

Schottky-contact plasmonic dipole rectenna concept for biosensing

Mohammad Alavirad,¹ Saba Siadat Mousavi,² Langis Roy,¹ and Pierre Berini^{2,3,*}

¹Department of Electronics, Carleton University, 1125 Colonel By Dr.,
Ottawa, ON, K1S 5B6, Canada

²School of Electrical Engineering and Computer Science, University of Ottawa, 800 King
Edward Ave.,
Ottawa, ON, K1N 6N5, Canada

³Department of Physics, University of Ottawa, 150 Louis Pasteur,
Ottawa ON, K1N 6N5, Canada

[*berini@eecs.uottawa.ca](mailto:berini@eecs.uottawa.ca)

Abstract: Nanoantennas are key optical components for several applications including photodetection and biosensing. Here we present an array of metal nano-dipoles supporting surface plasmon polaritons (SPPs) integrated into a silicon-based Schottky-contact photodetector. Incident photons coupled to the array excite SPPs on the Au nanowires of the antennas which decay by creating "hot" carriers in the metal. The hot carriers may then be injected over the potential barrier at the Au-Si interface resulting in a photocurrent. High responsivities of 100 mA/W and practical minimum detectable powers of -12 dBm should be achievable in the infra-red (1310 nm). The device was then investigated for use as a biosensor by computing its bulk and surface sensitivities. Sensitivities of ~ 250 nm/RIU (bulk) and ~ 8 nm/nm (surface) in water are predicted. We identify the mode propagating and resonating along the nanowires of the antennas, we apply a transmission line model to describe the performance of the antennas, and we extract two useful formulas to predict their bulk and surface sensitivities. We prove that the sensitivities of dipoles are much greater than those of similar monopoles and we show that this difference comes from the gap in dipole antennas where electric fields are strongly enhanced.

© 2013 Optical Society of America

OCIS codes: (240.6680) Surface plasmons; (290.5850) Scattering particles; (310.6628) Sub-wavelength structures, nanostructures; (130.6010) Sensors; (240.0240) Optics at surfaces.

References and links

1. S. A. Maier, *Plasmonics: Fundamentals and Applications* (Springer, 2007), 1st ed.
2. B. Hecht, H. Bielefeldt, L. Novotny, Y. Inouye, and D. W. Pohl, "Local excitation, scattering, and interference of surface plasmons," *Phys. Rev. Lett.* **77**, 1889–1892 (1996).
3. W. L. Barnes, T. W. Preist, S. C. Kitson, and J. R. Sambles, "Physical origin of photonic energy gaps in the propagation of surface plasmons on gratings," *Phys. Rev. B* **54**, 6227–6244 (1996).
4. S. S. Mousavi, P. Berini, and D. McNamara, "Periodic plasmonic nanoantennas in a piecewise homogeneous background," *Opt. Express* **20**, 18044–18065 (2012).
5. P. Berini, "Bulk and surface sensitivities of surface plasmon waveguides," *New Journal of Physics* **10**, 105010 (2008).

6. F. J. Rodriguez-Fortuno, M. Martinez-Marco, B. Tomas-Navarro, R. Ortuno, J. Marti, A. Martinez, and P. J. Rodriguez-Canto, "Highly-sensitive chemical detection in the infrared regime using plasmonic gold nanocrosses," *Applied Physics Letters* **98**, 133118 (2011).
7. C.-Y. Tsai, S.-P. Lu, J.-W. Lin, and P.-T. Lee, "High sensitivity plasmonic index sensor using slablike gold nanoring arrays," *Applied Physics Letters* **98**, 153108 (2011).
8. S. Lal, S. Link, and N. J. Halas, "Nano-optics from sensing to waveguiding," *Nat Photon* **1**, 641–648 (2007).
9. P. Berini, "Plasmon-polariton waves guided by thin lossy metal films of finite width: Bound modes of symmetric structures," *Phys. Rev. B* **61**, 10484–10503 (2000).
10. E. M. Larsson, J. Alegret, M. Kll, and D. S. Sutherland, "Sensing characteristics of nlr localized surface plasmon resonances in gold nanorings for application as ultrasensitive biosensors," *Nano Letters* **7**, 1256–1263 (2007).
11. G. I. Stegeman, J. J. Burke, and D. G. Hall, "Nonlinear optics of long range surface plasmons," *Applied Physics Letters* **41**, 906–908 (1982).
12. C. L. Nehl, H. Liao, and J. H. Hafner, "Optical properties of star-shaped gold nanoparticles," *Nano Letters* **6**, 683–688 (2006).
13. M. Piliarik, P. Kvasnička, N. Galler, J. R. Krenn, and J. Homola, "Local refractive index sensitivity of plasmonic nanoparticles," *Opt. Express* **19**, 9213–9220 (2011).
14. M. W. Knight, H. Sobhani, P. Nordlander, and N. J. Halas, "Photodetection with active optical antennas," *Science* **332**, 702–704 (2011).
15. H. Wang, D. W. Brandl, F. Le, P. Nordlander, and N. J. Halas, "Nanorice: a hybrid plasmonic nanostructure," *Nano Letters* **6**, 827–832 (2006). PMID: 16608292.
16. M. M. Miller and A. A. Lazarides, "Sensitivity of metal nanoparticle surface plasmon resonance to the dielectric environment," *The Journal of Physical Chemistry B* **109**, 21556–21565 (2005).
17. F. Mazzotta, G. Wang, C. Hgglund, F. Hk, and M. P. Jonsson, "Nanoplasmonic biosensing with on-chip electrical detection," *Biosensors and Bioelectronics* **26**, 1131 – 1136 (2010).
18. L. Guyot, A.-P. Blanchard-Dionne, S. Patskovsky, and M. Meunier, "Integrated silicon-based nanoplasmonic sensor," *Opt. Express* **19**, 9962–9967 (2011).
19. C. Wu, A. B. Khanikaev, R. Adato, N. Arju, A. A. Yanik, H. Altug, and G. Shvets, "Fano-resonant asymmetric metamaterials for ultrasensitive spectroscopy and identification of molecular monolayers," *Nat Mater* **11**, 69–75 (2012).
20. M. Casalino, G. Coppola, M. Iodice, I. Rendina, and L. Sirleto, "Critically coupled silicon fabry-perot photodetectors based on the internal photoemission effect at 1550 nm," *Opt. Express* **20**, 12599–12609 (2012).
21. S. R. J. Brueck, V. Diadiuk, T. Jones, and W. Lenth, "Enhanced quantum efficiency internal photoemission detectors by grating coupling to surface plasma waves," *Applied Physics Letters* **46**, 915–917 (1985).
22. C. Daboo, M. Baird, H. H. N. Apsley, and M. Emeny, "Improved surface plasmon enhanced photodetection at an augas schottky junction using a novel molecular beam epitaxy grown otto coupling structure," *Thin Solid Films* **201**, 9 – 27 (1991).
23. A. Akbari, R. N. Tait, and P. Berini, "Surface plasmon waveguide schottky detector," *Opt. Express* **18**, 8505–8514 (2010).
24. S. Zhu, G. Q. Lo, and D. L. Kwong, "Theoretical investigation of silicide schottky barrier detector integrated in horizontal metal-insulator-silicon-insulator-metal nanoplasmonic slot waveguide," *Opt. Express* **19**, 15843–15854 (2011).
25. I. Goykhman, B. Desiatov, J. Khurgin, J. Shappir, and U. Levy, "Locally oxidized silicon surface-plasmon schottky detector for telecom regime," *Nano Letters* **11**, 2219–2224 (2011).
26. E. S. Barnard, R. A. Pala, and M. L. Brongersma, "Photocurrent mapping of near-field optical antenna resonances," *Nat Nano* **6**, 588–593 (2011).
27. J. McSpadden, L. Fan, and K. Chang, "Design and experiments of a high-conversion-efficiency 5.8-ghz rectenna," *Microwave Theory and Techniques, IEEE Transactions on* **46**, 2053 –2060 (1998).
28. *FDTD Solutions* (Lumerical Solutions Inc.).
29. E. D. Palik, *Handbook of Optical Constants of Solids* (Academic Press, 1985).
30. D. J. Segelstein, "The complex refractive index of water," Master's thesis, University of Missouri, Kansas City, Missouri, USA (1981).
31. R. Soref and B. Bennett, "Electrooptical effects in silicon," *Quantum Electronics, IEEE Journal of* **23**, 123 – 129 (1987).
32. P. Nordlander, C. Oubre, E. Prodan, K. Li, and M. I. Stockman, "Plasmon hybridization in nanoparticle dimers," *Nano Letters* **4**, 899–903 (2004).
33. C. Scales and P. Berini, "Thin-film schottky barrier photodetector models," *Quantum Electronics, IEEE Journal of* **46**, 633 –643 (2010).
34. R. N. Stuart, F. Wooten, and W. E. Spicer, "Mean free path of hot electrons and holes in metals," *Phys. Rev. Lett.* **10**, 119–119 (1963).
35. S. M. Sze and K. K. Ng, *Physics of Semiconductor Devices* (Wiley, 2006), 3rd ed.
36. A. Akbari, A. Olivieri, and P. Berini, "Sub-bandgap asymmetric surface plasmon waveguide schottky detectors on silicon," Accepted for publication in *Sel. Top. Quantum Electronics, IEEE Journal of* (2013).

