

A study on the effect of light source on 1x2 fiber optic coupler vibration sensor

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A simple extrinsic intensity modulated vibration sensor using 1x2 plastic optical fiber coupler has been designed and the performance of the sensor is studied with different light sources like diode laser (650 nm), LED1 (650 nm) and LED2 (530 nm). The sensitivities of the sensor for these sources are 1.8027 mV/ μm , 2.3597 mV/ μm and 2.483 mV/ μm corresponding to the frequency range up to 750Hz, 1000Hz and 1300Hz respectively with amplitude resolution in microns. The results obtained conclude that the dependence on the source is only on the sensing range of frequency but not considerable effect on the amplitude resolution of the sensor.

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1. Introduction

Fiber optic sensors have been widely used for sensing several physical parameters like vibration, displacement and pressure. The advantage is being high sensitivity, immune to EMI and low cost of maintenance [1-3]. According to their working principle optical fiber vibration sensors are divided into two types; they are i) phase modulation type and ii) intensity modulation type. The first type uses an interferometer such as Fabry-Perot [4], Michelson or Mach-Zehnder [5], as used in self-mixing [6] and Doppler vibrometry [7, 8] to interrogate the phase shift caused by vibration. These methods offer very high performance but exhibit low stability and impose stringent mechanical requirements because their alignment is critical [9]. Consequently, these have a limited practical use. The second type takes the advantage of change in intensity to the corresponding vibration [10].

In this paper, a simple intensity modulated vibration sensor is designed using a 1x2 plastic fiber optic fused coupler [11]. It consists of three ports, port 2 for the coupling of light source, port 1 acts as a sensing head and the port 3 is connected to the photo-detector. Here, a single fiber is used as sensing probe for both transmitting and receiving of light, so it exhibits only single slope. Thus the sensor alignment becomes simpler in comparison with the dual-fiber and bifurcated bundle fiber vibration sensors [12, 13]. The performance of the sensor is investigated for different sources like diode laser (650 nm), LED1 (650 nm) and LED2 (530 nm).

2. Theory

The basic principle of the vibration measurement is intensity modulation with respect to the displacement of the reflecting surface glued on the vibrating target from

the sensing port. The sensor comprises a 1x2 fused 3dB (50:50) fiber optic coupler made of multimode PMMA (Polymethyl Methacrylate) step index fiber. The schematic diagram of the sensing principle is shown in Fig. 1. The light is incident on the reflecting surface (glued to the micrometre translation stage) positioned at a distance of 'x' from the sensing fiber probe (port 1) gets reflected and is coupled into the same fiber. A light source of power P_a is coupled to the port 2 of the coupler and directed to the port 1. The light incident on the reflector is of power P_b via port 1 and the power of light P_c is reflected from the reflector received by the same port 1 and it is a function of the gap between the sensing fiber probe (port 1) and the reflector. The light power received by the photo-detector via port 3 is denoted by P_d .

The light transmitted from the source with power of light P_a through the fiber to the sensing fiber (port 1) is given by [14]

$$P_b = (1 - cr)(10^{-0.1L} - 10^{-0.1D})P_a \quad (1)$$

Where cr , L and D are coupling ratio, excess loss and directivity of the fiber coupler respectively. The reflector is kept parallel to the sensing fiber cross-section and then the power of light coupled back, received by the sending fiber probe is given by

$$P_c = P_i \left(1 - \exp\left(-\frac{2a}{W^2(x)}\right) \right) \quad (2)$$

Where $P_i = kP_b$ is the light power coupled to the sensing fiber at $x = 0$, a is the core radius of the fiber, $W(x) = 2x \tan(\theta) + a$, $k=1.15$ and $\theta = \sin^{-1} NA$ is the divergence angle of the fiber [14]. Substituting equation (1) into (2) and written as

$$P_b = k(1 - cr)(10^{-0.1L} - 10^{-0.1D})P_a \left(1 - \exp\left(-\frac{2a}{W^2(x)}\right) \right) \quad (3)$$

