Significantly enhanced sensitivity using a gold aperture arrays-dielectric hybrid structure in optical fiber sensor

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Abstract

In this paper, we propose a novel gold aperture arrays-dielectric hybrid structure in optical fiber sensor (OFS) based on the extraordinary optical transmission (EOT) property to explore the possibility of increasing its sensitivity. Numerical investigations show that the match between effective indices of the fundamental core mode and surface plasmon polariton (SPP) mode of gold aperture arrays-dielectric interface affects the sensitivity enhancement by using mode analysis approach. The essential parameters of the hybrid structure including the gold film thickness and dielectric refractive index (RI) as well as its thickness, which affect the EOT, are discussed and optimized. An average sensitivity of $180 \pm 7$ nm/RIU in the sensing range 1.30–1.45 with high linearity is obtained. It is demonstrated that a significant sensitivity enhancement with a dielectric layer (its RI is 1.90 and its thickness is 50 nm) up to 105 arbitrary units ($\sim 140\%$) is clearly observed more than that without a dielectric layer. The averaged figure of merit (FOM) of the proposed OFS is calculated to be 12.5 RIU$^{-1}$. Our findings indicate that this proposed hybrid structure may offer great potential in designing and optimizing a high-performance OFS.

1. Introduction

Surface plasmon resonance (SPR) is the resonant oscillation of free electrons excited by light at the metal/dielectric interfaces [1]. SPR is very sensitive to the variations of refractive index (RI) and particularly useful for biosensing, owing to the label-free and real-time detection [2]. Several SPR-based techniques such as SPR enhanced imaging and SPR spectroscopy have been developed [3, 4]. Recently, SPR on periodic aperture arrays has garnered a great deal of research interest associated with an extraordinary optical transmission (EOT) phenomenon since first being reported by Ebbesen in 1998 [5]. A new generation of optical fiber sensors (OFS) based on EOT is continuously developed for (bio)chemical sensing purposes. Especially, SPR sensor based on EOT provides a well-established route for label-free biological sensing from various molecular detection to protein dynamics. Exploring the electromagnetic field localization properties of EOT for SPR sensing has been proposed to beat the limitations in operation and performance of other optical detection approaches [6]. The conventional SPR sensing structure is based on Kretschmann configuration [7]. But, this prism-based construction is bulky, because many optical and mechanical components are required. And so remote-sensing is difficult. Device miniaturization based on the optical fiber platform can overcome the drawbacks of traditional SPR sensors, and it offers numerous advantages such as simple and flexible optical design, remote-sensing capability, and in situ monitoring [8, 9]. This combination of SPR and optical fiber would have the possibility to far extend the scope of plasmonic utilization in biological and chemical communities. Several types of OFS based on SPR with different structures, including the D-shape [10] and based on EOT [11–18] has been demonstrated experimentally and theoretically.

Recently, owing to the impressive progress in the nanofabrication technology, many researchers have pursued this idea in a quest to create sensitive RI sensors by fabricating an array of nanostructures on an optical
fiber, for instance, apertures. Over the past few years, many fiber-based SPR sensors have been reported, including SPR sensor with single, multimode mode, and polarization maintaining fibers coated with a thin metallic layer \[19\]. More recently, Peipei Jia et al. have been successful attempts to realize SPR sensors based on EOT in optical fibers endface experimentally by template transfer technology \[12–15\]. The OFS using metallic aperture arrays is especially attractive to RI sensing. Its sensing principle is according to the SPR spectrum peak wavelength (\(\lambda_{\text{peak}}\)) and its intensity (\(T_{\text{peak}}\)) sensing, which indicates sensor signal variations in response to the RI change adjacent to the metallic surface. The basic research of plasmonic fiber sensing technologies is still attracting many researcher interests. These early proposals offer preliminary designs, for example, through an integration of large-area metallic nanohole arrays directly onto the optical fiber endfaces, which with little theoretical or experimental evidence to show that the sensing performance of OFS would be enhanced by a metallic nanostructure. We would like to develop some new types of plasmonic nanostructures that can improve the analytical performance, such as detection limits, sensitivity, and figures of merit (FOM). Such as, in 2008, Oulton R. F., et al. described ‘a hybrid plasmonic waveguide for subwavelength confinement and long-range propagation’, this important work was published in ‘Nature Photonics’ Journal \[20\]. The hybrid optical waveguide consists of a cylinder waveguide separated from a plane metal surface by a nanoscale dielectric gap (its thickness is less than 100 nm). To the best of our knowledge, few studies have been reported using this type of hybrid structure on fiber endface to explore the possibility of efficiently generating EOT for RI sensing.

