Depolying Tunable Metal-Shell/Dielectric Core Nanorod Arrays as the Virtually Perfect Absorber in the Near-Infrared Regime

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ABSTRACT: In this paper, the coupled Ag-shell/dielectric-core nanorod for sensor application is investigated and the different dielectric core plasmonic metamaterial is adopted in our design. The operational principle is based on the concept of combining the lattice resonance, localized surface plasmon resonance (SPR), and cavity plasmon resonance modes within the nanostructure. The underlying mechanisms are investigated numerically by using the three-dimensional finite element method and the numerical results of coupled solid Ag nanorods are included for comparison. The characteristic absorbance/reflectance peaks/dips have been demonstrated to be induced by different plasmonic modes that could lead to different responses required for plasmonic sensors. A nearly perfect absorbance and an approximate zero reflectance with a sharp band linewidth are obtained from the proposed system, when operated as an SPR sensor with the sensitivity and figure of merit of 757.58 nm/RIU (RIU is the refractive index unit) and 50.51 (RIU−1), respectively. Our work provides a promising method for the future developments of more advanced metamaterial absorber for chemical sensing, thermal radiation tailoring, field enhanced spectroscopy, and general filtering applications.

1. INTRODUCTION

Plasmonic perfect absorbers (PPAs) have fascinated increasing attention in the field of nanophotonic devices because of their unusual capacity of absorbing and enhancing electromagnetic (EM) waves to the nanometer-scale. It can be applied to different fields, such as resonators, refractive index (RI) sensors, nanoantennas, plasmonic solar cells, biosensing, and absorbers. Narrow-band plasmonic absorbers using surface plasmon resonance (SPR) effects are widely used in thermal radiation manipulation, detection, and sensors. On the basis of plasmonic nanostructures (PNSs) with the properties of gap plasmon resonance (GPR), cavity plasmon resonance (CPR), and metal–dielectric–metal structure, perfect plasmonic absorbers can be achieved in the visible, infrared regime, and other EM regimes.

Recently, researchers have made many advancing efforts on PPAs to achieve narrow band absorption for plasmonic sensing applications. The narrow spectrum bandwidth is required in medical sensing applications, for example the monitoring of chemical reactions, the measurement of gas concentrations, as well as the detection of biomolecules. However, the general PPAs exhibit complicated structure, and the resonance wavelength is at a fixed wavelength, and this limits the diversification of their deployment. The various approaches which have been reported to narrow the band linewidth giving sharp spectrum feature are plasmonic gap resonance, surface lattice resonance, and magnetic dipole resonance. There are several metastructures which have been studied for the purpose of absorption and they are based on gap resonance; however, these literature studies did not report on the design of sensors having perfect absorbance and zero reflectance properties. PPAs need to be designed with simple structure and tunable in the infrared regime if they are to be successfully implemented in sensor applications.

The large band linewidth of plasmon resonances causes strong radiative damping in metals, which is a major problem because it reduces the sensitivity and hence lowering the quality factor (Q-factor) of the sensor. An effective way to overcome this drawback is to couple the plasmonic effects to a system...
with a narrow resonance. There are several methods to narrow band tunability of PPA's, for example, the use of stacked graphene-dielectric sheet,31 applying phase-change material \((\text{Ge}_2\text{Sb}_2\text{Te}_5)\),32 and deploying microelectromechanical system.33 For practical applications, a large intensity variation of the absorbed or reflected light at a certain wavelength is desired, that is, sharp peaks/dips of absorptance/reflectance with a large modulation depth are required. In contrast to the above mentioned techniques, we proposed a dual band and tunability PPA consisting of coupled Ag-shell/dielectric-core (ASDC) nanorod array arranged in a square lattice. In our design, the PPA is made tunable by physically modifying the PPA's material and geometry. Each resonance obtained from our proposed PPA has excellent correlation with respect to geometrical and material parameters, and furthermore, it shows excellent tunability for each resonant wavelength \(\lambda_{\text{res}}\). In the proposed structure, an open cavity is introduced in ASDC nanorods such that it is accessible to the surrounding medium, and this makes the ASDC nanorods an attractive RI sensor. The ASDC nanorods and the bottom Ag thin film layer provide an optical response of SPR and CPR, and the positive-negative charge pairs will induce an electromotive force on the metal surface, thus causing an effective coupled mode which supports a nearly perfect absorptance and an approximate zero reflectance. ASDC nanorods that are placed at a Bragg distance above a metal mirror \((i.e., 100 \text{ nm Ag bottom layer})\) form a Fabry–Pérot nanocavity, and they constitute a coupled photonic–plasmonic system. The influences of structure and material parameters on the sensing performance are investigated by using the three-dimensional (3-D) finite element method (FEM). In addition, we put to use the strong localized enhancement of the EM wave in the gap and cavity regions in the ASDC nanorods, and we examine the RI infrared sensing performance. It is found that the absorptance bandwidth can be changed by varying the dielectric core in the Ag-shell nanorods, and a nearly perfect absorptance together with an approximate zero reflectance with a sharp band linewidth are obtained from the proposed system. The proposed structure can be operated as SPR sensors where the sensitivity and figure of merit (FOM) of \(757.58 \text{ nm/RIU}\) and \(50.51 \text{ (RIU}^{-1})\) are observed. This narrow band linewidth and perfect absorptance properties are required in sensing and filtering applications.34

