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Integrated optics for astronomical interferometry:

IV First measurements of stars.

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Abstract. We present in this paper the astronomical validation of a new approach to interferometric starlight combination. Using integrated optics technologies developed by the telecommunication industry, we have implemented optical circuits on coin-size chips that combine two beams and provide simultaneous photometric calibration signals. We report the first interferometric observations of stars using such beam combiners at the Infrared Optical Telescope Array (*IOTA*). This result opens the way to a new generation of miniaturized, high performance, and reliable instruments, dedicated to interferometric aperture synthesis.

Key words. interferometry – integrated optics – instrumentation

1. Introduction

Modern optical interferometry started in 1975 with the first interferometric combination between two separate telescopes (Labeyrie, 1975). However, to date, only two facilities have achieved aperture synthesis image reconstruction with three or four separated telescopes: COAST and NPOI. Direct imaging requires interferometers with a large number of separated apertures. The VLTI, the Keck Interferometer and CHARA interferometer will respectively provide 7, 6 and 6 telescopes. One of the main issues that has to be solved is the difficulty to combine many stellar beams with limited photon loss, high interferometric contrast and sufficient optical stability to provide accurately calibrated measurements. The complexity of a classical bulk optics beam combiner, using beam-splitters and mirrors, increases dramatically with the number of telescopes to be combined. For example, it takes $N(N-1)/2$ beam-splitters to combine N beams in a coaxial pairwise scheme. Each optical surface decreases the throughput and requires careful alignment. The layout must be symmetric to avoid differential effects that affect contrast and maintain an internal stability crucial for closure phase measurements.

The need for improved accuracy in the simultaneous combination of a high number of beams led us to look for alternative solutions to classical bulk optics. Since 1996 (Kern et al., 1996; Malbet et al., 1999; Berger et al., 1999; Haguenauer et al., 2000), we have been exploring the integrated optics (IO) field, a technology developed by the telecommunication and micro-sensor industries . This technique opens a new way to interferometrically combine beams from separated telescopes using IO optical circuits (analogous to integrated chips in micro-electronics), with the beam combination taking place in an assembly of optical waveguides lying in a solid substrate of few centimeters long and few millimeters large.

IO chips can be found today at every step of the light path in an optical telecom network. Several technologies, ion exchange and silica etching being the most developed ones, are key to the manufacture of various functions in optical chips based on the classical microphotolithography process used in micro-electronics. Integrated optics has proved to work remarkably well at the wavelengths used by telecom or micro-sensors, i.e. 0.8, 1.31 and 1.55 micrometers where low-cost laser sources and very trans-

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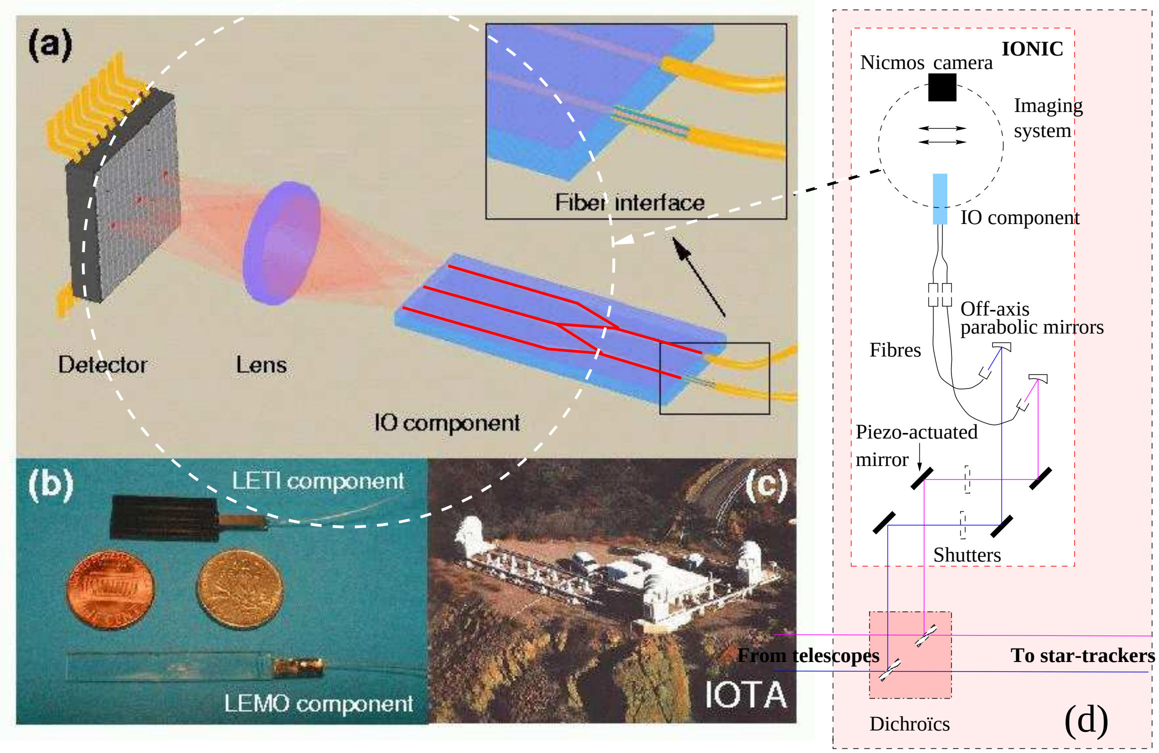

