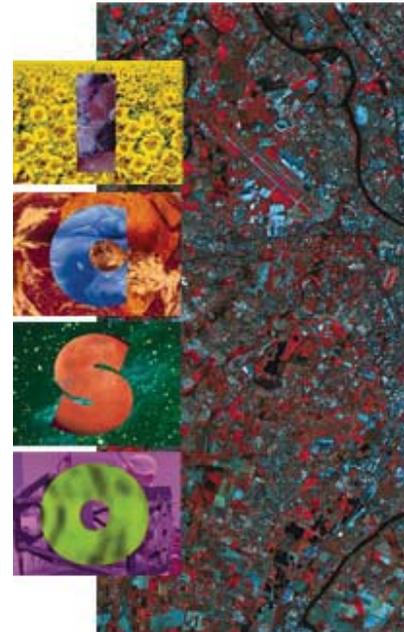


International Conference on Space Optics—ICSO 2000

Toulouse Labège, France

5–7 December 2000

Edited by George Otrio



Combining and cophasing a telescope array in a single chip-integrated optics: a new solution for spaced based aperture synthesis interferometry

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**COMBINING AND COPHASING A TELESCOPE ARRAY IN A SINGLE CHIP?
INTEGRATED OPTICS: A NEW SOLUTION FOR SPACED BASED APERTURE
SYNTHESIS INTERFEROMETRY.**

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1. Introduction.

Astrophysical key programs such as exoplanet detection, young stars accretion disk and active galactic nuclei imaging require high angular resolution capability. Today, optical long baseline interferometers are the only instruments to allow such resolutions. Consequently, optical aperture synthesis interferometry has become one of the cornerstone missions for both European and American spatial agencies. The ESA/IRSI cornerstone mission has two main objectives, achieving deep nulling interferometry for exoplanet detection and achieving aperture synthesis and image reconstruction. This should be done at thermal wavelengths with a six telescopes array. However, building such an instrument is far from trivial, current ground experiments have shown that long baseline interferometry brings many new challenging technical issues which still requires new reliable solutions. Telescope array cophasing, metrology, beam combination are one of those key points.

In this paper we propose to use integrated optics (IO) technologies for the beam combining and cophasing function of a spatial interferometer. We also try to give a summarized idea on ongoing research efforts carried out at Laboratoire d'Électromagnétisme Microondes and Microélectronique and Laboratoire d'Astrophysique de l'Observatoire de Grenoble that interest spatial optical interferometry and deserve particular attention in the forthcoming years. IO technologies, which development is triggered by the telecommunication industry growing requirements allow to integrate optical waveguides in planar substrates thanks to photomasking techniques. This permits designing complex optical singlemode instruments in coin-sized chips. Using IO-based instruments brings a total relaxation of optical alignment and stability requirements when compared to a classical bulk-optics beam combination instrument. The resulting weight and compactness has no equivalent. These features should be considered in the context of a preparatory space mission where IO instrument simplicity allow to focus technical efforts on other engineering problems.

In this paper Section 2 to 4 presents some of our current laboratory developments and projects.

2. Beam combining

2.1 Context

The role of a beam combiner in an aperture synthesis interferometer is to allow beams coming from several telescopes to interfere in order to extract fringe visibilities and partial fringe phase information in the form, for example, of phase closures. The final reconstructed image quality will depend mostly on the (u,v) coverage and on the visibility and phase closures accuracy.

One key point of every interferometric observation is the ability of calibrating a particular visibility measurement, which requires a perfectly stable instrument. The difficulty of such needs arises when one considers combination of more than two telescopes. Classical instrumental solutions are tricky (as ground experiments demonstrate) and are a call for new solutions. Following previous work ([Malb 99, Berg 99, HaguA 00, Berg 00, Kern 00]) we continue exploring IO applications to beam combination function. Our research and development effort is split into laboratory experiments and numerical simulations whose common purpose is to demonstrate the feasibility of integrated optics interferometric instruments. Here, we discuss preliminary results obtained on a 3-way IO pairwise multiaxial beam combiner, which nicely illustrates IO possibilities and their extension to a larger number of telescopes. It is out of the scope of this paper to discuss beam combination strategies, which belong to a farther step that concerns image reconstruction and are mainly target-dependent.