\[ S = \frac{\Delta \lambda}{\Delta n}, \quad \text{FOM} = \frac{S}{\text{fwhm}} \]  

where \(\Delta \lambda\) is the corresponding central wavelength shift of the resonant dips and \(\Delta n\) is the difference of the RI. \(\text{fwhm}\) is the full width at half maximum of the SPR spectrum, and it is defined as the corresponding \(\lambda_{\text{res}}\) width at half percentage of the reflectance dip. The Q factor can be calculated as the ratio of peak resonance wavelength \(\lambda_{\text{res}}\) and the full width at half maximum, that is, \(Q = \lambda_{\text{res}}/\text{fwhm}\).36

The coupled ASDC nanorods placed directly on the surface of a uniform Ag film. The unit cell repeats in the \(x\) and \(y\) direction forming a square array with periodicity \(a\). The origin \(\{(x, y, z) = (0, 0, 0)\}\) of the coordinate system is positioned in the middle plane of the simulation zone. The closely spaced ASDC nanorods have an outer radius \((R)\) and an inner radius \((r)\) of 80 and 70 nm, thickness \((t = R - r)\) of 10 nm, and gap distance \((g)\) of 20 nm. The filling relative permittivity \((\varepsilon)\) in the ASO is set to air \((\varepsilon = 1.00)\) and silica, respectively. The lattice constant \((a)\) of the arrays is 470 nm, and the bottom silver film has a thickness \((s)\) of 100 nm. In addition, the whole structure is placed on a silica substrate, and the surrounding medium is assumed to be air or \(n\), where \(n\) is the RI of the surrounding medium.

\[ \text{S} = \frac{\Delta \lambda}{\Delta n}, \quad \text{FOM} = \frac{S}{\text{fwhm}} \]  

\[ \Delta \lambda_{\text{res}} = \frac{\lambda_{\text{res}}}{\text{fwhm}} \]  

\[ \lambda_{\text{res}} = \frac{\lambda_{\text{res}}}{\text{fwhm}} \]  

\[ Q = \frac{\lambda_{\text{res}}}{\text{fwhm}} \]

Figure 1. Truncated view of the periodic arrays of coupled ASDC nanorods placed directly on the surface of a uniform Ag film. The unit cell repeats in the \(x\) and \(y\) direction forming a square array with periodicity \(a\). Thanks to the rapid advances in the fabrication technique of nanophotonic structures, the proposed PNSs are compatible with the current fabrication technology such as a manufacturing based on secondary electron lithography generated by ion beam milling38 and other manufacturing processes.43 Superior shell-to-shell uniformity with a well-ordered feature is established.40,42 Spacer lithography can construct uniformly patterned nanoshell arrays with sub-10 nm thicknesses.40,44

2. SIMULATION METHOD AND MODELS

To analyze the proposed plasmonic system, 3-D FEM is performed using a commercially available software package (COMSOL multiphysics). Because of the symmetry of the structures, a plane wave polarized in \(x\)-axis is used as the incident light at normal incidence from the top surface. Periodic boundary conditions are considered in \(x\) and \(y\)-directions, and perfectly matching layers are applied along the \(z\) direction. The Ag permittivity data cited in ref 35 is used. The absorptance \((A)\) is calculated as \(1 - \text{reflectance} (R) - \text{transmittance} (T)\), with transmittance being nearly zero in the infrared realm \(i.e.,\) the working region of the proposed PPA) because of the thickness of the bottom Ag film is thicker than the skin depth in the infrared region, the transmittance \((T)\) channel is prevented, and the absorptance is reduced to \(1 - R\). The sensing capability of the SPR sensor is usually defined by the following definitions of sensitivity \((S)\) and FOM.5,4

\[ S = \frac{\Delta \lambda}{\Delta n}, \quad \text{FOM} = \frac{S}{\text{fwhm}} \]  

\[ \Delta \lambda_{\text{res}} = \frac{\lambda_{\text{res}}}{\text{fwhm}} \]  

\[ \lambda_{\text{res}} = \frac{\lambda_{\text{res}}}{\text{fwhm}} \]  

\[ Q = \frac{\lambda_{\text{res}}}{\text{fwhm}} \]
Upon the illumination of the ASDC nanorod arrays with UV–visible–infrared light, the hybrid modes are excited and exhibited as sharp spectral peaks/dips in the optical absorptance/reflectance. These peaks/dips are associated with a manifestation of light trapping in the ASDC nanorod array system. The absorptance/reflectance spectra ascribe to the lattice resonance and the coupling from the nanochannel waveguide to the surface plasmon polariton (SPP) mode.

