



Integrated refractive index sensor based on hybrid coupler with short range surface plasmon polariton and dielectric waveguide

Boyu Fan, Fang Liu*, Yunxiang Li, Xiaoyan Wang, Kaiyu Cui, Xue Feng, Wei Zhang, Yidong Huang

Department of Electronic Engineering, Tsinghua National Laboratory for Information Science and Technology, Tsinghua University, Beijing 100084, China

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ABSTRACT

In this paper, an integrated sensor based on the vertical hybrid coupler composed of a short range surface plasmon polariton (SRSP) waveguide and a SiN_x dielectric waveguide has been studied theoretically and experimentally in detail by varying the structure parameters and the thickness of detection layer. It is demonstrated that the output power of the sensor changes significantly with the refractive index of the detection layer and the resolution is estimated to be as high as 7.3×10^{-6} refractive index units. The sensing range can be adjusted coarsely and delicately by varying the thickness of SRSP waveguide and the width of the SiN_x waveguide, respectively. Owing to the highly bounded mode field of SRSP, the sensor is also applied to detect a 5 nm-thick variation of detection layer with thickness detection sensitivity as high as 0.67 dB/nm. Further, the sensor is used to detect the bisphenol A.

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1. Introduction

Surface plasmon polariton (SPP) is a transverse-magnetic surface electromagnetic excitation that propagates along an interface between a metal and a dielectric medium [1]. Owing to the significant response to a variation in external refractive index, the SPP plays a critical role in chemical and biological sensing technology, especially in sensitive and label-free assays [2–12]. The conventional prism-based SPP sensors have rather high sensitivity, but their large volume, discrete components, and relative high cost limit their applications for the outdoor or home use. Therefore, the integrated SPP sensor with various structures has been proposed and studied in the recent years, such as the nanoplasmonic-based sensor [7,8], the plane waveguide-based sensor [9–11], the fiber-based sensor [12] and so on. These integratable SPP sensors always have much lower sensitivity than the prism based sensor, especially for ultra-thin layer and small bio-molecules sensing. Besides, the sensing range of the waveguide-based SPP sensor is not wide enough to meet the requirement of different applications. On the other hand, for outdoor or home use, it is expected to realize the on-chip sensor integrated with light source and detector. Nevertheless, adopting the optical spectrum as sensing measurand may not be the best scheme for on-chip sensor system, since the on-chip spectrometer has complicated structure and much lower resolution compared with the conventional one [13]. And it seems that

the sensor with optical power as sensing measurand is proper for integrating with on-chip laser and detector.

To get rid of above problems, our group recently has proposed and demonstrated an integrated SPP sensor based on the vertical hybrid coupling structure comprised of a short range SPP (SRSP) [1] waveguide and a dielectric waveguide (DW) [14–16]. In this paper, the sensing characteristics of this kind of SRSP sensor are studied in details theoretically and experimentally. It is demonstrated that the output power changes significantly with the refractive index of the detection layer and the minimum detectable refractive index change is as small as 7.3×10^{-6} RIU. The sensing center could be adjusted in both delicate and coarse range by varying the width of DW and thickness of SRSP waveguide, respectively. In addition, owing to the highly bounded mode field of the SRSP compared with that of general SPP mode, this SRSP sensor can realize much higher sensitivity for ultra-thin layer detection, which has been proved by monitoring the output power change as a function of the nano-thickness variation of the detection layer. It is observed that, for thickness change of 1 nm, the variation of 0.67 dB in output power can be obtained. Since the detection signal is the optical power rather than optical spectrum, this SRSP sensor is essentially propitious to integration with a detector. Moreover, the detection of small chemical molecular bisphenol A is performed. It is demonstrated that the minimum detectable concentration of BPA solution is about 0.1 ng/ml and the biosensor can be used for at least nine detection cycles without a significant worsen of sensitivity.

This paper is organized as follows. In Section 2, the structure of the integrated sensor and the simulation method is introduced.

* Corresponding author.

E-mail address: liu.fang@mail.tsinghua.edu.cn (F. Liu).

In Section 3, the working mechanism of SRSPP-DW hybrid coupling sensor and the sensing characteristics with different structure parameters are theoretically investigated. In Section 4, the integratable sensor based on the vertical SRSPP-SiN_x hybrid coupler with sensing region only 110 μm-long has been fabricated and measured by utilizing the refractive index matching liquid and the polyelectrolyte layer as the detect medium. In Section 5, the integrated sensor is used to detect the bisphenol A. Then, some conclusions are given.

2. Structure and simulation method

A. Structure

The proposed integrated sensor is shown in Fig. 1, which is based on the hybrid coupler composed of a SRSPP waveguide (Au stripe with thickness T_m , width W_m , and dielectric constant ε_m) and a dielectric waveguide (SiN_x stripe with thickness T_d , width W_d , and refractive index n_d). The distance between the two waveguides is D . The dielectric surrounding the two waveguides is SiO₂ with refractive index n_s . Above the SRSPP waveguide is the sensing window with length L along the z direction, in which the thickness (h_{net}) and refractive index (n_{det}) of detection layer is variable. The sectional view of the sensor in x - y plane and the detailed structure parameters are illustrated in Fig. 1(b).

B. Simulation method

To calculate the sensing characteristics (the output power vs. the refractive index of the detection layer n_{det}), this sensor is divided into three parts along z direction as described in Ref. [16], including the input (region I) and output (region III) region with only SiN_x waveguide, and the sensing region with hybrid coupler (region II) as shown in Fig. 1(c). The only difference of simulation method in this paper from Ref. [16] is that the eigenmodes in the x - y plane is calculated here by the finite element method (FEM).

Based on the FEM with software COMSOL [17], the field distribution and propagation constant of the eigenmodes in region I, II, and III can be obtained. For the structure parameters described in Section 3, only one TM mode exists for the DW in region I/III and there are two TM polarized eigenmodes (mode A and B) for the hybrid coupler in region II.

For the sensing region (region II), the TM mode ($\mathbf{H}_d, \mathbf{E}_d$) in region I can be assumed as the input and expanded by the two eigenmodes of region II according to the eigenmodes expansion method (EEM),

$$\mathbf{H}(x, y, z) = \sum_{m=A, B} a_m e^{-\beta_{mi}z} \mathbf{H}_m(x, y) e^{-i\beta_{mr}z} \quad (1)$$

where $\mathbf{H}_A$ and $\mathbf{H}_B$ are the complex magnetic field of mode A and B ($z=0$), and $\beta_m = \beta_{mr} - i\beta_{mi}$ ($m=A, B$) are the complex propagation constants of the eigenmodes in the sensing region. The corresponding mode coupling complex coefficients, a_m ($m=A, B$), can be derived from

$$a_m = \frac{1}{2} \int (\mathbf{E}_d \times \mathbf{H}_m) \cdot \hat{z} dA = |a_m| e^{i\theta_m} \quad (m=A, B). \quad (2)$$

where $|a_m|$ and θ_m represents the magnitude of amplitude and coupling initial phase of corresponding eigenmodes, respectively. Since SRSPP has a high transmission loss and the imaginary part of its mode field can be comparable with the real part, a theory adapted to the high-loss case, instead of energy normalization method, should be applied. According to the unconjugated versions of Eqs. (11)–(16) in Ref. [18], all the modes are normalized and orthonormalized,

$$\frac{1}{2} \int (\mathbf{E}_j \times \mathbf{H}_j) \cdot \hat{z} dA = 1 \quad (j=A, B, d) \quad (3)$$

Here it is confirmed that $a_A^2 + a_B^2 \approx 1$, which demonstrates that the categoricalness of EEM is guaranteed and the simulation results could commendably reflect the results with more modes. According to Eqs. (1) and (2), the intensity of the eigenmodes propagating in region II can be expressed as,

$$|\mathbf{H}(x, y, z)|^2 = \sum_{m=A, B} \left(|a_m e^{-\beta_{mi}z} \mathbf{H}_m(x, y)| \right)^2 + 2e^{-\beta_{Ai}z} e^{-\beta_{Bi}z} \times \text{Re}\{a_A a_B^* \mathbf{H}_A(x, y) \mathbf{H}_B^*(x, y) e^{-i(\beta_{Ar} - \beta_{Br})z}\} \quad (m=A, B) \quad (4)$$

After a propagation length L in region II, when the two eigenmodes couple back into output DW mode in region III, the corresponding coupling coefficient between the two eigenmodes and DW TM polarized mode is

$$a_L = \frac{1}{2} \int (\mathbf{E}_d \times \mathbf{H}(x, y, L)) \cdot \hat{z} dA = \sum_{m=A, B} |a_m|^2 e^{-\beta_{mi}L} e^{i(2\theta_m - \beta_{mr}L)} \quad (m=A, B) \quad (5)$$

and the TM polarized output power of DW P_{out} can be expressed as

$$P_{\text{out}} = -10 \lg(|a_L|^2) = -20 \lg \left(\sum_{m=A, B} a_m^2 e^{-\beta_{mi}L} e^{-i\beta_{mr}L} \right). \quad (6)$$

3. Simulation results and discussion

Based on the modeling method in Section 2, the sensing characteristics of the integrated sensor are simulated and discussed by studying the eigenmodes, coupling length, coupling efficiency, and output power of DW in this section. The dependence of sensor output power P_{out} on structure parameters, such as the sensing length L , the width of DW W_d , and the thickness of metal film T_m are discussed in parts B, C, D, respectively. Furthermore, the sensing characteristics for ultrathin detection layer are analyzed in part E.

