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OPTICAL FIBER LOSS ANALYSIS FOR AN APPLICATION OF SPECTROPHOTOMETER SYSTEM

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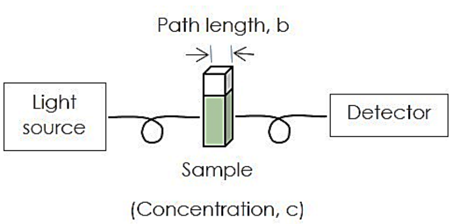
Graphical abstract



Abstract

Loss analysis due to the insertion of optical fiber in short wavelength spectrophotometer system is experimentally conducted to improve resolution and flexibility of the system design. In this paper, type, length and bending diameter of the optical fiber are analyzed as a preliminary work towards the development of a low-loss spectrophotometer system. In order to analyze a suitable type of fiber to be adopted in this system, a 20 mm length and 0 mm bending diameter of a single-mode fiber (SMF), multi-mode fiber (MMF) and Polymethyl methacrylate (PMMA) fiber are tested. The length and bending diameter of the suitable fiber is then varied from 20 mm to 60 mm and 6 mm to 22 mm respectively. In this paper, light emitting diode (LED) centered at 525 nm wavelength with 35 nm full width half maximum (FWHM) is used as the spectrophotometer light source while silicon photodiode is used as the detector. In this work, photodetector output voltage is recorded to analyze the loss contributed by these three parameters. At this particular wavelength, PMMA is found to be a suitable fiber to be adopted due to its minimal loss performance. Besides the fiber type, having a minimal fiber length with maximal fiber bending diameter can reduce loss due to the insertion of optical fiber in spectrophotometer system, hence improving the spectrophotometer resolution performance.

Keywords: Spectrophotometer, flexibility, optical fiber, low loss

Abstrak

Analisis kehilangan akibat penambahan gentian optik dalam sistem spektrofotometer gelombang pendek dijalankan untuk meningkatkan resolusi dan fleksibiliti reka bentuk sistem. Dalam artikel ini, jenis, panjang dan diameter lenturan gentian optik dianalisis sebagai kerja-kerja awal ke arah pembangunan sistem spektrofotometer berkehilangan rendah. Bagi menganalisis jenis gentian yang sesuai digunapakai dalam sistem ini, 20 mm panjang dan 0 mm diameter lenturan gentian mod tunggal (SMF), gentian mod pelbagai (MMF) dan gentian *polymethyl methacrylate* (PMMA) diuji. Kemudian, panjang dan diameter lenturan gentian yang bersesuaian diubah daripada 20 mm hingga 60 mm dan 6 mm hingga 22 mm bagi kedua-dua parameter ini. Dalam artikel ini, diod pemancar cahaya (LED) beroperasi di 525 nm panjang gelombang dengan 35 nm lebar penuh separuh maksimum (FWHM) digunakan sebagai sumber cahaya spektrofotometer, manakala silikon foto diod digunakan sebagai pengesan. Dalam artikel ini, voltan output pengesan foto dirakam untuk menganalisis kehilangan yang disumbangkan oleh ketiga-tiga parameter. Pada panjang gelombang ini, PMMA didapati merupakan gentian yang sesuai untuk diguna pakai kerana prestasi kehilangan yang minimum. Selain jenis gentian, panjang gentian yang minimum dengan diameter lenturan gentian yang maksimum boleh mengurangkan kerhilangan akibat penambahan gentian optik dalam sistem spektrofotometer, seterusnya meningkatkan prestasi resolusi spektrofotometer itu.

Kata kunci: Spectrophotometer, fleksibiliti, gentian optik, kehilangan rendah

1.0 INTRODUCTION

Spectrophotometer system has received much attention in recent years due to its ability in determining liquid concentration and impurities in organic molecules, both of which are important in biomedical and chemistry field. Basic spectrophotometer system consists of light source, sample and detector. Most of the commercial spectrophotometer nowadays are constructed using laser as the light source, which are bulky in size and expensive [1, 2]. On the basis of the matter, reducing the size and cost of spectrophotometer will make it suitable for wider range of applications such as biomedical home care device.