Figure 2a,b shows the absorptance/reflectance spectra of the coupled ASDC nanorods with different dielectric core (air and silica). The results include the data obtained for solid Ag nanorods which serves as a counterpart (solid case) for the purpose of comparison.

As displayed in Figure 2a,b, there is one peak/dip with the maximum absorptance and minimum reflectance of 60.524 and 39.463% at $\lambda_{\text{res}}$ of 955 nm for the solid case, and there are two peaks/dips with the maximum absorptance and minimum reflectance of 93.656 and 6.323% at $\lambda_{\text{res}}$ of 855 nm for ASDC with air core and 98.489 and 1.496% at $\lambda_{\text{res}}$ of 910 nm for ASDC with silica core for peak/dip 1, respectively. For cases involving ASDC nanorods, the absorptance/reflectance curves show two significant peaks/dips with extremely high/small values. They represent two distinct types of resonances, that is, the two narrow peaks/dips are result from the surface lattice resonance and gap and cavity plasmonic resonance, respectively.12 The number of absorptance/reflectance peak/dip is dependent on the resonant modes in the PNS, that is, only the SPR mode occurs in solid case, and for cases involving ASDC nanorods both the SPR and CPR modes occur simultaneously.

It is noteworthy to point out that the corresponding peaks/dips of the absorptance/reflectance spectra have the same $\lambda_{\text{res}}$. As the dielectric core in the ASDC cases is changed from air to silica, the $\lambda_{\text{res}}$ is red-shifted, which is in accord with previous literature studies.45 These resonances peaks and dips are
attributed to (1) the vertical GPR mode among incident EM wave, Ag/ASDC nanorod arrays and the bottom Ag thin film (i.e., 100 nm thickness of Ag film on the silica substrate) and (2) the transverse CPR mode between the incident EM wave and the dielectric cores in the Ag shells. The vertical Fabry–Pérot cavities of the ASDC nanorods waveguide are formed by the dielectric cores, and the air gaps between metal nanorods behave as the dielectric interfaces. With the help of the Ag film of the ASDC nanorods and the bottom Ag thin film, the vertical GPR and transverse CPR modes can be well-excited. As is well-known, the \( \lambda_{\text{res}} \) of PNSs is dependent on the changing RI of the surrounding dielectric medium, a characteristic that has been widely used for sensing applications. The case for ASDC with \( \varepsilon = 1.00 \) (air) can be regarded as an SPR sensor, where the change of \( \varepsilon \) in the cavity of the ASDC nanorods (e.g., ASDC nanorods with silica core) causes a spectral shift and a large near-field intensity variation.

To better understand the above-mentioned phenomena, we calculate the electric field intensity (\( |\text{E}| \), V/m, Figure 3a), magnetic field intensity (\( |\text{H}| \), A/m, Figure 3b), absorbed power density (\( Q_w \), W/m\(^3\), Figure 3c,d), and the surface charge density distributions (coulomb/m\(^2\), Figure 3e) at the corresponding \( \lambda_{\text{res}} \) extracted from peak 1 for the solid case and peak 1 and peak 2 for the ASDC case with silica core. From Figure 3, it is evident that the distribution profiles of each resonance have good correspondence with each PNS structure. It is obvious that the distribution profiles of \( |\text{E}| \), \( |\text{H}| \), and \( Q_w \) are strongly confined in the gap region (i.e., gap enhancement) at peak 1 and peak 2 for all the cases, while only the case of ASDCs with silica core at peak 1 shows an enhanced distribution profile of \( |\text{E}| \), \( |\text{H}| \), and \( Q_w \) around their outer sides (i.e., edge enhancement). The gap enhancement profiles indicate that the SPPs (i.e., GPR modes) were stimulated by the incident EM waves coupled with the Ag/ASDC nanorods and the bottom Ag thin film.\(^{36,47}\) The localized distribution profiles of \( |\text{E}| \), \( |\text{H}| \), and \( Q_w \) around the Ag MNPs, show that Peak 1 was induced by the constructive interference, and this has enhanced the Ag MNP absorptance.\(^{36,49}\) The distribution profiles of \( |\text{E}| \), \( |\text{H}| \), and \( Q_w \) for the case of ASDC with silica core at peak 2 is localized between the Ag MNPs and the Ag film, which indicates a stronger gap plasmon mode occurring between the gap of Ag MNPs and also between the Ag MNPs and bottom Ag film. They govern the absorptance and reflectance,\(^{38,46}\) hence resulting in stronger gap enhancement than that of the other cases.