The light power detected by the photo-detector from the sensing port through the port3 is given by

$$P_d = cr(10^{-0.1L} - 10^{-0.1D})P_b \quad (4)$$

Substituting $W(x)$, equation (3) into (4) yield

$$P_d = kcr(1 - cr)(10^{-0.1L} - 10^{-0.1D})^2 \left(1 - \exp\left(-\frac{2}{\left(\frac{2xtan(\theta)}{a} + 1\right)^2}\right) \right) P_a \quad (5)$$

Therefore

$$P_d = P \left(1 - \exp\left(-\frac{2}{\left(\frac{2xtan(\theta)}{a} + 1\right)^2}\right) \right) P_a \quad (6)$$

Where $P = kcr(1 - cr)(10^{-0.1L} - 10^{-0.1D})^2$, cr is coupling ratio, L is excess loss, D is directivity of the fiber coupler, a is the radius of the fiber core, and $\theta = \sin^{-1} NA$ is the divergence angle of the fiber.

For large value of $\frac{2xtan(\theta)}{a}$, equation (6) can be written as

$$P_d = \frac{P}{2} \left(\frac{(2a)^2}{(2xtan(\theta))^2} \right) P_a \quad (7)$$

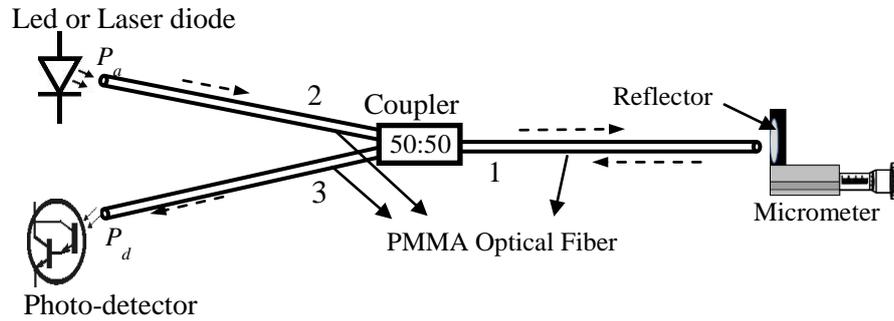


Fig. 1. Working principle of the fiber optic coupler vibration sensor.

This equation is the correlation function of the displacement sensor with multimode fiber coupler. It states that the power received by the photo-detector is directly proportional to the square of the diameter of the fiber and inversely proportional to the square of the distance between the fiber and the reflector. Since the diameter of the fiber is constant, the power received by the photo-detector is only a function of the distance between the sensing probe and reflecting surface [15].

A simple photo-detection circuit is used to convert the light intensity into equivalent voltage. Generally, the output voltage with respect to the intensity of incident light on photo-detector (P_d) is given by [16]

$$V_{out} = R_\lambda P_d R_E \quad (8)$$

Where $R_\lambda = \eta g \frac{\lambda}{1.24}$ is the responsivity of the photo-detector, R_E is the feedback resistance, η , λ and g are the quantum efficiency, wavelength of the incident light and photoconductive gain respectively. For a given photo detector the values of $\eta (<1)$ and g are the constants, therefore the responsivity (sensitivity) completely depends on the wavelength of the light

