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Fiber Optic Refractometers: A Brief Qualitative Review

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Abstract—*Refractometers are optical instruments used for measuring refractive index of different transparent and semi-transparent materials in solids and liquid states. Working principles of traditional refractometers are based on measurement of optical critical angle, Brewster angle, angular deviation of light beam etc. In the last two decades, rapid advances in fiber optic sensing technology led to development of fiber optic refractometers. These sensors possess many advantages as compared to traditional refractometers. In this paper, we present a brief review on some of the fiber optic refractrometers reported in recent times. This review paper will provide clear and precise ideas to the readers about the working principles, design processes and characteristic features of different fiber optic refractrometers reported till date.*

1. INTRODUCTION

Refractrometer is an optical instrument used for measuring refractive index (RI) of transparent and semi-transparent materials in solid and liquid states. RI of a material medium is obtained by finding the ratio of the velocity of light in vacuum to velocity of light in the medium. RI of a medium determines how fast light can travel in the medium. Measurement of RI is generally done in beverage industries and pharmaceutical plants to determine concentration of desired substances in liquid samples. In optical industries, RI measurement is done to determine optical properties of optical devices like thin films, mirrors, lens, prisms, glass and plastic sheets etc. Working principles of traditional refractometers are based on measurement of optical critical angle, brewster angle, angular deviation of light beam etc., as in [1]-[4]. In the last decade, rapid advances in fiber optic sensing technology led to development of fiber optic refractometers. These sensors possess many advantages as compared to traditional sensors [4]-[5]. In this paper, we present a brief review on some of the fiber optic refractrometers reported in recent times. This review paper will provide clear and precise ideas to the readers about the basic working principles, design processes and characteristic features of different fiber optic refractrometers reported till date.

2. BASICS OF FIBER OPTIC SENSORS

An optical fiber is a dielectric optical waveguide, which allows propagation of light beam through it by virtue of total internal reflection [5]. Fig.1 shows typical structure of an optical fiber and its light propagation principle, whereas Fig.2 shows simplified schematic of typical fiber optic sensor.

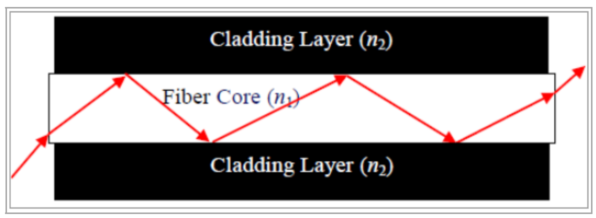

Fig. 1: Simplified diagram showing light propagation through optical fiber (cladding region has lesser RI as compared to core region, i.e. $n_2 < n_1$).

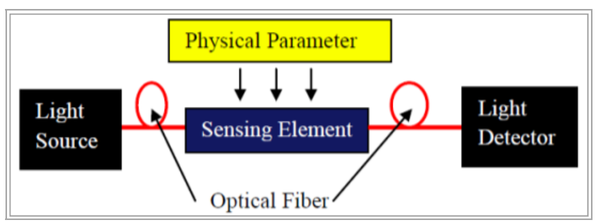

Fig. 2: Simplified schematic for a typical fiber optic sensor.

Fiber optic sensors are broadly classified into intrinsic and extrinsic sensors. In intrinsic sensor, light modulation takes place inside the fiber itself, which means that the sensing element itself is an optical fiber. In case of extrinsic fiber-optic sensor, the sensing element is not an optical fiber, but some other material media which can modulate light wave [5]-[6]. Sensing principle of fiber optic sensor may be based on modulation of intensity, wavelength, phase and polarization of light wave [5]-[6]. Intensity modulation based fiber-optic sensors have simple design and low cost, but it gives least sensitivity as compared to other modulation schemes.

3. FIBER OPTIC REFRACTOMETER SENSORS

Chetia *et. al* reported an extrinsic fiber optic refractometer based on longitudinal misalignment of multimode optical fiber [7],. In this sensor, two multimode fibers are inserted through a hollow glass tube and a longitudinal gap was maintained as shown in Fig.3.

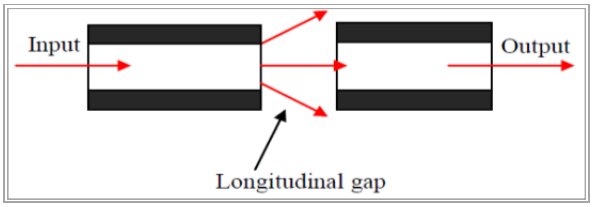

Fig. 3: Fiber optic refractometer based on longitudinal misalignment of fibers.