The mechanism of these distributions profiles in Figure 3a–d can be explained by the surface charge density distributions, as shown in Figure 3e. The surface current on the metal surface could be enhanced by the positive–negative charge pairs and they induced the electromotive force. The surface charge pairs of the solid case at peak 1 (\( \lambda_{\text{res}} = 955 \) nm) shows the same sign with an aggregation of (++) and (−−) charges at the opposite sides of the Ag nanorods, and there also is a weaker distribution of (++)(−−) on the surface of the bottom Ag thin film. These surface charges exhibit a typical dipole-like charge pattern, whose resonance is governed by the GPR mode. For the ASDC with silica core at peak 1 (\( \lambda_{\text{res}} = 910 \) nm), the charge pairs distribute strongly and uniformly in the form of (++) (+−) on the rims and on the surface of the Ag-shell nanorods, and (−−) (++) distribution is observed on the surface of the bottom Ag thin film. There is also a strong dipole-like charge pattern on the surface of inner/outer rims and the bottom, which is governed by the vertical GPR mode. This gives rise to a stronger dipolar effect and enhances the field pattern around the gap and edge regions. Besides the GPR mode occurring on the MNP-dielectric interface, the SPP waves are also included in the light–electron interactions which happens between the incident EM waves and the dielectric cores (or cavities) region. This produces a strong coupling between the incident light and the electrons on the inner and outer Ag-shell walls, hence bringing about the transverse CPR mode in the nano-cavities.\(^{38,52}\) A straightforward qualitative understanding to this is that the inner electric field in the ASDC is screened by the inner Ag-shell wall itself while the electric field skin effect makes its coupling to the outer Ag-shell wall dominant. As for the ASDC with silica core at peak 2 (\( \lambda_{\text{res}} = 1152 \) nm), the charge pairs distribute in the form of (−−) (++) at the opposite sides of Ag-shell nanorods and (++) (−−) on the surface of the bottom Ag thin film. In this case, the distribution of the GPR mode is larger than that of the CPR mode and this is due to the surface charge density in the gap region being denser than that of the lateral sides. This can be verified by the distribution profiles of \( |\text{E}| \), \( |\text{H}| \), and \( Q_w \) which show stronger field patterns in the gap region than those of the cases obtained from peak 1. This implies that the eigenmodes of peak 1 originate mainly from hybrid plasmon mode of the neighboring Ag-shell wall, which is caused by their strong mutual inductance and capacitive coupling but not from the individual ring resonator.\(^{46}\) Its near perfect absorption and approximately zero reflectance utilizes the Ohmic loss in the metal of the ASDC.
case. The resonance on the surface and in the cavity of the ASDC can be tuned by changing the geometric parameters of the structure, and this will be discussed latter.

These lattice resonances can be tailored over a wide spectral range by changing the array lattice constant (i.e., period).\(^{11}\) The lattice constant, \(a\), indicates the density of the ASDC nanorods in the period arrays along \(x\)- and \(y\)-axis, and it has a significant influence on the absorptance/reflectance spectra. To investigate the influence of the lattice constant, \(a\), the absorptance/reflectance spectra for the case of ASDC (with silica core) nanorod arrays with \(a\) values in the range of \([360, 370, 380, 400, 470, 500]\) nm were examined, see Figure 4a,b. As can be seen that the peak 1 has a noticeable blue shift with a stable magnitude of absorptance/reflectance as \(a\) is set in the range of \([360, 370, 380, 400, and 470]\) nm, whereas the absorptance/reflectance have a slight blue shift and a decreasing (increasing) magnitude of absorptance (reflectance) as \(a\) is at 500 nm, indicating that the stronger coupling effect occurred as \(a\) in the range of \([360, 370, 380, 400, and 470]\) nm. Note that the peak 2 and dip 2 of all cases possess the resonance wavelength around \(\lambda_{res} = 1150\) nm.

