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Detection of Back-Scattered Signal for Optical Fibre Resonant Scanner

(Pengesanan Isyarat Serak-Balik untuk Pengimbas Gentian Optik Resonans)

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ABSTRACT

We report the development of optical fibre resonant scanner that was developed using two multi-mode optical fibres that are attached side-by-side, producing a cantilevered optical fibre scanner. The optical fibre is mounted on photodiode and a small piezoelectric disk using polymer. The piezoelectric disk is driven with a sinusoidal signal that will then vibrate the mounted optical fibre, producing a single axis scan line. This paper reports on experimental detection of the back-scattered signal through dual-numerical aperture conFigureuration and identification of fibre position from a single scan line with respect to the optical reflections from the apertured reflector. The apertured reflector used was a brass metal with 1 mm of diameter that is placed before the imaging lens as a mechanism to differentiate the position of scan line. The single scan was obtained at its maximum length of 4.8mm with resonant frequency of 2.033kHz. The back-scattered signal from a target object is coupled back into the cladding of the optical fibre. The cladding mode is then stripped and detected by photodiode. The back scattered signal from the aperture is used to differentiate the position of fibre between the aperture and the target object itself. Differences in the position of the slots resulted pulses with different height and width, allowing the two back-scattered signals to be distinguished. The experimental result is verified and compared with the theory back-scattered signal produced by such scanner.

Keywords: Endoscopic Imaging; Fibre Scanner; Optical Imaging

ABSTRAK

Kertas kerja ini melaporkan pembangunan pengimbas resonans gentian optik yang dibangunkan menggunakan dua gentian optik mod berbilang yang dilekatkan bersebelahan dan menghasilkan pengimbas julur tuas gentian optik (cantilevered optical fibre scanner). Gentian optik dilekatkan pada fotodiod dan cakera piezoelektrik yang kecil dengan menggunakan polimer. Cakera piezoelektrik didorong dengan isyarat sinusoidal yang kemudiannya akan menggetarkan gentian optik yang telah dipasang, lalu menghasilkan garis imbasan paksi tunggal. Kertas kerja ini juga melaporkan pengesanan isyarat serak balik secara eksperimen melalui konFigureurasi dwi-apertur berangka (dual numerical aperture) dan pengenalpastian kedudukan gentian optik dari satu garis imbasan yang berkaitan dengan refleksi optik yang berasal dari refektor apertur. Reflektor apertur yang digunakan adalah logam tembaga dengan diameter 1 mm yang diletakkan sebelum lensa pengimejan sebagai mekanisme untuk membezakan kedudukan gentian optic dengan garis imbasan. Imbasan tunggal diperolehi pada imbasan maksimum sepanjang 4.8 mm dengan frekuensi resonans 2.033kHz. Isyarat serak-balik dari objek sasaran digandingkan ke dalam lapisan mod salut gentian optik. Isyarat di mod salut kemudian dikesan oleh fotodiod. Isyarat serak-balik dari apertur digunakan untuk membezakan kedudukan gentian optic antara apertur dan objek sasaran itu sendiri. Perbezaan dalam kedudukan slot menghasilkan denyutan dengan ketinggian dan kelebaran yang berbeza, yang membolehkan kedua-dua isyarat dapat dibezakan. Hasil eksperimen disahkan dengan simulasi teori isyarat serak balik yang dihasilkan oleh pengimbas tersebut.

Kata kunci: Pengimejan Endoskopi; Pengimbas Gentian Optik; Pengimejan Optik

INTRODUCTION

Optical fibre or waveguide are normally used in optical communication systems (Ab-Rahman et al. 2010). Optical imaging technique is a method to obtain an image of a target object of interest. In large scale imaging technique, a technique called LIDAR/LADAR has been developed and is used to detect palm fruit ripeness (Zulkifli et al. 2018). Similar method has also been developed using optical fibre (Leach et al. 2015). In small size of target object, endoscopic imaging probe is a tool to obtain images of a target object that is typically difficult to reach with a standard microscopy technique. An endoscope or endomicroscope utilizes optical fibre to guide the back-scattered signal from a target object to a photodetector or camera. Owing to the mechanical flexibility, ability to contain the light within its core and cladding and the small size diameter of optical fibre (125-200 μm), majority of endoscopic system is normally built with optical fibre as the main waveguide.

