INTERFERENCE METHOD FOR ULTRA-PRECISION MEASUREMENT OF ANGULAR MICRO-DEFLECTION

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Abstract:

A new interferometric method for ultra-precise measurement of laser beam angular deflection is presented. Also angular tilt of measuring device in relation to the beam axis can be measured. The method is based on interference fringe period analysis in the selected plane of measurement. We proof that if the number of beam reflections in the interferometer arms differs by an odd number, then the deflection of the input beam can be measured by evaluating the change of the observed interference fringe period.

The theoretical basis and experimental verification of the method are presented. Two interferometer designs are compared. Influence of the wavelength change and the lateral shifts of the beam axis on laser beam deflection measurement are analyzed. Resolution reaching single nanoradians (0,001 arcsec) is shown. The main feature of the proposed method is that the applied interference system can be very small (having a volume of approximately 1 cm^3). Design of the sensor can be extremely robust, and insensitive to the most common disturbances (like temperature, linear displacements etc.). Because of these feature, the system can be applied easily in laser design as a system for output beam angular stabilization. Also angular deflection of the interferometer set-up in relation to the input beam axis can be measured.

Keywords: Measurement, laser beam deflection, interferometer, pointing stability

1. INTRODUCTION

One of the laser's most useful properties is that it can propagate over great distances defining a straight line. Focused laser beam creates a laser spot defining a point in space. Both properties are strictly connected each other because the angular deviation of the beam axis causes linear displacement of the spot in focal plane. These properties are exploited by a huge amount of optical systems. The spatial drift of a laser beam is of particular concern in applications such as laser-based metrology from long-distance guiding systems to short-distance scanning microscopes, and laser-based material processing, from optical lithography, laser machining, to optical manipulation of DNA molecules. Laser beam spatial and especially angular position and it's stability is extremely important in all the laser systems where in space a laser spot is focused or aimed, which is relevant to a number of laser applications from laser range finding to optical scanning, laser marking to building laser printers. Finally laser beam angular stability is one of the most important laser beam parameter used in interferometric gravitational wave detectors that are applied in astrophysics. The beam spatial stability of a laser system and how it is actively compensated for in a given application is often the main factor that limits the achievable precision of the application.

Also, precision measurement of the angular position or its changes in relation to the laser beam axis are key part of many measuring systems (e.g. scanning microscope).

In order to measure the laser beam position that is known as optical-beam deflection sensing (OBDS), beam profilers, position sensitive detectors, split detectors (bi-cell detector), or quadrant photodiodes are used most often. All these devices are able to indicate the location of the beam on the detector in one or two axes. Highest accuracy and measuring range of laser beam position detection can be achieved using laser beam profilers [1-2]. Because of the high size these devices cannot be applied effectively in compact optical sensors.

Most often the deflection of an optical beam is detected using a position-sensitive detector in a triangulation configuration [see, e.g. 3-5].

The second group of ODBS techniques is based on so-called autocollimation scheme. In this case the beam angular tilt is transformed by a suitable lens into a transverse shift in order to be measured [see, for example, Refs 1,3,6].

The reference for mentioned above ODBS techniques of measurement is given by the position of the applied sensitive detector in relation to the other parts of the system. Thus, the key issue is the geometrical stability of the position sensitive detector and the other parts of the measuring system. Finally depending on the individual system configuration, particularly its mechanical stability, and applied data averaging, the present techniques gives the resolution of beam axis angular deviations measurement reaching 1 microradian.

Possibility for overcoming these disadvantages is to use so-called angle sensitive device (ASD) that is independent of the distance between the sensor and the deflection point instead of a position sensitive detector. These detectors are able to detect small angular deflections of a well-collimated laser beam. A majority of types of angle sensitive detectors are based on applying the critical-angle effect. [e.g. 7-16].

Some of the modern ASD techniques use different kinds of laser interferometers [14, 17-18].

Author of this article propose also to apply light interferometry for ultra-precise measurements of beam angular deflections, using a new measuring method based on interference fringe period analysis in the selected plane of measurement. The basis of the method has been presented in [19-20]

The proposed method provides resolution reaching singular nanoradians, comparable only with techniques presented in [12]. However, the main feature of the proposed method is that the applied interference system can be very small (having a volume of approximately 1 cm^3). Design of the sensor can be extremely robust, and insensitive to the most common disturbances (like temperature, linear displacements etc.). Because of these feature, the system can be applied easily in laser design as a system for output beam angular stabilization. Also angular deflection of the measuring device in relation to the beam axis can be measured.

