Sensitivity Enhancement of Fiber Optic Diesel Adulteration Detection Sensor Using Stripped Clad S-Bend Section

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ABSTRACT- **A novel geometry for enhancing the sensitivity of intensity modulated refractometric fiber optic sensor for detection of adulteration level in diesel by kerosene is proposed. In this multimode plastic optical fiber is uncladded for specific length and bent into S shape. This geometry is simulated and analyzed using Beam Propagation Method in Beam prop RSOFT software. When sensor is immersed in the diesel then diesel acts as a cladding for uncladded S shape portion of optical fiber. As diesel is adulterated by different volumes of kerosene, refractive index of cladding changes which in turn affects the output intensity of the sensor. The investigation revealed that when such structure of sensor is used to detect the adulteration level in diesel then sensitivity gets improved 4 times for two fold increase in bend curvature of fiber. Thus it is highly sensitive mechanism to determine on line adulteration of diesel and also can be used for other applications.**

KEYWORDS: Fiber optic sensors, Diesel adulteration level detector, S-bend fiber optic sensor, Sensitivity improvement, enhancing performance parameters, Stripped clad fiber.

I. INTRODUCTION

Adulteration of diesel with kerosene is common malpractice since kerosene is cheaper than diesel. Such adulteration results in increased pollution, reduced lifetime of components, decrease in engine or machine performance etc. There are number of techniques used to detect adulteration like use of markers, gas chromatography etc. Fiber optic sensors are widely used for detecting refractive index of liquids [1] because of its inherent advantages like low cost, small size, immunity EMI and RFI etc. Sukhdev Roy proposes a method for detecting adulteration of fuel which is based on the modulation of intensity of light guided in the fiber due to change in the refractive index of the cladding formed by adulterated fuel and the phenomenon of evanescent wave absorption [2]. Noteworthy feature of this sensor is sensitivity of the sensor can be improved by varying the length of unclad part however it is not practical solution. Yadav *et al.* [3] demonstrated that diesel adulteration by kerosene can be estimated by kinematic viscosity and opacity value which are good test parameters. Calibrated hydrometers, thermometers and viscometers are used to measure these parameters. Shukla *et al.* [4] proposed a method for detection of adulteration in liquid samples using two prisms. It is observed that all these methods are only different techniques of determining adulteration in liquid. Roy *et al.* [2] mentioned that sensitivity of the sensor can be improved by bending the fiber.

High sensitivity and high accuracy are prime important factors for good sensor performance. Harmer [5] has reported a refractometer for detecting presence or absence of fluid as well as determining some characteristic of liquid related to change in refractive index. Sensing portion is arranged in complex curvature geometry to achieve excellent sensitivity. Chandy *et al.* [6] developed on line sensor for bio film measurement using unclad multimode plastic fiber and measured refractive index changes as small as 0.07%. Mitsushio *et al.* [7] constructed gold deposited optical fiber sensor system using surface Plasmon Resonance (SPR) in a gold film around an unclad core for measuring refractive index of alcohol. Very small changes of the order of 0.0001 in the refractive index can be measured. Villatoro *et al.* [8] reported refractive index sensor having single mode fiber (SMF) inserted in multimode fiber (MMF). Resolution of the order 7×10^{-5} can be achieved by this. Fabrication of this type of sensor requires cleaving and fusing splicing. Banerjee *et al.* [9] reported that sensitivity of refractive index sensor is function of cladding thickness and the length of uncladded PCF fiber. Resolution of the order of precision up to fifth place of decimal can be achieved by adjusting cladding thickness and length of fiber. Valencia *et al.* [10] proposed a self referencing method for determining refractive index using intrinsic optical waveguide sensors where certain part of core is uncladded. In this sensitivity is improved by suitable adjustment of transmission angular ratio (TAR) and length to diameter ratio (LDR) of optical waveguide. MMF-SMF-MMF sensor is further investigated by Singh *et al.* [11] for achieving enhanced sensitivity by bending SMF at different curvatures. Cortes *et al.* [12] proposed highly sensitive mechanism in which twin hole fiber is used to measure refractive index of liquids using Beam prop in RSOFT. Single mode fiber in which birefringence is induced by enlarging the hole diameter. This paper reports refractometric intensity modulated multimode plastic fiber optic sensor geometry for detecting adulteration level of diesel and enhancing the sensitivity by inducing S bend curvature in unclad portion. This sensor is simulated and analyzed for sensitivity enhancement using commercially available software Beam prop in RSOFT [14].

