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Research Article

Sensitivity Approach of Optical Sensors of Cholesterol Detection through Gaussian Beam and Quasi-Gaussian Beam

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Abstract

Sensitivity is the comparison result between changes in output signal intensity and changes in input signal shift sensor. The purpose of this study was to analyze the sensitivity of fiber optic sensors using mathematical analysis through the Gaussian beam approach and quasi-Gaussian beam compared with the sensitivity of the optical sensor experimental results so that it can find the correct approach of sensitivity values between theory and experiment. The research method used mathematical analysis and experimental methods and mathematical descriptions for the description of the bundle optical fiber used in the experiment until the sensitivity equation is obtained. The results of the mathematical analysis of the Gaussian beam sensitivity values obtained of $S = 0.004$ *mV ppm*$^{-1}$ *and the sensitivity of quasi-Gaussian beam of* $S = 0.08$ *mV ppm*$^{-1}$*. The results of the sensitivity of experimentally obtained* $S = 0.11$ *mV ppm*$^{-1}$*. Based on the results of mathematical, experimental analysis, and sensor performance, sensitivity through the flat mirror reflection field, it can be concluded that the sensitivity of the optical fiber sensor tends to approach through the quasi-Gaussian beam approach to determine cholesterol concentration.*
Keywords: *sensitivity, Gaussian beam, Quasi Gaussian beam, cholesterol*

Pendekatan Sensitivitas Sensor Optik Deteksi Kolesterol Melalui Gaussian Beam dan Quasi Gaussian Beam

Abstrak

Sensitivitas hasil perbandingan antara perubahan intensitas sinyal keluaran terhadap perubahan sinyal masukan pergeseran sensor. Tujuan penelitian ini untuk menganalisis sensitivitas sensor serat optik dengan menggunakan analisis matematis melalui pendekatan Gaussian Beam dan Kuasi Gaussian Beam dibandingkan dengan sensitivitas sensor optik hasil eksperimen sehingga dapat mengetahui pendekatan yang benar nilai sensitivitas antara teori dan eksperimen. Metode penelitian menggunakan analisis matematis dan metode ekspeimen dengan deskripsi matematis untuk deskripsi serat optik bundle yang digunakan pada eksperimen sampai diperoleh persamaan sensitivitas. Hasil analisis *matematis nilai sensitivitas Gaussian beam diperoleh S = 0,0004 mV ppm^{-1} dan sensitivitas Quasi Gaussian beam S = 0,08 mV ppm^{-1}. Adapun hasil sensitivitas secara eksperimen diperoleh S = 0,11 mV ppm^{-1}. Berdasarkan hasil analisis matematis dan eksperimen dan kinerja sensor, sensitivitas melalui bidang pantul cermin datar maka dapat disimpulkan bahwa sensitivitas sensor serat optik cendrung mendekati melalui pendekatan berkas Quasi Gaussian untuk menentukan konsentrasi kolesterol.*

Kata Kunci: *sensitivitas, Gaussian beam, Quasi Gaussian beam, kolesterol*

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I. INTRODUCTION

Optical fiber includes type of cable for wave transmission or wave reflection channels made of glass and plastic. Optical fiber serves to guide electromagnetic waves with very fine shapes and sizes and can be used to transmit light signals from one place to other. The light source that passes through optical fibers is usually in the form of laser. This optical fiber is about 120 micrometers in diameter. The light inside the optical fiber does not come out because the refractive index of the glass is bigger than the refractive index of the air. In principle, optical fibers reflect and refract a number of light that propagates in them. The efficiency of optical fibers is determined by the purity of the glass or glass constituent. The purer the glass material of the fiber, the less light is absorbed by the optical fiber.

Applied research on fiber optic sensors of various types of optical fibers continues to develop, this is evidenced by many studies on fiber optic sensors conducted and published in international journals including the use of optical sensors to detect the purity of honey in distilled water [1], fiber sensors taper for glucose detection [2] and detection of NaCl salts using optical fiber sensors [3]. Research on the use of fiber optic sensors using fiber optic bundles to detect cholesterol solution concentration has also been carried out [4-6]. The results of the sensitivity of the use of fiber optic research is one example of the utilization Gaussian beam assumption upon the fact that there are still shortcomings. It is expected that future research about the use of optical fiber and its sensitivity increases assuming that quasi-Gaussian beam on the detection of concentrations of cholesterol.

