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Biosensor based on hollow-core metal-cladding waveguide

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ABSTRACT

A new hollow-core metal-cladding waveguide (HCMW) has been proposed in order to design and realize optical biosensor for the direct liquid probing. Two peculiar properties are exhibited with respect to the current evanescent wave sensors. First, the effective index of the HCMW can exist in the region of $0 < N < 1$, which is usually prohibited for the conventional guided modes and the surface plasmon resonance modes. Second, the analyte to be detected does not locate in the evanescent field but in the oscillating field. Glucose solution is utilized to characterize the device performance. According to the reflectivity changes and the signal-to-noise ratio, the new biosensor has been shown to be capable of directly detecting concentration of glucose as low as 0.5 ppm, which corresponds to a high resolution of 1.4×10^{-7} RI units. This new biosensor improves the detection limitation and shortens the analysis time significantly.

1. Introduction

The need for rapid and sensitive detection of microorganisms and their interactions is very important in areas of food safety, medical care, environmental protection, and biological warfare [1–7]. Among various detecting approaches, biosensors based on optical resonant mode are the subject of growing interest due to their peculiar properties, such as relatively high sensitivity, fast response, small dimensions, and high mechanical stability. Techniques reported include surface plasmon resonance (SPR) [8,9], long-range surface plasmon resonance (LRSPR) [10], resonant mirror (RM) [11], leaky mode waveguide (LMW) [12], reverse symmetrical waveguide (RSM) [13] and metal-clad leaky waveguide (MCLW) [14–16]. The common feature of these current sensors is that the analyte to be detected is located in the region where the evanescent wave of the resonant modes propagates. According to the sensitivity analysis, the use of such evanescent wave biosensors is problematic due to the limited sensitivity resulting from several reasons [4]. These include (1) the limited power portion propagating in the sensing region where the analyte is located; (2) refractive index of the analyte must be always less than the effective index of the resonant modes; (3) the short penetration depth of the evanescent field makes the large analytes, such as bacteria, outside the sensing region, resulting in further insufficient sensitivity of the system.

To achieve a high sensitivity, it is essential to get as much of the optical power as possible to propagate in the sensing region. Investigation of the mode power distribution suggests us to design a configuration that contains the sample in the guiding layer of the waveguide, where oscillating wave is located and most of the mode power concentrates. Addressed this issue, a sensor structure based on porous silicon (PS) waveguide [17] is proposed, in which the target material is filled inside the porous silicon where the oscillating field propagates. Theoretical calculations indicate that the PS sensor shows a greater sensitivity than the conventional SPR sensors. However, sensitivity enhancement is also limited due to the limited volume of the analyte locates in the region of oscillating field. Recently, several chemical and biological sensors based on liquid-core waveguides (LCWG) have been proposed to improve the detection efficiency [18]. Unfortunately, this idea is severely blocked by conventional waveguiding, since water-based solvent has a lower index than almost all the solids which acts as the clad layer of the waveguide.

Facing the above challenge in the biosensors, we proposed a hollow-core metal-cladding waveguide (HCMW) structure in which the hollow-core of sub-millimeter scale is surrounded by metal claddings. In this design the use of double metal claddings which exhibit negative dielectric constant implies that the effective index of the guided modes can exist in the region of $0 < N < 1$ [19], which is usually prohibited for the conventional guided modes and the surface plasmon resonance modes [20]. Analyte of interest

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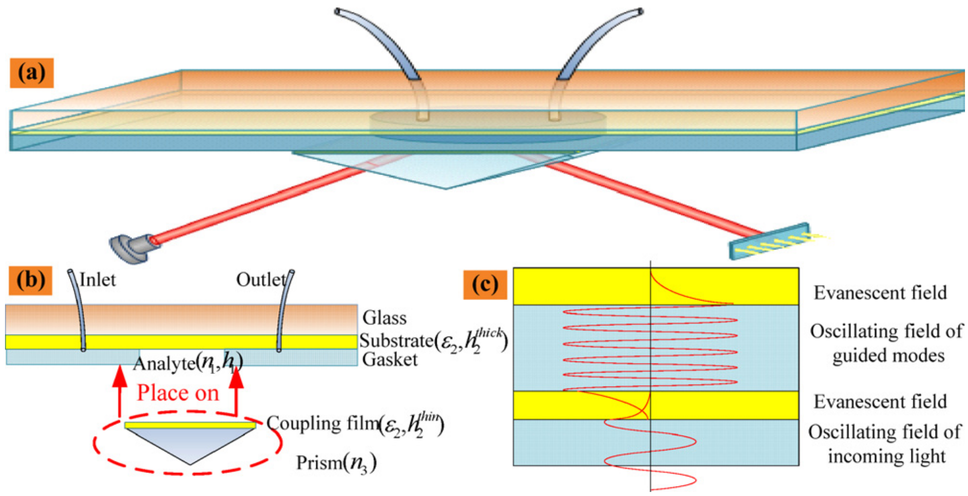

Fig. 1. Schematic diagram of hollow-core metal-cladding waveguide (HCMW): (a) stereogram, (b) plan view, (c) graphical representation of field distribution in HCMW.

