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Anomalous Sensitivity Enhancement of D-Shaped Fiber-Based Sandwiched Structure Optofluidic Sensor

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ABSTRACT A novel mechanism of sensitivity enhancement of D-shaped fiber-based surface plasmon resonance (SPR) sensors for the optofluidic device has been proposed. The sandwiched structure optofluidic platform is developed with metal-coated D-shaped fiber as the sensing device, while another thin metal layer is situated under the inner wall of the substrate as a second metal layer to construct the sandwiched microchannel. It has been found that the sensitivity of the D-type fiber SPR sensor is enhanced significantly with the sandwiched metal-coated structure of microchannel. In the proposed structure, the measurand analyte is considered as a sandwich channel layer between two thin metal layers. The sensitivity of the proposed structure is dependent on the volume of the measurand and the thickness of the metal layers. The computed sensitivity with a double metal layer and sandwich measurand layer concept is $\sim$ 4085 nm/RIU in the region of 1.33 to 1.36. The sensitivity is enhanced by more than a factor of '2.3' in comparison with the sensitivity of the normal D-shape fiber SPR sensor. It can be enhanced further up to $\sim$ 12,500 nm/RIU by the deposition of higher RI polymeric overlay just above the second metal layer. The computed resolution of the proposed sensor with standard interrogation technique is $\sim 1 \times 10^{-7}$ which is quite competitive within the optical fiber sensor domain. A detailed numerical analysis has been accomplished. This structure will be useful in distinct chemical and biological sensing applications where the volume of an analyte is critical. This new concept of enhancement of sensitivity with limited measurand volume will open a new designing methodology for optical fiber biosensors.

INDEX TERMS Optical fiber sensors, chemical sensors, optofluidic, surface plasmon resonance.

I. INTRODUCTION

Over the past year's extensive research has been accomplished with SPR sensors for distinct chemical and biological sensing applications [1], [2]. SPR biosensor is an efficient platform for biochemical sensing due to its label-free detection principle, online measurement, ease of use, and fabrications. The integration of optical fibers with SPR sensors was a revolutionized step towards the development of miniaturized SPR sensors for selective chemical and biological sensing applications [3], [4]. Side polished D-shaped fiber [5], fiber Bragg grating [6], long-period fiber grating [7] based SPR sensors were mostly used optical fiber-based SPR sensors over the past years. Interferometric based optical fiber sensors were also employed for successful measurement of the chemical and biochemical analyte [8], [9]. The fabrication

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and designing of interferometric sensors are complex and the optimization of the fabrication process is crucial to achieving superior performance. The interaction of the evanescent wave with the surrounding medium is the key factor for designing the fiber refractometers. D-shaped fiber provides an easy and efficient way for enhancement of the interaction between evanescent waves with the surrounding medium. Side polished D-shaped fiber was employed successfully for the measurement of axial strain and temperature before [10]. Different chemical and biological sensing applications were accomplished over the years with D-shaped fibers [11], [12]. Lossy mode resonance [13] was studied to enhance the sensitivity further. Optimization of the sensitivity of D-shaped fiber with a metal-coated layer was also studied extensively elsewhere [14]. D-shaped photonic crystal fiber (PCF) is also being explored over recent years. A detailed numerical study on optimization of the sensitivity of D-shaped PCF-SPR with side-polished depth, air hole size, and lattice constant was studied before. The sensitivity of the sensors was found to be ~ 21,700 nm/RIU in an SRI zone of ~ 1.33-1.34, with RI of the PCF material RI ~ 1.36. The fabrication of PCF with a material with RI ~ 1.36 is not convenient [15]. A comprehensive review of PCF based plasmonic sensors was reported in earlier work [16]. Symmetrical dual D-shaped PCF was explored for RI sensing in a range of 1.36-1.41 [17]. Very recently, D-shape high birefringence PCF based SPR is presented. An unprecedented sensitivity was found in the numerical work. The computed sensitivity was found to be ~ 44,850 nm/RIU within a RI zone of ~ 1.43-1.5 [18]. However, in the case of the successful fabrication of biosensors, the RI sensing zone must be near ~ 1.30-1.36 which is a RI zone of standard buffer medium like water, PBS, or citrate buffer. Double metal layer structure [19], [20], Metal Insulator Metal structure [21], and nanostructure coated thin metal layer [22] are considered recently to enhance the sensitivity of the SPR sensors. Very recently surface lattice resonances based on the parallel coupling of modes in metal-insulator-metal stacks were reported for localized SPR sensors [23]. Metallic nanostructures based SPR sensor with superior sensitivity was developed successfully [24]. Flexible localized SPR sensors with metal-insulator-metal nanodisks on polydimethylsiloxane (PDMS) substrate was developed recently for the detection of A549 cancer cells in a dedicated buffer medium (RI =~ 1.333) [25]. Magneto-optical oxide thin film was deposited to explore the transverse magneto-optical Kerr effect (TMOKE) in magneto plasmonic sensors [26]. The integration of photonics and microfluidics creates a new field 'optofluidic'. Measurement of RI is predominantly attractive for optofluidic devices that have extremely small detection volumes (femtoliters or nanoliters) [27]–[29]. Target analyte with extremely low quantities can be detected with optofluidic devices which couldn't be achieved with bulk refractometer sensors. The RI signal of the target specimen scales with the bulk concentration or surface density of analyte, rather than with the total number of molecules. Over recent years, huge progress has been found in the development of a single-mode fiber optofluidic sensor, and the state of the work was illustrated in a very good review [30].

In this paper, we have shown for the first time that a thin gold metal layer or thin metal and polymeric layer coated inner glass wall of the substrate of optofluidic devices can enhance the sensitivity of the D-shaped fiber SPR refractometer in a significant way. The enhancement of the sensitivity of the submicron width optofluidic analyte channel with the decoration of the inner wall of the substrate is the main objective of the proposed work. A minute detection of the change in analyte RI very near to water or water-like buffer medium within a lower volume of the analyte remains as a real challenge. The schematic structure of the proposed device is being shown in Figure 1.

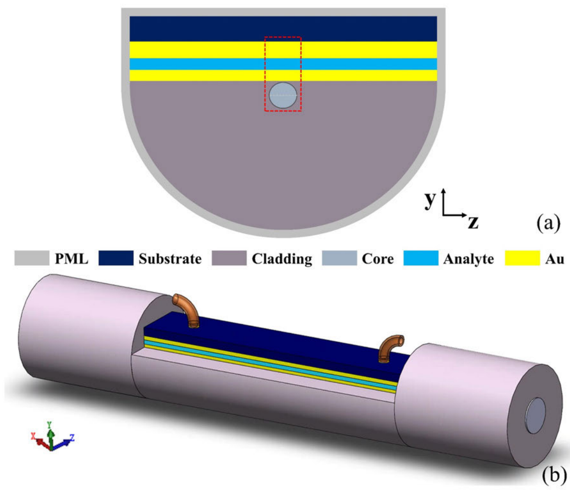


FIGURE 1. a. The proposed schematic structure of optofluidic channels with D-shaped fiber, b. Schematic diagram of the magnified planar structure of the proposed device. Figures are not to scale.

