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DESIGN OF AN EIT BASED HIGH SENSITIVE LCORR BIOSENSOR

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ABSTRACT

In this paper, we have studied the influence of Electromagnetically Induced Transparency (EIT) phenomena, by inserted Λ type 3-level nanoparticles on performance of Liquid Core Optical Ring Resonator (LCORR) Biosensor. We have investigated sensitivity improvement in this high detective biosensor theoretically. Where, we have compared two cases of normal and EIT based sensors. We have observed that by changing refractive index, the resonance modes will shift and the finesse of resonances will be enhanced considerably.

Keywords: *Electromagnetically Induced Transparency (EIT), Liquid Core Optical Ring Resonator (LCORR) Biosensor, Λ type 3-level nanoparticle, Refractive Index (RI) Enhancement.*

1. INTRODUCTION

Waveguide sensors based on resonance modes changing and RI such as Surface Plasmon Resonator (SPR) have been studied widely by Hoa, Gupta and Holoma *et al* [1-4], These biosensors, because of only once passing of the light through the waveguide, the sensor multiplexing capability reduced and the sample needed to detect must be increased. We have seen 3 types of biosensors based on ring resonators so far. In These biosensors the sensing signal is accumulative in nature, a longer light-analyte interaction length results in a lower detection limit. The first types of ring resonators are Planar Ring resonators. The second types are Micro Ring Resonators. Finally, LCORRs are the third type of Ring Resonators. The advantages and disadvantages of these rings have been investigated thoroughly in by Fan *et al* [5]. LCORR sensors have high integration capability and high Q-factors. Whispering Gallery Modes (WGM) of these sensors, due to total internal reflection of the light along the curved path between the low and high refractive index (RI) media, are used as sensing means. The WGM mode has the evanescent field extending in the low RI layer. So, this field has interaction with the biological samples.

The resonance wavelength is detected by transmission coefficient of the sensor through the fiber. The changes in refractive index induce resonance wavelength shift. By measuring this wavelength shift, one can calculate the refractive index changes as a tool for biosensing. Biosensors, with a large amount of wavelength shifting in respond to little changes in refractive index are desirable.

According to [5] planar biosensors have the most amount of sensitivity and highest integration capability because of their structure's figure, but quality factor of this sensor is lower in comparison with two other groups. Having higher bulk refractive index changes detection limit and more protein detection (about 250pg/mm2) in comparison to others. Microsphere biosensors based on WGM spectral shift have been studied by Hanumegowda, Vollmer and Arnold *et al* [6-9]. Microsphere biosensors have high quality factor, they have bulk refractive index changes detection limit more than planar biosensors in spite of they have low sensitivity. These types of sensors, in spite of high quality factor, have low capability of integration for their spherical structure. LCORR biosensors based on changes RI have been studied by White *et al* [10, 11]. These biosensors have high quality factor and more capability for integration in comparison to microspheres. They have also more capability of protein detection limit (10pg/mm2) in comparison to microspheres.

Due to circular path, the light has longer effective length's interaction with the samples. Therefore, these rings are equivalent to a few centimeters biosensors. So light has more interaction with the samples in comparison with Planar Biosensors.

In the following equation, effective length for these Biosensors is given [5]:

$$L_{eff} = \frac{Q\lambda}{2\pi n} , \qquad (1)$$

Here, Q is quality factor, λ is resonance wavelength, n is effective refractive index.

So, we will achieve more effective length biosensors by using high quality factor resonator. In other words, the light has more interaction with samples. That, Microsphere biosensors have been studied for detection of single molecule protein [9]. In this structure the light is coupled into ring and interacts with bimolecules on the sphere's surface and the protein molecule diffuse on the microsphere's surface immersed in water as an aqueous. The authors suggested that with taking the protein on the equator of microsphere, sensitivity will be improved, because of their configuration. Hence, we have limitation for reduction of the size.

Also Zhu *et al* [12] have studied LCORR biosensors for detecting bovine serum albumin (BSA) based on changes of refractive index because of the existence of bimolecules.

