Study on a co-phasing sensing technology based on integrated photonic chip merging arrayed waveguide grating with multi-axial combining

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ABSTRACT

Co-phasing technique is used to detect and compensate the fluctuation of optical path difference (OPD) between sub-telescopes of long baseline optical interferometers caused by atmospheric turbulence. At present, the sensitivity of co-phasing technology is limited, which cannot meet the observation needs for more and darker objects such as Broad Line Region of Active Galactic Nucleus and Quasars. A kind of chromatic phase diversity method (CPD) used to obtain OPD by extracting phase and unwrapping phase difference from the optical transfer function of multi-aperture interferometry was proposed in 2014. Compared to other traditional co-phasing or fringe tracking methods, this method is of some significant advantages such as less power loss, larger capture range of piston error and synchronous sensing for all apertures. In the past, the method was verified by bulk optics or integrated photonics chip only combining beams. Wavelength Separation was still accomplished by many dichroic beamsplitters and fold mirrors which would increase light loss. We present a new compact solution that Fizeau multi-axial beam combination and multiple spectral channels can be merged on single photonic chip. Our works including Verifying of CPD algorithm, model simulation and design of the chip on H-band will be introduced respectively.

Keywords: Optical interferometry, Integrated optics, Co-phasing, Chromatic phase diversity, Arrayed waveguide grating, Beam combiner

1. INTRODUCTION

The optical long baseline interferometers e.g. VLTI, CHARA, and et. al., based on the principle of Michelson interferometry, and are composed of multiple telescopes have broken through the limitation of single telescope on spatial resolution. A special resolution of ~10 micro-arcseconds has been achieved, which is far beyond any single aperture telescope on the ground. However, there are also limitations to optical interferometers such as the insufficient sensitivity to observing dim scientific targets due to co-phasing errors caused by atmospheric turbulence and instrumental attenuation. Fringe tracking technology can be used to detect and compensate co-phasing errors between unit telescopes. Through improving the stability of the fringes, the exposure time of detector can be extended to increase the instrumental sensitivity of optical interferometers.

The existing fringe trackers almost adopt the coaxial beam combining method in pairs. If new interferometric arms are appended into the optical long baseline interferometers, it is necessary to add more splitters, mirrors and combiners, which would reduce the sensitivity and closed-loop performance for these coaxial fringe trackers. Therefore, new fringe tracking technologies with higher sensitivity which should be fit for multiple beams combining simultaneously has become a big concern. In 2000, J.P. Berker proposed a 6-telescope multiaxial beam combiner based on a single chip-integrated optics[1]. In 2010, Nassima Tarmoul firstly built the SIRIUS test bench with 3 channels to test Chromatic Phase Difference (CPD) method using bulk optics[2]. In 2014, Denis Mourard obtained piston errors applying the CPD method to 6 telescopes with 3 channels successfully[3,4,5]. Their works have proved the CPD method increases the OPD capture range and solves the uncertainty of the 2π phase through chromatic channels. This method theoretically does not require too many beams splitting and can significantly improve sensitivity. On the other side, the main drawback of bulk optics lies in that many dichroic beamsplitters for all channels have to been adopted, also means that too many fold mirrors will be added in the optical path, resulting in energy loss, polarization effects and complexity of alignment and control.

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In recent years, some new techniques of photonic chip for astronomy have been concerned increasingly because of compact structure, small scale size and excellent special filtering effect. We propose a new on-chip scheme of CPD method instead of bulk optics. On a single photonic chip, chromatic channels will be realized through Arrayed Waveguide Grating (AWG) and a Fizeau-type multiaxial beam combiner is formed by the tapered planar waveguide.

2. BASIC PRINCIPLE

The beam from each unit telescope is divided into several spectral channels through an optical dispersion component. After that, the beams of the same spectral channels are combined on the image plane through a Fizeau-type multiple aperture interferometer with a line array configuration of different baselines. The phase difference between each channel can be measured and the optical path difference existed in each two-telescopes pair can be reconstructed finally.

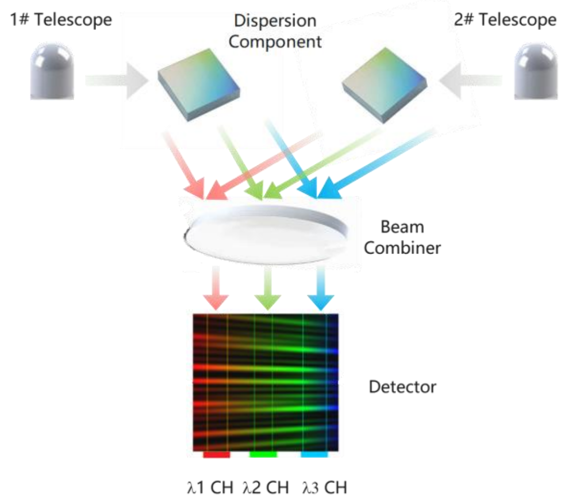

Figure 1. Basic conception of CPD method applied to optical long baseline interferometers