2. THEORETICAL ANALYSIS

2.1 Principle of Measurement

There are known many kind of two beam interferometers for measuring phase difference between interfering beams. In such optical systems a beamsplitter divides a laser beam into two beams that form two arms of the interferometer. The laser beam in each interferometer arm is directed by several reflecting surfaces to the second beamsplitter. This beamsplitter combines both beams to make them interfering.

Let as assume that in both interferometer arm a plane wavefront is propagating. Let as also assume that the beam entering the interferometer (i.e. incident first beamsplitter) is deflected by a small angle $d\theta$. If in both arm of the interferometer the same amount of reflections occurs than both interfering beams will finally deflect by the same angle. Generally if the reflections number is even or at the same time it is odd in both interferometer arms both interfering beams deflect equally by $d\theta$ or $-d\theta$ respectively. As a result the angle of interference will not change and the fringe period will remain unchanged. It is beneficial for majority of the interferometer applications.

Let's now differ amounts of beam reflections in both interferometer arms by odd number. This will cause that final deflection of one of the interfering beam will be equal to $d\theta$ while the second interfering beam will tilt by $-d\theta$. The interference angle will change by $2d\theta$. That will cause change of the observed fringe constant δ according to the equation [20-21]

$$\delta = \frac{\lambda}{2\sin(\theta)} \quad , \tag{1}$$

were λ is wavelength of the analyzed laser beam. For small values of interference angle, this can by simply written as:

$$\delta = \frac{\lambda}{2\theta} \, . \tag{2}$$

A relative change of the fringe period, caused by a small change of the interference angle, can be described by

$$\frac{d\delta}{\delta} \approx -\frac{d\theta}{\theta} \quad , \tag{3}$$

where *d* represents the differential. $d\delta$ denotes fringe constant change. This change can be detected with high resolution by many types of photodetection systems (e.g. CCD camera and relevant software for image analysis).

However, we propose a very simple photodetector, especially suited to the purpose of applying the proposed technique in a system for laser beam angular stabilization. The proposed photodetector is shown in Fig. 1 [19-20]. It consist of four linearly placed photoelements.

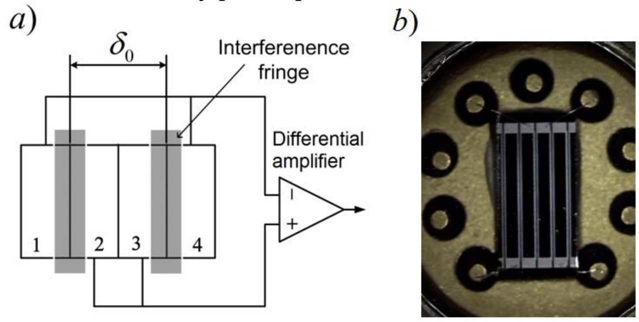


Fig. 1: Simple four-element photodetector to measure changes in interference fringe period. a) Electrical scheme b) View of the applied in experiments photodetector

Parameter δ_0 marked in Fig. 1 represents interference fringes of period that matches twice the distance between the photoelements. The output signal *I* of the differential amplifier shown in Fig.1 is the obtained as a following sum of the signals of the photoelements

$$I = I_1 + I_4 - I_2 - I_3 \, , \tag{4}$$

were indexes from 1 to 4 denote respective photoelement of the photodetector. In can be easy proved that the dependence of the photodetector output signal versus the deflection of the interferometer input beam can be written in the following form [20]:

$$dI \approx \frac{4\pi B}{\theta_0} d\theta \ , \tag{5}$$

where *dI* is observed change of the photodetector output signal caused by the tilt $d\theta$ of the input beam in relation to the initial value θ_0, that is equal the half-angle between the interfering beam wavefronts. θ_0 generates the fringe period equal to δ_0 i.e. equal to double value of the photodetector constant (see Fig. 1). *B* is a constant describing the system sensitivity.

It is easy to see that the sensitivity of the photodetection system is inversely proportional to the initial value θ_0 of the interference half-angle. Thus, it is proportional to the initial value of the fringe period. By changing initial value θ_0 sensitivity and measuring range of the interferometer can be selected.

A very simple form of Eq. (5) is especially useful when the system is used for the laser beam direction stabilization, i.e., Otherwise, a more accurate dependence given in [20] should be applied.