The absorptance and reflectance spectra can be also tuned by \(t\), \(h\), \(R\), and \(r\), respectively. To better understand both the characteristics of the GPR and CPR modes, the effects of the thickness \((t = R - r)\) of the Ag-shell nanorods, outer radius \((R)\), inner radius \((r)\), and the height \((h)\) of the ASDC nanorods on the absorptance/reflectance spectra are examined. The results of varying shell-thickness \(t\) in ASDC nanorods are shown in Figure 5a,b, respectively. The interaction between incident EM wave and ASDC nanorods could result in the splitting of SPR modes that are hybridized from an outer Ag-shell surface GPR mode and an inner Ag-shell surface CPR mode. The behavior of absorptance/reflectance spectra ascribed by varying Ag-shell thicknesses originates from capacitive coupling of the induced surface charges at the side wall of the ASDC nanorod gaps. As the thickness of the ASDCs increases from 8 to 13 nm, the \(\lambda_{res}\) is blue-shifted, which is consistent with previous studies.\(^{51}\) As the outer dimensions of ASDC nanorods remain intact, the \(\lambda_{res}\) is sensitive to the thickness of the Ag nanoshell \((i.e., t = R - r)\), which blue-shifts from 940 to 820 nm for the case of peak/dip 1 and from 1220 to 1050 nm for the case of peak/dip 2, as the thickness is increased from 8 to 13 nm. The stronger CPR can be obtained from increasing the transverse cavity resonance using smaller \(t\) (e.g., \(t = 8, 9\) and \(10\) nm) for peak/dip 1 while increasing the transverse cavity resonance using larger \(t\) (e.g., \(t = 11, 12\) and \(13\) nm) for peak/dip 2. The \(\lambda_{res}\) is blue-shifted with decreasing cavity size in ASDC nanorods. This implies that, by adopting with a proper size of Ag shell-thickness, one can carve out a cavity region to generate a contour PPA with tailored absorptance/reflectance spectra at the desired \(\lambda_{res}\). The key lies in the combination of the PNS with the photonic cavity in ASDC nanorods. The cavity in ASDC nanorods dramatically influences the resonance performance in PPA.
The absorptance/reflectance spectra for the case of ASDC (with silica core) nanorod arrays with varying outer radius ($R$), inner radius ($r$), and height ($h$) are investigated as shown in Figures 6 and 7, respectively. As it is shown in Figures 6 and 7, different cavity dimensions along transverse and vertical directions are demonstrated to be induced by different plasmonic modes that could lead to different responses required for plasmonic sensors. Being cavity in ASDC nanorods, the cavity channel can provide inner resonant modes with a localized electric field confinement far below the
Abbe diffraction limit. The $\lambda_{\text{res}}$ red-shifts with the increasing $R$, $r$ (i.e., increasing the transverse cavity volume), and $h$ (i.e., increasing the vertical cavity volume). The varying $R$, $r$, and $h$ would yield a change of the cavity volume in ASDC and result in the change of the surface charge density on the Ag-shell surface, which is related to the number of positive-negative charge pairs, that is, varying electron density distributed on the inner and outer Ag-shell of the ASDC, thus forming a strong-coupled mode which favors the near perfect absorption with proper cavity volume in the ASDC nanorods. In particular, the strong-coupled modes induce efficient broad band absorptance and reflectance, whose spectral width and position can be manipulated by changing ASDC nanorods radius ($R-r$) and height ($h$). This suggests that the CPR with respect to the cavity volume of ASDC nanorods can be affected by the coupling from $R$, $r$, and $h$. As the Ag-shell thickness of ASDC nanorods remains intact, the $\lambda_{\text{res}}$ red-shifts from 820 to 1020 nm with the increasing $R(r)$ in the range of $[60(50), 70(60), 80(70), 90(80), \text{and } 100(90)]$ (Figure 6a,b) and from 850 to 1000 nm with the increasing $h$ in the range of $[80, 90, 100, 110, 120, \text{and } 130]$ (Figure 7a,b) for peak/dip 1 cases. It is critically on the local electric nanorods and the overlap of hot spots with the RI of the position of the are depicted in Figure 8a,b. A noticeable red shift in the used, and the corresponding absorptance/reflectance spectra are signiﬁcantly different between peak/dip 1 and 2. There is a narrow corresponding to their SPR and CPR modes in Figure 8a,b are upright to each other and well-separated in wavelengths and in spatial distributions. Indeed, we find that the absorbing bands of peak 1 in Figure 8a displays good Lorentzian line shapes, and they are well-matched to the couple mode theory.

In an infrared absorptance (reflectance) spectra, the peaks (dips) correspond to the molecular groups which absorb (reflect) the infrared light at specific wavelengths, that is, it regulates the dipole moment by all (or some) number of its vibration normal coordinates, and it will surely result in some considerable infrared absorption bands. Therefore, all sensors have to be examined with respect to their sensitivity on marginal variations in the surrounding medium. The next sets of data are derived from the testing of the responsiveness of the proposed ASDC nanorod array under marginal conditions of the test sample (surrounding medium of the ASDC nanorod array). Figure 8c,d shows a comparison of the electric field intensity distributions (at the cross section across the ASDC nanorods center at $z = 0 \text{ nm}$ and $y = 90 \times 10^{-9} \text{ nm}$, respectively) and the surface charge density (including the 3-D profiles of electric force lines (pink lines) and the energy flows (cyan arrows) of the proposed ASDC (with silica core) nanorods exposed to air ($n = 1.00$) and a surrounding medium of RI, $n = 1.33$ (water). After the ASDC nanorods adsorbed by the surrounding RI medium, a remarkable gap enhancement and localization of electric field intensity distributions can be found along the $x$ axis because of the $x$-polarization of the incident EM wave. The electric force lines and energy flow arrows of $n = 1.33$ (Figure 8d) exhibit an irregular profile compared to that of $n = 1.00$ (Figure 8c), when the environmental RI perturbation influences the ASDC nanorods system. The proposed ASDC structure has a larger overspread capacity of the hot spots and the ambient media, which is approachable to the variation of surrounding medium, and would be applied not only for very sensitive RI sensing but also for improving most monolayer sensitivity, making it a greatly attractive PPA structure. More potentially, the localized electric field enhancement of the lattice resonance mode combined with the SPR and CPR modes is concentrated on the ASDC nanorod surface thus easily attainable for the measuring target biomolecules in the near infrared region.