Injection Λ type 3 levels nanoparticles in displacement sensors have been studied by Yadipour *et al* [13] to achieve high resolution. Authors proposed a new structure which can measure the wavelength in the nm range. In their proposed structure the light coupled to a ring by an optical fiber.

Having used EIT phenomena, they produce a transparency window that the light in this window can be transmitted with lowest losses, because the losses in this window are near zero.

In this article, we used EIT to enhance the sensitivity of the proposed LCORR biosensor, which have composed of three following sections.

2. THEORETICAL BACKGROUND

The proposed LCORR biosensor with three layers has been illustrated In Fig.1. The first layer is air which has surrounded the LCORR. The second layer is glass with high refractive index (RI) in compared with two other layers. The third layer consist samples as aqueous. The electrical field has a Gaussian distribution. Most of the light has been confined in the second layer due to its high RI. Therefore, only the evanescent field interacts with the biological sample.

The optical pulse with central wavelength of 960.8 nm has been coupled into the ring from the fiber. Resonant modes of the ring resonator have been demonstrated in the transmission spectra as dips in it.

We have inserted **Λ** type 3-level nanoparticles in the second layer. The probe and control fields has been applied to atomic transitions |a>-|b> and |a>-|c>, respectively as shown in Fig. 1. The control field intensity is very higher than the probe field intensity. Also, other conditions of the EIT phenomenon have been provided. Then, the probe field can transmit with negligible absorption, in other words we have produced a transparent environment.

With inserting nanoparticles in the second rejoin of biosensor we have changed the refractive index in mentioned layer and resonance condition.

Now we are going to investigate theoretically the influence of nanoparticles on LCORR biosensor's performance.

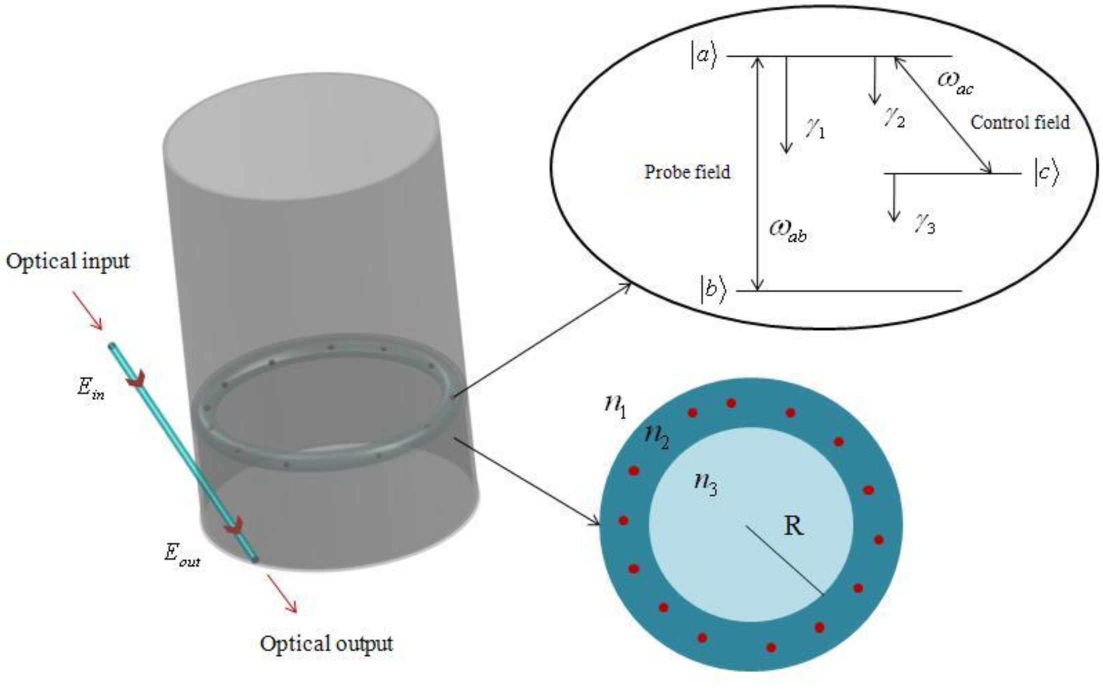


Figure 1.The proposed LCORR biosensor with inserted nanoparticles. Inner radius of LCORR: 128.38 µm. Wall thickness of LCORR: 2.6µm. Refractive indices: $n_1=1$, $n_2=1.45$, $n_3=1.33$, Wavelength: 960.797 nm.