II. THEORY

In conventional optical fibers light is guided in core region because it is surrounded by cladding and jacket material. Total internal reflection occurs at the interface of core and cladding as core refractive index is greater than that of cladding. In refractometric fiber optic sensor, there must be some interaction with guiding material of fiber and liquid whose refractive index is to be sensed. Generally cladding is removed from the small part of optical fiber so that core is exposed to surrounding material. When the light is launched through such unclad multimode plastic optical fiber, all the rays incident on interface at an angle greater than the critical angle undergo total internal reflection and are guided. The critical angle Φ_C is given by

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} \qquad (1)$$

where n_1 is the refractive index of core and n_2 is the refractive index surrounding material in this case. Thus when the refractive index of surrounding material is greater than that of core, critical angle will exceed and the rays will be lost in the surrounding due to refraction. As a result, transmitted power is function of the refractive index of surrounding material. For surrounding material with refractive index less than core light is properly guided due to total internal reflection.

Bending of optical fiber changes the angle of incidence of ray of light across the core cladding interface. Therefore, some rays will be incident at the core-surrounding material interface with an angle less than critical angle and refracted in the surrounding media. This results in reduced intensity at the output of the sensor. If the fiber is bent in S shape then it gets bent at two locations with same bending radius. Thus more rays are refracted out of fiber. These results in more decrease in output light intensity compared to single bend fiber. The bending radius of fiber for the sensor should be greater than the minimum bending radius of fiber provided by manufacturer. This implies that change in the output intensity is not due to loss but due to change in the refractive index of the material around the unclad core.

Rate of decrease in the light intensity at the output of the sensor is more in case of S bend type fiber optic sensor compared to single bend type fiber optic sensor. Thus it can be concluded that if one keeps the bend radius within the limit of minimum bending radius of fiber then by bending the fiber in S shape increases the sensitivity of the fiber optic sensor having unclad core.

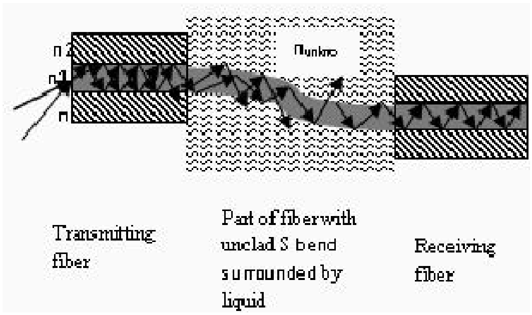


Fig. 1 Basic principle of S bend fiber sensor

Figure 1 illustrates basic structure of refractive index sensor with unclad S bend portion of fiber optic sensor. The sensitivity improvement can be better explained if it is interpreted in terms of mode profile. As the curvature increases mode profile shifts away from the fiber axis causing enhanced sensitivity. This is because modes near the core-surrounding material interface get affected more with the bent as well as with refractive index of surrounding material. The effective refractive index of bent fiber is a function of curvature because of photo elastic effect:

$$n(R) = \left[n(0,\lambda) + \frac{dn}{d\varepsilon}\varepsilon \right] \exp\left(\frac{r}{R}\right) \tag{2}$$

where $n(0,\lambda)$ is effective refractive index at λ for unbent fiber, r the radial distance from the centre of the fiber to the point where effective refractive index is $n(R)$, R is radius of curvature experienced by the fiber and ε is strain due to curvature. This equation indicates that effective index profile is non-uniform throughout the unclad region. Thus the maximum sensitivity range for bend sensor is larger than unbent sensor.

For multimode fiber the transmission losses can be analyzed by applying ray theory. The general principle of waveguide refractive index sensor is based on the Fresnel's reflection and transmission coefficients at the interface between two media. Fresnel coefficient is given by:

$$R_s = \left[\frac{n_1 \cos\theta_i - n_2 \cos\theta_t}{n_1 \cos\theta_i + n_2 \cos\theta_t} \right]^2 = \left[\frac{n_1 \cos\theta_i - n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2}}{n_1 \cos\theta_i + n_2 \sqrt{1 - \left(\frac{n_1}{n_2} \sin\theta_i \right)^2}} \right]^2 \tag{3}$$

where n_1 and n_2 are refractive indices of two media, θ_i is angle of incidence at the interface of two media; θ_t is angle of transmission from one media to another. To obtain the net power transmission of the incidence ray in the sensing region, we have to find the number of reflections at the core-external medium interface. The number of bouncing 'm' of the ray at the interface within the distance L is [15]:

$$m = \frac{L}{d \tan\varphi} \tag{4}$$

where d is the core diameter and φ is the angle that the incident ray makes with the normal at the core cladding interface.