Varieties of techniques are used in the endoscopic imaging. For instance, many authors used fibre, MEMS mirrors (Hwang et al. 2017) and resonant optical fibre scanner (Mokhtar & Syms 2014a) (Qiu & Piyawattanamatha 2017). The MEMS based components with optical fibres can be integrated into optical imaging modalities such as optical coherence tomography, confocal microscopic and multiphoton microscopy (Qiu & Piyawattanamatha 2017).

Although many literatures have reported a success of two-dimensional imaging using Lissajous (Hoy et al. 2011; Hwang, Seo, Ahn, et al. 2017; Mokhtar & Syms 2015; Park et al. 2012), spiral (Engelbrecht et al. 2008; Myaing et al. 2006; Oh et al. 2013) and raster scan (Rivera et al. 2011), most optical probes require the use of quadruple tubular piezoelectric (Moon et al. 2010; Wu et al. 2010), electrothermal fabrication of cantilever drive and piezoelectric disk (Seo et al. 2017) and membrane (Khayatzadeh et al. 2017). Different mechanisms of detection technique are also used to detect the back-scattered signal from the target object. For example, some inventors used position sensing detector (Leach et al. 2015) placed in between the waveguide and target object. Others have used a separate optical fibre and beam splitter or coupler to obtain the back-scattered signal (Tsai et al. 2014). While all the inventions are successful, the system setup and image reconstruction algorithm are complicated. More importantly, most papers do not discuss in detail on the back-scattered signal obtained during the experiment even though the image has been successfully reconstructed.

In this paper, we demonstrate a simple one-dimensional optical fibre scanner that only utilises a mechanically excited sinusoidal single scan line in vertical axis. A similar arrangement was proposed in (Mokhtar & Syms 2014b, 2015). In most literatures, the main focus of the papers is the driving mechanism or frequency ratio determination. But, most papers actually lack discussion in the building construction of the dual-core cantilevered optical fibre and also lack of explanation on identification back-scattered signal detection. One of the important features of this scanner lies on the use of metal aperture placed before the imaging lens. This is important because in order to obtain position sensing of the cantilevered fibre with respect to the scan line position and data from target object, the interlacing pulse segments within the logged data is analysed for further image reconstruction algorithm. Without the aperture, this task is impossible. This algorithm has been discussed extensively in (Mokhtar & Syms 2014a, 2014b, 2015). Here, we extend the idea of using interlacing pulse to extract the information of resonating fibre with respect to the position of the fibre.

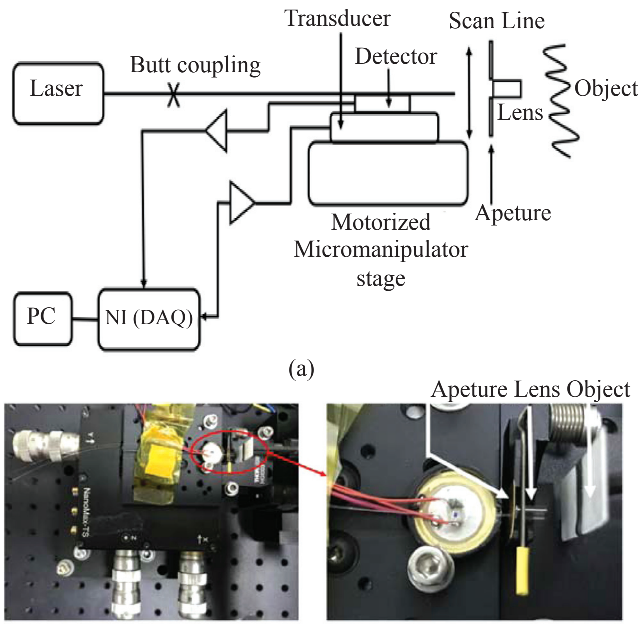
METHODOLOGY

In this section, the design of the scanner is discussed. The optical fibre is mounted on the photodetector, placed on the piezoelectric disk and attached to the micromanipulator stage. The differences are a smaller size piezoelectric disk is used and the bare fibre is the multi-mode type. The fibre is simply stripped, cleaved and mounted on the piezoelectric disk using index matching polymer. When the light is scanned on the target object, the target object will absorb and reflect some of the optical power diffusively. Some of the back-scattered signal will be coupled into the cladding via dual numerical aperture operation. The dual numerical aperture operation reduces the optical components needed to detect the back-scattered signal such as the cumbersome beam splitter or coupler. The diffusive reflected rays possess variety of scattered angle of entrance to the same optical fibre. Only the modes that fulfil the waveguide condition will be coupled back into the fibre that travels in to opposite direction of the illumination light. The backscattered signal from the target object is then coupled into the cladding and the mode will be stripped by the mode stripper and hence detected by the photodiode.