2.2 Lateral shifts of the Beam Axis

Let as assume that the beam entering the interferometer (i.e. incident first beamsplitter) is shifted perpendicularly to its axis by a small distance *dx*. Such a shift we can treat as a turn of the beam around a point laying on its axis and placed in infinity. Thus, the presented in a previous paragraph way of thinking can be repeated. Similarly to the previous analysis it is easy to show that the interfering beams axes at the output of the interferometer will be shifted relative to each other by a distance *2dx*. In the case of collimated this will not change the fringe constant. It means that the system will not be sensitive to the lateral shifts of the beam axis

However if we focus input beam to obtain strongly spherical wavefronts reaching photodetector a so-called shearing fringes will be generated there. The fringe constant will depend on distance *2dx* between virtual light sources, making possible measurement of *dx* shift.

2.3 Influence of the Wavelength Change

Equations (1) or (2) indicates that the wavelength change of beam will cause a change of the analyzed fringe period δ. According to the Eq. (2) a change of the fringe period (that is adjusted to the double value of the photodetector constant) caused by change of the the wavelength is equal to:

$$\frac{d\delta}{d\lambda} = \frac{1}{2\theta_0} \tag{6}$$

Taking into consideration Eq. (2) it can be expressed in the form:

$$\frac{d\delta}{\delta_0} = \frac{d\lambda}{\lambda} \tag{7}$$

Finally according to the Eq. (5) we obtain influence of the relative wavelength change on the output signal

$$dI \approx 4\pi B \frac{d\lambda}{\lambda} \ . \tag{8}$$

Comparing Eq. (8) with the Eq. (5) we can see that the sensitivity of the output signal on the relative wavelength change is equal to the sensitivity of the output signal to the relative change of the incident beam direction. Let us assume possible resolution of the system equal to about 4 nrad (see clause 3.1 or [20]) and let us assume used in experiments value of the θ_0 equal to about 0.4 mrad. Then minimum distinguishable relative change of the incident angle is equal to 10^{-5}. The relative wavelength instability of the stabilized HeNe laser is better than 10^{-8}. Thus, it is three orders of magnitude lower then sensitivity of the analyzed system.

Let us assume that the interference fringes are observed in the air. The relative change of the wavelength in air is equal to negative value of the air refraction index. Changing the temperature by 1° C causes the relative change of the refractive index of about 10^{-6}. It is still one order of magnitude lower then sensitivity of the analyzed system.

Temperature change can cause OPD change in the analyzed interferometer. In the result observed fringes will move. We have shown earlier [20], that proposed photodetection system is insensitive on fringe displacement.

Summarizing in most of the practical cases influence of the wavelength and ambient temperature on the measuring system is negligible.

2.4 Optical set-up comparison

It is possible to design many different interferometer set-ups that differ by odd value in number of reflections of which interfering beams are subjected to. However the optimal optical setup of the discussed interferometer should meet several additional conditions:

- It should be sensitive to angular tilts or lateral shifts of the input beam only in one plane to make possible accurate measurement of the spatial beam deflection by two separate sets.
- Optical path difference (OPD) of the interferometer should be as close as possible to zero to make possible measurements of a low coherence beam of light. We have proved in the previous article [20] that the fringe movement caused for example by the interferometer OPD change will not affect the laser beam angular deflection measurement.
- It should give a possibility to construct in future the measuring microsystem as stiff as possible to provide angular stability of the beams in both interferometer arms

Finally the receiving photodetector system should provide maximum sensitivity to the fringe period change and to be simultaneously insensitive to the fringe movement in the direction perpendicular to the fringe axis.

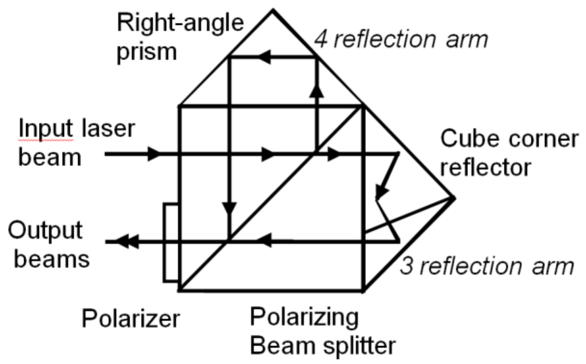


Fig. 2: Compact interferometer designed using simple commercially available optical elements [20]

Figures 2 and 3 show two compact interferometer configurations that we applied in our experiments and that fulfill generally the above specified condidions.

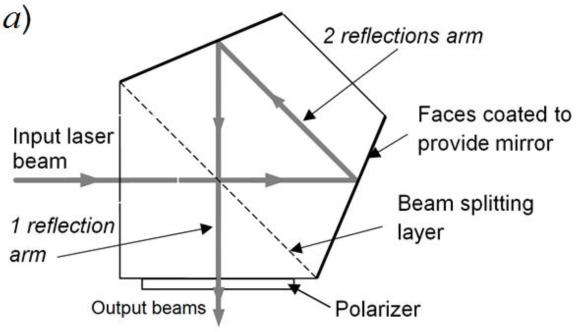
The interferometer shown in Fig. 2 comprises a polarizing cube beamsplitter, a right-angle prism that acts as one arm of the interferometer, and a cube corner reflector that acts as the second arm of the interferometer.

