

Analytical Exploration of Highly Sensitive Fiber Optic Bilirubin Detection using Gaussian Beam: A Wave Theory Based Approach

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Abstract: In the present study, a new approach towards the evanescent wave-based fiber optic biosensor using Gaussian beam is investigated for the detection of Bilirubin. The sensor structure consists of an unclad multimode fiber of 50 μm and followed by 90 μm of Bilirubin layer. Here Bilirubin is used as a sensing layer and a method based on wave theory is used to analyze the high-order modes in the optical fiber and to achieve the theranostics application in hyperbilirubinemia. The proposed biosensor intends to improve in the existing fiber optic based sensors in terms of sensitivity and resolution for the detection of Bilirubin. The proposed idea will result in a better screening platform to identify the hyperbilirubinemia by optically assessing the earlier stage of the hyperbilirubinemia.

Keywords: Fiber optic Sensor, Wave Theory Based Approach, Evanescent wave, Ray Theory, Hyperbilirubinemia.

1. Introduction

Bilirubin is a one kind of metabolic ravage that is expel through bile and urine. Accumulation of Bilirubin is very much common in neonates, causing neonatal jaundice. During the first week of life, around half of the all neonates are affected by jaundice, but for some disease conditions in liver and biliary tract, Bilirubin starts to accumulate in tissues and blood, leading to jaundice^{1,2}. The levels of Bilirubin in the human blood in normal and Jaundice conditions are 20 $\mu\text{M/l}$ and greater than 50 $\mu\text{M/l}$. For neonates the level of Bilirubin for jaundice is 0.05 g/l. If jaundice is severe, irreversible brain damage will occur due to the accumulation of Bilirubin in the brain. So far, phototherapy is the most effective way to treat neonatal jaundice. The neonates are placed under blue light in phototherapeutic processes, as

bilirubin absorbs light in the blue optical range^{3,4}. In traditional phototherapy, it is recommended to monitor the patient's bilirubin level by blood tests from time to time to determine the required dose and future course of action. In this context, a noninvasive/ minimally invasive procedure for the phototherapy can be very helpful⁵⁻⁷. Several methods for analysing bilirubin in clinical specimens have been developed. The diazo reaction, is one of the most commonly used methods for bilirubin analysis. In this process, bilirubin reacts with diazotized sulfanilic acid or direct spectrophotometry, which measures bilirubin absorption at 440 nm. However, the accuracy of determining Bilirubin using the diazo reaction is compromised because the reaction rate is pH dependent. Other methods for analysing bilirubin include the Vanadate oxidase method, chromatographic methods, electrochemical methods, and spectroscopic methods. All of these methods require a reference signal, and there is always electrical and chemical interferences^{2,8}. In order to make up for these shortcomings, a special type of optical fiber biosensor is designed to monitor Bilirubin, so as to quickly and label-free detection of Bilirubin with the smallest size, simplicity and mixed diversity, so as to achieve early diagnosis of hyperbilirubinemia. As a result, it demonstrates extraordinary competence in terms of practical application in the structure. Evanescent wave based sensors are now commonly employed to improve the sensitivity of fiber optic bio-sensors, and such sensors can be used for illness sensing, diagnosis, and detection in biomedical science for advanced treatments. Many improvements in the optical response of fiber optic sensors have been accomplished so far through physical modifications to the geometry of the sensing structures, such as tapering, D-shaped fiber, coiled structure, side-polished fiber, and so on⁹⁻¹². The generation of higher-order modes resulting in more evanescent waves by modifying the geometric features of the sensor probe is the principle for improving the sensitivity of such devices. Various types of fiber optic sensors are currently available on the market, all of which are based on the ray theory. However, wave theory, rather than ray theory, is more practical and useful for analyzing higher-order modes within the fiber. The wave theory-based approach can also be used to achieve similarities between analytical and experimental answers. The detection of Bilirubin by illuminating Gaussian beam is proposed in this study using a very sensitive wave theory-based two layered fiber optic sensor.

