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Design of Reflective Intensity Modulated Fiber-Optic Sensor Based on TracePro and Taguchi Method

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Abstract: Compare with traditional way of numerical simulation by establishing the mathematical model through geometry optic, we design a TracePro model to analyze the sensing process of reflective intensity-modulated fiber optic sensor base on ray tracing. This type of sensor has advantages over other fiber optic sensor, including simple structure, flexible design, reliable perform, low cost etc. In this paper, to design the reflective intensity modulated fiber optic sensor with concave reflected surface, TracePro software is used for modeling, TP modeling results are consistent with the existing conclusions show that the method is reasonably effectively, can improve the design efficiency. Meanwhile the Taguchi method is used to optimize coupling efficiency of receiving fiber in fiber optic displacement sensor design. Through optimizing three controllable factors the optimization configuration of A1B1C1 combinations is gain, presents a viable solution for the design of this sensor type. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Fiber optic sensor, Intensity modulated, Reflective surface, TracePro, Taguchi method.

1. Introduction

Reflective intensity-modulated fiber optic sensor (RIM-FOS) are widely used for such physical parameters measurements as distance, vibration, sound, pressure, temperature and acceleration because of their advantages over other fiber sensor, including simple structure, flexible design, reliable perform, low cost etc. [1]. Most works focus on the plane reflector [2-5], however such type of sensor with concave reflector which is seen frequently in mechanical circumstance could cause major differences in modulation property [6-9]. Such as the blind region of the sensor, having concave reflector is small as compare to the blind region of the sensor having plane reflector. Such type of sensor can be used, where the space required for the measurement is the major limitation.

So far the research of this kind of sensor is based on numerical simulation by establishing the mathematical model through geometry optic. The more complex the reflecting surface is, the more difficult to establish the mathematical model which is suit for qualitative discussions. With the change of the structural parameters, the corresponding mathematical models may need to re-establish. This is unfavorable for application of this type of sensor. In addition in the design process multi-parameter configuration optimization has been a major trouble for designers.

To better understand the working principle and improve the performance of the sensor, the ray - tracing simulation was carried out by using optical analysis software TracePro (TP), which provides the sensing process for us. Meanwhile Taguchi method was used to optimize the configurations.

2. TracePro Model

A typical two-fiber RIM-FDS configuration is shown in Fig. 1. It consists of a transmitting fiber (TF), concave reflector, receiving fiber (RF), an optical source (LED) and a photo detector (PD). The fiber tips and concave reflector are separated by a distance d. The mathematical models for optical fiber sensors with concave reflector were presented [6-9]. This paper focuses on the TP model of optical fiber sensor with concave reflector.

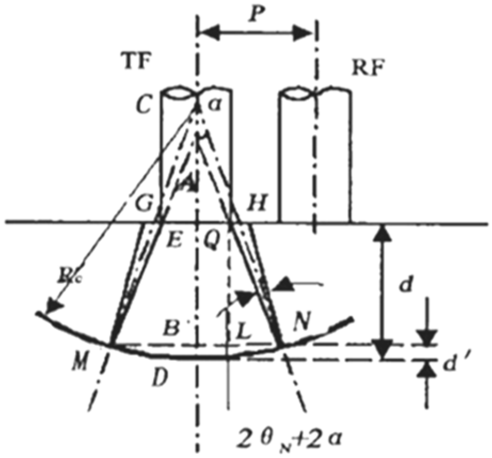


Fig. 1. Concave reflective surface.

Following assumptions are being considered for the TP model:

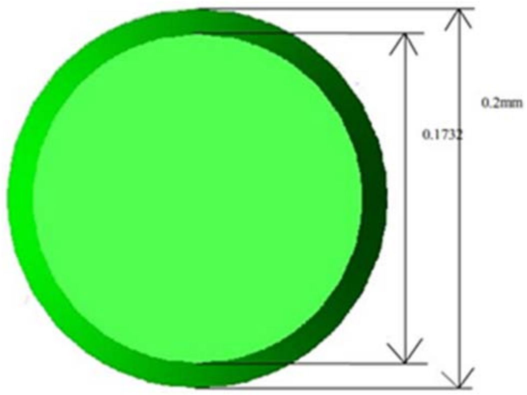
1. The transmitting fiber and receiving fiber have perfectly circular cross sections with radius of 0.1 mm.