The sensitivity of cholesterol detection results is almost the same and approaches Gaussian beams, such as fast and highly sensitive detection of cholesterol [7], namely magnetite as a platform for detecting materials for glucose, ethanol and cholesterol [8], amperometric glucose detection uses Cobalt (II) Chloride as an electrocatalyst on aprotic media [9], electrochemical sensors are sensitive and selectively use silver nanoparticles [9], electrochemical sensors in films smeared on carbon nanoparticles are translucent to request cholesterol [10], carbon nanotube layers and gold nanoparticles based on bienzyme biosensors are also for cholesterol detection [11], high-performance electrochemical biosensors for detecting total cholesterol [12], detection of cholesterol by digitonin conjugated gold nanoparticles[13], electrochemical and optical polymers use biosensors to detect cholesterol [14], detection of cholesterol by digitonin conjugated gold nanoparticles [15], amperometric detection of cholesterol using an indirect electrochemical oxidation method [16], and detection of cholesterol concentration assumes bundle fiber optics using a theoretical analysis of the Gaussian Beam approach [17-19]. But there are other assumptions from the development of the bundle fiber optic shift sensor using the quasi-Gaussian beam approach [20].

The applied articles of this optical fiber sensor have motivated researchers to analyze the sensitivity of the sensor to determine cholesterol concentration through the Gaussian beam approach and quasi-Gaussian beam through mathematical analysis and experimental approaches. The purpose of analyzing the sensitivity of fiber optic sensors using mathematical analysis of two approaches, namely the Gaussian beam approach and the quasi-Gaussian beam compared, to the sensitivity of the optical sensor experimental results so that it can find the correct approach of sensitivity values between theory and experiment. The novelty of fiber optic sensor research is an increase in sensor efficiency with a quasi-Gaussian beam approach through bundle optical fiber. The mathematical approach with quasi-Gaussian can be used as a reference for the intensity and power equation in determining high sensitivity.

II. METHOD

This study used mathematical analysis method and experimental method. The initial method with a mathematical description for the description of the bundle optical fiber used in the experiment until the sensitivity equation was obtained. Figure 1 shows the basic scheme of the optical fiber shift sensor, the light source (S) enters the transmitter fiber (TF) and hits the target, and then the light is reflected by the target surface and transmitted back through the fiber receiver (RF) and to the photo detector (D).

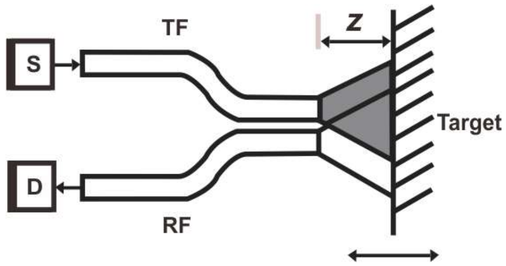

Figure 1. Basic Arrangement of Optical Fibers

The light leaving the fiber transmitter bundle is represented by perfect symmetrical cone with a divergence angle θ_a, the center at point O with the distance z_a in the bundle fiber (Figure 2a).

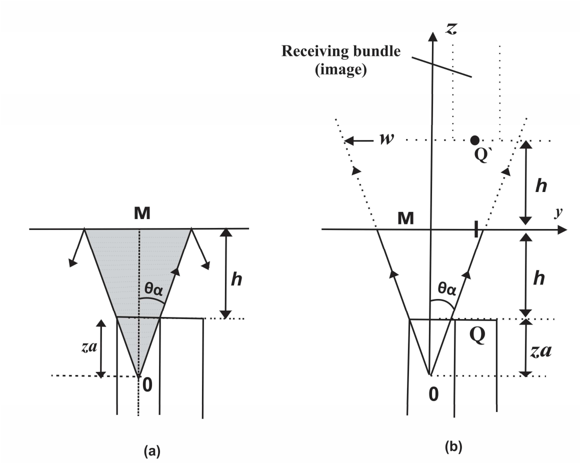

Figure 2. The Light Cone Beam Coming Out of the Transmitter Fiber (a) Concerning the Mirror and Reflected Back to the Receiving Fiber (b) The Beam Enters the Shadow Receiving Fiber