Submicron width channel for analyte medium is being sandwiched between two thin metal layers which initiate the tunneling of plasmon mode and the performance of the proposed sensor is being discussed in this work. Tunneling of a photon via surface plasmon coupling was demonstrated earlier where tunneling was accommodated through the (planar metal layer-dielectric layer-curved metal layer) structure [31]. The tunneling of an optical wave with (metal-dielectric-metal) structures was also proposed elsewhere, the lower RI metals were acted as a potential barrier and higher RI analyte sandwich dielectric medium was acted as a lower potential barrier like conventional electronics. The wave tunnel through this higher RI dielectric zone and penetrate the second metal layer. The transfer matrix method (TMM) was used to explain this tunneling mechanism [32]. Optimization of surface-plasmon-mediated tunneling through symmetric dielectric-metal-dielectric multilayers was also demonstrated experimentally and this concept was utilized in plasmonic, metamaterials, and super lenses system [33]. Potential transmittance (PT) theory is an appropriate theoretical concept for understanding and optimizing the tunneling efficiency of cascaded (metal-dielectric-metal) multi-layers [34]. In this work, the response of the (metal-dielectric-metal) layer on the sensitivity of microfluidic D-shaped fiber-based SPR sensors is being studied. The sensitivity of this device can be optimized with the thickness and dielectric properties of metal layers. It has been shown that the width of the optofluidic analyte channel can modulate the RI sensitivity which constitutes a key designing part of the fabrication. The paper is being organized as follows: in section II, basic theory and description of the proposed structure are being discussed. The RI sensitivity of the proposed D-shaped fiber SPR sensor is discussed elaborately in this section. Optimization of sensitivity with the parameters of the proposed structure is being analyzed in section III. Finally, discussion and conclusion are given in section IV.

II. BASIC THEORY AND INITIAL SIMULATION RESULT

Enhancement of evanescent wave interaction with the surrounding medium is the most efficient way for designing of optical fiber sensors for the measurement of change in surrounding RI (SRI). Side polished optical fiber is being studied extensively over the past two decades for the development of highly sensitive refractometer-based applications where side polishing method provides sufficient generation of the evanescent wave from the guided core mode. Initially, the sensitivity of the D-shaped SPR sensor was studied with a change in the SRI (1.3 to 1.36) in bulk or volume. Standard parameters of SMF-28 fibers are being selected for the numerical computation. Core diameter is considered to be $\sim 8.4\ \mu$m and the cross-section of the D-shaped fiber was chosen to be $\sim 67\ \mu$m. The refractive index of core and cladding are considered to be ~ 1.4494 and 1. 4444 @ 1500 nm, Sellmeier dispersion relation is being used to find the refractive index of core and clad at other wavelengths. The thickness of the gold metal layer is considered to be ~50 nm, where the values of relative permittivity about the gold layer are governed by the Drude model [35],

$$\varepsilon_{\mathrm{m}}(\omega) = \varepsilon_{\infty} - \frac{\omega_p^2}{\omega^2 + j\omega\gamma_D} \tag{1}$$

where ε_{∞} is the permittivity of the metal at an infinite frequency and the value is approximately 1, ω_p is the plasma frequency for the Drude model, γ_{D} is damping coefficients in the Drude model and these parameters are determined based on the experimental data of Johnson and Christy from COMSOL [36]. Guided fundamental core mode of the fiber is being coupled with surface plasmon mode (SPM) at a particular resonant wavelength which is governed by coupled-mode equations. A sharp transfer of energy can be found at this resonance wavelength in the transmission spectrum. The propagation loss formula is being defined as

$$\alpha_{loss} = 8.686\frac{2\pi}{\lambda}\mathrm{Im}(n_{eff}) \tag{2}$$

where λ is the propagation wavelength of core mode and $\mathrm{Im}(n_{eff})$ is the imaginary part of the effective refractive index of the guided core mode. Sharp resonance peak can be found in the loss spectrum.

In this paper, the 2D structure of the D-shaped fiber is being analyzed. The core mode field is studied along the transverse plane of a D-shape fiber using the electromagnetic computational utilities of COMSOL Multiphysics. The electromagnetic fields in fiber core are governed by the macroscopic Maxwell's equations in the absence of currents or external electric charges. The solutions of wave equations are being obtained by finite element method (FEM) which fundamentally contains in isolating the simulation domain into smaller subdomains forming a mesh. The confinement loss spectrum of the D-shaped SPR fiber sensor with a single metal-coated layer is being given in Figure 2a. This simulation result helps to find the resonance wavelength of the structure for a change in surrounding RI (SRI). This is the simple structure of D-shaped SPR sensors with consideration of a single metal layer.

The computed sensitivity within a change in the SRI from 1.30 to 1.36 is $\sim$ 1600 nm/RIU. This can be interpreted as volume or bulk RI sensitivity of the fiber SPR sensor where the RI of the medium is considered to be extended up to infinity from the surface of the gold-coated D-shaped fiber. The sensitivity of the same sensors within a microfluidic channel is being studied with the same parameter. The practical laboratory-based approach is being numerically simulated by extended the basic model of the D-shaped fiber SPR sensor with an additional two layers: 1) The optofluidic analyte channel (RI near water), and 2) polymeric or glass layer as a substrate for the micro-channel. The sensitivity of D-shaped fiber with a change in RI of the analyte within a sub-micrometer channel is studied to estimate the sensitivity of the sensors in an optofluidic analyte channel. The model is simulated by consideration of PDMS material as a substrate. The thickness of the PDMS layer is considered to be $\sim 200\ \mu$m and that of the width of the optofluidic analyte channel is considered to be $\sim 0.4\ \mu$m. A six-layer model was developed to study the sensitivity of the D-shaped SPR sensors like (core-clad-metal layer – optofluidic analyte channel-Glass/PDMS layer - air). The confinement loss spectrum for a change in RI of the analyte layer within that small volume of the channel has been represented in Figure 2b.