4. CONCLUSIONS

We have proposed a novel approach to the design of PPA which could support both tunability and sensitivity for highly sensitive RI sensor application. The influence of structure and material parameters, the SPRs and CPRs on the sensing the two groups of resonant peaks and dips are both highly sensitive, although the different plasmonic modes produce the different $\lambda_{\text{res}}$ responses. The physical inference for these red shifts is due to the effective increase in capacitance of the resonant structure attributed to the increase in the RI of the analyte. The trend of peak (dip) of the absorptance (reflectance) spectra shows a decreasing (increasing) with an increasing RI of the surrounding ambience. This is caused by the lesser SPR and CPR effects when higher RI of the surrounding medium is introduced into the PPA system. According to the absorptance and reflectance spectra for peak/dip 1, the calculated sensitivity, FOM, and $Q$ factor can be achieved to the values of 757.58 nm/RIU, 50.51 (RIU$^{-1}$), and 60.67, respectively. Noting that the near perfect absorptance and near zero reflectance resonant with a sharp band linewidth narrower corresponding to their SPR and CPR modes in Figure 8a,b displays good Lorentzian line shapes, and they are well-matched to the couple mode theory.

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performance have been investigated by 3-D FEM. The mechanisms of absorptance and reflectance spectra have been demonstrated to be induced by the different plasmonic modes generated on the periodic ASDC nanorods grating. In our design, the PPA is tuned by changing or modifying the device material and geometry. The proposed ASDC PNSs with a Fabry–Pérot nanocavity is shown to provide a means for reducing the band linewidth of the resonances, and therefore ameliorating the sensing properties of PNSs. The optical spectrum can be changed by varying the dielectric core of the ASDC, and a near perfect absorptance and an approximate zero reflectance having a sharp band linewidth can be obtained from the proposed system. The proposed ASDC PNS can be operated as SPR sensor with the sensitivity and FOM of 757.58 nm/RIU and 50.51 (RIU⁻¹), respectively. In addition, the open cavity of our proposed ASDC nanorod system is accessible to the surrounding medium, and this makes it attractive for RI sensor and filtering applications.

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**Notes**

The authors declare no competing financial interest.

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**REFERENCES**

(1) Landy, N. I.; Sajuyigbe, S.; Mock, J. J.; Smith, D. R.; Padilla, W. J. Perfect metamaterial absorber. *Phys. Rev. Lett.* 2008, 100, 207402.

(2) Kwon, M.-S.; Ku, B.; Kim, Y. Plasmofluidic Disk Resonators. *Sci. Rep.* 2016, 6, 23149.

(3) Yong, Z.; Zhang, S.; Gong, C.; He, S. Narrow band perfect absorber for maximum localized magnetic and electric field enhancement and sensing applications. *Sci. Rep.* 2016, 6, 24063.

(4) Lu, X.; Zhang, L.; Zhang, T. Nanoslit-microavity-based narrow band absorber for sensing applications. *Opt. Express* 2015, 23, 20715−20720.

(5) Chau, Y.-F. C.; Lim, C. M.; Chiang, C. Y.; Voo, N. Y.; Idris, N. S. M.; Chai, S. U. Tunable silver-shell dielectric core nano-beads array for thin-film solar cell application. *J. Nanopart. Res.* 2016, 18, 88.

(6) Artar, A.; Yanik, A. A.; Altug, H. Fabry-Pérot nanocavities in multilayered plasmonic crystals for enhanced biosensing. *Appl. Phys. Lett.* 2009, 95, 051105.

(7) Kumara, N. T. R. N.; et al. Plasmonic spectrum on 1D and 2D periodic arrays of rod-shape metal nanoparticle pairs with different core patterns for biosensor and solar cell applications. *J. Opt.* 2016, 18, 115003.

(8) D’Andrea, C.; Lo Faro, M. J.; Bertino, G.; Ossi, P. M.; Neri, F.; Trusso, S.; Musumeci, P.; Galli, M.; Cioffi, N.; Ierrena, A.; Priolo, F.; Fazio, B. Decoration of silicon nanowires with silver nanoparticles for ultrasonic surface enhanced Raman scattering. *Nanotechnology* 2016, 27, 375603.

(9) Fazio, E.; Neri, F.; Pontiero, R.; Trusso, S.; Tommasini, M.; Ossi, P. Laser Controlled Synthesis of Noble Metal Nanoparticle Arrays for Low Concentration Molecule Recognition. *Micromachines* 2014, 5, 1296−1309.

(10) Lai, C.-H.; Wang, G.-A.; Ling, T.-K.; Wang, T.-J.; Chiu, P.-K.; Chau, Y.-F. C.; Huang, C.-C.; Chiang, H.-P. Near infrared surface-enhanced Raman scattering based on starshaped gold/silver nanoparticles and hyperbolic metamaterial. *Sci. Rep.* 2017, 7, 5446.

(11) Chau, Y.-F.; Jiang, Z.-H. Plasmonics Effects of Nanometal Embedded in a Dielectric Substrate. *Plasmonics* 2011, 6, 581−589.

(12) Xu, J.; Zhao, Z.; Yu, H.; Yang, L.; Gou, P.; Cao, J.; Zou, Y.; Qian, J.; Shi, T.; Ren, Q.; An, Z. Design of triple-band metamaterial absorbers with refractive index sensitivity at infrared frequencies. *Opt. Express* 2016, 24, 25742−25751.