In this paper, we report a novel hybrid structure, which is composed of Au aperture arrays combined with a dielectric layer, for low-loss deep-subwavelength light transport. This study brings a full understanding of the SPR mode behavior in a new hybrid structure-coated on an optical fiber endface for us. And therefore, it is particularly useful for RI sensing design purpose. We begin with the analysis of various core-guided modes supported by the OFS to get a comprehensive understanding of the SPR properties. Here, the effect of crucial parameters of the hybrid structure such as Au film thickness \(t_{\text{Au}}\), and dielectric RI \(n_d\), as well as its thickness \(t_d\) on the EOT, is analyzed and optimized numerically using the finite-difference-time-domain (FDTD) method. Moreover, by tuning the geometrical properties of the hybrid structure, we can obtain a best EOT property and increase the sensitivity of OFS. We hope our findings provide guidance to fundamental research of high-sensitivity integrated OFS based on EOT.

2. Structure design and numerical modeling

Figure 1(a) shows the schematic of the proposed OFS, which is used by a hybrid structure of Au aperture arrays \(t_{\text{Au}} = 100 \text{ nm}\) combined with a dielectric layer \(50 \text{ nm} \leq t_d \leq 100 \text{ nm}, 1.45 \leq n_d \leq 1.90\) deposited on a core (its RI is denoted by \(n_1\))-cladding (its RI is denoted by \(n_2\)) optical fiber endface \(n_1 > n_2\). This is a single-material (silica glass) optical fiber that can be obtained by the well-developed stack-and-draw fabrication process, as shown in three-dimensional (3D) view of the structure. Au aperture arrays are placed onto the fiber.
core (its diameter is denoted by $d_1$, $d_2 = 10.0 \mu m$), the pitch of the square lattice is denoted by $\Lambda$, $\Lambda = 0.4 \mu m$, the diameter of air aperture is denoted by $d_a$, $d_a = 0.2 \mu m$, as shown in the top view structure of figure 1(b). Here, it’s important to emphasize the above the three parameters ($d_1$, $\Lambda$, $d_a$) remain the same throughout the process of simulation. Au aperture arrays combined with a dielectric layer constitutes a novel hybrid structure, as shown in the side view structure of figure 1(c). The main differences of the hybrid structure comparing with references literature [20] design lie in two aspects: (i) The core-cladding optical fiber endface is perpendicular to the dielectric layer instead of the cylinder waveguide, which is parallel to that. (ii) Au aperture arrays instead of a plane metal film.

Afterwards, we use the commercial full-wave electromagnetic field simulation software package, FDTD Solutions and MODE Solutions (Lumerical Solutions Inc., Canada) [21] to investigate the modal profiles, EOT and sensing performances of the proposed OFS. FDTD uses finite-difference approximation in both time and space domain to calculate the Maxwell’s curl equations step by step. Initially, Au aperture arrays are filled with air, $n_{air} = 1.0$. RI of the core-cladding was taken as $n_1 = 2$ and $n_2 = 1.45$ respectively. The dielectric constant of gold in the visible and near-IR region is defined by the Drude model described as [22]:

$$\varepsilon_{Au}(\omega) = \varepsilon_{\infty} - \frac{\omega_{p}^{2}}{\omega(\omega + i\omega_{c})}$$  \hspace{1cm} (1)