The loss spectrum with different thickness of optofluidic analyte channels ($\mathrm{d_a}$) have been studied in detailed and is being shown in Figure 2c. The $\mathrm{d_a}$ is considered to be $\sim 10\ \mu$m, 5 μm, 1 μm, 0.8 μm, 0.6 μm, 0.4 μm, and 0.2 μm respectively. Interestingly, it has been observed that the volume RI sensitivity of the metal-coated D-shaped fiber sensors not enhanced much with lower values of $\mathrm{d_a}$, and it is equal with volume RI sensitivity of the single metal-coated D-shaped fiber where the medium is extending up to infinity with $\mathrm{d_a}$ value greater than 0.6 μm. It has been understood that with a single metal layer-based D-shaped fiber SPR sensors the sensitivity with or without optofluidic analyte channel (OC) is almost the same. The resonance wavelength is being varied as per the coupling mode condition between

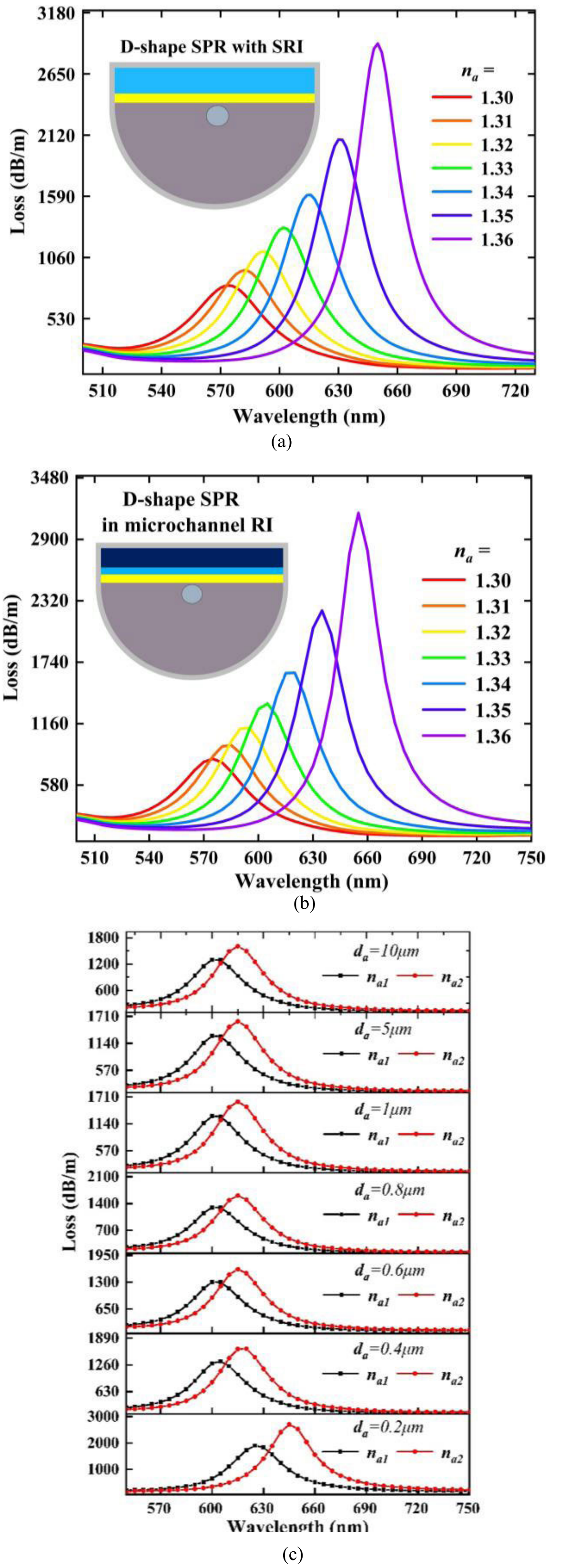


FIGURE 2. a. The confinement loss of D-shaped SPR sensors with a change in RI of the surrounding medium. b. The confinement loss of the D-shaped SPR sensor with the optofluidic analyte channel, the RI of the optofluidic channel has been changed from 1.30 to 1.36. c. Confinement loss spectrum with seven different thicknesses of the optofluidic analyte channel, two different sets of RI is considered, n_{a1} = 1.33, n_{a2} = 1.34.

TABLE 1. The computed sensitivity value with normal D-shaped fiber (S_1), optofluidic sensors without (S_2) and with (S_3) metal-coated inner wall.

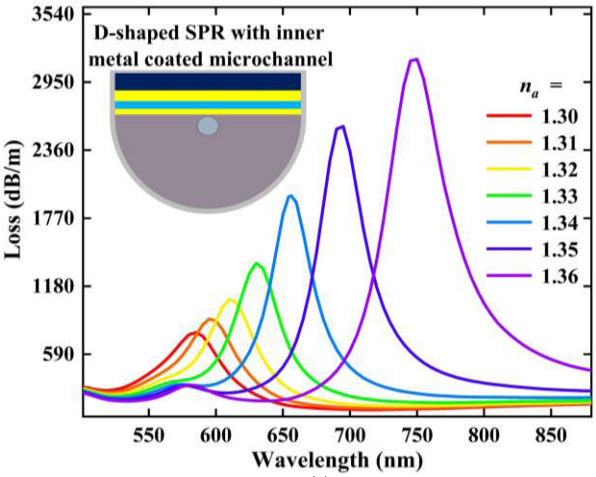
RI	S_1 (nm/RIU)	S_2 (nm/RIU)	S_3 (nm/RIU)
1.30~1.31	800	900	1100
1.31~1.32	1000	1000	1400
1.32~1.33	1000	1000	2000
1.33~1.34	1300	1500	2500
1.34~1.35	1600	1700	4000
1.35~1.36	1900	2000	5500

guided core mode and surface plasmon mode changes with the metal-dielectric interface.

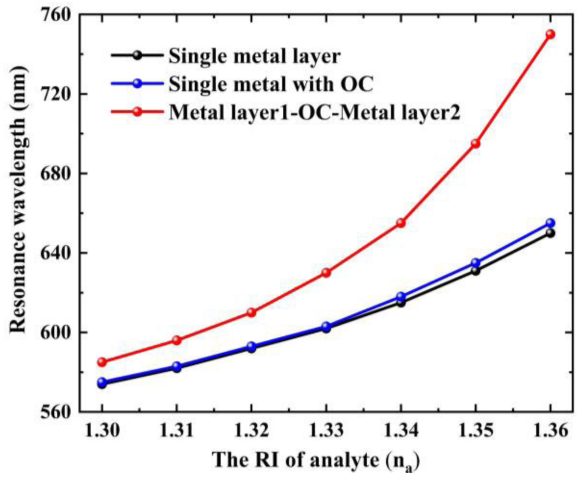
In the next part of the numerical computation, a second metal layer (metal2) is considered over the inner wall of the substrate (PDMS). The schematic cross-section of the proposed structure is being given in Figure 1. The 7-layer architecture is being used (core - clad - metal1 - OC - metal2 - Glass/PDMS - Air) to study the sensitivity characteristics of the proposed structure. In this proposed structure the analyte layer is being sandwiched between two metal layers. The thickness of metal1 is considered to be 50 nm ($d_1 \sim 50$ nm). The d_a was chosen to be ~ 400 nm and the thickness of the metal2 layer (d_2) is considered to be ~ 200 nm over a substrate of glass or polymer of RI ~ 1.44. The RI of the analyte channel is being changed near the RI zone of water. The loss spectrum for the proposed structure is being given in Figure 3a. It has been observed that the RI sensitivity enhanced significantly with a substrate which has a metal-coated inner wall. The sensitivity of the D-shaped SPR with a metal-plated optofluidic analyte channel is being shown here. The inner wall of the PDMS /glass can be coated with thin gold film with standard deposition methods like thermal evaporation, sputtering, or chemical vapor deposition.

