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D-Type Optical Fiber & its Applications

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Abstract— Fiber optic based sensors have a wide range of applications in real-time and fast sensing of optical industry for measurement, hazardous chemical identifications, bio sensors etc..Optical fiber sensors have attracted tremendous research interests in last few decades towards these applications. The D-type optical fiber is an optical fiber, where the cladding is side polished, results in D-shaped. D-shape optical fibers provide several applications including sensing. Dispersion relation of surface plasmon waves has been established between a metal and dielectric system. In this paper present the design of an SPR refractive index sensor, based on a D-type optical fiber. Firstly, a D-type optical fiber designed by symmetrical removing a portion of its cladding from a single mode step-index optical fiber. After symmetrical removing the cladding, effective refractive index changes w.r.t. wavelength. The sensitivity was found between $\mathbf{0.303 \times 10^2}$ to $\mathbf{0.556 \times 10^2}$ $\mathbf{(nm/RIU)}$.

Index Terms— D-type optical fiber, Optical fiber sensors, Propagation constant (K), Surface Plasmons (SPs), Surface Plasma Wave (SPW), Effective refractive index (n_{eff}),TM-polarized wave.

1. Introduction

Over the past century there has been significant progress in research and development of Optical sensors. During the year 2011 with new publications regarding sensors it was found about 53% of it dealt with Optical sensors.[1] The need for real-time, fast and more accuracy measurement, the SPR sensor technology has been commercialized by several companies. Optical methods have been used in chemical sensors and biosensors including ellipsometry, spectroscopy (luminescence, phosphorescence, fluorescence, Raman), interferometry (white light interferometry, modal interferometry in optical waveguide structures),
spectroscopy of guided modes in optical waveguide structures (grating coupler, resonant mirror), and surface Plasmon resonance. [2] The interaction of light with metal is often complicated and useful. The excitation of surface Plasmon's at metal interfaces using electrons observed by Powell and Swan. [3] Gas detection and curvature sensing are the examples of sensing applications using D-type fiber. Kretschmann and Otto were demonstrated the optical excitation of surface Plasmon's by the method of attenuated total reflection. One of the difficulties in Otto's configuration is metal has to be brought around 200 nm of prism surface. [3] Surface Plasma Wave (SPW) is a TM-polarized wave (magnetic vector is perpendicular to the direction of propagation of the SPW and parallel to the plane of interface). The field vectors of Surface Plasma Wave (SPW) reach their maxima at metal boundary and strongly decay in both media. Surface Plasmon Resonance is a charge-density oscillation between a metal and a dielectric interface. At optical wavelengths, metals i.e., Gold and Silver are most commonly used. [2] Most of the metals possess a negative dielectric constant at optical frequencies which causes a very high reflectivity. Gold has high chemical stability on exposure to the atmosphere rather than the other metals.

An optical fiber is a dielectric waveguide that operates at optical frequencies. [4] It confines EM energy in the form of light. Only a certain discrete number of modes are capable of propagating along the guide.[5]

Generally, two types of fiber according to the core material composition (a) Step-index fiber and (b) Graded-index fiber. Both the Step and Graded-index fibers can be divided into single-mode and multimode fiber. A Single Mode Fiber (SMF) contain only one mode of propagation. A typical single mode Step-index optical fiber has a core diameter between 8-12 µm and a cladding diameter of 125 µm.[5] In Step-index optical fiber the core of radius ''a'' has a refractive index n_1 and cladding of slightly lower index n_2, where

$$n_2 = n_1 (1 - \Delta) \quad (1)$$

The parameter Δ("delta") is called the refractive index difference or the core-cladding index difference. Typical values of Δ varies from 0.2 to 1.0 percent for single mode fibers.[4] For a confined mode there is no energy flow in the radial direction, thus the wave must be evanescent in the radial direction in the cladding. This is true only if $n_{eff} > n_2$. The parameter n_{eff} is called effective refractive index. On the other hand, the wave cannot be radially evanescent in the core region. Thus

$$n_2 < n_{eff} < n_1 \quad (2)$$

The waves are more confined when n_{eff} is close to the upper limit in this interval.

2. D-type Optical Fiber

D-shaped fibers are difficult to model theoretically, due to the lack of axial symmetry. [6] In the case of a optical fiber polishing in the longitudinal plane removes a portion of the cladding of the fiber. The uncladded fiber shows as D-shaped. So, the uncladded of the fiber allows evanescent field from the cladding to be coupled to the external medium. A metal film (i.e., gold or silver) coated on the cladding allows the resonant excitation of SPP on the metal dielectric interface. The change in coupling condition achieved through e.g. a refractive index change of the dielectric medium at interface with the metal film. In this paper we use single mode step-index optical fiber. The refractive index of the core, cladding and external medium or analytes are n_1, n_2, n_3 respectively; ϵ_m is the relative complex permittivity of the metal film.

