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A HIGHLY SENSITIVE FIBER-OPTIC ANGULAR ALIGNMENT SCHEME

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Abstract. The principle of operation and behaviour of a simple, highly sensitive differential fiber-optic angular alignment scheme is reported. Angular misalignments within the range of 10 arcsec and an accuracy of 0.02 arcsec are easily measurable. The scheme allows for the sign of misalignment to be identified and relative measurements to be performed thus reducing noise from power fluctuations of the source.

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1. Introduction

Precise measurement of angular misalignment has a wide range of applications such as accurate alignments in machine building as well as in refractometry. A simple and efficient way is to use laser autocollimation schemes [1-3]. The implementation of optical fibers in precise alignment schemes offers new possibilities and recently a highly sensitive fiberized version of an autocollimation refractometer has been proposed [4]. The accuracy of the angular deviation measurement is of the order of 1 arcsec over a range up to 70 arcsec, reflecting in a precision of refractive index measurement of the order of 10^{-5} to 10^{-6}. Due to the introduction of optical fibers the method features simplicity and flexibility. However, it does not allow for the sign of the angular misalignment to be determined. The use of fiber differential arrangements [5, 6] offers the possibility to increase accuracy by about two orders of magnitude and measure angular misalignments along two orthogonal directions.

In the present paper we report on the development of a highly sensitive fiber-optic autocollimation scheme. The scheme features four basic advantages. It first allows angular deviations as small as 0.02 arcsec to be measured. Second, the autocollimation condition is found by detecting a zero signal. Third, the sign of the angular changes along two mutually orthogonal axes can be determined. Fourth, it allows relative and not absolute measurements to be performed making thus the system immune to the power fluctuations of the source.

2. Principle of Operation and Theory

The basic operational scheme is presented in Fig. 1. Laser light is launched into a low birefringence single-mode fibre that propagates the fundamental LP_{01} mode whose distribution is considered Gaussian with a spot-size ω_0. This mode is then collimated by an objective whose focal length is f and passing through a beamsplitter is reflected by a mirror. The beam is then reflected by the beamsplitter and is incident upon a detection setup consisting of two identical fibers. The waist spot-size of the incident Gaussian wave is ω

$$\omega = \omega_0 \frac{L}{f} \tag{1}$$

where L is the length of the optical path between the objective and the detecting fibers. In the setup shown in Fig. 1 the optical path is $L = 2L_1 + L_2$.

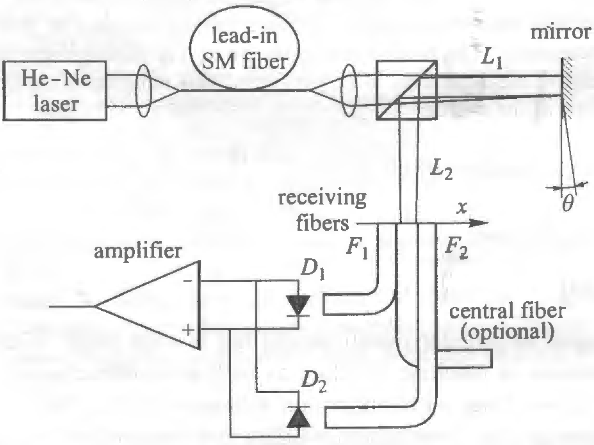

Fig. 1. Schematic representation of the differential angular alignment system

The detecting fibers are a linear array of two or three fibers. All fibers have the same outer cladding diameter. The setup with two fibers is the simplest and more sensitive. When three fibers are used, the third fiber is the central fiber. The light intensity accepted by the center fiber will reach a maximum when the system is aligned. When the beam is incident upon the detection fibers each of them accepts and guides a different light intensity. We denote by I_1 and I_2 the light intensities guided by the two receiving fibers. These two fibers illuminate two separate detectors which are branched in a differential scheme and thus the amplifier yields a signal which is proportional to the difference $\Delta I = I_1 - I_2$. Evidently if the fibers are equally illuminated the signal is zero. When the reflecting mirror is tilted to some angle θ the whole spot is displaced by an amount of $x = L\theta$ and the two multimode fibers are differently illuminated. The dependence $\Delta I(\theta)$ can be used to detect the perfect alignment $\theta = 0$ and measure the angular misalignment.