Here, the incident wavelength is fixed at 1.55 μm. For simulation, the refractive index of dielectric SiN_x and SiO₂ is set to be $n_d = 2$ and $n_s = 1.444$ [19], respectively, and the dielectric constant of Au is $\varepsilon_m = -132 + i \times 12.65$ [20]. Considering the vertical mode size of SRSPP mode with $W_m = 8 \mu\text{m}$ is close to that with wider W_m (i.e. 10 μm, 12 μm), the width of Au film is fixed at 8 μm for simulation. Of course, wider W_m could be also selected and leads to similar simulation results. With fixed $D = 1.5 \mu\text{m}$, the T_d , W_d , and T_m are varied to study the sensing characteristics of the integrated sensor. The thickness of detection layer is set to be $h_{\text{det}} = 3 \mu\text{m}$ in part A–D and decreased to dozens of nanometers in part E. Above the detection layer, the dielectrics is assumed as the water with refractive index of 1.333.

A. Eigenmodes and coupling characteristics

According to the theory of coupled mode, there are two coupled TM polarized guiding eigenmodes, mode A and B, which are calculated by using software COMSOL [17]. Here, the parameters of Au strip and SiN_x are set to be $T_m = 17 \text{ nm}$, $W_m = 8 \mu\text{m}$, $T_d = 175 \text{ nm}$, and $W_d = 3.0 \mu\text{m}$. Fig. 2(a) shows the effective refractive index ($\text{Re}\{n_{\text{eff}}\}$) of SRSPP mode of individual Au waveguide part as a function of n_{det} . The black line corresponds to ($\text{Re}\{n_{\text{eff}}\}$) of the TM mode supported by individual SiN_x waveguide part. When the refractive index of detection layer $n_{\text{det}} = 1.445$, the effective refractive index of the two TM eigenmodes are calculated to be $n_{\text{eff},A} = \beta_A/k_0 = 1.4915 - 5.53e-3i$ and $n_{\text{eff},B} = \beta_B/k_0 = 1.4706 - 3.09e-3i$, respectively. It is well known that SRSPP has the opposed-phase magnetic field component in the transverse plane [1]. Thus, the dominant component of two coupled

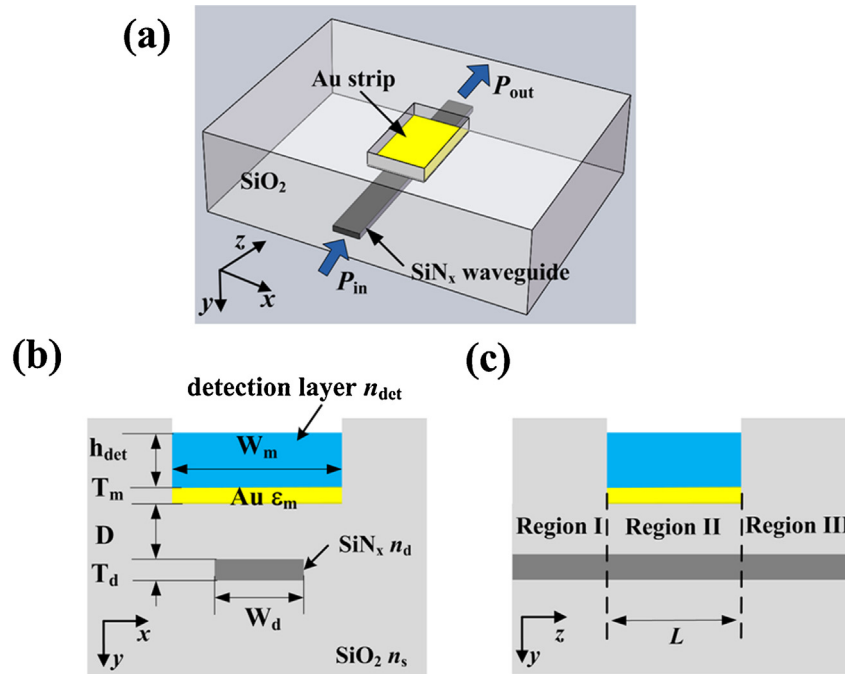


Fig. 1. (a) Schematic structure of the integrated sensor based on the vertical hybrid coupler with SRSPP waveguide (Au strip, yellow) and dielectric waveguide (SiNx strip, gray) embedded in SiO₂, (b) Sectional view of the sensor in the x–y plane. The detailed structure parameters are labeled in the figure. (c) Longitudinal view of the sensor in the y–z plane. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

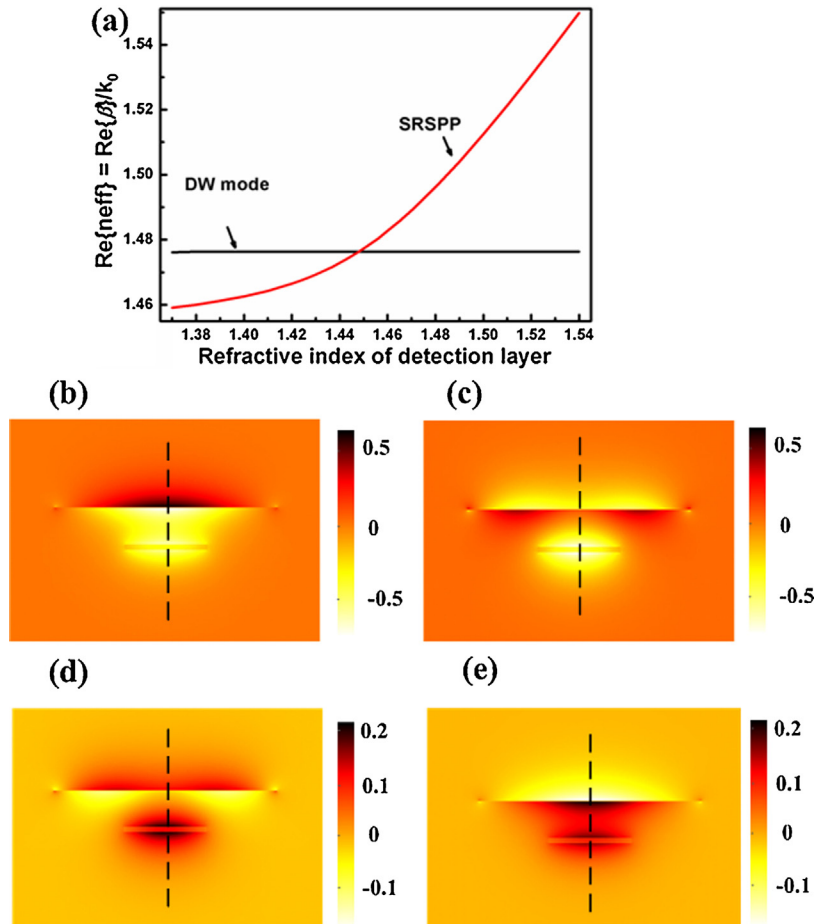


Fig. 2. (a) Effective refractive index ($Re\{n_{eff}\}$) of SRSPP (red) of individual Au waveguide part as a function of n_{det} . The black line corresponds to ($Re\{n_{eff}\}$) of the dielectric waveguide TM mode supported by individual SiNx waveguide part. (b)–(e) The x component of complex magnetic field profile of two eigenmodes in the x–y plane ($n_{eff,A} = 1.4915 - 5.53e-3i$ and $n_{eff,B} = 1.4706 - 3.09e-3i$) when $h_{det} = 3 \mu m$ and $n_{det} = 1.445$. (b) and (c) show the real part of mode A and mode B, respectively; (d) and (e) show the imaginary part of mode A and mode B, respectively.