Fig. 1 shows the D-shaped optical fiber with uncladded portion replaced by metal layer and analyte.

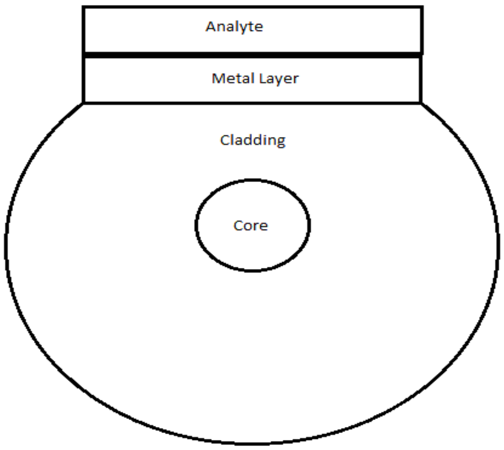


Fig. 1 Geometry of D-type Optical Fiber

3. Surface Plasmons

There are certain promises of plasmonics that are responsible for the current boom in research field. Surface Plasmons (SPs) are known solutions of Maxwell's equations. [3] The Maxwell's equations applied at an interface between a medium with a negative permittivity, i.e. a metal and a dielectric. These solutions are travelling waves that are exponsially decaying in both media. The charge density oscillations along the metal dielectric interface are known as surface plasma oscillations. The quantum of these oscillations is referred to as Surface Plasmon (also a Surface Plasmon Mode or a Surface Plasmon Wave). Surface Plasmons are TM-polarized wave.[2] The surface plasmon wave propagation constant (K_{SP} or K) is contineous through the metal-dielectric interface and is given by[3]

$$K_{SP} = \frac{\omega}{C}\sqrt{\epsilon_m\epsilon_s/\epsilon_m + \epsilon_s} \qquad (3)$$

Where ϵ_m and ϵ_s represent the dielectric constants of metal layer and the dielectric medium; ω represents the frequency of incident light and c is the velocity of light.

4. Optical constants of the Noble Metals

In 1972, Johnson and Christy published the experimental data of measured (bulk) material permittivity values.[7] Gold (Au) plays an important role in plasmonics type spectroscopies, biological applications. Gold is widely preferred for biological applications over Silver (Ag) for its relatively easier surface chemistry, the possibility of attaching molecules via thiol groups, good bio-compatibility, and chemical stability. Au has at least two interband transitions at $\lambda \sim 470$ and ~ 330 nm. The Drude model doesn't take into account electron-electron interactions. In terms of the dielectric permittivity, the Drude Model is expressed as [8]

$$\varepsilon(\omega) = 1 - \frac{\omega_P^2}{\omega^2 + i\omega\Gamma_p} \qquad (4)$$

Where ω_P is the plasma frequency of the material (a constant for each material), Γ_P is the damping (or relaxation) rate, ω is the frequency of interest and 'i' is the complex number, i = $\sqrt{-1}$.

$$\omega_P = \sqrt{\frac{4\pi Ne^2}{m_e}}$$

where N = electron density,
e = charge of electron and
m_e = mass of an electron

The calculated valves for the Drude model for silver and gold are summarized in Table 1. [8]

Table 1. Drude model valves for Silver and Gold

Metal	Plasma Freq. (**ω_P**, ev)	Damping Factor (**Γ_P**,ev)
Gold	9.062	0.070
Silver	9.172	0.021

The Lorentz oscillations terms can be added to the Drude model in order to provide a more accurate prediction of the permittivity. Because the frequency dependent nature of the interband transitions is important in an analysis of the permittivity of a metal.

In fig. 2 and fig. 3 the real and imaginary parts of electric permittivity of Gold and Silver are plotted w. r. t. frequency (THz) on Matlab.