To determine the beam of light that enters the receiving fiber, it is not necessary to review the reflection beam by the mirror to the receiving fiber. Because the reflector is a flat and perfect mirror, the receiving fiber can be considered as the shadow fiber behind the mirror (Figure 3b). Now it is introduced that the z coordinate is straight with the (longitudinal) axis of the beam cone that starts at 0 and extends to the mirror surface. Center coordinates in *Q'* at the end of the recipient bundle:

$$y = 2\omega_a$$
$$z = z_a + 2h \quad (1)$$

With h is the distance of the shift to be monitored. The approach will be based on electromagnetic waves paraxial Gaussian files. Now that the wave file is viewed with a Gaussian profile, the beam radiation of the emitted beam is not maintained but decreases radially which meets the exponential law, namely:

$$I(r,z) = \frac{2P_E}{\pi\omega^2(z)}\exp\left(-\frac{2r^2}{\omega^2(z)}\right) \quad (2)$$

With r being the radial coordinate, z is the longitudinal coordinate and ω is the file size at distance z which can be written as follows:

$$\omega(z) = \omega_0\sqrt{1+(z/z_R)^2} \quad (3)$$

The set ω_0 (the radius of the waist of the light file or waist radius) and Z_R (the Rayleigh range) are the parameters of the dynamic file that has a relationship with the wavelength of light $\pi\omega_0^2 = \lambda z_R$, for the far field of the file center ($z >> z_R$) the file meets the spherical waveform which is limited by cones which are characterized by the distribution angle as follows:

$$\theta_a \approx \tan\theta_a = \frac{\omega(z)}{z} = \frac{\omega_0}{z_R} = \frac{\lambda}{\pi\omega_0} \quad (4)$$

For simplification ($z >> z_R$) the radiation intensity function can be simplified as follows:

$$I(r,z) = \frac{2}{z^2}\frac{P_E}{\pi\theta_a^2}\exp(-\frac{2r^2}{\theta_a^2 z^2}) \quad (5)$$

For mirrors at position h from the end of the transmitter fiber and the receiving fiber bundle, there is a relationship $z = z_a + 2h$ and $\omega_a < r < 3\omega_a$, and for the far field it is necessary to assume $z_a >> z_R$ which is usually suitable for multimode optical fibers with a large numerical aperture value, which is about 0.2. The optical power entering the receiving fiber is done by integrating the intensity of the beam of light (I) given by equation (5) which includes the cross-sectional area of the bundle *Sa*:

$$P(z) = \int_{S_a} I(r,z)dS \quad (6)$$

The first approach used to calculate power in equation (6) is the surface area of the recipient's bundle $S_a = \pi\omega_a^2$, the intensity of the beam of light I (r, z) is kept constant and equal to the value at the center of the bundle (point Q'; $r = 2\omega_a \approx 2\theta_a z_a$), in this case obtained:

$$P = IS = \frac{2P_E}{\xi^2}\exp(-\frac{8}{\xi^2}) \quad (7)$$

With $\xi = z/z_a = 1+2h/z_a = 1+2h_N$, by analyzing the obtained state $\frac{dP}{d\xi} = 0$ (i.e. $h_N = 0.9142$). The power will reach the maximum, by reviewing this, equation (7) can be written in normalized power, as a normalized distance function (h_N) as follows:

$$P_N = \frac{8}{\xi^2}\exp(1-\frac{8}{\xi^2}) \quad (8)$$

Equation (8) will be used as the reference to compare the output power of the experimental results, especially for the ends of the fiber bundles in the form of pairs. Graph equation (8) can be seen in Figure 3, the curve shows that the optical fiber output power will increase by increasing the distance of the object shift from the optical fiber bundle, after reaching the peak, the output power will decrease exponentially with increasing distance.