The sensitivity of the proposed fiber SPR sensor where the measurand is in between two metal layers is found to be ~ 4085 nm/RIU for a RI zone of (1.3-1.36). The sensitivity is being enhanced by a factor of '~ 2.31' than the sensors with a single metal layer and OC of width 400 nm. Figure 3b depicts the comparison of sensitivity for a) 'single metal layer' where the analyte medium is being extended up to infinity (S_1) without any optofluidic analyte channel b) 'Single metal layer with OC' (S_2) and c) 'metal layer1-OC-metal layer2' (S_3) where the width of d_a is considered to be ~ 400 nm. It has been observed in Figure 3b. that the sensitivity for the 'double metal layer with OC (metal layer1-OC-metal layer2)' is quite high than the other two structures. The sensitivity value (S_1, S_2, S_3) with these three structures are given in Table 1. The sensitivities are computed with the range of RI values of the analyte from 1.3 to 1.36.

Significant enhancement of sensitivity has been found with consideration of the second metal layer as depicts in table 1. The sensitivity enhancement phenomena can be explained with the local enhancement of the electric field.



(a)



(b)

FIGURE 3. a. The confinement loss for the D-shaped SPR sensor with the 'metal1-optofluidic analyte channel-metal2' concept has been incorporated, the RI of the optofluidic channel has been changed from 1.30 to 1.36. b. The computed shift of resonance wavelength with a change in RI of the analyte medium for a) a) 'Single metal layer', 'Single metal layer with OC', and 'Metal layer1-OC-Metal layer2' structure.

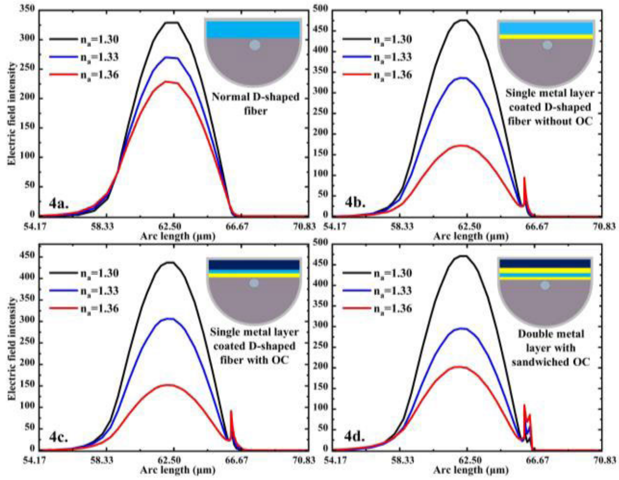


FIGURE 4. The computed electric field with a). 'Normal D-shaped fiber', b) 'Single metal layer coated D-shaped fiber without OC', c) 'Single metal layer coated D-shaped fiber with OC', and d) 'Double metal layer with sandwiched OC' structure of D-shaped fiber SPR sensor.

The electric field profile for each sensor along the radial direction of the fiber is being calculated. Figure 4 represents the one-dimensional electric field profile along the radial direction from the core of the fiber. In particular, 'Normal D-shaped fiber', 'single metal layer coated D-shaped fiber without OC', 'single metal layer coated D-shaped fiber with OC', and 'double metal layer with sandwiched OC' is being considered for the numerical computation. The electric fields of each of the structures are being shown. The schematic structure of the sensor is also being portrayed in the inset of each figure.

The electric field of normal D-shaped fiber is shown in Figure 4a, the electric field of single metal layer coated D-shaped fiber without OC is being shown in Figure 4b, Figure 4c represents the electric field with 'single metal layer coated D-shaped fiber with OC' and Figure 4d presents the electric field for 'double metal layer with sandwiched OC. A significant amount of local enhancement of the electric field can be found with a' double metal layer with sandwiched OC' for a change of refractive index. The outer perimeter of unpolished fiber is designated as '0 μm in the x-axis/Arc length' and the distance is chosen to be positive towards the polished surface. The local enhancement of the electric field is most prominent with a 'double metal layer with sandwiched OC concept' where the second metal layer is the metal-coated inner wall of the substrate. The variation of the electric field with a change in RI within sandwich analyte is maximum with this concept of the double metal layer with sandwiched OC. The first metal layer is deposited above the D-shaped fiber. The second metal layer is being considered to be deposited inside the inner wall of the substrate of the microchannel. This effect is like tunnel-coupled surface electromagnetic waves between (metal-dielectric-metal) structures. The concept of tunnel coupled plasmon wave was explored and studied in a detailed manner with conclusive theory in earlier reported work [32], [33], [37]. Plasmon leaky mode generation was shown in an asymmetric three-layer (Metal-dielectric-metal) structure [32], [33], [37]. In this paper, we have shown the significant enhancement of sensitivity by utilizing the tunneling concept of the leaky plasmonic wave with a sandwiched dielectric layer between two metal layers. In this structure, plasmon-leaky mode/mixed-mode was initiated and it is being understood with electric field profile inside the analyte layer. In the next part of the work, the sensitivity of the sensor is optimized with a variation of three parameters: the thickness of metal layer1 (d_1), the thickness of OC (d_a), and the metal layer2 (d_2). Evanescent mode interaction with the surrounding medium is enhanced with higher etching depth of the D-shaped fiber. In this numerical work, the etching depth of the fiber is considered to be $\sim$ 58.3 μm which means fiber has been etched down to the perimeter of the core. Standard side

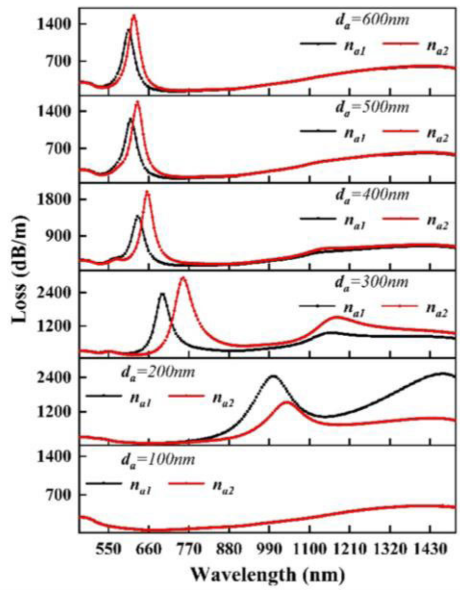


FIGURE 5. Confinement loss spectrum of the proposed D-shaped SPR sensor with six different sub μm width of optofluidic analyte channel (d_a), two different RI of the medium is considered, $n_{a1} = 1.33$, $n_{a2} = 1.34$.

polishing techniques will be employed for the side polishing purpose, the speed of the polishing wheel and time will be optimized for a smooth surface and exact etching depth [10]. The first metal layer can be deposited with standard thin film deposition techniques like thermal evaporation, e-beam evaporation, or sputtering.