(13) Gong, Y. K.; Liu, X.; Li, K.; Huang, J.; Martinez, J. J.; Whaypper, D. R.; Copner, N. Coherent emission of light using stacked gratings. *Phys. Rev. B: Condens. Matter Mater. Phys.* 2013, 87, 205121.

(14) Tao, T. D.; Chen, K.; Ishii, S.; Ohi, A.; Nabatame, T.; Kitajima, M.; Nagao, T. Infrared Perfect Absorbers Fabricated by Colloidal Mask Etching of Al-AZ03-Al Trilayers. *ACS Photonics* 2015, 2, 964−970.

(15) Hao, J.; Zhou, L.; Qiu, M. Nearly total absorption of light and heat generation by plasmonic metamaterials. *Phys. Rev. B: Condens. Matter Mater. Phys.* 2011, 83, 165107.

(16) Pryce, I. M.; Kelatia, Y. A.; Aydin, K.; Atwater, H. A. Compliant metamaterials for resonantly enhanced infrared absorption spectroscopy and refractive index sensing. *ACS Nano* 2011, 5, 8167−8174.

(17) Wu, P. C.; Liao, C. Y.; Savinov, V.; Chung, T. L.; Chen, W. T.; Huang, Y.-W.; Wu, P. R.; Chen, Y.-H.; Liu, A.-Q.; Zheludev, N. I.; Tsai, D. P. Optical Anapole Metamaterial. *ACS Nano* 2018, 12, 1920−1927.

(18) Wu, P. C.; Papasimakis, N.; Tsai, D. P. Self-Affine Graphene Metasurfaces for Tunable Broadband Absorption. *Phys. Rev. Appl.* 2016, 6, 044019.

(19) Chau, Y.-F.; Jiang, Z.-H.; Li, H.-Y.; Lin, G.-M.; Wu, F.-L.; Lin, W.-H. Localized resonance of composite core-shell nanospheres, nanobars and nanospherical chains. *Prog. Electromagn. Res.* B 2011, 28, 183−199.

(20) Chau, Y.-F. Surface Plasmon Effects Excited by the Dielectric Hole in a Silver-Shell Nanospherical Pair. *Plasmonics* 2009, 4, 253−259.

(21) Liu, N.; Mesch, M.; Weiss, T.; Hentschel, M.; Giessen, H. Infrared perfect absorber and its application as plasmonic Sensor. *Nano Lett.* 2010, 10, 2342−2348.

(22) Meng, L.; Zhao, D.; Ruan, Z.; Li, Q.; Yang, Y.; Qiu, M. Optimized grating as an ultra-narrow band absorber or plasmonic sensor. *Opt. Lett.* 2014, 39, 1137−1140.

(23) Yanik, A. A.; Huang, M.; Artar, A.; Chang, T.-Y.; Altug, H. Integrated nanoplasmonic-nanofluidic biosensors with targeted delivery of analytes. *Appl. Phys. Lett.* 2010, 96, 021101.

(24) Nau, D.; Seidel, A.; Ozerekowski, R. B.; Lee, S.-H.; Deb, S.; Giessen, H. Hydrogen sensor based on metallic photonic crystal slabs. *Opt. Lett.* 2010, 35, 3150.

(25) Willets, K. A.; Van Duynne, R. P. Localized surface plasmon resonance spectroscopy and sensing. *Annu. Rev. Phys. Chem.* 2007, 58, 267−297.

(26) Shioi, M.; Lodewijks, K.; Lagaee, L.; Kawamura, T.; van Dorpe, P. Tuning plasmonic interaction between gold nanorings and a gold film for surface enhanced Raman scattering. *Appl. Phys. Lett.* 2010, 97, 163106.

(27) Ameling, R.; Langguth, L.; Hentschel, M.; Mesch, M.; Braun, P. V.; Giessen, H. Cavity-enhanced localized plasmon resonance sensing. *Appl. Phys. Lett.* 2010, 97, 253116.

(28) Nielsen, M. G.; Gramotnev, D. K.; Pors, A.; Albrektsen, O.; Bozhevolnyi, S. I. Continuous layer gap plasmon resonators. *Opt. Express* 2011, 19, 2019310−1922.

(29) Li, Z.; Butun, S.; Aydin, K. Ultranarrow band absorbers based on surface lattice resonances in nanostructured metal surfaces. *ACS Nano* 2014, 8, 8242−8248.

(30) Liu, N.; Mesch, M.; Weiss, T.; Hentschel, M.; Giessen, H. Infrared perfect absorber and its application as plasmonic Sensor. *Nano Lett.* 2010, 10, 2342−2348.
(31) Othman, M. A. K.; Guclu, C.; Capolino, F. Graphene-based tunable hyperbolic metamaterials and enhanced near-field absorption. Opt. Express 2013, 21, 7614–7632.

(32) Cao, T.; Wei, C.; Simpson, R. E.; Zhang, L.; Cryan, M. J. Rapid phase transition of a phase-change metamaterial perfect absorber. Opt. Mater. Express 2013, 3, 1101.