Here, we present the building construction of the dual-core cantilevered optical fibre and the experimental signal of the back-scattered signal identification as compared the theoretical signal. We investigate the signal from single scan line based on the backscattered signal from the target object. This is crucial in order to extract the relevant back-scattered signal that only belongs to target object for image reconstruction algorithm.

SCANNER DESIGN

Figure 1(a) shows the schematics of the scanner design. Note that there are two planes, namely calibration and imaging plane shown in the Figureure. The calibration plane is used to determine the initial scanning position of the fibre and the imaging plane is to place the target object within the focus point. Figure 1(b) shows the real setup for this experiment. The light from the laser diode source with wavelength of 635 nm is butt-coupled into the multimode fibre. The transducer piezoelectric disk was placed near the free end of the optical fibre, forming a short cantilever. Transducer was driven with sinusoidal voltage from NI data acquisition card and amplifier, cause a vibration in cantilever and forming a scan line. The detector was surface-mount PIN photodiode with trans-impedance amplifier and attached on the transducer. A glass slide was placed between a photodiode and transducer to prevent any short circuit between them. The aperture reflector was a thin brass metal with 1 mm of diameter and GRIN lens was a 1.8 mm diameter. The fibre and target object were mounted on the x-y-z stage and aperture reflector was attached with in front of lens surface. The position of scan line is adjusted using motorized micromanipulator stage. The target object will be scanned through the aperture reflector and imaging lens. Backscattered signal from the target object and aperture will be coupled back into the cladding and detected by the photodiode. The aperture lies in the calibration plane and the target object is in the imaging plane. In theory, due to the different position of calibration and imaging plane, the backscattered signal from the aperture and target object will produce different magnitude of pulse. In such case, theoretically the back-scattered signal from the apertured reflector and target object will have higher and lower amplitude respectively. Hence the position of the scan line can be easily identified. The weak signal that is detected by the photodiode is amplified by the transimpedance amplifier.



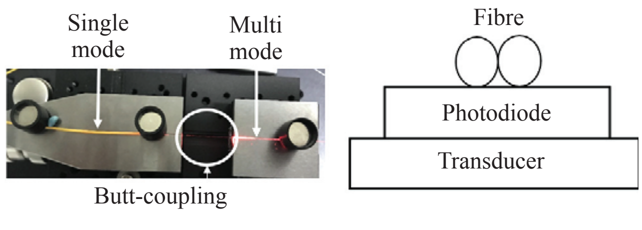
(b)

FIGURE 1. (a) Scanner design schematic, (b) Experimental setup

OPTICAL FIBRE PREPARATION

In this section, the preparation of the fibre optic will be discussed in detail. The coating layer or jacket is removed with conventional stripping tools to expose the cladding. The fibre is then cleaned from any debris after stripping with the isopropyl alcohol. After the cleaning process, both end of the fibre was cleaved using a cleaver to make sure the end face is perfectly flat. To make sure fibre was cleaved properly, both end of fibre is launched with laser source as shown in Figure 2(a). A point of light source will be seen at the other end of the fibre. If there is no light that is emitted from the end of the fibre, the cleaving process must be repeated.

Once this process is done, the two cleaved fibres are attached side by side with the polymer (glue) as shown in Figure 2(b). This method is performed due to the geometrical issue of the optical fibre which the shape of fibre is circular. Due to the fibre is circularly in shaped; when the fibre is excited in one direction it will excite both the vertical and horizontal bending modes. As a result, an elliptical scan will be formed where only one-dimensional scan line is intended. This is because the second moment area of a circle is $I_{xx} = I_{yy} = \pi r^4/2$, resulting in frequency ratio is equal to one. To mitigate from this issue, hence two fibres are used in the construction where the frequency ratio is now modified $I_{xx} = \pi r^4/2$ and $I_{yy} = 5\pi r^4/2$, giving frequency ratio of high and low resonances of $\omega_{high} / \omega_{high} = \sqrt{5}$. Because of the non-unity value, the fibre is now fundamentally able to undergo a single scan line as intended. After the drying process of the polymer, finally the laser source is then launched and coupled into the tailored multimode fibre that is placed on the manual micromanipulator stage. Micro-manipulator stage is used to adjust in x-y-z direction to position the butt coupling.



