Integrated optics for astronomical interferometry

II. First laboratory white-light interferograms

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Abstract. We report first white-light interferograms obtained with an integrated optics beam combiner on a glass plate. These results demonstrate the feasibility of single-mode interferometric beam combination with integrated optics technology presented and discussed in paper I (Malbet et al. 1999). The demonstration is achieved in laboratory with off-the-shelves components coming from micro-sensor applications, not optimized for astronomical use. These two-telescope beam combiners made by ion exchange technique on glass substrate provide laboratory white-light interferograms simultaneously with photometric calibration. A dedicated interferometric workbench using optical fibers is set up to characterize these devices. Despite the rather low match of the component parameters to astronomical constraints, we obtain stable contrasts higher than 93% with a 1.54-µm laser source and up to 78% with a white-light source in the astronomical H band. Global throughput of 27% for a potassium ion exchange beam combiner and of 43% for a silver one are reached. This work validates our approach for combining several stellar beams of a long baseline interferometer with integrated optics components.

Key words: Instrumentation, astronomical interferometry, integrated optics

1. Introduction

Since Rochly (1981) proposed guided optics for astronomical interferometry, important progress has been made. In particular, the FLUOR instrument which combines two interferometric beams with single-mode fiber couplers (Coudé du Foresto 1994) has led to astrophysical results with unprecedented precision. This experiment demonstrated the great interest of spatial filtering combined with photometric calibration to improve the visibility accuracy. More recently, Kern et al. (1996) suggested to combine interferometric beams with integrated optics components since this technology allows to manufacture single-mode waveguides in a planar substrate. In paper I (Malbet et al. 1999), we presented and discussed thoroughly the advantages and limitations of integrated optics for astronomical interferometry. To validate the latter analysis, we have performed several laboratory experiments with existing components not optimized for interferometry but allowing to get first clues on this technology. The first experimental results are reported in this Letter.

2. Experimental set-up

We carried out laboratory tests with off-the-shelves integrated optics components designed for micro-sensor applications. The waveguides are made by ion exchange (here potassium or silver) on a standard glass substrate thanks to photolithography techniques (Schanen-Duport et al. 1996). The exchanged area is analogous to the core of an optical fiber and the glass substrate to the fiber cladding. Our 5 mm × 40 mm component is schematically depicted in the right part of Fig. 1. We use it as a two-way beam combiner with two photometric calibration signals. The component operates in the H atmospheric band (1.43 µm - 1.77 µm ) and its waveguides are single-mode in that domain. From an optical point of view, the reverse Y-junction acts as one of the two outputs of a classical beam splitter. The second part of the interferometric signal with a π phase shift is radiated at large scale in the substrate. Light is carried to the component thanks to standard non-birefringent silica fibers.
Interferometric workbench

Fig. 1. Left: laboratory interferometric workbench for testing integrated optics beam combiners based on a Mach-Zehnder interferometer concept. The collimated beam provided by the sources (laser, laser diode or white-light source) is splitted in two beams which are focused onto low-birefringence single-mode fibers by off-axis parabolae. Fibers are directly connected to the integrated optics beam combiner. The optical path difference between the beams is modulated by a translating stage to produce a delay. The three outputs of the beam combiner are imaged on a cooled infrared HgCdTe array. The angle between the incident and reflected beams on the beamsplitter is close to 20°. Right: integrated optics two-way beam combiner. The light from the telescopes is coupled into the integrated optics beam combiner thanks to optical fibers. Two direct Y-junctions provide photometric calibration signals for each beam. A reverse Y-junction combines the two input beams. Each output is imaged by a lens onto an infrared array.

We have set up a laboratory Mach-Zehnder interferometer to test the interferometric capabilities of our components (see the left part of Fig. 1). The available sources are: a 1.54-µm He-Ne laser, a 1.55-µm laser diode and an halogen white-light source. The latter is used with an astronomical H filter.