III. OPTIMIZATION OF THE PROPOSED STRUCTURE

In this section, optimization of the sensitivity of the optofluidic device with metal-coated polymer/glass wall has been studied extensively. In this section, detailed work will be accomplished with the concept of 'double metal layer with sandwiched OC'. At the very beginning, the variation of sensitivity with a change in the width of the OC (d_a) is being studied to achieve the highest sensitivity. It has been observed that sensitivity is maximum with a thickness of OC ~ 300 nm of the analyte layer. The tunneling mechanism of plasmonic waves plays the most important role in the enhancement of sensitivity [32], [33], [37].

The width of the optofluidic analyte channel (OC) must accommodate the tunneling length of specific plasmon mode. It has been noted that when the d_a is low then the amplitude of the measurand signal is also small and the loss spectrum is broad and wide. There is a limit of lowering down the d_a as per the practical limitation from the fabrication methods. The side polished length of the fiber is keep fixed with 5 mm. The confinement loss spectrum with alteration of the width of the sub-micron optofluidic analyte channel (d_a) is being given in Figure 5.

The analyte layer is being a sandwich layer between two metal layers. The response of the sensor with two different RI of the analyte is depicted in Figure 5. RI of the analyte within the channel is being considered to be near the water medium. In the next part, the variation of sensitivity with the thickness of the first metal layer (d_1) is studied, the first metal layer plays an important role to control the confinement loss of the D-shaped fiber. The resonance wavelength can be modulated with the thickness of the first metal layer. The value of d_a was fixed at ~ 300 nm, the d_2 is considered to be ~ 200 nm and the thickness of glass / PDMS substrate is being considered to be 200 μm during the computation of the response with the variation of d_1. The variation of loss spectrum with different values of thickness of d_1 with two selective values of RI is being shown in Figure S1 in the supporting document. The shift of resonance wavelength with the thickness of the first metal layer has been shown in Figure 6a.

The variation of the sensitivity of the sensors with a change in the thickness of the first metal layer is being shown in Figure 6b. It has been observed that the sensitivity is enhanced linearly with deposition of d_1 from 10 nm to 50 nm and after that, the sensitivity is almost constant. Confinement loss of the sensor is also high with a larger thickness of d_1 > 70 nm. It is to be mentioned that the computed sensitivity is increased with the enhancement of the thickness of d_1 but the confinement loss is lower with higher thickness of d_1 so there is a tradeoff between the sensitivity and the confinement loss. The variation of confinement loss with d_1 is being shown in Figure 6c. It has been found that sensitivity is maximum with a thickness of d_1 ~ 50-70 nm. A blue shift of the resonance wavelength can be observed with a higher value of d_1.

Finally, the sensitivity optimization is being carried out for the second metal layer (d_2). The loss spectrum of the D-shaped SPR fiber sensor with different thickness of d_2 has been shown in Figure 7.

The generation of second-order plasmonic bands was predominant with lower values of thickness of d_2. Change in resonance wavelength with alteration of the d_2 for two different sets of RI has been shown in Figure S2. The variation of sensitivity with d_2 has been shown in Figure S3. The change in the propagation loss with d_2 is being shown in Figure S4. The sensitivity of the proposed sensor is highest for ~ 100 nm of the thickness of d_2, and after that, the sensitivity of the D-shaped fiber SPR sensor is decreased abruptly. The peak resonance loss of the guided mode is following the same pattern as being shown in the supplementary document.

The sensitivity of the structure can be enhanced further if another higher RI polymeric/sol-gel layer can be considered over the second metal layer. A thin overlay layer with a thickness of 150 nm layer of RI 1.7 (standard silica-titania sol-gel) is considered for the numerical computation. The structure looks like an eight-layer cross-sectional structure of metal coated D-shaped fiber: (core-clad-metal1- optofluidic analyte channel-metal2-(silica-titania overlay)-polymer substrate-air). The cross-sectional diagram of the proposed structure is being given in Figure S5. The sensitivity of the proposed structure was