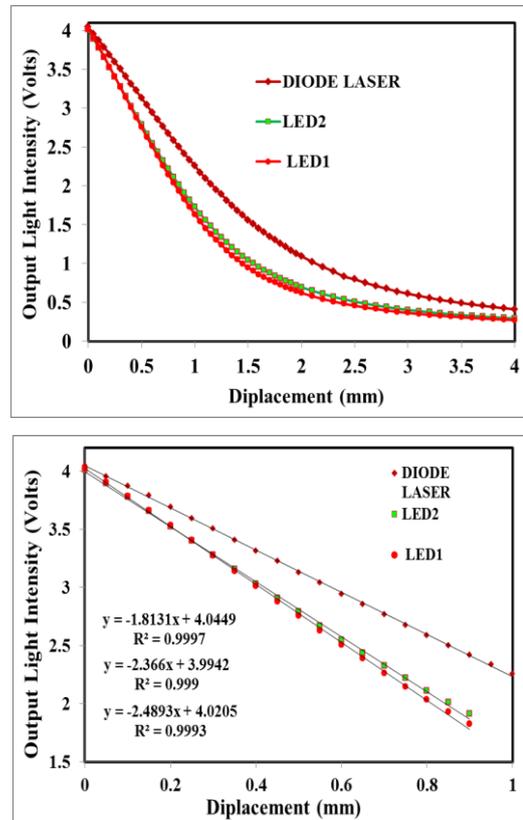


Fig. 2. The displacement characteristic curve of the sensor for three different light sources.

3. Experiment

Fig. 1 describes the method to calibrate the amplitude of vibration of the sensor. A small reflector is pasted on the surface of the rectangular block which is fixed to the micro translation stage perpendicular to the sensing head of the fiber. The light source is coupled to port 2 and the light is incident on the reflector through the port1. The reflected light from the reflector is coupled back to the same fiber (port1) and is made to incident on the photo-detector through port 3. A high resolution digital multimeter is used to measure the light power incident on the photo detector in terms of voltage with respect to variation in displacement between the reflector and the

sensing head (port1) in steps of 10 μ m over a span of 4000 μ m. Fig. 2 shows the displacement characteristic curve of the sensor for three sources of LED1 (650 nm), LED2 (530 nm) and laser diode (650nm). All the curves correspond to displacement follows the inverse square law as given by equation (7). The range of linear region, slope and the linearity of the sensor for three sources are given in Table 1. It is observed that there is a small discrepancy in sensitivity of LED1 and LED2 response is owing to source wavelength which effects the responsivity. Whereas in case of LED1 and Laser sources the disparity in sensitivity is due to minimization of the speckle especially at low frequencies [17].

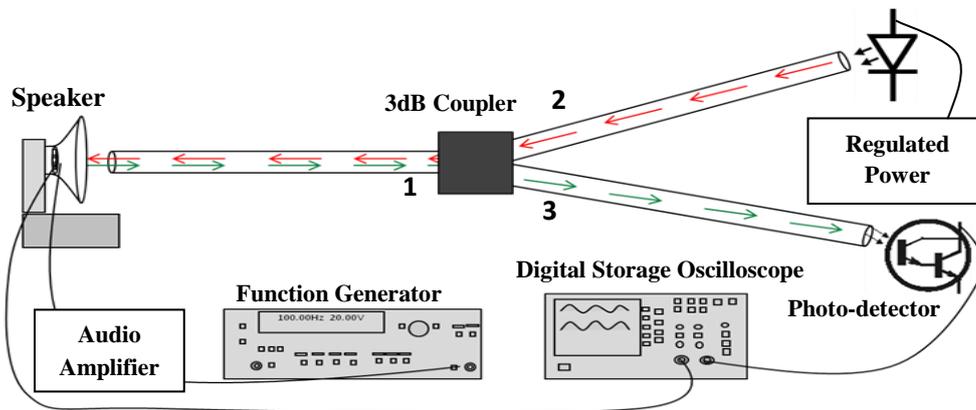


Fig. 3. Schematic of the experimental Setup.

Table 1. The parameters measured from displacement characteristic curve.

Source	Linear Region (mm)	Sensitivity (slope) mV/mm	Linearity
Diode Laser	1	1.8027	0.9994
LED2	0.9	2.3597	0.9991
LED1	0.9	2.483	0.9993

Fig. 3 shows the schematic experimental setup of the fiber optic vibration sensor. It consists of an LED or LASER diode as a source, a 1x2-3db Plastic optical fiber coupler (IF-562, i-fiberoptics) is used as a sensor to detect the vibration of the vibrating object, and a photo-detector (IFD-93, i-fiberoptics) with a detection circuit is used to convert the light intensity into its equivalent electrical signal. A synthesized function generator (HM8130, Scientific) and a commercial speaker with a calibrated reflector which is attached at the centre of it are used to test the sensor response. To record and monitor the vibration of the speaker at different frequencies and amplitudes a digital storage oscilloscope (SM1060, Scientific) is used. The whole setup is mounted on a vibration free table (Newport).