37. S. J. Zalyubovskiy, M. Bogdanova, A. Deinega, Y. Lozovik, A. D. Pris, K. H. An, W. P. Hall, and R. A. Potyrailo, "Theoretical limit of localized surface plasmon resonance sensitivity to local refractive index change and its comparison to conventional surface plasmon resonance sensor," *J. Opt. Soc. Am. A* **29**, 994–1002 (2012).
 38. J. Homola, "Surface plasmon resonance sensors for detection of chemical and biological species," *Chemical Reviews* **108**, 462–493 (2008). PMID: 18229953.
 39. V. Brioude and O. Parriaux, "Normalised analysis for the design of evanescent-wave sensors and its use for tolerance evaluation," *Optical and Quantum Electronics* **32**, 899–908 (2000).
 40. L. Tang, S. E. Kocabas, S. Latif, A. K. Okyay, D.-S. Ly-Gagnon, K. C. Saraswat, and D. A. B. Miller, "Nanometre-scale germanium photodetector enhanced by a near-infrared dipole antenna," *Nat Photon* **2**, 226–229 (2008).
 41. R. F. Harrington, *Time-Harmonic Electromagnetic Fields* (McGraw-Hill, 1961), 1st ed.
-

1. Introduction

Surface plasmon polaritons (SPPs) are of great interest in a wide range of fields from physics, chemistry, materials processing, to biology. SPPs are electromagnetic surface waves coupled to free electron oscillations propagating along a metal-dielectric interface at optical wavelengths [1]. SPPs have many interesting properties such as highly-enhanced fields [2], strong confinement (to sub-wavelength scale) [3,4] and high bulk and surface sensitivities [5–7]. These characteristics are of interest to several applications such as waveguides [5, 8, 9], sensors [10], and nonlinear optics [11].

Advances in nanofabrication have made periodic metallic nanostructures and nanoantennas attractive for practical uses [2, 8, 12]. SPP biosensors have become key tools for the investigation of biomolecular interactions and for detection applications. Piliarik *et al.* measured the localized surface plasmon resonance shift of an arrays of chains of metallic nanorods in response to bulk refractive index changes as 140 nm/RIU [13]. Knight *et al.* reported an active optical monopole array which can be considered as a highly compact, wavelength-specific, and polarization-specific light detector appropriate for the sensing applications [14]. Rodriguez *et al.* reported a chemosensor fabricated from gold nano-crosses exhibiting a strongly localized SPP in the infrared and obtained a high bulk sensitivity of 740 nm/RIU [6]. Tsai *et al.* described an optical sensor consisting of square-lattice slab-like gold nano-rings, reporting a bulk sensitivity of 691 nm/RIU [7]. Star-shaped nanoparticles suitable for microscopic imaging exhibited a wavelength peak shift of 665 nm/RIU [12]. Rice-shaped nanoparticles are reported to have even larger sensitivity but with a broader spectral response [15]. The bulk sensitivity of a rod-like metal nanoparticle surface plasmon resonance is reported in [16]; the natural resonance frequency of this structure strongly depends on its aspect ratio and thickness: narrow rods with a high aspect ratio have lower resonant frequencies. Bulk sensitivities reported for cylindrical rods of aspect ratio ranging from 0.5 to 3 are from 150 to 450 nm/RIU. Mazzotta *et al.* measured photocurrent ratio sensitivity of a nanoplasmonic biosensor chip with integrated electrical detection (an array of gold nanodisks) using hole-mask colloidal lithography and they achieved a value around 133 nm/RIU as of it biosensing property [17]. Guyot *et al.* developed miniaturized silicon based nanoplasmonic biosensing platform as a symmetric nanohole array structure and got the sensitivity of 4×10^{-5} RIU which is greatly improved and promising for the application in portable nanoplasmonic multisensing and imaging [18]. The bulk sensitivity was also calculated by a quasistatic theory which serves as an upper bound to sensitivities of nanoparticles on dielectric substrates such as those associated with biomolecule sensing. Achieving a sharp resonant peak (which is easier to track) is a difficult challenge with most plasmonic nanostructures. A multipixel array of Fano-resonant asymmetric metamaterial is presented in [19], which is capable of confining light to nanoscale regions with a very sharp resonant peak. The narrower linewidth of this structure can also increase the electric field enhancement in regions of the metamaterial, which improves the sensitivity.

A Schottky barrier photodetector formed at the interface between a metal and a lightly

doped semiconductor can be used to detect infrared radiation below the bandgap energy of the substrate via the internal photoelectric effect (IPE) [20]. Such detectors involving SPP excitations in grating [21], prism [22], waveguide [23–25] and antenna [14, 26] geometries have been reported. The combination of a classical (microwave) antenna with a rectifier, termed a “rectenna”, is characterized (in part) by its ability to convert microwave to dc power [27]. In this paper we propose a plasmonic rectenna array comprised of Au nanowires of rectangular cross-section operating as optical dipole antennas. The difference between dipole and monopole antennas is the existence of a gap in the former where highly localised fields are existed. The dipoles are inter-connected electrically (in an optically non-invasive manner), on a p -doped Si substrate forming a Schottky contact thereon. The antennas are assumed covered with H_2O to represent use as a biochemical sensor. We investigate the spectral response of the rectenna as a function of the index of the superstrate and with various thicknesses of biochemical adlayer grown on the antennas. We combine numerical methods (FDTD, modal analysis) with an analytical model for IPE, and a transmission line model for the nano-dipole antennas to determine the performance characteristics of the proposed structure.

First the rectenna geometry and the methods applied in its analysis are discussed. Secondly, a particular geometry is considered and computed results are presented. Thirdly, we discuss the operation of the rectenna as a Schottky contact detector and we estimate its responsivity and detection limit. Finally, we assess the potential of the structure for bulk and surface (bio)chemical sensing.

2. Geometry

Figure 1(a) shows our rectenna concept, consisting of an array of Au nano-dipole antennas on Si, electrically interconnected via Au lines running perpendicularly to the dipole axes through the middle of each arm to a common circular contact pad; as the array is illuminated via x -polarized light, such interconnects do not affect the optical behavior of the array. The array is symmetric about the x and y axes. It is illuminated by a Gaussian beam focused onto the array through the substrate near $\lambda_0 = 1310$ nm (Si is transparent at this wavelength) and its response monitored via the photocurrent generated by (IPE) using the Au contact pad (on top) and the Al Ohmic contacts (below). In a biosensing application, this arrangement is advantageous as it simplifies interrogation, because only the photocurrent need be monitored, and it separates the optics (bottom) from the micro-fluidics (top). A single dipole is depicted in Fig. 1(b) showing our definition of its dimensions and the coordinate system used for the analysis; $a = 0$ throughout except for the surface sensitivity computations.

The finite difference time domain (FDTD) method [28] with a $0.5 \times 0.5 \times 0.5$ nm³ discretisation in the region around the antenna was used for the modeling along with Paliks material data [29] for Au and Si, and Segelsteins data [30] for H_2O which takes the water absorption into consideration. Transmittance and reflectance monitors were placed $2.5\mu\text{m}$ above and below the Si/ H_2O interface, respectively, parallel to the $x - y$ plane. We consider the case of an array that is small compared to the waist of the Gaussian beam, so the beam can be considered as a plane wave in the simulations. Thus, an x -polarised plane wave source located $2.8\mu\text{m}$ below the interface illuminates the array along the $+z$ direction. We assumed doping levels for p^+ -Si and p -Si of 10^{+18} cm⁻³ and 10^{+15} cm⁻³; the attenuation of a plane wave at $\lambda_0 = 1310$ nm propagating through a $500\mu\text{m}$ thick p^+ -Si substrate of this doping level, calculated using the Drude model [31], is 0.2037 dB, which is negligible in this work.

3. Optical response

From Fig. 1(b), we define the nanoantenna length (l), width (w), thickness (t), and the gap length (g), as well as the vertical and horizontal distance (p , q) between any two adjacent

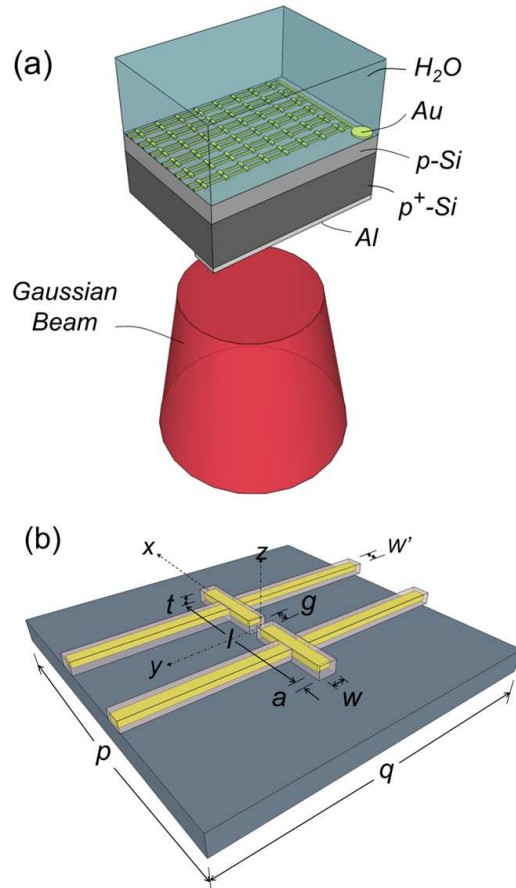


Fig. 1. (a) Array of Au dipoles on p -Si on p^+ -Si covered by H_2O . Al Ohmic contacts are located at the bottom of the structure and an Au circular contact pad is connected to all dipole arms via optically non-invasive perpendicular Au interconnects. A plane wave source illuminates the array in the $+z$ -direction from below. (b) Geometry of a unit cell of the array under study (interconnects are shown as well); the dipole is assumed covered by an adlayer of thickness a when the surface sensitivities are computed.

