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## Fiber Optic Ring Resonator Sensor Detection Technique Based on Spectral Intensity Integration

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### Abstract

Resonant field phenomenon in optical ring resonator has been a major theme for various studies and can be used for various sensor applications. The spectral response shape changes are subjects to be discussed and analyzed for detection in optical sensor system. The spectral response changes are caused by various factors ranging from refractive index of the surrounding medium, medium loss due to absorption and scattering, and coupling variation between waveguides. These optical phenomena are mostly used for bio-sensor applications, since it is free from electromagnetic interference (EMI) and non-physically destructive. In this paper, we discuss our current research in developing optical bio-sensor in the form of a fiber optic ring resonator with monochromatic laser source based on spectral integration detection method, which is sufficiently sensitive and accurate.

### Abstrak

**Teknik Mendeteksi pada Sensor Fiber Optik Ring Resonator Berbasis Integrasi Intensitas Spektral.** Fenomena medan resonansi di dalam ring resonator optik sudah lama dipelajari dan digunakan untuk berbagai aplikasi sensor. Perubahan-perubahan bentuk dari respon spektral adalah topik yang akan dibahas dan dianalisis di dalam sistem sensor optik. Perubahan-perubahan respon spektral disebabkan perubahan indeks bias pada medium sekelilingnya, hilangnya energy optik akibat penyerapan dan difraksi dalam medium, dan bervariasinya nilai kopleng di antara *waveguides*. Fenomena optik ini sebagian besar digunakan untuk aplikasi bio-sensor karena sifatnya yang bebas dari interferensi elektromagnetik dan secara non-fisik tidak merusak. Makalah ini akan membahas penelitian terkini yang kami lakukan untuk mengembangkan bio-sensor optik dalam bentuk *ring resonator fiber* dengan sumber laser monokromatik berdasarkan metode deteksi integrasi spektral yang lebih sensitif dan akurat.

*Keywords: fiber-optic ring resonator, integration detection, optical bio-sensor, resonance, spectral response*

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### 1. Introduction

Fiber optics is the most important part in nowadays telecommunication technology, but it is also intensively developed as a biosensor device [1-2]. The varying physical parameters detected by the fiber, can result in various forms, for instances: scattered mode radiation due to fiber bending [3], leakage mode due to radiating evanescent wave mode. Furthermore, the change of mode confinement inside fiber and various coupling mode due to varying physical condition outside the fiber are effectively used for optical sensing parameters. Fiber optic sensor has been used for various sensor applications, such as temperature sensor [4], gas sensor [5] and etc.

To improve the sensor sensitivity and measurement resolution, fiber optic is configured in the loop or ring structure to generate resonant effect [6-7]. In order to improve the sensing effectiveness of the resonant effect, the fiber optic type uses the single-mode (SM) polarization-maintenance fiber (PMF). Fiber optic sensor that uses resonant effect later on is named as fiber-optic ring resonator (FORR) sensor.

In general, the measurement of light by the sensor can be conducted in several methods. The first method is conducted by using a monochromatic laser signal, where the photodiode detector measures the signal level change due to the variation of the detected medium. This method is very obvious for a plain fiber sensor

without resonance ring structure. However, fiber-optic sensor designed with loop or ring structure to obtain resonant effect, has a resonant response profile with respect to wavelength. The resonant fiber (FORR) sensor, has a repeatable resonant spectral response profile. FORR-type sensor requires a coherent light source, which spans a sufficient a large area of bandwidth to scan the large response profile. Tuneable laser source (TLS) is good for this measurement. The response profile detection is conducted by optical spectral analyzer (OSA). The response profile data should be sent to signal analyzer system to be analyzed. So far, the high-cost of resonant type sensor is partially caused by the requirements of OSA and signal analyzer equipments, which are very expensive and complicated.

By considering the advantages of FORR type sensor and to decrease the instrument cost, in this research, we propose a method for FORR sensor measurement and analysis with power spectral integration technique. Instead of using OSA and signal analyzer, this new proposed technique uses a monochromatic laser signal, where its line width should be larger than the frequency spectral response (FSR) of the FORR sensor. A monochromatic semiconductor laser source usually has typical line width of ~2-nm. It is much larger in comparison to FSR of 10-cm FORR, which has a typical value of  $\sim 1.5 \times 10^{-3}$ -nm. In this proposed technique, in detecting the varying of spectral response profile, it does not need to analyze the response profile, since it is sufficient to detect the total intensity, which is the integral intensity of the spectral response profile with respect to the wavelength. This proposed FORR sensor intensity integration detection method is promising as it is more accurate, more sensitive, provide higher resolution and simpler to be implemented.