where $\varepsilon_{\infty} = 9.75$ is the dielectric constant of gold at high frequency, $\omega_p = 1.36 \times 10^{16}$ is the plasma frequency of gold, and $\omega_{c} = 1.45 \times 10^{14}$ is the scattering frequency of electron, and the data are given by Johnson and Christy [23]. In our calculation, we use mesh sizes ranging from 3 to 6 nm. The dielectric constant in cells at the metal-dielectric interface is taken as that of the medium with the largest volume inside that cell. For the calculation of the transmittance, the structures were excited by a mode sources packet composed of normally incident single fundamental mode waves (with the electric field pointing along one of the axes of the square array). Infinite periodic aperture arrays are simulated by applying Bloch conditions at the boundaries of the unit cell and imposing ‘uniaxial perfectly matched layer (PML)’ at surfaces parallel to the metal film. The calculated zero-order transmission spectra around the circular apertures are shown in figures 3(a), (b), 4(a), (c), (e), and 5(a).

3. Results and discussion

3.1. Mode analysis and sensitivity enhancement of OFS

In order to gain a deeper understanding, we analyse the dependence of the OFS mode’s effective index ($n_{eff}$) on different $n_2$ (from 1.30 to 1.50 in steps of 0.05) using a Finite-Difference Eigenmode (FDE) solver of MODE Solutions. Figure 2(a) depicts the variation tendency of the real parts of $n_{eff}$ (Re ($n_{eff}$)) with different $n_2$ as a function of the wavelength. Re ($n_{eff}$) decreases with increasing wavelength corresponding to different $n_2$. We have plotted a set of amplifying curves (the wavelength range being between 0.55 and 0.60 $\mu m$), which is shown in the inset for clear observation. At the wavelength of 0.58 $\mu m$, the values of Re ($n_{eff}$) are 1.957, 1.957 43, 1.9579, 1.958 41, 1.958 99, with $n_2$ of 1.30, 1.35, 1.40, 1.45 and 1.50, respectively. In addition, we also take into account the effective index ($n_{eff}$) of SPP mode in Au aperture arrays-dielectric hybrid structure, while

$$n_{eff} = \sqrt{\varepsilon_{Au}/(\varepsilon_{Au} + \varepsilon_4)} = 1.9584,$$  \hspace{1cm} (2)

which is consistent with references literature [20]. We suggest that $n_2 = 1.45$ is the optimal value. To test the idea, we also analyse the dependence of OFS mode’s modal loss on different $n_2$. The supermode 1 (s1 mode for short) is analyzed to investigate the propagation loss. By using the imaginary part of effective index ($\text{Im}(n_{eff})$), the propagation loss is defined by the following equation [24].

$$\alpha = 40\pi \text{Im}(n_{eff}) / (\text{ln}(10) \lambda) \approx 8.686 \times k_0 \text{Im}(n_{eff}) \times 10^{-3} \text{dB} / \text{nm}$$  \hspace{1cm} (3)

where $k_0 = 2\pi / \lambda$ is the wave number in the free space and the wavelength $\lambda$ is in micron. Figure 2(b) shows the dependence of the modal loss spectra of s1 mode on different $n_2$. It is found that the leaky energy loss exhibits an upward trend initially and then a downward one, which indicating the occurrence of SPR. It is clearly visible that the electric field is well confined in the fiber core at the wavelength of 0.58 $\mu m$ from inset (@1.45-s1). At 0.58 $\mu m$, the core guided mode and SPP mode are coupled together. This indicates the maximum energy transfer from the core-guided fundamental mode to the SPP mode in term of $n_2 = 1.45$. The coupling conditions of plasmonic and core guided mode can be modified by adding this hybrid structure. Finally, the obtained electric field distributions and $n_{eff}$ of the relevant modes are illustrated in figure 2(c). It is readily to recognize that the discrete core-guided modes interact with each other, forming core-guided supermodes. It should be noted that the mode field distributions have a Gaussian profile, rather than a splitting nature as a higher order mode features in a standard single mode fiber, so it is not appropriate to name these modes as higher order modes. The figures in figure 2(c) are arranged according to Re ($n_{eff}$) which are (1) 1.961 074, (2) 1.900 057, (3) 1.897 212, the corresponding electromagnetic modes are named fundamental mode, s1 mode, and s2 mode, respectively. Concerning the propagation loss, $\alpha$ defined in equation (2), which is in proportional
to the Im($n_{eff}$), the s1 mode and s2 mode exhibit a much larger loss property than the fundamental mode. Though $n_{eff}$ difference between the three supermodes is quite small, in the order of $10^{-6}$RIU, all the three guided-modes are able to excite and resonate with plasmonic modes. It is clearly visible that there is a distinguishable coupling between the fundamental mode and plasmonic mode from inset ((1)@1.45-fund. mode). For the purpose, we use 1.45-fund. mode as the base mode of the incident light source, as shown in figure 1(c).