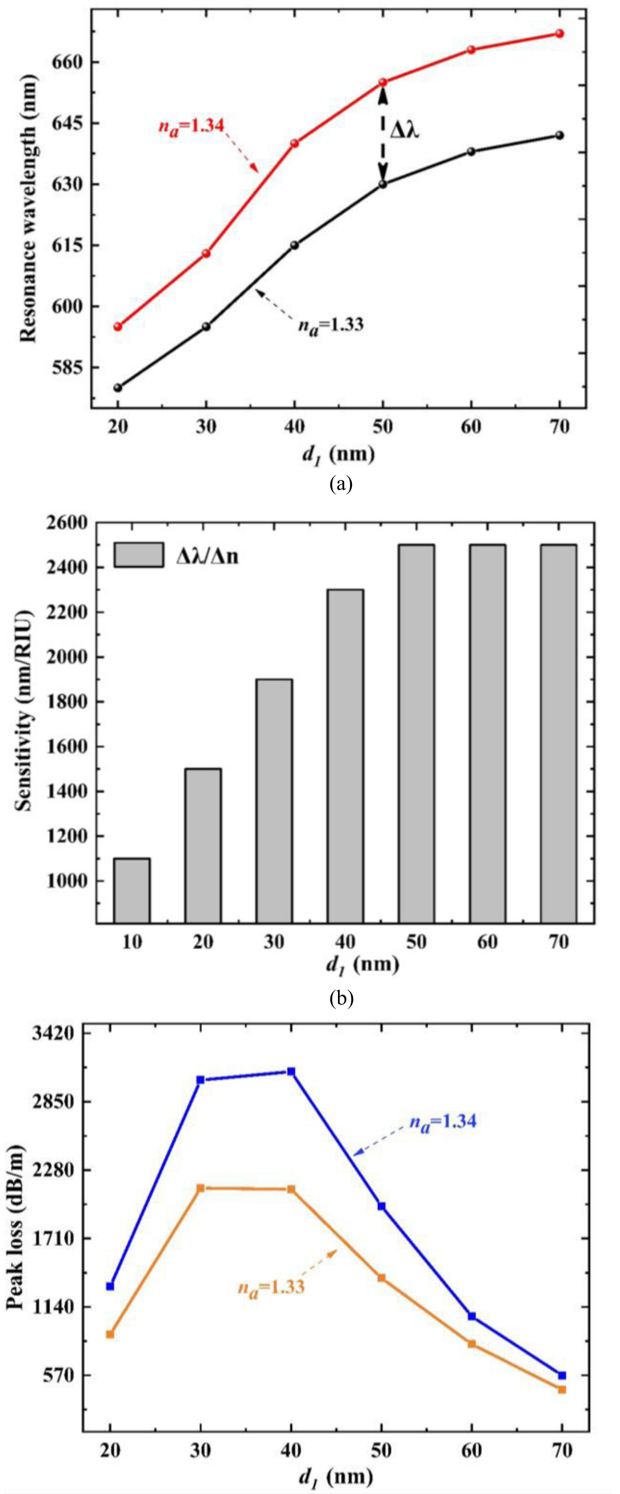


FIGURE 6. a. The variation of resonance wavelength of the proposed D-shaped SPR sensor with the thickness of the first metal layer (d_1). b. The column chart of the sensitivity of the proposed sensor with different values of d_1. c. The variation of confinement loss of the proposed sensor with the thickness of the d_1.

computed and the shift of the confinement loss with different RI of the analyte inside the channel is being shown in Figure 8.

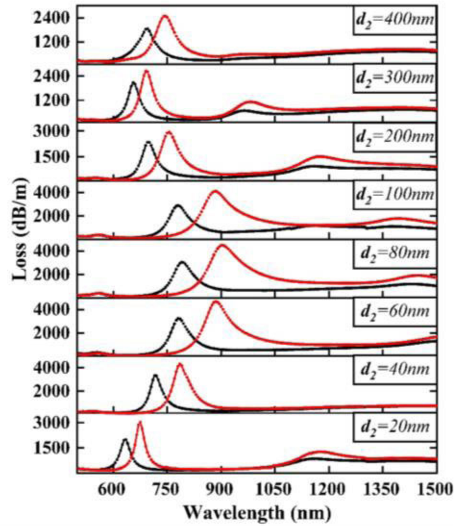


FIGURE 7. Confinement loss spectrum of the proposed sensor with seven different thickness of the second metal layer (d_2), two different RI of the analyte is considered, $n_{a1} = 1.33$, $n_{a2} = 1.34$.

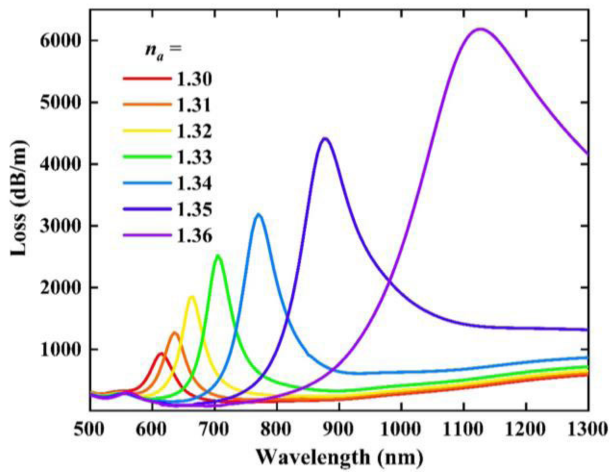


FIGURE 8. Confinement loss spectrum of the complete seven-layer (core- clad- metal1- optofluidic analyte channel- metal2- high RI overlay- PDMS- air) architecture, RI of the analyte medium is being changed from 1.3 to 1.36.

Computed resonance wavelength and the sensitivity of the proposed structure with a different zone of RI is being shown in Figure 9. The considered parameters of this structure for computation include $d_1 \sim 50$ nm, d_a-300 nm, $d_2 - 100$ nm. Nonlinear sensitivity was found within a range of 1.3 to 1.36i, the sensitivity of the proposed sensors from 1.33-1.34 is ∼ 6800 nm/RIU, 1.34-1.35 is ∼ 9300 nm/RIU, and 1.35-1.36 is ∼ 25000 nm/RIU. This structure shows an important aspect of designing of optofluidic analyte channel with a small volume of the measurand. The enhancement of the local electric field of the proposed structure with overlay above the second metal layer has been computed. The enhancement of the electric field with three different RI of the analyte has been shown in Figure S6.

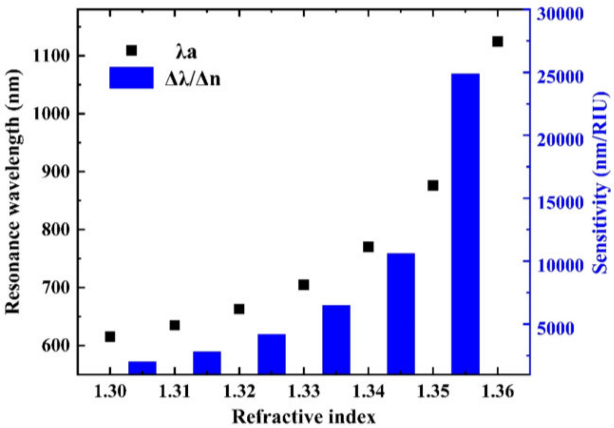


FIGURE 9. The simulated values for the resonance wavelength of the proposed structure with higher RI overlay and the column chart of wavelength sensitivity within different RI zone.