2. The transmitting fiber is placed on the focal axis of the concave reflector.

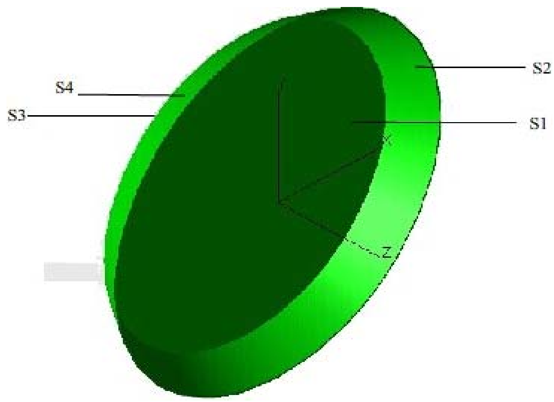
3. Both the fibers are straight parallel, with no space left between them and having the same numerical aperture NA of 0.56. So the beam divergence angle can be described as

$$\theta = \sin^{-1}\frac{\mathrm{NA}}{\mathrm{n}_0} \quad (1)$$

n_0 was the refractive index of the medium present in between the fiber tips and the concave reflector. Here was zero, then $\theta = 34^0$. A hollow thin round table structure shown in Fig. 2 was built to compensate the light loss caused by NA, where S1 and S2 plane is set to be completely absorbed in TP.



(a)



(b)

Fig. 2. Thin round table structure (a) Bottom view (b) three-dimensional view.

4. Light source: The light emitting characteristics of transmitting fiber (TF) tip was generally recognized as Gaussian distribution [10]. For this reason a grid light was set with an outer diameter of 0.1 mm and divergence angle 34°, the angular distribution was set to be Gaussian density distribution.

The amount of the light collected by the receiving fibers is directly correlated to the distance between the fibers tips and the reflector. Therefore, the distance variation can be measured by monitoring the intensity change of the collected light. However, most of the light representing useful sensing information is lost at the transduction region between the fiber tips and the reflector. Only a small portion of the light is reflected to the receiving fiber for collecting. Thus, much work has been done to improve the collecting efficiency. In order to analyze the distribution of light intensity in the receiving side (XY plane), which is conducive to reasonable arrangements for TF and RF position, a rectangular receiving surface structure was constructed in Fig. 3.

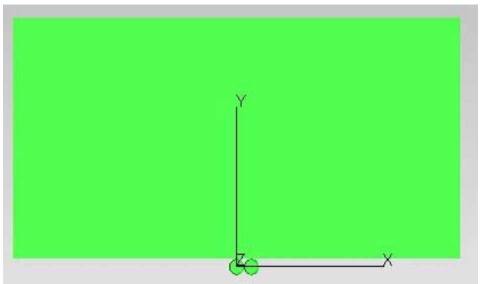


Fig. 3. Rectangular receiving surface.

By now the TP model was constructed as shown in Fig. 4.

In the configuration with radius of curvature R = 6 mm, distance d=0.3 mm, the irradiance of the receiving surface was gain as shown in Fig. 5, the light intensity distribution appear to be the ladder distribution. The cross-sectional view of the right figure shows corresponding areas of the horizontal light intensity distribution of and vertical direction.

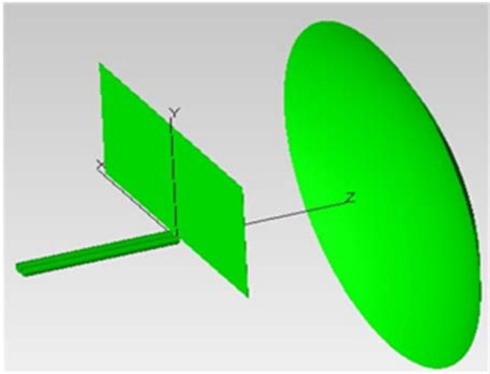


Fig. 4. TP model.

