# Analytical study of performance variations of fiber optic micro-displacement sensor configurations using mathematical modeling and an experimental test jig

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**Abstract:** Optical fiber sensors are studied and fabricated for number of industrial applications. It has certain advantages such as light weight, low cost etc. Number of configurations is considered depending upon the need of applications. These configurations are modeled mathematically and analyzed for studying their performance. It is observed that modeling is done for specific geometry of the configuration. These models signify the ideal behavior of the configuration of sensor system. Practically there are always some tolerances associated with the sensor system. Hence it is necessary to develop a flexible mathematical model considering the practical scenarios. A mathematical model which is used to represent all possible configurations of fiber optic micro displacement sensor is proposed. The model is developed using ray trace technique in MATLAB. Some identified configurations are simulated using this model and it is validated using the developed test jig. Simulated results show good agreement with the experimental results obtained using test jig. The fiber optic sensor configurations tested are extendable to other practical physical and chemical sensing applications.

**Index terms**: configurations of fiber optic sensor , Fiber optic sensor, Fiber optic micro displacement sensor, mathematical modeling of sensor, ray tracing technique.



## 1 INTRODUCTION

In the recent years, there is a need of high quality sensors. In parallel with rapid advance in the development of sensors in the field of microelectronics, those based on optical techniques have expanded significantly over last few years. Optical fiber sensor development has matured to the point where the impact of this new technology is now evident. They offer number of advantages such as increase in sensitivity over the existing techniques, geometric versatility in which fiber sensors can be configured in arbitrary shapes, a common technology base from which devices can be used to sense various physical and chemical parameters. It can be constructed so that it can be used in high voltage, electrically noisy conditions, high temperature, corrosive or other stressing environments. Mathematical modeling of fiber optic micro displacement sensor is done by many researchers as per the requirement of the application and geometry of the sensor under consideration. Experimental studies are also reported for various configurations of these sensors [1-3]. These efforts are meant only for desired application and configuration and are not applicable for any perturbation in sensor parameters. Patil etal [4] developed a mathematical model using ray tracing approach which can be useful in simulation of any configuration of fiber optic displacement sensor. It is possible to analyze and to study effects of variation in physical and geometrical parameters of sensor on performance characteristics. The model is verified and validated by performing number of experiments using the test jig developed. Various configurations are studied using this test jig such as configuration with variation in physical parameters such as horizontal

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distance(s), core radii of transmitting and receiving fiber (a). These are tabulated in Table I and Table II. This review article focuses mainly on use of developed model and test jig for studying different configurations of fiber optic micro displacement sensor. It is further used for studying different performance parameters of sensor.

## 2 EXPERIMENTAL SETUP

Figure 1 shows test jig which is designed so that all possible configurations of fiber optic micro displacement sensor can be configured easily. It has following arrangements namely

a. Linear scale with resolution of 0.1mm for variation in horizontal distance(s)
b. Linear scale with resolution of 0.1mm for variation in distance(Z)
c. Angular scale with resolution of $1^{o}$ for inclination of fibers
d. Arrangement for changing the LEDs with different colour with diameter=5mm
e. Arrangement for changing the photodetectors with proper coupling mechanism
f. Arrangement for changing the fibers (TF as well as RF) with proper coupling mechanism
g. Arrangement for changing the refractive index (RI) of medium between the sensor probe and reflector.
h. Arrangement for changing the reflector type having different roughness values.

Using these arrangements number of experiments are performed for different configurations tabulated in table 1. For all the configurations fibers having fiber diameter=2.2mm, NA=0.47 are used. Sensor parameters are varied as follows for the experimental purpose

a. Distance between sensor probe and reflector: 0 mm to 20mm
b. Horizontal distance: 0 mm to 2 mm
c. Refractive index of medium: 1.0 to 1.5
d. Inclination angle: $0^{o}$ to $30^{o}$
e. Fibers with different core diameter: 0.5mm, 1mm, 1.5mm,2.0mm

These experiments are carried out varying only one parameter at a time keeping all others constant.