Optical transfer function (OTF) is the autocorrelation of the aperture function, which maps each baseline of a pair of apertures to a second peak spot of OTF plane corresponding to the same angle as the baseline on spatial plane. Synchronous optical path difference of between two apertures can be retrieved from the phase of the second peak spot[4]. For a photonic chip with a planar structure, all pupils need to be rearranged as a line array. An optimal configuration of non-redundant baselines is necessary to avoid overlapping second peak spots which maybe happen due to redundant baselines. There must be a repeated 2π period between phase and optical path difference for monochromatic light. By using multiple channels with different wavelengths, the phase difference between different channels is measured to obtain a linear relationship between the phase difference signal and the optical path difference between different apertures. This method can increase the capture range of OPD and solve the uncertainty of 2π phase period. Meanwhile, by using the Fizeau-type multiple aperture interferometry, the optical transfer function is obtained on the image plane, and the phase mapped to the baseline position is extracted to retrieve the relative optical path difference of the corresponding aperture. This method can simultaneously obtain the optical path difference between different apertures without additional energy loss, and theoretically can significantly improve the instrumental sensitivity.

3. SOLUTION

We present a new compact solution that chromatic spectral channels and Fizeau multi-axial beam combination and can be merged on single photonic chip. The waveguide structure of the former could be realized through the AWG and the later could utilize a tapered planar waveguide structure.

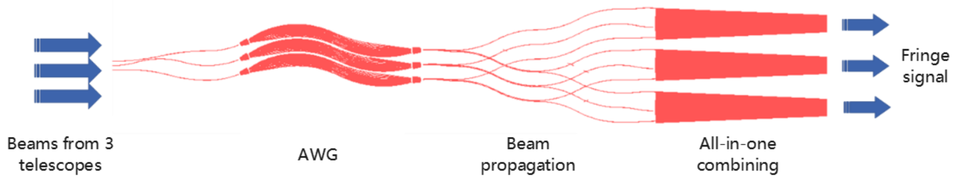

Figure 2. Basic conception of CPD method applied to optical long baseline interferometers

3.1 Chromatic spectral channels

The concept of chromatic spectral channels is similar to the channel spectra of group delay method applied to traditional fringe tracking. Only 2~3 channels, and the bandwidth of each channel is about of tens of nanometers. By acquiring intensity signal from all spectral channels corresponding to the same baseline, capture range of piston error can be extended to 11~55 central wavelength. Whatever visible or near-infrared light, the OPD capture range can cover the optical path fluctuations and jitter caused by atmospheric disturbances and solve the 2π phase ambiguity.

AWG is a kind of wavelength multiplexing components in the field of optical communication. This device consists of several input waveguides, output waveguides, array waveguides and free transmission zones. The fixed difference in optical path length between adjacent array waveguides would produce the wavefront slope which is wavelength-dependent, resulting in dispersed diffraction phenomenon. The incident light enters the first free transmission zone which is equivalent to a collimating lens and emits the scattered beam to excite the waveguide array, which guides the light back to the second free transmission zone which is equivalent to a focusing lens. Lights of different wavelengths are focused on the output end of the transmission area and then coupled to different output waveguides.

3.2 Multiple axial beam combiner

The multiple axial beam combiner unit of integrated photonic chips is used to achieve the instantaneous combining of multiple beams. This All-in-one structure can arrange conical optical waveguides in a non-redundant line array, and form Fizeau interferometry on the image plane. The integrated photonic chip has a compact structure and spatial filtering effect, which can eliminate disturbance induced by atmospheric transmission and improve the imaging quality.

4. SIMULATION

Fringes formed by three beams have been obtained utilizing modeling. We also have finished OPD extraction through a sequence of CPD algorithms including position of second peak of OTF and phase unwapping[7].

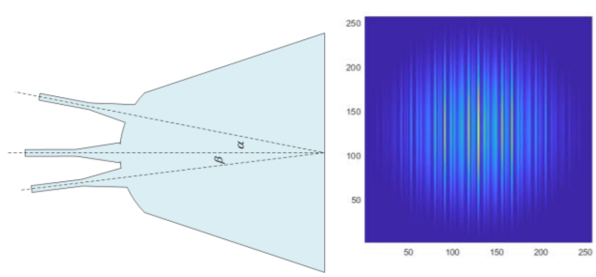

Figure 3. The tapered waveguide structure and simulated fringes captured at the output end of the chip

Phase delay gradually is applied to the beam with an incidence angle of 0.02 radians in one spectral channel. Meanwhile, The phase delay of the other incident beams with angles of 0.08 radians and -0.09 radians is set to zero. Figure 4 (above) shows the OTF phase of the aperture 1 and aperture 2 in pairs captured by three spectral channels with sweeping of phase delay step by step. It is obvious that the OTF phase has a 2π entanglement. Figure 4 (center) shows the OTF phase difference between two channels with central wavelengths of 1.48 micrometers and 1.45 micrometers, respectively. It can be seen that there is no phase entanglement in the phase difference signal, only phase jumps occur in a limited number of positions, with jumps of 2π, which can be easily detected and eliminated. Figure 4 (bottom) shows the phase difference result after eliminating phase jumps. It can be seen that the signal has a clear linear distribution, with a linear range close to 8 microns.