Fig. 1. (a) Optical layout of the experiment (credits: E. Stadler). The LEMO chip's three outputs (described in the text) are imaged onto a liquid nitrogen cooled infrared detector matrix. (b) Integrated optics components, top : LETI beam combiner, bottom LEMO beam combiner. (c) IOTA interferometer.(d) Optical breadboard.

parent fiber optics are available. The achievable functions provide not only all the usual optical ones (divider or combiner) but also diffracting and dephasing devices. Output beams of these planar guides can act as the input slit of a spectrograph, avoiding complex anamorphic optics. An important additional advantage is that single mode waveguides also spatially filter the wavefronts, leading to excellent calibrating properties in the presence of atmospheric turbulence.

2. An integrated optics beam combiner

2.1. Description of two IO chips

For the sky validation reported here, we used two different IO chips designed for two-telescope beam combination in H band[1] (see Fig. 1a & b). The component labelled LEMO was designed and manufactured using the ion exchange process (Benech, 1996): Na^+ ions from a glass substrate are exchanged with Ag^+ ions in a molten salt through a dedicated mask. It combines two input beams injected by fibers in a direct Y-junction, and calibrates the flux contribution from each beam using two reverse Y-junctions located before the combining function. The component labelled LETI was designed and manufactured using the silica etching technique (Mottier, 1996). Doped silica layers, a few microns thick, are deposited on a silicon substrate, etched following the mask drawing and covered by a silica layer. The component combines two input beams in an asymmetric directional coupler giving two interferometric outputs in phase opposition and calibrates the flux as described above for the LEMO component using two Y junctions located before the coupler. Both beam combiners were connected with two equal-length 1m optical fibers.

2.2. Optical interface with IOTA

Following a complete laboratory characterization of the optical properties of these components (Berger et al., 1999; Haguenauer et al., 2000), we set up an experiment at the *Infrared Optical Telescope Array* (IOTA, Traub (1998)) at Mt Hopkins, Arizona], At the IOTA, 2 telescopes of 45cm diameter (a 3rd one is currently being implemented) may be configured in baselines of length ranging from 5 to 38 meters (see Fig. 1c). The two IOTA light beams are carried from the telescopes to the beam combination table (see Fig. 1d). Off-axis parabolic mirrors are used to couple light into the fibers connected to the component which outputs are imaged on a NICMOS 3 infrared camera (Millan-Gabet et al., 1999) using custom optics (see Fig. 1a and d). The optical path in one arm is sawtooth-modulated with a maximum optical path difference (OPD) of 85 μm by a piezo-actuated mirror in one of the arms. The data acquisition is synchronized with the piezoelectric displacement

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[1] 1.43 μm - 1.77 μm

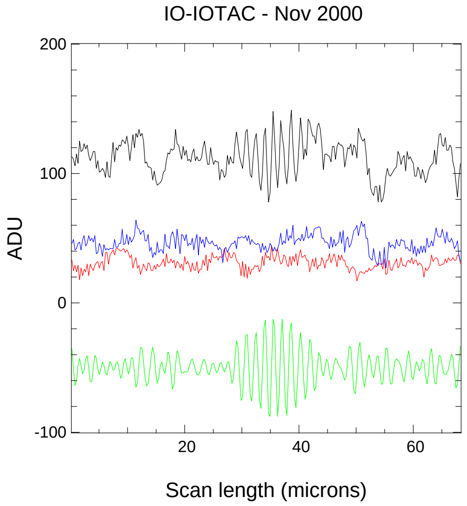

Fig. 2. Fringes obtained with an IO two-telescope beam combiner. Top: raw interferometric signal, middle: the two photometric signals showing flux variations, bottom: frequency filtered interferogram corrected from photometry. Each trace is vertically shifted for clarity.

and the piezo stroke is centered around the zero OPD position. For each scan an interferogram is recorded in each of the interferometric outputs while simultaneously recording the calibration photometric outputs as, shown in Fig 2.

3. Observations

3.1. Data acquisition and data reduction

This first observation run was mainly aimed at characterizing our two beam combiners under interferometer observing conditions. We observed 14 stars with known diameters between November 26-30, 2000. Each observation consists of a set of 100 scans, as described above, plus a corresponding measurement of the background signal. A few minutes later, an identical sequence on the calibrator is recorded. As an illustration of the technique we present here results for the Mira star U Ori. The data reduction procedure employed is similar to that used in previous guided optics instruments (Coudé du Foresto et al., 1997), namely.

1. Background signal subtraction from interferogram;
2. Photometric correction of interferograms using photometric channels to calibrate influence from coupling fluctuations;
3. Construction of a photometry corrected single interferogram obtained from the subtraction of the two outputs (LETI case);
4. Visibility estimation from average power spectrum.

