Optimization of Peak Type Metal Clad Waveguide Sensor Using Different Metals.

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Abstract: The comprehensive analysis for the prism coupled peak type metal clad waveguide sensor in reflection mode has been done for different metals. The proposed four layer structure contains very thin cladding of metal layer deposited on the substrate for the peak type operation. The proposed sensor has been analyzed in TE mode.

Keywords: Metal clad waveguide (MCWG), Refractive Index (RI), Surface Plasmon Resonance (SPR), Transverse Electric (TE)

I. INTRODUCTION

In the last few decades, the optical sensors have proven great interest in sensing field like chemical sensor [1], gas and humidity sensor [2]-[3] and biosensor etc [4]-[6]. Intensive research in the field of optical sensing has resulted in variety of optical sensors like SPR sensor [7]-[8], interferometers [9], resonant mirror sensors [10] and dielectric waveguide sensor [11]. Most of optical sensors are based on evanescent wave sensing[12]-[13]. Itsensing principle is to detect change in refractive index of the waveguide due to change in cover refractive index when evanescent wave interacts with cover medium[14]. The penetration depth of evanescent field in cover medium is important parameter for measuring the performance of the sensor. Higher penetration depth is required to sense the micrometer scale object. The MCWG sensor is preferred to SPR sensor due to two reasons. The first reason is tuning of penetration depth is possible in MCWG sensor but it is constant over whole detection range in SPR sensor. Second advantage is that MCWG sensor provides chemical and mechanical stability to metal layer. MCWG sensor operates in two modes dip type and peak type MCWG [15]. The peak type MCWG has been used for the detection of micrometer scale objects[16]-[17]. The peak type MCWG sensor can be used for measuring wide range of RI as they have infinite penetration depth of evanescent field in the cover. In this paper, prism coupled peak type MCWG has been used in reflection mode. The sensing principle of peak type MCWG sensor is to detect the shift in peak position with respect to change in cover RI. The structure for the peak type MCWG consists of substrate (S), metal layer(M), waveguide film (F) and cover layer (C) similar to that of dip type MCWG sensor. The difference in two structures is (a) Smaller thickness of metal layer, and (b) Larger value of imaginary part of dielectric
constant of metal for peak type MCWG sensor. On increasing incident angle the peak in reflectance occurs when it reaches to 1 at $N = n_c$ i.e., at critical angle. With further increase in angle the reflectance drops down to zero. In this paper optimization of the parameters for peak type MCWG in TE mode has been done. Thereafter, the role of different metals on peak type MCWG has also been studied for the different MCWG structures.

In section II, fundamental background and related equations have been derived to study the performance of the proposed MCWG sensor. In section III, the results obtained through simulation for the proposed sensor has been discussed and finally section IV, concludes the paper.

II. THEORETICAL MODELLING

Fig.1 represents the four layer peak type MCWG structure. The first layer is glass substrate(S) i.e., prism with refractive index $n_g = 1.517$. The second layer is metal i.e., aluminium with thickness $d_{Al} = 3$ nm and permittivity $\varepsilon_{Al} = -54.26 + i19.45$. The third layer is $SiO_2$ waveguide film deposited over metal layer with layer thickness, $d_{Al} = 253$ nm (optimized value) and refractive index, $n_f = 1.47$. The last layer i.e., fifth layer of the sensor is cover layer or sensing layer with RI, $n_c$ varying from 1.33 to 1.40. The operating wavelength for the proposed sensor is 632.8nm.

![Fig.1 Proposed peak type MCWG sensor](image)

The basic sensing principle of MCWG sensor has been already explained in section I. The profile of the electromagnetic field is calculated by applying Maxwell’s equations and boundary conditions for the proposed structure. The Eigen modes of the proposed waveguide sensor can be obtained by solving Maxwell’s equations. The Helmholtz equation can be written as

$$\frac{\partial^2 \psi(z)}{\partial z^2} + [\omega^2 \varepsilon(z) \mu(z) - \beta^2] \psi(z) = 0$$  \hspace{1cm} (1)$$

where $\psi$ represents the electric field for TE-polarized light and the magnetic field for TM-polarized light; $\omega$ is the angular frequency of the field and $\beta$ is the propagation constant in x-direction, which can be written as $\beta = k_0 N_{eff}$, where $k_0$ is the free space wave number, and $N_{eff}$ is the modal effective index. Hence, the solutions of the proposed waveguide for different regions can be written as
\[
\psi(z) = \begin{cases} 
Ae^{i(kz)}e^{i(\alpha-k_x)x} & \text{Coverlayer} \\
Af e^{i(kz)} + Bf e^{-i(kz)} & \text{GuidingFilm} \\
Am e^{i(kz)} + Bm e^{-i(kz)} & \text{Metallayer} \\
As e^{i(kz)}e^{i(\alpha-k_x)x} & \text{SubstrateLayer}
\end{cases}
\]