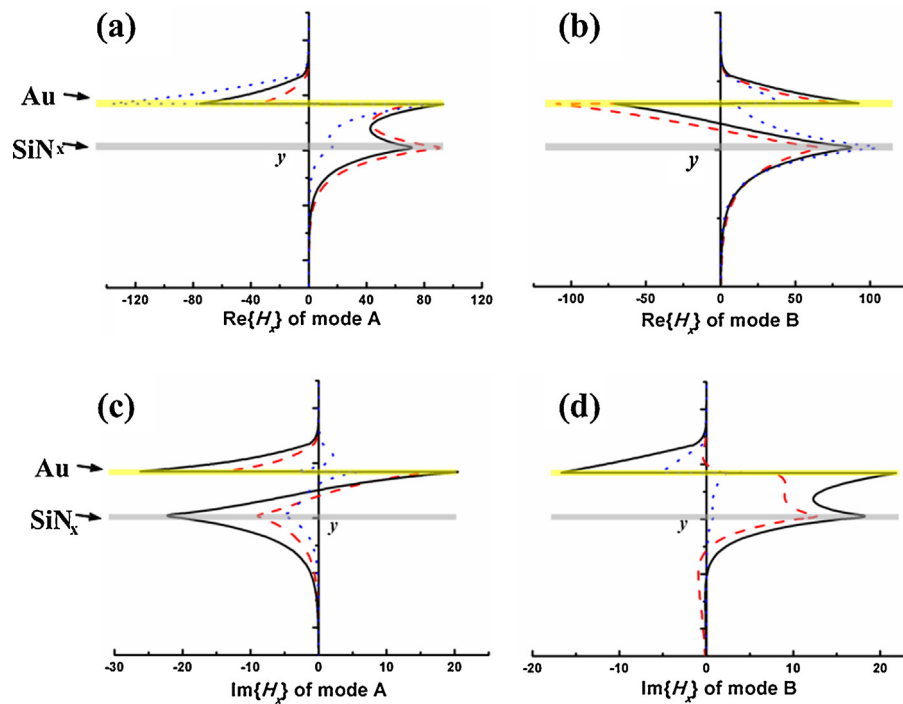


Fig. 3. (a)–(d) 1D electric field component H_x of the two eigenmodes sampled along dashed line shown in Fig. 2(b)–(e) when $n_{\text{det}} = 1.445$ (black solid), 1.41 (red dashed), 1.49 (blue dotted). (a) and (c) are the real and imaginary part of mode A; (b) and (d) are the real and imaginary part of mode B. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

eigenmodes (H_x) are analyzed and shown in Fig. 2(b)–(e). Different from the long range SPP (LRSPP)-based coupler [21–23], in the case of the SRSPP, the imaginary part of the field can be comparable with the real part and should be taken into account, as shown in Fig. 2(d) and (e).

For reflecting the field distribution of the two eigenmodes intuitively and its variation with n_{det} , the field distribution along the symmetric axis of the sensor (dashed line shown in Fig. 2) is depicted as shown in Fig. 3, in which the black solid curves correspond to the eigenmode field pattern in Fig. 2(b)–(e). Here, it can be noted that, when $n_{\text{det}} = 1.445$, the concentrations of the mode fields surrounding the Au and SiN_x are almost equal, which results from the $\text{Re}\{n_{\text{eff}}\}$ match between the SRSPP and SiN_x waveguide mode shown in Fig. 2(a). Furthermore, varying n_{det} will cause the unbalanced field concentrations surrounding the Au and SiN_x waveguide illustrated by the red dashed and blue dotted profiles in Fig. 3(a)–(d), which corresponds to the $\text{Re}\{n_{\text{eff}}\}$ deviation of the individual SRSPP mode from the crossing point.

According to Eq. (4), the n_{det} dependence of the coupling between the SRSPP and the DW modes can be examined by studying the field intensity transmitting along the z direction. Fig. 4(b) shows that the power transfers completely from the DW to SRSPP and then couples back when $n_{\text{det}} = 1.445$. According to Eq. (6), how P_{out} changes as a function of L can be calculated and illustrated by the black solid curve shown in Fig. 4(d). In this case, the P_{out} declines rapidly along L with strong ripple. The large decline slope and strong ripple result from the high-loss SRSPP mode and the complete energy exchange between SRSPP and DW modes. Decreasing n_{det} to 1.41, less energy transfer to the high-loss SRSPP mode from DW mode illustrated in Fig. 4(a), owing to the $\text{Re}\{n_{\text{eff}}\}$ mismatch between SRSPP mode and DW mode. Correspondingly, the P_{out} has much weaker ripple and smaller slope shown as the red dashed line in Fig. 4(d). Similarly, when $n_{\text{det}} = 1.49$, the coupling between the two modes is even weaker with most of the energy propagating through DW as shown in Fig. 4(c), and the corresponding P_{out}

shown as blue dotted curve in Fig. 4(d) has little ripple and much smaller slope.

The above discussion indicates that the n_{det} could greatly affect the $\text{Re}\{n_{\text{eff}}\}$ match between the SRSPP and DW mode, the coupling

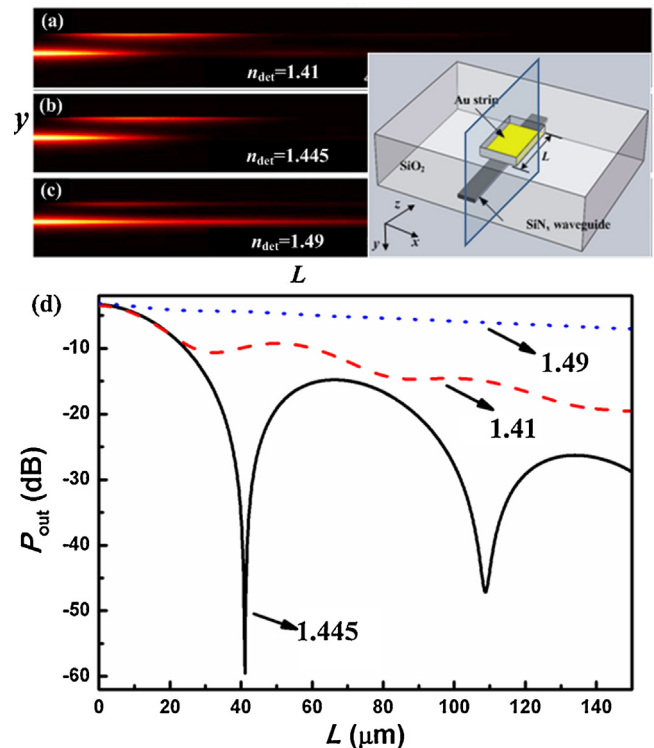


Fig. 4. Field intensity propagating along z in y - z plane of the inset when (a) $n_{\text{det}} = 1.41$, (b) $n_{\text{det}} = 1.445$, (c) $n_{\text{det}} = 1.49$. (d) Output power P_{out} versus the sensing length L labeled with different n_{det} .

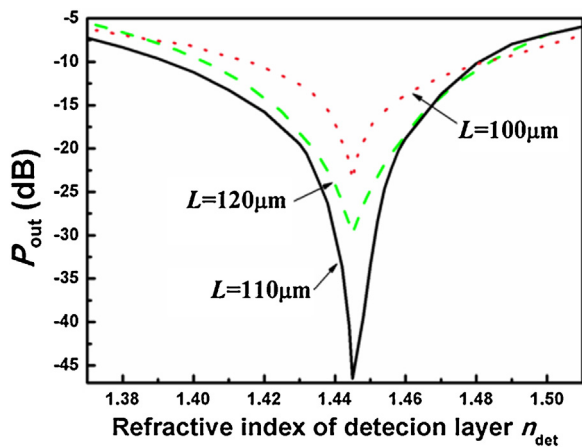


Fig. 5. Output power P_{out} as a function of n_{det} labeled with different sensing length L .

efficiency and the P_{out} from DW. Therefore, a high sensitive sensor could be realized based on the hybrid coupler, and the sensing characteristics will be discussed theoretically in part B, C, D and E.