The Hamiltonian for the 3 level nanoparticle can be described as following:

$$H=\begin{bmatrix} \hbar\omega_a & \frac{\wp_{ab}\varepsilon}{2}e^{-i\nu t} & \frac{\hbar}{2}\Omega_\mu e^{-i\phi_\mu}e^{-i\nu_\mu t} \\ -\frac{\wp_{ab}\varepsilon}{2}e^{i\nu t} & \hbar\omega_b & 0 \\ \frac{\hbar}{2}\Omega_\mu e^{i\phi_\mu}e^{i\nu_\mu t} & 0 & \hbar\omega_c \end{bmatrix}, \qquad (2)$$

Where $\omega_a, \omega_b, \omega_c, \wp_{ab}, \varepsilon, \nu, \nu_u, \phi_\mu$ and Ω_μ are frequencies corresponding to three levels, decay rate between levels $|a\rangle$ and $|b\rangle$, amplitude of the control field, probe field frequency, control field frequency, control field phase and Rabbi's frequency of the control field respectively.

Using density matrix method we have achieved these equations for susceptibility [14]:

$$\chi' = \frac{N_a|\wp_{ab}|^2\Delta}{\varepsilon_0\hbar Z}\left[\gamma_3(\gamma_1+\gamma_3)+\left(\Delta^2-\gamma_1\gamma_3-\Omega_\mu{}^2/4\right)\right],$$
$$\chi'' = \frac{N_a|\wp_{ab}|^2}{\varepsilon_0\hbar Z}\left[\Delta^2(\gamma_1+\gamma_3)-\gamma_3\left(\Delta^2-\gamma_1\gamma_3-\Omega_\mu{}^2/4\right)\right], \qquad (3)$$

Where, N_a is the density of inserted nanoparticles and Z is given by following equation [14]:

$$Z=(\Delta^2-\gamma_1\gamma_3-\Omega_\mu{}^2/4)^2+\Delta^2(\gamma_1+\gamma_3)^2, \qquad (4)$$

Using the relationship between the susceptibility absorption and refractive index we have following equations [13]:

$$\alpha=\frac{\kappa}{2}\chi'' \quad , \quad \delta\mathrm{n}=\mathrm{n}\frac{\chi'}{2} \quad , \qquad (5)$$

Here, the real part referred to change of refractive index and the imaginary part referred to losses. In Fig 2, the real part and imaginary part of susceptibility have been shown. In fact with EIT condition, we have produced a transparent window that losses are zero in it. We can manage resolution with control field.