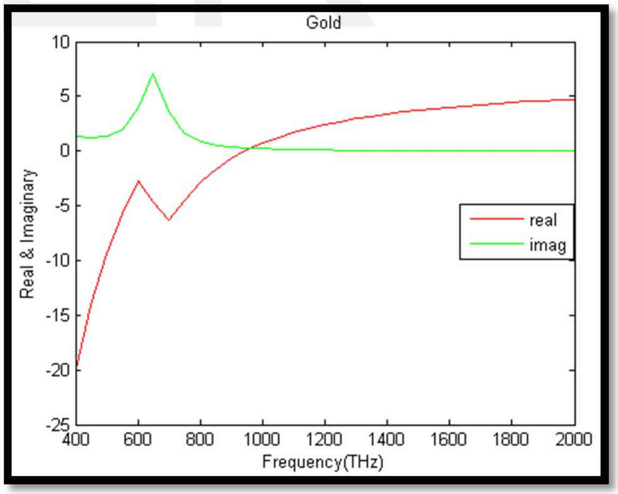


Fig. 2 Dielectric function of Gold (Au)

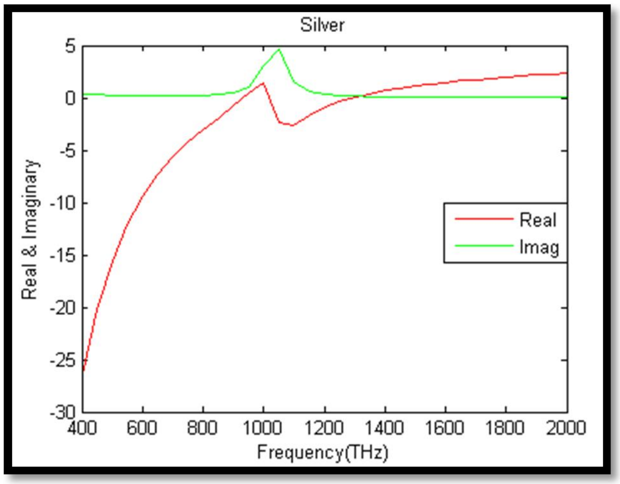


Fig. 3 Dielectric function of Silver (Ag)

5. Simulation Results

I have taken COMSOL Multiphysics software for simulation, as it is a simple programme due to existence of a graphical environment, to perform simulations with good accuracy. [9] For better sensitivity, I have taken SMF. The core and cladding diameters are 8 and 125 μm respectively. The sensitivity of D-type optical fiber can be increased by chemical etching method for measurement of temperature and external refractive index. I have confirmed that the decreasing the core to cladding distance of D-shaped (i.e., distance between center of the core to outer cladding layer) optical fiber (λ varies from 1 to 2 μm, Δ varies from 0.002 to 0.0055), the changes on ‘n_{eff}’ range on microscale. With the simulation data and results, Fig. 4 has been plotted on Matlab.

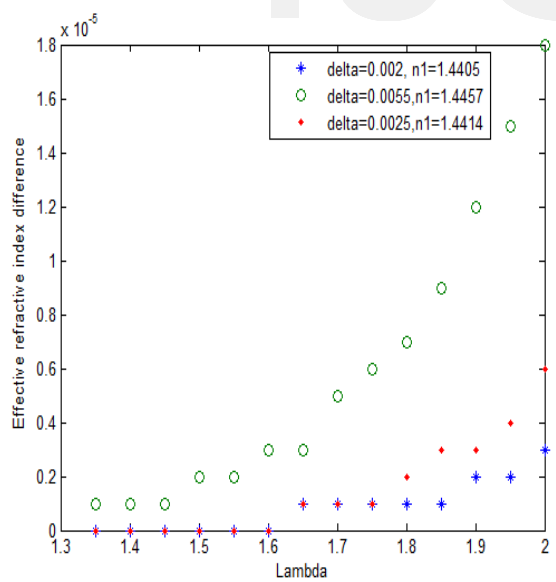


Fig. 4. Variation of Effective refractive index difference on the basis of core to cladding distance as well as the delta.

COMSOL Multiphysics uses the FEM (Finite Element Method), which basically consists in dividing the simulation domain into smaller subdomains forming a mesh as shown in Fig. 5.

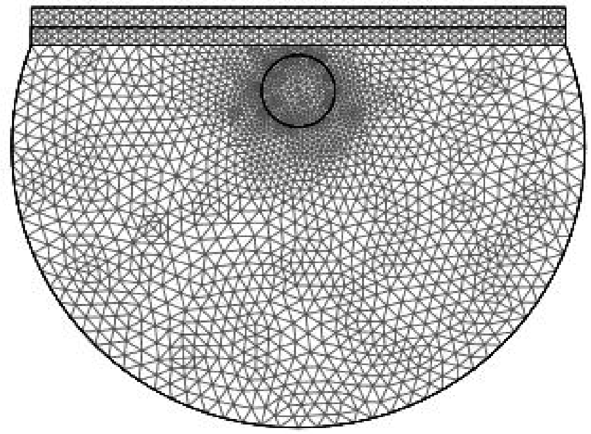


Fig. 5 Structure of the finite elements in COMSOL Multiphysics for a D-type optical fiber with a metallic layer for SPR.