## 2. Methods

FORR type sensor has some advantages in comparison to the fiber sensor without resonant effect, i.e. more sensitive and higher resolution. FORR sensor requires to use SM PMF rather than multi-mode fiber (MMF) optics. Moreover, in this sensor type, polarization effect and phase noise due to vibration on the coupler connectors must be kept and suppressed as low as possible in order to maintain the resonant effect advantage.

Basic configuration of our proposed FORR sensor is shown on Fig.1 below. This figure shows a configuration named as a direct-loop FORR [8]. This optical sensor structure consists of a single mode dielectric rectangular waveguide (WG) optical coupler on substrate as the sensing area and fiber optics incorporated with the second optical coupler to form optical ring resonator sensor. There are two basic analyses for

this optical sensor, i.e. the optical ring resonator spectral response and the sensing coupling analysis, which are explored in this paper. Another important discussion is discussion about how the power spectral integration technique works.

**Optical ring resonator analysis.** Stokes et al. [6] started to analyze FORR characteristics based on cross-loop FORR [6] configuration, where the method to obtain the spectral response output is adopted here for direct-loop FORR configuration [8]. The complex amplitude relationship between 4 terminals in direct-loop FORR at sensing area coupler is shown in Fig.1 and is written as following:

$$\begin{aligned} E_3 &= (1 - \gamma_0)^{1/2} \left[ j\sqrt{\kappa}E_1 + (1 - \kappa)^{1/2} E_2 \right] \\ E_4 &= (1 - \gamma_0)^{1/2} \left[ (1 - \kappa)^{1/2} E_1 + j\sqrt{\kappa}E_2 \right] \end{aligned} \quad (1)$$

where  $\gamma_0$  is the fractional intensity coupling loss and  $\kappa_1$  is the intensity coupling value of sensing coupler. Furthermore, the fractional intensity coupling loss  $\gamma_0$  is defined as following:

$$|E_3|^2 + |E_4|^2 = (1 - \gamma_0) (|E_1|^2 + |E_2|^2) \quad (2)$$

Relationship between E2 and E3 is formulated as

$$E_2 = E_3 (1 - \gamma_0)^{1/2} (1 - \kappa_2)^{1/2} e^{\alpha_0 L} e^{j\beta L} \quad (3)$$

Hence, the intensity ratios in the ring resonator can be written as:

$$\frac{|E_3|^2}{|E_1|^2} = \frac{(1 - \gamma_0)\kappa}{Z} \quad (4)$$

$$\frac{|E_5|^2}{|E_1|^2} = \frac{(1 - \gamma_0)\kappa_1\kappa_2}{Z} \quad (5)$$

Where

$$Z = \left(1 - (1 - \gamma_0)^{1/2} (1 - \kappa)^{1/2} e^{-\alpha_0 L}\right)^2 + 4(1 - \gamma_0)^{1/2} (1 - \kappa)^{1/2} e^{-\alpha_0 L} \sin^2 \frac{\beta L}{2} \quad (6)$$

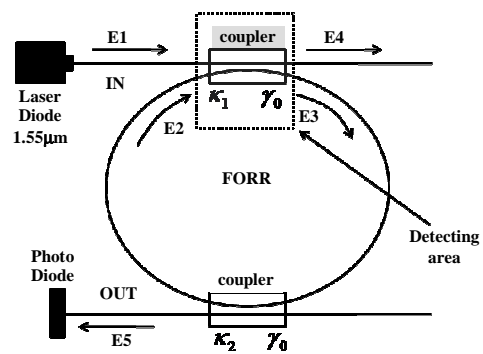


Figure 1. The Proposed Direct-loop Type FORR Sensor based on Spectral Intensity Integration Technique. The Output Analyzed Signal is E5

and  $\alpha_0$  is fiber optic loss coefficient,  $L$  is the total length of the fiber ring,  $\kappa_2$  is the intensity coupling value of ring coupler and  $\beta$  is fiber optic propagation constant and formulated as below (7) where  $n_{eff}$  is refractive index effective of fiber.

