailored by the proper design of the nanoantenna and can be deeply subwavelength. Thus interaction with photodetector active region can be vastly enhanced.

Nanoantennas are isolated structures, i.e. they are not connected to a feeding circuitry like the conventional antennas. With this in mind, a simple spherical nanoparticle may be regarded as the most basic nanoantenna. Its scattering properties are shortly presented in Section 4 of this paper.

Various types of nanoantennas were experimentally produced and presented in literature. Fig. 7 shows some of the basic geometries, including the most basic type, the nanosphere. If two such spheres are brought together, they form a nanodimer with a coupling gap with a subwavelength width between them (denoted as the feed gap). A field hotspot appears in the feed gap, where localization is deeply subwavelength and field enhancement is very strong. In this manner larger field localizations are obtained than those using single structures.

Another generalization is the introduction of elongated ellipsoid (also described in Section 4) that can be within this context described as dipole nanorod antenna, which is one of the most basic nanoantenna geometries. If two nanorods acting as linear dipoles are aligned and brought together to a subwavelength distance, ensuring an end-to-end coupling, they form a two-wire nanoantenna [68]. This is another basic type of optical antenna. It can be further generalized by introducing two additional dipoles perpendicularly to the first ones, all foud having a joint feed gap (the cross-antenna).

Nanoparticles can be ordered in an array (nanoparticle chain) to form an optical antenna [99] effectively behaving as linear nanorod antenna.

Another prototypical structure is the bowtie nanoantenna [100], consisting of two triangular shapes aligned along their axes and forming the feed gap with their tips. Such geometry ensures a broader bandwidth together with large field localizations in the feed gap.

A diabolo-type nanoantenna has been proposed in [101]. An optical Yagi-Uda nanoantenna can be fabricated by placing a resonant nanorod antenna between a reflector nanorod and a group of director nanorods [102]. Similar to such antennas used in radiofrequent domain, a good directivity is obtained.

More exotic shapes include spiral nanoantennas [103] and those with fractal geometries [104]. A plethora of other shapes can be used. Different geometries include e.g. the use of split rings, various crescent shapes. An important group are nanoantennas making use of the Babinet principle (a metal shape surrounded by dielectric and a dielectric-filled hole in metal with identical shape and size have identical diffraction patterns). Thus bow-tie holes in metal substrates are used, two holes as a Babinet equivalent of a nano-dimer, arrays of nanoholes, crossed arrays of nanoholes, etc. [105].

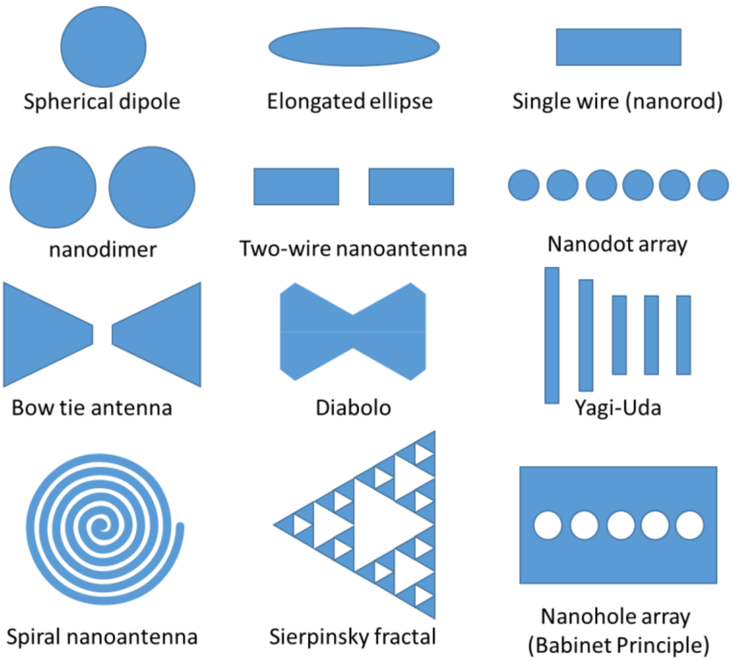


Fig. 7 Some different types of experimental plasmonic nanoantennas

The obvious way to use nanoantennas in photodetection is for coupling between propagating and localized modes and for field localization, especially through the use of hotspots within the feed gaps. A large number of works has been dedicated to the use of optical nanoantennas for photodetector enhancement [59, 68, 97, 106]

The applicability of optical antennas for photodetection has been recognized very early [61]. Today it is still one of the foci of interest in the application of optical antennas [59, 106].