Advantage of the configuration shown in Fig. 2 is relatively low cost due to possibility of construction using commercially easy available elements. However there are two drawbacks of this design. Firstly the size of the beamsplitter cube must be two times larger than diameter of the tested beam. Secondly, adjusting the interferometer requires not only setting the initial angle θ_0 i.e. rotation of the system in relation to the input beam, but also linear displacement of the set-up in order to position cube corner top.

This configuration has been tested in the previous paper[20].

Interferometer configuration shown in Fig 3 is designed only from two prisms: a right-angle prism and an isosceles triangular prism that has one 45° angle. Both prisms are cemented together to form a pentaprism. Advantage of the configuration shown in Fig 3 is very compact design. Size of laser beam input face can be equal to diameter of the tested beam. The drawback of the design is requirement of a high accuracy of manufacturing prism having 45 degree.

a)



b)

Fig. 3: Low dimensional compact interferometer based on pentaprism configuration. a) Schematic design of the interferometer. b) View of the interferometer prism

3. ESPERIMENTAL VERIFICATION

A schematic diagram of the applied experimental setup is shown in Fig. 4. It consists of the following base elements: an angularly tilted HeNe laser, a tested interferometer (TI), and an angle interferometer (AI), and electronic measuring and regulating systems. The TI measures the laser beam angular deflections using the proposed method.

We have performed experimental verification, using as a TI optical setups shown in Fig. 2 and Fig. 3. The set-up shown in Fig 2a we constructed from three separate commercially available optical prisms. According to optical configuration shown in Fig 3a we designed compact interferometer that was ordered and manufactured in optical factory. The resulting final interfereometer prism is shown in Fig. 3b.

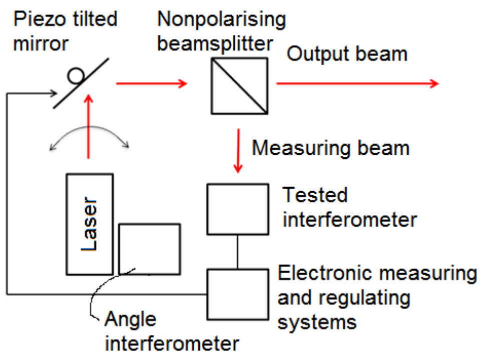


Fig. 4: Schematic diagram of the experimental setup

For the experiments, we have chosen an HeNe laser (model 05-STP-903) manufactured by Melles-Griot because of its good pointing stability (angular instability, according to the manufacturer's specifications, does not exceed 0.03 mrad - verified experimentally as smaller than 0.01 mrad over a one-hour period). The applied laser was mounted in housing supported by the piezoelement, which allowed small tilts of the housing together with the laser tube and the laser beam in the plane of interference of the TI. The laser tilts were measured by the reference angle interferometer. As the reference AI used for measuring tilts of the laser head, we have applied the system developed in our institute, which is described in details in [22]. It allows the measurement of angle deflections using small size and low weight optical elements with resolution of about 0.5 arcsec (3.8 × 10-7 rad). During experiments we compared laser beam tilts measured by the tested interferometer with the reference angle measurements perfomed by the angle interferometer. Piezo tilted mirrror schown in Fig. 4 has been used to compensate the laser beam tilts in a feedback loop basing on the output signal from the tested interferometer.

3.1 *Experimental results*

Since we performed our experiments in short periods of time (several minutes) the experimental results obtained in both discussed optical configurations did not differ significantly. The compact micro-interferometer shown in Fig 3 will be much more stable than the system constructed from separate optical elements in a longer period of time.

In order to evaluate constant B in the Eq. (5) which is equivalent to find the experimental dependence $dI(d\theta)$, we generated periodic (sinusoidal) deflections of the laser beam by tilting the housing of the laser head with a small frequency (of about 0.15 Hz). The generated angular fluctuations of the laser beam were measured simultaneously by the TI and the reference AI (interferometer readings were triggered by the same square-wave signal). Examples of the obtained results are shown in [20]. Next, based on selected rising or falling parts of the both signals, the regression line between the output voltage and deflection angle has been evaluated. That allowed calculation of the sensitivity coefficient of the system. In our set-up the obtained sensitivity was equal to about 100000 V/rad. Calibration of the system can be also performed without using any reference interferometer. We have shown in the previous article [20] that the constant B in the Eq. (5) can be simple calculated basing on the peak-to-peak value of the output system measured in full measuring range of the tilts.