Most of the light sources for the commercial spectrophotometers such as halogen and deuterium light are developed using laser [3, 13, 14, 16-19]. Though these light sources offer a wide range of wavelength, they are expensive and significantly large. Recently, LED has been utilized in the development of spectrophotometers due to its advantages on energy efficiency, small sizes and cost effectiveness [4-7]. As for the spectrophotometer detectors, color sensor, photodiode and charge-coupled device (CCD) sensor are used depending on the requirement of spectrophotometer resolution and light source wavelength range [4-15].

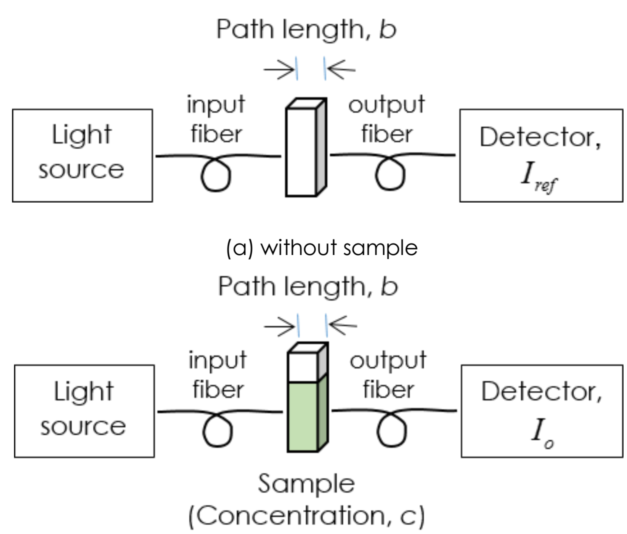
Despite the basic configurations of spectrophotometer, previous inventions also added other components such as optical fiber in the system [8, 16-19]. Previously, optical fiber has been adopted to filter certain wavelength range for the improvement of spectrophotometer transmittance precision [8, 16, 17]. Optical fiber has also been used for system sensitivity improvement [18] and offer flexibility in the system design [19]. Regardless of these advantages, the usage of optical fiber in spectrophotometer system will cause optical loss hence affecting the spectrophotometer resolution performance.

Choosing the suitable type, length and bending radius of optical fiber will minimize loss in the spectrophotometer system. In view of the matter, this paper presents an analysis of the optical fiber type, length and bending radius for short wavelength spectrophotometer application. A simple spectrophotometer system constructed using LED and photodiode has been developed for this testing purposes. This testing and its analysis will provide a guideline on how to choose a suitable fiber type, length and bending radius for the development of a low-loss spectrophotometer system.

1.1 Spectrophotometer System

Spectrophotometer system quantifies the concentration of a specific substance by comparing the light intensity before and after it passes through the sample at a specific wavelength. The relationships between the before-and-after sample output light indicates the absorbance, *A*, caused by the substance. The substance concentration, *c*, can be calculated by determining the absorbance, *A*, for a specific sample path length, *b*. Beer-Lambert law stated in equation 1 presents the relationship between these parameters. Equation 1 also indicates that absorbance caused by substance in the sample, can be measured by determining the ratio between the intensity of the output light with sample, I_o and output light without sample I_{ref} . Basic configurations of the spectrophotometer system with input and output fiber is illustrated in Figure 1.

$$A = \varepsilon cb = \log \frac{I_{ref}}{I_o} \qquad \text{(Eq.1)}$$



(b) with sample

Figure 1 Spectrophotomerer system with an addition of input and output optical fiber

In this paper, the light intensity is measured using photodetector. Thus, the light intensity, I_o and I_{ref} are analyzed based on photodetector output voltage, $V_{Photo\,detector}$. Both these parameters are direct proportional with the detected voltage as stated in equation 2 and equation 3 [29].

$$I_o \;\alpha\; V_{\text{Photodetector}} \quad \text{[Eq.2]}$$

$$I_{ref} \;\alpha\; V_{\text{Photodetector}} \quad \text{[Eq.3]}$$

In the spectrophotometer system, resolution performance can be quantified by measuring capability of the system to distinguish the closest adjacent sample concentration value. In the proposed system, the concentration is detected by detecting photodiode output voltage. Minimizing losses in the system allow for a larger range of detected voltage, ΔV that represent the specific range of sample concentration, Δc, hence improving capability of detecting the smallest sample concentration value. Previous research conducted by Redding B. and Chao H. has improved spectrophotometer resolution performance by having a multimode fiber that contributes to a low loss spectrophotometer system [28].