We scan the interferograms by modulating the optical path difference (OPD) with four points per fringe. The delay line speed is restricted by the integration time (≈1 ms for laser sources and ≈10 ms for the white-light source to get a sufficient signal-to-noise ratio) and the frame rate (50 ms of read-out time for the full frame). The OPD scan and the data acquisition are not synchronized, but for each image the translating stage provides a position with an accuracy of 0.3 µm. The simultaneous recording of the photometric and interferometric signals allows to unbias the fringe contrast from the photometric fluctuations as suggested by Connes et al. (1984) and validated by Couédé du Foresto (1994).

A typical white light interferogram $I_0$ is plotted in Fig. 2a together with the simultaneous photometric signals $P_1$ and $P_2$. To correct the raw interferogram from the photometric fluctuations, we subtract a linear combination of $P_1$ and $P_2$ from $I_0$. The expression of the corrected interferogram is then

$$I_c = I_0 - \alpha P_1 - \beta P_2$$

with $\alpha$ and $\beta$ coefficients determined by occulting alternatively each input beam. The resulting corrected interferogram is displayed in Fig. 2b.

3. Results and discussion

As far as an astronomer is concerned, the physical quantities of interest when dealing with an interferometric instrument are the instrumental contrast, the optical stability, and the total optical throughput.

3.1. Laser-light constrasts

A 93% contrast is obtained with the He-Ne laser. The main source of contrast variations with time comes from temperature gradient and mechanical constraints on the input fibers. When special care is taken to avoid fiber bending and twists, the laser contrast variation is lower than 7% rms over a week. Using high-birefringent fibers which are far less sensitive to mechanical stresses will improve the contrast stability.
3.2. White-light contrasts

With an halogen white-light source, the contrast obtained is of the order of 7% with a potassium ion beam combiner connected with low-birefringent fibers (Fig. 2b) and 78% with a silver ion beam combiner connected with high-birefringent fibers (Fig. 2c). Two main sources of interferometric contrast drops between the two components have been identified: chromatic dispersion and polarization mismatch.

The consequence of residual differential dispersion between the two arms is to spread out the fringe envelope and decrease the contrast. Since the delay line translation is not perfectly linear, the Fourier relation between space and time is affected and an accurate estimate from the dispersion is difficult. Only the number of fringes and the shape of the interferogram gives an idea of the existing differential dispersion. The theoretical number of fringes is given by the formula $2\Delta\lambda/\Delta\lambda \sim 10$ and the interferogram contains about 13 fringes. Such a spread is not sufficient to explain the contrast drop between the laser- and white-light contrasts. More detailed studies of residual chromatic dispersion are in progress.

In the present case the contrast decay is mainly explained by differential birefringence. Low-birefringent fibers are known to be highly sensitive to mechanical constraints and temperature changes, leading to unpredictable birefringence. Coupling between polarisation modes can occur leading to a contrast loss which can be significant for unpolarized incident light (case of the white-light source). This is confirmed by the preliminary results obtained with high-birefringent fibers and the incident light polarized along the neutral axes: the contrast reaches 78% (Fig. 2). The apparent asymmetry of the interferogram could be due to residual differential polarization and/or dispersion. Full characterizations are in progress and will be reported in Paper III (Haguenauer et al. 1999).

3.3. Total throughput

Fig. 3 summarizes the photon losses in the two components. We express the losses in terms of remaining photons when 100 incoherent photons are injected at each waveguide input. For the component made from potassium ion exchange, we obtain 20 and 14 photons on each photometric channel and less than 20 photons in the interferometric channel leading to a total of 54 photons for 200 photons injected, hence a total throughput of 27%. For silver ion exchange, respectively 30, 31 and 25 photons have been measured leading to a throughput of 43%. The main difference between the two results comes from the coupling losses.
efficiency between the fiber and the waveguides and the propagation losses.

Table 1 summarizes estimation of losses coming from different origins. The propagation losses and the coupling losses have been measured with a straight waveguide manufactured in the same conditions. The Fresnel losses have been theoretically estimated to 4%. Any function causes additional losses which cannot be evaluated separately but have been estimated to 10%. One should notice that the reverse Y-junction acts as only one of the two outputs of an optical beamsplitter (see paper I). Therefore 50% of the light is radiated outside the waveguide. The first two columns of Table 1 show that our measurements are consistent with the theoretical performances computed from the different optical losses reported in the Table.