Instrumental calibration was performed by observing 119 Tau within 25 minutes. The average projected baseline length was 25 meters.

Table 1. U Ori observation log. Estimation of 119 Tau diameter is an average of previous near infrared measurements. The average calibrated visibility and its corresponding error is the average and standard deviation of five visibilities measured on five batches of 100 interferograms with both beam combiners. One batch was obtained using the LEMO beam combiner, 4 using the LETI one.

Source	119 Tau	U Ori
Wavelength	1.6μm	1.6μm
Projected baseline	~ 25 m	~ 25 m
Previous diameter	9.65 ± 0.5 mas[1]	11.08 ± 0.57 mas[2]
Calibrated visibility	—	0.34± 0.01
Measured diameter	—	11.0 ± 0.5 mas

(1) Dyck et al. (1998), Richichi et al. (1998) (2) van Belle et al. (1996)

3.2. Results

U Ori was observed during three nights providing a total of five batches of 100 interferograms, one with the LEMO beam combiner (night Nov. 26th), four with the LETI beam combiner (2 during night Nov. 28th, 2 during night Nov. 29th). Each batch leads to one average visibility. After calibration, we used these five visibilities to perform a least square fit of a uniform diameter model.

If we adopt a 119 Tau diameter of 9.65±0.5 mas we find a U Ori diameter of 11.0 ± 0.5 mas fully compatible with a previous determination of 11.08 ± 0.57 in the K band[2] at the IOTA (van Belle et al., 1996). Table 1 summarizes our observations. Figure 3 displays our calibrated data points obtained with both beam combiners and the best uniform diameter model fit.

Each batch of 100 visibilities has an average standard deviation smaller than 5% which translates into a statistical precision of 0.5%. The uncertainty on the calibrator diameter dominates the final estimation. The flux ratios between the interferometric and photometric channels were found to be be remarkably stable all over the observation run allowing a precise calibration of the beam combiner behaviour. We see no statistical difference between the LEMO and the LETI beam combiner measurements which are all compatible with the model fit (see figure 3) within a maximum of 2% of absolute visibility. Although the number of points is not sufficient here to test the night to night repetability, we see no significative trend down to the same 2% precision.

4. Instrumental tests

In addition to these observational tests we carried out several instrumental tests. A full description of the performances of the instrument will be described in a forthcoming paper.

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[2] $2.0 - 2.4\mu$m

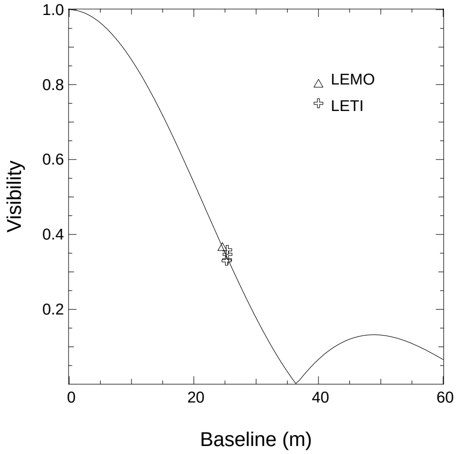

Fig. 3. Visibility points measured with LEMO (triangle) and LETI (cross) beam combiner. The curve represents the best uniform diameter fit.

1. We succesfully switched our two beam combiners in less than two hours. This versatility will be maintained for an increasing number of apertures and will allow quick change of configurations.
2. Although not designed for this wavelength, we succesfully recorded fringes at 2.2 μm (Laurent et al., 2001). With technological improvements we can thus expect to use the same single-mode IO chip in two different broad H and K bands.
3. First estimations of the system visibility show that the average instrumental contrast of the instrument and interferometer is higher than 60 %. This number will be improved once polarisation control is implemented.
4. The faintest star observed (HR 3779) has an H-magnitude of 2. However, since the experimental setup was not optimized for faint astronomical observations we estimate, based upon considerations on the actual coupling efficiency of light into the fiber, that the limiting magnitude of these components should be three magnitudes better.

5. Conclusions

These results have demonstrated, for the first time that telecom-based integrated optics components can be used to combine stellar beams collected by separated telescopes in an optical long-baseline interferometer. These beam combiners are very stable and lead to precise measurements, moreover, they are versatile and easy to handle. The number of optical aligment adjustments is reduced, which dramatically reduces the complexity of multiple-beam combination for aperture synthesis imaging.

This is not only vital for large ground-based interferometers under construction but also for upcoming space missions. This technology will likely find many applications in the field of optical interferometry. Several concepts for up to eight telescopes beam combination are already under study (Berger et al., 2000).

Our next goal is to combine three telescopes beams at IOTA using integrated optics components recently developed for closure phase measurements and imaging applications (Haguenauer et al., 2000). The spectral coverage is also currently being extended to longer wavelengths. Finally, we propose this technology as a solution to combine the 7 telescopes of the VLTI.

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