B. Sensing characteristics vs. sensing length

For the integrated sensor, the length L of the hybrid coupler is fixed to observe the change of the P_{out} as a function of n_{det} . According to Fig. 4, it is obvious that the P_{out} is related to the sensing length L , which is an important issue to affect the performance of the integrated sensor. In this section, the L dependence of sensing characteristics is demonstrated with the same structure parameters in part A.

By fixing the sensing length $L = 110 \mu\text{m}$ in Fig. 4, the black solid curve in Fig. 5 illustrates that the P_{out} varies dramatically with n_{det} . Here, the dip of the curve is referred to as the sensing center and the P_{out} variation over the corresponding n_{det} change is defined as the sensitivity [2]. According to the black solid curve with sensing center as 1.445, the average sensitivity in the range from $n_{det} = 1.445$ to 1.45 is about 8880 dB/RIU (RIU, refractive index units). Assuming the resolution of the powermeter as 0.01 dB^2 , the minimum detectable refractive index change can be as small as 1.1×10^{-6} RIU. It is better than that of the nanoplasmonic sensor [7,8] ($\sim 10^{-5}$ RIU) and comparable to that of the previous integrated waveguide sensor [9–11]. However, owing to the highly bounded mode field of SRSPP, the proposed integrated coupler sensor has the potential to detect the ultrathin layer with higher sensitivity. The detailed analysis is given in part F in Section 3.

When the sensing length L deviates from $m \times L_c$ ($L_c = \pi/(\beta_{Ar} - \beta_{Br})$, $m = 1, 3, 5, \dots$), there is part of the power of SRSPP mode coupling back to the DW mode and the ΔP_{out} becomes smaller for the same Δn_{det} shown as the green dashed line and red dotted line in Fig. 5, resulting in an obvious decrease of the sensitivity. Although the globally minimized P_{out} corresponds to $L = 40 \mu\text{m}$ in Fig. 4, for the same deviation of sensing length ΔL from the dips, the degeneration of sensitivity is much weaker around $L = 110 \mu\text{m}$. Therefore, the sensing length is fixed at $L = 110 \mu\text{m}$ by considering both the sensitivity and fabrication tolerance. By the way, the sensing center (the dip of the curves) keeps the same in this case.

C. Sensing characteristics vs. width of dielectric waveguide

According to the result shown in Fig. 5, it seems that the sensitive region is not wide enough to meet the requirement of different sensing applications. Actually, for this integrated sensor, the sensing range is easy to be extended by adjusting the structure parameters, which is discussed in part C and D.

Here, fixing length $L = 110 \mu\text{m}$, the width of DW is varied ($W_d = 3.0, 3.5, 4.0 \mu\text{m}$). As shown in Fig. 6(a), when varying the

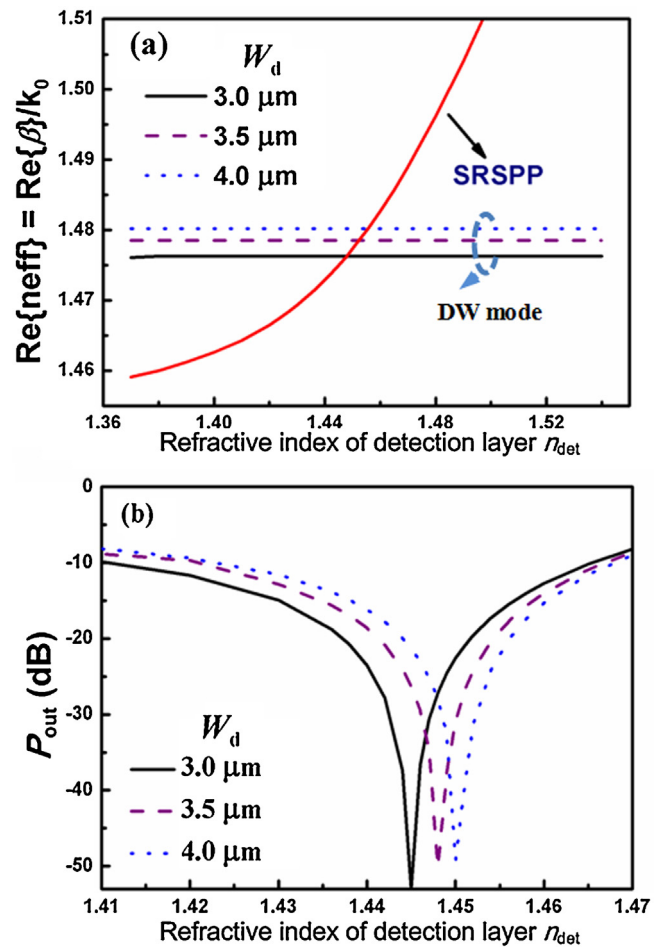


Fig. 6. (a) Effective indices of the DW mode with different width W_d and $\text{Re}\{n_{eff}\}$ of SRSPP mode as a function of n_{det} . (b) Output power P_{out} as a function of n_{det} labeled with different W_d .

width of DW, the crossing point of effective indices between the DW and SRSPP waveguide moves along the axis of n_{det} . Considering that the crossing point corresponds to the sensing center as described in part A and B, the sensing curve can be adjusted and illustrated in Fig. 6(b). It can be noted that a $0.5 \mu\text{m}$ increase of W_d corresponds to a 3.0×10^{-3} increase of the sensing center. Therefore, changing the width of DW provides a method of adjusting the sensing center delicately.

D. Sensing characteristics vs. thickness of metal strip

From the previous part, it is known that the sensing center of the integrated coupler sensor can be adjusted delicately by varying the width of DW. Similarly, the sensing center could also be adjusted by varying the propagation constant of SRSPP mode. In this part, different from part C, the thickness of Au strip is varied ($T_m = 15, 17, 20 \text{ nm}$) with fixed width of DW $W_d = 3.0 \mu\text{m}$ and sensing length $L = 110 \mu\text{m}$.

It is well known that SRSPP mode is formed owing to the coupling of the SPPs on the upper and lower metal–dielectric interfaces when the metal film is thin and its mode field becomes even more bounded on the metal film as the metal thickness is reduced [24], which is accompanied by the intense increase of $\text{Re}\{n_{eff}\}$ of SRSPP mode. Thus, the $\text{Re}\{n_{eff}\}$ of SRSPP mode shown in Fig. 7(a) moves significantly when changing the thickness T_m of Au strip, which results in the more variation of the $\text{Re}\{n_{eff}\}$ crossing point on x-axis compared with that in Fig. 6(a). Correspondingly, Fig. 7(b) illustrates that the sensing center moves more widely than that shown in Fig. 6(b). The minimum detectable refractive index

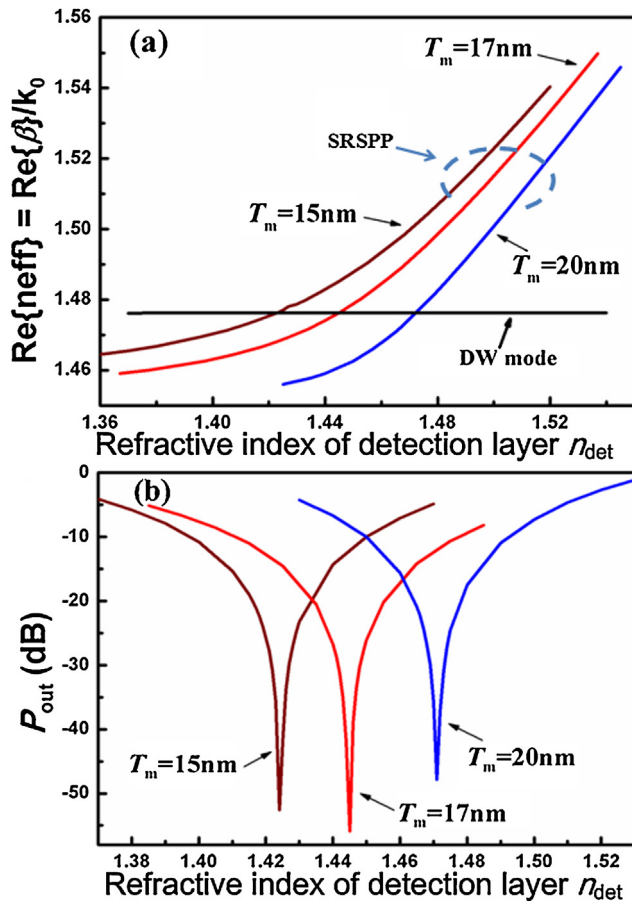


Fig. 7. (a) Effective indices of the DW mode and $\text{Re}\{n_{\text{eff}}\}$ of SRSPP mode with different thickness T_m as a function of n_{det} . (b) Output power P_{out} as a function of n_{det} labeled with thickness of Au strip T_m .

change remains about 1.1×10^{-6} RIU under different T_m . Therefore, by fabricating a sensor array with variable Au thickness, a large refractive index detection range can be obtained with high sensitivity.