TABLE I
Parallel Pair Fiber Configuration

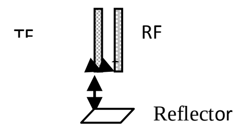
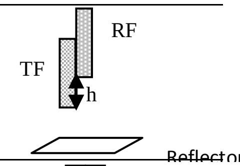
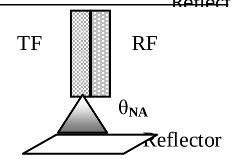
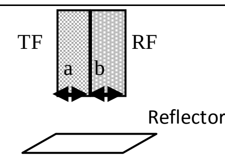
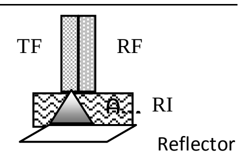
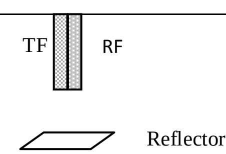
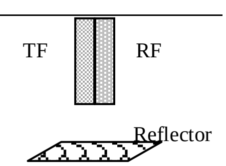
| Configuration type | Parameters | Diagram |
|---|---|---|
| Parallel Pair configuration | Horizontal distance(s) |  |
| | Vertical offset(h) |  |
| | Numerical Aperture(NA) |  |
| | Core radius(TF-'a' and RF-'b') |  |
| | Refractive Index (RI) |  |
| | Surface property - Reflectivity |  |
| | Surface property- Roughness |  |

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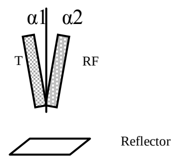
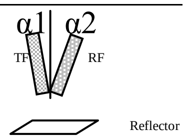
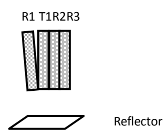
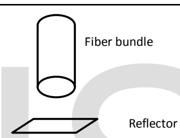
TABLE II
Other Configurations Of Fiber Optic Micro Displacement Sensors

| Configuration type | Parameters | Diagram |
|---|---|---|
| Symmetrically inclined fiber Configuration | TF angle($\alpha$1)=RF angle($\alpha$2)≠0° |  |
| Asymmetrically inclined fibers configuration | TF angle($\alpha$1) ≠RF angle($\alpha$2) |  |
| Self referencing configuration | Horizontal distance (s)=0<br>R1 angle $\alpha$=5° |  |
| Fiber bundle configuration | Any arrangement of optical fibers in the form of bundle |  |

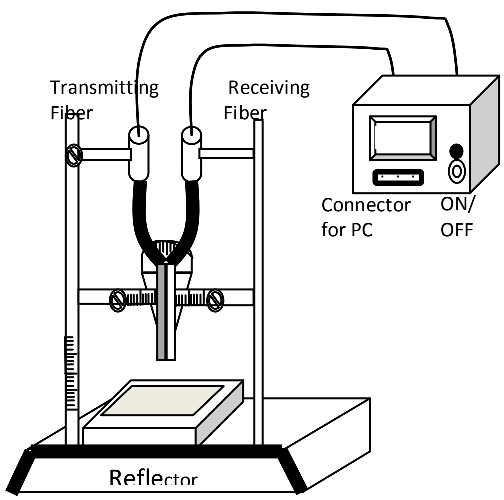



Fig 1: Test Jig for studying fiber optic micro displacement sensor



## 3 RESULTS AND DISCUSSION

Different configurations of fiber optic micro displacement sensor are studied by using developed ray trace model using MATLAB and test jig. Number of experiments is carried out for different arrangement of sensor using test jig. Similar configurations are simulated using the software developed based on ray tracing technique.

Performance parameters such as linear operating range and sensitivity are also studied. Three configurations of fiber optic micro displacement sensors are considered here. These are studied for the improvement in performance as well.

