Giant Extra-Ordinary Near Infrared Transmission from Seemingly Opaque Plasmonic Metasurface: Sensing Applications

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Abstract

In the present study, we report giant extra-ordinary transmission of near infrared (NIR) light, more than 90%, through a seemingly opaque plasmonic metasurface, which consists of two metal nano-slits arrays (MNSAs) with alternate opening arrangements. By using perfect coupling of the plasmonic modes formed between the sharp edges of the upper and lower MNSAs of silver, a giant, wavelength selective transmission could be obtained. The study is accompanied by optimization of electromagnetic (EM) field coupling for different interlayer spacings and lateral overlap between the two MNSAs to understand their significance in light transmission through the metasurface. The interlayer spacing between the MNSAs works as the transmitting channel for light. The optimization of performance with different fill factors and plasmonic metals was performed as well. Because of the excitation of extended surface plasmons (ESPs) generated at both the MNSAs, the metasurface can be used for refractive index (RI) sensing as one of its applications by using a transparent and flexible polymer, such as polydimethylsiloxane (PDMS), as substrate. The maximum sensitivity which could be achieved for the optimal configuration of the metasurface was 1435.71 nm/RIU, with a figure of merit (FOM) of 80 RIU⁻¹ for 90.45% optical transmission of light for the refractive index variation of analyte medium from 1.33 to 1.38 RIU. The present study strengthens the concept of light funneling through subwavelength structures due to plasmons, which are responsible for light transmission through this seemingly opaque metasurface and finds use in highly sensitive, flexible, and cost-effective EOT-based sensors.

Keywords Extra-ordinary optical transmission · Metasurfaces · Surface plasmon · Nano-slits · Coupled plasmonic mode · Sensor

Introduction

Plasmonic metasurfaces exhibit light controlling property in the same way as the metamaterials exhibit for the incoming radiation on the structure itself. That is why the metasurfaces are called 2D version of the metamaterials [1–3]. Such metasurfaces are designed with an array of unit metal/dielectric nanostructures having specific geometry, size, and orientation [4–6]. Plasmonic metasurfaces offer an ability to control the optical surface waves, such as surface plasmon polaritons (SPPs) in the near field regime [7–11]. It is possible to manipulate the light propagation and SPPs by using transformation optics approach [12–15]. It has also been explained by several groups that SPPs can be controlled efficiently by

specific patterning of the metasurfaces [9–11]. The plasmonic metasurfaces having patterned nanostructures generate SPPs as the part of re-radiative energy with the direct interaction of light. Such plasmonic nanostructures perform as SPPs emitters. By controlling the relative phase among the emitters via modifying the geometry of the nanostructures or the polarization state of the incident light, one can achieve unidirectional excitation of SPPs [7, 12]. Because of amazing light controlling property, the plasmonic metasurfaces having metallic nanostructures of subwavelength size have been used for many applications in photonics, including bio-sensing [16, 17], spectroscopy [18, 19], nanolasing [20], all-optical switching [21], non-linear optical processes [22], and metasurface technologies [23–25]. Most of the plasmonic metasurfaces possess subwavelength openings as compared to the wavelengths of incident EM wave, where the transmission is based on the principle of extra-ordinary transmission (EOT) due to excitation of surface plasmons.

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EOT is the phenomenon in which the intensity of the light transmitted through a plasmonic structure containing sub-wavelength periodic apertures is much higher than the intensity of light falling on the structure's openings. In 1998, the term EOT was coined and experimentally demonstrated by Ebbesen and Kuipers et al. [26]. EOT has extensively been investigated for the last two decades because of its considerable scientific interest and broad potential applications in various technical fields, for example, photolithography [27], near field microscopy [28, 29], light-emitting diodes and lasers [30–33], sensors [34, 35], surface-enhanced Raman spectroscopy (SERS) [36, 37], surface-enhanced IR absorption (SEIRA) [38, 39], surface-enhanced fluorescence (SEF) [40–43], as a wave plate to control light polarization [44, 45], etc. The EOT is attributed to the excitation of surface plasmons (SPs), which are responsible for funneling the light through the sub-wavelength aperture [46, 47]. In the history of light transmission through a subwavelength aperture, the reported transmission efficiencies have been very low for a long time, the reason being the evaluation on the basis of very weak coupling of radiative electromagnetic modes excited by the subwavelength spacing and decaying evanescent electromagnetic fields inside the subwavelength apertures [48–51]. Hence, strongly coupled plasmonic modes may lead to improved transmission efficiencies. It is possible to achieve optical transmission through subwavelength transmission gratings or metal nano-slits array (MNSA) at wavelengths larger than the period of the structure by optimizing the geometrical parameters such as groove width and height of the MNSA [26, 52]. In another approach, EOT is explained via quasi-cylindrical waves, which are generated at the emerging side of the structure; such waves are generated because of the funneling of propagating surface plasmons [53–55].