nanoantennas. Also the interconnect width is labeled as w' . Good dipole (infinitely periodic, "good dipole" means a dipole that resonates near a desired wavelength and that performs well in terms of enhancement and absorptance) dimensions were determined via modeling to be: $w = 30\text{nm}$, $t = 30\text{nm}$, $l = 210\text{nm}$, $g = 20\text{nm}$ and $p = q = 300\text{nm}$. Interconnect dimensions were taken as $w' = 20\text{nm}$ and $t = 30\text{nm}$. All dimensions except for g remain constant throughout the paper. Figure 2(a)-2(c) show the electric field distribution of the dipole array at resonance over $x - y$ cross-sections slightly inside the Au close to the Si/Au interface, through the middle of the Au dipoles, and slightly above the Au surface in H_2O . As noted, the field intensity is very high in the dipoles near the Au/Si interface (Fig. 2(a)) and in the gap (Fig. 2(b)), compared to along the dipole arms and the ends. Localized fields in the gap make small-gap antennas highly sensitive to changes in this region (as discussed below), and strong fields in the Au near the Au/Si interface are desirable to enhance IPE; both attributes are useful for the envisaged biosensors. It is evident that the Au interconnects have a negligible influence on the field distribution, and that the periodicity is large enough for coupling between two neighboring dipoles

to be negligible. Given the uniform illumination and their length, the dipoles resonate in their lowest order bonding mode [32], in the sa_b^0 mode propagating along the nanowire waveguides forming the dipole arms [4, 5].

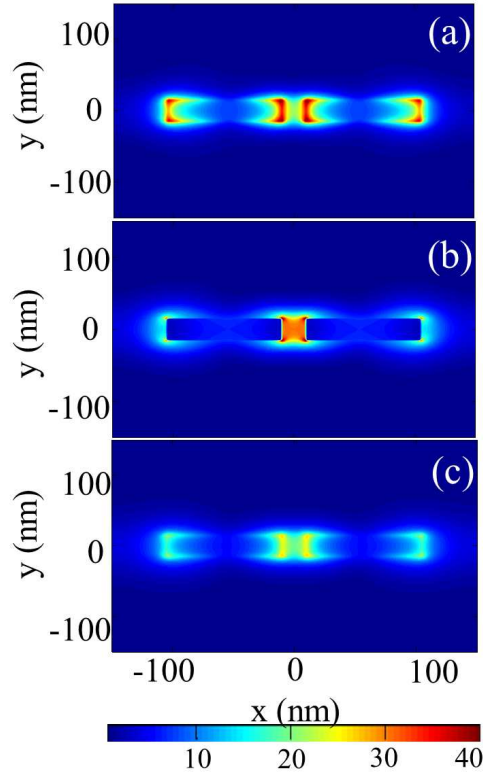


Fig. 2. Distribution of $|\mathbf{E}| = \sqrt{|\mathbf{E}_x|^2 + |\mathbf{E}_y|^2 + |\mathbf{E}_z|^2}$ on $x - y$ cross-sectional planes for an Au dipole of dimensions $w = 30$ nm, $t = 30$ nm, $l = 210$ nm, $g = 20$ nm and $p = q = 300$ nm (a) 3 nm above the Au/Si interface, (b) 15 nm above the Au/Si interface, and (c) 3 nm above the Au surface in H_2O . Computations performed at $\lambda_0 = 1353$ nm (resonance wavelength).

The transmittance T is calculated as a function of frequency (f) or wavelength via:

$$T(f) = \frac{\int_S \text{Re}(\mathbf{P}_m) \cdot d\mathbf{s}}{\int_S \text{Re}(\mathbf{P}_s) \cdot d\mathbf{s}} \quad (1)$$

where $\mathbf{P}_m$ and $\mathbf{P}_s$ are Poynting vectors at the location of the monitor where T is calculated and at the location of the source, respectively. S is the surface of the reference plane where the transmittance is calculated [28]. Eq. (1) can also be used to compute the reflectance R of the system by replacing S with the appropriate reference plane.

Figure 3 plots the calculated transmittance (T), reflectance (R), absorptance (A), and the electric field enhancement E_{en} of the array over wavelength, where A is given by:

$$A = 1 - T - R \quad (2)$$

and the electric field enhancement E_{en} is calculated at the center of the gap, 15 nm above the Si/ H_2O interface, relative to the electric field at the same location in the absence of the antenna.

From Fig.3 it is noted that E_{en} peaks near resonance to a value of about 25. (Throughout this paper the resonant wavelength of the antennas (λ_{0r}) refers to the free-space wavelength at which the absorptance curve reaches its maximum value.) The misalignment of extrema in the T , R , and A responses is due to absorption in Au. The absorptance of the system is due almost entirely to absorption in Au (losses are negligible in Si and H₂O by comparison) [4].

One can relate the optical performance and response of the dipoles to their geometry via the full parametric study reported in [4]. Decreasing the gap size changes the transmittance and reflectance as the proportion of Au covering the surface changes. Also, decreasing the gap size increases the capacitance causing a red-shift in the resonance of the system. Finally, decreasing the gap size increases the electric field therein, which as we show below, increases the bulk and surface sensitivities of the dipoles.

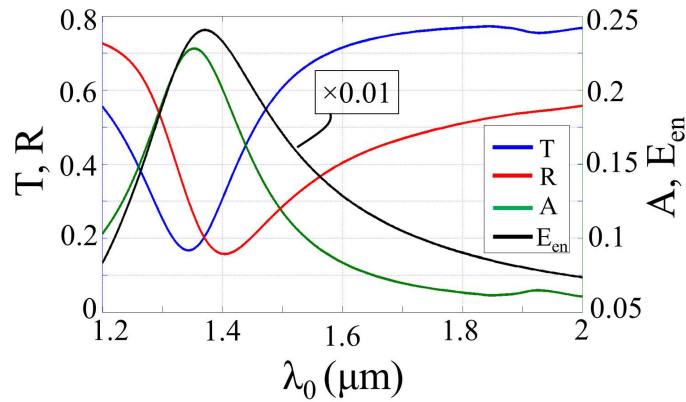


Fig. 3. Calculated transmittance (T), reflectance (R), absorptance (A) and electric field enhancement (E_{en}) vs. free space wavelength (λ_0).

4. Quantum efficiency and responsivity

The Au dipoles are assumed to form a Schottky contact to Si thereby creating an infrared photodetector operating on the basis of IPE (Fig. 1(a)). Hot (energetic) conduction carriers are created in the Au dipoles by absorption of SPPs resonating on the antennas. If the photon energy is greater than the Schottky barrier energy, then hot carriers may be emitted over the barrier and collected in the Si as photocurrent. The internal quantum efficiency η_i^t is the number of hot carriers that contribute to the photocurrent per absorbed photon per second. We assumed p -Si because Schottky barriers are lower thereon than on n -Si, leading to increased quantum efficiency and detection at longer wavelengths. Also the effective Richardson coefficient for holes is lower than that for electrons which helps manage the dark current. We have used the thin-film model described in [33] to estimate the internal quantum efficiency, taking the attenuation length of hot holes in Au as 55 nm [34] and the Schottky barrier height as $\phi_B = 0.34$ eV for Au on p -Si [35]. Figure 4(a) shows η_i^t computed over the wavelengths of interest.

Taking all Au/Si contacts into consideration (a 25×25 network of dipoles and their related interconnects, and a circular contact pad of diameter $10\mu\text{m}$), a total contact area of $\sim 95.5 \times 10^{-12} \text{ m}^2$ is obtained. Consequently, a dark current of $I_d = 5.4\mu\text{A}$ is obtained [35] at 300 K. The rectenna and interconnect area is $\sim 0.17 \times 10^{-12} \text{ m}^2$ and the contact pad area is $95.45 \times 10^{-12} \text{ m}^2$, so the pad area dominates; the dark current associated with the latter could be eliminated by inserting a dielectric between the pad and the Si surface.

The responsivity R_{esp} is defined as the ratio of the photocurrent to the incident optical power and can be expressed in terms of η_i^t as [36]:

$$R_{esp} = \kappa \frac{A \eta_i^t q}{h \nu} \quad (3)$$

where A is the absorbance, taken as that of the dipole array (Eq. (2)), and κ is the fraction of the absorbance that contributes to the photocurrent [36] (taken as $\kappa = 1$ herein). The minimum detectable power is given as the ratio of the dark current to the responsivity $S_{min} = I_d/R_{esp}$.

