We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

6,300

Open access books available

172,000

International authors and editors

190M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities

WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com

Fiber Optic Vibration Sensors

*Putha Kishore, Dantala Dinakar
and Manchineellu Padmavathi*

Abstract

The sensors presented in this chapter are fiber optic intensity modulated vibrations sensors which are non-contact (extrinsic sensor) to the vibrating object. Three sensors presented make use of non-contact vibration measurement method with plastic fiber using distinct designs, improvement of the sensor response and advantages of one sensor over the other for diverse applications. First discussed about dual plastic optical fiber vibration sensor design and its response. Secondly, discussed about 1x2 fused coupler plastic optical fiber vibration sensor design with advantages over the first one. Finally, discussed about the 2x2 fused coupler plastic optical fiber vibration sensor design along with advantages than other two methods. At the end reported the final results with comparison.

Keywords: optical fiber, vibration sensor, intensity modulation, resolution, sensitivity and fiber Bragg grating

1. Introduction

It has been over five decades since the first emerged thought about the optical fibers could be used for sensing and measurement of the physical various parameters. Around 1960 the first patent was filed in the Photonic sensor, which is based on bifurcated bundle of fibers with half of the bundle used as transmitting fibers to illuminate on a reflecting surface and the other half of the bundle used as receiver to receive the reflected light from the reflector. The relative distance between the fiber bundles tip to the reflection precisely estimated by the suitable calibration process. In non-contact vibration sensing the Photonic sensors i.e. fiber optics have been continue for their unmatched offering of the results [1]. Fiber Optic sensors (FOS) provide many advantages over conventional sensors [2, 3], some of them as listed in **Table 1**.

In general, Fiber optics sensors are classified in to two groups: Intrinsic and Extrinsic sensors. In first type, the physical properties of the optical fiber itself can be used to convert effect of an environmental parameter on the optical fiber into a modulation of light parameters by passing through it. The light modulation parameters may be one of the following phase, intensity or polarization. Whereas, intrinsic FOS takes place within the optical fiber itself. Virtually, an environmental effect will be converted into light signal to be perturbed. In contrast, in extrinsic FOS, the optical fiber strictly used for carrying the information only that can be act as a black box to embed the information on an optical light, which is propagating through an optical fiber to a remote receiver. This black box usually contains optical elements such as a gas/liquid cells, a mechanical arm or so many other mechanisms that may

Conventional sensors	Fiber optic sensors
Bulk in size and weight dependent	Compact Size and light in weight
Most of them employ physically contact	Both contact and non-contact
Conductive	Nonconductive (Insulator)
Corrosive materials	Non-Corrosive materials
Chemically and electrically active	Chemically and electrically inert
Effected by Electromagnetic interference (EMI) and radio frequency interface (RFI)	Immune to EMI and RFI
Less bandwidth, no geometrical versatility and cost effective	Wide bandwidth, geometric versatility and economy
Low accuracy and sensitivity	Comparatively high accuracy and sensitivity
Difficult for distributed and multiplexed sensing	Can be easily used for distributed and multiplexed sensing
Not suitable for harsh environments and remote sensing applications	Suitable for harsh environment and remote monitoring systems can be made easily. Potentially easy to install

Table 1.
Comparison between conventional and fiber optic sensors.

cause modulation or transforming a light beam. Further, FOS sensors can also be classified based on their principle of working such as wavelength coding, Interferometric and Intensity modulated sensors. Intensity modulated FOS sensors are worked based intensity of light modulation with respect to the external perturbation. Phase modulated FOS sensors are passive in nature with optical elements that use phase change of the light field by the external perturbations, it is also called interferometric based sensor. The disadvantages of the optical fiber vibration sensors are the narrow frequency range of measurement and unfamiliarity to the end user. Thus, the fiber optic vibration sensors has required further research and development [4, 5].

1.1 Interferometric based vibration sensors

There exists few types of fiber optic interferometric vibration sensors such as Fabry-Perot, Mach-Zahnder, Michelson, and Sagnac [31] to interrogate the phase shift caused by vibration. In these sensors, the optical fiber as all-fiber interferometer which is usually a single mode optical fiber (SMF) rather than the multimode optical fiber (MMF). Because, the transfer function of SMF interferometers nearly reflects that of conventional interferometers. Whereas the transfer function of a MMF interferometer is independent of time owing to the more number of modes of the optical light in the optical fiber. Usually, phase variation in the interferometer can be produced either by an extrinsic or intrinsic effect. This phase can be encoded by the transfer function of the interferometer into modulation of light intensity at the photo-detector in a nonlinear method, using the usual interface cosine function. For most of the interferometers practical applications, a small sensor heads having a fiber optic Fabry-Perot (FP) interferometer along with a small length optical cavity are especially attractive. Because, they have the advantages of being simple in design, compact size, cheap, with lower cross sensitivity to ambient temperature and offers both high resolution and down lead insensitivity without the fading of polarization, usually faced by all in fiber optic interferometers [6]. A system using alternative EFPI arrangement is reported for the sensing of vibration, and its sensor head is shown in **Figure 1**. The sensor head uses a simple reflective configuration with an extrinsic FP cavity. An adjacent dual step-index MMF couple light into it

Figure 1.
 The EFPI vibration sensor head of schematic (a) single fiber (b) dual fiber.

and out of the optical cavity. The light is incident by a low power LASER diode as a source. Here, a movable reflecting surface used as a transducer and a suitable pitch gradient index cylindrical (GRIN) lens has been used for efficient light guiding device between the input and output optical fibers. A partial reflecting coating (R_1) on the output face of the GRIN lens act as an interference reference. A high reflective surface (R_2) moves in sympathy with respect to the target object vibrations, it provides the interference signal. The FP cavity has a length of d in air as shown in **Figure 1**. These interferometric methods offer better performance but shows low stability, expensive, critical alignment, mechanical requirement because of their, need complex analysis (fringe counting) and are not well suitable for sensing the vibration at various testing points. These sensors require an electronically driven element to change the interferometer conditions. As a consequence, these sensors have a limited practical use. Thus, most of the recent optical fiber sensors are employing using intensity modulation only [7, 8].