E. Sensing characteristics vs. ultra-thin layer detection

Different from LRSP and general SPP mode, the field of SRSPP mode is more concentrated on the metal strip surface. The SRSPP-based sensor is expected to have a significantly high sensitivity when applied for ultra-thin layer detection of small bio- or chemical molecules. In this part, the ultra-thin layer sensing characteristics of the sensor are simulated. The thickness of detection layer is decreased from several micrometers to hundred or dozens of nanometers.

Fig. 8 shows that the output power P_{out} as a function of n_{det} labeled with different detection thickness h_{det} by fixing L at 110 μm . When the thickness of the detection layer h_{det} is decreased to 100 nm, 75 nm or even 50 nm, the minimum detectable refractive index change remains as high as 3×10^{-6} RIU. The high resolution for such thin detection layer (thinner than $1/30$ wavelength) can be attributed to the extremely bounded field of the SRSPP mode on the metal film. It should be also noted that the sensing center shifts from $n_{\text{det}} = 1.474$ to a higher value $n_{\text{det}} = 1.501$. The shift of the sensing center can be interpreted that the total dielectric refractive index above the metal film decreases with thinner h_{det} and a larger n_{det} is required to get a high coupling efficiency between SRSPP and DW modes.

In some applications, such as the reaction detection of antibody and antigen [4,6], what changes is the thickness of the detection layer with fixed refractive index. Although this situation can be

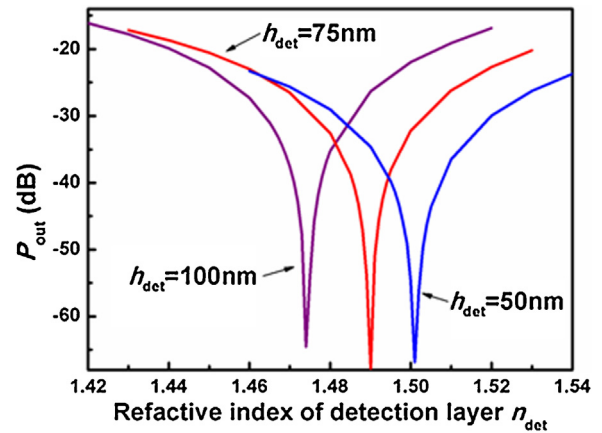


Fig. 8. Output power P_{out} as a function of n_{det} labeled with different detection thickness h_{det} .

equalized as the model applied above with variable refractive index in a layer with fixed thickness, we would like to know exactly how the output power changes with the thickness of detection layer. Therefore, the sensing characteristics of the sensor are studied according to the actual situation.

When the refractive index of detection layer is set to be 1.495 considering the refractive index of the polymer layer [25] to be detected in our experiment, Fig. 9(a) shows the effective refractive indices ($\text{Re}\{n_{\text{eff}}\}$) of DW mode and the SRSPP mode as a function of h_{det} . For $T_m = 15$ nm, the $\text{Re}\{n_{\text{eff}}\}$ of SRSPP and DW mode matches well at the crossing point of $h_{\text{det}} = 30$ nm. In this case, most of the power transfers from SiN_x waveguide to Au film with little output power, which corresponds to the dip of the black curve shown in Fig. 9(b). When the h_{det} deviates from 30 nm, the coupling between SRSPP mode and SiN_x waveguide mode becomes weak, which results in the larger output power from the SiN_x waveguide. To be noticed, in the range of $h_{\text{det}} = 30$ –35 nm, the change of the output power is 8.26 dB. Here, defining the variation of P_{out} over the corresponding change of h_{det} ($\Delta P_{\text{out}}/\Delta h_{\text{det}}$) as thickness-detection sensitivity (TDS), the average TDS is approximately 1.65 dB/nm indicating a rather high sensitivity for ultra-thin layer detection. In addition, increasing the Au thickness T_m , the $\text{Re}\{n_{\text{eff}}\}$ crossing points of the two waveguides mode shown in Fig. 10(a) move to larger h_{det} . Thus, the corresponding sensing curves illustrated in Fig. 9(b) get the minimum P_{out} when $h_{\text{det}} = 65$ nm and 105 nm, respectively.

From the above simulation results of this section, it can be seen that the proposed SRSPP-dielectric coupling sensor have many advantages compared with the traditional SPP sensors [5–12], such as compact size, large sensing range, high sensitivity for detecting films thinner than $1/30$ of a wavelength.

4. Fabrication and measurement results

In this section, to prove the theoretical results, the integrated sensors with different parameters are fabricated and the sensing characteristics are studied by detecting the refractive index matching liquid and the nanometer-thick polyelectrolyte layer.

A. Fabrication process and measurement method

To fabricate this sensor, a Si wafer with 15- μm -thick SiO_2 on the surface is selected as the substrate. On the substrate, a layer of SiN_x with a thickness of $T_d = 175$ nm is deposited by plasma-enhanced chemical-vapor deposition (PECVD). After standard UV lithography, reaction ion etching (RIE) and photoresist removal, the SiN_x strips with different width W_d (3.0, 3.5, 4.0 μm) are obtained. Covering a $D = 4$ μm -thick SiO_2 layer by PECVD on the SiN_x strips, the

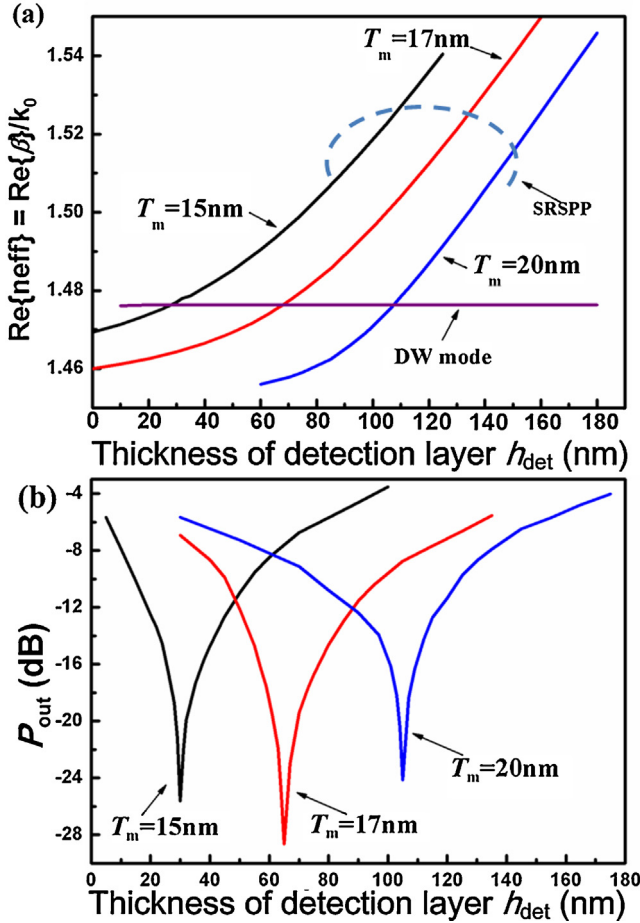


Fig. 9. (a) Effective refractive index $\text{Re}\{n_{\text{eff}}\}$ of SRSP labeled with different thickness of the Au strip as a function of h_{det} . The purple line corresponds to $\text{Re}\{n_{\text{eff}}\}$ of the dielectric waveguide supported by SiN_x waveguide. (b) Output power P_{out} as a function of h_{det} when n_{det} is setting to 1.495 labeled with different thickness of the Au strip. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

fabrication of the SiN_x waveguide is completed. Then, a 2.5 μm -depth groove structure with different length L changing from 0 to 150 μm with a step of 10 μm is formed by cover-lithography and wet etching process with buffered hydrofluoric acid (BHF). The depth of the groove (correlated with the distance D between SiN_x strip and Au strip) is controlled by the concentration of BHF and the etching time. Further, sputtering an Au film with thickness of T_m (15, 17, 20 nm) by magnetic sputtering and lifting off the photoresist/Au film outside the groove structure, the fabrication of the sensor based on the hybrid coupler is finished. In the fabrication processes, the Au strip with much larger width compared with the simulation one is designed for reducing the difficulty of overlap lithography. Fig. 10 shows the integrated sensor based on the SRSP- SiN_x coupler under microscope, where the yellow strip

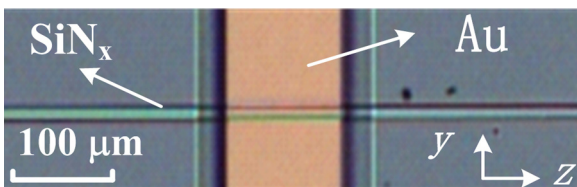


Fig. 10. Optical microscopy images of the integrated sensor based on the SRSP- SiN_x coupler.