In this sensor, light power coupled to the receiving fiber varies with the RI of liquid sample introduced in the gap, and it is governed by (1), as in [7].

$$\eta = \left(1 - \frac{4(NA)z}{3\pi a n_L}\right) \quad (1)$$

Where, η is normalized light coupling efficiency; NA is numerical aperture of the fibers; z is longitudinal gap; a is radius of fiber core; n_L is RI of liquid.

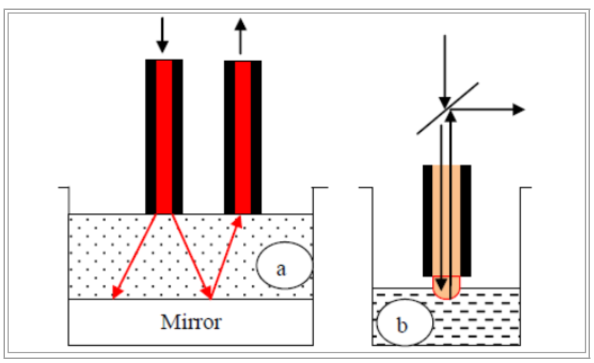

Fig. 4: Fiber optic refractometer based on detection of back reflected light.

In [8]-[10], fiber optic refractometers that measures RI based on Fresnel reflection of light are reported. In this sensor, one fiber directs light beam onto a reflecting mirror over which a liquid medium exists, while another fiber collects light reflection from the mirror, as shown in Fig.4(a). The intensity of collected light beam varies with RI of liquid and it is governed by proportionality relation (2).

$$\eta \propto R_m \cdot T_i(n_L) \cdot T_O(r, h, n_L) \quad (2)$$

Where, η is light coupling efficiency; R_m is mirror reflectivity; $T_i(n_L)$ is Fresnel transmittance of input fiber; $T_O(r,h,n_L)$ is Fresnel transmittance of output fiber; r is the distance measured along the receiving fiber from transmitting fiber; h is the distance between fiber tips and mirror. In [11], Nath *et.al* used frustrated TIR phenomenon to measure RI change of liquid medium with the help of hemispherical fiber tip, as shown in Fig.4 (b). Due to TIR, a part of the forward propagating modes is reflected back from fiber tip-liquid interface. Depending on the RI of the liquid sample, the intensity of the back-reflected light varies with the RI of the liquid.

Optical evanescent wave is a standing electromagnetic wave that exists at core - cladding interface of a fiber. This wave penetrates inside the cladding and its amplitude decays exponentially in the cladding region. Evanescent wave based fiber optic refractometers were also reported by many researchers and they are more sensitive than the sensing methods reported in [7]-[11]. In these sensors, optical power lost due to interaction of evanescent wave and liquid at fiber - liquid interface is governed by Fresnel reflection provided that light absorption co-efficient of the liquid medium is very small. Banerjee *et. al* measured RI of the liquid by allowing liquid to interact with evanescent wave of a partially decladded region of an optical fiber [12]. Highly sensitive fiber optic refractometers designed with tapered optical fiber were also reported in [13]-[15]. These sensors also used evanescent wave absorption principle. Fig.5 shows a simplified view of tapered optical fiber. In tapered fiber optic sensor, liquid sample is introduced at the tapered region to obtain enhanced sensitivity.

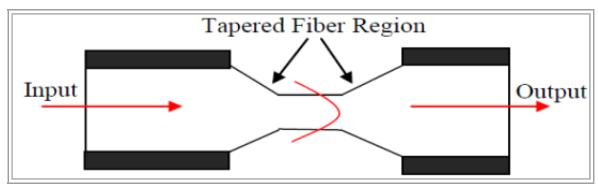

Fig. 5: Tapered fiber optic sensor for RI measurement.

Fig.6 shows schematic of U-shaped bent sensor used in RI measurement. Such sensors were reported in [16]-[18].