Periodic plasmonic nanostructure-based optical sensors are highly promising because of their excellent sensing characteristics such as high sensitivity, large durability, good repeatability, and long shelf life [56, 57]. EOT-based sensing technique can be used in wavelength modulation-based refractive index (RI) sensing. It was reported both experimentally and theoretically that plasmonic MNSA could support dual surface plasmon modes, one of which is confined to the substrate that does not interact with the analyte medium. In contrast, the second one interacts with the analyte medium, which helps in sensing the change in the analyte medium [58–60]. A self-referenced sensor based on EOT through gold (Au) nano-slits array was designed and both theoretically and experimentally studied by Srivastava and Abdulhalim [61]. They achieved around 30% transmittance through MNSA. The response of periodic subwavelength plasmonic structures for incoming radiation in reflection or transmission mode depends on geometrical parameters of the structure such as period, size, shape,

and surface roughness [62–65]. It was both experimentally and theoretically demonstrated that by tuning the geometrical parameters of periodic grating structure, it is possible to excite various types of cavity modes or even higher order of plasmonic modes with varying sensor sensitivity [66].

In this work, we have focused on the enhancement of light transmission through a seemingly opaque plasmonic metasurface consisting of two MNSAs and studied the roles of the vertical interlayer distance and lateral overlap between the upper and lower MNSAs in the enhancement of light transmission. Such enhancement in EOT is possible by the perfect coupling of the plasmonic modes generated by the upper and lower MNSA. The periodic geometrical structure provides the additional phase to match that of surface plasmons supported by the structure to excite plasmonic modes. Such structure, as simulated in this study, can be used for refractive index sensor using polydimethylsiloxane (PDMS).

Simulations

A schematic of the proposed metasurface, consisting of two plasmonic MNSAs has been shown in the Fig. 1, in which Λ is the period, W is the width of the metal nano-slit, a is groove width of the structure, H is the vertical distance between upper and lower MNSA, and h is the thickness of the metal nano-slits. The definitions of W and a are opposite to each other for the lower MNSA. In all simulations, the period of the structure was kept constant, which is 1600 nm, keeping in mind the experimental demonstration of the same after the opening of the lockdown due to COVID-19 using a compact disk (CD) as a template for its fabrication, and hence the height of the metal films has been kept the same for both the MNSAs. The fill factor of the structure is defined by $f = W/\Lambda$, which is also optimized for optimal transmission. EOT through the proposed metasurface was simulated using COMSOL Multiphysics (Version 5.5) under the normal incidence of TM polarized light for the near infrared (NIR) range of the electromagnetic spectrum from the top side of the structure, and 0th order of diffraction of the light transmitted through the bottom of the plasmonic metasurface was analyzed.