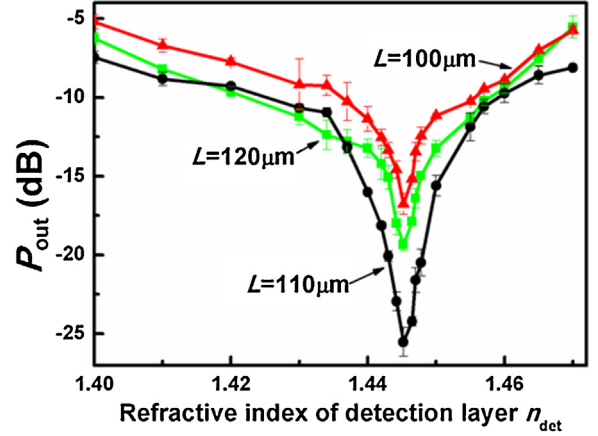


Fig. 11. Measurement results of output power P_{out} as a function of n_{det} labeled with different sensing length L .

(Au) is the SRSP waveguide and the light green one is the SiN_x waveguide.

Here the chip is cut into 2.5-mm-long pieces for easier measurement, though the sensing length L (the length of the Au strip along z -axis) is only about 100 μm . The measurement system consists of a laser emitting at a wavelength of 1.55 μm , a polarization controller, an input and output tapered-lens fibers, a precise fiber alignment system controlled by computer, and a power meter. In the fiber-to-waveguide butt-coupling measurement, the refractive index matching liquid with different n_{det} and the polyelectrolyte layer with different h_{det} are measured.

Since there is no coupling between the TE mode and the SRSP mode [15], it is observed that the TE-polarized output power changes negligibly with n_{det} and the insertion loss is as low as 0.2 dB for the sensor with a sensing length of 110 μm . Therefore, to eliminate the influence of the coupling loss between the input/output fibers and the SiN_x waveguide, the output power of the TM mode (P_{TM}) is normalized with that of the TE mode (P_{TE}), namely $P_{\text{out}} = P_{\text{TM}}/P_{\text{TE}}$, in Section 4.

B. Refractive index matching liquid detection

The detection refractive index matching liquids are purchased from Cargille Labs with certified refractive indices of 1.4, 1.41, 1.42, 1.43, 1.44, 1.45, 1.46, and 1.47. To obtain detection liquids with a refractive index between 1.4 and 1.47, the certified refractive index matching liquids are mixed in the proper proportion, and the refractive index is checked by an Abbe refractometer. Dropping the detection liquid with a certain refractive index on the sensor, the output power of the sensor is measured as described above, and then the sensor chip is cleaned by phenoxin, ethanol, and deionized water to remove the detection liquid. The measurement is then repeated by varying the refractive index of the detection liquid.

Fig. 11 shows the measured output power P_{out} (dB) from the SiN_x waveguide versus the refractive index of the detection liquid n_{det} , which is normalized by the output power P_{out0} without the detection liquid ($n_{\text{det}} = 1$). The three curves correspond to the sensors with different sensing length L . Each point of the curves is derived by measuring three sensors with the same structure parameters, and the small error bars indicate that the sensors have good consistency in sensing performance. For the sensor with $L = 110 \mu\text{m}$, it is shown as the red curve that the P_{out} changes significantly with n_{det} values around $n_{\text{det}} = 1.445$, which results from the remarkable change of the coupling efficiency between the SRSP mode and DW mode under different n_{det} . The average sensitivity in the range of 1.445–1.455 is approximately 1365 dB/RIU. Assuming the resolution of the power meter to be 0.01 dB², the minimum detectable refractive index change can be as small as 7.3×10^{-6} RIU.

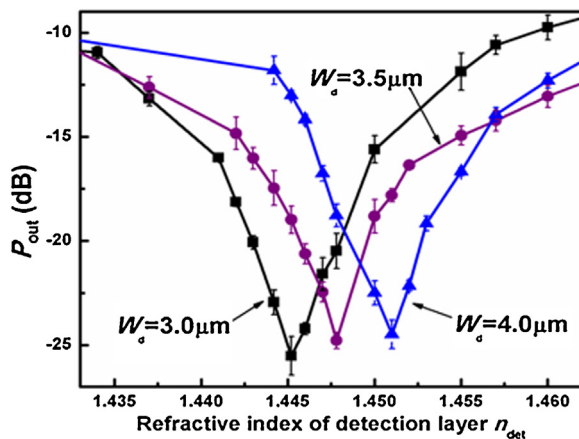


Fig. 12. The range of sensing centers of the measured results labeled with different widths (W_d) of the DW. Here, the sensing length is fixed at 110 μm .

For $L = 100 \mu\text{m}$ and $120 \mu\text{m}$, part of energy of SRSP mode transfers back to DW mode, accompanied by a worsen of the minimum detectable refractive index change ($\sim 10^{-4}$ RIU). And the sensing center maintains the same value with different sensing length L . Obviously, the measurement result is consistent with the simulation as shown in Fig. 5.

The simulation result shown in Fig. 6 indicates that the sensing center could be adjusted by varying the width of the SiN_x waveguide. To verify this simulation result, sensors with different W_d are fabricated, and the subsequent measurement result is shown in Fig. 12 with L fixed at 110 μm . For the sensors with $W_d = 3.0 \mu\text{m}$, the sensing center is around $n_{\text{det}} = 1.445$. When W_d increases to 3.5 μm and 4.0 μm , the similar sensing curve of P_{out} vs. n_{det} is also obtained and the sensing center increases to 1.448 and 1.451, respectively. A 0.5 μm increase of W_d corresponds to a 3.0×10^{-3} increase of the sensing center, which well proves the simulation results shown in Fig. 6.

Fig. 7 indicates that the sensing center can be adjusted more widely by changing Au thickness. Thus, the sensors with different Au thickness T_m are fabricated and measured to analyze the sensing characteristics. As shown in Fig. 13, although the blue curve ($T_m = 20 \text{ nm}$) ends at $n_{\text{det}} = 1.47$ owing to the tough cleaning of detection liquid with $n_{\text{det}} > 1.47$, the shift of the sensing curve along x-axis with the Au thickness is obvious.

In this part, based on the refractive index liquid, it can be seen that the measurement results for thick detection layer is consistent with the theoretical prediction in Section 3 very well. It is indicated

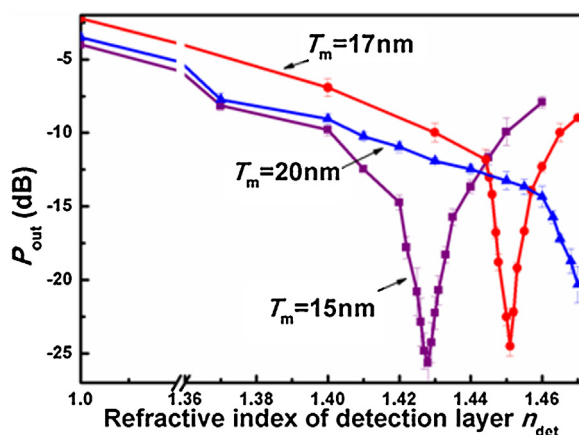


Fig. 13. Measurement results of output power P_{out} as a function of n_{det} labeled with different Au thickness T_m .

that the sensing length L should be well selected to get a high sensitivity and, by varying the width of DW and thickness of Au strip, the sensing center can be adjusted flexibly in a delicate and coarse refractive index range respectively.