To derive an explicite expression for $\Delta I(\theta)$ we assume that the core centers of the two fibers are aligned along an axis which we denote as X, the intensity distribution of the Gaussian beam along this axis is

$$I = I_0 \exp\left[-\left(\frac{x}{\omega}\right)^2\right] \tag{2}$$

where I_0 is the light intensity at the center of the distribution (i. e. for $x = 0$). In the general case all of the fibers will be illuminated. We next suppose that the core centers of the receiving fibers are at distance D. We also assume that the cores of the receiving fibers act as point detectors, i. e. their radii are sufficiently smaller than the spot-size ω. In this case the intensities I_1 and I_2 are written as follows:

$$I_1 = I_0 \exp\left[-\left(\frac{x-\frac{D}{2}}{\omega}\right)^2\right], \qquad I_2 = I_0 \exp\left[-\left(\frac{x+\frac{D}{2}}{\omega}\right)^2\right]. \tag{3}$$

Thus the differential signal $I_1 - I_2$ is

$$I_1 - I_2 = 2I_0 \exp\left[-\left(\frac{D}{2\omega}\right)^2\right] \sinh\left(\frac{xD}{\omega^2}\right) \exp\left[-\left(\frac{x}{\omega}\right)^2\right]. \tag{4a}$$

Fluctuations of the optical power of the source will result in random variations of I_0. Since the level of the differential signal $\Delta I = I_1 - I_2$ is proportional to I_0 then fluctuations of the optical power of the source will lead to instabilities in the signal. To avoid this the differential signal must be divided by the total signal captured by the two multimode fibers $I_1 + I_2$ which easily found to be

$$I_1 + I_2 = 2I_0 \exp\left[-\left(\frac{D}{2\omega}\right)^2\right] \cosh\left(\frac{xD}{\omega^2}\right) \exp\left[-\left(\frac{x}{\omega}\right)^2\right]. \tag{4b}$$

The ratio of (4*a*) and (4*b*) is then

$$\xi = \tanh\left(\frac{xD}{\omega^2}\right). \tag{5}$$

In (4) and (5) sinh, cosh and tanh are correspondingly the hyperbolic sine, cosine and tangent. The ratio does not depend on the power of the source and the measurement is free from instabilities.

A plot of $I_1 - I_2$, $I_1 + I_2$ and x is presented in Fig. 2. As is clearly seen the differential signal and the ratio exhibit a central part of the response which is practically linear around the zero level. While at perfect alignment ($x = 0$) the sum ($I_1 + I_2$) reaches a maximum and exhibits the lowest sensitivity and is insensitive to the sign of the misalignment, the difference and the ratio are at zero, and the sensitivity is the greatest around the value of the perfect alignment and the sign of the misalignment is always accounted for.

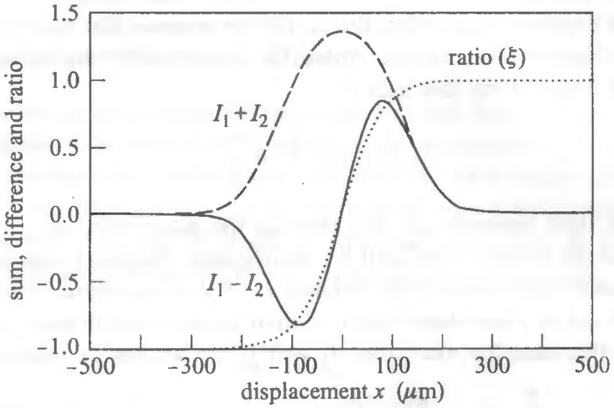

Fig. 2. Difference, sum and ratio of I_1 and I_2 for $D = 125$ μm and $\omega = 100\mu$m

3. Results and Comments

The experimental setup for the differential alignment system shown in Fig. 1 makes use of a He–Ne laser (633 nm), a polarization insensitive beamsplitter and a high precision tilt positioner. Synchronous detection was used to reduce noise during measurements. The lead-in optical fiber was a standard nonbirefringent fiber single-mode at 633 nm. To obtain the differential signal, both single- and multimode receiving fibers were used in the experiments. The spot-size at the plane of the receiving fibers was varied by finely tuning the illuminating fiber end with respect to the focal plane of the objective. The change of the spot-size affects the sensitivity of the measurement scheme in a way that as long as $\omega \geq D$ the sensitivity decreases with ω. In case $\omega \leq D$ the response of the differential signal is not linear around the zero level. Also sensitivity increases with the length of the optical path $L = 2L_1 + L_2$. In our experiments $L_1 = 170$ mm and $L_2 = 180$ mm which results in $L = 520$ mm.