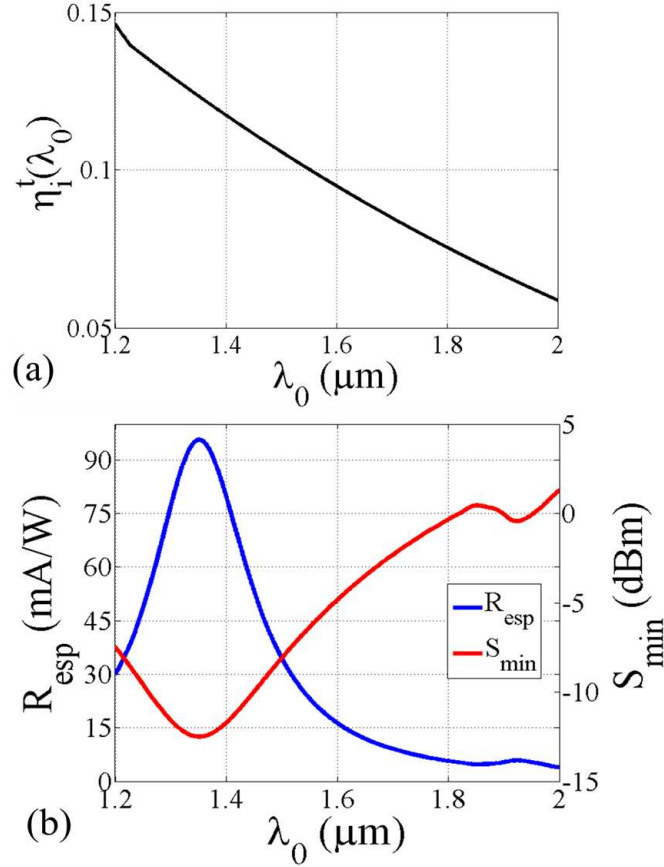


Fig. 4. (a) Internal quantum efficiency (η_i^t) vs. λ_0 . (b) Responsivity (R_{esp}) and minimum detectable power (S_{min}) vs. λ_0 .

The detection performance of the rectenna was assessed over a range of wavelengths and is plotted in Fig. 4(b). Compared to other SPP Schottky detectors, the responsivity and minimum detectable power of this detector are quite reasonable, even with a large contact pad [23, 25]. This performance level is suitable for low-cost silicon based detection and for the intended biosensing, optical monitoring and interconnect applications. The wavelength response follows closely that of the absorbance of the dipole array (Fig. 4(b)), except that the former drops more rapidly at longer wavelengths due to the decrease in internal quantum efficiency (η_i^t) as shown in Fig. 4(a).

5. Bulk sensitivity

Monitoring changes in a surface plasmon resonance is a widely used interrogation approach for measuring changes in the refractive index of bulk solutions and changes in the thickness or composition of thin bio(chemical) adlayers on the biosensor surface.

For bulk sensing, the index of the cover material n_c was changed from the nominal one (H_2O) over a large range, and absorbance spectra were computed using the FDTD method and the same mesh size as in the first section of this paper ($0.5 \times 0.5 \times 0.5 \text{ nm}^3$). Figure 5(a) shows A for all test cases considered. Increasing n_c decreases A and increases the electric field enhancement (not shown). The bulk sensitivity $\partial\lambda_{0r}/\partial n_c$ of the rectenna and the peak responsivity ($R_{\text{esp},r}$) are plotted in Fig. 5(b). The bulk sensitivity was computed by interpolating the spectral shifts using a cubic spline, then computing the derivative of the spline.

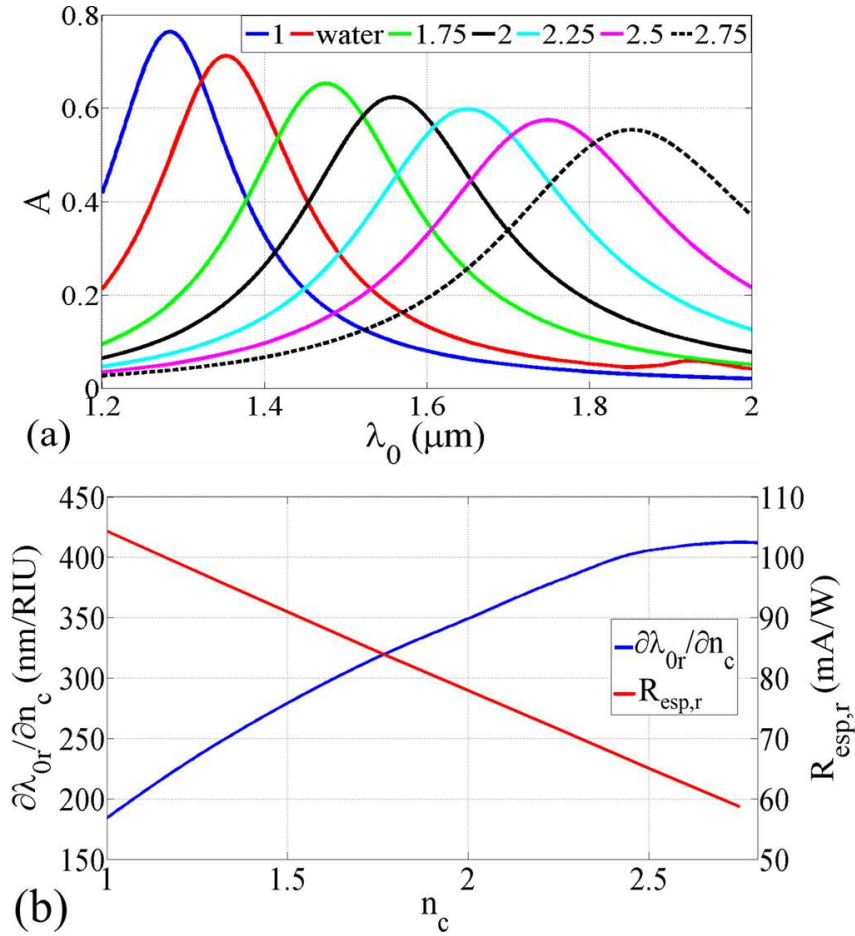


Fig. 5. (a) Absorbance (A) vs. λ_0 for several cover refractive indices n_c ranging from 1 to 2.75). (b) Bulk sensitivity ($\partial\lambda_{0r}/\partial n_c$ - blue) and peak responsivity ($R_{\text{esp},r}$ - red) of the rectenna as a function of n_c .

The rectenna has a bulk sensitivity comparable to what is reported in [6, 7, 13]. Recent analytical studies show that the bulk sensitivity increases with the surface plasmon resonance wavelength and the upper limit of this sensitivity is totally independent of nanostructure shape [37]; the

results of Fig. 5 are consistent with this trend. The peak responsivity drops linearly with n_c following the peak absorptance, with the largest peak responsivity occurring for $n_c = 1$. The drop in responsivity would translate to a commensurate drop in the monitored photocurrent as the bulk index changes. An incident optical power of 1 mW would yield a change in photocurrent of $\sim 40\mu\text{A}$ over the full index range, which is easily measurable.

5.1. Waveguide modal analysis

Modal analysis was carried out on the waveguide used as the arms of the dipoles using a mode solver based on the finite-difference method [26] in order to identify the mode propagating thereon. The wavelength for the modal analysis was set to $\lambda_0 = 1353\text{ nm}$, which is the resonant wavelength of the rectenna covered by H_2O . Figures 6(a) and 6(b) show the real part of the main transverse electric field (E_z) of the mode, plotted over the $y-z$ cross-section of one of the dipole arms for the extreme cases of bulk index used in the sensitivity study, *i.e.*, $n_c = 1$ and $n_c = 2.75$. The distribution of E_z identifies the mode propagating along the nanowires as the sa_b^0 mode [9, 32], which is excited on the dipoles given the polarization, orientation and uniformity of the source field (x -polarised plane wave). The field distribution is clearly perturbed by changes in the cover index (Fig. 6).

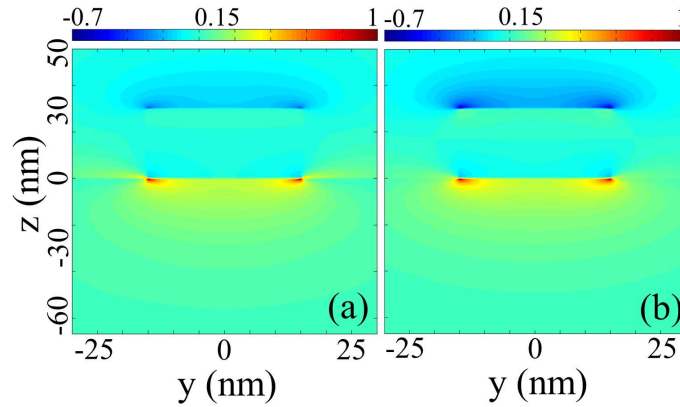


Fig. 6. Real part of E_z of the sa_b^0 mode plotted over the cross-section of a nanowire waveguide ($\lambda_0 = 1353\text{ nm}$) computed using a mode solver. (a) $n_c = 1$ (air) and (b) $n_c = 2.75$.

We compute the effective refractive index (n_{eff}) and the mode power attenuation (α) of the sa_b^0 mode as a function of n_c and plot the results in Fig. 7. Increasing n_c increases the effective refractive index which causes, in part, the red shift observed in the absorptance curves of Fig. 5(a) ($\lambda_{0r} \propto n_c$); the red shift is also due to changes in the gap capacitance C_g as n_c changes. The mode power attenuation is also observed to increase with increasing n_c explaining in part the broadening of the responses of Fig. 5(a) as n_c increases.

