Absolute interferometric angle measurement

J Tkaczyk, G Budzyn and J Rzepka
Faculty of Electronics, Wroclaw University of Technology, Janiszewskiego 7, 50-370 Wroclaw
Tel. (4871) 3202309, Fax. (4871) 3202334

jakub.tkaczyk@pwr.wroc.pl

Abstract. A new method of absolute angle measurement based on analysis of interference fringe patterns is proposed. This approach is a bridge between interferometry, offering high accuracy, and other methods that are using position sensors or amplitude effects, which can give information about absolute value of angle. Utilisation of quadrature signals makes it possible to achieve better stability, with comparison to some other methods, thanks to reduced influence of thermal expandability. Usage of special signal processing algorithms facilitates wide measurement range and high resolution. Simulations and experiments show the possibility of achieving the range of 1 deg with arc-sec accuracy. Using commercially available optical and electronic components makes it possible to create lightweight, battery operated device that could be applied in CNC machine alignment process.

1. Introduction
In many scientific and industrial applications, there is need for a method of assessing the angular position with respect to the laser beam. The most commonly used techniques are based on laser beam position measurement or total internal reflection effect. Both are burdened with some limitations that reduce the attainable accuracy. Devices that are using position sensitive detectors, calculate the value of angle according to the lateral displacement of the beam on a known distance [1,2]. It is possible to achieve very good resolution with this method, but the accuracy is limited due to linearity of PSD and influence of thermal expandability [3,4]. It is especially evident, when a long reference arm is used. Total internal reflection does not react on lateral movement and allows for a smaller detector circuit. It can also be a lot simpler, as it requires only two photodiodes. Unfortunately, this effect is highly nonlinear and can be affected by difference in sensitivity of used sensors. Those factors effectively limit the accuracy to about 2% [5-8].

In this paper we present a novel interferometric method, that is based on the analysis of fringe pattern. This technique features lower sensitivity on standard sources of error and allows for higher range/accuracy ratio.

2. Measurement method
Two plane waves traveling at some angle to each other will interfere and generate a fringe pattern. Described situation is presented in the figure 1. From the analysis of wave functions it can be concluded that for a monochromatic waves of the same wavelength and polarization, created intensity pattern will have a sinusoidal form with a period that can be described with equation (1)[9].

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd
Figure 1. Interference of two plane waves and generated fringe pattern [9].

\[ p = \frac{\lambda}{2 \sin \theta} \]  

We propose to perform the analysis of interference pattern in order to find the distance between fringes and calculate the angle \( \theta \). In a real situation it is necessary to use a laser beam instead of the planar wave. This implies some physical limitations to the beam shape and the wavefront flatness, that have to be considered. Those aspects are included in our further investigation.

In order to generate the fringe pattern, it is necessary to use special optical setup (two beam interferometer) that will split incoming laser beam in two and that will travel at some angle connected with angle of incidence. Some setups capable of this are showed in the figure 2. We decided to work with the setup composed of a polarization beam splitter PBS, a mirror prism and a retroreflector, as all of those components are easily available.

Figure 2. Optical setups for fringe pattern generation based on PBS and right-angle etalon (left), pentaprism (centre) and PBS, mirror prism and retroreflector (right).

At the output of presented optical setups, there are two beams with orthogonal polarizations. The quarter waveplate should be placed in the beam paths to change the linear polarization into the circular one. In order to generate and detect the fringe pattern there is needed a special detector presented in the figure 3.
Proposed method requires usage of two linear image detectors with polarizers set so that two generated fringe patterns will be shifted in phase by 90 degree, creating sinusoidal and cosinusoidal signals. Detected images may look similar to the one presented in the figure 4. It can be seen that image is composed of beam shapes and interference pattern. The only relevant information is the distance between fringes. Having two sets of such data, with identical beam shapes and orthogonal fringe patterns, it is possible to apply signal processing algorithms, in order to extract only the information about the interference. One of the possible algorithms for this purpose is Principal Component Analysis (PCA). Its usage will also decrease the influence of any beam distortions that can be seen in real systems, as they will appear identical in both images and therefore efficiently separated from signal of interest [10,11].
Extracted image of the fringe pattern should be then processed by frequency estimation algorithms that effectively gives the information about distance between fringes. This approach utilizes the whole fringe pattern and averages over many visible fringes. This is the main difference in comparison to the method presented in [12] where beam shape can have great influence on the results. Presented data processing makes this method not vulnerable to the lateral movements of the beam or the sensor. Also the change in amplitude response of photodetectors will not impact the accuracy. Base values used in calculations of angle are laser wavelength and distance between pixels in linear detector.

We have created a prototype that implements proposed measurement method. It is presented in the figure 5 with a calliper for the scale. Small size makes it possible to build a wireless device suited for the industrial use.

![Image of the prototype](image_url)

Figure 5. Created prototype of a measurement device.