(a) (b)

FIGURE 2. (a) Butt coupling of laser source, (b) cross-section of dual fibre

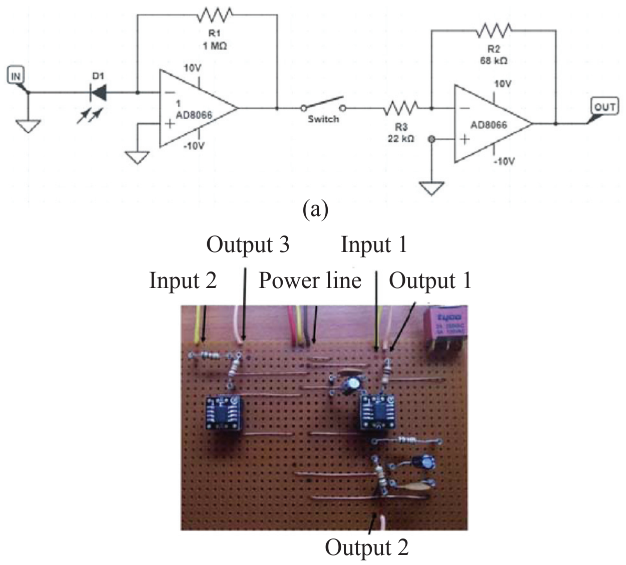
TRANSIMPEDANCE DESIGN

Figure 3(a) and 3(b), shows the schematics and circuit of amplifiers used in the experiment. Two types of amplifier are used in the experiment, namely the inverting and trans-impedance amplifier. Since only weak signal from backscattered signal is detected by photodiode, trans-impedance amplifier must be used to amplify the signal for the computer system to read the data. The light is detected by the photodiode and is converted into the electrical signal. The signal is then fed to the NI Data Acquisition Card and transferred into PC. High performance of FastFET amplifier (AD8086) was used because its low input bias current of 1 pA and high gain bandwidth product (GBP) of 145 MHz at unity gain. The design consists of two outputs, one is trans-impedance amplifier (TIA) and another one in inverting amplifier. An inverting amplifier is optional because it will be used when the voltage output of TIA is insufficient for the NI DAQ to read the data.

RESULTS AND DISCUSSION

OPTICAL POWER MEASUREMENT

Before performing experiment, the measurement of optical loss and attenuation was conducted. This measurement describes the difference amount of light sent into the transmitting end of an optical fibre and the amount of light successfully received at the free end. The optical loss is caused by absorption by the core and the cladding, the mode leaking into cladding over the distance, insertion loss and connector loss. The black line graph in Figure 4 shows the result of measuring the optical power of a single fibre coupled



(b)

FIGURE 3. Transimpedance and inverting amplifier; (a) schematic (b) circuit

laser directly connected to the optical power meter. This line shows the optimum lasing condition lies in the region of diode current 50 to 75 mA which provides 0 to 9 dBm optical power. The red line shows the measurement using fibre coupled laser source connected to a pigtail optical fibre and the power is measured at the free end. The reduction of optical power is caused by the butt-coupling, connector and fibre loss. Nevertheless, the optical power at the free end is sufficient to be used for imaging operation.

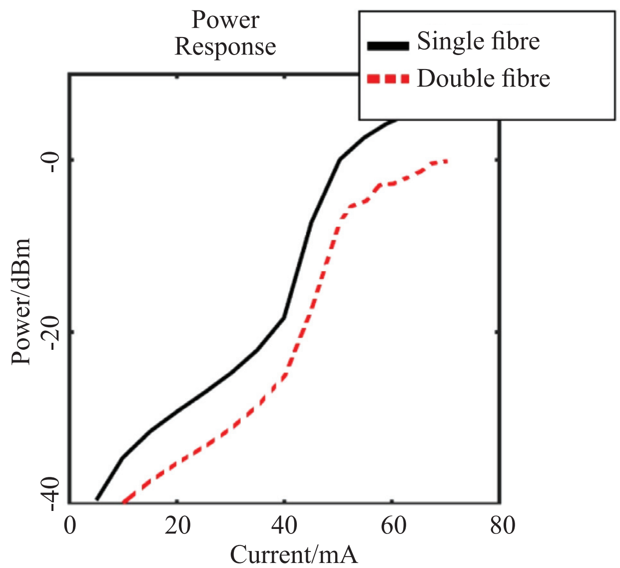


FIGURE 4. Optical power measurement from the source

SCAN LINE

Due to the issue of energy coupling of the orthogonal vibration mode in circular fibre, the scan pattern that is produced is normally elliptical as shown in Figure 5(a) (Park et al. 2014). Before the imaging operation can take place, this issue must be solved first. This method was proposed before (Mokhtar & Syms 2015). But to prove the repeatability, the methodology is simply repeated here. Figure 5(b) shows the line scan that obtained by driving the transducer at resonant frequencies of f = 2.033 kHz and voltage of 20V. Two fibres are attached side by as discussed in methodology section and this is mounted on the transducer. Since the frequency ratio side between the orthogonal bending modes are non-unity, hence, when the fibre is excited in one direction, the resultant scan line is always a one-dimensional scan. Even though the scan line shown is tilted, this is actually due to the imperfection of mounting regime and can be easily corrected in future.