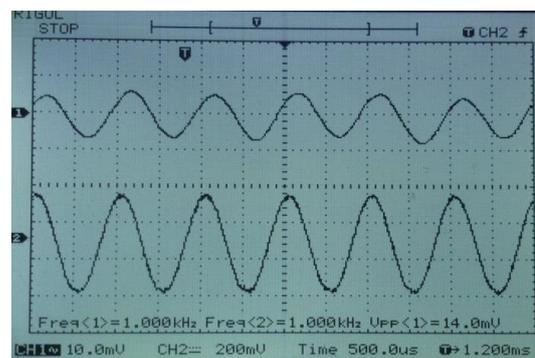
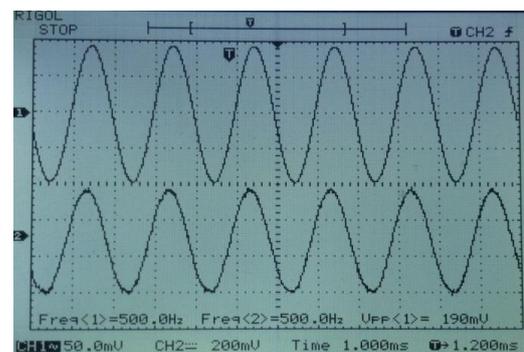


Fig. 4. Experimental Results of the sensor at a) 500 Hz and b) 1k Hz.

The sensor head is placed perpendicular to the reflector glued on the front surface of the speaker and adjusted to place within the linear region of the displacement curve from the sensing probe. The modulated reflected light corresponding to the vibrating object (speaker) is received by photo-detector which in turn is converted into its equivalent voltage signal. It is recorded and monitored by the storage oscilloscope. The Fast Fourier Transform (FFT) technique is used to convert the time domain signal into frequency domain and to analyse the vibration in terms of frequency of the object and also to measure the amplitude of vibration. The experiment is repeated for different frequencies and amplitudes of vibration. The sensor performance is also investigated for different sources of light by changing the wavelength and type of source.

4. Results and discussion

Since the responsivity of the sensor depends on wavelength of the light source, the sensor is tested for different sources of wavelengths 650 nm and 530 nm for measurement of vibrations. The sensor is also tested with different types of sources of same wavelength that is with LED1 and diode laser. The input sine wave applied to the speaker (CH1) and the response of the sensor (CH2) recorded by the oscilloscope for LED1 is shown in Fig. 4. The FFT of both the signals that give the frequencies of the applied signal to the speaker and output signal of the sensor is also shown in figure 4. The frequency response at constant amplitude of vibration (constant driving voltage), the frequency applied to the speaker and measured frequency from the sensor output for different sources is plotted in Fig. 5. A perfect matching between input and output signals is evident from Fig. 5.

The amplitude response of the sensor, that is the plot between driving voltage to the speaker and FFT peak voltage of the sensor output signal, at different frequencies is as shown in Fig. 6 for three different sources. It is observed that the amplitude of vibration is linear with respect to the driving voltage to the speaker with linear coefficient of 0.99. The resolution of the sensor is calculated from the minimum amplitude of vibration detected by the sensor at maximum frequency using the slope of the sensor characteristic curve. From the test results it is observed that the range of frequency and resolution of the amplitude of vibration depends on wavelength of the light source as well as type of source. The Table 2 shows the effect of source on the range of frequency and resolution of the amplitude.