In order to assess the possible resolution of the presented technique, we looked for the minimum amplitude of the angular vibration of the laser beam that could be detected. In this case the laser beam periodic deflections were generated using the piezo mirror. During the experiment, the TI output data were collected in computer memory. Exemplary results of the experiment are shown in Fig. 5.

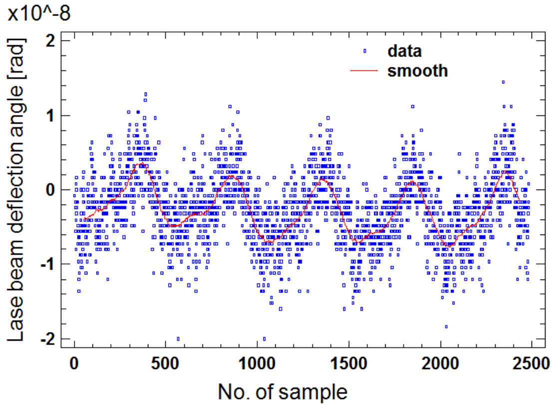


Fig. 5: Micro-vibration of the laser beam measured by the tested interferometer. Points denotes respective samples. lines represent results of applying moving average for digital data filtration

The response of the TI is shown by square points. Visible horizontal lines created by points are caused by limited resolution of the applied analog to digital converter. Middle full line denotes results of data smoothing by means of moving average (100 respective samples has been used for averaging). It is clear that simple output data filtering can improve the resolution of the TI by nearly one order of magnitude. Resolution reaching singular nanoradians is observed.

In order to verify possibility of applying the proposed technique for laser beam angular stabilization we applied the feedback loop controlled by the tested interferometer. We generated sinusoidal deflections of the laser beam by means of the piezotranslator that tilted the housing of the laser head with frequency of about 1 Hz. The amplitude of the generated laser beam tilts was equal to about 1 microradian. The angular fluctuations of the laser beam were measured by the TI. The output voltage of this interferometer was applied to control the piezo mirror via a feedback loop to compensate the introduced laser beam deflections.

The exemplary results of the compensation are shown in Fig. 6. The full sinus shaped curve (bottom) in Fig. 6 represents generated tilts of the laser beam axis. The truncated (upper) sine line of the figure shows observed output laser beam deflections obtained before (left part) and after (right side) closing the feedback loop i.e. with and without laser beam angular stabilization respectively. A reduction ratio at the level of 0.1 is visible.

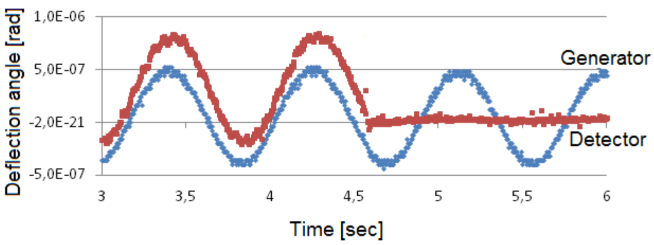


Fig. 6: Generated sinusoidal fluctuation of the laser beam angle (bottom sinus curve) and angular fluctuations of the output laser beam before and after closing the feedback loop of the stabilization system.

4. CONCLUSIONS

A new interferometric method for the ultra-precise measurement and compensation of laser beam angular deviation has been presented. The technique is based on interference fringe period analysis in the selected plane of measurement. By applying two sets of micro-interferometers operating in perpendicular planes spatial instability of the laser beam can be tracked and measured.

Also angular tilt of the measuring device in relation to the beam axis can be measured with high sensitivity.

The theoretical basis for the method has been given and verified experimentally. Two tested interferometer design were compared. We have shown that if the tested beam has approximately plane wavefront a transverse linear displacement of the beam does not affect the measurement of the angular tilts.

Also we have indicated that in majority of possible applications wavelength instability caused by the tested laser construction or by the influence of ambient temperature variations have negligible effect on beam deflection angle measurement.

The advantage of proposed measurement method is that a real laser beam is used as reference and therefore the angular tilt can be measured at any point along the beam axis. We have shown by experimental embodiment, that the measuring system can be very compact, having a volume of approximately one cubic centimeter. Thus, the measurement accuracy is not affected by the mechanical stability of its internal components. Furthermore, because of this compactness, the measuring device can be applied in laser design as a system for output beam angular stabilization.

Our preliminary theoretical analysis and initial experimental research demonstrated universality and simplicity of the new method as well as its high resolution reaching several nano radians

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