(a) (b)

FIGURE 5. (a) Elliptical scan line (Park et al. 2014) (b) Experimental scan line

BACK-SCATTERED SIGNAL

This section discusses the back-scattered signal obtained during the experiment. In most literature, the back-scattered signal obtained is normally not shown due to its complexity. Here, we demonstrate the experimental signal that is has slight imperfections and distortions which always occur during the experiment. Nevertheless, each portion of the signal is still fundamentally correct and can be theoritically verified. All this justifications can be attributed to the addition of the apertured reflector placed before the imaging lens. This reflector will signify which portion of the signal belongs to which position along the scan line even though the scan line is imperfect. The theory of the one-dimensional optical feedback resonator has been throughly explored by (Mokhtar & Syms 2014b). Here we compare the theory with the result and show the real back-scattered signal that has been converted into electrical for further computational purpose and image reconstruction. The back-scattered signal is obtained when a scan is performed through the reflector and target object as shown in Figure 6(a). The Figureures on the left and right show the side and front view of the scanner, respectively. On the Figureures, there are three positions that are marked by letter A, B and C. Point A signifies the scan extremity, B at the edge of apertured reflector and C is at the centre of aperture which the optical signal will pass through the grin lens onto the target object.

With the annotations in mind, Figure 6(b) shows the experimental back scattered signal that is obtained with respect to the position of the fiber as in Figure 6(a). First, the back-scattered signal that originates from the reflector is identified. From the theory point of view, when the the fibre vibrates at resonance frequency, the position of the pulse peak must align with the zero-crossing of the drive signal. This condition can be easily identified in Figure 6(b) and is marked with two perpendicular black lines on the Figureure. Equivalently, this is the position of the fibre at point B, moving to point A and back to point B which is the full scan on the brass reflector. With similar argument, the rest of the signal must be from the target object only, which is labelled by point B to point C and back to point B. In this section, there is no second positive going pulse at the zero-crossing of the drive. Therefore, it can be concluded that the fibre never reaches the other opposite edge of the reflector, as shown in Figure 6(b). This is due to the imperfection of the scan line and scan length where only one side of pulse is obtained from aperture at zero crossing of the drive signal. Furthermore, the back-scattered signal from the target object consists of two mirrored signals. This is true because the fibre scans the target object at the same path twice, producing a mirrored signal characteristic.