2. Proposed scheme

The schematic diagram of the proposed two layer fiber-optic sensor for detection of Bilirubin is shown in Figure1. The proposed scheme comprises a multimode fiber with a radius 50 μm and 90 μm of Bilirubin layer. Here

Bilirubin acting as a sensing layer. First, a specific length of the cladding at its central part is removed by utilizing the appropriate etching technique. Then this decladded area is deposited in the Bilirubin solution which acts as the absorbing media and as a result evanescent wave absorption will occur. At first broadband laser source from a Stabilized single mode diode Laser source which has the spectra similar to a Gaussian profile is propagated through the multimode fiber. The Bilirubin solution absorbs the light at the wavelength being transmitted through the fiber and this absorbance depends on the concentration of Bilirubin solution. Therefore, the total transmitted power at the output end of the fiber varies with the concentration of Bilirubin. This variation in output power is collected using a suitable optical power meter that can be calibrated with reference to the surrounding concentration levels of Bilirubin. Figure 2 shows, the absorption co-efficient (μ_a) of Bilirubin for different wavelength. The input applied to the MMF is Gaussian beam which has no azimuthal components.

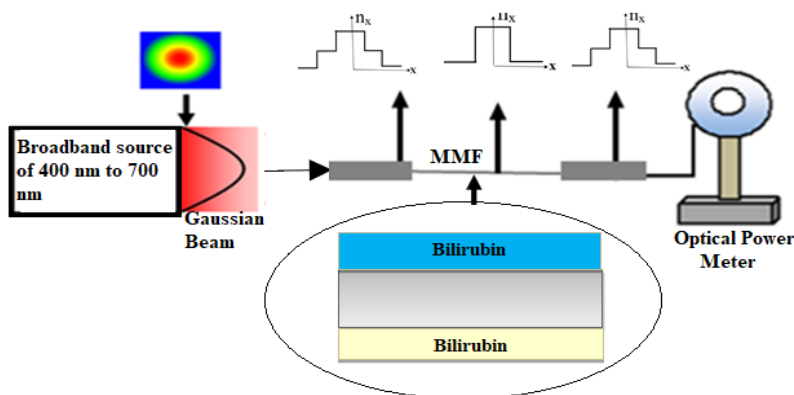


Figure1: Schematic diagram of fiber optic biosensor for the detection of Bilirubin using Gaussian Beam

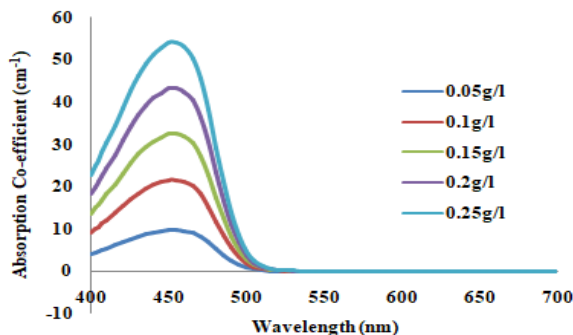


Figure 2:- Absorption co-efficient of Bilirubin for different wavelengths.

So the modal distribution inside the MMF has just radial parts and the overall integral for each mode is given by^{9,13}

$$(1) \quad \eta_m = \frac{\left| \int_0^\infty E_s(r) E_m(r) r dr \right|^2}{\int_0^\infty |E_s(r)|^2 r dr \int_0^\infty |E_m(r)|^2 r dr}$$

Here, E_m is radial fields for the m th ordered modes

$$(2) \quad E_m = \frac{J_0\left(\frac{u_m r}{a}\right)}{J_0(w_m)}; r \leq a$$

$$= \frac{K_0\left(\frac{u_m r}{a}\right)}{K_0(w_m)}; r > a$$

The overlap integral is solved by Webber's 2nd exponential integral and it is given by

$$(3) \quad \eta_m = \frac{\left| \int_0^\infty \exp\left(-\frac{r^2}{w^2}\right) J_0\left(\frac{u_m r}{a}\right) r dr \right|^2}{\left[\int_0^\infty \exp\left(-\frac{2r^2}{w^2}\right) r dr \int_0^\infty J_0^2\left(\frac{u_m r}{a}\right) r dr \right]}$$

$$(4) \quad \eta_m = \frac{\frac{2w^2}{a^2} \exp\left(-\frac{(u_m^2 \cdot w^2)}{2a^2}\right)}{[(J_0^2(u_m) + J_1^2(u_m)) + \left(\frac{J_0(u_m)}{K_0(w_m)}\right)^2 (K_1^2(w_m) - K_0^2(w_m))]}$$

where u_m and w_m are the normalized wave no. of core and cladding respectively.