5.2. Analytical expression for the bulk sensitivity of dipoles

An equivalent circuit was proposed in [4] to relate the resonant wavelength of dipole antennas to the effective index (n_{eff}) of the sa_b^0 mode propagating along the nanowires forming the dipole, and to the characteristics of the dipole gap. We briefly summarize this circuit as it will be required in what follows. The circuit consists of two open-circuited transmission lines, one for each arm of the dipole, connected by a capacitor modeling the effects of the gap. The resonant

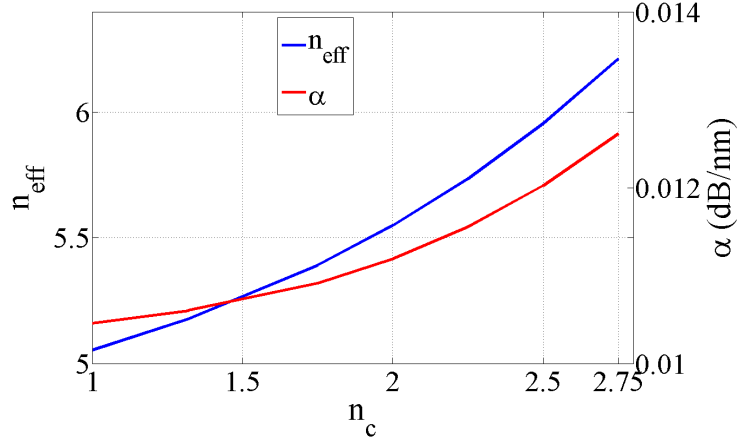


Fig. 7. Effective refractive index (n_{eff} - blue) and mode power attenuation (α - red) of the sa_b^0 mode resonating along the dipoles as a function of n_c .

frequencies of dipole antennas ω_{0r} satisfy the following transcendental equation derived for the circuit:

$$\tan(n_{eff} \omega_{0r} \sqrt{\epsilon_0 \mu_0} (d + \delta_m)) = -2 \omega_{0r} C_g Z_0 \quad (4)$$

where

$$\omega_{0r} = \frac{2 \pi c_0}{\lambda_{0r}} \quad (5)$$

In Eq. (4), $d + \delta_m$ is the effective length of each transmission line section, where $d = (l - g)/2$. The parameter δ_m is the distance from the end of each arm where the main field component decays to $1/e$; in our dipole design $\delta_m \approx 21$ nm, taken as the decay of E_z (the main transverse electric field component of the sa_b^0 mode - Fig. 6). Neglecting fringing fields, the capacitance of the gap C_g is:

$$C_g = \epsilon_c \frac{A_d}{g} \quad (6)$$

where $\epsilon_c = \epsilon_0 \epsilon_{r,c}$ and $\epsilon_{r,c}$ are the absolute and relative permittivities of the material filling the gap at the wavelength of modal analysis, which is taken as a wavelength near the expected resonant wavelength of the dipole antenna. $A_d = wt$ is the cross-sectional area of the dipole arms. In Eq. (4), Z_0 is the characteristic impedance of the transmission lines calculated as:

$$Z_0 = \frac{\iint_{\infty} f(y,z) \text{Re}[Z_{\omega}(y,z)] dS}{\iint_{\infty} f(y,z) dS} \quad (7)$$

where Z_{ω} is the wave impedance of the sa_b^0 mode:

$$Z_{\omega} = \frac{\hat{\mathbf{k}} \cdot (\mathbf{E} \times \mathbf{H}^*)}{(\hat{\mathbf{k}} \times \mathbf{H}) \cdot (\hat{\mathbf{k}} \times \mathbf{H}^*)} \quad (8)$$

$\hat{\mathbf{k}} = \hat{\mathbf{x}}$ is the direction of modal propagation which is along the dipole axis, and $\mathbf{E}$ and $\mathbf{H}$ are the mode fields. In Eq. (7), $f(y,z)$ is a weighting function defined from the sa_b^0 mode fields as:

$$f(x,y) = \sqrt{|E_y(y,z)|^2 + |E_z(y,z)|^2} \quad (9)$$

Figure 8 plots the gap capacitance as a function of the bulk index. The red-shift in the absorptance curves are caused in part by the increase in C_g which is noted to increase from 0.4 to 3 aF. Figure 8 also plots Z_0 as a function of n_c , showing a non-negligible variation (compared to the surface sensing case as discussed below).

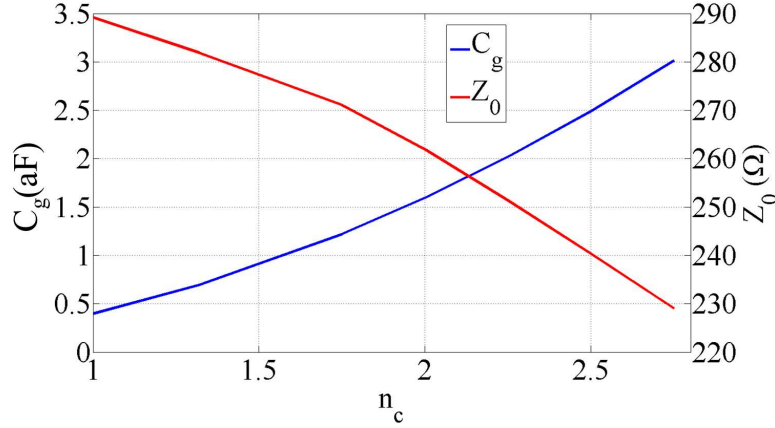


Fig. 8. Gap capacitance C_g (blue) and characteristic impedance Z_0 of the sa_b^0 mode (red) as a function of n_c .

We use now the equivalent circuit model to gain insight on the bulk sensing performance of the dipoles. Taking the derivative of both sides of Eq. (4) with respect to n_c yields:

$$\left[(d + \delta_m) \sqrt{\epsilon_0 \mu_0} \omega_{0r} \frac{\partial n_{eff}}{\partial n_c} + (d + \delta_m) \sqrt{\epsilon_0 \mu_0} n_{eff} \frac{\partial \omega_{0r}}{\partial n_c} \right] \times [1 + \tan^2(n_{eff} \omega_{0r} \sqrt{\epsilon_0 \mu_0} (d + \delta_m))] \\ = -2 \omega_{0r} C_g \frac{\partial Z_0}{\partial n_c} - 2 \omega_{0r} Z_0 \frac{\partial C_g}{\partial n_c} - 2 C_g Z_0 \frac{\partial \omega_{0r}}{\partial n_c} \quad (10)$$

where we note that $n_{eff} = n_{eff}(n_c)$, $\omega_{0r} = \omega_{0r}(n_c)$, $\delta_m = \delta_m(n_c)$, $C_g = C_g(n_c)$ and $Z_0 = Z_0(n_c)$. In writing Eq. (10) we have supposed that $\partial \delta_m / \partial n_c \approx 0$, which is justified based on verifications carried out at our extreme values for n_c . After some manipulations, the following equation for the bulk sensitivity is obtained from the above:

$$\zeta_\omega \frac{\partial \omega_{0r}}{\partial n_c} = \zeta_n \frac{\partial n_{eff}}{\partial n_c} + \zeta_C \frac{\partial C_g}{\partial n_c} + \zeta_Z \frac{\partial Z_0}{\partial n_c} \quad (11)$$

where

$$\zeta_\omega = \left(\frac{d + \delta_m}{c_0} \right) n_{eff} (1 + 4 \omega_{0r}^2 C_g^2 Z_0^2) + 2 C_g Z_0 \quad (12)$$

$$\zeta_n = \left(\frac{d + \delta_m}{c_0} \right) n_{eff} (1 + 4 \omega_{0r}^2 C_g^2 Z_0^2) \quad (13)$$

$$\zeta_C = -2 \omega_{0r} Z_0 \quad (14)$$

$$\zeta_Z = -2 \omega_{0r} C_g \quad (15)$$

and c_0 is the speed of light in vacuum. The term $\partial C_g / \partial n_c$ in Eq. (11) can be expressed in terms of dipole dimensions and gap material properties. Ignoring the imaginary part of the bulk material permittivity ($\epsilon_{r,c} \approx n_c^2$) this term can be simplified to:

$$\frac{\partial C_g}{\partial n_c} = \left(\frac{wt}{g} \right) \frac{\partial \epsilon_c}{\partial n_c} = 2 \epsilon_0 \left(\frac{wt}{g} \right) n_c \quad (16)$$

Substituting Eqs. (12) to (16) into Eq. (11), the expression for the bulk sensitivity becomes:

$$\frac{\partial \omega_{0r}}{\partial n_c} = -\zeta_\omega^{-1} \left[4 \left(\frac{wt}{g} \right) \omega_{0r} Z_0 \right] n_c + \zeta_\omega^{-1} \left(\zeta_n \frac{\partial n_{eff}}{\partial n_c} + \zeta_Z \frac{\partial Z_0}{\partial n_c} \right) \quad (17)$$