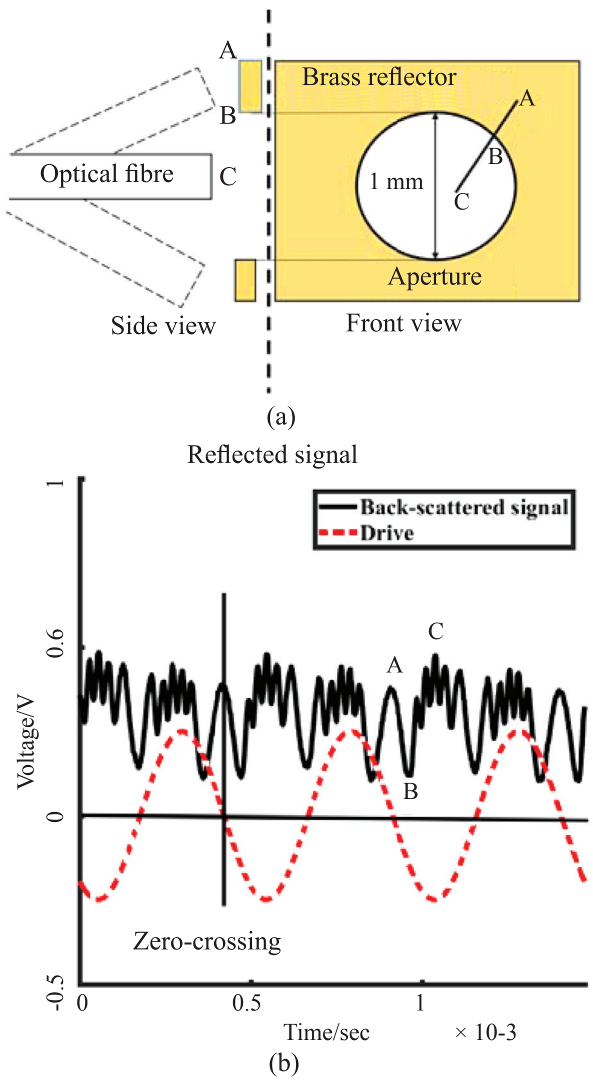


FIGURE 6. (a) Position of the fibre during scanining (b) Back scattered signal

Now, we demonstrate the different condition of fibre, aperture and target object placement and how these conditions affect the back-scattered signal. Figure 7(a) shows the result when the target object is placed at out of focus point of the grin lens. The region where the back-scattered data from the target object has extremely low amplitude. This signifies that the target object is placed at out of focus point. If the target object is placed at the focus point, maximum amplitude will be obtained as shown in Figure 6(a). In Figure 7(b), the fibre is placed relatively nearer to the apertured reflector. This results in slightly higher amplitude at the pulse peak (aligned with zero-crossing drive signal) as compared to Figure 6(a). This is consistent with the theory since the nearer the fibre with the apertured reflector, the higher the optical power that is coupled into the cladding, resulting in higher magnitude of the peak pulse.

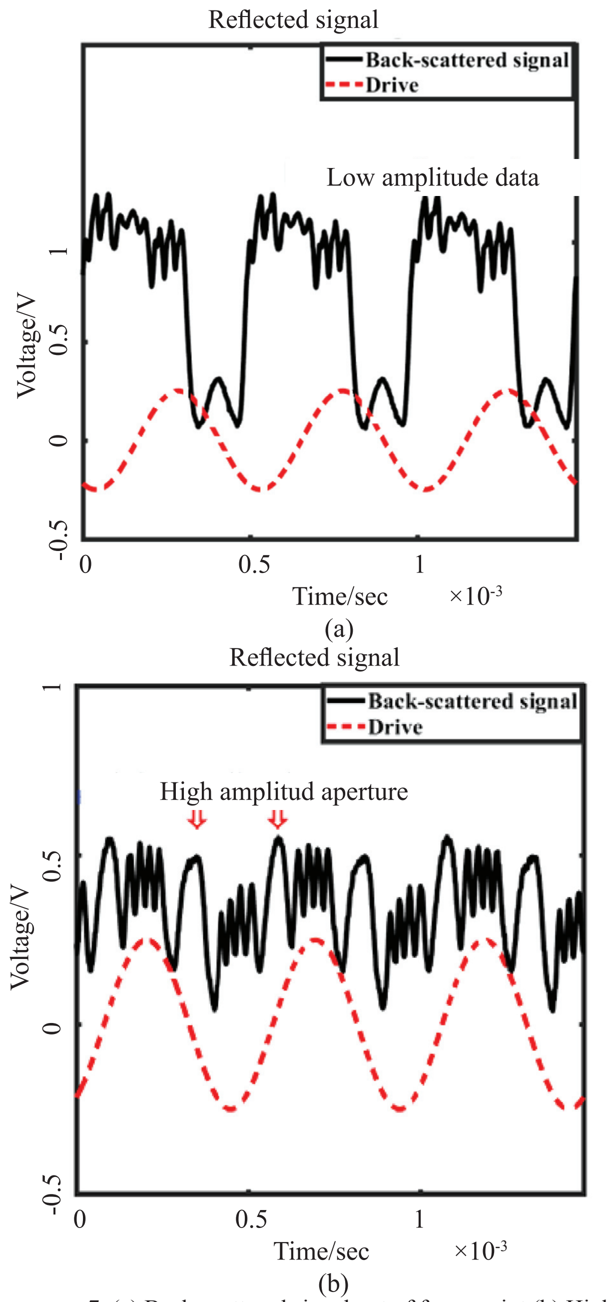
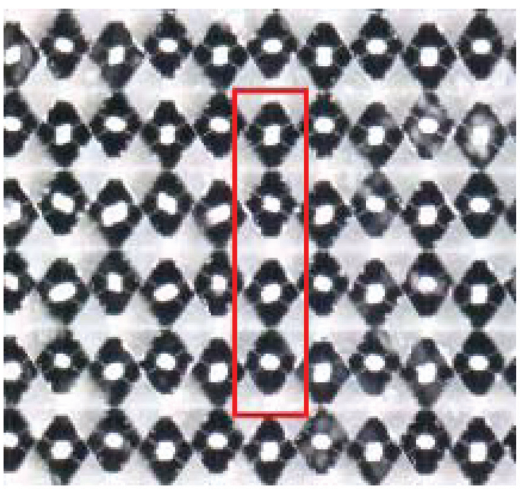
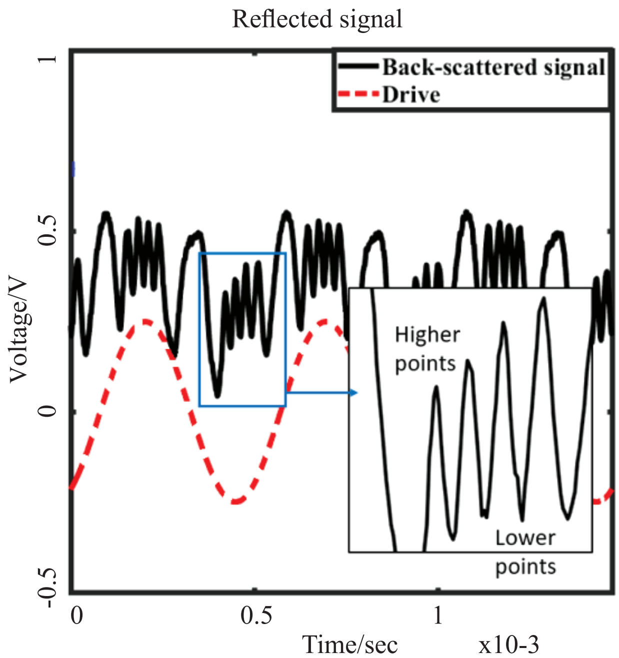