Extended surface plasmons (ESPs) are supported in both the MNSAs of such a metasurface. The excitation of ESPs in both the MNSAs is governed by the following plasmonic phase matching equation at the metal-dielectric interface [67, 68]:

$$\text{Re}(K_{\text{inc}}) + K_G = \pm \text{Re}(K_{\text{SP}}) \quad (1)$$

where $\text{Re}(K_{\text{inc}})$ and $\text{Re}(K_{\text{SP}})$ are the real parts of the propagation vector of the incident light in the polarization direction and that of surface plasmons, respectively, and K_G is the

Fig. 1 Schematic of the proposed metasurface consisting of two MNSAs separated by “H” distance

k-vector of the periodic structure, which provides the additional phase to achieve SPR condition, and it can be defined by the following equation as:

$$K_G = nG_x + mG_y \quad (2)$$

where $G_x = G_y = 2\pi/\Lambda$ are the grating momentum vectors for a two-dimensional (2D) array of periodic structure, and n and m are integers. The propagation vector of SPs, $Re(K_{SP})$, is given [66] as:

$$K_{SP} = K_0 \sqrt{\frac{\epsilon_m \epsilon_d}{\epsilon_m + \epsilon_d}} \quad (3)$$

where ϵ_m and ϵ_d are the dielectric constants for the metal and the dielectric media, respectively, and $K_0 = 2\pi/\lambda$ is the wave vector of light in free space for incident light of wavelength λ . After algebraic simplifications using Eqs. (2) and (3), Eq. (1) can be re-written in the following form for 1D periodic structure:

$$K_0 n_d \sin \theta + m \left(\frac{2\pi}{\Lambda} \right) = \pm K_0 \sqrt{\frac{Re(\epsilon_m) \epsilon_d}{Re(\epsilon_m) + \epsilon_d}} \quad (4)$$

where $n_a (= \sqrt{\epsilon_d})$ is the RI of analyte medium and θ is the angle of incidence of light. For the normal incidence ($\theta=0^\circ$) of light, the ESP resonance wavelength is given by the following equation [66]:

$$\lambda = \frac{\Lambda}{m} \sqrt{\frac{Re(\epsilon_m) \epsilon_d}{Re(\epsilon_m) + \epsilon_d}} \quad (5)$$

The value of the dielectric constant ϵ_d is chosen according to the application, and the first, second, or even higher-order resonance wavelengths can be calculated by using Eq. (5). For $n_d = 1$, the real part of the dielectric constant of the metal $Re(\epsilon_m) \gg \epsilon_d$, the first order resonant wavelength λ can analytically be estimated, using Eq. (5), as $\lambda \sim \Lambda$, and

for $\Lambda = 1600$ nm, the first order resonance wavelength should be around 1600 nm individually for both the MNSAs. From Eq. (5), it is also evident that the ESP resonance wavelength will change if the value of n_d changes. This property is utilized for sensing applications.

The whole simulation work was done by using licensed version of COMSOL-Multiphysics version 5.5 based on the principle of finite element method (FEM) of computation. For noble metals (Ag, Au, Al), the refractive indices were taken from Johnson and Christy [69], which is also inbuilt in the material database of COMSOL. Electromagnetic wave frequency domain (ewfd.) module for normal incidence of a transverse magnetically polarized (TM) plane electromagnetic wave along with Floquet periodic boundary conditions [70] for the lateral boundaries was used, and perfectly matching layers (PMLs) were applied at the longitudinal boundaries in the simulation window. For the simulation of proposed plasmonic metasurface, the superstrate and substrate media were considered infinitely thick. Polychromatic light was incident normally from the superstrate side on the metasurface. The superstrate, substrate, and the media in the grooves and the gap between MNSAs were considered as air (with RI, $n=1$) to study the coupled-mode behavior of the plasmonic modes excited at the upper and lower MNSAs, responsible for the giant EOT. Using COMSOL, the resonance wavelength for the complete metasurface comprising coupled MNSAs was obtained to be equal to 1641.2 nm. Control simulations towards the optimization of h and H were performed for the maximum possible strength of the transmitted peak for the 0th order of the diffracted light through the metasurface.

To analyze the sensing capabilities of the proposed metasurface, the superstrate medium was considered as analyte, and its RI was varied from 1.33 to 1.38 RIU in the steps of 0.01 RIU. The substrate medium was replaced with PDMS polymer to make a practically feasible sensor and also because of various useful optical

and mechanical properties of PDMS [71, 72] for the same range of refractive index of the analyte medium. The refractive index (n_{PDMS}) of PDMS is given by the following equation [73]:

$$n(\lambda)_{PDMS} = \sqrt{1 + \frac{1.0093\lambda(\mu m)^2}{\lambda(\mu m)^2 - 0.013185}} \quad (6)$$

where λ is wavelength of the incident light.