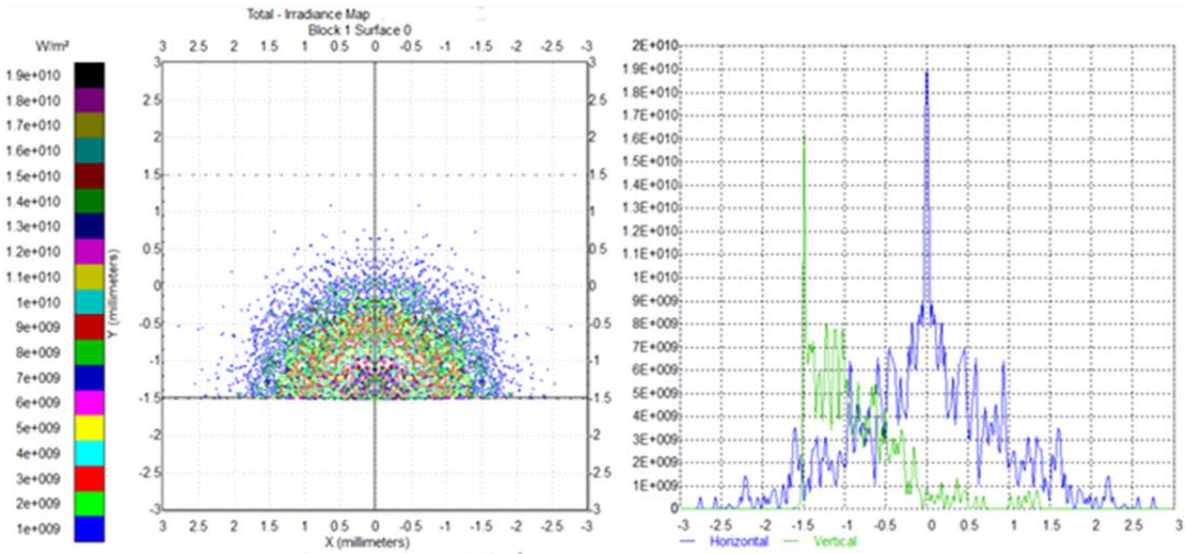


Fig. 5. Irradiance chart of receiving surface.

Here light intensity function M could be expressed as

$$M = \frac{N}{N_{Total}}, \tag{2}$$

where N represents the light intensity collected from S1 surface, N_{Total} represent the total light number of light source from TF. In this case coupling efficiency of the light intensity could replace with M.

By changing the radius of curvature R and the distance d which was between reflecting surface center and RF tip (with spacing of 0.05 mm) we obtain light intensity values of different radii of curvature, their modulation curves were shown in Fig. 6 by Origin software process.

In Fig. 6 the distance between two optical fibers p was set to be 0.3 mm and the radius of curvature R were taken by 3 mm, 6 mm, 9 mm respectively.

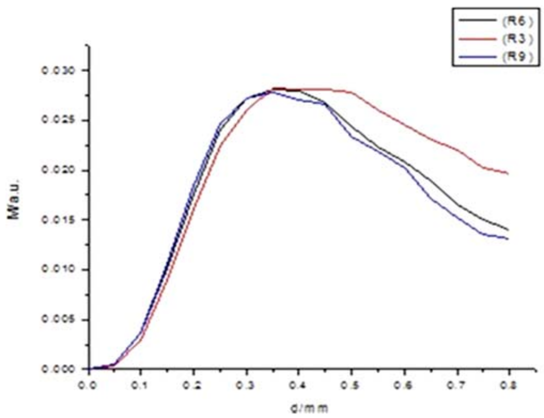


Fig. 6. Light intensity curve of Concave reflective surfaces with different R.

As the concave radius of curvature becomes large, the dead zone of the characteristic curve becomes smaller, the linear range of the front slope decreases and the sensitivity increases, the linear range of the back slope decreases and the curve slope increases. The property of low signal loss in optical fibers permits long distance optical data transmission, enabling remote physical quantity measurements to be conducted without losing significant sensing accuracy. As there is a deviation between mathematical modeling and the actual situation, tp modeling method also has its difference. This work was aimed at providing designers with a cost-effective methodology to enhance the fiber coupling efficiency compare with numerical simulation approach. For now these conclusions are consistent with the numerical simulation results, showing that this method is reasonable.

3. Taguchi Method

The Taguchi method combined with principal component analysis can use in the extended optimization of non-image optics, because this method does not depend on the number of ray tracings [11]. Most commercial optical software performs well in analysis work; however, during optimization, ray tracing numbers are used.

In the Taguchi method, experiments are conducted to determine the best levels based on an orthogonal array (OA) [12]. An orthogonal array is a fractional factorial matrix that assures a balanced comparison of levels for any factor or interaction of factors. Assuming an orthogonal array of strength t is expressed by a matrix of j rows and i columns that makes a_i^j

$$\text{Each } a_i^j \in \{0, 1, \ldots, q-1\}.$$

When setting $t \leqslant i$ in each j by t sub-matrix of all q^t possible rows occur the same number of λ times, so $\lambda q^t = j$ [13]. Such an array is denoted by OA (j, i, q, t), in which all possible combinations of symbols in any array of strength t appear with equal frequency [14]. The orthogonal array is to set up experiments that require only a fraction of the full factorial combinations. The treatment combinations are chosen to provide sufficient information to determine the factor effects using the analysis of means (ANOM). Orthogonal refers to the balance between the various combinations of factors so that no one factor is given more or less weight in the experiment than the other factors. Orthogonal also refers to the fact that the effect of each factor can be mathematically assessed independently of the effect of the other factors.