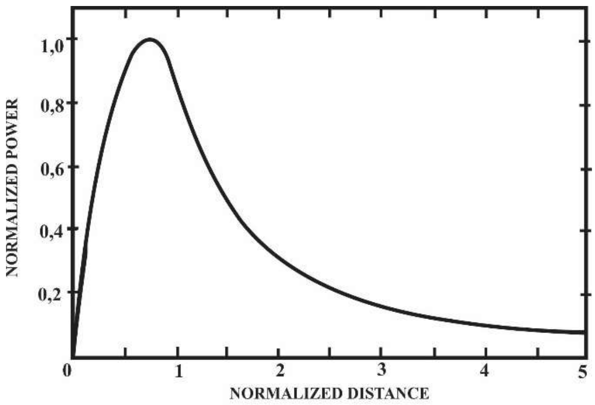

Figure 3. Output Power Normalized to Normalized Shifts

The sensitivity equation of the shift sensor by using a receiver fiber with pair arrangement has been shown and has been derived, while the sensitivity of the shift sensor has been successfully derived [21-25] using 16 recipient fibers with concentric arrangement (Equation 13). Both results of the theory have been successfully tested experimentally using a type of plastic optical fiber. Experimental test results show that the optical fibers with 16 pieces of fiber showed better performance compared to shift sensors with a receiving fiber. Based on the results of a reduction in the sensitivity of the above research, if the number of optical fiber receivers is larger, then the number of beam of light captured by the receiving fiber will be even greater, so that the sensitivity of the sensor will be even higher.

The experimental method was carried out using these research tools including He-Ne lasers (Thorlabs, 632.5 nm, 5 mW) as electromagnetic waves with wave transmission and reflection properties, optical fiber bundle to guide the wave to the sample, 818-SL (Newport) optical detector to detect reflected waves, chopper and chopper controllers (SR540, Stanford Research System, Inc.) for wave selection, Lock-in amplifiers (SR510, Stanford Research System, Inc.), flat mirrors as reflected fields, position micrometers (Newport) for shifting distance to solution samples, and computer devices.

The experimental variable of optical fiber cholesterol sensor is the output peak voltage of the sensor (in units of mV) in the optical fiber bundle and the concentration of cholesterol (in units of ppm). Furthermore, in the experimental test, the data obtained were in the form of the peak output voltage of the sensor as a function of variation in cholesterol concentration. With this function, the front slope and the back linear area will be determined. Linearity test on the area of front slope and rear slope used linear regression test; both slopes are linear regions, and the area is a sensor working area.

III. RESULTS AND DISCUSSION

Figure 4 shows the location of the center point of $Q\ (z, \theta)$ for the receiving fiber (RF) of the fiber bundle with light intensity as it is in the equation (9) for the case of the Gaussian beam and equation (10) for the case of the quasi-Gaussian beam. The Gaussian approach shows the location of point 0 is the light cone point on the transmitting fiber (TF) which is w/θ to the end surface of the bundle optical fiber with θ is the angle of divergence. In the quasi Gaussian approach, the angle of divergence changes $\theta\ (1 + \delta)$, with $\delta \neq 0$.

The radiation intensity functions in the Gaussian file is shown in equation (9) and the quasi-Gaussian file in equation (10).

$$I_Q(z,\theta) = k\frac{P_T}{z^2}\exp\left\{-2\left|\frac{\theta}{\theta_a}\right|^2\right\} \tag{9}$$

$$I_Q(z,\theta) = k\frac{P_T}{z^2}\exp\left\{-2\left|\frac{\theta}{\theta_a(1+\delta)}\right|^{(2+\Delta)}\right\} \tag{10}$$

The normalized power function $P_N = P/P_{maks}$, as a normalized distance function (h_N) in the Gaussian beam is shown in equation (11) and the quasi-Gaussian beam in equation (12).

$$P_N = \frac{P_R(h)}{P_{ref}} = 2x\Psi^2 \exp\left\{1-2|\Psi|^2\right\} \tag{11}$$

$$P_N = \frac{P_R(h)}{P_{ref}} = 2x\left\{(1+\delta)\Psi\right\}^2 \exp\left\{1-2|\Psi|^{2+\Delta}\right\} \tag{12}$$

with Ψ, $\Psi(h) = 2\left\{1+\mu_2(1+\delta)\frac{h}{h_{ref}}\right\}^{-1}$ (13)

$P_n = 1$; if $h = h_{ref}$ and $\Delta = \delta = 0$ for Gaussian and $\Delta = 0.888$, $\delta = -0.110$ for quasi-Gaussian.