To investigate the sensitivity enhancement property of the proposed OFS, we firstly use a FDTD numerical simulation to model the EOT spectra on the same core-cladding optical fiber endface with two different structures: Au aperture arrays ($t_{Au} = 100$ nm) structure (without D for short) and Au aperture arrays-dielectric ($t_{Au} = 100$ nm, $t_d = 100$ nm, $n_d = 1.50$) hybrid structure (with D for short). Then, their RI sensing properties are analyzed. The simulated results are presented in figure 3(a). Figure 3(a) shows the obvious difference of zero-order transmittance spectra in the wavelength range of 0.5 and 0.7μm of two different structures. In the first place, it is found that their $T_{peak}$ and full-width-at-half-maximum (FWHM) values are different, as shown in the blue background region of figure 3(a). Comparing with the two different $\lambda_{peak}$, 560 and 567 nm, it is found that a higher and narrower solid-line peak is obtained with D. It shows that solid-line $T_{peak}$ value is up to 4 arbitrary units (∼37%) more than that of dashed-line. The solid-line FWHM value is 30 nm, less than 45 nm of dashed-line FWHM value. It is quite evident that the hybrid structure shows the better EOT performance. Afterwards, we introduce another important parameter to evaluate the EOT, which is the quality factor (Q-factor) [25]. Q-factor is defined as:

$$Q = \frac{\lambda_{peak}}{FWHM}$$

(3)

According to the equation (3), we discover that the solid-line Q-factor value is 19, greater than 12 of dashed-line Q-factor value. This is because of the introduction of a hybrid structure on the fiber core center, the coupling between SPR and fiber core-guided mode across a nanoscale dielectric layer enables ‘capacitor-like’ energy storage, which allows effective subwavelength transmission. It should be addressed that its working mechanism is consistent with that of the previous reported literature [20]. We desire to demonstrate the coupling role enhanced the EOT, which is supported by the hybrid structure and lays emphasis on improving its RI sensitivity. In order to illustrate the phenomenon mentioned above, the electric field ($|E|$) near-field profile of $\lambda_{peak} = 560$ nm and $\lambda_{peak} = 567$ nm of the two corresponding structures were investigated respectively for this purpose, as shown in the insets of figure 3(a). The $|E|$ intensity at $\lambda_{peak} = 560$ nm and $\lambda_{peak} = 567$ nm, are
characteristic in x-y plane. It is found that there is an evident difference in the \( |E| \) distributions of the two different structures. By comparing the two insets, it can be found that the \( |E| \) distributions in x-y plane at \( \lambda_{\text{peak}} = 567 \) nm, \( \lambda_{\text{peak}} \) were all much greater than those of \( \lambda_{\text{peak}} = 560 \) nm, due to the strong coupling role between the fundamental mode and plasmonic mode. So, the entire \( \Delta T_{\text{peak}} \) is enhanced.

