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Split Mach–Zehnder interferometer for surface plasmon resonance based phase modulation

Jayeta Banerjee, Mahua Bera, Mina Ray *

Department of Applied Optics & Photonics, University of Calcutta, Acharya Prafulla Chandra Siksha Prangan, JD-2, Salt Lake, Sec III, Kolkata—700 106, India

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ABSTRACT

Split Mach–Zehnder interferometer is proposed for demonstration of phase modulation of p- and s- polarized beams in a surface plasmon resonance based phase sensitive interference imaging platform. Significant phase change has been observed in Al coated prism based SPR configuration for p-polarized beam, whereas practically no phase change occurs for s-polarized beam. Qualitative analysis of SPR modulated interference fringes also validates the observed effects. A proposed Split Mach–Zehnder set up is shown for simultaneous sensing of two different samples.

1. Introduction

Surface plasmons (SPs) are free charge oscillations at the interface between a thin metal layer and a dielectric over-coating and associated surface plasmon wave (SPW) propagates along the interface. The light incident at a specific angle, greater than the critical angle can cause excitation of SPs, based on attenuated total reflection (ATR) coupler method. When the wavevector of SPW matches with that of the incident transverse magnetic (TM) polarized light, surface plasmon resonance (SPR) occurs resulting in the dip in the angular or wavelength spectra concerned [1]. SPR technique permits the precise measurement of changes in the refractive index or thickness of the sensing medium adjacent to the metal. Gold, silver, aluminum are ideal metal films especially in the visible wavelength region. Silver and aluminum give sharper resonance spectra than gold, but they are very much oxidation prone. The choice of the particular metallic film varies from application to application [2]. In view of the increasing need for detection and analysis of chemical and biochemical substances in many important areas including medicine, environmental monitoring, biotechnology, drug and food monitoring, SPR sensor technology holds a significant potential [3]. Metal thickness optimization is very important for efficient excitation of SPR [4].

Phase detection method based on SPR provides certain advantages over conventional techniques [5]. Both theoretical and experimental SPR phase imaging has been reported by earlier researchers [6,7]. Recently, Huang et al. have reviewed a large number of interferometric phase measurement approaches utilized in SPR based sensor [8]. In order to increase the sensitivity of a bio-sensor, differential phase analysis is found to be more advantageous [9]. Phase profile analysis based on 4f set-up [10] has been reported using adjustable two window Mach–Zehnder interferometer. Another type of Mach–Zehnder interferometer [11] offering very high sensitivity has been reported with refractive index (RI) detection limit in the order of 10^{-6}. Differential reflectance and phase response has also been studied for four layered SPR structures by Ray et al. [12,13]. The experimental differential phase analysis is one of the best reported in literature [14]. A vertical plasmonic Mach–Zehnder interferometer has been reported which can be used in nanoplasmonic integration due to denser array packing [15].

In view of this scenario, in this paper we realize a completely unconventional Split Mach–Zehnder (SMZ) set-up by essentially utilizing each arms of the conventional interferometer separately and incorporating a birefringent lens (BL) for producing interference between *p*- and *s*-polarization components where the birefringent lens itself can be looked upon as a radial shear interferometer in one sense. Polarizing beam splitter (PBS) is used to separate two orthogonal polarization components.

Advantage of SMZ interferometer is simultaneous observation of polarization modulated fringes without going into critical alignment [16] necessary in conventional Mach–Zehnder interferometer and also simultaneous sensing of two samples in two opposite arms. Interference image gets modulated due to SPR occurrence for *p*-polarization. At the same time, fringes remain unaffected for *s*-polarization as it has no contribution to surface plasmon excitation. The experimental set-up has

* Corresponding author.
E-mail address: mraphy@caluniv.ac.in (M. Ray).

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been developed to observe the influence of plasmonic excitation on the fringe pattern, which can be further utilized for photonic applications such as sensing and imaging. A simple and cost effective moiré pattern generation by dual (radial and lateral) shearing has already been reported [17,18] by us showing the fringe modulation due to surface plasmon resonance effect.

2. Mathematical background

2.1. Calculation of reflectance and phase of three layer Kretschmann configuration

The wavevector of the incident light in the coupling prism (pr) must be phase match to the wavevector of the SPs at the metal–dielectric interface. The resonance condition for the Kretschmann–Raether configuration is

$$\sqrt{\varepsilon_1}\frac{\omega}{c}\sin\theta_1 = \frac{\omega}{c}\sqrt{\frac{\varepsilon_2\varepsilon_3}{\varepsilon_2+\varepsilon_3}} \quad (1)$$

where, ε_1, ε_2 and ε_3 are the dielectric permittivity of coupling prism, plasmon generating metal film and dielectric layer respectively. θ_1 is the incident angle of light in the prism. The reflectance of the three layer structure is given by

$$R = \left|r_{123}\right|^2 = \left|\frac{r_{12} + r_{23}\exp\left(2ik_{z2}d_2\right)}{1 + r_{12}r_{23}\exp\left(2ik_{z2}d_2\right)}\right|^2 \quad (2)$$

where, d_2 is the thickness of the metal film. Fresnel equations for calculating reflection coefficient for TM and TE modes are

$$r_{lk}^{TM} = \frac{n_k\cos\theta_l - n_l\cos\theta_k}{n_k\cos\theta_l + n_l\cos\theta_k}, \qquad r_{lk}^{TE} = \frac{n_l\cos\theta_l - n_k\cos\theta_k}{n_l\cos\theta_l + n_k\cos\theta_k} \quad (3)$$

where $l = 1, 2$ and $k = 2, 3$. We used Snell's law as

$$n_1\sin\theta_1 = n_2\sin\theta_2 = n_3\sin\theta_3. \quad (4)$$

The phase of the reflected wave is

$$\phi_r = \arg\left(r_{123}\right) = \tan^{-1}\left[\frac{\mathrm{Im}\left(r_{123}\right)}{\mathrm{Re}\left(r_{123}\right)}\right]. \quad (5)$$