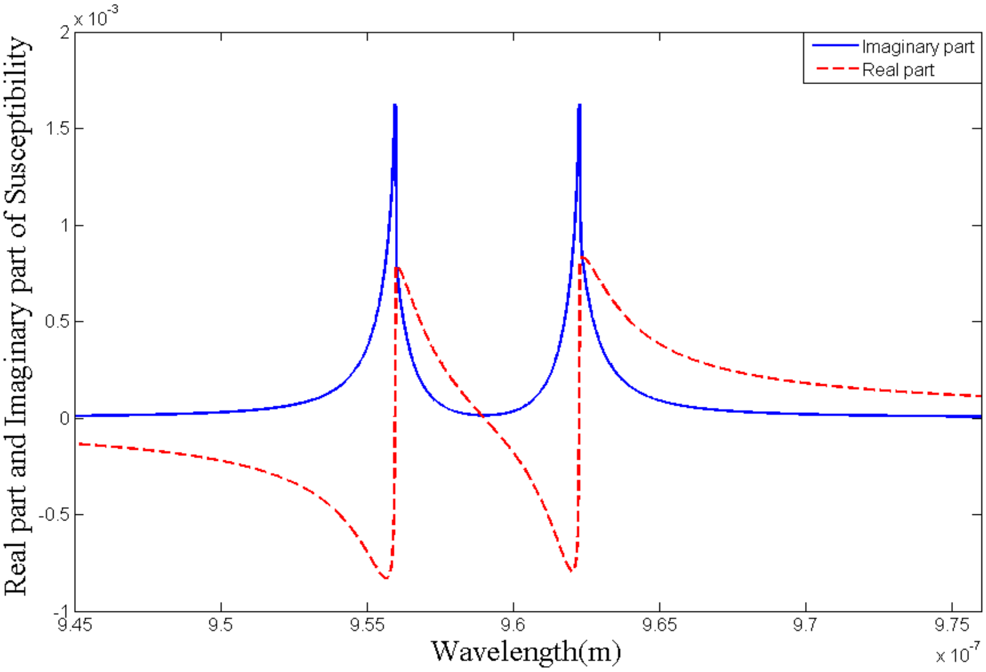


Figure 2. Real part and Imaginary part of susceptibility versus wavelength (m).

The speed of pulse carried energy by propagation along the ring known as group velocity (v_g) given by [15].

$$v_g = \frac{d\omega}{d\beta}, \tag{6}$$

$$v_g = \frac{d\omega}{d\beta} = \frac{d\lambda}{d\beta}\frac{d\omega}{d\lambda} = \frac{d\lambda}{d\beta}\frac{d}{d\lambda}\left(\frac{2\pi c}{\lambda}\right) = -\frac{2\pi c}{\lambda^2}\frac{d\lambda}{d\beta}, \tag{7}$$

$$\beta = kn_{eff} = 2\pi n_{eff} / \lambda, \tag{8}$$

Then by using above equations, we can get

$$\frac{d\beta}{d\lambda} = \frac{2\pi}{\lambda}\frac{dn_{eff}}{d\lambda} - \frac{2\pi n_{eff}}{\lambda^2}, \tag{9}$$

Thus group velocity can be given as:

$$v_g = \frac{c}{n_{eff} - \lambda \dfrac{dn_{eff}}{d\lambda}}, \tag{10}$$

By increasing control field's strength, RI changing versus wavelength or dispersion will be slow according to Eq.(10). Then group velocity will be increased. So, the resonant frequency or mode of the ring will be increased. Thus the resolution will be improved, which will be studied In the next section by biosensor's parameters.

3. BIOSENSOR'S PARAMETERS

One of the most important concerns in biosensor is its sensitivity. LCORR biosensors work based on refractive index's changing of the sample and RI differences between layers, where sensitivity described as shifting of resonance wavelength due to change of refractive index. Change of refractive index in third layer of biosensor, changes the resonance condition, therefore the resonance wavelength will be shifted. For LCORR biosensors sensitivity has been introduced as [12]:

$$S = \left(\frac{\delta\lambda}{\delta n_3}\right) \approx \frac{2\pi R}{l}\eta_3 \approx \frac{\lambda}{n_2}\eta_3, \tag{11}$$

Where, $\delta\lambda$ is resonance wavelength changing due to refractive index changing in the third layer known as sample. R is the internal radius of LCORR and η_3 is the fraction of light surrounded in the third layer that samples are in it and l is:

$$l = 2\pi n_2 R / \lambda, \tag{12}$$

Where, n_2 is the refractive index of the second layer which we have injected by impurities.
And η_3 can be introduced as [12]:

$$\eta_3 = \frac{2\pi h \times \int_0^{\pi} \varepsilon_0 \varepsilon_3 \left|E_0\right|^2 . e^{-(R-r)/L} r dr}{\int \varepsilon_0 \varepsilon(r) . \left|E(r)\right| dV} \approx \frac{2\pi Rh\varepsilon_0 n_3 \left|E_0\right|^2 L}{\int \varepsilon_0 \varepsilon(r) . \left|E(r)\right|^2 dV}, \tag{13}$$