When the cladding is replaced by an absorbing medium, the transmitted output power can be expressed as

$$(5) \quad P_L = P_0 \exp(-R_e \alpha_e cL)$$

The transmitted output power for all the propagating guided is given by

$$(6) \quad P_L = P_0 \exp(-(R_{e1} + R_{e2} + R_{e3} + \dots) \alpha_e cL)$$

This fractional power residing in the absorbing medium is a critical parameter, which has a prominent role in the sensor design and can be expressed as⁹:

$$(7) \quad R_e = \frac{P_{\text{absorbing}}}{P_{\text{total}}} = \frac{u^2}{V^2} \left[1 - \frac{K_l^2(w)}{K_{l+1}(w) K_{l-1}(w)} \right]$$

The overall transmission loss for the sensor structure is given by:

$$(8) \quad T_L = 10 \log_{10} \exp(-(R_{e1} + R_{e2} + R_{e3} + \dots) \alpha_e cL)$$

3. Result and Discussion

The transmission loss, power coupling co-efficient, and electric field distribution within the fiber core for the Gaussian beam has been represented through graphical representations for predicting the output from the fiber core. The propagation of the electric field within the multimode fiber for the Gaussian beam and a propagation length of 1 mm is shown in Figure 3 and it is obtained by using Lumerical’s Mode Solutions software. From that figure it is observed that the beam is guided inside the multimode fiber. Figure 4 shows the power coupling coefficient for a Gaussian beam at a wavelength of 450 nm with the same propagation distance, with the radial mode number 6 being the most dominant mode. More power has interacted inside the multimode fiber at this dominating mode and also has the highest effect in the modal interference inside the multimode fiber.

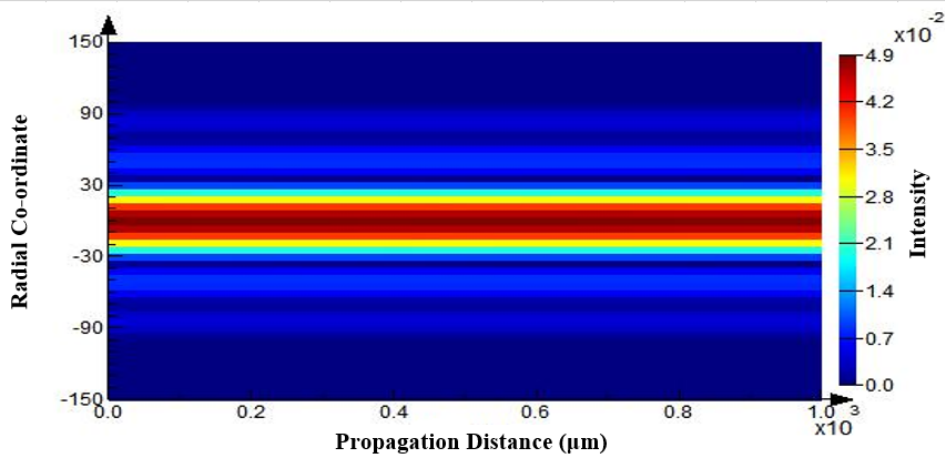


Figure 3.Guiding of Gaussian beam inside the MMF.