2.2 A three telescope multiaxial beam combiner.

Description

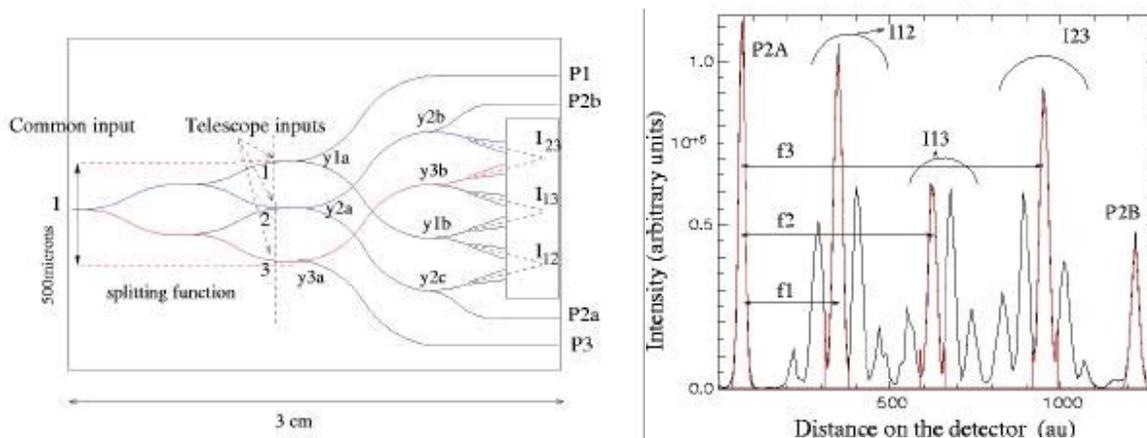


Figure 1: Left: schematic representation of an IO pairwise 3-way beam combiner. Right: Intensity profile of the IO beam combiner output with only 2 of the 4 photometric channels and interferograms

We have integrated, using ion-exchanged technologies, an optical circuit that combines 3 beams pairwise. This beam combiner can be seen in figure 1 left. Light can be carried either by fibers or bulk optics to three input singlemode waveguides (1,2,3). Those waveguides act as singlemode

spatial filters. Going from left to right one can see that Y junctions are used in each waveguide to extract 50 % of the light for photometric calibration requirements (y1a, y3a, y2b, y2c). For symmetry reasons, and to reduce the waveguides crossings, one of the three photometric channels is in fact split in two (P2a and P2b). Following interferometric arms a second Y junction in each arm is used to form three pairs of spatial interferograms (y1b,y3b,y2a). The optical function that allows the interferogram spatial encoding uses two tapers that collimate the two interfering beams. These beams are slightly inclined to focus on the same point. The beam inclination and wavelength define the final fringe spacing. Consequently at the output of such a beam combiner one can record 4 photometric channels (P1, P2a, P2b, P3) and three spatially encoded interferograms (I12, I31, I23).

Before any test in a real interferometer at the heart of a bulk optics interferometer, we wanted to test integrated optics interferometric intrinsic properties without any instrumental bias. For that purpose, instead of using the IO from the 3 telescopes inputs, we designed a preliminary optical function made of three Y junctions that allow, from one initial input to light three telescopes inputs (see “splitting function on” figure 1 left). That way, any perturbation noticed will be mostly attributable to integrated optics properties.

Results

A fiber optics was used to send broadband light on the entrance waveguide. The experiment wavelength range was [1.43-1.77] microns. The beam combiner output was imaged onto an infrared detector matrix. Figure 1 right displays an intensity profile of the beam combiner output two photometric channels (P2a, P2b) and 3 interferograms (I12, I23, I31) are visible. We can see that the 3 interferograms are modulated by a gaussian-shape envelope (coming from gaussian beams interfering). Visibility and fringe phase are extracted with a dedicated data reduction software. Each interferogram phase (respectively f1, f2, f3) is computed (fitted) as the distance (in pixels) of the central fringe to a reference point, which is here the centroid of photometric channel P2a. The central fringe is defined as the highest amplitude fringe.