1.2 Intensity modulated vibration sensors

Intensity modulated fiber optic sensor techniques have been studied and implemented for the last three decades. A wide range of fiber optic configurations are reported, like fiber optic microbending, reflected light coupling to optical fiber, direct fiber-to-fiber coupling, fiber Bragg gratings, and modified cladding of optical fiber. All these sensors are classified into two fundamental methods either in physically in-contact or non-contact with the vibrating target or not. Usually non-contact configurations use a reflecting signal for detecting the displacement or vibration while the other configurations use the trans-missive configuration, i.e., microbending. As a general rule, in the intensity modulated sensor configuration, the intensity of light from the source is modulated by the optical fiber; then it is guided through the optic fiber to the photo-detector, then the light intensity pulses are translated into equivalent electronic signal, and adequately processed. In most of the case, a referencing mechanism is required in order to eliminate the other noises and maintain the stable sensor calibration. Without using referencing signal, the fluctuations owing of the power in light source, noise induced by the connectors, couplers, or any other optical components in the sensing system can become the significant relative errors. In this section, some of the intensity modulated sensors are discussed. For few decades, so many fiber optic sensors (FOS) works based on intensity modulation techniques have been demonstrated [4, 5].

1.3 Microbending vibration sensor

The microbend optical fiber sensor is one of the earliest sensor reported which is works on the principle of the Intensity modulated. The sensing principle is works of the transmitted light power variation of as a function of applied physical variable like pressure/stress [38]. Generally, in this configuration, the amplitude of light

intensity reduced by the cause of loss by the strain induced micro curvatures. The structure of the microbend fiber optic vibration sensor is shown in **Figure 2**. The sensing element (optical fiber) is sandwiched between a pair of strain induced plates having micro structure of saw tooth, it is capable to bend the optical fiber structure in a regular geometrical pattern with a periodicity of Λ . This deforms the fiber, with respect to an appropriate physical change (ΔE), owing to applied force (ΔF) to bent fiber, which cause the change in amplitude of the fiber (X) to vary its quantity (ΔX). The transmission coefficient of light which is propagating through the bent optical fiber (T_p) is changed by a quantity (ΔT_p), therefore

$$\Delta T = \left(\frac{\Delta T_p}{\Delta X} \right) D \Delta E \tag{1}$$

Here, D is a constant which is depends on the physical change ΔE .

The deformation triggers a coupling of the light power from the optical fiber core guiding modes to higher order radiation (cladding) modes; which are easily perturbed by the surrounding medium. Both MMF and SMF have been used for the development of these sensors. In SMF microbend sensors, the maximum sensitivity is observed when the spatial bend frequency equals to the difference between the propagation constants of the fundamental mode and a discrete cladding mode [5, 9]. The microbending sensor has to be placed in-between the deformer plates to detect applied pressure. Denis Donlagic and Miha Zavrsnik reported a novel structural method by single-mode leads and multimode fiber (SMS) based on microbending on the multimode section of the optical fiber is shown in **Figure 3**. It exhibits higher sensitivity than classical microbend sensors [10].

In addressing the fiber strength issues, it is to be remembered that the deformer plates clamp the optical fiber. Therefore, a large stress can be produced on to the fiber. Suppose the deformer plates are brought very close together, the optical fiber may leads to the breakage. An empirical design instruction is to maintain the ratio of maximum applied stress to fiber break stress less than one to four. Since, microbend saw teeth push into the buffer coating of the optical, it should be very important to know the interaction of the buffer coating material and optical fiber with respect to the various testing properties Therefore, the principal disadvantage of the microbending sensors is that low accuracy.

Figure 2.
Sensing principle of the microbend vibration sensor.

Figure 3.
 Sensing principle of the SMS structure microbending sensor.

1.4 Non-contact vibration sensors

Most of the non-contact dynamic displacement sensors commonly can be used for the sensing of vibration. Here, a reflective mechanism is used for detecting the vibrations, where one optical fiber is used as a transmitting of the light source and another fiber is used as a collector. The reflection of the surfaces of the target object can be minimized with help of data treatment methods. Binu et al., presented a simple, rugged, and cheapest non-contact intensity modulation based fiber optic sensor with configuration of two PMMA optical fibers cemented together [11]. The same design was proposed by the Yasin et al., [12]. The important benefits of this design is the low fabrication cost of the device. Although intensity modulated based fiber optic sensors are cheap and easy to fabricate, a weighty error in the measurement can be presented owing to effect of light source power variations. Losses owing to physical design and reflective planes outside of the measuring structure often effect on the accuracy of the final measurement. Fortunately, source light intensity fluctuations can be easily eliminate with referencing port.