IV. DISCUSSION AND CONCLUSION

In this paper, we have shown tunneling of plasmonic mode can be utilized for enhancement of the sensitivity of D-shaped side polished SPR sensors with the sandwich sub-micron optofluidic analyte channel through a (metal-di electric-metal) structure. This proposed sensor is useful for biochemical applications within a narrow optofluidic analyte channel where the measurand volume is low. Lab on chip-based optofluidic sensors is the most promising platform for the applications where the analyte volume is a matter of concern. In this work, a thorough investigation is accomplished with the D-shaped fiber SPR sensor for the measurement of change in RI within a sub-micron optofluidic channel. The performance of the sensors is being studied in terms of sensitivity and confinement loss. A complete seven-layer (core-clad-metal1- optofluidic analyte channel-metal2-glass/polymeric substrate layer-air) architecture model is being used for this analysis to match closely with the practical situation of sensing applications. It has been observed that the sensitivity can be enhanced significantly with metal-coated glass or polymer substrate layer which is acting as a wall of the optofluidic channel. The sub-micron optofluidic analyte channel is acted as a sandwich layer between two metal layers. More than '$\sim$ 2.3'-fold enhancement of sensitivity has been found with a dual metal layer concept. The resolution of the limit of detection can be as low as 1×10^{-7} with a standard interrogation instrumentation setup. The enhancement of the local electric field is the backbone reason for the improvement of the sensitivity. Further, the sensitivity of the proposed sensors is optimized with the thickness of first and second metal layers along with the width of the optofluidic analyte channel. The variation of resonance wavelength, confinement loss, and sensitivity has been studied with the thickness of metal layers and the width of the optofluidic channel. Finally, it has been shown that sensitivity can be enhanced in a significant way with a consideration of a higher RI polymeric layer as an overlay above the second metal layer. An $\sim$ 10-fold enhancement of sensitivity is observed. Parameters of a commercial single-mode fiber are being used and the enormous sensitivity can be achieved with deposition of standard metal and polymeric layer no special material is required which makes this system convenient. The main aim is to achieve high sensitivity near the RI region of water with side polished fiber. It has been observed that the sensitivity of the sensor can be enhanced quite significantly with standard fabrication processes. Numerical results of this work suggest that with proper optimization of the layer thickness and RI of the polymer and metal, the sensitivity can be enhanced further. The fabrication step will be simple and cost-effective. The applications of the sensors with the sub-micron channel will not be effective for the detection of larger size bio-molecular target specimen but these sensors can be useful for a smaller size of bio-analyte like DNA, antibodies, and in case of detection for several protein molecules with a fewer number of amino acid chains. In the future, material aspects of different metal and polymer overlay layers along with nanostructured 2-dimensional layers or surface grating concepts will be introduced into the model. This concept of enhancement of sensitivity with low analyte volume can be helpful in the case of designing lab-on chip biochemical sensors where the volume of the measurand is small. The sensitivity enhancement methods by changing the structures of walls of the microchannel without modifying the basic sensor platform will show new designing guidelines for the fabrication of optical sensors for specific biochemical applications.

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Yatao Yang and Sankhyabrata Bandyopadhyay contributed equally to this work.)

REFERENCES

[1] J. Homola, "Surface plasmon resonance sensors for detection of chemical and biological species," *Chem. Rev.*, vol. 108, no. 2, pp. 462–493, Feb. 2008.

[2] A. K. Sharma, R. Jha, and B. D. Gupta, "Fiber-optic sensors based on surface plasmon resonance: A comprehensive review," *IEEE Sensors J.*, vol. 7, no. 8, pp. 1118–1129, Aug. 2007.

[3] B. Gupta, A. Shrivastav, and S. Usha, "Surface plasmon resonance-based fiber optic sensors utilizing molecular imprinting," *Sensors*, vol. 16, no. 9, p. 1381, Aug. 2016.

[4] Z.-W. Ding, T.-T. Lang, Y. Wang, and C.-L. Zhao, "Surface plasmon resonance refractive index sensor based on tapered coreless optical fiber structure," *J. Lightw. Technol.*, vol. 35, no. 21, pp. 4734–4739, Nov. 1, 2017.

[5] H.-T. Yan, Q. Liu, Y. Ming, W. Luo, Y. Chen, and Y.-Q. Lu, "Metallic grating on a D-shaped fiber for refractive index sensing," *IEEE Photon. J.*, vol. 5, no. 5, Oct. 2013, Art. no. 4800706.

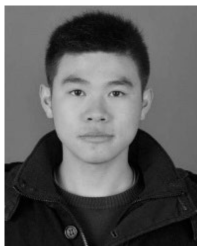
[6] L.-Y. Shao, Y. Shevchenko, and J. Albert, "Intrinsic temperature sensitivity of tilted fiber Bragg grating based surface plasmon resonance sensors," *Opt. Express*, vol. 18, no. 11, pp. 11464–11471, May 2010.

[7] T. Schuster, R. Herschel, N. Neumann, and C. G. Schaffer, "Miniaturized long-period fiber grating assisted surface plasmon resonance sensor," *J. Lightw. Technol.*, vol. 30, no. 8, pp. 1003–1008, Apr. 15, 2012.

[8] J. Hu, M. Smietana, T. Wang, T. Lang, L. Shao, G. Gu, X. Zhang, Y. Liu, X. Song, Z. Song, J. Feng, and R. Buczynski, "Dual Mach–Zehnder interferometer based on side-hole fiber for high-sensitivity refractive index sensing," *IEEE Photon. J.*, vol. 11, no. 6, pp. 1–13, Dec. 2019, doi: 10.1109/JPHOT.2019.2948087.

[9] H. He, L. Y. Shao, H. Qian, X. Zhang, J. Liang, B. Luo, W. Pan, and L. Yan, "Novel birefringence interrogation for Sagnac loop interferometer sensor with unlimited linear measurement range," *Opt. Express*, vol. 25, no. 6, pp. 6832–6839, Mar. 2017.