Where,
\[
k_x = \sqrt{\beta^2 - n_C^2 k_0^2}, \quad k_f = \sqrt{\beta^2 - n_N^2 k_0^2},
\]

Now, applying the boundary conditions stating from equation (2) that \(\psi\) and \(d\psi/dz\) are continuous across the two boundaries for TE modes, \(\psi\) and \((n-2)d\psi\) are continuous across the two boundaries for TM modes. After applying boundary conditions, we get equations that can be written as

\[
G_{\rho} \psi = 0
\]

where,

\[
G_{\rho} = \begin{bmatrix}
A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} \\
A_{21} & A_{22} & A_{23} & A_{24} & A_{25} & A_{26} \\
A_{31} & A_{32} & A_{33} & A_{34} & A_{35} & A_{36} \\
A_{41} & A_{42} & A_{43} & A_{44} & A_{45} & A_{46} \\
A_{51} & A_{52} & A_{53} & A_{54} & A_{55} & A_{56} \\
A_{61} & A_{62} & A_{63} & A_{64} & A_{65} & A_{66}
\end{bmatrix}
\]

In order to get non-trivial solutions the determinant \( (\Delta) \) would be zero, which leads to an equation identical to the mode equation found from the ray-tracing technique. The field distribution of proposed sensor is obtained by calculating the effective refractive index \(N_{eff}\) from equation (2) with an assumption that one of the field amplitudes \(A_f = 1\) is unity.

Here, the MCWG sensor is operated in reflection mode, where reflectance is measured on changing the angle of incident light from substrate. The reflectance can be easily calculated using Fresnel’s reflection laws for the four layer MCWG configuration [18-19]. The reflectance for the proposed sensor can be written as:

\[
R_{mf} = \left| \frac{r_{mf} + r_{mfc} e^{2i\delta_{mfc}}}{1 + r_{mf} r_{mfc} e^{2i\delta_{mfc}}} \right|^2
\]

where

\[
R_{mfc} = \left| \frac{r_{mfc} e^{2i\delta_{mfc}}}{1 + r_{mf} r_{mfc} e^{2i\delta_{mfc}}} \right|^2
\]

\[
r_{mf} = \frac{(n_f^2 - n_m^2) \rho k_f}{(n_f^2)^{\rho} k_f + (n_m^2)^{\rho} k_m}, \quad r_{mfc} = \frac{(n_m^2)^{\rho} k_m - (n_f^2)^{\rho} k_f}{(n_m^2)^{\rho} k_m + (n_f^2)^{\rho} k_f}
\]

Here, \(\rho\) is the polarization index that equals 0 for TE and 1 for TM polarized light.

III. SIMULATED RESULTS AND DISCUSSION:

Fig. 2 explains, the sensing principle of peak type metal clad waveguide. It shows that as incident angle increases from lower angle values to higher one, the peak in reflectance is observed at \(N = n_C\) i.e. at critical angle and further increase in incident angle resulting in broader resonance curve leading to dip.
in reflectance value. The dip in reflectance occurs above critical angle because of excitation of waveguide mode in the waveguide film. Here, the shift in peak position is directly related to change in sensing medium refractive index. The shape of the peak should be sharper for the better detection and various parameters of the peak type MCWG sensor must be chosen for the optimization of peak shape.

Variation in refractive indices and thicknesses of waveguide film, metal cladding, and cover shows their influence for designing optimum peak type MCWG sensor like that of dip type metal clad waveguide sensor [15]. Fig. 3 shows reflectance curve for three different waveguide film thickness, \( d_f = 243 \text{nm}, 253 \text{nm} \) and \( 263 \text{nm} \). Fig. 4 shows the reflectance curve for three different waveguide film refractive indices, \( n_f = 1.43, 1.47 \) and \( 1.51 \). Fig. 3 and 4 indicates that on increasing waveguide film thickness or refractive index changes the angular position of the resonance dip. The behaviour of peak type MCWG is similar to dip type MCWG sensor. Waveguide film thickness for peak type MCWG sensor should be thin of the order of few nm but must be above the cut of film thickness so that critical angle appears within the range of the reflectance dip for obtaining distinct peak. For the lower values of film thickness and film refractive index, soft peak appears which is not useful for the sensing purpose as it will not indicate clear shift in the position of the peak with respect to change in refractive index of the cover layer. Fig. 5 explains, the position of peak remains same for peak type MCWG sensor with changes in metal thickness because critical angle is only influenced by cover refractive index \( n_c \) and substrate refractive index \( n_s \) but minimum reflectance rises to higher value when metal thickness is either increased or decreased. Minimum reflectance is observed at some optimum value of metal thickness for obtaining relatively sharper peak with a maximum difference in reflectance for peak and dip.