2.0 METHODOLOGY

In this section, working principle and experimental setup of a basic spectrophotometer with fiber insertion is discussed. To analyze the loss in this system, a green LED centered at 525 nm wavelength with 35 nm full width half maximum (FWHM) is arranged in series with a 2 cm optical fiber and a silicon photodiode. The photodiode has 0.3 A/W responsivity performances at this particular wavelength. In this experiment, the detected light is measured using multimeter in the form of output voltage, $V_{\text{Photodetector}}$. This experimental setup has 0.05 mm air gap in between LED to fiber and fiber to photodiode connection as illustrated in Figure 2.

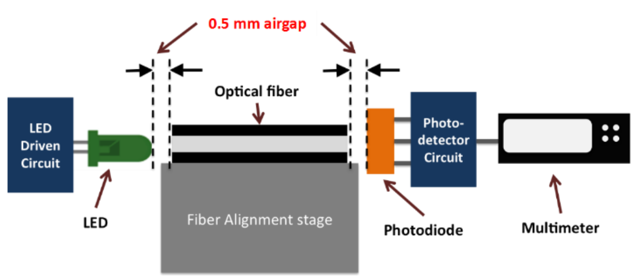


Figure 2 Basic experimental setup

In general, loss of light energy in optical fiber can be categorized into four main factors which are absorption, scattering, dispersion and bending. Loss caused by all these factors vary according to the different types of fiber as influenced by the different materials used in their fabrication. However, loss due to the first three factors are proportional with length while bending loss is proportional with bending diameter configuration of the optical fiber. In this paper, loss in the system is calculated using Equation 4 [30].

$$L_{dB} = 20\log\frac{V_o}{V_i} \quad \text{[Eq.4]}$$

where V_i and V_o are input and output voltage of the system respectively.

2.1 Loss Due to Different Type of Fiber

In fiber optics, absorption, scattering and dispersion loss will result in light dimming at the fiber tip. Absorption depends on electron vibration that occurs at a specific frequency, which is commonly known as the natural vibration frequency [20]. As for scattering loss, it is caused by fluctuations in the refractive index through the fiber material. Dispersion loss also depends on the refractive index of the optical fiber. Therefore, loss of light in the spectrophotometer system using the optical fiber may differ at different wavelengths of the light source and fiber material.

In this paper, three types of fiber are tested; Single Mode Fiber (SMF), Multimode Fiber (MMF) and Polymethyl methacrylate (PMMA) fiber. The core material of PMMA fiber is PMMA itself while the core of SMF and MMF is silica. Since these fibers are fabricated using different materials and configurations, it will result in different amounts of loss. Figure 3 shows the loss in PMMA and Silica fiber for wavelengths ranging from 400 nm – 900 nm [21]. From the graph, the PMMA fiber is found to be more suitable for short wavelength applications since it experiences lower loss at the short wavelength range compared to Silica [22]. Meanwhile, Silica shows better performances at long wavelength region [22].

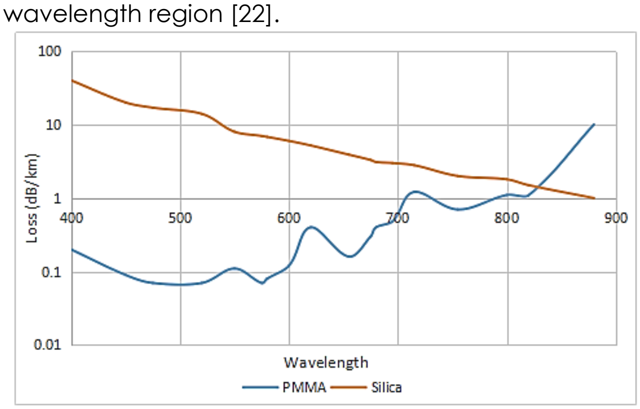


Figure 3 Loss in PMMA and Silica fiber [20, 21]