Recently, Perrone et al., reported a low cost and high resolution using plastic optical fibers (POF) based on the reflected intensity modulation using dual POF. It is capable to measure the vibrations of up to several KHz by using an intensity modulation technique with a simple data processing and compensate the reflectivity of the vibrating surface. The received optical signal is incident onto the photo-detector and processed for the conversion. However this process is not user friendly and poses critical analysis process just like interferometric sensor. Those intensity modulated based fiber optic sensors are usually very cheap, easy to build and versatile in structures [13].

Further, an intensity modulated based displacement sensor reported, which is working on guiding optical light through the optical fiber onto a reflecting surface. Lewis et al., demonstrated the configuration in which the reflected light is collected by the same incident optical fiber [14]. The transducer itself can be a simple reflecting surface which is attached to the surface of a vibrating object. This fiber optic vibration sensor is a low cost and reliable, which is alternative for non-contact vibration detection with high-resolution frequency analysis. However, the multimode fiber having low dimension is limiting the practical application of the sensor. Because the sensor was positioned perpendicular to the vibrating body, it is difficult to align and maintain the sensor position constant at this dimensions.

This chapter have a more concentration on the plastic optical fiber vibration sensors design and development for the last few decades.

2. Dual optical fibers

The sensing head consists of two fibers made up of PMMA (Polymethyle Methacrylate) [15, 16], where one fiber acts as a transmitting fiber (TF) and other fiber acts as a receiving fiber (RF) which are bundled together parallel to each other [17]. The schematic setup is show in **Figure 4(a)**, the displacement response of the sensor along with overlapping mechanism between TF and RF cones is shown in **Figure 4(b)**. It is predicted that the sensor exhibits two linear regions namely the front slope and back slope. The detector output shows minimal at zero distance ($Z = 0$) between reflecting target and sensor probe, because the reflecting light cone of the TF does not reach the receiving cone of RF. As the distance from the sensor probe increases ($Z < Z_{max}$), the cone size of the transmitted light on the reflecting surface also increases, thereby causing the overlap with the RF cone which leads to a negligible output voltage. Further an increase in distance leads to larger overlap leading to rise in the voltage. This response reaches a maximum voltage where complete overlapping of the RF with TF reflecting cone occur ($Z = Z_{max}$), and then the output starts decreasing even though the distance increased ($Z > Z_{max}$). Because, the size of the reflecting light cone increases to very large which leading to decrease in power density, whereas the overlapping area remains constant [18, 19].

The front slope exhibits high linearity in the range of about 350-800 μm with a sensitivity of 4.786 $\text{mv}/\mu\text{m}$. A dark region of 350 μm is observed in the characteristic curve, where the intensity of light is not linear with the displacement for a small distance due to the cladding of the optical fiber. On the other hand, the back slope shows high linearity in the range between 1600 μm and 2600 μm with sensitivity of 1.696 $\text{mv}/\mu\text{m}$. Therefore, the front slope exhibits relatively high sensitivity but over small measurable range compared to the back slope and is better suited for the measurement of amplitude of vibration in micro level [20, 21].

2.1 Theory

According to the light intensity distribution function, the irradiance of emitted light from transmitting fiber is expressed as [20, 21].

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

Figure 4.
(a) Schematic of the sensor and (b) displacement response of the sensor.

Where r and z represent the radial and longitudinal coordinates respectively, and $\omega(z)$ is the beam radius which can be expressed as a function of z given below

$$\omega(z) = \omega_o \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \quad (3)$$

where z_R is expressed as

$$z_R = \sqrt{\frac{\pi \omega_o^2}{\lambda}} \quad (4)$$

where, z_R is the Rayleigh range and ω_o is the beam waist radius. The quantity of reflected intensity of light power received by the RF from the target is solved by taking the integration of the irradiance over the core area S_r

$$P(z) = \int_{S_r}^0 I(r, z) ds_r \quad (5)$$

The quantity of reflected intensity of light power collected by the RF is a function of the displacement between probe and target (reflecting surface) which can be expressed as [6, 7].

$$P(z) = \frac{2P_E}{\pi \omega^2(z)} \int_{y=-R_r}^{R_r} \int_{x=m_1}^{m_2} \exp \left[\frac{-2(x^2 + y^2)}{\omega^2(z)} \right] dx dy \quad (6)$$

Where $m_1 = R_t + R_r + R_d - \sqrt{R_r^2 - y^2}$ and $m_2 = R_t + R_r + R_d + \sqrt{R_r^2 - y^2}$, P_E is the power of light from the TF incident on the reflector, R_t and R_r are the core radius of TF and RF respectively and R_d is the distance between the centers of RF and TF cores.

A simple photo-detection circuit is used for the conversion of the light intensity into equivalent output voltage. Generally, the output voltage with respect to the intensity of light incident on photo-detector is given by [8, 9].

$$V_{out} = R_\lambda P R_E \quad (7)$$

Where $R_\lambda = \eta g \frac{\lambda}{1.24}$ is the photo-detector responsivity, 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 η (< 1) and g are constant, therefore the responsivity (sensitivity) depends on the wavelength of the light source. Thus light source and photo-detector should be matched.

2.2 Experimental setup

The schematic of the experimental setup of the fiber optic vibration sensor is shown in **Figure 5**. The sensing head consists of two PMMA fibers, with constant diameters bundled together in parallel. A commercial speaker/PZT can be used as a vibrator to test the response of the FOS.