The second term in Eq. (17) comes from mode properties and the first term is directly related to the gap capacitance. In Eq. (12), $2C_g Z_0 \ll ((d + \delta_m)/c_0) n_{eff} (1 + 4\omega_{0r}^2 C_g^2 Z_0^2)$; neglecting this term and substituting in the expressions for ζ_ω , ζ_n and ζ_Z from Eqs. (12) to (15) into Eq. (17), leads to the simplified expression for the bulk sensitivity:

$$\frac{\partial \omega_{0r}}{\partial n_c} \approx - \left[\frac{2 wt c_0 \omega_{0r}}{g(d + \delta_m) n_{eff}} \right] \frac{2 Z_0 n_c + \frac{\partial Z_0}{\partial n_c} n_c^2}{1 + (2 wt g^{-1} \omega_{0r} Z_0)^2 n_c^2} - \frac{\omega_{0r}}{n_{eff}} \frac{\partial n_{eff}}{\partial n_c} \quad (18)$$

The bulk sensitivity can be written in terms of the resonant wavelength using:

$$\frac{\partial \lambda_{0r}}{\partial n_c} = - \left(\frac{2 \pi c_0}{\omega_{0r}^2} \right) \frac{\partial \omega_{0r}}{\partial n_c} \quad (19)$$

which yields

$$\frac{\partial \lambda_{0r}}{\partial n_c} \approx \left[\frac{2 wt c_0 \lambda_{0r}}{g(d + \delta_m) n_{eff}} \right] \frac{2 Z_0 n_c + \frac{\partial Z_0}{\partial n_c} n_c^2}{1 + (4 \pi wt g^{-1} c_0 \lambda_{0r} Z_0)^2 n_c^2} + \frac{\lambda_{0r}}{n_{eff}} \frac{\partial n_{eff}}{\partial n_c} \quad (20)$$

Figure 9(a) compares the resonant wavelengths computed using the FDTD method (Fig. 5(a)) with those generated by the transmission line model (Eq. (4)) using the corresponding modal parameters (n_{eff} , Z_0) computed at the resonant wavelength of each FDTD test case. From Fig. 9(a) one observes that for small bulk indices, and perhaps for very large ones, the two curves diverge slightly from each other. However over most of the index range, the transmission line model agrees very well with the FDTD results. Based on these curves we compute $\partial \lambda_{0r} / \partial n_c$ by numerical differentiation of cubic spline interpolants as in Fig. 5(b) and plot as Fig. 9(b). The black curve plots the bulk sensitivity calculated analytically using Eq. (20). For all values of n_c the analytical solution (Eq. (20)) agrees very well with the transmission line model (Eq. (4)), and both agree very well with the FDTD results for large values of n_c . The agreement deteriorates at lower values of n_c which probably comes from neglecting $\partial \delta_m / \partial n_c$ and the fringing fields in the model for the gap capacitance (Eq. (6)). Still the transmission line model (Eq. (4)) and the analytical solution (Eq. (20)) can be used over a broad range of bulk indices to estimate performance rather than the more time-consuming FDTD computations.

One interesting and important property extracted from Fig. 9(b) is that we can fit a linear model to the black curve as $\partial \lambda_{0r} / \partial n_c \approx 81 n_c + 199$ (nm/RIU). Strictly, the slope and intercept of this linear model are functions of λ_{0r} and the modal parameters n_{eff} and Z_0 which change with n_c ; however, the model fits well over the range of n_c investigated here. Comparing Eq. (20) with a linear model reveals that the slope term (81 nm/RIU²) comes from the gap capacitance and the intercept term (199 nm/RIU) mostly from perturbation of the mode fields.

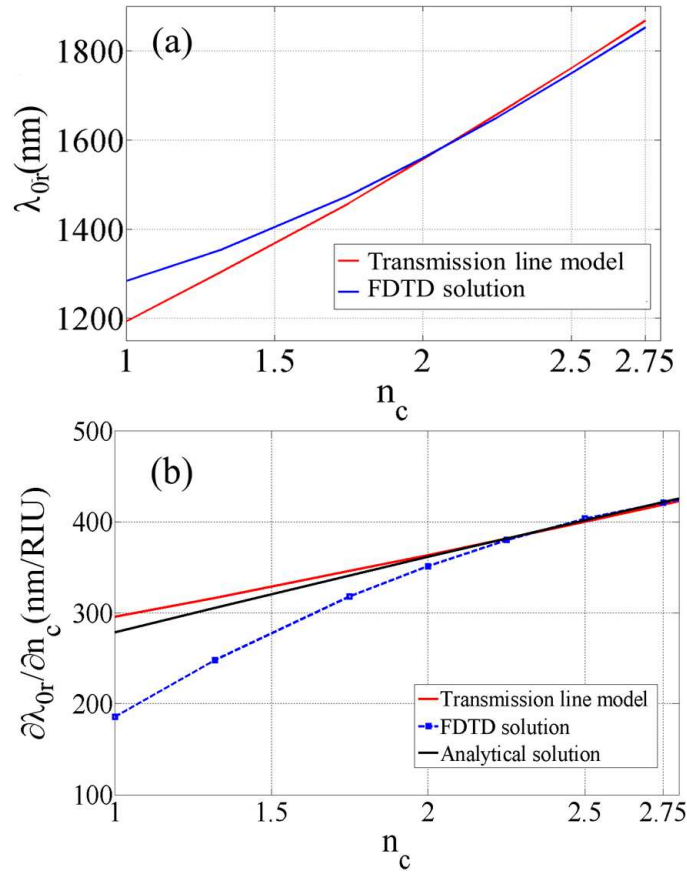


Fig. 9. (a) Resonant wavelengths computed using the transmission line model and the FDTD method as a function of bulk index n_c . (b) Bulk sensitivity computed using the FDTD method (dashed blue), the transmission line model (Eq. (4) - red), and the analytical solution (Eq. (20) - black).

6. Surface sensitivity

The surface sensitivity can be defined in a number of ways [5, 38, 39]. The definition adopted here is $\partial\lambda_{0r}/\partial a$ where a is the thickness of the adlayer of refractive index n_a (Fig. 1(b)). The adlayer is modeled as uniform dielectric layer with its thickness and index (a, n_a) being effective parameters [5]. The adlayer index is taken as $n_a = 1.45$, which is representative of biochemical material [5], and it is assumed to grow on all Au/H₂O interfaces.

Previous studies [4, 40] indicate that the electric field enhancement is very sensitive to the gap size. Specifically, decreasing the gap increases the field enhancement in the gap, which in turn increases the overlap between the resonant mode and the adlayer, leading to increased sensitivity [41]. We therefore reduced the gap size from 20 to 10 nm and computed a series of absorbance curves as a increases from 0 to 5 nm using the FDTD method and a very small mesh size ($0.2 \times 0.2 \times 0.2$ nm³), as plotted in Fig. 10(a). For the case $a = 5$ nm the gap is fully loaded with adlayer and the shift in resonance relative to the no adlayer case ($a = 0$) is 30 nm.

Fig. 10(b) gives $\partial\lambda_{0r}/\partial a$ computed by interpolating the spectral shifts of Fig. 10(a) using a cubic spline, then computing the derivative of the spline. The largest surface sensitivity observed is $\partial\lambda_{0r}/\partial a \sim 8$ nm/nm, occurring in the early stages of adlayer growth, and then drop-

ping off significantly as the adlayer fills the gap region. The sensitivity is due mainly to the enhanced electric field in the gap and near the ends of each dipole where the enhanced fields overlap much more with the adlayer. Peak responsivity ($R_{\text{esp},r}$) values are also plotted in Fig. 10(b); an incident optical power of 1 mW would yield a change in photocurrent of $\sim 1\mu\text{A}$ over the full adlayer range, which should be readily measurable.

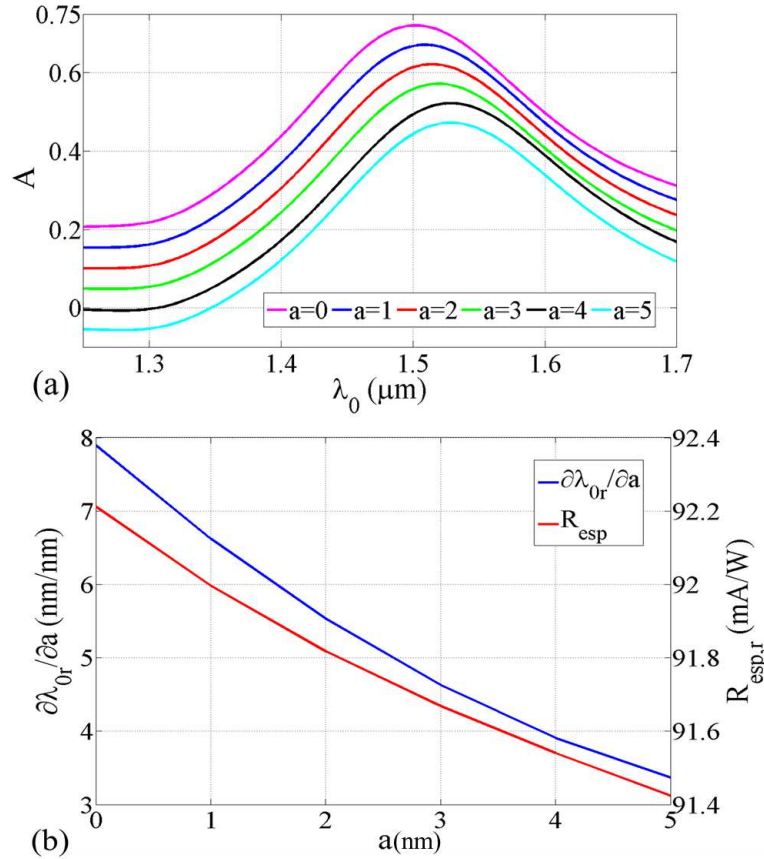


Fig. 10. (a) Absorbance A vs. λ_0 for several adlayer thicknesses ($a = 0$ to 5 nm); the curves are offset vertically by -0.05 for clarity. (b) Surface sensitivity ($\partial\lambda_{0r}/\partial a$ - blue) and peak responsivity ($R_{\text{esp},r}$ - red) as a function of a .