C. Nanometer-thick polyelectrolyte layer detection

To verify the simulation results of ultra-thin layer sensing characteristics shown in Fig. 10(b), the self-assembly method [25] is adopted to obtain the polyelectrolyte layer with controllable thickness and fixed refractive index on the metal surface. The polyelectrolyte is purchased from Aldrich without further purification including poly (sodium 4-styrenesulfonate) (PSS, MW = 70,000), cationic poly (allylamine hydrochloride) (PAH, MW = 65,000), and cationic poly (ethyleneimine) (PEI, MW = 70,000). Sodium chloride (purity >99.5%) is purchased from Fluka, and its 0.9M solution is used as dissolvent for these polyelectrolyte and buffer/rinse solution in the experiment. The detailed preparation processes of the nano-thick polyelectrolyte multiplayer are the same as that described in Ref. [25]. Fig. 14 shows the SEM images of polyelectrolyte multiplayer above the gold film with 13 layers (Fig. 14(a) and (b)) and 4 layers (Fig. 14(c) and (d)), respectively.

Fig. 15 shows the measured output power P_{out} (dB) from the SiN_x waveguide versus the thickness of detection layer h_{det} . For the sensor with $T_m = 15 \text{ nm}$, the output power varies significantly with the thickness of polyelectrolyte layer h_{det} and get the minimum P_{out} when $h_{\text{det}} = 25 \text{ nm}$. Owing to the $\text{Re}\{n_{\text{eff}}\}$ shift of SRSP mode introduced by the variation of Au strip thickness as described in Fig. 9(a), when T_m increasing to 17 nm, the minimum P_{out} moves to about $h_{\text{det}} = 55 \text{ nm}$ as shown in Fig. 15(b). Here, the average sensitivity (TDS) is as high as 0.67 dB/nm in the range of 50–55 nm. Further increasing T_m to 20 nm, the dip of the curve shifts to $h_{\text{det}} = 90 \text{ nm}$. Therefore, it is verified that SRSP–dielectric coupling sensor has the ability of detecting the small bio- or chemical molecules.

5. Application in detecting bisphenol A

In the bio- or chemical application field, most of the reaction process can be seen as the immunoreaction between the antigen and antibody, including the detection of DNA and some organic molecules [26,27]. In this section, taking bisphenol A (BPA) for example, the integrated coupler sensor is used for immunoreaction detection.

A. Preparation of bisphenol A

BPA is an organic compound commonly used as an intermediate in the production of polycarbonate plastics, epoxy coatings, etc. Due to its widespread use, BPA has become a significant environmental contaminant present in wastewater, river water, and plastic products [28].

According to the method illustrated in Ref. [29], the mercaptan layer for anchoring the BPA antigen is deposited on the sensor surface. Subsequently, BPA conjugated with bovine serum albumin (BSA–BPA) is flowed along the surface and attached to the mercaptan layer. Finally, the phosphate buffer solution (PBS, including 10 mM phosphate, 2.9 mM KCl, 0.75 M NaCl, pH 7.4) is mixed with a known concentration of BPA antibody and then the unreacted antigen is detected by the sensor attached with BSA–BPA. Fig. 16 shows the schematic preparation processes of the BPA immunosensor and the SEM image of the corresponding functional layers.

B. Detection results of BPA

In Section 4, it has been demonstrated that the sensitive region of h_{det} can be adjusted widely by varying the thickness of the SRSP waveguide. For the thickness variation of BPA antigen-antibody reaction shown in Fig. 16, the thickness of SRSP waveguide for the immunosensor is fixed at $T_m = 30 \text{ nm}$. Subsequently, by injecting 3.0 ng/ml BPA detection solution on the integrated sensor, the temporal response of the sensor is performed as shown in Fig. 17.

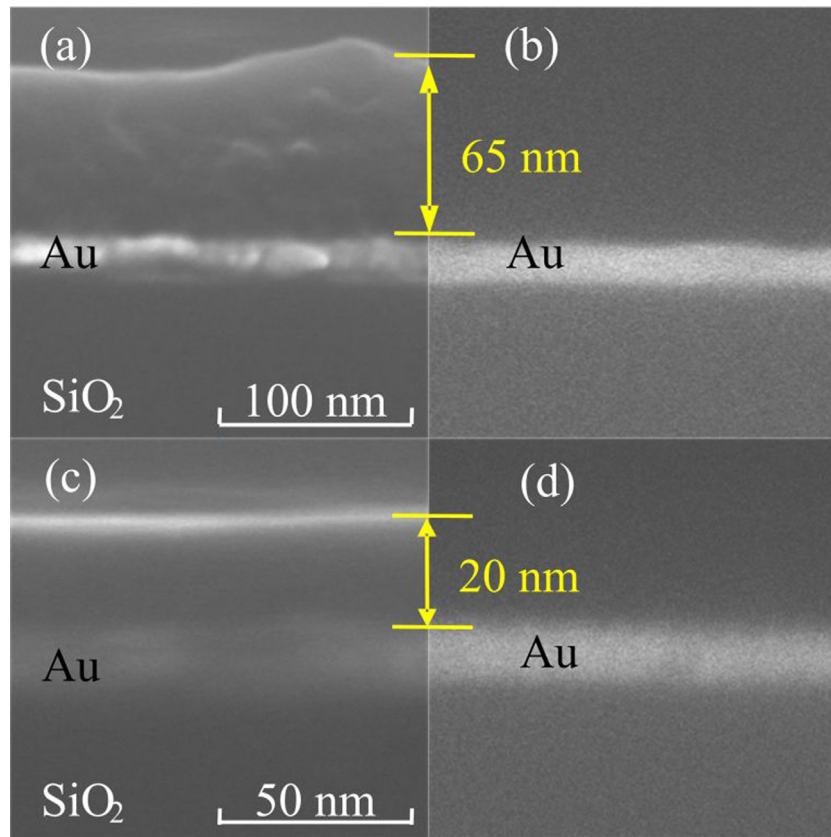


Fig. 14. The SEM photo of polymer multilayer grown on the gold surface (a) and (c) secondary electron imaging, (b) and (d) back-scattered electrons imaging.

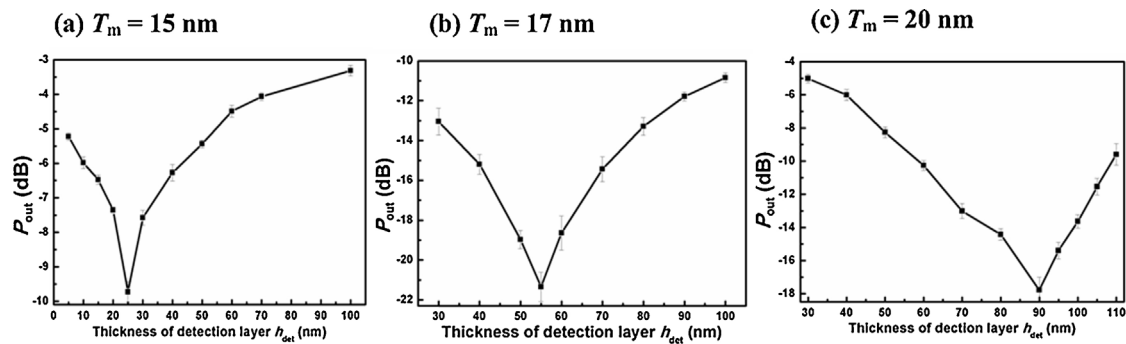


Fig. 15. The measured output power P_{out} (black rectangles with error-bar) versus the thickness of the detection layer h_{det} labeled with different Au thickness, (a) $T_m = 15$ nm, (b) $T_m = 17$ nm, (c) $T_m = 20$ nm.