A thin plastic reflector of thickness $100\mu\text{m}$ is glued at the center of the speaker to act as reflecting surface. An LED is used as a light source which should be matched to the optical transmission window of the PMMA fiber. The LED is housed in a special package which facilitates perfect holding and provide maximum coupling of

Figure 5.
Schematic experimental setup of the dual POF vibration sensor.

light into the fiber. One end of the transmitting fiber is fixed to the housing of the LED. The frequency and amplitude of vibrations of the speaker is controlled through a Function Generator and Power Amplifier.

The design of a dual plastic optical fiber (POF) vibration sensor using different fiber pair combinations reported along with necessary theory and experimental results. From displacement response of all the combinations, it is evident that the sensitivity of the sensor increases as the diameter of the fiber decreases and vice versa. The vibration response of the sensor for all the combinations reveals that when the fiber diameter of either TF or RF decreases, the frequency range is increased and resolution is improved. Further, the dynamic range, and the range of frequency can be optimized by using the suitable diameters of the fiber. Moreover, the dark region of the sensor can be minimized by choosing the diameter of the fiber as small as possible. The fiber combination of lower diameter shows better response than any combination and it exhibits the high frequency response with high resolution when compare with others. However, this dark region is one of the major drawback of the sensor configuration [20, 21].

3. Fiber optic fused 1x2 coupler

The sensor system consists of a 3 dB fiber optic 1x2 coupler made of PMMA fiber having three ports, in which the first port is used as a sensing probe while the second port is for coupling of light from the light source, and the third port is used to direct the reflected light, to be incident on the photo-detector [22–24]. The principle of the vibration measurement is based on intensity modulation with respect to the displacement between the reflecting surface glued on the vibrating

Figure 6.
 Working principle of the fiber optic coupler vibration sensor.

target and the sensing fiber port [25–28]. The schematic diagram of the sensing principle is illustrated in **Figure 6**. Light from the sensing fiber is allowed to be incident on the reflecting surface (glued on the front surface of the micro translation stage) which is kept at a distance of x from tip of the sensing fiber (port1) and the reflected light is allowed to be coupled back into the same fiber.

3.1 Theory

If P_a, P_b, P_c and P_d represent the power of light coupled to port 2, light incident on the reflector through port1, the light reflected from the reflector coupled back into port1 and the light power received by the photo-detector via port3 respectively, then, the light transmitted from the source through the fiber to the sensing fiber port1 can be given by [29, 30].

$$P_b = (1 - cr)(10^{-0.1L} - 10^{-0.1D})P_a \quad (8)$$

Where cr, L and D are coupling ratio, excess loss and directivity of the optical fiber coupler respectively.

If the reflector is kept parallel to the sensing fiber cross-section, the power of light coupled back and received by the sensing fiber probe can be expressed as

$$P_c = P_i \left(1 - \exp \left(-\frac{2a}{W^2(x)} \right) \right) \quad (9)$$

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 optical fiber [30].

Substituting Eq. (8) into (9), we have

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

Finally, the light power detected by the photo-detector from the sensing port through the port3 can be written as

$$P_d = cr(10^{-0.1L} - 10^{-0.1D})P_c \quad (11)$$

Substituting $W(x)$, Eq. (10) into (11) yield

$$P_d = k cr(1 - cr)(10^{-0.1L} - 10^{-0.1D})^2 \left(1 - \exp \left(-\frac{2}{\left(\frac{2xtan(\theta)}{a} + 1 \right)^2} \right) \right) P_a \quad (12)$$

Therefore

$$P_d = P \left(1 - \exp \left(-\frac{2}{\left(\frac{2xtan(\theta)}{a} + 1 \right)^2} \right) \right) P_a \quad (13)$$

Where

$$P = k cr(1 - cr)(10^{-0.1L} - 10^{-0.1D})^2$$

For large value of $\frac{2xtan(\theta)}{a}$, Eq. (13) can be written as

$$P_d = \frac{P}{2} \left(\frac{(2a)^2}{(2xtan(\theta))^2} \right) P_a \quad (14)$$

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 is inversely proportional to the square of the distance between the sensor head and the reflecting surface.

3.2 Experiment

This simple sensor configuration can eliminates the presence of dark region and it exhibits only single slope that enables easy setup when compared to other configurations [31–33].

Figure 7 illustrates the schematic experimental setup of the fiber optic fused 1x2 coupler as a vibration sensor. It consists of a LED source of suitable wavelength, which is driven by a simple circuit with regulated power supply. A 3 dB Plastic

Figure 7.
The 1x2 fiber optic coupler vibration sensor experimental setup.

optical fiber 1x2-coupler is used to configure the sensor to detect the vibration. A photo-detector along with detection circuit is used to convert the light intensity into equivalent electrical signal. A synthesized function generator and a commercial speaker with a calibrated reflector attached at the center of it are used to test the sensor response for vibration. To record and monitor the vibration of the speaker at different frequencies and amplitudes, a digital storage oscilloscope is used. The whole experimental setup is installed on a vibration less table to eliminate the ground vibrations [31–33].