### 3. Simulation results

We have performed many simulations to select the best data processing algorithms and assess the attainable accuracy of the presented method. Aspects of signal noise, beam shape and lateral beam shift were taken into consideration. We tried to create a model closest to the reality, therefore signal resolution, pixel count and pitch were set according to the specification of a linear photodetector that was chosen for a prototype.

For a comparison, there were selected algorithms of frequency estimation based on IFFT, SinFit and ESPRIT. Signal noise level was varied from 0 to 10% and the beam shifts of few millimeters were simulated. In the figure 6 there are presented results for a realistic situation with 5% additive noise and the beam shift.
Algorithm ESPRIT proves to work best in this situation and was chosen for implementation on a prototype platform. Estimation error was lower than 0.5 arcsec in the measurement range of 1°. With increase of angle above the presented values, frequency in the fringe pattern is getting bigger and soon the spatial aliasing will occur.

4. Potential sources of error

Proposed method is based on interferometric effect and requires using linear detector for a reception of fringe pattern. This implies some possible sources of errors like wavelength instability, influence of thermal effects on detector, precision of mechanical mounting and wavefront flatness.

Figure 7 presents the error caused by change of laser wavelength. It can be seen that 1 nm change will introduce more than 5 arcsec of error. Therefore, this aspect have to be considered when semiconductor lasers are used but with stabilised HeNe lasers, like the one used in our tests, can be completely omitted.
Thermal effects can influence the results in two ways, changing the response of detector pixels and the distance between them. As all the pixels in a detector are fabricated on one substrate, they all should be affected in the same manner. This should not cause any change in detected fringe pattern and therefore will not have any adverse effect on the accuracy.

Pixel pitch is one of the constants used in calculations of angle. Its change due to thermal expandability of a detector itself will introduce some scale mismatch and error. However its influence was found to be <0.01 arcsec on every Celsius degree.

Effective pixel pitch can be changed also with tilt of a detector caused by non-ideal mechanical mountings. This is showed in the figure 8. This problem can be solved with one time calibration as it will not change in time.

Equations used for calculation of the angle are derived from the interference of two plane waves. If the waves do not have planar wavefront, created fringe pattern will be disrupted. It is hard to estimate its influence but we assumed that devices based on the proposed method should be built with commercially available optical components which have surface flatness $\lambda/10$. Aside from optical components, wavefront distortions may come from a laser beam itself. Due to physical limitations of gaussian beam, wavefront have always some finite radius of curvature ROC. This is showed in the figure 9. To limit the error caused by wavefront flatness, laser beam have to have ROC high enough to introduce smaller phase disturbance than optical components. Therefore, we concluded that laser beam should have width greater than 5mm.
5. Conclusions
In the paper we propose a new method of interferometric angle measurement. It has some significant advantages over other, well known techniques. It is less vulnerable to thermal effects and can possibly offer very good resolution and accuracy. This method can be implemented in a miniature measurement device that could be used in the out of laboratory environment. Greatest errors may be caused by a laser wavelength instability and wavefront flatness in the beam. Those two problems can be solved with a stabilised laser and a high quality optical components that are widely used in other interferometric devices.

References
[1] Fitzsimons E D et al. 2013 Precision absolute positional measurement of laser beams Applied Optics
[2] Cary A 2012 Application Note: Measuring Laser Position & Pointing Stability Ophir Photonics
[3] Ivan I A, Areleanu M, Laurent G J, Tan N and Clevy C 2012 The metrology and applications of PSD (position sensitive detector) sensors for microrobotics IEEE
[4] Makynen A, Ruotsalainen T and Kostamovaara J 1997 High accuracy CMOS position-sensitive photodetector (PSD) Electronics Letters
[5] Wang S F et al 2013 Improved Small-Angle Sensor Based Total-Internal Reflection and Surface Plasmon Resonance in Heterodyne Interferometry Sensors and Materials Vol. 25
[6] Chiu M H and Su D C 1997 Angle measurement using total-internal reflection heterodyne interferometry Society of Photo-Optical Instrumentation Engineers
[7] Zhang W Y, Zhang J and Wu L Y 2006 Small-Angle Measurement of Laser Beam Steering Based on Total Internal-Reflection Effect Journal of Physics: Conference Series 48
[8] Huang P and Kiyono S 1993 Method and apparatus for angle measurement based on the internal reflection effect US Patent 5,220,397
[9] Bass M 2010 Handbook of optics Optical Society of America
[10] Kluwer M 2003 A Practical Approach to Microarray Data Analysis: Singular value decomposition and principal component analysis LANL LA-UR-02-4001
[11] Abdi H and Williams L J 2010 Principal component analysis John Wiley & Sons
[12] Dobosz M and Iwasinska-Kowalska O 2014 Interference method for ultra-precision measurement and compensation of laser beam angular deflection Applied Optics