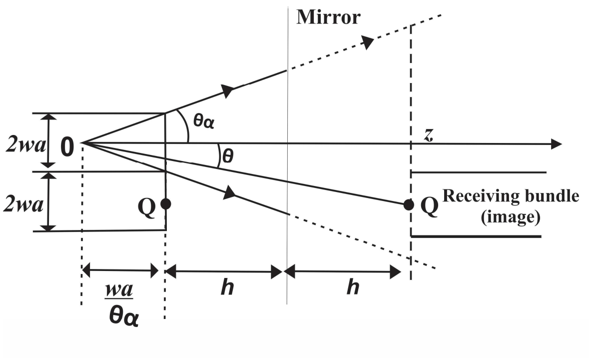

Figure 4. The Light Cone File Coming Out of the Transmitting Fiber (TF) Hits the Mirror and is Reflected Back to the Receiving Fiber (RF)

Analysis of sensor sensitivity results using equation (14).

$$S = \frac{\partial P_n}{\partial h_n} \tag{14}$$

The normalized power function (P_n) and the shifting function of the normalized distance (h_n) in the Gaussian file are shown in the Equation (15) and (16).

$$P_n = \frac{P_R(h)}{P_{ref}} = 2\Psi^2 \exp\left\{1-2\Psi^2\right\};$$

$$\Psi(h) = 2\left\{1+\mu_2\frac{h}{h_{ref}}\right\}^{-1};\ h_n = \frac{h}{h_{ref}};$$

$$\Psi = 2\left\{1+\mu_2 h_n\right\}^{-1} \tag{15}$$

$$\text{So, } h_n = \frac{1}{\mu_2}\left(\frac{2}{\Psi}-1\right);\ \partial h_n = -\frac{1}{\mu_2}\left(\frac{2}{\Psi^2}\right)\partial\Psi \tag{16}$$

The sensitivity of fiber optic sensors can be determined using equation 4, with;

$$\frac{\partial P_n}{\partial h_n} = \mu_2\Psi\left(2\Psi^2-1\right)\left\{2\Psi^2\exp\left(1-2\Psi^2\right)\right\} \tag{17}$$

$$\text{So that, } S = \mu_2\Psi(2\Psi^2-1)P_n \tag{18}$$

Where $\mu_2 = \sqrt{8}$ -1, $\Psi = 0.707$ and $P_n = 1$, then the sensitivity value of Gaussian beam is S = 0.0004 mV ppm^{-1}.

The normalized power function (P_n) and the shifting function $\Psi(h)$ of the normalized distance (h_n) in the quasi-Gaussian file are shown in the following equation:

$$P_n = \frac{P_R(h)}{P_{ref}} = 2\left\{(1+\delta)\Psi\right\}^2 \exp\left\{1-2\Psi^{2+\Delta}\right\};$$

$$\Psi(h) = 2\left\{1+\mu_2(1+\delta)\frac{h}{h_{ref}}\right\}^{-1};\ \ h_n = \frac{h}{h_{ref}}; \tag{19}$$

and $\Psi = 2\left\{1+\mu_2(1+\delta)h_n\right\}^{-1}$

$$h_n = \frac{1}{\mu_2(1+\delta)}\left(\frac{2}{\Psi}-1\right)$$

$$\partial h_n = -\frac{1}{\mu_2(1+\delta)}\left(\frac{2}{\Psi^2}\right)\partial\Psi \tag{20}$$

Equation of quasi-Gaussian sensitivity is obtained,

$$S = \mu_2(1+\delta)\Psi\left\{(2+\Delta)\Psi^{2+\Delta}-1\right\}P_n \qquad (16)$$

Where $\mu_2 = \sqrt{8}$; $h_n = 0.914$; $\Delta = 0.888$; $\delta = -0.110$; and $P_n = 1$, then the sensitivity value of quasi-Gaussian beam is $S = 0.08$ mV ppm^{-1}.