The proposed OFS operation is based on the SPR evanescent fields and its interaction with the analytes. The sensitivity is analyzed by using the \( \lambda_{\text{peak}} \) and \( \Delta T_{\text{peak}} \) interrogation method. The corresponding sensitivities are expressed as [24], which are given in units of nm/RIU and %/RIU.

\[
S_{(\lambda)} = \frac{\Delta \lambda_{\text{peak}}}{\Delta n_i} (\text{nm/RIU}) \\
S_{(T)} = \frac{\Delta T_{\text{peak}}}{\Delta n_i} (\%/\text{RIU})
\]  

where \( \Delta \lambda_{\text{peak}} \) is the resonance peak shift, \( \Delta \lambda_{\text{peak}} \) is the variation of \( T_{\text{peak}} \), and \( \Delta n_i \) is the variation of the RI of analyte. Then, we do sensitivity analysis of OFS with D and without D by calculating the zero-order transmission spectra in \( n_i = 1.3 \) and \( n_i = 1.4 \), as showed in figure 3(b). The inset of figure 3(b) shows the \( |E| \) distributions of fundamental core mode and SPP mode in x-z plane at resonance wavelength. With a dielectric layer added, the \( T_{\text{peak}} \) observably enhances, meanwhile \( \lambda_{\text{peak}} \) large range redshifts. \( T_{\text{peak}} \) enhancement is due to the increasing SPP excitation caused by a hybrid structure as explained above. From upper inset of figure 3(b), it is clearly visible that at the core guided fundamental mode, its electric field is well confined in the fiber core, and the SPP mode, the electric field is introduced on the metal surface. The largest energy is transferred from the core-guided mode to the SPP mode, when both modes are strongly coupled. Conversely, in under inset of figure 3(b), the fundamental core mode and SPP mode are not phase matched at resonance wavelength, and are infirmly coupled together. As the \( n_i \) increases, the OFS with D undergoes a larger \( \lambda_{\text{peak}} \) redshift, as well as a larger \( T_{\text{peak}} \) enhancement, leading to the improved sensitivities in both wavelength and intensity interrogations.

Subsequently, we mainly focus our attention on the OFS sensing performance by calculating the zero-order resonant spectra in a large dynamic RI range to find the corresponding \( \lambda_{\text{peak}} \). It is preferable to get an average \( S_{(\lambda)} \) within a given analyte RI range. What’s more, \( S_{(\lambda)} \) is dependent on the EOT performance of \( \lambda_{\text{peak}} \). The air
aperture is filled with different \(n_t\) in alternating sequence in order to analyze the \(S_{\lambda_f}\). The \(n_t\) in aperture varies between 1.30 and 1.45. The simulated \(\lambda_{peak}\) underwent a regular red-shift as the \(n_t\) surrounding them increased. The results are not presented in figure. The purpose is to avoid duplication with the following content. With this consideration in mind, we investigate the \(S_{\lambda_f}\) only analyzing the above \(\lambda_{peak} = 560\) nm and \(\lambda_{peak} = 567\) nm. The corresponding linear fitting lines of \(\lambda_{peak}\) with respect to \(n_t\) is presented in figure 3(c). The slopes give an average \(S_{\lambda_f}\) of the analytes, i.e., \(90 \pm 5\) nm/RIU (solid-line) and \(75 \pm 2\) nm/RIU (dashed-line) within the relevant sensing range. This result shows that a distinguishing \(S_{\lambda_f}\) enhancement with \(D\) up to 15 arbitrary units (\(-20\%\)) is clearly observed, more than that without \(D\). This is due to the hybrid structure for effective subwavelength confinement, which enhances the EOT and \(S_{\lambda_f}\). The study presented here also provides a basic concept that we can control the \(S_{\lambda_f}\) enhancement using a novel hybrid structure. Hence, this narrower bandwidth peak with high \(T_{peak}\) and high \(Q\)-factor may have a productive application in RI sensing. By a suitable parameters choice, including \(t_{fAu}, n_d\), and \(t_d\), we can achieve an extreme high \(S_{\lambda_f}\). To find the appropriate parameters, a series of FDTD simulations have been done. First, we investigate the influence of three parameters (including \(t_{fAu}, n_d\), and \(t_d\)) on \(Q\)-factor and FWHM. Then, \(S_{\lambda_f}\) and \(S_{\gamma_f}\) of the proposed OFS is analyzed.