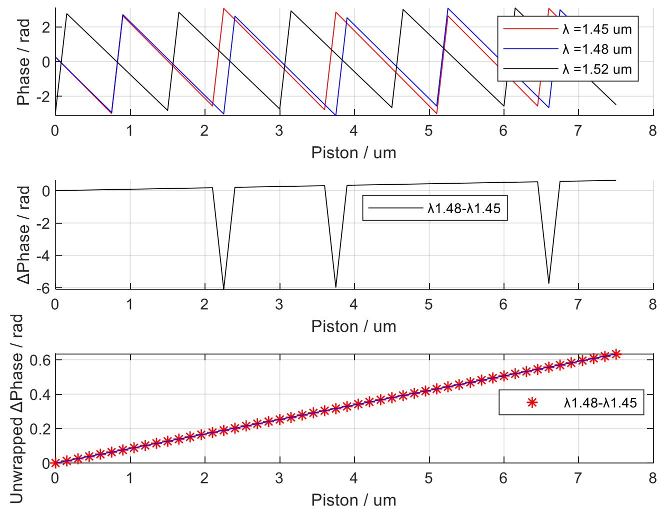

Figure 4. The linear relationship between CPD and OPD utilizing piston sweeping

5. PROGRESS

The photonic chip for photonic is based on silicon dioxide and form optical waveguides using a deposited core layer and photolithography process. The chip had been taped out successfully[5,6] on May in 2024. We plan to test the chip on June in 2024.

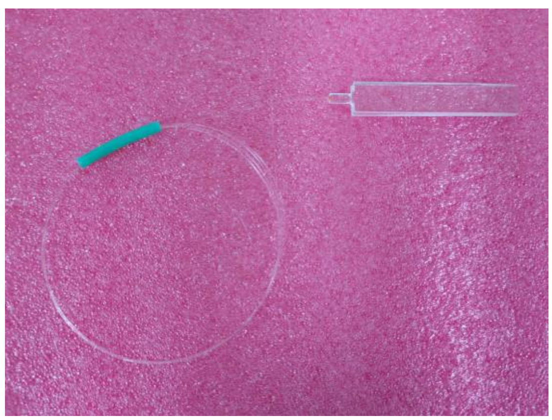

Figure 5. The actual photo of photonic chip

An experimental set-up had been designed and prepared in order to verify CPD algorithm based on the photonic chip. The design scheme (see Figure 6) is that the experimental system of the fringe tracker consists of an optical fiber injection unit, a fiber delay line, an integrated fringe tracking optical chip, a secondary imaging unit, and an infrared camera. The incident starlight from the unit telescope is coupled to the optical fiber through the lens of the fiber injection optical unit, and then transmitted to the integrated optics chip through the fiber and the fiber delay line to multiple axis combiner. The fringe image of the output end of the chip is magnified by the microscope lens of the secondary imaging unit, and finally captured and imaged again by an infrared camera. The OPD correction value is fed back to the fiber delay line for compensation. We plan to complete the experiment of the set-up on October in 2024.

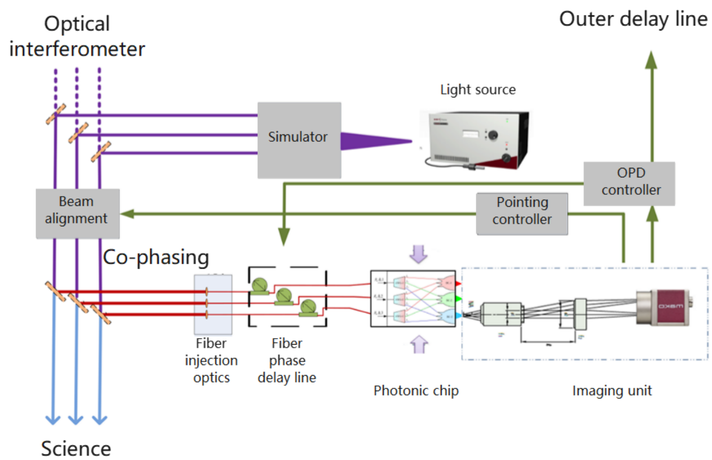

Figure 6. The schematic map of CPD co-phasing experimental set-up

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