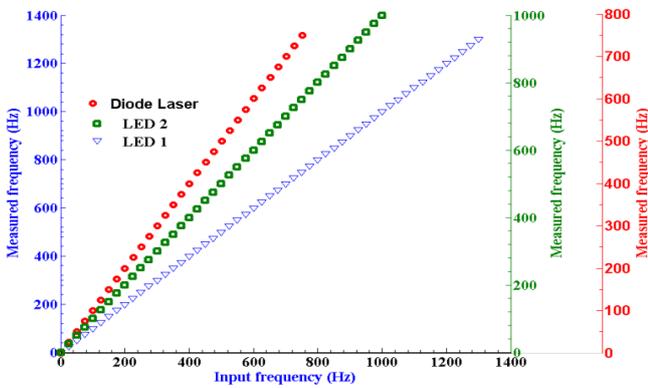


Fig. 5. Frequency response of the vibration sensor for different sources.

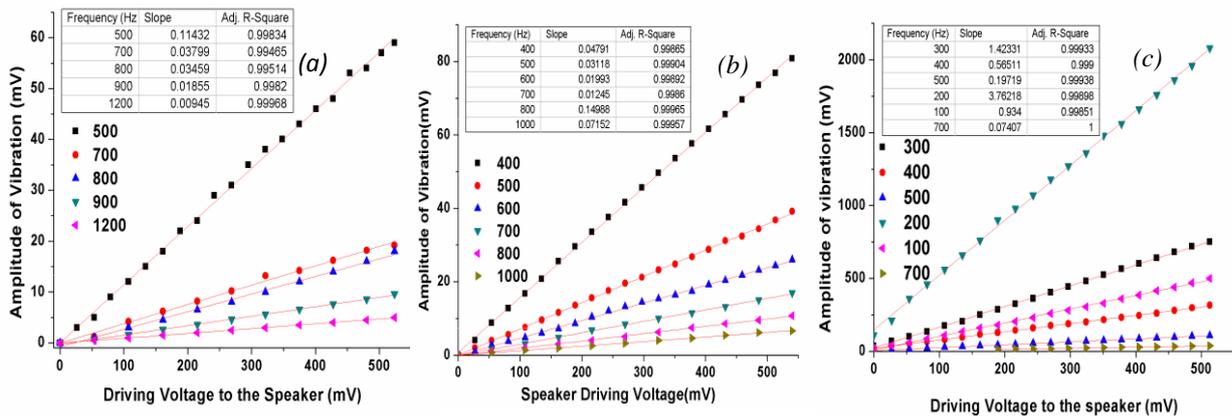


Fig. 6. Amplitude response of the sensor for different sources, a) LED1, b) LED2 and c) diode Laser.

Table 2. Sensor frequency range and resolution of amplitude.

Source	Frequency range (Hz)	Amplitude Resolution ~
Diode laser	0-750	7 μ m
LED2	0-1000	1 μ m
LED1	0-1300	1 μ m

The experiment is repeated for testing the reliability of the sensor system and is observed that the response of the sensor is consistent. The possibilities of errors that might be occurred in measurements are fluctuation in the source of light and the stray light effect. To reduce the fluctuations in the source of light a well regulated power supply is used. A sensor protection tool is designed in such a way that the stray light cannot interfere with the source

light and it does not have any effect on the sensor output. A hollow cylindrical protection tool is arranged surrounding of the reflector that protects from the stray light interference with the source light and the dust formation on the mirror as shown in Fig. 7. The sensor is

installed very close to the vibrating target but it should be within the linear region of the characteristic curve and does not require any special optics enabling the sensor useful for sensing applications in embedded situations.