FIGURE 7. (a) Back-scattered signal out of focus point (b) High pulse of an aperture

We now focus on the back-scattered signal of the target object. A few condition must first be calibrated. First, the fibre must be driven at resonant in order to obtain the maximum scan length. This can be ensured by tuning the drive frequency until the maximum scan length can be seen at imaging plane. This process can be further tuned by observing the position of pulse peak with the zero-crossing of the drive. Secondly, the target object must be placed at focus point. This can be ensured by observing the highest amplitude of the back-scattred data from the target object. Thirdly, the fibre must be positioned as close as possible to the apertured reflector. This can be ensured by observing the highest magnitude possible from the apertured reflector and also ensuring the peak pulse is aligned with the zero-crossing of the drive. As an example of one-dimensional scan, we used the reteroflective tape as a target object as shown in Figure 8(a). This target object consists of peaks and valleys that will produce retroreflection when light is shone onto it. Figure 8(b) shows a typical back-scattred signalobtained during the scan. The insert in the Figureure shows the zoomed signal that has high and low magnitude which corresponds to the topography of the target object. The low magnitude signal corresponds to the black surface of the target object while a relatively high magnitude point corresponds to the white white surface. The varying amplitude point of data from the insert represents when the fibre scans on squared marking on the target object. By identifying the exact portion of the signal from the apertured reflector and target object, the image reconstrctuion technique can be continued in the future. More importantly, it is important to appreciate the addition of apertured reflector as a mechanism to identify and correlate the fibre position with respect to the back-scattered signal. Without it, the signal will always look distorted an noisy but actually, the each portion can be easily identied using this method.



(a)



(b)

FIGURE 8. (a) Target object (b) Backscattered signal of target object

CONCLUSION

Based on this experiment, a single scan line can be obtained by attaching two optical fibres side by side, resulting in modification of frequency ratio in the orthogonal axis to be non-unity. Without any modification of cross-sectional area, an elliptical scan will be generated where only single scan line is intended. The fibre is excited with sinusoidal mechanical vibration in vertical axis. Apertures reflector is placed before the imaging lens. Over-scanning the aperture results in varying amplitude indicate that signifies the origin of signal from the aperture and the target object. Therefore, the position of the fibre with respect to the back-scattered signal can be identified. The non-ideal signal of experimental result has been presented. Even though the signal is slightly distorted, the results are consistent with the theory and fundamentally correct. These steps are important for the more complicated two-dimensional scan system such as the Lissajous and spiral scan.

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REFERENCES

Ab-Rahman, M. S., Zain, N. M. & Baharudin, A. 2010. The Design Multi Ratio Optical Splitter (MROS) based on plannar waveguide for an effective power usage. *Jurnal Kejuruteraan* 22: 107-117.