The experimental results of sensitivity detection of cholesterol concentration sensors were obtained by analysis of the experimental data. However, the detector output voltage detection data started when the bundle fiber is placed coincides with the mirror, which is at shift z = 0. The bundle fiber was placed on a micrometer where the position is shifted every 50 µm. In each shift position, the detector output voltage was measured to obtain the maximum output voltage from each variation in cholesterol concentration. The results of the study of detection of cholesterol concentration in standard cholesterol samples obtained a sensitivity approach close to the sensitivity value of quasi-Gaussian beam [26]. This study presents the results of further research for more complex cholesterol samples, namely cholesterol samples plus cupric acid solutes with varying values. There is a graph of the maximum output voltage value of the variation in cholesterol concentration as shown in Figure 5.

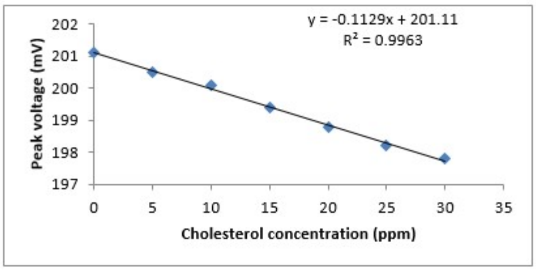

Figure 5. Maximum Voltage Curve for Cholesterol Concentration in Seven Samples

Figure 5 shows a graph of the relationship of the maximum output voltage of the seven samples of cholesterol concentration from 0 to 30 ppm. The maximum output voltage of each sample were measured from optical detectors with the manipulation of the distance towards the samples. The maximum output voltage indicates a decrease in linear seven concentration samples against cholesterol. The results of detection analysis showed that the maximum output voltage had a linear decrease in the concentration of cholesterol solution with a sensitivity of 0.1129 mV ppm^{-1} and linearity of 99.63 %.

The form of normalized power curve, as a normalized distance function (h_N), is used to compare the output power output of the experimental results, Gaussian files and quasi-Gaussian files, especially for the ends of the fiber bundles in the form of pairs as it is presented in Figure 6. The curve shows that the optical fiber's output power will increase as increasing bundle optical fiber shift distance, after reaching peak, output power will decrease exponentially with increasing distance.

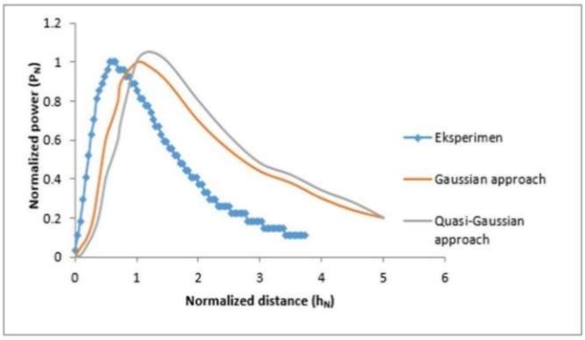

Figure 6. Graph of power output is normalized to normalized shiftsexperimental results, Gaussian beam, and quasi-Gaussian beam

Figure 6 shows the sensitivity curve of a power change against normalized distance normalized. The curve shows the approach slopes between Gaussian beam with quasi-Gaussian experimental results. The results of the sensitivity analysis mathematically obtained the Gaussian beam sensitivity value of 0.0004 mV ppm^{-1}, the sensitivity of the quasi-Gaussian beam is 0.08 mV ppm^{-1}, and the sensitivity analysis is experimentally obtained 0.11 mV ppm^{-1}.

IV. CONCLUSION

Gaussian beam and quasi-Gaussian beam mathematical approach can be used as a reference for the intensity and power equation in determining high sensitivity. The elemental sensing experiment validation can be used to determine the output voltage value (maximum) as a concentration function based on shift profile between fiber optic probes and cholesterol samples. Shifting the tip of the fiber optic to the reflecting plane can receive the maximum reflected laser beam by the fiber receiving and produce higher efficiency. Sensitivity through mathematical analysis using the quasi-Gaussian S = 0.08 mV ppm^{-1}, and the quasi-Gaussian approach is higher than the sensitivity in the Gaussian S = 0.0004 mV ppm^{-1}. Based on the output power profile, sensor performance, and sensitivity through the flat mirror reflection field, it can be concluded that the sensitivity of the optical fiber sensor is closer to the sensitivity of the quasi-Gaussian beam to determine cholesterol concentration.

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