(33) Xu, W.; Sonkusale, S. Microwave diode switchable metamaterial reflector/absorber. Appl. Phys. Lett. 2013, 103, 031902.

(34) Grande, M. Experimental demonstration of a novel bio-sensing platform via plasmonic band gap formation in gold nano-patch arrays. Opt. Express 2013, 19, 21385–21395.

(35) Johnson, P. B.; Christy, R. W. Optical Constants of the Noble Metals. Phys. Rev. B: Solid State 1972, 6, 4370–4379.

(36) Ma, T.; Yuan, J.; Sun, L.; Kang, Z.; Yan, B.; Sang, X.; Wang, K.; Wu, Q.; Liu, H.; Gao, J.; Yu, C. Simultaneous Measurement of the Refractive Index and Temperature Based on Microdisk Resonator With Two Whispering-Gallery Modes. IEEE Photonics J. 2017, 9, 6800913.

(37) Bach, H.; Neuroth, N. The Properties of Optical Glass; Springer: Heidelberg, 1995.

(38) Li, X.; Zhu, J.; Wei, B. Hybrid nanostructures of metal/two-dimensional nanomaterials for plasmon-enhanced applications. Chem. Soc. Rev. 2016, 45, 3145–3187.

(39) Tsuji, M.; Gomi, S.; Maeda, Y.; Matsunaga, M.; Hikino, S.; Uto, K.; Tsuji, T. Rapid Transformation from Spherical Nanoparticles, Nanorods, Cubes, or Bipyramids to Triangular Prisms of Silver with PVP, Citrate, and H2O2. Langmuir 2012, 28, 8845–8861.

(40) De Angelis, F.; Malerba, M.; Patrini, M.; Miele, E.; Das, G.; Toma, A.; Zaccaria, R. P.; Fabrizio, E. D. 3D Hollow Nanostructures as Building Blocks for Multifunctional Plasmonics. Nano Lett. 2013, 13, 3553–3558.

(41) Xu, X.; Yang, Q.; Wattanatorn, N.; Zhao, C.; Chiang, N.; Jonas, S. J.; Weiss, P. S. Multiple-Patterning Nanosphere Lithography for Fabricating Periodic Three-Dimensional Hierarchical Nanostructures. ACS Nano 2017, 11, 10384–10391.

(42) Seol, M.-L.; Im, H.; Moon, D.-I.; Woo, J.-H.; Kim, D.; Choi, S.-J.; Choi, Y.-K. Design Strategy for a Piezoelectric Nanogenerator with a Well-Ordered Nanoshell Array. ACS Nano 2013, 7, 10773–10779.

(43) Park, Y.-B.; Im, M.; Im, H.; Choi, Y.-K. Superhydrophobic Cylindrical Nanoshell Array. Langmuir 2010, 26, 7661–7664.

(44) Choi, Y.-K.; et al. Fabrication of Sub-10-nm Silicon Nanowire Arrays by Size Reduction Lithography. J. Phys. Chem. B 2003, 107, 3340–3343.

(45) Chau, Y.-F. C.; Wang, C.-K.; Shen, L.; Lim, C. M.; Chiang, H.-P.; Chao, C.-T. C.; Huang, H. J.; Lin, C.-T.; Kumara, N. T. R. N.; Voo, N. Y. Simultaneous realization of high sensing sensitivity and tunability in plasmonic nanostructures arrays. Sci. Rep. 2017, 7, 16817.

(46) Meng, L.; Zhao, D.; Ruan, Z.; Li, Q.; Yang, Y.; Qiu, M. Optimized grating as an ultra-narrow band absorber or plasmonic sensor. Opt. Lett. 2014, 39, 1137–1140.

(47) Li, Y.; An, B.; Jiang, S.; Gao, J.; Chen, Y.; Pan, S. Plasmonic induced triple-band absorber for sensor application. Opt. Express 2015, 23, 17607–17612.

(48) Zhang, Y.; Zhang, K.; Zhang, T.; Sun, Y.; Chen, X.; Dai, N. Distinguishing plasmonic absorption modes by virtue of inverted architectures with tunable atomic-layer-deposited spacer layer. Nanotechnology 2014, 25, 504004.

(49) Yan, M.; Dai, J.; Qiu, M. Lithography-free broadband visible light absorber based on a mono-layer of gold nanoparticles. J. Opt. 2014, 16, 025002.

(50) Liu, N.; Mesch, M.; Weiss, T.; Hentschel, M.; Giessen, H. Infrared perfect absorber and its application as plasmonic Sensor. Nano Lett. 2010, 10, 2342–2348.

(51) Chau, Y.-F. C.; Lim, C. M.; Lee, C.; Huang, H. J.; Lin, C.-T.; Kumara, N. T. R. N.; Yoong, V. N.; Chiang, H.-P. Tailoring surface plasmon resonance and dipole cavity plasmon modes of scattering cross section spectra on the single solid-gold/gold-shell nanorod. J. Appl. Phys. 2016, 120, 093110.