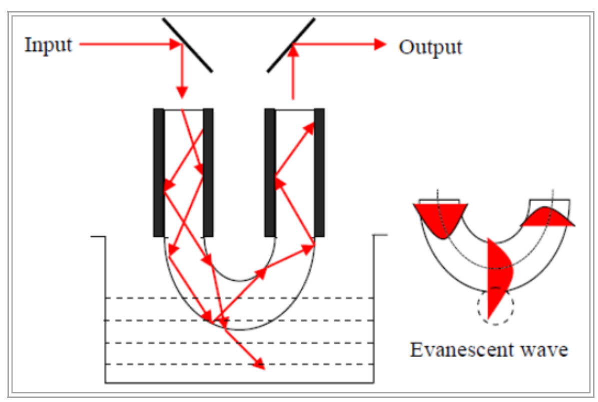

Fig. 6: Simplified schematic of U-shaped bent fiber refractometer.

In U-shaped region of the bent fiber, evanescent wave penetrates beyond the thickness of fiber cladding. Penetration depth of evanescent wave becomes more pronounced in outer side of a U-shaped bent fiber depending on bending radius and wavelength of light. When the bent region is dipped in liquid medium, evanescent wave strongly interacts with liquid medium. Hence, enhanced sensitivity is obtained.

Fiber Bragg grating (FBG) is obtained by inducing periodic variation of RI inside the optical fiber with the help of intense laser beam exposure. FBG sensors exploits Bragg's reflection phenomenon [19]-[21]. The grating acts as wavelength selective filter satisfying Bragg's resonance wavelength λ_B given by (3), as in [19].

$$\lambda_B = 2\Lambda n_{eff} \quad (3)$$

Where, n_{eff} is effective RI of grating region; Λ is grating period. When cladding layer is removed from the grating region, evanescent wave can interacts with liquid medium that comes into contact with grating region. This results in shifting of λ_B w.r.t. RI of the liquid. Fig.7 shows a simplified schematic of FBG sensor, which reflects green color light waves from the grating region. In FBG refractometer, the wavelength of reflected light undergoes shift with RI. Spectra of the transmitted wave are usually observed in optical spectrum analyzer (OSA).

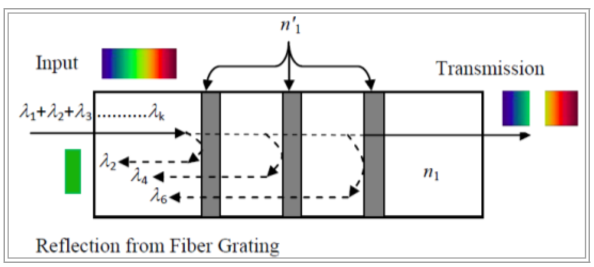

Fig. 7: Simplified schematic of fiber Bragg refractometer sensor.

Surface Plasmon is a quantum of plasma oscillation that occurs at metal-dielectric interface [22]. Excitation of surface Plasmon by photons involves transfer of energy from photon to the Plasmon. During resonance condition, maximum energy is transferred to Plasmon and energy of reflected light decreases to a minimum level. The angle of incidence of light under this condition is known as resonance angle. This resonance angle varies with RI of dielectric material that comes into contact with metal layer. Fiber optic SPR refractometers are designed by depositing or coating ultrathin layer of silver or gold film on the surface of optical fiber, as in [22]-[24]. Photonic crystals have periodicity in RI change along one or more dimensions, and they exhibit photonic band gap effect to propagation of light through them. Photonic crystal fiber refractometers designed with such fiber were also reported and details of these sensors can be found in [25]-[27].

4. CONCLUSION

A brief qualitative review of fiber optic refractometers has been presented in this paper. Although review papers have already existed in this field of research, the present paper is expected to act as useful source of information for students and young researchers in the field of fiber optic sensors. Among the fiber optic refractometers reported till date, FBG, SPR and Photonic crystal based refractometers have best resolution of measurement, ranging from $10^{-5} – 10^{-8}$ RI units, which is far better than that of intensity modulated fiber optic refractometers (10^{-4} - 10^{-5}). However, intensity modulated sensors have the novelty of being the cheapest and simplest of all. There is a need for doing further research on developing appropriate signal processing electronics for FBG and SPR sensors. OSA is currently used for characterization and testing of these sensors. Using OSA makes SPR and FBG sensors unsuitable for use in commercial applications, because OSA is very sophisticated and very costly equipment. This is one of the unaddressed problems of research works in FBG and SPR sensors. Over and above, Photonic crystal based sensors are also very expensive due to complexity and sophistication involved in fabrication of the sensor.

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