In non thermalized lab conditions we measured visibility during 3h30, we found that average visibility is 92 % +/-0.4 peak to peak which is, in fact, a lower limit on the visibility since we could not use unbalance photometry correction. Moreover, we have measured fringe position (f1, f2, f3) throughout a 4h period in non thermalized laboratory conditions. The following table displays phase variation (in fringe units) as a function of pixels and fringe size for narrowband (laser diode) and broadband (halogen lamp) source.

Source type	f1 (fringes)	f2 (fringes)	f3 (fringes)
Laser diode	4.444 +/- 0.001	8.830+/-0.002	14.130+/-0.003
Tungsten halogen lamp	4.4832+/-0.0001	8.8671+/-0.0005	14.074+/-0.0003

Discussion

These results demonstrate intrinsic qualities of IO optical circuits from the interferometric point of view. The presence of white light fringes shows that inside integrated optics beam combiner optical paths are equal to within a coherence length (here ~ 10 microns). In fact the high contrast of the central fringe indicates that OPD is lower than a fringe spacing (see section 3 for confirmation).

The high contrast of white light fringes shows:

- 1) that differential chromatic dispersion is low
- 2) that differential birefringence, which could lead to polarization axis differential rotation or delay is low.
- 3) that differential effects are stable throughout time (even in non stable thermal conditions see Berg 00).

These are natural properties which have no equivalent in fiber beam combiners. The stability of fringe visibility and position with time shows that IO beam combiners are particularly attractive in the context of aperture synthesis where stability of phase closure is mandatory for high quality image restoration. **It can be expected that integrated optics beam combiners do not introduce instrumental instability in the measurements.**

2.1 A 6 telescope multiaxial beam combiner.

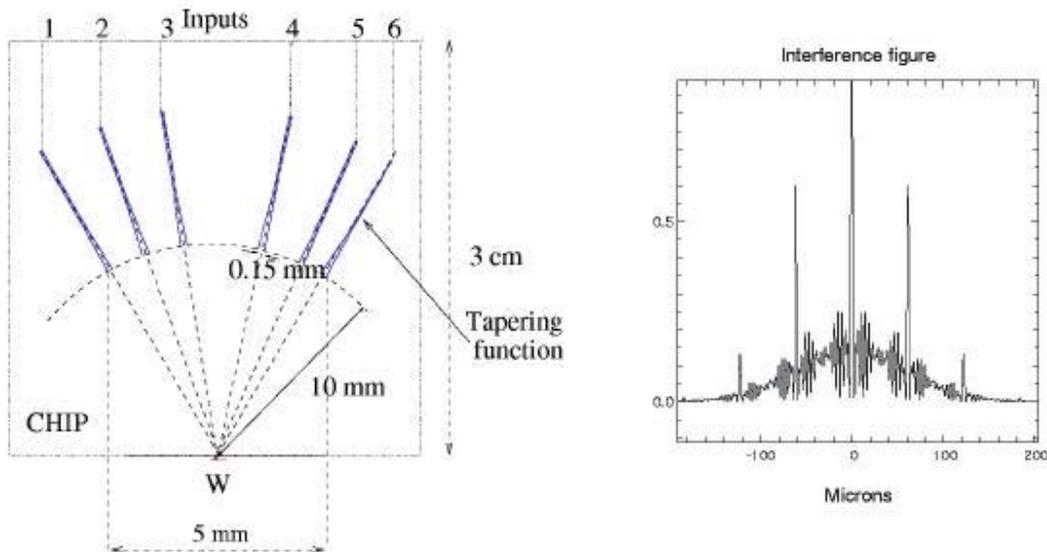
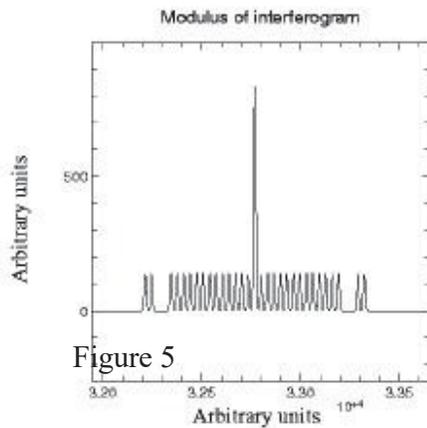


Figure 4: Left schematic principle of a six telescope multiaxial IO beam combiner. Right: simulated interferogram.