$$\beta = n_{eff} (2\pi/\lambda) \quad (7)$$

At resonant condition, the phase relationship inside direct-loop FORR configuration is written simply as:

$$\beta L = q2\pi \quad (8)$$

There are three interesting conditions of the resonance intensity spectral responses, i.e.: (1) Frequency Spectral Response (FSR), (2) Full width half maximum (FWHM) and (3) Finesse (F). The advantages of each condition are used for various applications such as for optical wavelength filtering and sensors. Thus, the three conditions can be derived directly based on Eqs. (6) and (8). The profile of theoretical output wavelength response towards input intensity is shown on Fig.2.

FSR is determined by Eq. (6) which shows the relationship with term  $\sin^2(\beta L/2)$  and Eq. (9). The sinusoidal function causes the resonance wavelength response profile to be repeatable. From Eqs. (6) dan (9), we obtain FSR:

$$FSR = \frac{\lambda^2}{n_{eff} L - \lambda} \quad (9)$$

At condition of  $n_{eff} L \gg \lambda$ , we can write  $FSR = \lambda^2/(n_{eff}L)$ . Sometimes, it is needed to express FSR in frequency rather than in wavelength.

$$FSR = \frac{\Delta\lambda \cdot f}{\lambda} = \frac{\Delta\lambda \cdot c}{\lambda^2} \quad (10)$$

where  $c$  is the speed of light in vacuum and  $f$  is frequency and  $\Delta\lambda$  is FSR in wavelength.

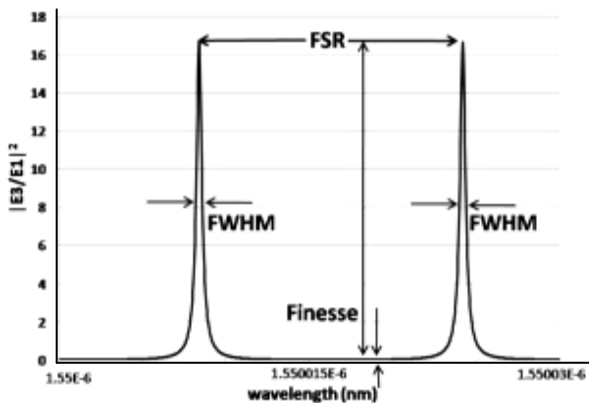


Figure2. Resonance Intensity Response Profiles: (a)  $|E4/E1|^2$  and (b)  $|E3/E1|^2$  vs Wavelength, where We use Typical Fiber-Optical Values of:  $\gamma_0 = 0.05$ ,  $\kappa = 0.1$ ,  $L = 0.1$  m and  $\alpha_0 = 6.9E-5/m$

Linewidth of the spectral response profile or FWHM is derived mainly by Eq. (6) and (8). The FWHM expressed in wavelength and is written as following:

$$FWHM = 2\Delta\lambda = \frac{2\lambda^2}{\pi n_{eff} L} \sin^{-1} \frac{1}{2} \left( \frac{1}{a} - a \right) \quad (11)$$

if it is expressed in frequency, then it is written as:

$$FWHM = 2\Delta f = \frac{2c}{\pi n_{eff} L} \sin^{-1} \frac{1}{2} \left( \frac{1}{a} - a \right) \quad (12)$$

where:

$$a = (1 - \gamma_0)^{1/4} (1 - \kappa)^{1/4} e^{-\frac{1}{2}\alpha_0 L} \quad (13)$$

Finesse  $F$  per definition is ratio of maximum response towards the minimum of the resonance intensity response profile  $|E5/E1|^2$  as shown on Fig.2b. It is derived directly from Eq.(6) and written as following:

$$F = \pi \frac{a}{1 - a^2} \quad (14)$$

where  $a$  is stated in Eq.14.