### 3.2. Influence of \(t_{fAu}, n_d\), and \(t_d\) on \(Q\)-factor and FWHM

Firstly, \(t_{fAu}\) is introduced to optimize the EOT performance. Figure 4(a) plots the calculated zero-order transmission spectral (stack lines by \(Y\) offsets) in the wavelength range of 0.45 and 0.7 \(\mu m\) with \(t_{fAu}\) of 100, 140, 180, 220, 260, and 300 \(nm\), respectively, when the other parameters remain unchanged. The peak shape of transmittance spectra can be tuned by merely adjusting \(t_{fAu}\) which shows a way to tailor the EOT. Then, we plot two curves of \(Q\)-factor and FWHM of the corresponding six resonance peaks connected by a dashed-line, as shown in figure 4(a), as functions of \(t_{fAu}\) in figure 4(b). It can be found that \(Q\)-factor value is firstly decreased, then consistently increased; FWHM value is firstly increased, then consistently decreased with \(t_{fAu}\) increasing from 100 to 300 \(nm\). \(Q\)-factor maximal value is 27, FWHM minimum value is 21 \(nm\) with \(t_{fAu} = 300\) \(nm\). With a balanced view, the blue-solid-line (\(t_{fAu} = 300\) \(nm\)) shows a best EOT peak. Secondly, \(n_d\) and \(t_d\) are introduced to optimize the EOT. Figure 4(c) plots the calculated zero-order transmission spectral (stack lines by \(Y\) offsets) in the wavelength range of 0.45 and 0.7 \(\mu m\) with the \(n_d\) of 1.45, 1.54, 1.63, 1.72, 1.81, and 1.90, respectively. The peak shape of transmittance spectra can be tuned by merely adjusting \(n_d\). Then, we plot two curves of \(Q\)-factor and FWHM of the corresponding six resonance peaks, as functions of \(n_d\) in figure 4(d). It can be found that \(Q\)-factor value is firstly increased, then decreased, and finally increased; FWHM value is firstly decreased, then increased, and finally decreased with \(n_d\) increasing from 1.45 to 1.90. \(Q\)-factor maximal value is 29, FWHM minimum value is 23 \(nm\) with \(n_d = 1.90\). With a balanced view, the red-solid-line (\(n_d = 1.90\)) shows a best EOT peak. Figure 4(e) plots the calculated zero-order transmission spectral (stack lines by \(Y\) offsets) in the wavelength range of 0.45 and 0.7 \(\mu m\) with the \(t_d\) of 50, 60, 70, 80, 90, and 100 \(nm\), respectively. The peak shape of transmittance spectra can be tuned by merely adjusting \(t_d\). Then, we plot two curves of \(Q\)-factor and FWHM of the corresponding six resonance peaks connected by a dashed-line, as shown in figure 4(e), as functions of \(t_d\) in figure 4(f). It can be found that \(Q\)-factor value is firstly increased, then increased, and finally decreased; FWHM value is firstly increased, then decreased, and finally increased with \(t_d\) increasing from 50 to 100 \(nm\). \(Q\)-factor maximal value is

![Figure 4](image-url)
23, FWHM minimum value is 25 nm with \( t_d = 50 \text{ nm} \). With a balanced view, the green-solid-line \(( t_d = 50 \text{ nm} )\) shows a best EOT peak.