Extrapolating from these results we propose a simple way to combine up to six telescope in a single chip. Based on a similar principle we designed a multiaxial all-in-one 6 way beam combiner. The purpose of such a device is to allow the extraction of $N(N-1)/2$ visibilities and $(N-1)(N-2)/2$ independent phase closures (i.e for $N=6$, respectively 15 and 10). The concept is of course extendable to a different number of telescopes provided that the final interferogram can be technically recorded.

This beam combination principle is an extrapolation of a Fizeau type interferometer with 6 interfering beams. A schematic representation of this beam combiner can be seen in figure 4 left. Six input waveguides collect light either from fibers or from bulk optics systems. These

waveguides converge inside the chip towards a circular beam planar waveguide with same index as waveguides core. Each waveguide is designed to have the same length between the component input to the planar waveguide. Each waveguide is also adiabatically enlarged thanks to a taper function so that beam size increases while remaining singlemode. This function act as a collimator, it limits the diffraction angle and wavefront curvature. All the beams emerging from these tapered waveguides converge towards the same point. The interference figure observed (fig. 4 right) is the



superposition of all the pairwise interferences. If a nonredundant set of inclination angles is chosen, each pair of interference has its own fringe spacing (or fringe frequency). Figure 5 displays interferogram corresponding modulus (Fourier transform). We can see 15 fringes peaks that lead to the simultaneous measurement of 15 visibilities. A similar beam combination concept using bulk optics would require tricky optomechanical schemes including optical anamorphosis (in order to compress one beam direction). Here the beam combination requires a 5 mm large chip and no anamorphosis since propagation takes place in a plane.

This example is one among others that show IO potential in the field of optical complex interferometry. Other concepts leading to a temporal encoding of the fringes are under study.

In a farther step, aperture synthesis interferometry should take advantage of telecom developments in the field of switching matrixes which should allow to reconfigure combined beams actively according to a given observational strategy.

3. Coherencing and cophasing.

Context

Performances of ground-based interferometers are strongly affected by random fluctuations of optical paths at each apertures mainly due to atmospheric fluctuations. Although OPD fluctuations should be lower in space, imaging still requires optical path equalization as perfect as possible and needs to compensate from any instability. First ground based interferometers used interferometric science signal as a provider for feedback information on OPD. As pointed out by Cassaing (see [Cass 00], and references herein) OPD sensing deserves dedicated instruments that operate on a different wavelength than the science beam. There is often a distinction between a group delay tracking instrument and a phase tracking instrument; the first tracks the fringe envelope so that OPD remains within a coherence length and the second allows an accurate tracking of the central fringe. Both of them involve different time responses and therefore may need different instrumental set.

Preliminary description

Although this work is in its early steps we introduce here an experimental concept using an integrated optics beam combiner that should allow group delay tracking on a three telescopes array.