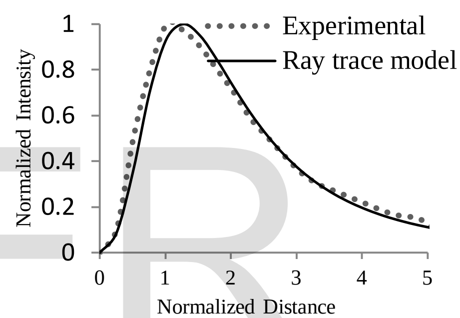



Fig.: 2(a) Sensor Response

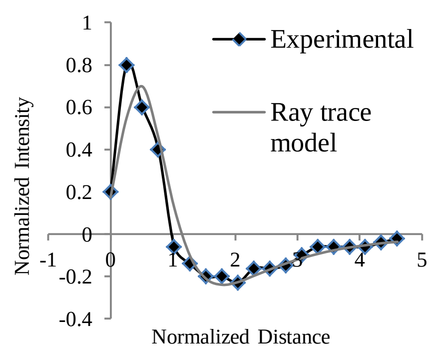



Fig.:2(b) Performance Parameters

### 3.1 Parallel fiber configuration

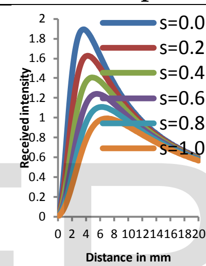
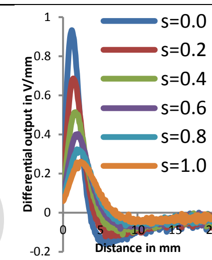
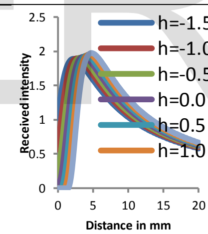
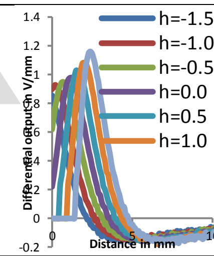
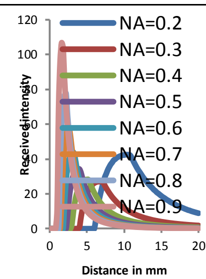
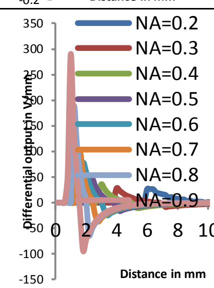
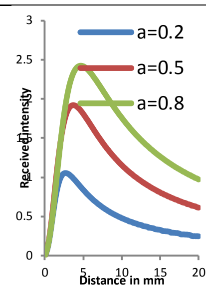
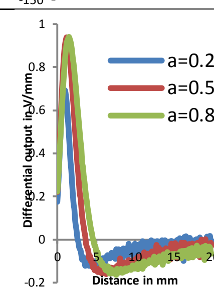
In parallel fiber pair configuration, two parallel optical fibers are facing the reflector. For smaller distance Z, the reflected light circle is of small radius and there is less overlap with receiving fiber core. This is called blind region. As distance Z increases, radius of reflected light circle increases and starts overlapping the receiving fiber core. This results in the linear increase in the received light in the receiving fiber. This continues for certain range of distance (3mm). The region is called linear region. Receiving fiber is fully illuminated in this region. With further increase in Z, intensity drops down non linearly due to the inverse square law. This region is called as non linear region. This configuration is tested and also modeled using ray trace model and results are shown Fig. 2(a). Experimental and simulated results are showing good agreement. The developed ray trace model is reported in [4]. The results also agree well with the mathematical model based on geometrical approach, proposed for this configuration by Faria et. al. [1], considered Gaussian beam profile. The performance of fiber optic displacement sensor is studied based on two important parameters viz., sensitivity and operating range. Fig. 2(b) shows the sensitivity curves or differential response for the sensor which is obtained after differentiating the sensor response w.r..t distance. The distance at which it cuts X axis is linear operating range while the peak of the curve signifies the sensitivity of the FODS. Figure 2(b) also shows the experimental results and shows congruency with the simulated results. The model is further analyzed for variation in manufacturing parameters and its effect on the performance of the FODS. The parameters can be deviated from the ideal values and can take any random value within manufacturing limits. A simulation was carried out to study the effect of such practical tolerances and variation in fiber parameters as well. The individual effects of the offset between the transmitter and receiver fiber tip(h), lateral separation between transmitting and receiving fibers(s), numerical aperture(NA), core radius(a) are studied by varying one, keeping others constant as shown in Table III.