6.1. Waveguide modal analysis

Figure 11(a) and (b) show the real part of the main transverse electric field (E_z) of the mode, plotted over the $y-z$ cross-section of one of the dipole arms for the extreme cases of surface adlayer thickness used in the sensitivity study, *i.e.*, $a = 0$ (no adlayer) and $a = 5$ nm. The distribution of E_z identifies the mode propagating along the nanowires as the sa_b^0 mode [9,30], which is excited on the dipoles given the polarization, orientation and uniformity of the source field (x -polarised plane wave). The field distribution is slightly perturbed by changes in the adlayer thickness (Fig. 11).

We have therefore computed the parameters of this mode (n_{eff} and α) as a function of a and we plot the results in Fig. 12. Increasing a decreases slightly n_{eff} and α of the mode.

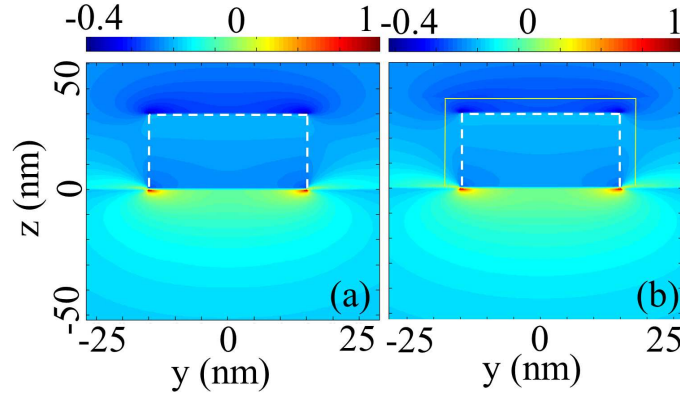


Fig. 11. Real part of E_z of the sa_b^0 mode plotted over the cross-section of a nanowire waveguide ($\lambda_0 = 1353$ nm) computed using a mode solver. (a) $a = 0$ (no adlayer) and (b) $a = 5$ nm.

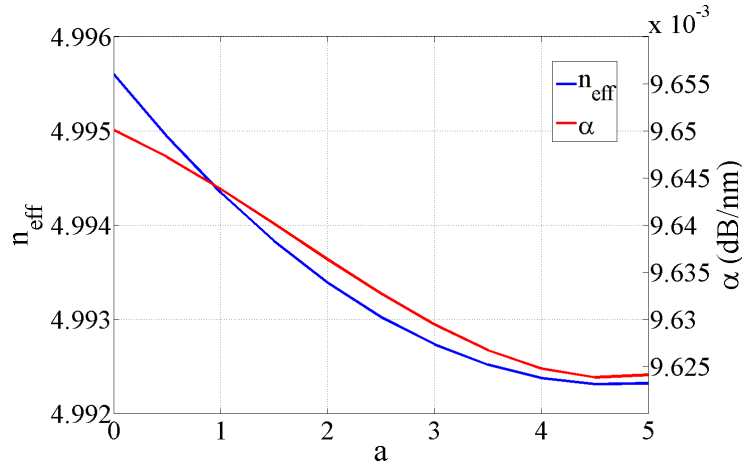


Fig. 12. Effective refractive index (n_{eff} - blue) and mode power attenuation (α - red) of the sa_b^0 mode resonating along the dipoles as a function of a .

6.2. Analytical expression for the surface sensitivity of dipoles

The red shift in the absorbance curves is due to changes in the parameters of the sa_b^0 mode resonating along the dipoles (Fig. 12) and to changes in the gap capacitance as the adlayer grows. The equivalent transmission line circuit described in the previous section can be used to take both effects into account using a new expression for C_g . Adding the adlayer produces three capacitors in series within the gap. Two capacitors (C_1) are due to the adlayers growing on the ends of the right and left arms, and the third (C_2) is formed by H_2O filling the gap, as sketched in Fig. 13.

From circuit theory, the total gap capacitance is calculated as:

$$C_g = (2C_1^{-1} + C_2^{-1})^{-1} \quad (21)$$

where C_1 and C_2 are:

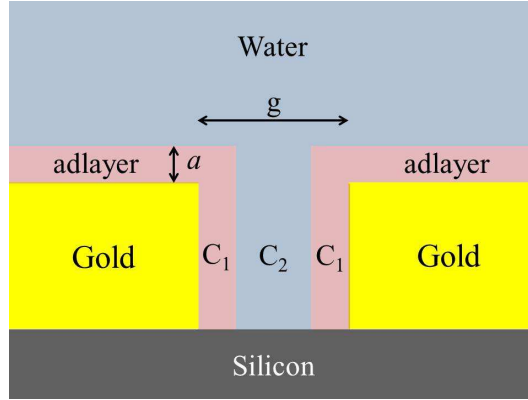


Fig. 13. Schematic of a dipole gap showing three plate capacitances in series.

$$C_1 = \epsilon_a \left(\frac{wt}{a} \right) \quad (22)$$

and

$$C_2 = \epsilon_c \left(\frac{wt}{g - 2a} \right) \quad (23)$$

In the above, $\epsilon_c = \epsilon_0 \epsilon_{r,c}$ and $\epsilon_a = \epsilon_0 \epsilon_{r,a}$ are the absolute permittivities of the bulk solution (H₂O) and the adlayer, respectively. We ignore the imaginary parts of the permittivities and take $\epsilon_{r,c} \approx n_c^2 \approx 1.32^2 \approx 1.74$ and $\epsilon_{r,a} \approx n_a^2 \approx 1.45^2 \approx 2.11$. After some manipulations, we write C_g as:

$$C_g = \frac{\epsilon_a \epsilon_c wt}{2 (\epsilon_a - \epsilon_c) a + \epsilon_a g} \quad (24)$$

Figure 14 plots C_g (Eq. (24)) and Z_0 of the sa_b^0 mode (Eqs. (7) to (9)) as a function of the adlayer thickness a , showing that C_g increases and Z_0 decreases slightly with a .

Taking the derivative of Eq. (4) with respect to a yields:

$$\zeta_\omega \frac{\partial \omega_{0r}}{\partial a} = \zeta_n \frac{\partial n_{eff}}{\partial a} + \zeta_C \frac{\partial C_g}{\partial a} + \zeta_Z \frac{\partial Z_0}{\partial a} \quad (25)$$

where ζ_ω , ζ_n , ζ_C and ζ_Z are defined in Eqs. (12) to (15). The term $\partial C_g / \partial a$ in Eq. (25) can be evaluated using Eq. (24) and expressed in terms of dipole dimensions and the properties of the materials filling the gap (emph.i.e., the adlayer and H₂O) as:

$$\frac{\partial C_g}{\partial a} = \frac{2 \epsilon_0 \epsilon_{r,c} \epsilon_{r,a} (\epsilon_{r,a} - \epsilon_{r,c}) wt}{[2 (\epsilon_{r,a} - \epsilon_{r,c}) a + \epsilon_{r,a} g]^2} \quad (26)$$

The above reveals that $\partial C_g / \partial a$ is a saturating nonlinear function of the adlayer thickness a . Substituting Eq. (26) into Eq. (25), we obtain the following expression for the surface sensitivity as a function of a :

$$\frac{\partial \omega_{0r}}{\partial a} = \frac{2 \epsilon_0 \epsilon_{r,c} \epsilon_{r,a} (\epsilon_{r,a} - \epsilon_{r,c}) wt}{[2 (\epsilon_{r,c} - \epsilon_{r,a}) a + \epsilon_{r,a} g]^2} \zeta_\omega^{-1} \zeta_C \omega_{0r} Z_0 + \zeta_\omega^{-1} \left(\zeta_n \frac{\partial n_{eff}}{\partial a} + \zeta_Z \frac{\partial Z_0}{\partial a} \right) \quad (27)$$

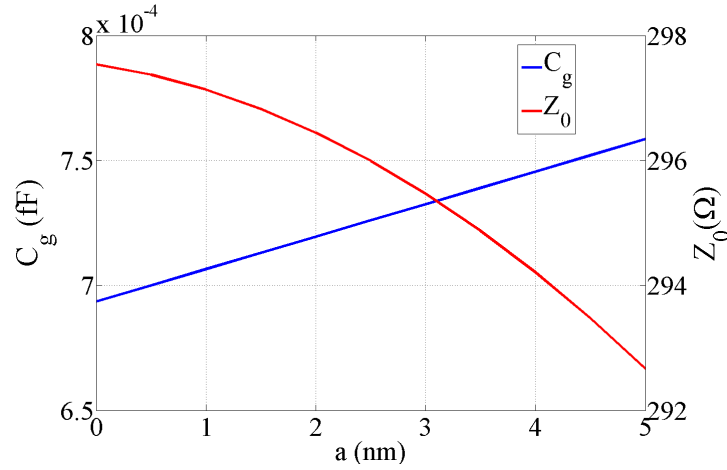


Fig. 14. Gap capacitance C_g (blue) and characteristic impedance Z_0 of the sa_b^0 mode (red) as a function of a .