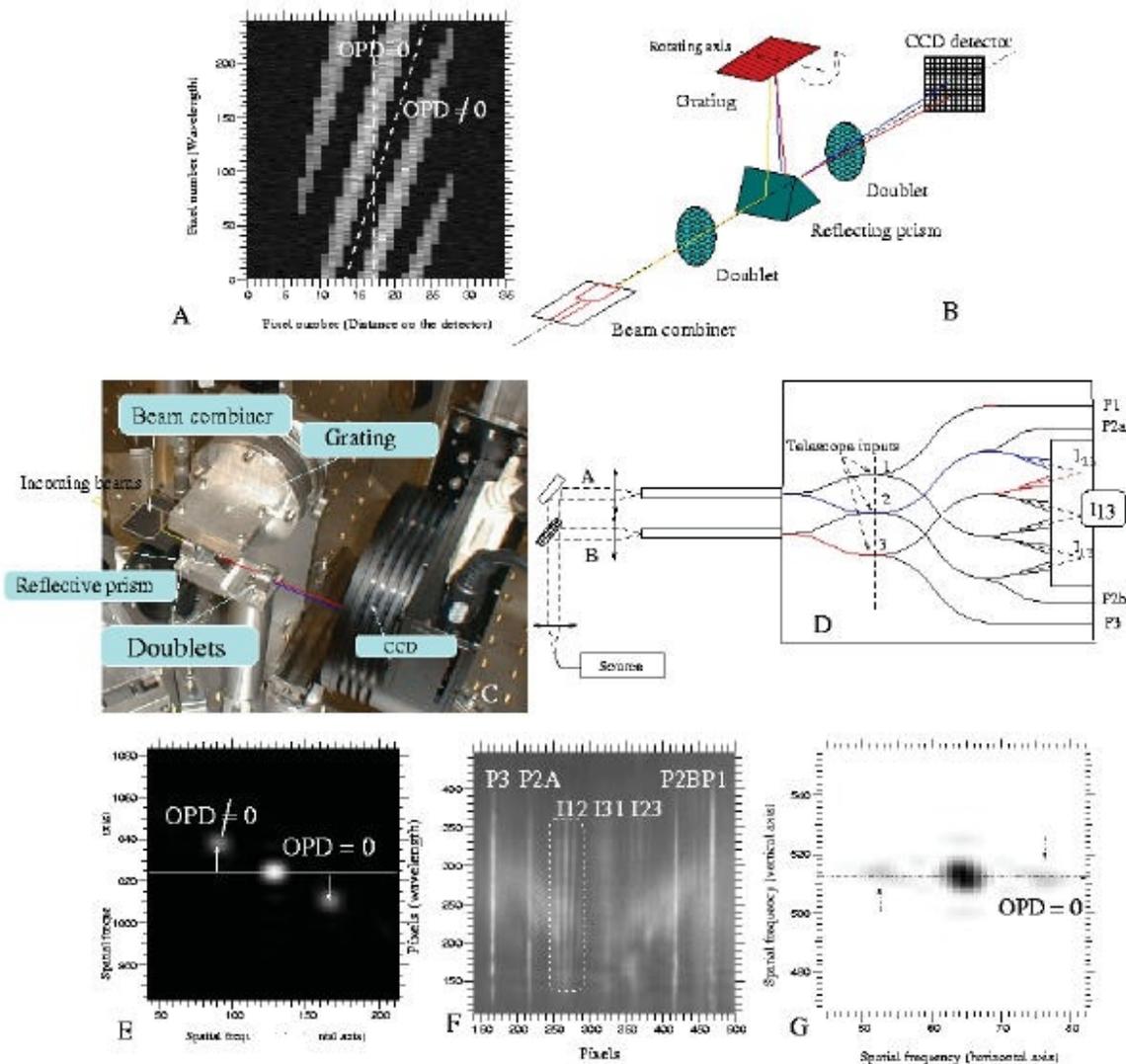


Figure 6: Description of a three telescope IO cophasing instrument.

The principle is to use the same pairwise multi-axial beam-combiner as described above. The output of this planar beam combiner is a perfect slit for a spectrograph. The basic idea here is to disperse the fringes perpendicularly to beam-combiner axis on a detector matrix. If the OPD between one or two arms is equal to zero then we should see vertically oriented fringes. Otherwise the dispersed fringes will be inclined thus providing a way to evaluate optical path difference, figure 6a shows a simulation of inclined fringes. We have designed a very compact spectrometer that disperses light coming out of the beam combiner perpendicularly on a detector matrix. Figure 6b schematically presents the instrument that has been developed to operate in the visible, near infrared [0.7, 0.9 microns]. A first doublet collimates the outgoing beam, a reflective prism deviates light onto a grating that disperses the light back to the prism, a second doublet then reimages the dispersed beam combiner output onto a CCD detector. Fig 6c is a photograph of the whole device. This time

the integrated beam combiner has been cut to provide two inputs. A Mach-Zehnder interferometer provides two beams of arbitrary OPD that are injected thanks to fiber onto the IO beam combiner (fig. 6d). In this case, dispersed interferograms I23 and I12 will probe optical path difference inside the component and I13 will probe Mach Zehnder OPD (i.e between arm A and B). The OPD sensing algorithm is similar to the one proposed by [Koec 00], a Fourier transform of each of the 3 interferograms will provide information on where the fringes are. If OPD is close to zero then the resulting Fourier transform will be composed of a central peak (continuum) and two fringes peak located either side of a reference central axis. Otherwise the fringes inclination will correspond in the Fourier space with displacement of the peaks (see fig 6e). This displacement is used to measure the OPD and provide a feedback correction signal for OPD control.