contained in the hollow core serves as guiding medium where oscillating wave propagates. Furthermore, in the HCMW structure, the thickness of guiding layer can be expanded to sub-millimeter scale, which makes it easy to inject the aqueous sample into the guiding layer and to excide the sensitive ultrahigh-order modes [21]. It is expected that guiding both light and liquid through the same physical volume maximizes their interaction and should allow for extremely sensitive and rapid sensing. In order to characterize the device performance, a significantly lower concentration of glucose is utilized in our experiment. In the conventional biosensor [22,23], glucose usually is present in relatively high concentrations so that most assays have been developed for a rather high concentration range. Nevertheless, analytical methods for relatively small concentrations of glucose are needed as well, for example when analyzing body fluids that do contain low concentrations (such as tear, sweat and urine). Owing to (1) light power concentrated in the guiding region can enlarge the interaction with the analyte of interest; (2) using of the ultrahigh-order modes with smaller effective index further increases the interaction distances, concentration of glucose as low as 0.5 ppm has been unambiguously identified in our experiment within a several minutes assay. The proposed HCMW sensor exhibits a minimum refractive index variation of $\Delta n = 1.4 \times 10^{-7}$. Aside from higher detection efficiency, the proposed platform offers additional benefits: such as small analyte volume, label-free and real-time detection, and enables environmentally stable, compact, and inexpensive sensing.

2. Hollow-core metal-cladding waveguide

The schematic diagram of hollow-core metal-cladding waveguide (HCMW) in our experiment is illustrated in Fig. 1. Excepting a glass prism with a big vertex angle which serves as a coupling element, HMCW is basically a three-layered optical waveguide, analyte solution confined in hollow core acts as the guided medium, while the two metal films serve as the claddings. For simplicity in sensitivity analysis, we neglect the effects resulting from the limited thickness of the metal film due to the weak coupling [24], dispersion equation of the HCMW can then be written as [21]

$$\kappa_1 h_1 = m\pi + 2\arctan\left|\rho\frac{\alpha_2}{\kappa_1}\right|, \quad (m = 0, 1, 2, \cdots), \tag{1}$$

where $\rho = 1$ for TE modes, while $\rho = \varepsilon_1/\varepsilon_2$ for TM modes. $\varepsilon_1 = n_1^2$ and ε_2 represent dielectric constants of the analyte and the metal films, respectively. h_1 is the thickness of the analyte and m is mode-order number. The vertical propagation constant κ_1 in the guiding medium and the decay coefficient α_2 in the metal claddings are defined by

$$\begin{cases} \kappa_1 = (k_0^2 n_1^2 - \beta^2)^{1/2} \\ \alpha_2 = (\beta^2 - k_0^2\varepsilon_2)^{1/2} \end{cases}, \tag{2}$$

$k_0 = 2\pi/\lambda$ is the wavenumber with light wavelength λ in free space, and $\beta = k_0 N$ is the transverse propagation constant with the effective index N of the guided modes. For most commonly used noble metals in the visible and near-infrared regions, since the imaginary part of its dielectric constant is much less than its real part, it is often convenient to neglect the imaginary part in the analysis. The dispersive curves of the HCMW are shown in Fig. 2. When the thickness of the guiding medium is extended to sub-millimeter scale (see the dashed line $h_1 = 700\,\mu$m), the waveguide can accommodate thousands of guide modes ($m > 1000$), in our terminology, we denote these modes as ultrahigh-order modes [21]. Since the real part of the dielectric constant of the coupling film (metal) is negative, the allowed range of the effective index of both TE and TM modes of proposed HCMW is $0 < N < n_1$ [20]. It is quite different from the conventional guided modes and the surface plasmon

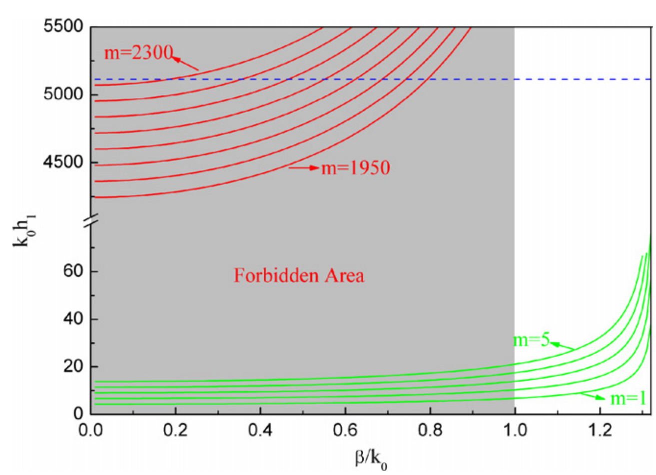

Fig. 2. Dispersive curves of the HCMW with the parameters: $n_1 = 1.330$, $\varepsilon_2 = -10.2$, $\lambda = 632.8$ nm. The blue transverse dashed line denotes $h_1 = 700\,\mu$m, the red and green curves indicate the ultrahigh-order modes and low order modes, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).