One of the alternative approaches is to use a Schottky metal-semiconductor junction where the optical antenna forms the metal mart of the metal-dielectric contact at the semiconductor detector surface [107]. Photoexcitation generates hot electron-hole pairs by plasmon decay and the electrons are injected over the Schottky barrier, thus directly generating photocurrent. A problem with this approach is a low efficiency when using hot electrons.

9. Redshifting Methods for Nanoparticle-based Plasmon-assisted Infrared Detection

Most of the approaches described in this paper are applicable in different part of the spectrum (subwavelength plasmon crystals/designer plasmon structures and optical antennas). However, the use of metal nanoparticles as Mie scatterers is limited to frequencies near the surface plasmon resonance, which is for usual plasmonic materials (good metals) in ultraviolet or visible part of the spectrum. This makes them unsuitable for night vision devices and infrared detection.

In this Section we consider possible strategies to ensure the usability of plasmonic particles in the IR range [108]. The main point is that one needs to shift their resonance frequency toward longer wavelength, i.e. to perform a redshift of the characteristics. One obvious approach is to use materials with lower plasma frequency. It is known that plasma frequency of transparent conductive oxides is redshifted compared to metals and can be further shifted through proper doping and fabrication techniques [109-111]. Another pathway toward redshifting is the immersion of plasmonic nanoparticles into high refractive index material [70], either by incorporating it into a dielectric film at the detector surface or utilizing core-shell particles with external dielectric layer. Finally, one of the possible methods is the adjustment of interparticle spacing.

Fig. 8 shows the calculated scattering cross section for a spherical dipole indium tin oxide nanoparticle with a radius of 60 nm. The assumed doping concentration was $1.2\cdot10^{21}$ cm^{-3} which together with an effective mass of $m^* = 0.4\, m_0$ furnishes a plasma frequency of $4.8\cdot10^{14}$ Hz. The nanoparticle is placed at the top of the active surface of the detector and is embedded in dielectric, a layout similar to that shown in Fig 4b. Finite element method was utilized for simulation; no approximations were used. The plasmon resonance redshift described by maxima in scattering cross-section dispersion relations shown in Figure 8 is caused by the increase in the embedding dielectric permittivity. Figure 9 shows the radial distribution of the scattered electric field, presenting forward and back scattering. Spreading of the forward scattering region with the increase of the permittivity of the dielectric layer is readily seen Figure 9.a as well for larger operating wavelengths Figure 9.b. Finally, Fig. 10 shows the electric field x-axis component (parallel to the incident light polarization) around the spherical nanoparticle at the surface of the detector for a permittivity of the embedding layer of 8.

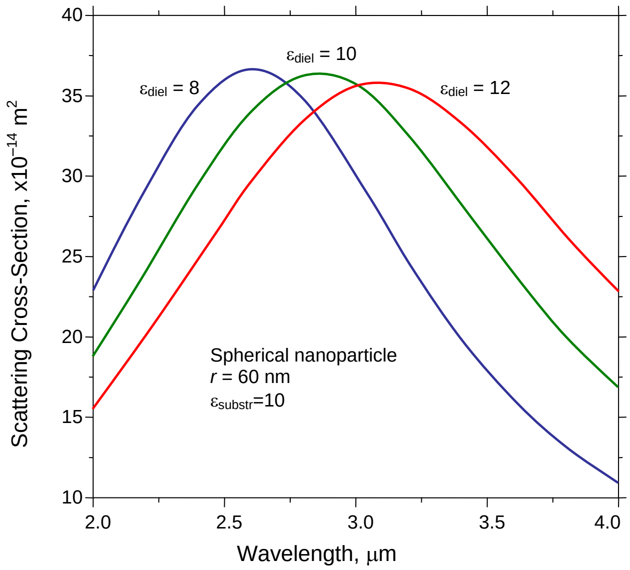
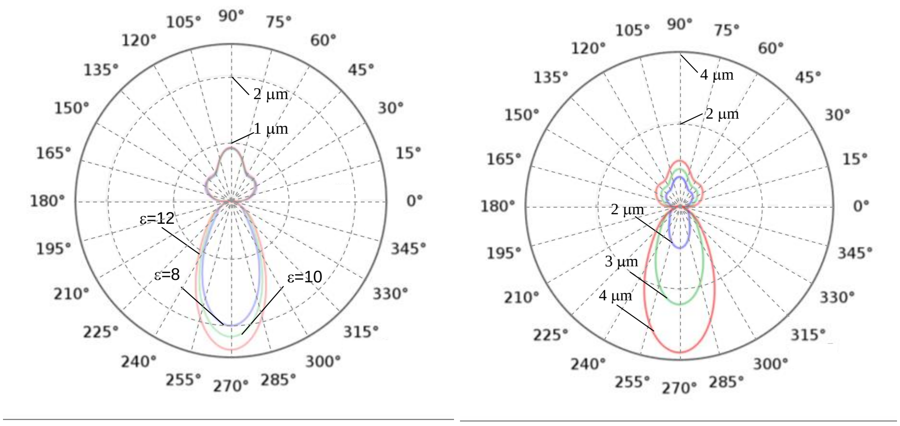