2.2 Loss Due to Fiber Length

As stated previously, loss due to absorption, scattering and dispersion in optical fiber are proportional with the length of the fiber. Therefore, in this section, five different lengths of PMMA fiber are analyzed to investigate the impact of using a longer fiber in a spectrophotometer system. Since this system is normally constructed using short fiber, the maximum length is set to 6 cm. Similar experimental setup as in Figure 2 is used for loss analysis due to fiber length, except that the length, L now is varied from 2 cm, 3 cm, 4 cm, 5 cm and 6 cm as shown in Figure 4.

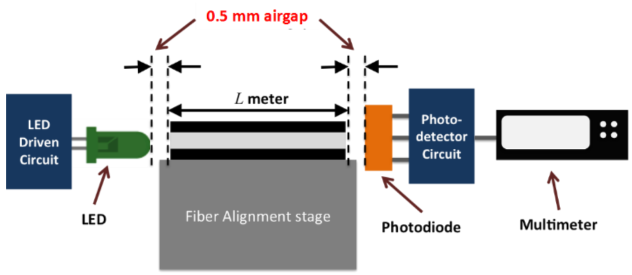


Figure 4 Loss analysis for various fiber length experimental setup

2.3 Loss Due to Fiber Bending

Bending loss occurs when an optical fiber undergoes bending. There are two types of fiber bending which are macroscopic and microscopic bending. Macroscopic bending occurs when the bending diameter is larger than the fiber diameter while microscopic bending occurs when the core or cladding undergoes a slight bend at its surface [22]. In this paper, only macroscopic bending loss is measured since the analysis involves an external bending of the optical fiber.

Macroscopic bending loss is dependent on fiber core refractive index, n_1, fiber cladding refractive index, n_2 as well as wavelength, λ of the light propagated in the fiber. Minimum bending radius can be calculated using the critical radius, R_c as stated in Eq. 5. This equation shows that fiber loss can be reduced by using larger refractive index differences [23]. Furthermore, shorter wavelength implies a lower critical bend radius which is considered more suitable for less bending loss effect [24].

$$R_C = \frac{3n_1^2\lambda}{4\pi[n_1^2 - n_2^2]^{3/2}} \quad \text{(Eq.5)}$$

The PMMA fiber used in this analysis has n_1=1.492 and n_2=1.42 [27]. Therefore, at 525 nm wavelength, the calculated critical radius is found to be 2.9 μm and the critical diameter is 5.8 μm. This analysis is conducted using 6 mm, 10 mm, 16 mm, 18 mm and 22 mm bending diameter and constructed by 2 cm length of PMMA fiber. The experimental setup used for this measurement is illustrated in Figure 5.

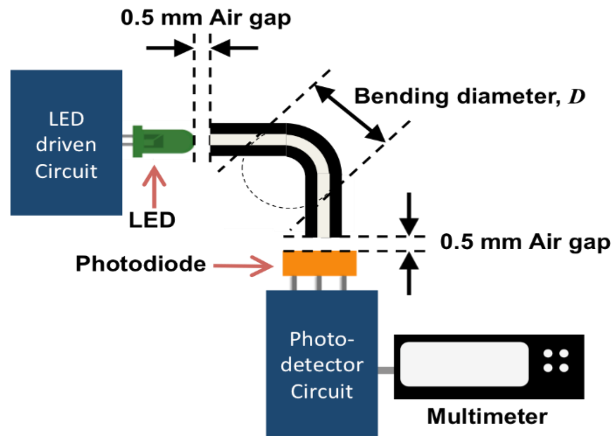


Figure 5 Block diagram for analysis on bending diameter

3.0 RESULT AND DISCUSSION

In this paper, three analyses are conducted to determine the suitable optical fiber type, length and bending radius that contribute to a low loss in a basic spectrophotometer system.