Any sensor is characterized by two essential parameters: one, the sensitivity, and the other is the figure of merit (FOM). In the whole study, the wavelength interrogation has been performed to study the spectral response of the proposed structure. The sensitivity of the sensor will be defined as follows [74]:

$$S = \frac{\Delta\lambda_{res}}{\Delta n_a} \quad (7)$$

where $\Delta\lambda_{res}$ is the shift in plasmonic resonance wavelength with the corresponding change in the refractive index of the analyte medium (Δn_a). FOM of the sensor is defined as the ratio of the sensitivity of the sensor to the full width half maximum (FWHM) of the spectral response and can be estimated by the following equation [70]:

$$FOM = \frac{S}{FWHM} \quad (8)$$

Results and Discussion

First, we optimized the proposed structure of metasurface for maximum optical transmission, around 90% with a fill factor of 0.625, by changing the thickness (h) of Ag nano-slits from 10 to 125 nm and the vertical distance between upper and lower nano-slits array (H) from 115 to 0 nm (consequently) with refractive index, $n = 1$ for both substrate and superstrate media.

In Fig. 2a and b, the transmission spectra for various thicknesses of Ag have been plotted. In Fig. 2a, it can be observed that when h is kept 10 nm, no wavelength selective transmission is obtained. As the value of h was increased to 20 to 30 nm, the transmission spectrum showed one distinct resonance peak along with a broad spectral shoulder (another plasmonic mode, confirmed at greater metal thicknesses) at longer wavelengths for the 0th order of the transmitted light through the proposed plasmonic metasurface. When h was increased to 40 nm, the resonance peak around 1600 nm showed slight red shift, while the broad spectral shoulder

Fig. 2 (a, b) Transmission spectra for various thicknesses of Ag metal nano-slits; (c–e) electric field profiles for 20 nm, 60 nm, and 100 nm Ag film thicknesses at respective resonance wavelengths, respectively. The insets in (c–e) show the zoomed in view of the field profile near edges

turned into a more distinct, broad plasmonic resonance. The two resonance peaks for the 0th order of the transmitted light correspond to the two resonant plasmonic modes at λ_1 and λ_2 , each corresponding to the upper and lower MNSAs, respectively. The trend of variation in the second resonance peak with increase in h has been shown by a red dotted arrow in Fig. 2a. A clearer understanding of the claim that one of the resonances corresponds to each of the MNSAs will follow from the subsequent discussions on Fig. 3. For the case of 20 nm Ag film thickness, the gap between both the MNSAs, H , was 95 nm, while it was 115 nm initially when h was 10 nm. The value of H decreases with an increase in the value of h , as the total thickness cannot exceed 125 nm, pertaining to practically feasible, cost-effective fabrication of the metasurface. With an increase in the value of h up to 60 nm, both the peaks are observed to shift towards each other. This is a consequence of two inter-linked processes: increase in the value of h and (consequently) decrease in the value of H . An increase in the value of h is responsible for shift of the resonance peaks and change in percentage transmission, while that in H leads to coupling of the plasmonic modes at the sharp edges of the nano-slits of upper

and lower MNSAs, as it is evident from the electric field profiles plotted in Fig. 2c and d. The insets of these figures give a clear understanding of the electromagnetic (EM) field coupling, while the color bars show the strengths of the electric field. In continuation to the aforementioned discussions of Fig. 2a, c and d, when the thickness of the Ag film is further increased, leading to a decrease in H , the coupling between the EM modes becomes even more stronger, which leads to merging of both the resonance peaks to one. It can be observed in Fig. 2b that when the value of h was increased from 70 to 125 nm, the merged resonance peak shows a monotonous red shift, while the transmittance first increases to maximum of 90.45% at 100 nm film thickness with an increase in the film thickness from 70 to 100 nm and then starts decreasing with further increase in the film thickness up to 120 nm. At $h = 125$ nm, both the MNSAs touch each other by their edges, leading to complete blockage of light, and hence, the transmittance becomes zero. The coupling between the plasmonic modes plays an essential role in facilitating a very high value of EOT through the metasurface, which is 90.45%. In a usual MNSA, the mechanism of EOT has been explained by the coupling of the slit