The calibration of the sensor for the measurement of amplitude of vibrations has been carried out. A weightless plastic reflector is glued on the surface of a rectangular block fixed to micro translation stage which is positioned perpendicular to the sensing head of the sensor. A digital Multimeter is used to measure the photo-detector output light in terms of voltage with respect to the displacement between the reflector and the sensing head (port1). **Figure 8** shows the experimental and theoretical displacement characteristic curves using Eq. (14). As shown in **Figure 8**, the linear region in the range of 0-1000 μm . The weightless reflector is now glued on to the speaker diaphragm and is placed perpendicular to the sensor probe (port1). The distance between the speaker and the sensor head is fixed within the linear region of the displacement curve shown in **Figure 8**. The light from the LED is coupled to the port2 of the coupler and is directed to the port1. The light incident on the reflector through port1 gets reflected back while modulated in response to the vibration, and is received by the same fiber (port1). The light power received by the photo-detector is then converted into its equivalent voltage signal by a simple receiving circuit and is recorded or stored by the DSO. FFT technique is implemented for the conversion of the time domain signal into frequency domain signal to analyze the vibration in terms of frequency and amplitude. The experiment is repeated for different frequencies and amplitude of vibrations to detect the maximum frequency and amplitude resolution that can be measured by the designed sensor and also to test the reliability of the sensor.

The experimental is setup on a vibration less table. The speaker is allowed to vibrate by a sine wave (CH1) through the Signal Generator and the response of the sensor (CH2) is recorded using DSO for different frequencies. The FFT of these signals gives the frequencies of the applied signal and output of the sensor. It is evident from the figure that, there is a perfect agreement between the applied signal and response of the sensor. The amplitude d_p of displacement can be computed from the knowledge of the peak to peak voltage of the output signal and the slope of

Figure 8.
 The displacement characteristic response of the 1x2 fiber optic coupler as vibration sensor.

Figure 9.
Arrangement of the cylindrical sensor protection tool on the reflecting surface.

the calibration curve. For a given frequency f_p the peak velocity v_p and peak acceleration a_p of vibrating body can be computed by [31–33].

$$v_p = (2\pi)f_p d_p \quad (15)$$

$$a_p = (2\pi)^2 f_p^2 d_p \quad (16)$$

The possibilities of errors which might be present in measurement can be, light source fluctuations, stray light effect and dust formation on the mirrors. To reduce the fluctuations in the source of light a standard regulated power supply can be used. A hollow cylindrical protection tool is arranged surrounding the reflector to protect it from the stray light interference with the light from source and to reduce the dust formation on the mirror as shown in **Figure 9**. The sensor is positioned very close to the vibrating target within the linear sensing region and it does not require any special optics for enabling its use for sensing applications in embedded situations [31–33].

4. Fiber optic fused 2x2 coupler

In this second part discussed the design of the fiber optic 2x2 fused coupler as a vibration sensor. Study the displacement response and vibration response of the sensor. Implementation of the rational output method to improve response of the sensor than the 1x2 coupler [34, 35].

4.1 Displacement response of the sensor

Figure 10 illustrates the schematic of the proposed plastic multimode fiber optic 2x2 fused coupler made of Poly methyl methacrylate having a split ratio of 80:20 as a vibration sensor.

Figure 10.
Schematic of experimental setup for the displacement response of the sensor.

The sensor consists of an LED used as a light source and two numbers of photo-Darlington detectors (PD) of high sensitivity housed in a connector less package used to detect the intensity of light at reference and sensing ends. A simple photo detection circuit is developed for conversion of the modulated intensity of light into its equivalent output voltage signal and a DAQ is employed to record the time domain signals (TDS) corresponding to the reference and sensing arms from which the rational output (RO) is calculated.

The fiber optic fused 2x2 coupler has core/cladding diameters of 980/1000 μm , with split ratio of 80:20, and having four ports. All the ports of the coupler are used for vibration detection. The light from the LED and coupled to the port2 is split into the ratio of 80:20; and one part of light (80%) is transmitted through the port1, which act as a sensing probe and the other part (20%) is directed towards PD1 through port4 which is used as a reference signal [36, 37]. The light through port1 projects onto a weightless plastic reflector having the reflectivity of 40% which is attached to the center of the speaker diaphragm (the vibrating object). The reflected light modulations corresponds to vibration is recoupled into the same fiber (port1) and is directed to be incident on the PD2 through port3. In order to avoid the effect of power fluctuations in light source and bending losses in optical fiber, a reliable method of the rational output (RO) of PD1 and PD2 is taken into consideration and is expressed as [38–40].

$$\text{Rational Ouput (RO)} = \frac{\text{PD1} - \text{PD2}}{\text{PD1} + \text{PD2}} \tag{17}$$

A Step Motorized Actuator has been used to move the reflector attached to the micrometer stage to and fro from the sensing probe with a step size of 1 μm over a dynamic range of 4 mm. The experimental results depicts that the sensor displacement characteristic curve is presented in **Figure 11**, follows the inverse square law given by Eq. (14) and the linear region of this curve is used for the vibration measurement. It can be observed that the characteristic curve representing the response of PD2 with respect to the displacement of the reflector from the sensing probe (**Figure 11**) has a linear region of about 1 mm with a sensitivity of 2.1 mV/ μm , whereas the response curve representing the RO has a sensitivity of 0.36a.u./mm. This linear region of both responses can be considered for vibration measurement [34, 35].

Figure 11.
Displacement characteristic curve of the fiber optic 2x2 coupler vibration sensor.