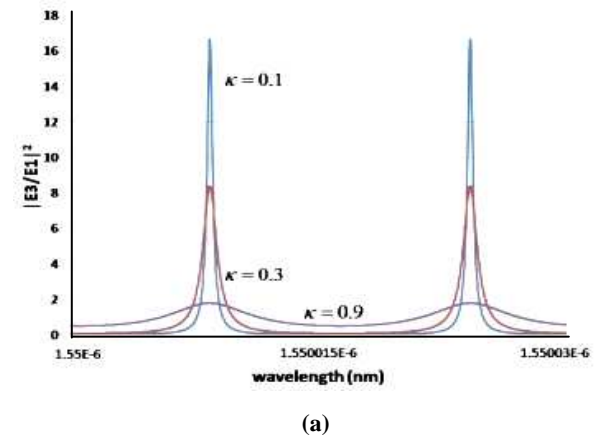


Figure3. The Changes of Resonance Intensity Response Profile  $|E3/E1|^2$  vs. Wavelength Due to (a) Varying Coupling value  $\kappa$  and (b) Varying Fiber Attenuation  $\alpha_0$

When  $a \rightarrow 1$ , then  $F = \pi a / 2(1-a)$ ,  $F$  becomes very high, and opposite when  $a \rightarrow 0$ . To obtain high  $F$ , then  $a$  must be close to 1, where  $\gamma_0$ ,  $\kappa_1$ ,  $\kappa_2$  and  $\alpha_0$  must be close to 0.

The shape of resonance response profile i.e. indicated by values of Finesse and FWHM is determined mostly by parameters of  $\gamma_0$ ,  $\kappa$  and  $\alpha_0$ .

On the other hand, the FSR is mostly determined by the value of  $L$  the length of the fiber ring. Hence, in order to utilize the FORR as a sensor, we have to decide which parameter to be used as dominant sensing parameter.

The following Fig.3a and 3b show how the change of coupling value  $\kappa_1$  and fiber attenuation  $\alpha_0$  in the FORR loop, respectively can change resonance response profile.

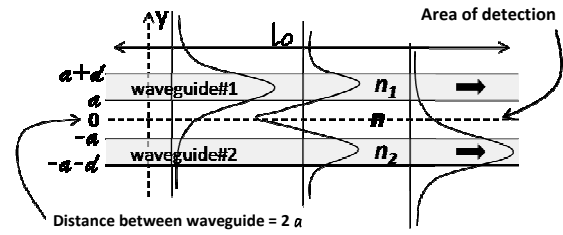
**Waveguide Coupling Analysis.** The influences of the surrounding optical parameter variations to  $\kappa_1$  and  $\alpha_0$  variations. The following discussion is exploring how coupling value  $\kappa_1$  of a single mode dielectric rectangular waveguide (WG) optical coupler on substrate as optical sensor is influenced by optical parameters of the waveguides and surrounding medium as shown on Eq. (15) and illustrated on Fig.4 [9]:

$$\begin{aligned} \mathcal{S}_{2,1} &= \frac{1}{2} (n_2^2 - n^2) \frac{k_0^2}{\beta_1} \int_a^{a+d} u_1(y) u_2(y) dy \\ \mathcal{S}_{1,2} &= \frac{1}{2} (n_1^2 - n^2) \frac{k_0^2}{\beta_2} \int_{-a-d}^{-a} u_2(y) u_1(y) dy \end{aligned} \quad (15)$$

where  $\mathcal{S}_{2,1}$  is coupling coefficient from waveguide 2 to 1 and  $\mathcal{S}_{1,2}$  is vice versa.  $\mathcal{S}_{2,1}$  and  $\mathcal{S}_{1,2}$  is equal to  $\mathcal{S}$  when the waveguide coupling is symmetric, i.e.  $n_2 = n_1$  and of course  $\beta_2 = \beta_1$ . Eq.(15) shows that the coupling coefficient  $\mathcal{S}$  is mostly determined by the structure design of the waveguide coupler, which is represented by the distance between waveguides  $2a$  that is fixed, the waveguide refractive index  $n_2 = n_1$  that is fix and the surrounding refractive index  $n$  that can be varying due to the variation of the refractive index medium. The variation of refractive index medium between 2 waveguides in the coupler as shown in Fig.4 will be sensed as variation of  $\mathcal{S}$  coefficient. The total value of sensing waveguide coupling [9] or called as sensor coupling value is defined as  $\kappa_1$ :

$$\kappa_1 = \sin^2 \mathcal{L}_0 \quad (16)$$

Attenuation coefficient  $\alpha_0$ , which is accounted in optical ring resonator propagation loop of Eq.3  $E_2 = E_3 (1-\gamma_0)^{1/2} (1-\kappa_2)^{1/2} e^{-\alpha_0 L} e^{j\beta L}$ , is able to be used to detect the varying of optical parameters medium