## a. Effect of ‘h’ vertical offset variation

Effect of variation in the vertical offset ‘h’ is simulated and studied. The plots are as shown in the row 1 of the Table III. Results are matching with experimental results reported by Kishore et. al. [6] . The variation in the vertical offset ‘h’ changes the effective distance between the reflector and the receiving fiber and hence amount of light entering the fiber is related to the area of overlap corresponding to effective distance i.e. z+h. There no change in the sensitivity of the sensor. Slight increase in the operating range is observed because of the overlap starts earlier due to vertical movement of the receiving fiber w.r.t. transmitting fiber.

TABLE III

Graphs showing the effect of variation in geometrical parameters for two parallel fiber optic displacement sensor

| Parameters | Simulated Sensor Response | Sensor Performance |
|---|---|---|
| S |  |  |
| h |  |  |
| NA |  |  |
| Core Radius (a:TF b: RF) |  |  |

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### b. Effect of variaton in horizontal offset ‘s’:

Simulations are carried out for different values of inter fiber spacing ‘s’ and results are as shown in the row 2 of the Table III. As inter fiber spacing increases the total overlap occurs at larger distances which in turn increase the linear operating range but at such distance the rate of change of intensity w.r.t. distance is less hence decrease in the sensitivity is observed.

### c. Effect of change in Numerical Aperture (NA):

Table III row 3 shows the effect of variation in the numerical aperture of the receiving fiber on the sensitivity and linear operating range. Due to the increase in NA most of the light will be collected by the fiber at smaller value of fiber probe reflector distance Z and hence peak position is shifted towards lesser distance. As NA increases more light is gathered by the fiber, which in turn increases the sensitivity and the sharper peak. But linear operating range decreases as total overlap occurs at smaller distances.

### d. Effect of core radius(a):

The effect of core radius was studied by simulating the FODS characteristics for different core radii. It is clear from the row 4 of Table III that for the same fiber probe reflector distance(Z) output increases with increase in core radius. As core radius increases more light gets coupled into the fiber and that accounts for increase in sensor output. It is observed that linear operating range and sensitivity increases with core radius.

## *3.2* Symmetrically inclined fiber configuration

Buchade et.al.[3] did the same for symmetrically inclined fibers using geometrical approach and showed that inclination results in improvement in sensitivity. Experiments are carried out with fiber parameters having fiber diameter=2.2mm, NA=0.47 for different angles over the range of $0^{o}$ to $30^{o}$. Simulations were carried out using the ray trace model for the same range. As angle of inclination increases from $0^{o}$ to 30o overlapping starts at smaller distances. Due to angle between T and R fibers the image of core of transmitting fiber gets shifted towards the core of receiving fiber and hence for the same distance Z with angle the light collected by receiving fiber core is more showing improvement in sensitivity. Linear operating range decreases as peaks occurs at smaller values of Z with increase in inclination of transmitting and receiving fibers. Fig 3(a) and Fig 3(b) shows the good agreement with simulated and experimental results.