Fig. 6 indicates the reflectance curve for peak type MCWG in TE mode using different metals with optimum metal thickness giving zero dip reflectance. Metals used for above simulation are chromium, titanium, aluminium, nickel and platinum. Fig. 6 clearly indicates that use of aluminium provides sharpest peak in peak type MCWG sensor. So, aluminium has been used for the proposed peak type MCWG sensor.

Fig. 2 Reflectance curve for peak type MCWG sensor in TE mode for different cover refractive indices. The refractive indices and thicknesses used are: \( n_s = 1.517 \) (Glass substrate RI), \( \varepsilon_{Al} = -54.26+i*19.45 \) (Aluminium permittivity), \( n_f = 1.47 \) (SiO\(_2\) waveguide film RI), \( n_c = 1.33, 1.35, 1.37, \) and \( 1.39 \) (Cover RI), \( d_{Al} = 3 \text{nm} \) (Metal thickness), \( d_f = 253 \text{nm} \) (film thickness).
Fig. 3 Reflectance curve for peak type MCWG sensor in TE mode for three different waveguide film thicknesses. The refractive indices and thicknesses used are: $n_g = 1.517$ (Glass substrate RI), $\varepsilon_{Al} = -54.26+i*19.45$ (Aluminium permittivity), $n_f = 1.47$ (SiO$_2$ waveguide film RI), $n_c = 1.33$ (Cover RI), $d_{Al} = 3\text{nm}$ (Metal thickness), $d_f = 243\text{nm}$, $253\text{nm}$, and $263\text{nm}$ (film thickness).

Fig. 4 Reflectance curve for peak type MCWG sensor in TE mode for different film refractive indices. The refractive indices and thicknesses used are: $n_g = 1.517$ (Glass substrate RI), $\varepsilon_{Al} = -54.26+i*19.45$ (Aluminium permittivity), $n_f = 1.43$, $1.47$, and $1.51$ (SiO$_2$ waveguide film RI), $n_c = 1.33$ (Cover RI), $d_{Al} = 3\text{nm}$ (Metal thickness), $d_f = 253\text{nm}$ (film thickness).
Fig. 5 Reflectance curve for peak type MCWG sensor in TE mode for three different metal thicknesses. The refractive indices and thicknesses used are: $n_s = 1.517$ (Glass substrate RI), $\varepsilon_{Al} = -54.26 + i*19.45$ (Aluminium permittivity), $n_f = 1.47$ (SiO$_2$ waveguide film RI), $n_c = 1.33$ (Cover RI), $d_{Al} = 2$nm, 3nm & 4nm (Metal thicknesses), $d_f = 253$nm (film thickness).

Fig. 6 Reflectance curve for peak type MCWG sensor in TE mode for different metals. The refractive indices and thicknesses used are: $n_s = 1.517$ (Glass substrate RI), $\varepsilon_{Cr} = -6.9 + i*30.35$, $\varepsilon_{Ni} = -9.64 + i*14.02$, $\varepsilon_{Al} = -54.26 + i*19.45$, $\varepsilon_{Pt} = -11.54 + i*18.86$, $\varepsilon_{Ti} = -3.84 + i*12.15$ (Metal permittivity), $n_f = 1.47$ (SiO$_2$ waveguide film RI), $n_c = 1.33$ (Cover RI), $d_{Al} = 3$nm (Metal thickness), $d_f = 264$nm, 248nm, 253nm, 252nm, and 254nm (optimized film thickness) for Cr, Ni, Al, Pt, and Ti respectively [15].

IV. CONCLUSION

The optimization of peak type MCWG sensor in TE mode has been done by varying its parameters and also by using different metals. Sensitivity of this sensor does not depend on film thickness because of appearance of peak at off resonance condition but it is dependent on penetration depth of the evanescent field in the cover region. However for peak type MCWG sensor the cover refractive index sensitivity
being always maintained at 1 as it have infinite penetration depth of the evanescent field in the cover medium for ranges of cover refractive index due to peak position at critical angle.

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