When $r_{123} = 0$, the reflectance possess its minimum value (zero) associated with a sharp phase jump. Detailed analysis of reflectance and phase using characteristics transfer matrix for 3 and 4-layer structures has already been established long back [19,20].

2.2. Dispersion relation and Drude model

In our analysis we have considered fused silica glass as the coupling prism material. The refractive index of the prism material (substrate) can be calculated using Sellmeier's dispersion equation [21]. Here we have used aluminum as the plasmon generating metal film. The refractive index of the metal can be calculated by Drude model [22].

2.3. Numerical expressions for split Mach–Zehnder interferometer

Mach–Zehnder interferometer with PBS has been analyzed using tensor algebra. The circular polarized beam is represented as

$$In = \begin{pmatrix}1 & 0\\ 0 & -i\end{pmatrix}\times\begin{pmatrix}1\\ 1\end{pmatrix} = \begin{pmatrix}1\\ -i\end{pmatrix} \quad (6)$$

where, transmission axis of linear polarizer is at 45° and fast axis of quarter wave plate (QWP) is kept vertical.

The circularly polarized parallel beam is incident upon the birefringent lens with its optic axis perpendicular to its principal axis. BL has two focal lengths, one corresponding to the ordinary (o) vibration and the other corresponding to the extraordinary (e) vibration due to the two distinct RI values in a birefringent medium for o- and e-rays. When this beam is incident upon BL, two spherical waves of equal amplitude (A) are produced at the output,

$$\psi_{o,e} = A\exp\left[i\frac{2\pi}{\lambda f_{o,e}}\left(x^2+y^2\right)\right] \quad (7)$$

where, f_o and f_e are the focal lengths of o- and e-rays respectively. If the analyzer is placed at an orientation of ±45° to that of the lens the output beam forms a set of circular fringes, with the central fringe bright or dark depending upon whether the analyzer angle is +45° or −45° respectively.

Also the transfer matrix of the BL is

$$M_{BL} = \begin{pmatrix}1 & 0\\ -1/f & 1\end{pmatrix} \quad (8)$$

where, f is the mean focal length of f_o and f_e.

The transfer matrix of the Collimating Lens (CL) is

$$M_{CL} = \begin{pmatrix}1 & 0\\ 1/f & 1\end{pmatrix} \quad (9)$$

where, f is the focal length of lens.

The spatial transformation is performed by PBS with reflection and transmission amplitude 'r' and 't' respectively. Subscripts 'H' and 'V' denote the two possible polarization states. The general matrix representation for PBS is

$$M_{PBS} = \begin{pmatrix}t_H & ir_H & 0 & 0\\ ir_H & t_H & 0 & 0\\ 0 & 0 & t_V & ir_V\\ 0 & 0 & ir_V & t_V\end{pmatrix}. \quad (10)$$

Matrix representation of PBS for transmitting arm is denoted by PBS^t and that for reflecting arm is PBS^r. Here, PBS^t has values of $t_H = 1$ and PBS^r has values of $r_V = 1$.

Total internal reflection (TIR) can be expressed by the following matrix

$$M_{TIR} = \begin{pmatrix}r_{p_{TIR}} & 0\\ 0 & r_{s_{TIR}}\end{pmatrix}. \quad (11)$$

Similarly, SPR can be expressed as

$$M_{SPR} = \begin{pmatrix}r_{p_{SPR}} & 0\\ 0 & r_{s_{SPR}}\end{pmatrix}. \quad (12)$$

The matrix representation for the beam coming out from uncoated prism in arm 1 is

$$O_1 = M_{TIR}M^t_{PBS}M_{CL}M_{BL}In. \quad (13)$$

The matrix for the beam coming out from uncoated prism in arm 2 is

$$O_2 = M_{TIR}M^r_{PBS}M_{CL}M_{BL}In. \quad (14)$$

If uncoated prism is replaced by an Al-coated prism, these two equations under SPR condition are modified as

$$O_1 = M_{SPR}M^t_{PBS}M_{CL}M_{BL}In \quad (15)$$

and

$$O_2 = M_{SPR}M^r_{PBS}M_{CL}M_{BL}In. \quad (16)$$

Matrix multiplications are done by making matrices of same order using Kronecker function.

3. Polarization dependent SPR based interferometric phase imaging

A three-layer (prism/metal/analyte) Kretschmann configuration has been considered in our experiment. 40 nm thin Al film was deposited on the hypotenuse face of the fused silica glass prism. Metal thickness optimization and angle selection are both very important as far as efficient plasmonic excitation is concerned [23]. The experiment is carried out