For the purpose of this conference we had no time to measure external OPD but we recorded an image of dispersed fringes that can be seen on figure 6f. Only interferograms I12 and I23 are present, a Fourier transform of interferogram I12 (fig. 6g) clearly shows that internal OPD is very small since peaks are located on a horizontal line (the slight inclination is in fact caused by a component inclination). The absence of fringes in the I13 location is simply an indication that Mach-Zehnder arms are unbalanced more than one spectral channel coherence length (ie ~ 300 microns).

Discussion

This experiment was done with an off-the-shelf non optimized component. The interferogram sampling requirements does not need three fringes per interferograms as we can see here which enhances detector noise contribution. A specific design of the multiaxials interferometric heads with reduced inclinations angles can lead to a minimum sized interferogram containing approximately 1 and a half fringe which would reduced the number of sampling pixels.

Once the OPD is maintained within a coherence length thanks to a group delay tracking a further step is to remain locked onto the central fringe. This requires faster analysis which is not compatible with a dispersing experiment that is photon expensive. The central fringe sampling algorithm requires to sample the fringe on a few number of points. The ABCD algorithm developed and successfully applied at MarkIII and PTI requires 4 points [shao 88]. More recently Cassaing et al suggested an AC algorithm that enhances the signal to noise efficiency [Cass 00]. Integrated optics offer solutions to provide the optical part of an instrument that samples the fringe either in ABCD scheme with a four port instrument that extract simultaneous quadratures [Berg 98] or in the AC scheme which uses the achromatic pi phase shifting properties of a coupler [HaguB 00].

4. Integrated instruments

Parallel to this work, strictly devoted to aperture synthesis interferometry, LEMO has developed a wide range of research areas triggered by communications networks new requirements. These promising results should be considered in the framework of spatial interferometry. As a ground based-interferometer a space born interferometer needs several optical instruments:

- A beam combiner for science operation
- A beam combiner for active cophasing
- A metrology stage.