Fig. 3 Transmission spectra for (a) decreasing and (b) increasing interlayer vertical distance (H) between upper and lower MNSAs; (c–f) are the electric field profile at shifting resonance wavelength for $H = 25$ nm, 55 nm, 75 nm, and 95 nm, respectively. The insets of (c–f) show the zoomed in view of the EM field enhancement at the edges of both the MNSAs

modes to surface plasmons generated at both the interfaces of the MNSA [52]. However, the proposed metasurface has two MNSAs, thereby having four metal dielectric interfaces available for the excitation of SP modes. The aforementioned four interfaces have been marked by dashed lines in Fig. 2d as ①–④. These four interfaces are valid for all the structures simulated in this manuscript. It can be observed that the interfaces ① and ③ are directly exposed to the incident light. For the optimal thickness of MNSAs, the SP mode generated at interfaces ① and the coupled plasmonic mode formed at the sharp edges between the interfaces ② and ③ result in giant extra-ordinary optical transmission. It is interesting to observe that due to efficient coupling of the plasmonic mode between interfaces ② and ③, negligibly small coupling occurs between the plasmons at interfaces ③ and ④. From the aforementioned, it can be concluded that the metasurface provides additional mechanism for funneling of light through excitation of SPs, as compared to traditional MNSAs, thereby leading to a giant EOT. Figure 2e shows the electric field profile for metasurface with 100 nm Ag film thickness at resonance wavelength of 1641.2 nm. The value of electric field normalized by the incident field was much larger for 100 nm optimum thickness of Ag nano-slits, because of the excitation of perfectly coupled modes at the sharp edges of nano-slits.

After achieving the maximum transmittance of 90.45% for 100 nm thickness (h) of Ag nano-slits and interlayer vertical distance ($H=25$ nm), we studied the role of variation of H on the characteristics of the metasurface. The transmission spectra were simulated and have been plotted in Fig. 3a and b for decreasing the value of H from 25 to 0 nm and increasing it from 25 to 190 nm, respectively, while keeping the Ag-nano slits thickness (h) as 100 nm in both the MNSAs.

In Fig. 3a, it is observed that for each configuration, the transmission vs wavelength plot shows a maximum at a particular wavelength for the reasons explained in the discussions of Fig. 2. It is further observed that with a decrease in the value of H , the transmittance decreases monotonously with a slight red shift in the resonance wavelength. This is attributed to decrease in the opening of the structure for light transmission in the current spectral window of simulation. For $H=0$, the upper and lower MNSAs touch each other, thereby leading to zero transmission. Figure 3b shows the transmission spectra with an increase in the value of H varying between 25 and 190 nm for $h=100$ nm. It can be observed that with an increase in the value of H , the coupled plasmonic resonances start to decouple, and hence a slight redshift, accompanied by a decrease in the transmittance, is seen with an increase H from 25 to 75 nm.

To make a better understanding of the role of H over the metasurface transmittance, we have plotted the EM field profiles for $H=25$, 55, and 75 nm in Fig. 3c, d and e, respectively. The insets of the aforementioned figures show the

zoomed in views of the EM field profiles near the edges of both the MNSAs. It can be clearly observed that with an increase in the value of H up to 75 nm, the EM field coupling and hence the value of the normalized field in the hotspots reduces by 1/4th of its value for the optimum configuration, which is a consequence of the mode decoupling, thereby leading to decrease in the transmission efficiency. Further, when H is increased more than 75 nm up to 190 nm, the coupled modes formed at the sharp edges of upper and lower MNSA start to decouple and show two plasmonic resonances, while the overall transmittance for both the resonances going down plasmonic resonances, while the overall transmittance for both the resonances going down.