If I_0 is the power launched into the fiber, then the output power after propagation through the sensing region is given by

$$I = I_0 R^m \tag{5}$$

where $R=|r^2|$ and r is Fresnel's coefficient of reflection. Here r is considered as the reflection coefficient for an arbitrary polarization. From the Fresnel's reflection, the general behavior of the sensor can be explained as follows. Liquids having refractive indices much lower than that of core yields the same maximum output power since all the rays undergo total internal reflection. As the refractive index of the liquid approaches the core refractive index, the output power decreases sharply. For refractive indices larger than the core the output intensity shows only slow increase. The effect of variation in the launch angle and fiber geometry is studied theoretically. From the equation (5) we can say that the sensor response to change in refractive index i.e. sensitivity depends on the reflection coefficient at core cladding interface and the number of reflections in the sensing region. These two parameters depend on φ- angle which the ray incident on core cladding interface makes with the normal. In the case of a straight fiber, the incident angle of the guided ray launched into the fiber remains the same in the sensing region. Hence m is fixed and r is also fixed for fixed value of refractive index of cladding. In case of bent fiber as the ray enters the bent region, the angle that the ray makes with the normal to the core-cladding interface at the outer surface of the bent region decreases. Considering only meridional rays the angle φ for the bent region is given by [14]:

$$\varphi^{'} = \sin^{-1}(K \sin\varphi) \tag{6}$$

where $K = \dfrac{(BR+h)}{(BR+d)}$, and BR is bending radius, d is diameter of the core, h is distance at which the ray is incident on the entrance of the bent section of the fiber from the core cladding boundary. The sensitivity of the device for a particular cladding refractive index depends on the value of K and φ. A decrease in the value of K and φ increases the power loss through the sensing region. The value of K can be lowered by decreasing the bending radius BR. Lowering the K value causes decrease in the value of φ'. This increases the value of m i.e. reflections at the core cladding boundary but decreases the value of 'r' i.e. decrease in R. From the equation (5) we can conclude that the total output power propagated through the sensing region decreases. This rate of decrease in the output intensity with respect to refractive index of cladding increases with increase in the value of BR. Bending radius is also expressed as bending curvature given by:

$$\text{Bending curvature} = \frac{1}{BR} \tag{7}$$

Differentiating equation (5) with respect to n_2 gives:

$$\frac{dI}{dn_2} = \frac{2I_0 L}{d\tan\left(\sin^{-1}\left(\left(\dfrac{BR-h}{BR-d}\right)\sin\varphi\right)\right)} \times \frac{d}{dn_2}\left[\frac{n_1\cos\theta_i - n_2\cos\theta_t}{n_1\cos\theta_i + n_2\cos\theta_t}\right] \tag{8}$$

From the equation one can conclude that the sensitivity improves with increase in bending curvature.

III. MODELING FIBER OPTIC SENSOR WITH UNCLADDED S-SHAPED PORTION

For multimode fibers, the fundamental mode of the straight portion couples into the fundamental bending mode as well as higher order bending modes which are nonexistent for single mode fiber. These modes radiate more power than fundamental bending mode due to the fact that the field intensity of the higher order modes is larger at the waveguide boundaries than the fundamental mode. This phenomenon is modeled using Beam Propagation Method (BPM). This method or propagation technique is widely used to model integrated and fiber optic photonic devices. RSOFT developed a software package using BPM to simulate the propagation of light waves through arbitrary waveguides.

A. *BPM Simulation*

The BPM is used to estimate improvement in the sensitivity of fiber optic refractive index sensor with unclad portion bend in S shape. The RSOFT Beam prop package used beam propagation method to solve the wave equations along the direction of propagation and monitor the power of fundamental model along the direction of propagation. Beam prop package has the option called the Pade based model to simulate fiber with bending angle greater than 15^{o}. Beam prop allows the user to launch the fundamental mode into the three dimensional (3-D) waveguide or fiber and monitor the power of the mode along the waveguide or fiber. Simulations are carried out for different values of cladding refractive index. For each value of this refractive index different values of bending curvature or bending radii are considered and overlap integrals are computed to monitor the transmitted power through waveguide. The structure of fiber optic refractive index sensor with uncladded S bend is illustrated in Figure 2.