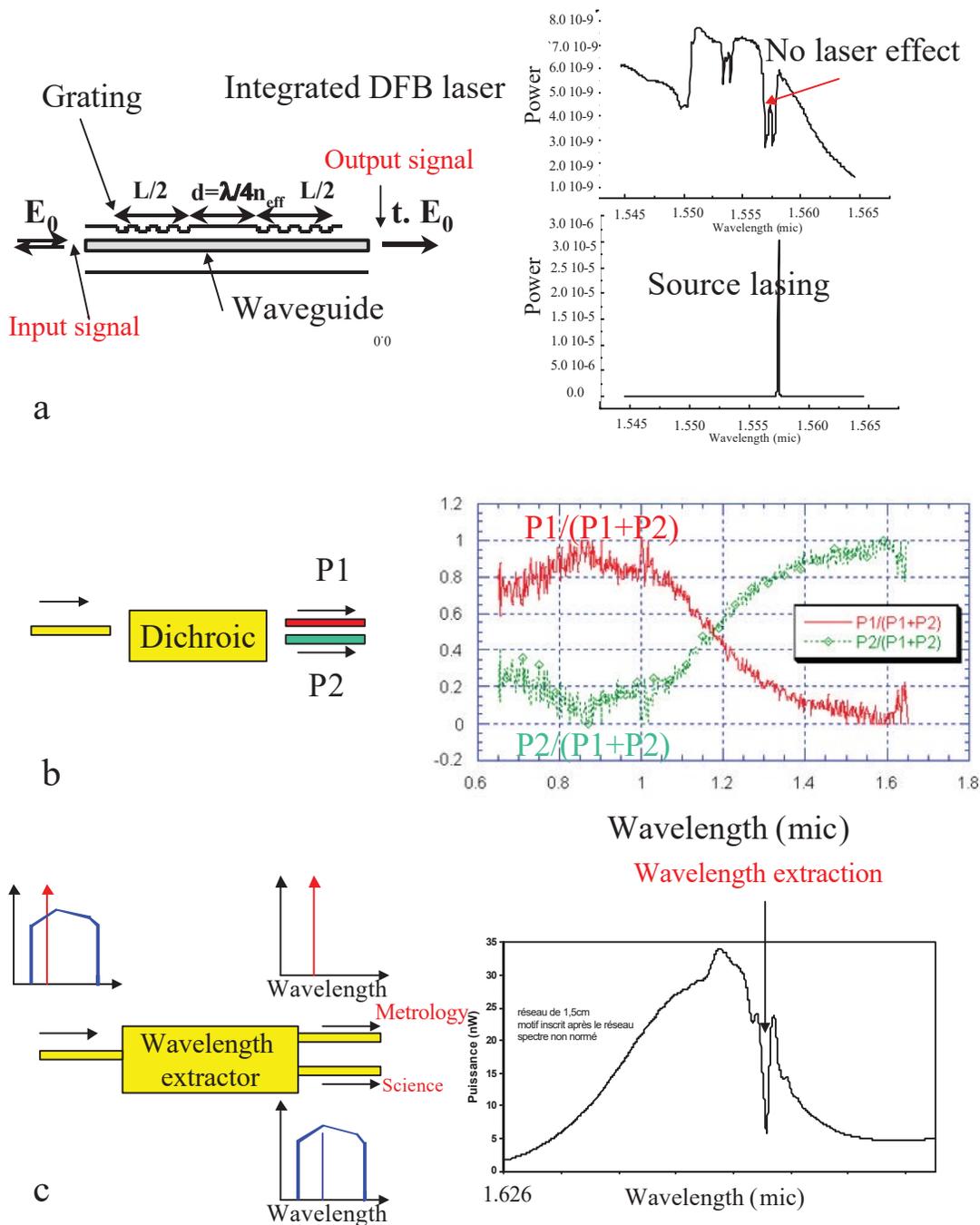


Figure 8 Miscellaneous new integrated functions

Making the difference between science and cophasing signals using source light requires **dichroic** function for each of them to operate in a distinct bandpass. The dichroic function can also be used to separate different astronomical bands. At the same time, controlling the interferometer **requires internal metrology** which needs **highly coherent laser light source** and **interferometric heads** to measure quadrature signals. This metrology stage should allow to measure internal paths from telescopes to the beam combiner (see [Reyn 00] for an example of end to end metrologically-

controlled imaging fiber-linked interferometer). The metrology signal should follow as much as possible the science beams optical path and consequently requires to be extracted from the science signal with as less alteration as possible. For all this requirements, IO solutions developed at LEMO are promising since they bring intrinsic stability, weight and compactness. Figure 8 shows up-to-date results obtained with ion-exchanged technology.

- Figure 8a is an example of integrated DFB laser source obtained by etching a grating at the surface of a waveguide embedded in active material. A narrow band emission spectrum (below 130 MHz) is obtained from the amplification and wavelength selection of broadband signal [Blai 00] (see right part of the figure).
- Figure 8b shows the experimental transmission function of a broadband dichroic. We can see that this function allows to split (or to combine) signals from different wavelengths even if they are broadband (in the astronomical sense).
- Figure 8c shows an example of narrowband signal extraction from a broadband signal thanks to a wavelength extraction function. This function allows to separate the optical broadband science signal from the metrology signal.
- Interferometric heads made with ion-exchanged technology are not discussed here. The CSO company has been contracted by CNES to develop a metrology system using those IO technologies. Preliminary space tests such as radiation tests have been successful. The interested reader is referred to a paper by Lang et al. [Lang 96] for an example of IO metrology sensor.

5. Conclusion

The aim of this paper is to focus attention on new developments of integrated optics technologies. It shows ongoing research effort at LEMO and LAOG in the field of aperture synthesis interferometry, metrology and wavelength extraction. Such developments have timescales compatibles with interferometric space missions and deserve therefore attention. Their intrinsic excellent optics properties, stability weight and compactness should be considered in the context of a preparatory space interferometric mission where using IO could relax considerably some of the constraints.

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Part of the results presented here have been obtained thanks to fundings from CNES and CNRS-INSU. JPB acknowledges financial support through from CNES through a post-doctoral fellowship. We would like to thank P Rabou in helping designing the group delay tracking spectrograph.