Engelbrecht, C. J., Johnston, R. S., Seibel, E. J. & Helmchen, F. 2008. Ultra-compact fiber-optic two-photon microscope for functional fluorescence imaging in vivo. *Optics Express* 16(8): 5556–5564.

Hoy, C. L., Durr, N. J. & Ben-Yakar, A. 2011. Fast-updating and nonrepeating Lissajous image reconstruction method for capturing increased dynamic information. *Applied Optics* 50(16): 2376-2382.

Hwang, K., Seo, Y. H., Ahn, J., Kim, P. & Jeong, K.-H. 2017. Frequency selection rule for high definition and high frame rate Lissajous scanning. *Scientific Reports* 7(1): 14075.

Hwang, K., Seo, Y. H. & Jeong, K. H. 2017. Microscanners for optical endomicroscopic applications. *Micro and Nano Systems Letters* 5(1): 1.

Khayatzadeh, R., Ferhanoglu, O. & Civitci, F. 2017. Unwarped Lissajous scanning with polarization maintaining fibers. *IEEE Photonics Technology Letters* 29(19): 1623-1626.

Leach, J. H., Chinn, S. R. & Goldberg, L. 2015. Monostatic all-fiber scanning LADAR system. *Applied Optics* 54(33): 9752-9757.

Mokhtar, M. H. H. & Syms, R. R. A. 2014a. Optical feedback control of resonant fibre scanners. In 2014 International Conference on Optical MEMS and Nanophotonics (OMN), 93-94.

Mokhtar, M. H. H. & Syms, R. R. A. 2014b. Resonant fiber scanner with optical feedback. *Optics Express* 22(21): 25629-25634.

Mokhtar, M. H. H. & Syms, R. R. A. 2015. Tailored fibre waveguides for precise two-axis Lissajous scanning. *Optics Express* 23(16): 20804-20811.

Moon, S., Lee, S.-W., Rubinstein, M., Wong, B. J. F. & Chen, Z. 2010. Semi-resonant operation of a fiber-cantilever piezotube scanner for stable optical coherence tomography endoscope imaging. *Optics Express* 18(20): 21183-21197.

Myaing, M. T., MacDonald, D. J. & Li, X. 2006. Fiber-optic scanning two-photon fluorescence endoscope. *Optics Letters* 31(8): 1076-1078.

Oh, G., Chung, E. & Yun, S. H. 2013. Optical fibers for high-resolution in vivo microendoscopic fluorescence imaging. *Optical Fiber Technology* 19(6): 760-771.

Park, H. C., Seo, Y.-H. & Jeong, K. H. 2014. Lissajous fiber scanning for forward viewing optical endomicroscopy using asymmetric stiffness modulation. *Optics Express* 22(5): 5818-5825.

Park, H. C., Song, C., Kang, M., Jeong, Y. & Jeong, K.H. 2012. Forward imaging OCT endoscopic catheter based on MEMS lens scanning. *Optics Letters* 37(13): 2673-2675.

Qiu, Z. & Piyawattanamatha, W. 2017. New endoscopic imaging technology based on MEMS sensors and actuators. *Micromachines* 8(7): 210.

Rivera, D. R., Brown, C. M., Ouzounov, D. G., Pavlova, I., Kobat, D., Webb, W. W. & Xu, C. 2011. Compact and flexible raster scanning multiphoton endoscope capable of imaging unstained tissue. *Proceedings of the National Academy of Sciences* 108(43): 17598-17603.

Seo, Y. H., Hwang, K. & Jeong, K. H. 2017. Compact OCT endomicroscopic catheter using flip-chip bonded Lissajous scanned electrothermal MEMS fiber scanner. *In Micro Electro Mechanical Systems (MEMS), 2017 IEEE 30th International Conference on* 518-52.

Tsai, T.-H., Fujimoto, J. & Mashimo, H. 2014. Endoscopic optical coherence tomography for clinical gastroenterology. *Diagnostics* 4(2): 57-93.

Wu, Y., Zhang, Y., Xi, J., Li, M. J. & Li, X. 2010. Fiber-optic nonlinear endomicroscopy with focus scanning by using shape memory alloy actuation. *Journal of Biomedical Optics* 15(6): 060506.

Zulkifli, Z. M., Hashim, F. H., Raj, T. & Huddin, A. B. 2018. A rapid and non-destructive technique in determining the ripeness of oil palm fresh fruit bunch (FFB). *Jurnal Kejuruteraan* 30(1): 93-101

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