[10] X. Yang, S. Bandyopadhyay, L.-Y. Shao, D. Xiao, G. Gu, and Z. Song, "Side-polished DBR fiber laser with enhanced sensitivity for axial force and refractive index measurement," *IEEE Photon. J.*, vol. 11, no. 3, pp. 1–10, Jun. 2019.
[11] J. Zhao, S. Cao, C. Liao, Y. Wang, G. Wang, X. Xu, C. Fu, G. Xu, J. Lian, and Y. Wang, "Surface plasmon resonance refractive sensor based on silver-coated side-polished fiber," *Sens. Actuators B, Chem.*, vol. 230, pp. 206–211, Jul. 2016.
[12] X. Li, L. V. Nguyen, Y. Zhao, H. Ebendorff-Heidepriem, and S. C. Warren-Smith, "High-sensitivity sagnac-interferometer biosensor based on exposed core microstructured optical fiber," *Sens. Actuators B, Chem.*, vol. 269, pp. 103–109, Sep. 2018.
[13] I. Del Villar, C. R. Zamarreno, M. Hernaez, F. J. Arregui, and I. R. Matias, "Lossy mode resonance generation with indium-tin-oxide-coated optical fibers for sensing applications," *J. Lightw. Technol.*, vol. 28, no. 1, pp. 111–117, Jan. 1, 2010.
[14] I. D. Villar, P. Zubiate, C. R. Zamarreño, F. J. Arregui, and I. R. Matias, "Optimization in nanocoated D-shaped optical fiber sensors," *Opt. Express*, vol. 25, no. 10, pp. 10743–10756, 2017.
[15] T. Wu, Y. Shao, Y. Wang, S. Cao, and Y. Wang, "Surface plasmon resonance biosensor based on gold-coated side-polished hexagonal structure photonic crystal fiber," *Opt. Express*, vol. 25, no. 17, pp. 20313–20322, 2017.
[16] A. A. Rifat, R. Ahmed, A. K. Yetisen, H. Butt, A. Sabouri, and G. A. Mahdiraji, "Photonic crystal fiber based plasmonic sensors," *Sens. Actuators B, Chem.*, vol. 243, pp. 311–325, May 2017.
[17] C. Liu, W. Su, X. Lu, F. Wang, T. Sun, and P. K. Chu, "Symmetrical dual D-shape photonic crystal fibers for surface plasmon resonance sensing," *Opt. Express*, vol. 26, no. 7, pp. 9039–9049, 2018.
[18] Y. Liu, S. Li, H. Chen, J. Li, W. Zhang, and M. Wang, "Surface plasmon resonance induced high sensitivity temperature and refractive index sensor based on evanescent field enhanced photonic crystal fiber," *J. Lightw. Technol.*, vol. 38, no. 4, pp. 919–928, Feb. 15, 2020.
[19] H.-S. Lee, T.-Y. Seong, W. M. Kim, I. Kim, G.-W. Hwang, W. S. Lee, and K.-S. Lee, "Enhanced resolution of a surface plasmon resonance sensor detecting C-reactive protein via a bimetallic waveguide-coupled mode approach," *Sens. Actuators B, Chem.*, vol. 266, pp. 311–317, Aug. 2018.
[20] X.-C. Yuan, B. H. Ong, Y. G. Tan, D. W. Zhang, R. Irawan, and S. C. Tjin, "Sensitivity–stability-optimized surface plasmon resonance sensing with double metal layers," *J. Opt. A, Pure Appl. Opt.*, vol. 8, no. 11, pp. 959–963, Nov. 2006.
[21] K. Q. Le, Q. M. Ngo, and T. K. Nguyen, "Nanostructured metal–insulator–metal metamaterials for refractive index biosensing applications: Design, fabrication, and characterization," *IEEE J. Sel. Topics Quantum Electron.*, vol. 23, no. 2, pp. 388–393, Mar. 2017.
[22] Q. Ouyang, S. Zeng, L. Jiang, L. Hong, G. Xu, X.-Q. Dinh, J. Qian, S. He, J. Qu, P. Coquet, and K.-T. Yong, "Sensitivity enhancement of transition metal dichalcogenides/silicon nanostructure-based surface plasmon resonance biosensor," *Sci. Rep.*, vol. 6, no. 1, Jun. 2016, Art. no. 28190.
[23] A. S. Yu, W. Li, Y. L. Wang, and T. Li, "Surface lattice resonances based on parallel coupling in metal-insulator-metal stacks," *Opt. Express*, vol. 26, no. 16, pp. 20695–20707, 2018.
[24] M. H. Elshorbagy, A. Cuadrado, and J. Alda, "High-sensitivity integrated devices based on surface plasmon resonance for sensing applications," *Photon. Res.*, vol. 5, no. 6, pp. 654–661, 2017.
[25] C.-Y. Chang, H.-T. Lin, M.-S. Lai, T.-Y. Shieh, C.-C. Peng, M.-H. Shih, and Y.-C. Tung, "Flexible localized surface plasmon resonance sensor with metal–insulator–metal nanodisks on PDMS substrate," *Sci. Rep.*, vol. 8, no. 1, 2018, Art. no. 11812.
[26] J. Qin, Y. Zhang, X. Liang, C. Liu, C. Wang, T. Kang, H. Lu, L. Zhang, P. Zhou, X. Wang, B. Peng, J. Hu, L. Deng, and L. Bi, "Ultrahigh figure-of-merit in metal–insulator–metal magnetoplasmonic sensors using low loss magneto-optical oxide thin films," *ACS Photon.*, vol. 4, no. 6, pp. 1403–1412, 2017.
[27] X. Fan and I. M. White, "Optofluidic microsystems for chemical and biological analysis," *Nature Photon.*, vol. 5, no. 10, pp. 591–597, Oct. 2011.
[28] C. Monat, P. Domachuk, and B. J. Eggleton, "Integrated optofluidics: A new river of light," *Nature Photon.*, vol. 1, no. 2, pp. 106–114, Feb. 2007.
[29] L. Shao, Z. Liu, J. Hu, D. Gunawardena, and H.-Y. Tam, "Optofluidics in microstructured optical fibers," *Micromachines*, vol. 9, no. 4, p. 145, Mar. 2018.
[30] R. Blue, A. Duduś, and D. Uttamchandani, "A review of single-mode fiber optofluidics," *IEEE J. Sel. Topics Quantum Electron.*, vol. 22, no. 2, pp. 380–391, Mar./Apr. 2016.
[31] A. Passian, A. Wig, A. L. Lereu, F. Meriaudeau, T. Thundat, and T. L. Ferrell, "Photon tunneling via surface plasmon coupling," *Appl. Phys. Lett.*, vol. 85, no. 16, pp. 3420–3422, Oct. 2004.
[32] A. Q. Jian, X. M. Zhang, W. M. Zhu, and A. Q. Liu, "Liquid refractive index sensors using resonant optical tunneling effect for ultra-high sensitivity," *Sens. Actuators A, Phys.*, vol. 169, no. 2, pp. 347–351, 2016.
[33] M. C. Zhang, T. W. Allen, and R. G. DeCorby, "Experimental study of optimized surface-plasmon-mediated tunneling in metal-dielectric multilayers," *Appl. Phys. Lett.*, vol. 103, no. 7, pp. 071109.1–071109.5, Aug. 2013.
[34] P. Berning and A. F. Turner, "Induced transmission in absorbing films applied to band pass filter design," *J. Opt. Soc. Amer. B, Opt. Phys.*, vol. 47, no. 3, pp. 230–239, 1957.
[35] A. Vial, A.-S. Grimault, D. Macías, D. Barchiesi, and M. L. de la Chapelle, "Improved analytical fit of gold dispersion: Application to the modeling of extinction spectra with a finite-difference time-domain method," *Phys. Rev. B, Condens. Matter*, vol. 71, no. 8, 2005, Art. no. 085416.
[36] H. Jiang, J. Sabarinathan, T. Manifar, and S. Mittler, "3-D FDTD analysis of gold-nanoparticle-based photonic crystal on slab waveguide," *J. Lightw. Technol.*, vol. 27, no. 13, pp. 2264–2270, Jul. 1, 2009.
[37] N. M. Lyndin, V. V. Svetikov, V. A. Sychugov, B. A. Usievich, and V. A. Yakovlev, "Radiatively and tunnel-coupled surface electromagnetic waves in metal—Dielectric structures," *Quantum Electron.*, vol. 29, no. 9, pp. 817–821, Sep. 1999.



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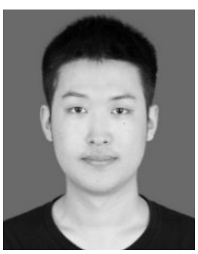

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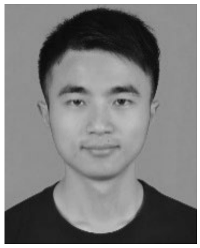

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