A clear insight of the aforementioned sentence can be seen in Fig. 3f, where the EM fields of both the MNSAs decouple almost completely for $H=95$ nm and so on. If the value of H is increased further, the transmittance goes down to zero, ultimately. Hence, it can be concluded that the maximum transmission occurs only when the plasmonic modes generated by upper and lower metal slits array coupled ideally at an optimal combination of h and H .

After achieving giant extra-ordinary transmission of more than 90% through the optimal metasurface and performing control simulations on the effect of interlayer vertical distance (H) variation on the plasmonic mode coupling between upper and lower MNSAs, we studied the impact of lateral gap of the upper slit (g) variation on the optical transmission through the metasurface by covering the lower MNSA with upper MNSA from 0 to 100% overlap measured from the edges of lower MNSA in terms of covering percentage. Till now, in the aforementioned discussions, the simulated results with 0% overlap have been presented.

Figure 4a shows the transmittance spectra simulated for metasurfaces having constant values of h ($=100$ nm) and H ($=25$ nm) and that of varying g in steps of 20% increase. It can be seen that transmittance maxima show a red spectral shift with an increase in the lateral overlap (g), while the transmittance through the metasurface goes down ultimately to zero for 100% lateral overlap, when the opening of the slit in upper MNSA becomes zero, for obvious reasons. A clear understanding of the transmission spectra was made by studying the light confinement between upper and lower MNSAs, through the EM field profiles displayed in Fig. 4b, c and d. To our surprise, about 60% transmission is achieved for about 90% closure of the slit in the upper MNSA; the credit goes to surface plasmons. However, the value of normalized electric field which is confined between upper and lower MNSAs also goes down. This study also confirms that during the fabrication of such metasurfaces, a fabrication tolerance of about 40% lateral opening does not alter the performance much, except slight variation in peak wavelength.

Fabrication tolerances in terms of the fill factor f were also estimated. It is also possible to achieve good optical

Fig. 4 (a) Transmission spectrum for increasing value of g . (b–d) are the electric field profiles at resonance wavelengths for 20%, 60%, and 90% lateral overlap, respectively. The insets of figures (b–d) show enlarged views of the EM field profiles confined in the hot spot between both the MNSAs

transmission through the proposed structure for different values of the f as shown in Fig. 5 for fixed values of h , H , and Λ , which are 100, 25, and 1600 nm, respectively.

In Fig. 5a, we have plotted the transmittance spectra for 0th order of the transmitted light through the plasmonic metasurface for different values of f ranging from 0.625 to 0.375 in steps of 0.125. With a decrease in the f , the peak resonance wavelength showed a red spectral shift. Also, the width of the resonance curve was slightly larger for 50% f . The aforementioned responses can be explained by understanding the roles of superstrate and substrate coupled MNSA on EM modes and their coupling, which will be evident more clearly in the subsequent discussions of Fig. 7.

Various plasmonic metals, such as Ag, Au, and Al, have been reported for study of metasurfaces [25, 75]. We have also simulated the same geometrical structure of proposed

plasmonic metasurface with different noble metals (Ag, Al, Au) to properly select material for the highest EOT and specified spectral response.

The values of different geometrical parameters, e.g., h , H , Λ , and f , were considered to be 100, 25, 1600, and 0.625 nm, respectively, for the simulation of transmission spectra with different metals. The metal thickness was optimized for each metal to achieve maximum EOT, and it was obtained to be 100 nm for all the three metals. Figure 5b shows a comparison among the transmission spectra for plasmonic metasurfaces made of Ag, Au, and Al with respective optimized thicknesses. It can be observed that for silver (Ag), the FWHM is the lowest, while transmission peak strength is the highest as compared to that of gold (Au) and aluminum (Al). The reason behind such a variation might be due to high values of the imaginary dielectric functions of Al and Au at the resonance wavelengths,

Fig. 5 Transmittance spectra for different—(a) values of fill factor f ; (b) different noble metals

Fig. 6 (a) Electric and (b) magnetic field profile of the optimal plasmonic metasurface at the resonance wavelength = 1641.2 nm

respectively, 56.61 and 13.75, as compared to that of Ag, 3.82 [69]. The FWHM and the peak strength of the plasmonic response curve are the two main factors which decide the accuracy and the FOM of a plasmonic sensor. That is why Ag was considered for simulations.