Last column of Table 1 gives an order of magnitude of expected improvement in the future. The main progress concerns the beam combination function. We should be able to retrieve the second half of the combined photons thanks to new combination schemes like X-couplers, multiaxial beam combiners or multimode interferometric (MMI) multiplexers (see paper I) at the cost of a slight chromaticity of the function. Some components including these new functions are being manufactured and will be soon tested. The ultimate optical throughput would be around 70-80%, twice more than our current results.

### 4. Conclusion and future prospects

We have obtained first high-contrast white-light interferograms with an off-the-shelves integrated optics component used as a two aperture beam combiner. The high and stable contrasts as well as the high optical throughput validate our approach for combining stellar beams by means of integrated optics presented in paper I.

This preliminary analysis requires further characterizations and improvements. The importance of dispersion, birefringence and other phenomena in the fibers and in the components have to be fully understood. For this purpose, two-way beam combiners optimized for astronomy are under characterization (spectroscopic and polarimetric measurements for instance) in order to carefully control their optical properties. A complete description of optical and interferometric properties of integrated optics component will be presented in a forthcoming paper (Haguenaou et al. 1999). The optical fibers should maintain polarization to avoid specific contrast losses and have optimized lengths to avoid chromatic dispersion. This experimental precaution is decisive to achieve image reconstruction (Delage 1998).

Our research program is based on the study of new integrated optics technologies for long baseline interferometry in the infrared, and, the design of beam combiners for multiple apertures (see paper I). Some specific beam combiners will then be eventually used in a scientific instrumental prototype on astronomical interferometers. Preliminary tests on the GI2T/Regain interferometer (Mourard et al. 1998) will be carried out with the Integrated Optics Near-infrared Interferometric Camera (IONIC) prototype (Berger et al. 1998).

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### References

Berger J.P., Rousselet-Perraut K., Kern P., Malbet F., Schanen-Duport I., Nabias L., Benech P. 1998, Proc. SPIE 3350, 898

Connes P., Froehly C., Facq P. 1984, A Fiber-Linked Version of Project TRIO. In: Longdon N., Melita O. (eds.) Proc. ESA Colloq., Kilometric Optical Arrays in Space. ESA, Cargése, p. 49

Coudé du Foresto V. 1994, PhD Thesis, Université de Paris, France.

Coudé du Foresto V., Ridgway S., Mariotti J.M. 1997, A&AS, 121, 379

Delage L. 1998, PhD Thesis, Université de Limoges, France.

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1 Actually 3-way and 4-way beam combiners have already been manufactured.
Froehly C. 1981, Coherence and Interferometry through Optical Fibers. In: Ulrich M.H., Kjær K. (eds.) Proc. ESO conf., Science Importance of High Angular Resolution at Infrared and Optical Wavelengths. ESO, Garching, p. 285
Kern P., Malbet F., Schanen-Duport I., Benech P. 1996, Integrated optics single-mode interferometric beam combiner for near infrared astronomy. In: Kern P., Malbet F. (eds) Proc. AstroFib’96, Integrated Optics for Astronomical Interferometry. Bastianelli-Guirimand, Grenoble, p. 195.
Haguenauer P. et al. 1999, in preparation.
Lagorceix H. 1995, PhD Thesis, Université de Limoges, France.
Malbet F., Kern P., Schanen-Duport I., Berger J.P., Rousselet-Perraut K., Benech P. 1998, A&AS, submitted (paper I).
Mourard D. et al. 1998, SPIE proceedings, 3350, 517
Schanen-Duport I., Benech P., Kern P., Malbet F. 1996, Optical Waveguides Made by Ion Exchange for Astronomical Interferometry Applications at the Wavelength of 2.2 Microns. In: Kern P., Malbet F. (eds) Proc. AstroFib’96, Integrated Optics for Astronomical Interferometry. Bastianelli-Guirimand, Grenoble, p. 99.