**Figure 4. The Illustration of a Single Mode Dielectric Rectangular WG Coupler on Substrate Structure Analysis. For a Symmetrical Waveguide Coupler Structure  $n_2 = n_1 > n$ , where  $n$  is Varying due to the Varying of the Detected Medium. Distance between WGs ( $2a$ ), Wavelength of Light  $\lambda$ , WG Thickness  $d$  and Coupling Area Length  $L_0$  [9]**

surrounding the waveguide ring such as: refractive index, absorption, and scattering. The varying of refractive index medium surrounding the waveguide ring causes the mode confinement inside waveguide varying. Mode confinement variation causes the evanescence part of the mode varying when overlapping the area outside the waveguide. If the area outside the waveguide is absorbing and scattering, then the attenuation coefficient  $\alpha_0$  is determined by complex combination analysis of those three optical parameters.

We have discussed that  $\kappa$  and  $\alpha_0$  parameters are able to be used to detect the varying of optical parameters such as: refractive index, absorption and scattering of the detected medium surrounding the optical ring resonator. The varying of  $\kappa$  and/or  $\alpha_0$  indicate the varying degree of the detected medium. The advantage is that the detection process does not need a destructive and invasive action. The sophisticate detection method is by using OSA and processing the resonant spectral response profile by using a signal processing system, which is complicated and costly.

In this research, we propose a FORR sensor intensity integration detection method which is simpler to be implemented, however it is more accurate, more sensitive, and higher resolution.

### 3. Results and Discussion

We propose the FORR sensor detection technique is based on spectral integration by using direct-loop FORR configuration, as shown on Fig.1. The input is E1 and the detection output is E5. The received signal PE5 at photodiode (PD) is an integration of Resonance Intensity Response Profile with respect to the wavelength and limited by the monochromatic laser source linewidth. The output signal level of PE5 at the receiver photodiode is the representation of the integral intensity response profile of E5.

The following Fig.5 illustrates how the spectral intensity integration detection works. The envelope modulation is the spectral of monochromatic laser source applied at terminal 1 at Fig.1. The spectral response of the optical ring resonator is modulated by the spectral laser source and shown as repeating response. The Receiving Photo-detector receives all received light power, which means integration of receiving power.

To simulate PE5, we integrate Eq. (5) with respect to  $\beta L/2$  limited by monochromatic laser source linewidth at wavelength of 1.55  $\mu\text{m}$ .

$$\int \left| \frac{E_3}{E_1} \right|^2 d \frac{\beta L}{2} = \int \frac{(1-\gamma_0)\kappa}{Z} d \frac{\beta L}{2} \quad (17a)$$

There are 3 solutions regarding to the integral [10]:

$$(1-\gamma_0)\kappa \frac{\text{sign}p}{\sqrt{p(p+q)}} \text{arctg}\left(\sqrt{\frac{p+q}{p}} \text{tg} \frac{\beta L}{2}\right) \text{ if } \left[\frac{q}{p} > -1\right]$$

$$(1-\gamma_0)\kappa \frac{\text{sign}p}{\sqrt{-p(p+q)}} \text{arcth}\left(\sqrt{-\frac{p+q}{p}} \text{tg} \frac{\beta L}{2}\right) \text{ if } \left[\frac{q}{p} < -1, \sin^2 \frac{\beta L}{2} < -\frac{p}{q}\right]$$

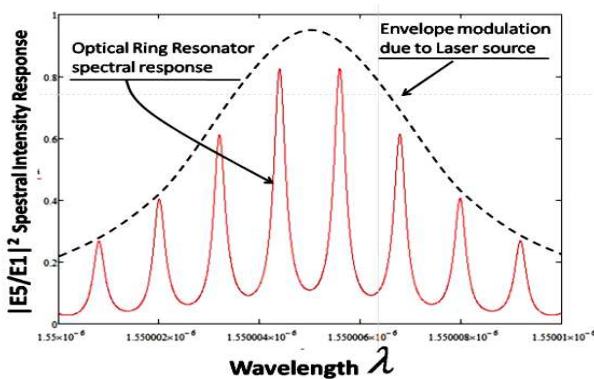
$$(1-\gamma_0)\kappa \frac{\text{sign}p}{\sqrt{p(p+q)}} \text{arctg}\left(\sqrt{\frac{p+q}{p}} \text{tg} \frac{\beta L}{2}\right) \text{ if } \left[\frac{q}{p} < -1, \sin^2 \frac{\beta L}{2} < -\frac{p}{q}\right] \quad (17b)$$

where:

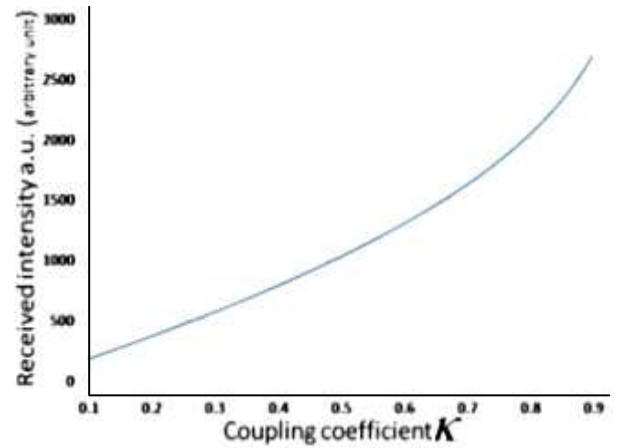
$$p = \left(1 - (1-\gamma_0)^{1/2} (1-\kappa)^{1/2} e^{-\alpha_0 L}\right)^2 \text{ and}$$

$$q = 4(1-\gamma_0)^{1/2} (1-\kappa)^{1/2} e^{-\alpha_0 L}$$

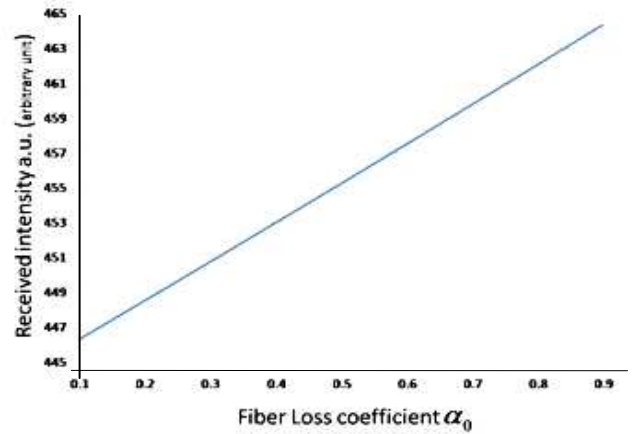
Fig.6 shows the varying of PE5 due to variation of  $\kappa$  and  $\alpha_0$ . As shown on Fig. 6(a), the ratio of received intensity to the change of  $\kappa$  is  $dPE5/d\kappa = 2500$  in  $\kappa$  range from 0.3 to 0.7 and  $dPE5/d\kappa = 5000$  in  $\kappa$  range



**Figure 5. Illustration of the Concept how the FORR Sensor Detection Technique based on Spectral Intensity Integration Works**



(a)



(b)

**Figure 6. The Simulation of PE5 the Spectral Integration Receiving Intensity of FORR Detection Technique based on Varying: (a)  $\kappa$  and (b)  $\alpha_0$ . Simulation Uses a Typical Fiber-optical Values of:  $L=0.1$  m,  $\kappa=0.1$ ,  $\gamma=0.05$  and  $\alpha_0=69E-5/m$**

from 0.7 to 0.9. On the other hand, as shown on Fig.6 (b), the ratio of received intensity to the change of  $\alpha_0$  is  $dPE5/d\alpha_0=22.5$ .

From the simulation  $dPE5/d\kappa \gg dPE5/d\alpha_0$ , we show that detection based on  $\kappa$  variation at the coupling part is much more sensitive in comparison to detection of  $\alpha_0$  variation at the waveguide ring part.

## 4. Conclusions

We propose our future research in developing a simple in-situ fiber-optic ring resonator type bio-sensor with detection technique based on spectral intensity integration. We show that by varying  $\kappa$  and  $\alpha_0$ , will result in varying received signal PE5.

The relationship between PE5 and the detecting parameters ( $K$  and  $\alpha_0$ ) are very linear as shown on Fig.6. The linearity will ensure the accuracy of the measurement, while the large gradient will ensure the higher resolution of detection. In the near future, we will realize and fabricate the system.

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