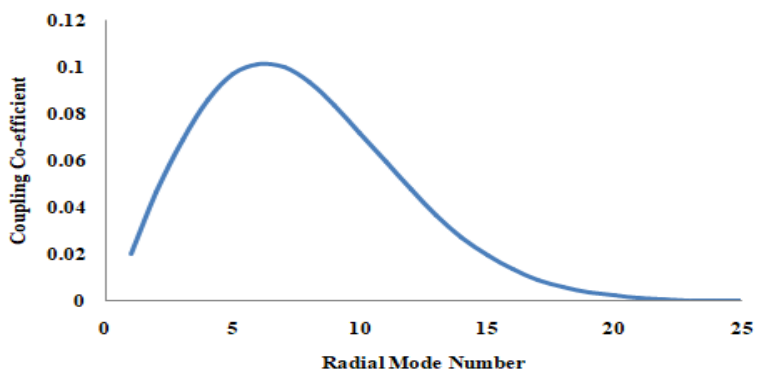


Figure 4. Power coupling co-efficient as a function of mode number for Gaussian beam

Figures 5 and 6, shows the transmission loss of the proposed structure with respect to time and wavelength inside the MMF using a Gaussian beam. With the change in time and wavelength, refractive index of the sensing layer means Bilirubin changes, as a result transmission loss of the proposed sensor changes. From Figure 6, it is observed that the transmission loss of the proposed sensor varies from -20 dB to -24 dB. The suggested sensor has a sensitivity of 304.4 dB/RIU and a resolution of 3.29×10^{-5} at a given concentration.

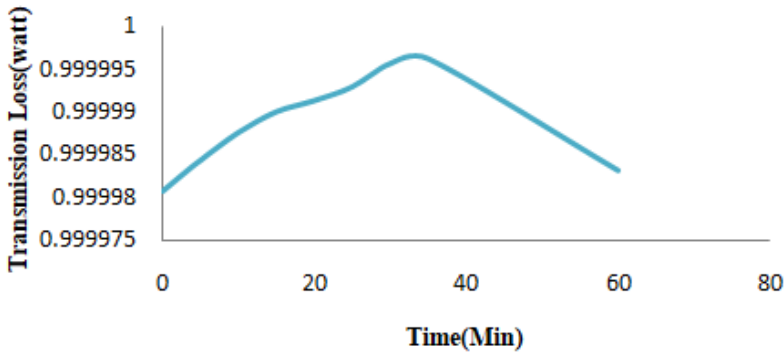


Figure 5. Transmission loss with varying time using incident Gaussian beam

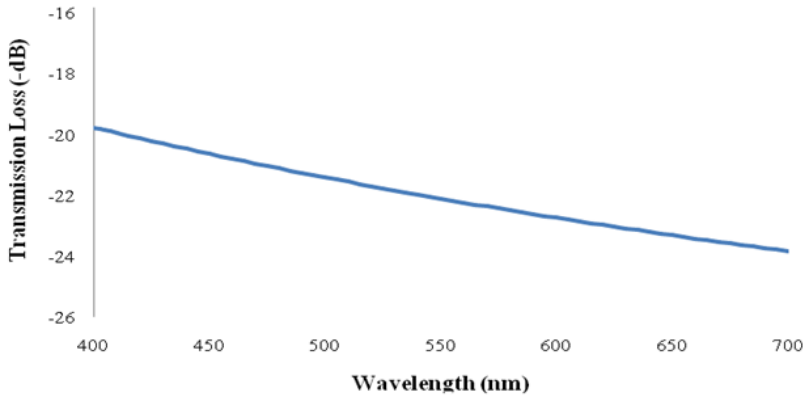


Figure 6. Transmission loss with varying wavelength for incident Gaussian beam

Conclusion

In a two-layer structure, an idea for an evanescent wave-based fiber optic biosensor is developed, designed, and simulated using wave theory. The sensor structure consists of an unclad multimode fiber of 50 μm and followed by 90 μm of Bilirubin layer. Here, Bilirubin is employed as a sensing layer, with concentrations ranging from 0.05 g/l to 0.25 g/l. To investigate the

higher-order modes within the fiber and accomplish theranostics application in hyperbilirubinemia, a wave theory-based technique is used. Here, the proposed technique is shined by a Gaussian beam and the output beam is observed with the help of power-meter head. The spread of the electrical field within the MMF for the proposed fiber sensor was also observed through graphical representations. The graphic display shows that the radial mode number 6 has the highest connective efficiency between all modes within the MMF. The proposed biosensor intends to improve in the existing fiber optic based sensors in terms of sensitivity and resolution for the detection of Bilirubin. The proposed idea will produce a better screening platform to identify hyperbilirubinemia through the optical assessment of the earlier stage of hyperbilirubinemia.

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