Where, h is an arbitrary length of the LCORR longitude. We have calculated the denominator by assuming electric field E(r) with a Gaussian distribution in the ring and integration has been done over whole space. The electric field decays exponentially with this decay constant [12]:

$$L = \frac{\lambda}{4\pi}\frac{1}{\sqrt{n_2^2 - n_3^2}}, \tag{14}$$

As we know, if the electric field has lower decay rate, interaction between samples and light will be weaker.
Temperature and pressure induce noise in these structures. However, in this structure we have considered thickness of the second layer equal with 2.6μm, to be able to ignore the temperature noise [5].

WGM spectral shift versus RI changes for EIT condition and Normal condition have been shown in Fig.3. As one can observe slope line for EIT condition is greater than normal case, so sensitivity has been enhanced.

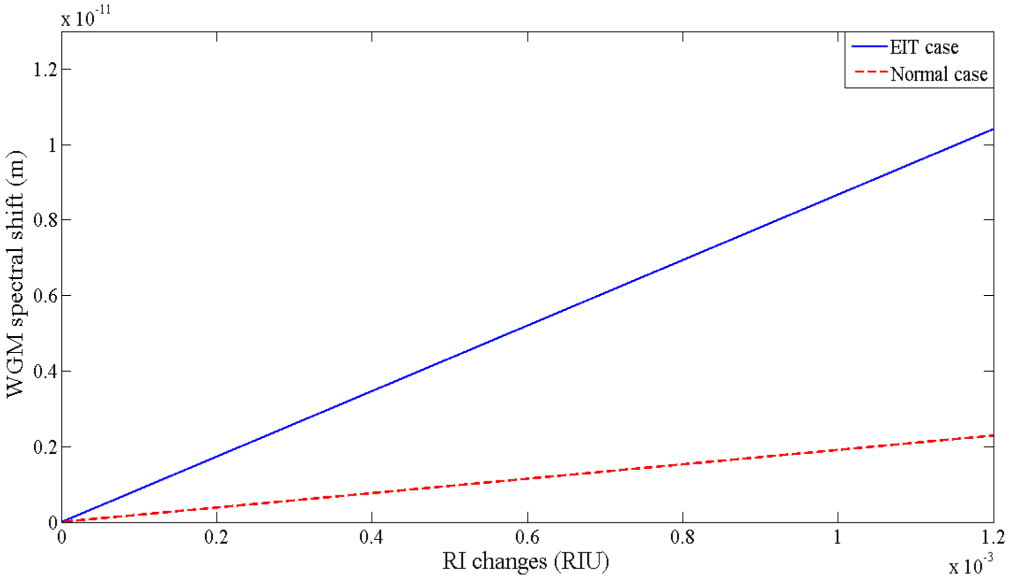


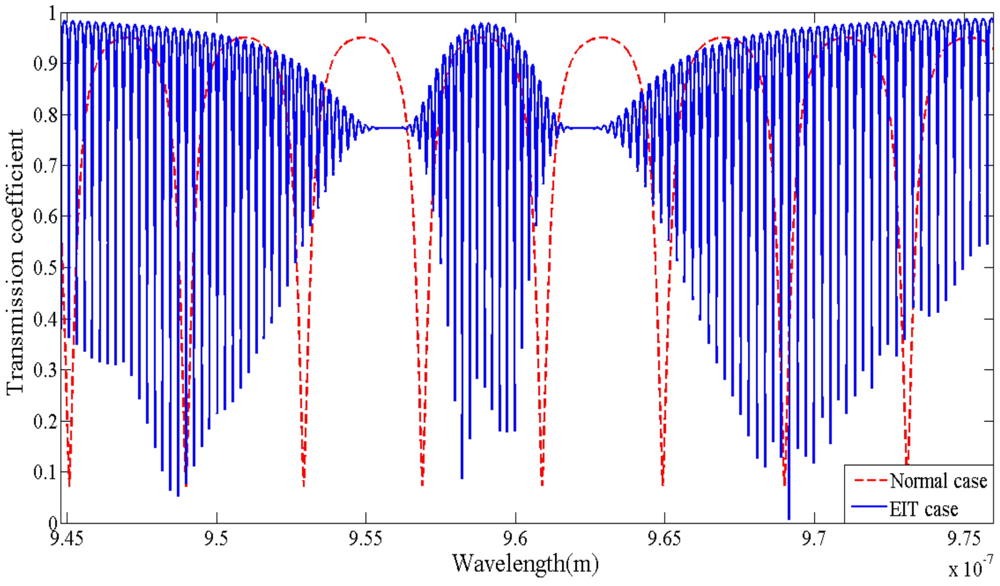
Figure 3. WGM spectral shift versus RI changes for normal and EIT conditions with 1.9083 (nm/RIU) and 8.6764 (nm/RI) slopes, respectively.