Since the plasmons are excited at the metal-dielectric interface between the Ag nano-slits and the superstrate/substrate media, the plasmon resonance modes encounter a spectral shift with a change in the RI(s) of the substrate/superstrate, thereby providing RI sensing ability to the metasurface. Hence, the electric and magnetic both the field profiles of the optimal metasurface were studied in detail and have been presented in Fig. 6. Figures 6a and b respectively represent the electric and magnetic field profiles of the optimal metasurface structure having geometrical parameters h , H , Λ , and f equal to 100 nm, 25 nm, 1600 nm, and 0.625, respectively, for both the substrate and superstrate as air. The insets of both the figures show enlarged view of the field profiles in the space between both the MNSAs. It can be observed that for the optimal parameters of the metasurface at the resonance wavelength, the electric field gets confined in the space between the two MNSAs, creating a hotspot and thereby leading to giant EOT. There is relatively weak oscillating electric field in the superstrate region. However, as is evident from the Fig. 6b, the magnetic field shows an enhanced and oscillatory behavior in the superstrate region. Though the magnitudes of the both the electric and magnetic fields are the same in the superstrate region, the penetration depth of the magnetic field is much larger as compared to electric field. Hence, the superstrate region can be used as analyte region for sensing applications.

PDMS was chosen as substrate material on which the metasurface was fabricated to realize an EOT-based flexible

sensor. The refractive index of PDMS was taken from Eq. (6). The structural parameters of the metasurface were re-optimized for the maximum value of optical transmission, which was achieved to be 90.06% for the optimized values of h and H as 70 and 55 nm, respectively, for $f=0.625$.

The effect of change of substrate on the optical response of the metasurface can be seen in Fig. 7a. It can be observed that when the substrate was changed from Air to PDMS, the optimal thicknesses of Ag for maximum achievable EOT became 70 nm from 100 nm. Further, a slight red-shift in the transmission maximum (from 1641 to 1649 nm) was obtained. The shift in the resonance wavelength is a consequence of the change in the SP resonance conditions at the interfaces ② and ④. Even though there was a huge change in RI when substrate was replaced from air ($n=1$) to PDMS ($n=1.42$), since the interaction volume was very small, a small red shift is observed. The strengths of the resonant peaks are attributed to the phase differences of the incident and reflected waves. Hence, when the substrate changed to PDMS, the optimal metal thickness became 70 nm to facilitate a phase difference of nearly π between the light incident and reflected off the metasurface, thereby maintaining giant EOT. For exploring the RI sensing applications of the metasurface, the superstrate was considered as analyte with refractive index (n_a) ranging from 1.33 to 1.38 in the steps of 0.01. Since the interaction volume of the analyte with the EM field was large, when the analyte RI was changed from $n_a=1$ to $n_a=1.33$, the resonance wavelength shifted from 1649 to 1888 nm. To demonstrate the transmission spectra for varying the value of n_a in the same plot, a break around 1700–1850 nm in the horizontal axis of Fig. 7a was introduced.

Fig. 7 (a) Transmission spectra for varying n_a over the metasurface based flexible sensor and (b) characteristic response curve of the sensor

Fig. 8 Transmission spectra for (a) constant value of n and varying k values and (b) both n and k varying. The corresponding insets show the quantitative variation of the resonance wavelength and peak transmittance with changes in the complex RI