The surface sensitivity can be written in terms of the resonant wavelength using:

$$\frac{\partial \lambda_{0r}}{\partial a} = - \left(\frac{2\pi c_0}{\omega_{0r}^2} \right) \frac{\partial \omega_{0r}}{\partial a} \quad (28)$$

which yields:

$$\frac{\partial \lambda_{0r}}{\partial a} = \frac{4\epsilon_0 \epsilon_{r,c} \epsilon_{r,a} (\epsilon_{r,c} - \epsilon_{r,a}) \omega t}{[2(\epsilon_{r,c} - \epsilon_{r,a})a + \epsilon_{r,a}g]^2} \zeta_\omega^{-1} \zeta_C \lambda_{0r} Z_0 - \zeta_\omega^{-1} \frac{\lambda_{0r}^2}{2\pi c_0} \left(\zeta_n \frac{\partial n_{eff}}{\partial a} + \zeta_Z \frac{\partial Z_0}{\partial a} \right) \quad (29)$$

From Fig. 12, it is clear that $\partial n_{eff}/\partial a$ and $\partial Z_0/\partial a$ are approximately constant ($\sim -0.0014 \text{ nm}^{-1}$ and $1\Omega/\text{nm}$) over the range of a considered. Thus from Eq. (29) we find that $\partial \lambda_{0r}/\partial a$ is also a saturating nonlinear function of a (which follows from Eq. (24)).

Figure 15(a) compares the resonant wavelengths obtained via the FDTD (Fig. 10(a)) and with those obtained by solving Eq. (4) using the corresponding modal parameters (n_{eff} , Z_0) computed at the resonant wavelength of every FDTD test case. Based on these results we compute $\partial \lambda_{0r}/\partial a$ (by numerical differentiation of spline interpolants) and plot this as Fig. 15(b). The black curve plots the surface sensitivity calculated using the analytical solution, Eq. (29). For all adlayer thicknesses, the analytical solution (Eq. (29)) agrees very well with the transmission line model (Eq. (4)), and both are in reasonable agreement with the FDTD computations. The error probably comes from neglecting $\partial \delta_m/\partial a$ and the fringing fields in the model for the gap capacitance (Eq. (24)). Still the transmission line model (Eq. (4)) and the analytical solution (Eq. (29)) can be used over a broad range of adlayer thicknesses to estimate the surface sensitivity of dipoles rather than the more time-consuming FDTD method. The results from the transmission line model differ from the FDTD results by a maximum of 25%.

7. Comparison of dipole and monopole sensitivities

Using the transmission line model we derive the bulk and surface sensitivities of monopole antennas and compare them to those of dipole antennas. Replacing all dipoles with monopoles of comparable length ($d = 2l$ and $g = 0$), we find the following equation for the resonant wavelengths of the equivalent transmission line circuit:

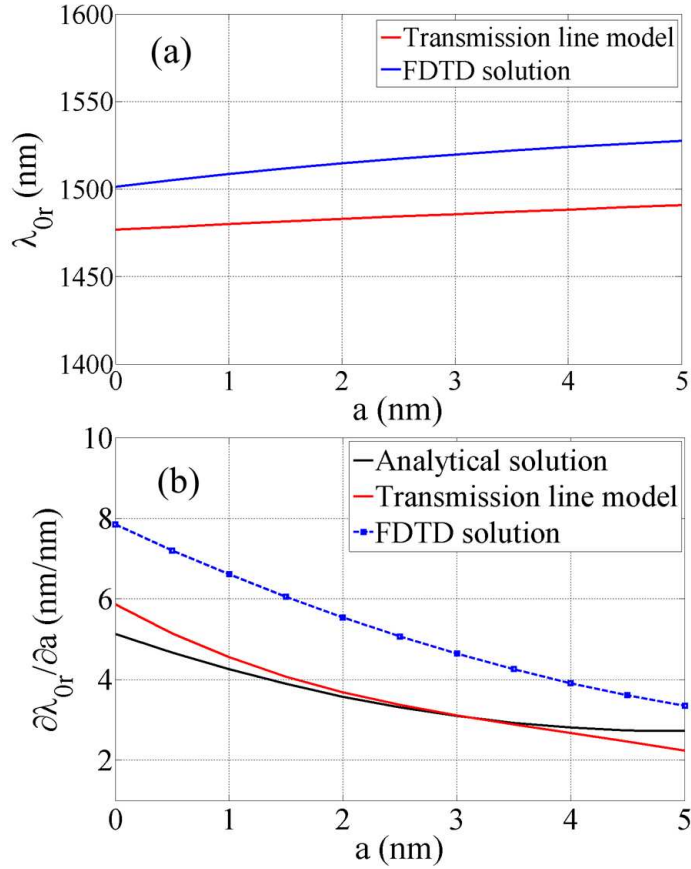


Fig. 15. (a) Resonant wavelengths computed using the transmission line model and the FDTD method as a function of adlayer thickness a . (b) Surface sensitivity computed using the FDTD method (dashed blue), the transmission line model (Eq.(4) - red), and the analytical solution (Eq.(29) - black).

$$\cot(n_{eff} \omega_{0r} \sqrt{\epsilon_0 \mu_0} (d + \delta_m)) = 0 \quad (30)$$

where the symbols retain the same meaning as in Eq. (11). We note, of course, that there is no lumped capacitance in this model because there is no gap. By taking the derivative of the above with respect to n_c and a we find the following expressions for the bulk and surface sensitivities:

$$\frac{\partial \lambda_{0r}}{\partial n_c} = \frac{\lambda_{0r}}{n_{eff}} \frac{\partial n_{eff}}{\partial n_c} \quad (31)$$

$$\frac{\partial \lambda_{0r}}{\partial a} = \frac{\lambda_{0r}}{n_{eff}} \frac{\partial n_{eff}}{\partial a} \quad (32)$$

We note that a monopole corresponds to a dipole in the limit of $g \rightarrow 0$, which leads to an infinite gap capacitance, *i.e.* $C_g \rightarrow \infty$. In this limit, ζ_ω , ζ_n and ζ_z become very large (Eqs. (13), (14) and (15)) and Eqs. (20) and (29) simplify to Eqs. (31) and (32).

Comparing Eqs. (31) and (32) with the corresponding ones for dipoles (Eqs. (20) and (29)), we observe that the sensitivities of monopole antennas are smaller than those of dipole antennas.

This is due to the absence of the gap in the former; thus, monopole resonances are altered only by changes in the properties of the sa_b^0 mode resonating on the antenna, whereas in dipoles, changes in the cap capacitance lead to a larger shift in resonance. Also, the electric field is strongly enhanced in the gap of dipoles compared to other locations on the antenna. The bulk sensitivity of dipoles is at least $1.65\times$ greater than that of comparable monopoles. Similarly the surface sensitivity of dipoles is at least $1.5\times$ greater than that of monopoles. In both cases, the importance of the gap is manifest.

8. Conclusion

Arrays of Au nano-dipole antennas forming a Schottky contact to Si were proposed and investigated theoretically for use as a wavelength-selective sub-bandgap rectenna and biosensor. Photodetection occurs via the internal photoelectric effect for photon energies above the Schottky barrier height but below the bandgap of Si. Excitation by a normally-incident plane wave polarized along the length of the dipoles was considered. Under this excitation, non-invasive electrical contacts to each dipole arm can be introduced, facilitating collection of the photocurrent. The plane-wave source excites a specific strongly-confined SPP mode (sa_b^0 [9]) propagating along the arms of the dipole antennas, forming a bonding resonance as the main resonance of operation of the antennas. Utilizing a Schottky detector structure simplifies interrogation in that the transmittance or reflectance need not be measured; rather only the photocurrent collected at the contacts needs to be monitored. Illuminating the antennas through the substrate leaves the top side of the device available for integrating microfluidics.

As a rectenna, high responsivities (100 mA/W) and practical minimum detectable powers (-12 dBm) are predicted at wavelengths near 1310 nm. As a biosensor, the rectenna structure offers significant advantages as it simplifies the interrogation set-up: only the photocurrent generated by the device need be monitored, and the excitation optics (bottom) are physically separated from the micro-fluidics (top) by the device. Compelling sensitivities are predicted for the dipoles: 250 nm/RIU in bulk sensitivity and 8 nm/nm in surface sensitivity (biochemical adlayer in H_2O). In terms of changes in photocurrent, an incident optical power of 1 mW would yield a change of $\sim 1\mu A$ as an adlayer grows to 5 nm in thickness, which is readily measurable.

Using a transmission line model to represent the dipole antennas, we derive analytical expressions for the bulk and surface sensitivities of the structure and validate them via comparisons with numerical results. We proved using these expressions that dipole antennas provide much greater bulk and surface sensitivities than monopole antennas because of the existence of the gap in the former, which introduces a capacitance (and enhanced fields) that strongly affects the resonance.