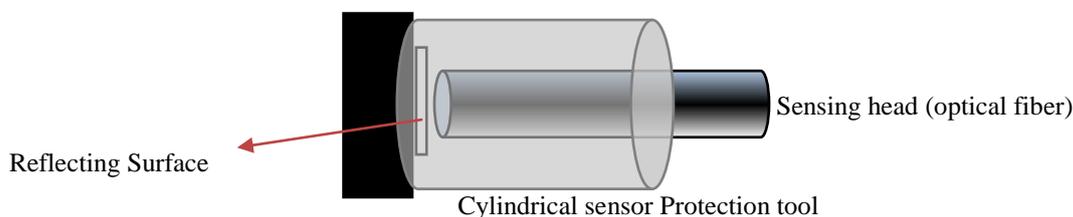


Fig. 7. Arrangement of the cylindrical sensor Protection tool on the reflecting surface.

5. Conclusions

A simple intensity modulated noncontact vibration sensor has been designed using fiber optic fused 1x2 coupler and also investigated the effect of source on vibration parameters. The sensing head exhibits single slope with high sensitivity and facilitates for easy alignment and accurate measurement. The frequency response of the sensor shows that there is a linear matching between the input and measured frequencies under constant amplitude of vibration. The amplitude resolution attained by the sensor is in microns. From the results it is observed that the frequency range and resolution of the amplitude of vibration depends on light source wavelength as well as type of source. This simple geometrical vibration sensor has all the advantages of optical fiber and it is suitable and useful in *in situ* real time monitoring and embedded systems.

References

- [1] Y. Alayli, S. Topcu, D. Wang, R. Dib, L. Chassagne, *Sensors and Actuators, A* **116**, 85 (2004).
- [2] Maria Luisa Casalicchio, Guido Perrone, Alberto Vallan, *I2MTC2009, Singapore*, 5 (2009).
- [3] M. R. Saad, Dr. M. Rehman, Dr. Othman Siddiqui, *IEEE LTIMC2004, Palisades, New York, USA* (2004).
- [4] N. Sathitanon, S. Pullteap, *International Journal of Computer Science and Engineering* **2**(2), 63 (2008).
- [5] S. Donati, Upper Saddle River: Prentice Hall, 2004.
- [6] G. Giuliani, M. Norgia, S. Donati, T. Bosch, *J. Opt. A: Pure Appl. Opt.*, **4**, S283 (2002).
- [7] P. Castellini, M. Martarelli, E.P. Tomasini, *Mechanical System and Signal Processing*, **20**, 1265 (2006).
- [8] A. Chijioke, J. Lawall, *Appl. Opt.*, **47**, 4952 (2008).
- [9] J. Chang, Q. Wang, X. Zhang, D. Huo, L. Ma, X. Liu, T. Liu, C. Wang, *Laser Physics*, **19**(1), 134 (2009).
- [10] S. Binu, K. Kochunaryanan, V. P. Mahadevan Pillai, N. Chandrasekaran, *microwave and optical technology letters*, **52**(9), 2114 (2010).
- [11] Vijay K. Kurkarni, Anandkumar S. Lallasangi, I. I. Pattanashetti, U. S. Raikar, *J. Optoelectron. Adv. Mater.* **8**(4), 1610 (2006).
- [12] P. Kishore, D. Dinakar, D. Sengupta, P. Saidi Reddy, M. Sai Shankar, K. Srimannarayana, *Sensors & Transducers Journal*, **136**(1), 50 (2012).
- [13] P. Kishore, D. Dinakar, M. Sai Shankar, K. Srimannarayana, P. Vengal Rao, D. Sengupta, *International Journal of Optoelectronic Engineering*, **2**(1), 4 (2012).
- [14] Samian, Yono Hadi Pramono, Ali Yunus Rohedi, Febdian Rusydi, A. H. Zaidan, *J. Optoelectron. Biomedical Materials*, **1**(3), 303 (2009).
- [15] M. Yasin, S. W. Harun, Samian, Kuminarto, H. Ahmad, *Laser Physics*, **19**(7), 1446 (2009).
- [16] Emmanuel Rosencher, Borge Vinter, *Optoelectronics*, English edition Cambridge University Press, 475 (2004).
- [17] Nicholas Lagakos, J. H. Cole, J. A. Bucaro, *Applied Optics*, **26**(11), 2171 (1987).

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