4.2 Elimination of source and bending fluctuations

Prior to the vibration measurement, the sensor response is tested against source fluctuation and fiber bending at the source end. **Figure 3** shows the effect of source fluctuation on the sensing and reference signals. The measured signals from PD1 and PD2 show a change in intensity of light with respect to variation in light intensity of LED by means of varying the driving voltage, whereas the RO of these signals show insensitive to the source fluctuations. It is apparent from the test results that the RO method minimizes the effect of source fluctuations on the response of the sensor. Similarly, to test the effect of bending losses of optical fiber on the sensor output, the optical fiber is allowed to undergo bending by using a microbending pressure element. **Figure 12** illustrates the effect of fiber microbending at the source end (port2) on individual outputs of PD1 and PD2 as well as on RO of both the signals. It is evident from the test results that even though the outputs of PD1 and PD2 are affected by the fiber bending, the same is not present in the RO [34, 35].

4.3 Vibration measurement setup

The schematic experimental setup of the fiber optic 2x2 fused coupler for the vibration measurement is shown in **Figure 13**. The setup is mounted on a vibration free table. To test the sensor response for corresponds to vibrations, a synthesized function generator and a commercial speaker having dimension of 25 mm depth and diaphragm of 65 mm diameter with a reflector attached at the center of the diaphragm are used. Data acquisition system is employed to record the TDS of the sensor and to monitor the sensor response for known frequencies and amplitudes of vibration of the speaker.

In general, most of the vibrations are sinusoidal displacements of the vibrating object about its mean position. Generally, this nature of vibrations can be detected by measuring its amplitude and frequency only. Thus, the FFT technique have been used for the conversion of the TDS response into frequency domain response to analyze the object vibrations in the form of frequency and also to compute the amplitude. The experimentation is repeated for various frequencies to compute the detectable high frequency and to test the reliability of and also amplitude resolution.

4.4 Results and discussion

In general, the signal to noise ratio (SNR) is well-defined as the ratio between the power strength of the signal and the noise. It can be derived from the following formula [41].

Figure 12.
(a) Effect of source fluctuation on PD1, PD2 and RO, (b) effect of fiber bending on the output of PD1, PD2 and RO.

Figure 13.
 Schematic of the 2x2 fiber optic vibration sensor experimental setup.

$$SNR = \frac{\text{Power of signal}}{\text{Power of noise}} = \frac{\mu}{\sigma} \tag{18}$$

Where σ is the standard deviation of the noise signal and μ is the expected value. The SNR is a nominal term which used for the characterization of the quality of the detected signal in a measurement system. In order to measure SNR of the signals of PD1, PD2 and RO, without vibration the sensing probe is maintained at constant distance from the speaker for a period time as shown in **Figure 14(a)**. This reveals the stability of the detection signals. The SNR of the normalized RO, PD1 and PD2 signals is calculated using Eq. (18) and found that the SNR of the RO is improved when compared to PD2 which is clearly shown in **Figure 14(b)**.

To assess the sensor vibration response, a sine wave is applied to the speaker and corresponding TDS response of the sensor is recorded by using DAQ at certain frequency as shown in **Figure 15**. The TDS waveform of RO recorded by the DAQ and corresponding FFT spectrum at 1 kHz signal brings out the closeness with which the sensor responds to a given frequency of applied vibration [34, 35].

The sensor is also tested for its amplitude response by the application of a gated signal of constant frequency, and noting the corresponding PD1, PD2 and RO waveforms as shown in **Figure 16**. It is illustrated that the amplitude of the signal applied to the speaker is constant for a period of 1.1 sec, followed by damped decay of the signal representing that the signal generator is switched off and later by the dc signal, indicating the absence of the signal during this period. This figure also depicts that the output of the vibration sensor at a given frequency the amplitude

Figure 14.
 (a) Stability of the signals and (b) base noise in the signals.

Figure 15.
The TDS waveforms of (a) PD1, (b) PD2 and (c) RO for a frequency of 700 Hz.

Figure 16.
The amplitude response of the sensor for corresponding speaker vibration at 390 Hz. TDS spectra of the sensor corresponds to continuous variation.

response for the vibration. The amplitude response of the vibration sensor for the applied driving voltage to the vibrator and peak voltage of the FFT from the output signal at for various frequencies observed that the linear in response. The sensor amplitude sensitivity with respect to applied frequency to the speaker exhibits a linear response [34, 35].

From the above reported results, when compared all the responses of different configuration such as dual POF, 1x2 fused coupler POF and 2x2 fused coupler POF vibration sensors, and it was found that among these sensors, 2x2 coupler has been shown better response, which are tabulated in **Table 2**.

Configuration	Linear region (μm)	Range (μm)	Sensitivity (mV/μm)	Linearity	Frequency range (Hz)	Amplitude resolution ~ μm
Dual fiber	600–1300	700	9.83	0.999	900	1
1x2 Coupler	0–1000	1000	2.483	0.9993	1300	1
2x2 Coupler	0–1000	1000	2.1	0.99	3500	0.03

Table 2.
The effect of light source on the vibration response of the sensor.

5. Summary

An all Plastic optical fiber (POF) physically non-contact vibration sensors are discussed, that works based on the reflected light intensity modulation reported with various structures. For every system, observed development and an

improvement, with proper design and eliminated the dark region, having a single slope. It enables the system of easy alignment. By considering the rational output measurement, it has eliminated some of the significant effects on sensing such as power fluctuation in light source and also bending losses. When compared the dual POF, POF fused 1x2 coupler and POF fused 2x2 coupler vibration sensors response results. It is clearly predicted that the POF 2x2 fused coupler vibration sensor exhibits enhanced response with 0.03 μm high resolution up to 3.5 kHz frequency range.