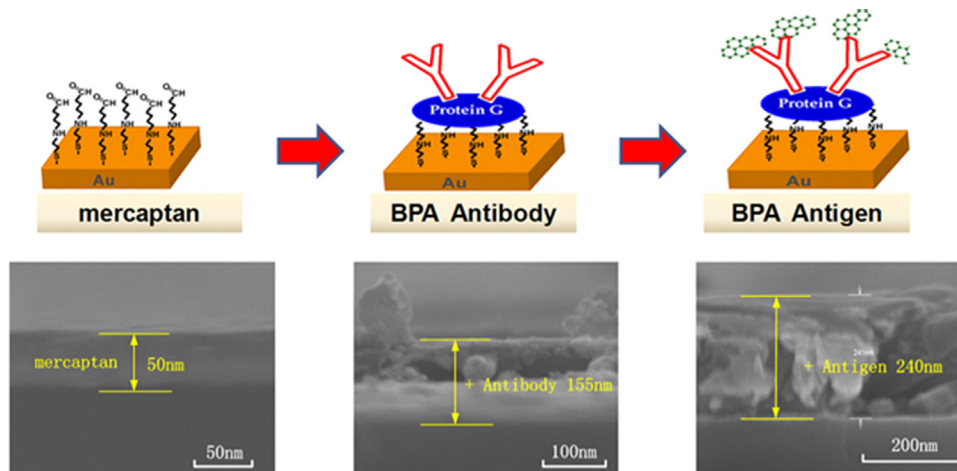


Fig. 16. Schematic drawing of BPA immunosensor fabrication and the SEM image of the corresponding functional layer.

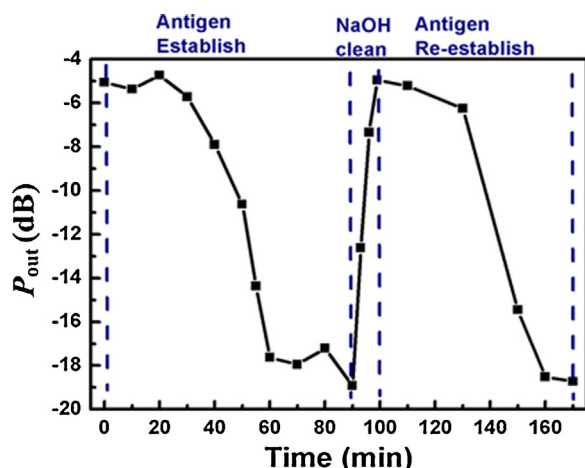


Fig. 17. Temporal sensor response to 3 ng/ml BPA sample.

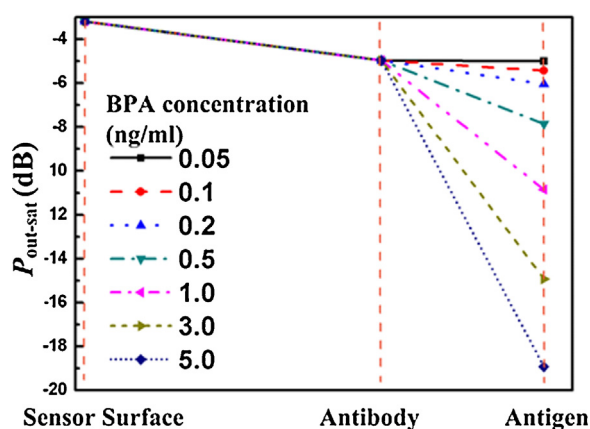


Fig. 18. The saturate reaction output power ($P_{\text{out-sat}}$) labeled with different BPA concentration.

For the initial 20 min, P_{out} remain -5 dB owing to only BSA–BPA layer deposited above the sensor surface. With 3.0 ng/ml BPA detection solution flowed through the sensor surface, the BPA antibody is immobilized to BPA antigen progressively, which is accompanied by the decrease of P_{out} . After 60 min, P_{out} remains about -18 dB owing to the saturate reaction. This stable P_{out} is referred to as the saturate reaction output power ($P_{\text{out-sat}}$). Subsequently, regeneration of the sensor surface is accomplished by injecting 10 mM NaOH for 10–20 min, followed by the P_{out} of the sensor restoring to the initial value -5 dB. Moreover, the re-reaction between BPA antigen and antibody is performed and it proceeds in the same fashion as the first reaction process. It is proved that the integrated sensor can be regenerated at least nine times using 10 mM NaOH without diminishing the activity of the immobilized BPA antigen, which is comparable to the previous BPA SPP sensor [29].

Furthermore, the response of the sensor to the different concentration of BPA solution (0.05, 0.1, 0.2, 0.5, 1.0, 3.0, 5.0 ng/ml) is performed. As shown in Fig. 18, when the BPA concentration decreases from 5 ng/ml to 0.05 ng/ml, the $P_{\text{out-sat}}$ enhances significantly owing to the increase of unreacted BPA antibody. In addition, it is demonstrated that obvious variation of $P_{\text{out-sat}}$ can be measured with at least 0.1 ng/ml BPA solution, which is close to the limit of detection based on lens SPP sensor (0.05 ng/ml [29]). According to the analysis in Section 4, the lower concentration of BPA solution is expected to be detected by optimizing the structure parameters, such as Au thickness T_m , sensing length L and so on. Considering the low cost and integration of the coupler sensor, it has potential

to realize the BPA immunosensor with high sensitivity for outdoor and home use.

6. Conclusions

This paper is theoretically and experimentally devoted to the sensing characteristics of the vertical hybrid coupler comprised of a SRSPP waveguide and DW in detail by considering structure parameters and thickness of detection layer. Based on this hybrid coupler, a highly compact sensor (110 μm) has been realized with resolution as high as 7.3×10^{-6} RIU for refractive index matching liquid detection. It is also demonstrated that the sensing length L is an important issue to affect the sensitivity of the integrated sensor and, by varying the thickness of Au strip and width of DW, the sensing center could be adjusted flexibly and the sensing range could be extended. Considering the high bounded field of SRSPP mode, this kind of sensor has significantly high effective sensitivity for ultra-thin film or small molecule detection. By preparing a polymer layer with controllable thickness and refractive index on the surface of the sensor, it is observed that even 5 nm-thick variation of molecular layer could be detected with sensitivity ($\Delta P_{\text{out}}/\Delta h_{\text{det}}$) as high as 0.67 dB/nm, which would have rather high sensitivity for small bio-chem molecule detection. The sensitive region of h_{det} can also be adjusted widely by varying the thickness of the SRSPP waveguide. Further, the molecular BPA is detected by the sensor with minimum detectable concentration about 0.1 ng/ml.

Acknowledgements

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Biographies

Boyu Fan received his BS degree from Tsinghua University, and he is the PhD candidate in the Department of Electronic Engineering of Tsinghua University from 2008. His current research interest is in the area of surface plasmon polariton based integrated optical devices.

Fang Liu received the B.S. degree from the Beijing Institute of Technology, Beijing, China, in 2003, and the Ph.D. degree from the Department of Electrical Engineering, Tsinghua University, Beijing, China, in 2008. He is currently an Assistant Professor at Tsinghua University. His current research interests include the area of integrated optical devices.

Yunxiang Li received his BS degree from Tsinghua University, and he is the PhD candidate in the Department of Electronic Engineering of Tsinghua University from 2009. His current research interest is in the area of nanometer lithography based on surface plasmon polariton.

Xiaoyan Wang received her BS degree from Beijing University of Posts and Telecommunications, and she is the master candidate in the Department of Electronic Engineering of Tsinghua University from 2010. Her current research interest is in the area of surface plasmon polariton based integrated optical devices.

Kaiyu Cui received her B.S. degree from Jilin University, Beijing, China, in 2005, and her Ph.D. degree from Tsinghua University, Beijing, China, in 2010, respectively, all in Electrical Engineering. Then, she works as an assistant professor in the Department of Electrical Engineering, Tsinghua University till now. Since 2005, she has been engaging in photonic crystal research, and her current focus of research lies in optomechanics.

Xue Feng received his B.S. degree and Ph. D degree from Electronic Engineering Department, Tsinghua University, China, in 1999 and 2004, respectively. Then, he worked there and currently an associate professor at Tsinghua University. His current research interests is silicon-based optical subassembly.

Wei Zhang received his B.S. degree and Ph. D degree from Electronic Engineering Department, Tsinghua University, China, in 1998 and 2003, respectively. Then, he worked there and currently an associate professor at Tsinghua University. His current research interests include microstructure optoelectronic materials and their applications in opto-/quantum devices.

Yidong Huang received the B.S. and Ph.D. degrees in optoelectronics from Tsinghua University, Beijing, China, in 1988 and 1994, respectively. From 1991 to 1993, she was with Arai Laboratories, Tokyo Institute of Technology, Tokyo, Japan, on leave from Tsinghua University. She was with the Photonic and Wireless Devices Research Laboratories, NEC Corporation, from 1994 to 2003, where she was engaged in the research on semiconductor laser diodes for optical-fiber communication. In 2003, she joined the Department of Electronics Engineering, Tsinghua University, as a Professor, where she is currently engaged in research on nanostructure optoelectronics.