3.1 Loss Analysis Due to Different Type of Fiber

In this experiment, at a specific 525 nm wavelength, 2 cm length of fiber with 0.1 mm air gap in the system produce $V_{\text{Photodetector}}$ of 0.329 V, 0.464 V and 5.515 V for SMF, MMF and PMMA type of fiber respectively. This $V_{\text{Photodetector}}$ pattern agrees well with the loss for Silica and PMMA fiber core material at the short wavelength range. This analysis proves that PMMA is the suitable fiber type to be adopted in a short wavelength spectrophotometer system application. In this experiment, $V_{\text{Photodetector}}$ without fiber and air gap is 5.528 V while loss due to 1 mm air gap is found to be 0.01 V. Therefore, loss due to fiber insertion in the system is calculated to be -24.5 dB, -21.5 dB and -0.02 dB for SMF, MMF and PMMA type of fiber respectively. The following section will discuss an analysis of loss due to the length and bending radius of PMMA fiber.

3.2 Loss Analysis Due to Fiber Length

Recorded loss due to increment of fiber length is plotted in Figure 6. This figure shows that the increment of fiber length linearly increases loss in the system. Therefore, the length of the fiber in spectrophotometer system must be set at a minimal to reduce loss in the system and at the same time, increase resolution of the system [28].

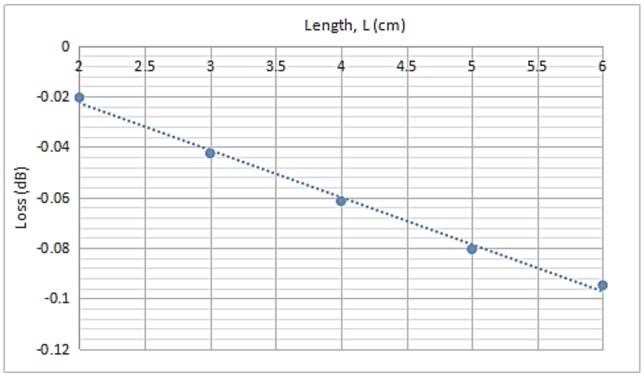


Figure 6 Loss due to different length of PMMA fiber

3.3 Loss Analysis Due to Fiber Bending

Recorded loss due to fiber bending experiment is visualized in Figure 7. The loss pattern indicates that an increment of 4 mm bending radius will reduce about 2 dB loss in the system. This graph shows that the bending diameter of fiber used in the spectrophotometer system needs to be as large as possible in order to minimize loss in the system.

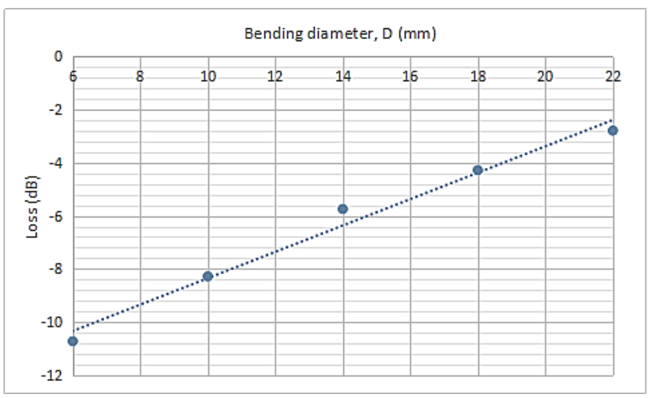


Figure 7 Loss due to different value of PMMA fiber bending diameter

4.0 CONCLUSION

Optical fiber offers several advantages to spectrophotometer system which include design flexibility. For short wavelength spectrophotometer system, PMMA is found to be the best fiber to be adopted due to the lower absorption, scattering and dispersion loss compared to Silica fiber such as SMF and MMF. The length of optical fiber in spectrophotometer system must be kept as short as possible for a low loss spectrophotometer as this helps to improve the system resolution. In contrast, the fiber bending diameter in this system must be set as large as possible. Findings from this experiment is essential as a guideline in choosing the type and configuration of optical fiber for a short wavelength spectrophotometer application.

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