Author details

Putha Kishore^{1*}, Dantala Dinakar² and Manchineellu Padmavathi³

1 Global College of Engineering and Technology, Kadapa, India

2 National Institute of Technology Warangal, India

3 SKR and SKR Government Degree College for Women (A), Kadapa, AP, India

*Address all correspondence to: kishore.photonics@gmail.com

IntechOpen

© 2020 The Author(s). Licensee IntechOpen. This chapter is distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/3.0>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

References

- [1] Brain Culshaw and Alan Kersey, "Fiber Optic Sensing: A Historical Perspective," *Jour. of Lightwave Tech.*, vol. 26, no. 9, may 2008.
- [2] Eric Udd, "An overview of fiber-optic sensors", *Rev. Sci. Instrum.*, Vol. 66, No. 6, pp. 4015–4030, 1995.
- [3] D. A. Krohn, "Fiber Optic Sensors: Fundamentals and Applications," Second Edi., *ISA publisher*, USA, 1992.
- [4] Tarun Kumar Gangopadhyay, "Review: Prospects for Fiber Bragg Gratings and Fabry-Perot, Interferometers in fiber-optic vibration sensing," *Sensors and Actuators A*, vol. 113, pp. 20–38, 2004.
- [5] Yoany Rodriguez Garcia, Jestis M. Corres and Javier Goicoechea, "Review Article: vibration Detection using Optical Fiber Sensors," *Journal of Sensors*, vol. 2010, no. 936487, 2010.
- [6] N. Sathitanon, and S. Pullteap, "A Fiber Optic Interferometric Sensor for Dynamic Measurement," *International Journal of Computer Science and Engineering*, vol.2, no.2, pp. 63–66, 2008.
- [7] K. T. V. Grattan, Dr. T. Sun, "Fiber Optic sensor technology: an overview," *Sensors and Actuators*, vol. 82, pp. 40–61, 2000.
- [8] Bahareh Gholamzadeh and Hooman Nabovati, "Fiber Optic Sensors," *World Aac. Of Sci. Eng. and Tech.*, vol. 2, pp. 06–29, 2008.
- [9] N. K. Pandey and B. C. Yadav, "Embedded fiber optic microbend sensor for measurement of high pressure and crack detection," *Sensors and Actuators A*, vol. 128, pp. 33–36, 2006.
- [10] Denis Donlagic and Miha Zavrsnik, "Fiber-optic microbend sensor structure," *Optics Letters*, vol. 22, no. 11, pp. 837–839, 1997.
- [11] S. Binu, V. P. Mahadevan Pillai and N. Chandrasekaran, "Fiber Optic displacement sensor for the measurement of amplitude and frequency of vibration", *Optics & Laser Technology*, Vol. 39, pp.1537–1543, 2007.
- [12] M. Yasin, S. W. Harun, Kusminarto and H. Ahmad, "A simple design of vibration sensor using fiber optic displacement sensor," *OAM-RC*, Vol. 4, No. 1, pp. 1795–1797, 2010.
- [13] Guido Perrone and Alberto Vallan, "A Low-Cost Optical Sensor for Noncontact Vibration Measurements," *IEEE Trans. On Inst. And Meas.*, vol. 58, no. 5, pp. 1650–1656, May 2009.
- [14] N. E. Lewis, M. B. Miller, W. H. Lewis, "Fiber Optic sensors utilizing surface reflections, in
- [15] A. Buffa, G. Perrone, and A. Vallan, "A Plastic Optical Fiber Sensor for Vibration Measurements," in *I2MTC 2008 - IEEE International Instrumentation and Measurement Technology Conference Victoria, Vancouver Island, Canada, 2008*, pp. 1–5.
- [16] M. Linec and D. Donlagic, "A Plastic Optical Fiber Microbend Sensor Used as a Low-Cost Anti-Squeeze Detector," *IEEE Sens. J.*, vol. 7, no. 9, pp. 1262–1267, 2007.
- [17] P. B Buchade and A. D Shaligram, "Influence of fiber geometry on the performance of two-fiber displacement sensor," *Sensors Actuators A*, vol. 136, pp. 199–204, 2007.
- [18] M. Yasin, S. W Harun, K. Karyono, and H. Ahmad, "Fiber-Optic Displacement Sensor Using a Multimode Bundle Fiber," *Microw. Opt.*

Technol. Lett., vol. 50, no. 3, pp. 661–663, 2008.

[19] M. L. Casalicchio, G. Perrone, and A. Vallan, “A Fiber Optic Sensor for Displacement and Acceleration Measurements in Vibration Tests,” in IEEE, I2MTC 2009 - International Instrumentation and Measurement Technology Conference Singapore, May 2009, 2009, no. May, pp. 5–7.

[20] P. Kishore, D. Dinakar, D. Sen Gupta, P. Saidi Reddy, M. Sai Shankar, K. Srimannarayana, “Fiber Optic Vibration Sensor Using PMMA Fiber for Real Time Monitoring” *Sensors & Transducers journal*, Vol.136, Issue 1, pp.50–58, January 2012.