Fig. 8 Spectral dependence of scattering S_{scat} cross-section for an embedded ITO particle, r=60 nm, λ_p=625 nm



a) b)

Fig. 9 Radial distribution of electric field around an ITO nanoparticle obtained by finite element modeling; r=60 nm, λ_p=625 nm. Light is incident from top.
a) Scattering curves obtained for dielectric permittivity values 8, 10 and 12 for an operating wavelength of 3 μm. b) Scattering curves for operating wavelengths of 2, 3 and 4 μm. Permittivity of the dielectric layer is 12

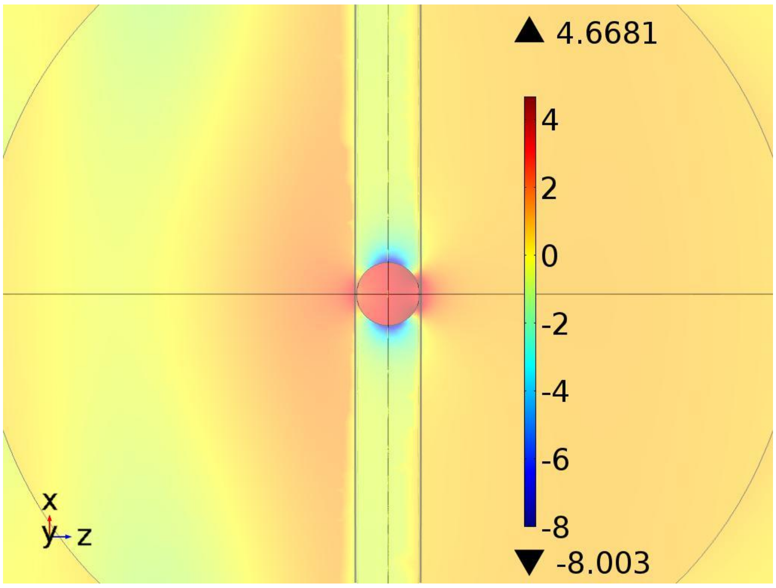


Fig. 10 Field enhancement around ITO nanoparticle for infrared detector enhancement, calculated by FEM simulation. Light is incident from right. r=60 nm, λ_p=625 nm, λ =2.6 μm, permittivity of the dielectric layer is 8

10. Conclusion

A broad overview is given of the currently available possibilities to use plasmonics for the enhancement of different classes of photodetectors, stressing solar cells and night vision devices. The consideration is based on the point of view of non-imaging photodetection devices (single detector elements) intended for detection of a broadband spectrum that can be represented as blackbody radiation. A classification of the approaches proposed until now is given, including some original results by the authors. The list of the available methods and approaches must be far from finished, since both plasmonics and solar cells fields of research are rapidly expanding, and new ideas and approaches appear almost every day.

Acknowledgement: *The paper is a part of the research funded by the Serbian Ministry of Education and Science within the projects TR32008 and III45016 and by the Qatar National Research Fund within the project NPRP 09-462-1-074.*

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