It can further be observed in Fig. 7a that when the value of n_a is increased from 1.33 to 1.38, a red shift in peak transmission spectrum is obtained. This is due to the excitation of resonance plasmonic modes at larger wavelengths for high values of n_a . In Fig. 7b, the values of resonance wavelengths corresponding to the highest transmittance, extracted from Fig. 7a, have been plotted with varying n_a . A linear variation in the resonance wavelength with n_a was observed. A sensitivity 1435.71 nm/RIU was estimated by linear fitting of the data points and calculating the slope. The FOM was obtained to be 80 RIU⁻¹ which remained constant with the variation of n_a . This provides an added advantage over the conventional SPR, as the FWHM of the SPR curves increase with increase in analyte refractive index [76], while in the present case, the width of the plasmonic peaks remains constant. One of the major applications of the plasmonic metasurface could be in the area of biomedical sensors for detection of analytes in blood. Such analytes are absorptive in nature and rather having only a real value of RI, they possess complex RI in the NIR window. The response of the metasurface sensor for analytes with complex refractive indices was simulated, and the transmission spectra were studied. In Fig. 8a, the transmission spectra for analytes of complex RI having real value $n = 1.31$ and imaginary value k varying from 0.000 to 0.010 have been plotted in order to analyze the effect of the imaginary part of the refractive index over sensor performance. It can be seen that the transmission peak shows a slight red shift with an increase in the k , while the peak transmittance decreases monotonically. It can more clearly be observed in the inset of the same figure, where the peak wavelength (λ_{res}) values have been plotted on the left Y-axis and the peak transmittance values have been plotted on right Y-axis with respect to the changes in the k values of the analyte. Since, with an increase in the k value, the effective RI of the analyte increases slightly, a small red-shift in λ_{res} is observed. However, with increase in k , the absorbance increases, thereby leading to decrease in peak transmittance. In Fig. 8b, the transmission spectra for various analytes of complex RI have been plotted, where both the n and k values were increased from 1.31 to 1.40 and

0.001 to 0.010, respectively. When both the n and k values increase, the overall change in effective RI of the analyte is relatively large; hence, larger red shift in λ_{res} was observed, while the maximum transmittance decreased for the reasons already mentioned in discussion of Fig. 8a. The inset of Fig. 8b, similar to that of Fig. 8a provides accurate quantitative variation of both the parameters. It can be observed that variation in λ_{res} with complex RI is almost linear, while that of peak transmittance is non-linear. However, the figure of merit decreases with increase in complex RI, because the FWHM of the spectral curve increases.

Conclusions

In summary, we have designed, simulated, and optimized a seemingly opaque plasmonic metasurface consisting of two plasmonic MNSAs to achieve giant EOT and then used it for RI sensing applications. A design inspired for cost, labor, and time effective metasurface was first proposed and then optimized for the interlayer vertical distance as well as lateral overlap between both the MNSAs. The observations on the enhancement of light transmission were supported by EM field profiles. For the optimized metasurface structure, a giant EOT of more than 90% was achieved, which was attributed to the perfect coupling between the plasmonic modes generated by the upper and lower MNSAs. It was also substantiated that the plasmonic mode coupling depends on the parameters of the MNSA (e.g., thickness and fill factor) and the optimized interlayer vertical distance. An EOT-based flexible RI sensor using PDMS as substrate was also studied to propose a highly sensitive metasurface-based sensor. A refractive index sensitivity of 1435.71 nm/RIU with the figure of merit (FOM) 80 RIU⁻¹ was achieved. The current study can be useful in understanding the fundamental reasons of EOT, high performance optical filters, polarizers, and flexible sensors. The response of the sensor for ideal absorbing materials with complex refractive indices was also studied. This study also opens new avenues, with inclusion of ideal absorption materials with complex

refractive indices, to study intriguing new optical properties and applications of the metasurface.

Author Contribution Sachin K. Srivastava (SKS) supervised this research. Both the authors contributed to the study conception and design. Sagar K. Verma (SKV) did COMSOL simulations and developed the code. Both SKS and SKV participated in the interpretation of the data. Both the authors wrote the paper and participated in the revisions of it. Both the authors have read and approved the final version of the manuscript.

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Data Availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Code Availability The code developed for this study is available from the corresponding author upon reasonable request.

Declarations

Ethics Approval The paper reflects the author's own original research and analysis in a truthful and complete manner. This research does NOT involve human participants or animals; thus, no ethical approval and patient consent are required.

Consent to Participate The authors provide consent to participate.

Consent for Publication The authors provide consent to publish.

Conflict of Interest The authors declare no competing interests.

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