[21] D. Dinakar, P. Kishore, M. Padmavathi, “Study on Intensity Modulated Non-Contact Optical Fiber Vibration Sensors of Different Configuration”, Boston USA, Apr 24–25, 2017, 19 (4), pp. 2008–2011, Part XVI, World Academy of Science, Engineering and Technology, International Journal of Physical and Mathematical Sciences Vol:4, No:4, 2017.

[22] K. Imoto, H. Sano, and M. Maeda, “Plastic optical fiber star coupler,” *Appl. Opt.*, vol. 25, no. 19, p. 3443, Oct. 1986.

[23] G. Economou and D. E. N. Davies, “Studies of an optical fibre displacement sensor,” *J. Inst. Electron. Radio Eng.*, vol. 57, no. 2, p. 63, 1987.

[24] T. Sugita, T. Abe, K. Hirano, and Y. Itoh, “Bidirectional optical coupler for plastic optical fibers,” *Appl. Opt.*, vol. 44, no. 15, pp. 2933–42, May 2005.

[25] H. A. Rahman, S. W. Harun, N. Saidin, M. Yasin, and H. Ahmad, “Fiber Optic Displacement Sensor for Temperature Measurement,” *IEEE Sens. J.*, vol. 12, no. 5, pp. 1361–1364, May 2012.

[26] M. Yasin, S. W. Harun, Z. a. Ghani, and H. Ahmad, “Performance

comparison between plastic-based fiber bundle and multimode fused coupler as probes in displacement sensors,” *Laser Phys.*, vol. 20, no. 10, pp. 1890–1893, Sep. 2010.

[27] A. Wang, M. S. Miller, A. J. Plante, M. F. Gunther, K. A. Murphy, and R. O. Claus, “Split-spectrum intensity-based optical fiber sensors for measurement of microdisplacement, strain, and pressure,” *Appl. Opt.*, vol. 35, no. 15, pp. 2595–601, May 1996.

[28] M. Yasin, S. W. Harun, and H. Ahmad, “Simple design of optical fiber displacement sensor using a multimode fiber coupler,” *Laser Phys.*, vol. 19, no. 7, pp. 1446–1449, Jul. 2009.

[29] Samian, Y. Hadi Pramono, A. Yunus Rohedi, F. RUSYDI, and A. ZAIDAN, “Theoretical and experimental study of fiber-optic displacement sensor using multimode fiber coupler,” *J. Optoelectr. Biomed. Mate.*, vol. 1, no. 3, pp. 303–308, 2009.

[30] A. R Crawford and S. Crawford, “The Simplified Handbook of Vibration Analysis Volume 2: Applied Vibration Analysis,” *Computational Systems, Incorporated (CSI)*, vol II, 1992.

[31] P. Kishore, D. Dinakar, K. Srimannarayana, P. Vengal Rao, “A simple 1x2 plastic optical fiber coupler based vibration sensor”, an International conference on Optics in Precision Engineering and Nano Technology, Singapore Expo, Expo 1 Drive, Singapore, April, 2013, *Proc. Of SPIE Vol. 8769*, pp. 876929–1 to 876929–4.

[32] P. Kishore, D. Dinakar, P. Vengal Rao, K. Srimannarayana, “Fiber Optic Fused 1x2 Coupler as a Vibration Sensor”, *Optica Applicata*, issue 4, vol. 43, pp. 793–800, 2013.

[33] P. Kishore, D. Dinakar, K. Srimannarayana and P. Vengal Rao, “A

Study on the effect of light source on Fiber Optic Fused 1x2 Coupler Vibration Sensor”, *Journal of Optoelectronics And Advanced Materials*, Vol. 16, No. 11–12, pp. 1232–1236, Jan-Dec. 2014.

[34] D. Dinakar , P. Kishore, P. Vengal Rao and K.Srimannarayana, “Remote vibration sensor using fiber optic fused 2x2 coupler”, *Proceeding of SPIE Volume 8836*, pp. 883605–1 to 883605–9, *Optomechanical Engineering 2013*, USA.

[35] P. Kishore, D. Dinakar, P.Vengal Rao, K. Srimannarayana, “Vibration sensor using 2x2 fiber Optic Coupler”, *Optical Engineering*, issue 10, vol. 52, pp. 10704, 2013.

[36] A. Djordjevic and S. Savovic, “Investigation of mode coupling in step index plastic optical fibers using the power flow equation,” *IEEE Photonics Technol. Lett.*, vol. 12, no. 11, pp. 1489–1491, Nov. 2000.

[37] J. Chang, Q. Wang, X. Zhang, L. Ma, T. Liu, and Z. Liu, “Single-end vibration sensor based on an over-coupled fiber-loop reflector,” *Laser Phys.*, vol. 18, no. 4, pp. 452–454, 2008.

[38] J. M. Lourenço and P. M. Cavaleiro, “Data processing for intensity based fiber optic sensors,” *Appl. Opt.*, vol. 35, no. 34, pp. 6835–6, Dec. 1996.

[39] X. Jian and M. Bin, “Experimental Investigation of Coupling Fiber-Optic Sensor for Vibration Measurement,” *International Conference on Electrical and Control Engineering*, pp. 936–939, 2010.

[40] M. Endong, W. Min, P. Fufei, and W. Tingyun, “Fiber Optic Coupler as Sensing Probe of Temperature Sensor,” *8th International Conference on Electronic Measurement and Instruments*, pp. 4–186–4–189, 2007.

[41] Daniel J. Schroeder, “*Astronomical Optics*,” Academic Press, Second Edition, San Diego, pp. 433–435, 2000.