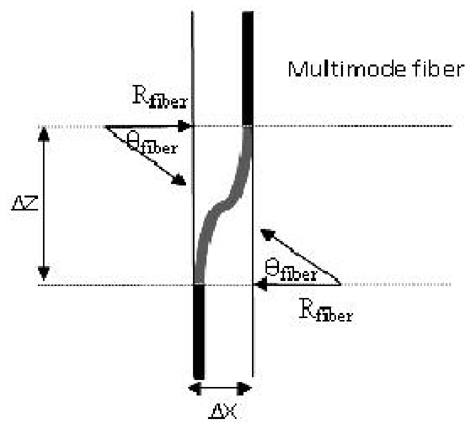


Fig. 2 Structure of the fiber bend.

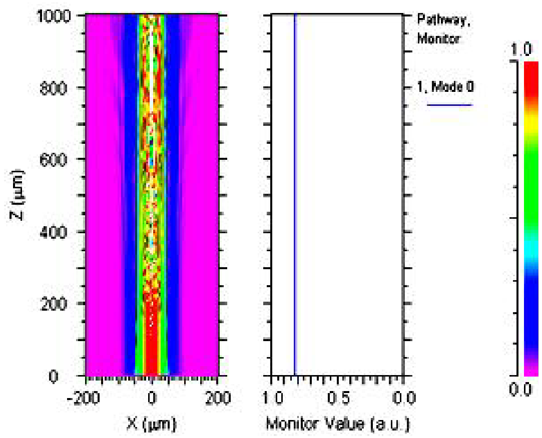
The structure consists of two straight sections connected by S bend structure. This S bend structure is composed of two arcs of equal radii (R_{fiber}) and angles (θ_{fiber}). Bend length (ΔZ) is approximately kept constant to 20mm. As the bend radius R_{fiber} is increased in steps, the bend angle θ_{fiber} is adjusted to keep bend length constant. The Figure 2 is drawn in XZ plane. The direction of propagation is Z axis. ΔX represents lateral separation between the two straight segments of optical fiber.

IV. SIMULATION RESULTS

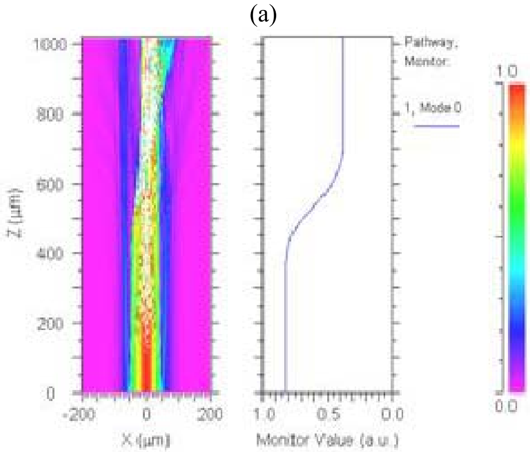
Fiber optic refractive index sensor with unclad S bend having circular cross section is simulated using Beam prop RSOFT software. After laying down the device in the Beam prop, the propagation of light through straight fiber is studied by varying the refractive index of background i.e. cladding from 1.46 to 1.44 which refers to diesel and kerosene respectively. This means diesel is adulterated by kerosene for 0% adulteration level (i.e. pure diesel) to 100% adulteration (i.e. pure kerosene) [12]. This is incorporated by using beam propagation method for fixed core refractive index=1.492 at the wavelength 673nm and core radius=100µm. Cladding refractive index is changed in steps of 0.005 to simulate different adulteration levels from pure diesel (1.46) to pure kerosene (1.44). Figure 3(a) shows how light intensity modulation takes place as light propagates through straight fiber with unclad portion. When this unclad portion of fiber is bent in S shape Figure 3(b) shows how light propagates through such structure. Decrease in the output light intensity is observed because of S bend structure. Similar S bend structures of optical fiber having different bending radii are simulated using the RSOFT. Figure 4 shows that as bending radius increases then the rate of change of output intensity increases with increase in refractive index of surrounding media i.e. adulterated diesel. Remember that bending of the fiber should not exceed the minimum bending radius given by the manufacturer.

It is observed that as bending radii R_{fiber} increases the output intensity decreases compared to straight fiber. For a fixed value of R_{fiber} if refractive index of background or cladding is varied then output intensity decreases. This rate of decrease is more if the bending radius is increased.