According to light propagation in linear and isotropic media, the following transmission coefficient is obtained to study interaction between the field and the material.

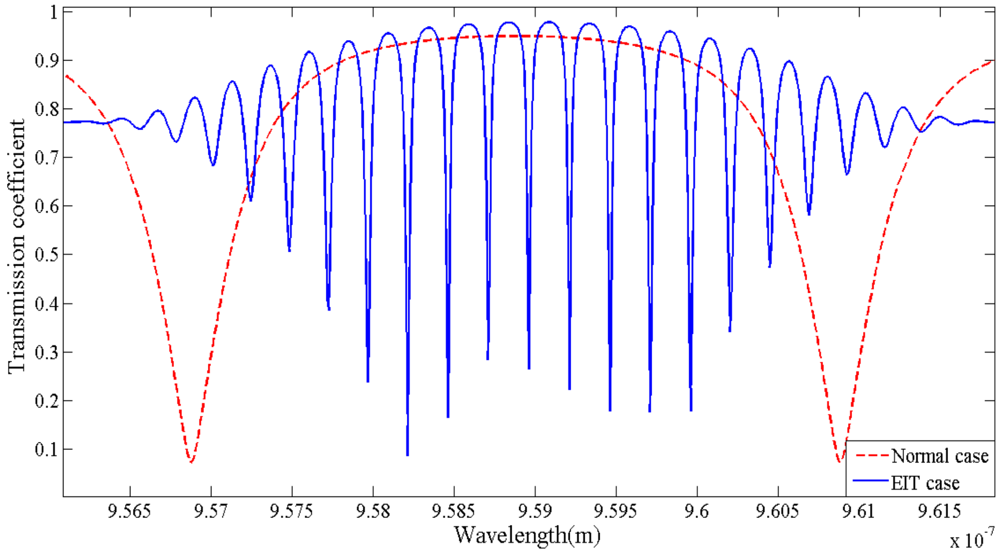
$$\frac{E_{out}}{E_{in}} = \frac{1-\gamma-e^{\frac{\alpha L}{2}}.e^{j\beta L}\sqrt{(1-\gamma)(1-K)}}{\sqrt{(1-\gamma)(1-K)}-e^{\frac{\alpha L}{2}}.e^{j\beta L}}, \qquad (15)$$

Where, γ, K, α and β are Coupler's loss, the coupling coefficient, the ring (and fiber) loss coefficient and wave propagation vector, respectively. The appeared *L* parameter is the peripheral length of the ring resonator.

Transmission coefficient for Normal case and EIT condition has been illustrated by Fig.4.



(a)



(b)

Figure 4. (a)Transmission coefficient for normal and EIT cases versus optical signal wavelength, (b) Zoom in the (a) in EIT window.

We have calculated the the resolution in EIT case, which has been improved to above 10 times in the normal case's resolution.

4. CONCLUSION

In this paper a high sensitive biosensor based on EIT by inserting Λ type 3-level nanoparticles has been proposed. Where, sensitivity has been enhanced in about 5 times and Resolution has been enhanced above 10 times. These results can improve the sensor application in noisy environments effectively.

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