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A symmetrical surface plasmon resonance sensing structure excited by a stripe waveguide

Yang Haima*, Song Jia, Zhang Dawei, Huang Yuanshen

School of Optical-Electrical and Computer Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

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ABSTRACT

A symmetrical metal–medium–metal surface plasmon resonance (SPR) structure was excited by a stripe waveguide. The wave-vector matching condition is adjusted by changing the metal-film spacing, which in turn allows a variation of the refractive-index testing range. This structure overcomes the range limitations encountered in the intensity SPR detection method using waveguides and makes the matching condition of wave vectors more flexible. A single-mode stripe waveguide was designed and fabricated to excite the symmetrical sensing structure based on a planar waveguide using the complementary error function as the refractive-index distribution. The stripe waveguide is analyzed more conveniently and is easily cured with optical fibers for remote online measurement. The coupling testing system of the optical fiber with the symmetrical structure excited by the stripe waveguide was constructed to facilitate the excitation of surface plasmon waves. The impacts of the metal type, the metal film thickness, and the medium thickness in the symmetrical structure were investigated to optimize the sensing structure. The resonance condition is achieved much more easily in the symmetrical than in the traditional structure, and the detection range is adjustable via the medium thickness. Online and adjustable measurements were realized simultaneously by the detection system.

1. Introduction

A surface plasmon resonance (SPR) sensor excited by a waveguide does not require high precision angle adjusting devices or control systems, as is needed in the Kretschmann prism configuration. Moreover, the mode characteristic of this sensor is more conveniently analyzed than in an optic fiber SPR sensor. Waveguide based SPR sensors have several advantages, such as their simple integrated structure, small volume, fast response, convenience for conducting theoretical analysis, and suitability for online measurement and multi-point testing [1–5]. They have thus attracted much attention in the field of sensing [6–11].

Most waveguide based SPR sensors involve planar waveguides currently. They cannot therefore be cured with an optical fiber and are not ideal for remote online measurements. Moreover, at a given wavelength, the propagation constant of waveguides prepared with multi-component glass is large. The refractive index of the test dielectric medium should therefore be large enough to satisfy the wave-vector matching condition, which limits the sensing range. New sensing structures are therefore necessary to enhance detection flexibility and online sensing. Dostalek J. [12] presented an SPR sensing structure composed of a Cr-Au-Ta_2O_5 waveguide. Hong S.H. et al. [13] developed a structure, consisting of Cr and Au thin films, fused

* Corresponding author.
E-mail address: snowyhm@sina.com (H. Yang).

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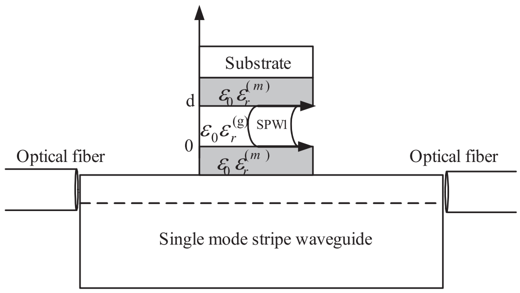

Fig. 1. The symmetrical SPR sensing structure excited by a stripe waveguide.

with a silica substrate. Although these structural designs allow a variety of sensing ranges, the testing range for a given structure is difficult to adjust at the time of measurements.

To address this problem, we investigated the sensing method and structure of a symmetrical SPR structure excited by a stripe waveguide. The main challenges are adjusting the testing range and designing the single-mode waveguide. The wave-vector matching condition was adjusted by varying the spacing between the two metal films, which in turn controls the refractive-index testing range. A single-mode stripe waveguide was designed, based on a planar waveguide, using the complementary error function to describe the refractive-index distribution. We propose an experimental method for interpreting the effective refractive-index distribution of the single-mode stripe waveguide and for calculating the single-mode condition at wavelength 1310 nm. A coupling testing system for the optical fiber, with the symmetrical structure excited by the stripe waveguide, was fabricated to facilitate the excitation of surface plasmon waves (SPW). The impacts of the metal type, the metal film thickness, and the medium thickness in the symmetrical structure were investigated to optimize the sensing structure. Online and adjustable measurements were realized simultaneously by the detection system, demonstrating advantages such as online capability, strong adaptability, efficiency, accuracy, high reliability, and easy operation. The detection system can thus successfully measure liquid and gas concentrations.

2. Principle

2.1. Design and fabrication of the stripe waveguide

The proposed sensing structure is outlined in Fig. 1. A single-mode stripe waveguide is used to excite the SPW in the symmetrical metal-medium-metal sensing structure. It is prepared using ion exchange, based on the preparation and analysis of a planar waveguide and using the complementary error function. Single-mode conditions can be controlled via the ion exchange time t.

For the gradient refractive index planar waveguide, the refractive-index distribution can be expressed as

$$n(x) = n_s + \Delta n f(x) \tag{1}$$

where Δn is the surface refractive-index increment, n_s the substrate refractive index, and $f(x)$ the refractive-index distribution function.

If the mixed molten salt $AgNO_3$-$NaNO_3$ is chosen, $[Na^+]$ and $[Ag^+]$ denote the molar concentrations of natrium and silver ions. When the molar fraction of silver ions in the mixed molten salt is less than 0.05%, the refractive-index distribution function can be expressed in terms of the complementary error function:

$$f(x) = erfc\left(\frac{x}{2\sqrt{D_{eff}t}}\right), t \geq 0, x \geq 0 \tag{2}$$

where D_{eff} is the effective diffusion coefficient and t the ion-exchange time. In mixed molten salt of $AgNO_3$-$NaNO_3$, the molar fraction of $[Ag^+]$ is made to be less than 0.05%. The propagation constant of the planar waveguide can be determined by the m-line method. According to the eigenvalue equations for the TE or TM modes, Δn_i and D_{effi} (calculated for each mode) can be obtained. The average values can then be substituted for Δn and D_{eff}, for the corresponding exchange temperature T, time, and $[Ag^+]$.

The fabrication of stripe waveguides is based on that of planar waveguides, using the complementary error distribution, under fixed ion-exchange conditions. In other words, the concentration of $AgNO_3$-$NaNO_3$, the temperature T, and the glass-substrate parameters are the same as those for planar waveguides. Consequently, the obtained surface-refractive-index increment Δn and the effective diffusion coefficient D_{eff} remain valid. The half width of the mask opening for ion exchange