### 3.3. \( S_\lambda \) and \( S_{T,\lambda} \) analyzes of the proposed OFS

By above these findings, we advise that through a suitable choice of \( t_{(d_t)} \), \( n_d \), and \( t_d \), a feasible narrow peak can be obtained. We can use it as a sensing device for tracking the \( \lambda_{\text{peak}} \) and \( T_{\text{peak}} \) with the variation of \( n_s \). Thus, the proposed OFS with the following one set of parameters \(( t_{(d_t)} = 300 \text{ nm}, n_d = 1.90, t_d = 50 \text{ nm} )\) were selected to explore the RI sensing capability. Then, we analyze the OFS sensing performance by calculating the resonant spectra in a large dynamic \( 1.30 \leq n_s \leq 1.45 \) range to find the corresponding \( \lambda_{\text{peak}} \) and \( T_{\text{peak}} \), as shown in figure 5(a). The \( \lambda_{\text{peak}(1)}, \lambda_{\text{peak}(2)}, \) and \( \lambda_{\text{peak}(3)} \) undergo a regular red-shift, as the \( n_s \) increased from 1.30 to 1.45. Among them, the \( \lambda_{\text{peak}(2)} \) red-shift quickly. We have plotted one amplifying curve of peak (2), which is shown in the inset for clear observation. Although \( \lambda_{\text{peak}(1)} \) and \( \lambda_{\text{peak}(3)} \) red-shift slowly, their \( T_{\text{peak}} \) have a regular enhancement with increasing \( n_s \) from 1.30 to 1.45. With this consideration in mind, we also investigate the OFS sensitivity in EOT amplitude in this work. Finally, we investigate the RI sensitivity by analyzing the above \( \lambda_{\text{peak}} \) and \( T_{\text{peak}} \) with respect to \( n_s \) is presented in figure 5(b). The regression equations in figure 5(b) are

\[
\begin{align*}
T_{\text{peak}(1)}(\%) &= 18n - 17, \\
\lambda_{\text{peak}(2)}(\text{nm}) &= 180n + 370, \\
T_{\text{peak}(3)}(\%) &= 44n - 56.
\end{align*}
\]

(6)

The slopes of these equations give an average \( S_{T,\lambda} \) and \( S_\lambda \) of the analytes, i.e., \( 18 \pm 2\% / \text{RIU}, 180 \pm 7 \text{ nm} / \text{RIU} \), and \( 44 \pm 5\% / \text{RIU} \) within the relevant sensing range. The adjusted R-Square values of \( T_{\text{peak}(1)}, \lambda_{\text{peak}(2)}, \) and \( T_{\text{peak}(3)} \) fitting lines are 0.9615, 0.9887 and 0.9232, respectively, indicating a high linearity of the OFS. This result also shows that a distinguishing \( S_\lambda \) enhancement in \( \lambda_{\text{peak}(2)} \) with \( t_d = 50 \text{ nm} \) up to 105 arbitrary units \((\sim 140\%) \) is clearly observed, more than that without D. In order to understand the sensing property more deeply, FWHM and FOM are taken the resolution into account. The FWHM values of peak (2) are extracted from figure 5(a).
and them as a function of $n$, are plotted in figure 5(c). One can see that the FWHM values are slightly decreased from 27 to 8 nm as $n$ increased from 1.30 to 1.45. Furthermore, FOM is expressed as [26]

$$FOM = \frac{S(t)}{FWHM}$$

(7)

We have calculated the $S(t)$ and FWHM values of peak (2). According to equation (7), the averaged FOM of the OFS is calculated to be 12.5 RIU$^{-1}$. The FOM is used to comprehensively characterize the performance of OFS. The goal of the design is to obtain high values of both $S(t)$ and FOM. These findings presented here also provides a theoretical basis for experimentally obtaining a high-performance OFS, using the hybrid structure of Au aperture arrays combined with a dielectric layer, with one set suitable parameters combination of $t_{Au} = 300$ nm, $n_d = 1.90$, $t_d = 50$ nm.

4. Conclusion

In summary, using the FDTD method, we have numerically demonstrated $S(t)$ and $S(f)$ enhancement of OFS achieved with a novel Au aperture arrays-dielectric hybrid structure under the critical coupling condition $n_{eff} = n_{dpp}$. The effects of $t_{Au}$, $n_d$, and $t_d$ on EOT phenomenon are discussed and optimized, correspondingly. It is found that when $t_{Au} = 300$ nm, $n_d = 1.90$, $t_d = 50$ nm in this hybrid structure, it has the best EOT properties, its $S(t)$ and averaged FOM being 180 $\pm$ 7 nm/RIU and 12.5 RIU$^{-1}$, respectively. A significant $S(t)$ enhancements with $t_d = 50$ nm up to 2.4 times, is solidly achieved, which compared with that without D. These results offer an important basis for improving the sensing performance of a new OFS based on a hybrid structure, which potential in the future chemical and biological sensors application.

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