With negligible interactions between the control factors, the S/N effects can be modeled by simply adding the main effects from each control factor. This is referred to as an additive model, which takes on the following form [12].

$$M_{predict} = \bar{M} + (\bar{M}_A - \bar{M}) + (\bar{M}_B - \bar{M}) + \cdots + \text{error}, \quad (3)$$

where $\bar{M}$ is the overall average response for the entire OA and $\bar{M}_A$, $\bar{M}_B$ are the response average for factors A, B, C, respectively. The error term is the difference between the actual response on the left and the predicted response based on the additive model.

To use TP software for simulation, first we should define the sensitivity of coupling for each parameter. There are some factors that could affect the efficiency of RF receiver:

1) Theoretically the radius of curvature of the reflecting surface R could range from 0 to infinity. In fact when the R value exceeds a certain range, the result is close to the plane reflector of the case. To highlight the characteristics of a concave reflector, the values of R were given in 0 ~ 8 mm.

2) Based on longitudinal sectional view of the right in Fig. 5, the configuration with distance p between TF and RF is obtained reasonable in 0.2 mm to 0.6 mm.

3) By the light intensity modulation curve in Fig. 6, the characteristic area is 0 ~ 0.8 mm.

4) Other variables, including the selection of the light source, the reflective surface, the optical fiber type, in order to better control variable values were set to be constant values.

According to the above principles, controllable factor table was design (Table 1).

Table 1. Controllable factor table.

	Level 1	Level 2	Level 3	Level 4
A(R)	2 mm	4 mm	6 mm	8 mm
B(p)	0.2 mm	0.3 mm	0.4 mm	0.5 mm
C(d)	0.2 mm	0.4 mm	0.6 mm	0.8 mm

According to Table 1, there are three factors and four levels, thus we could selected L_{16} orthogonal table to plan the simulation experiments. The results were shown in Table 2.

Table 2. Coupling efficiency test table.

No.	Configuration	M
1	A1B1C1	0.063165
2	A1B2C2	0.029224
3	A1B3C3	0.01617
4	A1B4C4	0.0096883
5	A2B1C2	0.044618
6	A2B2C1	0.01685
7	A2B3C4	0.014221
8	A2B4C3	0.0096876
9	A3B1C3	0.026546
10	A3B2C4	0.014007
11	A3B3C1	0.0035795
12	A3B4C2	0.0071622
13	A4B1C4	0.01859
14	A4B2C3	0.020013
15	A4B3C2	0.014741
16	A4B4C1	0.0013687

Table 2 shows that, the optimal configuration can be get from A1B1C1 configuration. According to Eq. (3), the predictive result is 0.057329 compare with the simulation result which is 0.063165.

Convert to coupling efficiency, the predictive and simulate value are 5.73 % and 6.31 % respectively, the difference which is reasonable between them can be used to predict the impact of the overlapping effect of factors.

At the meantime

$$y_k = \frac{sum\ of\ y_k\ in\ tab.2}{4} \quad (4)$$

y=A, B, C; k=1, 2, 3, 4

The coupling efficiency of each factor can be calculated by Eq. (4) (Shown in Fig. 7). Fig. 7 shows the smaller the radius of curvature R, the higher the coupling efficiency is obtained, indicating the good light gathering ability and of high coupling efficiency concave reflector compare with the plane reflector. Decreasing fibers distance p could help to improve the coupling efficiency.

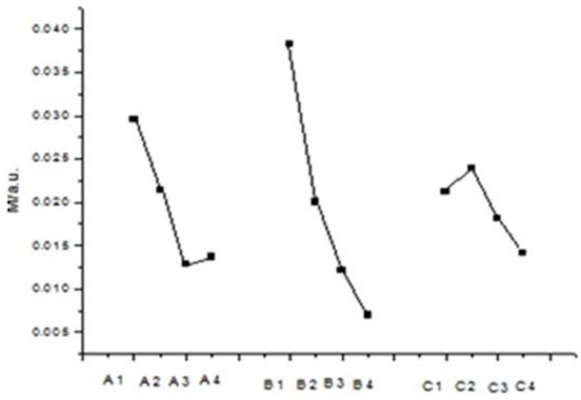


Fig. 7. Coupling efficiency of each factor.

4. Conclusions

For the analysis of complex reflective surfaces, the introduction of TP model can effectively improve the efficiency of this type of sensor design. The results show that the proposed model can simulate the output response in an effective way. Using the Taguchi method to obtain optimized configuration A1B1C1 whose coupling efficiency can reach 6.31 %. While the smaller the radius of curvature R and fibers distance p, the higher the coupling efficiency. As the numerical analysis method has certain defects, tp modeling in the specific design of the sensor also needs to be calibrated. Further work should be focus on that.

Acknowledgements

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