Figure 3*a* presents the differential response when a single-mode fiber pair is used. The curve is in close agreement with the theoretical dependence ((4*a*) and the corresponding theoretical plot in Fig. 2). As is clearly seen, the central part of the response is practically linear over an angular range of 26 arcsec. The signal was stable to within 0.1 mV which translates into an accuracy of 0.016 arcsec. Figure 3*b* shows the intensity distribution of the beam in the plane of the receiving fibers. For the specific values of the optical path in the experimental arrangement, the spot size ω is 100 μm.

The use of multimode fibers shows the same type of response and sensitivity. The advantage of multimode fibers is that they can collect more optical power from the reflected beam. This allows us to use lower power sources or increase the optical path L. The latter in turn leads to an increase of the sensitivity.

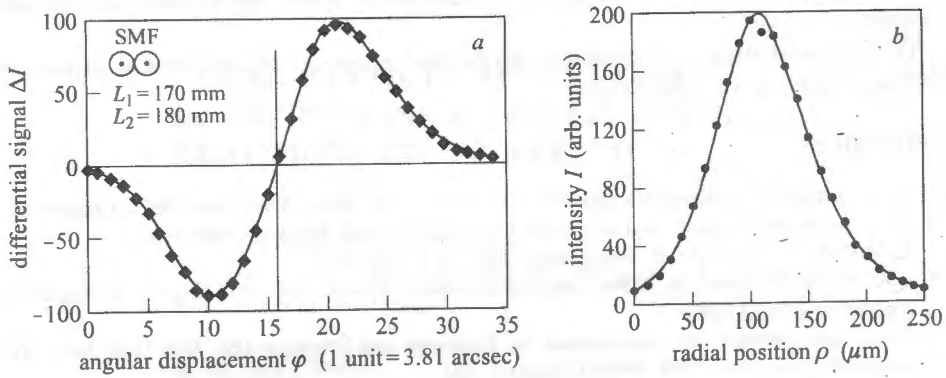

Fig. 3. (*a*) Differential response of the sensor with a single-mode receiving fiber pair (*b*) Intensity distribution of the field at the plane of the single-mode receiving fiber pair

If two receiving fiber pairs are mounted as shown in Fig. 5, the differential scheme will be able to measure angular misalignments along two orthogonal directions.

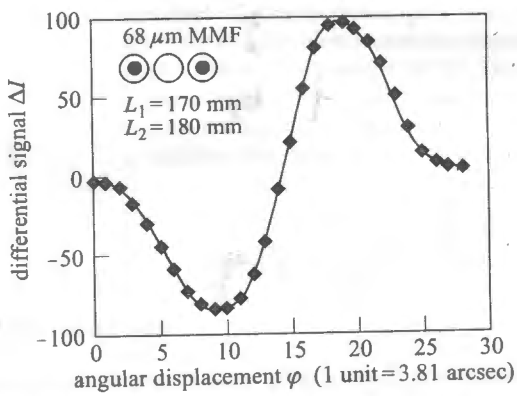

Fig. 4. Differential response of the sensor with a multimode receiving fiber pair and a central fiber

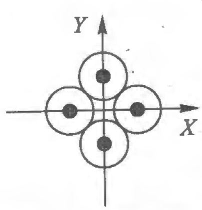

Fig. 5. A double receiving fiber pair permitting measurement of angular misalignments along two orthogonal directions

4. Conclusion

We have studied both theoretically and experimentally the performance of a differential fiber-optic angular misalignment scheme. It allows a simple measurement of angular deviations with an accuracy better than 0.02 arcsec over a range of about 25 arcsec. The scheme determines the sign of the misalignments and absolute alignment is detected by finding a zero output signal. It also offers the possibility for relative measurements. An improved version of the scheme permits to determine angular misalignment along two orthogonal directions. The use of optical fibers makes the scheme flexible and compact.

The proposed alignment technique can be used in optical and mechanical alignment systems as well as in refractometry.

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