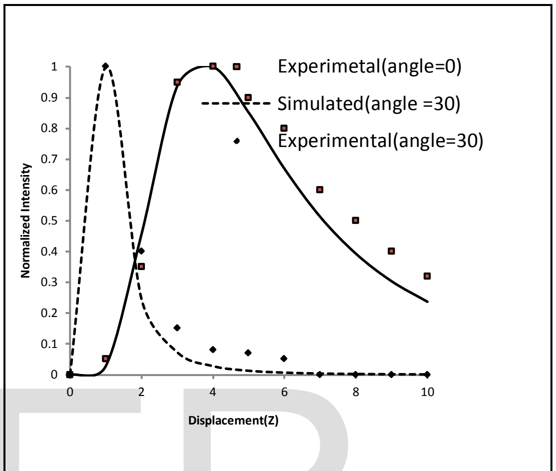


Fig.: 3(a) Sensor response

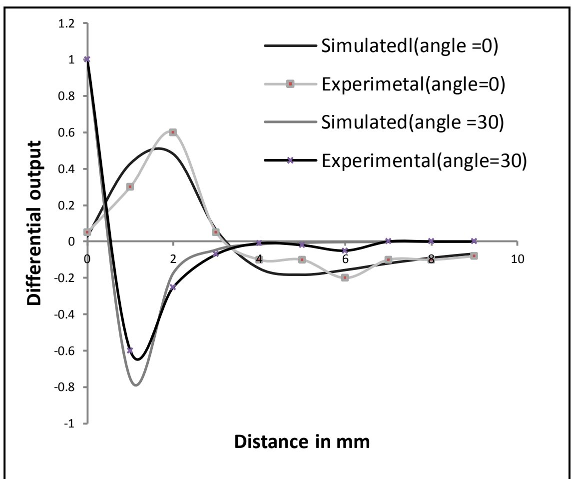


Fig.: 3(b) Performance Parameters

## *3.3* Asymmetrically inclined fiber configuration

Asymmetry in the configuration is inserted for analyzing the sensor for improvement in performance parameters. Lim et. al.[7] used transmitting and receiving fibers having different core radii and analyzed it for improvement in linear operating range. It is observed that linear operating range increases at the cost of decrease in the sensitivity. Similar configuration is used with symmetrically inclined fibers [3]. Slight improvement in the sensitivity is observed compared to the Lim et. al. [7] configuration. Patil et. al. [4] developed a model having identical fibers with unequal inclination. Due to unequal inclinations more light is coupled into the receiving fibers due to elliptical reflected cone. Thus for smaller Z values more light is coupled compared to those reported in literature. Experiment was carried out for different value of beta, where beta is difference between the angles of inclinations of transmitting and receiving fibers.

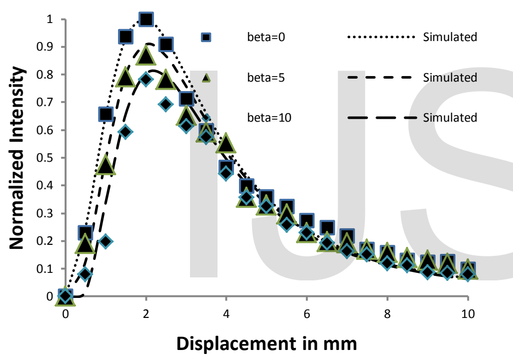


Fig.: 4(a) Sensor response

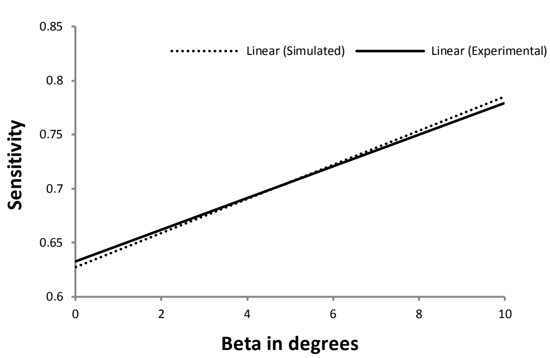


Fig.:4(b) Performance Parameters

Fig 4(a) shows experimental and simulated results and it is clear from the graph simulation shows good agreement with experimental data. Fig. 4(b) shows improvement in sensitivity of the sensor with increase beta.