Fig. 6 (a) Shows the intensity of the electric field distribution near the fiber core without a metallic layer and (b) with a metallic layer, in this case of a 65-nm-thickness (or below 65nm can be possible) gold layer . The wavelength operation of light was taken 740-830 nm.

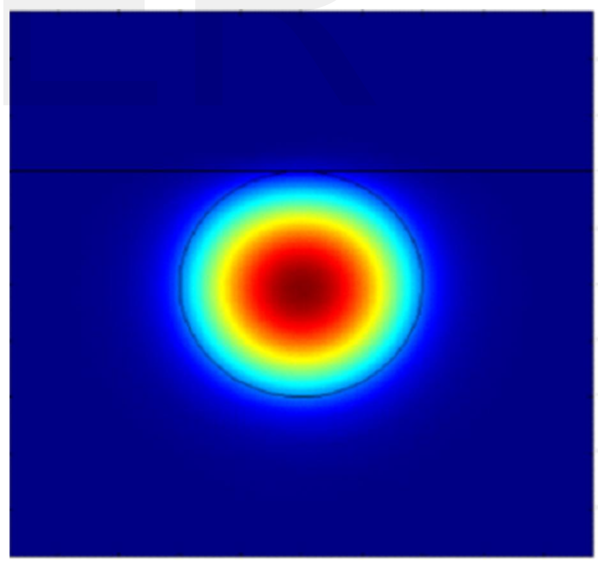
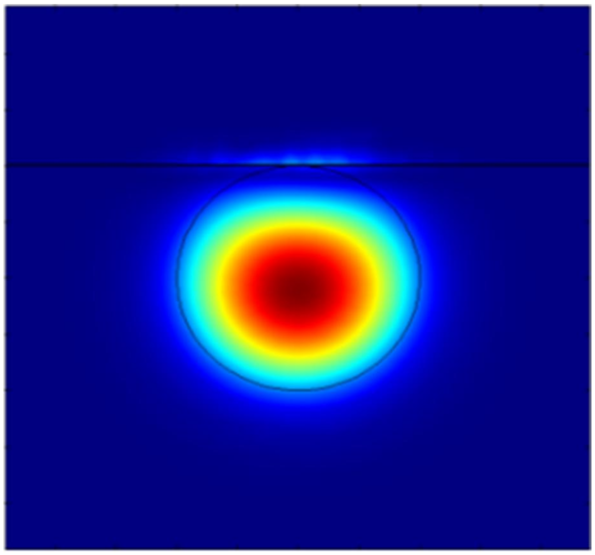


Fig. 6 Electric field distribution 2D near the fiber core
(a) without the metal

The sensitivity of sensors can be determined that changes in the transmitted power as a function of refractive index for a given wavelength or the shift in the resonance wavelength per unit change in refractive index. [10]



(b) with the metal (Au) on nm scale.

The study allowed confirming the single-mode behaviour propagation in the optical fiber. Based on the simulation results provided by the COMSOL Multiphysics, one can compute the effective refractive index n_{eff} of the sensor. The transmittance (T) through the fiber as a function of wavelength λ can be found out.

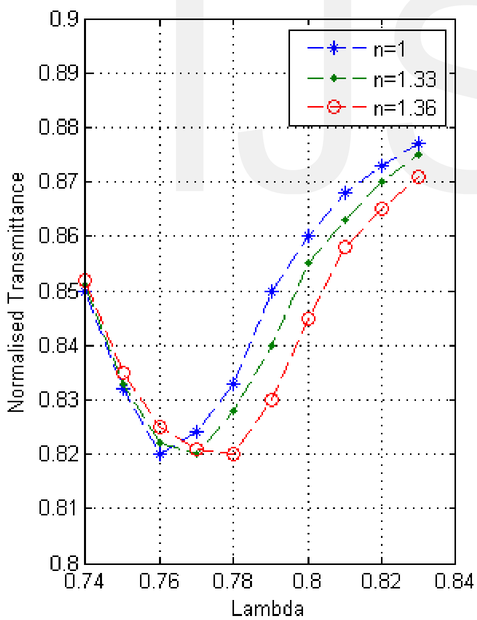


Fig.7 Simulation of normalized transmittance as a function of wavelength (lambda) for different refractive index.

6. Conclusion

D-type optical fiber properties and it application in sensing have been studied in this work. The fiber design was simulated using finite element method based solver. D-type optical fibers give flexibility for greater interaction with surrounding environment. This results in the shift in the transmission characteristics of the fiber. Through numerical simulations and obtained the sensitivity of D-type optical fiber sensor 0.303×10^2 to 0.556×10^2 (nm/RIU).

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