Bend curvature is another terminology used to represent bending radius. Figure 5 shows improvement in the sensitivity of the sensor with increase in the bending curvature. Sensitivity is calculated from the graphs plotted for different values of refractive index i.e. from 1.44 to 1.46 in steps of 0.01 around the S bend section of fiber. Output intensity decreases with increase in the value of refractive index. This rate of change of output intensity with respect to refractive index of the outer medium is calculated i.e. slope of the graph is calculated. This procedure is repeated for each value of bending radius R in order to calculate the sensitivity of the sensor. Figure 6 shows comparison of simulated and experimental data [13] for diesel adulteration. Simulated results for straight fiber show good agreement with the experimental results. From the literature review, it is concluded that single mode optical fibers are used to detect the change in the refractive index of the solution under consideration. Special arrangements such as MMF-SMF-MMF are used to improve the sensor performance [8]. Clad stripped fiber optic sensors are used to detect the change in the refractive index and resolution of the order of 0.0001 can be achieved. Gold particles are also deposited on the stripped part in order improve the resolution of the sensor [7]. In all the techniques described above, special arrangements and equipments are required. While in case of bending of the fiber no such instruments are required. S bend section definitely improves the sensitivity.



(a)



(b)

Fig. 3 Contour map using beam propagation method for (a) straight fiber and (b) bent fiber structure at bend radius of R_{fiber}= 2000 µm for background index=1.44 and length ΔZ=20 µm.

Refractometeric fiber optic sensor with geometry to enhance the sensitivity of the sensor is proposed and simulated using the commercially available software RSOFT. The sensor is based on the loss of intensity due to bending as well as due to uncladded part of the multimode fiber. This is useful in detecting percentage adulteration in diesel by kerosene.

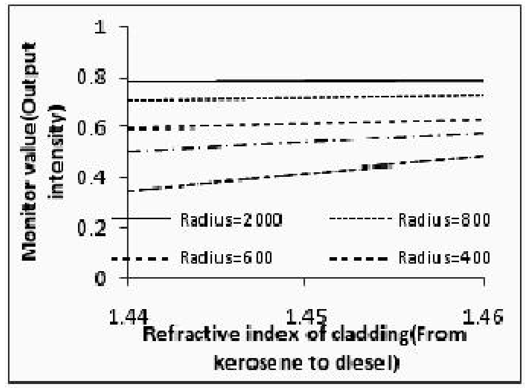


Fig. 4 Output intensity variations with refractive index (from diesel to kerosene).

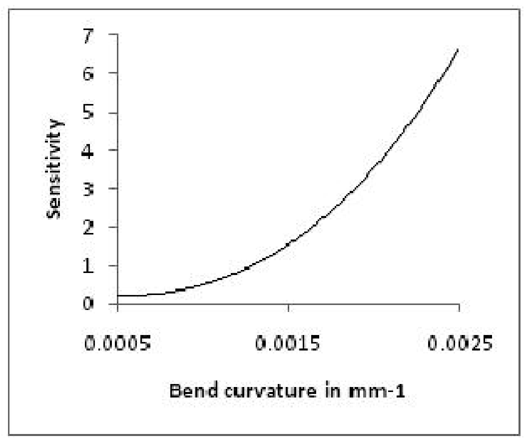


Fig. 5 Improvement in sensitivity with bending curvature

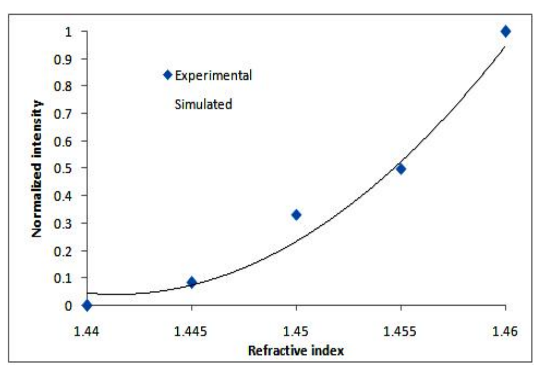


Fig. 6 Comparison of simulated and experimental data for straight optical fiber.

It is shown that refractive index of n=1.46 (diesel) to kerosene n=1.44 variation results in significant variation in output intensity of sensor. Bending of the unclad portion of the optical fiber in S shape at different bend radii causes sensitivity improvement.

Table 1 gives clear idea of improvement in the sensitivity compared to straight fiber.

Table 1: Comparative analysis of methods used to improve the sensitivity of the refract metric sensor

Sr. No.	Fiber sensor geometry	Factor of improvement in Sensitivity compared to straight fiber
1	U shape	4
2	MMF-SMF-MMF with bend	15
5	S bend geometry	20

V. Conclusion

It is observed that if bend radii is increase two times then sensitivity of the sensor get improved by the factor of 4. Thus this process provides effective and highly sensitive mechanism for detecting the refractive index of liquids and can also be used for many other applications.

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