### 3.3 Fiber bundle configurations

Every model is representing different configuration and such six different configurations are modeled. Fiber bundles having different configurations are simulated using the developed model and results are as shown in the graphs. These models are useful in improving the sensitivity and linear operating range. Three configurations of fiber bundle displacement sensor are discussed and simulated using the developed software. Table IV shows the simulated results for the three configurations viz. concentric, random and hemicircular.

a) Concentric configuration

In this configuration, as next ring of receiving fibers is added light left out from the fibers in the first ring is collected by fibers in the second ring which in turn extends the linear operating range. This is because peak position is shifted due additional ring of receiving fibers. Using concentric configuration as shown in row 1 of the Table IV , there is 2 times increase in the operating range as compared to single pair fiber sensor. It reveals that linear interval as well as sensitivity is increasing with number of receiver rings.

b) Random Configuration

Table IV row 2 shows the random fiber bundle configuration. In this configuration number source fibers and receiving fibers are arranged in random way. For each receiving fiber there are nearby more than two transmitting fibers which in turn increases the sensitivity. Not much improvement in the linear operating range is observed as number of receiving fiber rings are limited around the single transmitting fiber.

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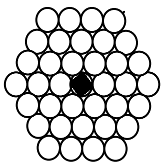
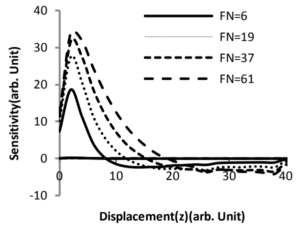
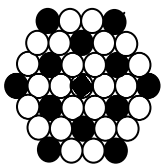
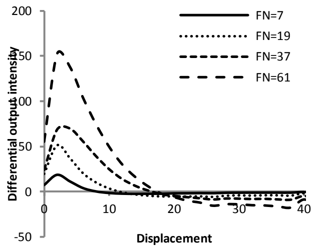
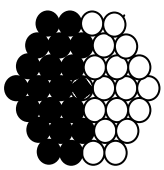
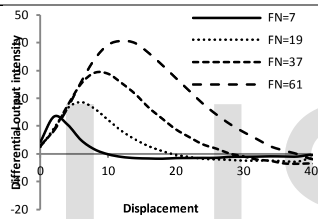
**TABLE IV**
Fiber bundle configurations

| Configuration | Sensitivity curves |
|---|---|
|  |   |
|  |   |
|  |   |

b) Hemi circular configuration

Table IV row 3 shows the sensor response and sensitivity curves for the hemicircular configuration. This is because for every added ring equal number of source fibers and receiver fibers are added in the configurations. Thus for every receiving fiber neighboring source fiber/s are present. Due to this significant amount of light enters in corresponding receiving fiber. Thus each receiving fiber collects light due to nearby as well as other source fibers. This causes in increase in the received light intensity and hence improvement in sensitivity. For each source fiber in the neighborhood of every receiving fiber there is another receiving fiber near it due to close packed configuration of receiving fibers in a fiber bundle. This shifts the peak positions for longer distances which results in the extension of linear operating range. Significant improvement in sensitivity and linear range is resulted for each added ring in this configuration as compared to concentric or random configurations.

## 4. Conclusion

Fiber optic micro displacement sensors can be modeled for any configuration using the proposed model and verified using the test jig. This model is further validated by considering number of other configurations proposed by other researchers and results are found to be in good agreement with it. This paper discussed some identified configurations which can be further extended for any configuration. It is also suggested that simulation using this model results in the practical behavior of sensor response as number of fabrication or manufacturing parameters variation is studied. Thus this model can be considered as a generalized model for fiber optic micro displacement sensors. The fiber optic sensor configurations tested are extendable to other practical physical and chemical sensing applications.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