Modulation Function Study of Coupling Based Intensity Modulated Fiber-Optic Sensors

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Abstract: The modulation function for fiber-optic sensors based on coupling between fiber ends is studied for different fiber configurations. Sensitivity aspects are evaluated experimentally and theoretically, being shown that multiple passes practically do not increase sensitivity.

1. Introduction

Intensity modulated sensors based on coupling between fibers enable simple and cheap displacement sensor solutions (Fig. 1). In the field of vibration measurement applications, the modulation may be produced by micro-structure cantilevers in the light path [1] or by letting the transmitting fiber itself act as a cantilever [2-3]. Similar sensor designs based on, or combined with, integrated optics have also been realized [4-5].

Some of the most important parameters to consider in the optical design of the sensor are the signal-to-noise ratio, the sensitivity and the linearity of the sensor in the intended measurement range. These parameters are improved, in turn, if the received optical power, the slope (index) of the modulation curve and the linearity of the modulation over the total displacement range are as high as possible. In terms of received optical power, multimode fibers are to be preferred to single-mode fibers. Radial (transverse) displacement gives the most significant change in coupled power [6], and should therefore be considered for sensitivity reasons. Furthermore, the choice of fiber type also affects the sensitivity and the linearity of the sensor.

A way of further improving the sensitivity could be to arrange multiple passes over a connection according to Fig. 2, thus giving a multiple change in coupled power for a certain displacement. The possibility of realizing this, and the practical use, is investigated and analyzed experimentally and theoretically below.

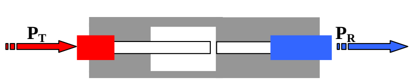

Fig. 1. Principal coupling-based vibration sensor

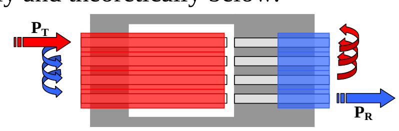

Fig. 2. Multiple pass configuration using fiber ribbons.

2. Experimental pre-study

Measurements of the transmission ratio (received/transmitted power, P_R/P_T) versus the transverse displacement were performed for 62.5 µm core GI multimode fibers and 4-fiber ribbons (R4), V-groove arrays (V4) and MT-connectors (MT4), see fiber data in Table 1. Transmitting and receiving fibers of 5 m length each were coupled to a 1300 nm LED and a HP81521B detector, respectively. An xyz-translator was used to optimize fiber-to-fiber coupling (1 mm free ends with a 10 µm gap), and a transverse scan in 1 µm steps was made from +50 to -50 µm. The result, shown in Fig. 3, is that no sensitivity improvement is achieved for multiple passes compared with a single one.

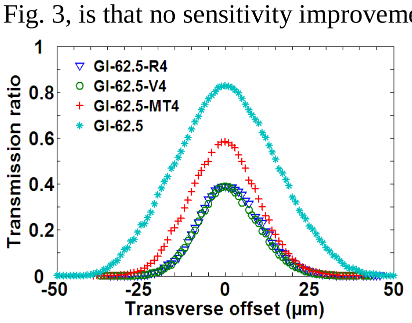

Fig. 3. Experimental modulation curves

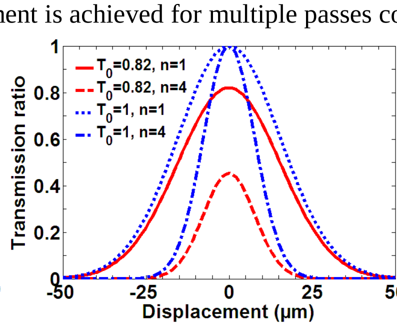

Fig. 4. Theoretical modulation curves

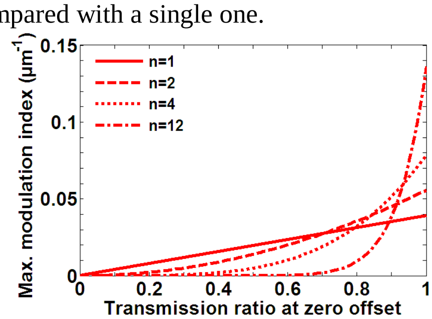

Fig. 5. Maximum modulation index vs. T_0

3. Theoretical analysis

A very simple, though for multimode fibers not exact, way of describing the modulation function is by using a Gaussian expression for the transmission ratio T for n multiple passes as a function of displacement x:

$$T(x) = \left(T_0 \cdot e^{-\alpha x^2}\right)^n = T_0^n \cdot e^{-n\alpha x^2} \qquad (1)$$

where T_0 is the transmission ratio per pass at zero displacement. The slope S(x) of the modulation curve is given by

$$S(x) = \frac{dT}{dx} = -2n\alpha T_0^n \cdot x \cdot e^{-n\alpha x^2} \qquad (2)$$

with a maximum absolute value S_{max} for $x=\pm 1/\sqrt{(2n\alpha)}$. With $0 \leq T_0 \leq 1$ and $n \geq 1$, S_{max} can be expressed as

$$S_{\max}(n, T_0) = T_0^n \cdot \sqrt{(2n\alpha / e)} \qquad (3)$$

With α=0.0021 μm^{-2} and T_0=0.82, T(x) approximates experimental data of a single pass in Fig. 3. In Fig. 4, this modeled T(x) is plotted for n=1 and n=4, also with T_0=1. Fig. 5 shows the corresponding modulation index S_{max} plotted versus T_0 for some values of n, using α=0.0021 μm^{-2}. From Fig. 5 it is clear that a very high T_0 is needed to take benefit from multiple passes. The more passes, the higher T_0 is needed per fiber pair. This fact flags for problems with fiber alignment. Fig. 4 gives a picture of what could be expected from an ideal multiple pass case, compared with the experimental result of Fig. 3: a higher slope and a narrower displacement range.

4. Further experimental work

With the same experimental conditions, modulation curves were recorded for other fiber types (Fig.6). In order to increase T_0 also hybrid fiber pairs, where the receiving fiber has a larger core diameter and numerical aperture (NA) than the transmitting fiber, were investigated. Finally a hybrid, three-pass V-groove fiber array was measured on. The result, seen in Fig. 7, is an increase in T_0 for the array. Also it can be noted that the fiber with the highest modulation index determines S_{max} for the hybrid array, i.e. the same index could be achieved with just a fiber pair.

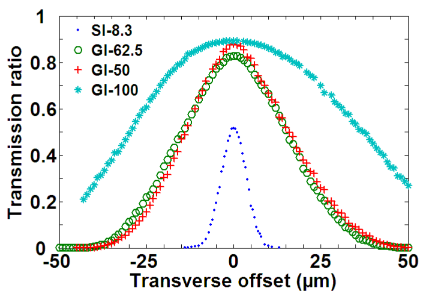

Fig. 6. Experimental modulation curves for single pass (n=1) of some different fiber types

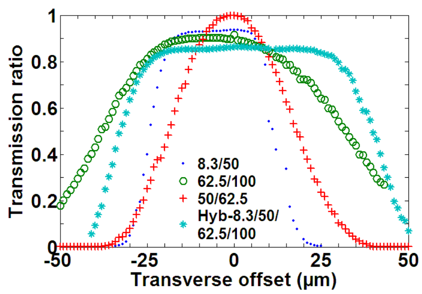

Fig. 7. Experimental modulation curves for hybrid fiber pairs and V-groove array

Table 1. Fiber sample data

Fiber sample	NA	P_T (μW)
SI 8.3/125 μm	0.11	0.37
GI 50/125 μm	0.20	13.0
GI 62.5/125 μm	0.275	39.3
GI 100/140 μm*	0.29	36.0
R4 x 62.5/125 μm	0.275	31.9
V4 x 62.5/125 μm	0.275	35.8
MT4 x 62.5/125 μm	0.275	17.7
Hyb-8.3/50/62.5/100	0.11-0.29	0.32

*connected to source with 62.5-fiber

6. Conclusions

It has been shown theoretically and experimentally that multiple passes, due to unreachable alignment and coupling demands, do not increase sensitivity in practice. Also, the multiple pass effect on sensitivity could be realized with a single fiber pair with suitable core diameter. In reality, fiber types in such a pair should be chosen depending on the displacement range of interest in each sensing application.

7. References

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