Combining up to eight telescope beams in a single chip.

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ABSTRACT

In this paper we show that integrated optics offer a very simple and low cost way to combine up to eight beams of an interferometric optical array. These beam combiners will allow accurate visibilities and phase closure terms measurements, and provide consequently, high quality information for astronomical image reconstruction. We present optical designs for two different chips. Using previous laboratory experiments we extrapolate the performances, constraints and limits of different beam combination concepts. In particular spatial encoding and temporal encoding of "all-in-one" schemes are compared and their main properties are evaluated.

Keywords: Interferometry, Optical aperture synthesis, Beam combination, Integrated optics.

1. INTRODUCTION.

Present and planned aperture synthesis arrays do not provide direct images of the observed source. For sake of instrumental simplicity visibilities and closure phase are retrieved in a first step, then an *a posteriori* numerical processing transforms this information into an image. An array of N telescopes should in principle provide $N(N-1)/2$ visibilities and $(N-1)(N-2)/2$ independant closure phases. The beam combiner functions allow to interfere the beams in order to extract the desired previous quantities.

Designing a beam combiner is a trade-off between retrieving as much information as possible with a maximum signal-to-noise ratio and the lowest technical complexity. Several works[1–3] have shown that, from a theoretical point of view beam combination is not a major issue. However, with increasing number of telescopes, technical issues become dominant.

In this paper, we focus our attention on a new concept of singlemode beam combiners using integrated optics (IO) that could help solving important technical problems such as alignment constraints, mechanical and thermal stability, internal reconfiguration capability. The reader is referred to Kern[4] for a review on integrated optics. In section 2, we recall general characteristics on beam combination, section 3 summarizes IO 3-way beam combiners main laboratory optical properties. Extrapolating from our current results we propose in section 4 and 5 two concepts of "all-in-one" beam combiners and we finally discuss future developments and prospects in section 6. A more complete description of integrated beam combiners concepts and properties will be given in a forthcoming paper.[5]

2. GENERAL CONSIDERATIONS ABOUT BEAM COMBINATION.

2.1. Some definitions.

Nomenclatures describing beam combiners are multiple. For sake of clarity, we choose here the beam combination classification proposed by J. M. Mariotti.[6] In the case of single mode operation the pupil plane and image plane distinctions are not relevant anymore.

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Beam combination geometry. The coaxial beam combination is considered when interfering beams have common directions. This leads to a temporal encoding of the fringe pattern and requires active optical modulation. A classical Michelson interferometer uses this type of combination. A multiaxial beam combination is acheived when the beams have different directions after interference. This leads to a spatial encoding of the fringe as in a Young's hole experiment.

Beam combination organization. When considering a telescope number greater than 2 one has to consider different beam combination strategies. The two extreme possibilities are "pairwise" in which each of the N beams is splitted $N-1$ times to finally provide $N(N-1)/2$ outputs with corresponding interference pairs and "all-in-one" in which N beams are correlated and provide a common output containing all the possible interference pairs. We call "intermediate" combination the cases where only a subset of beams are combined together. This beam combination choice will depend mostly on the degree of visibility and phase information that has to be retrieved to provide sufficient dynamic range and image quality. Splitting the array in several sub-arrays can be mandatory with an increasing number of telescopes.

Beam combiner requirements. A beam combiner should have the following properties to provide best interferometric information.

- High instrumental contrast;
- Stability;
- High throughput;
- Optical paths must be equal.

2.2. Beam combiners over the world.

Table 1 recalls the beam combiners concepts used by the different interferometers including laboratory x1experiments using guided optics. It is interesting to notice that new generation interferometers (VLTI, Keck, CHARA) have all chosen the singlemode multiaxial concept. GI2T is the only existing instrument with multiaxial beam combination but it was designed for multimode operation.

Interferometer (or experiment)	Beam combiner description (number of beams)
COAST[7]	Coaxial/all-in-one (4)
NPOI[8]	Coaxial/ pairwise-intermediate (3-6)
IOTA (FLUOR[9])	Coaxial (2)
PTI[10]	Coaxial (2)
Shaklan[11]	Coaxial/intermediate (5)
Delage[12]	Coaxial/all-in-one (3)
GI2T[13]	Multiaxial (multimode operation) (2)
VLTI[14]	Multiaxial /all-in-one (AMBER) (3)
Keck[15]	Multiaxial /all-in-one (3)
CHARA[16,17]	Multiaxial /all in one (7)

Table 1. Current and future interferometers beam combination scheme.

2.3. The guided optics context.

Fiber or integrated optics devices provide the simplest way to spatially filter external light. This filtering associated with a corresponding photometric calibration is the best way to obtain accurate visibility measurements.[9] But guided optics introduce two main new constraints that have to be carefully managed in the beam combination context.

- Differential birefringence.

- Differential dispersion.

Both lead to a contrast decrease. Standard fiber optics, which are particularly sensitive to external perturbations, can have time varying birefringence which introduce strong instabilities that critically affects visibilities and closure phase measurements.

3. A SUMMARY OF IO BEAM COMBINERS MAIN PROPERTIES.

I0 technologies allow to integrate waveguides in a planar substrate thanks to photomasking techniques. The resulting integrated optical instruments can be complex which is particularly interesting for the beam combining issue.

We have carried out characterizations on several types of 3-way beam combiners. We summarize here typical optical properties at 1.55μm (see Haguenauer et al.[18] for a global review). For further details on these results the reader is refered to papers from several authors.[19–21] These properties should be similar to different technologies whith small index difference (ion exchange, IOS_2, $LiNb0_3$).

Optical throughput. Beam combiners optical throughput have been extensively studied (see Haguenauer et al.[18] for more details). Our non optimized 3-way beam combiners all have throughputs greater than 50%. There is no main photon loss source. Each step introduces losses, fiber/waveguide coupling (10%), Fresnel reflexion (4%), propagation (5% for 1 cm), Y junction (40%), couplers (10-20%), etc[*].

Optical path equality, birefringence and dispersion. Optical paths from the source to the interference point must be equal to within a coherence length. Figure 1 (top) displays an example of integrated 3-way pairwise beam combiner. It is ∼ 4cm long and ∼ 2mm wide. 3 inputs are splitted into 2 waveguides each (thanks to Y junctions). These waveguides reach a planar guide with a tilt angle allowing pairwise interference resulting in three separated spatially encoded interferograms. To ensure a correct collimation which provides planar wavefronts, we use adiabatic transitions (also called tapers). In this particular experiment, a single input waveguide allows to send light in the three inputs. Bottom of Fig. 1 shows one laser diode and white light interferogram (obtained with an halogen lamp and a standard H filter). Three important results arise from this experiment:

- In WL source the central fringe position corresponds to its theoretical position to within 1μm (average value). This means that the OPD error is $\leq 1\mu$m for interferometers with 3cm long arms.
- WL contrast is greater than 90%. This means that chromatic differential dispersion and birefringence have a negligible influence (differential effects are reduced by the nearly perfect equality between optical paths). Moreover, birefringence must be very homogeneous along the optical path, which is nearly impossible to obtain with standard fibers.
- In a 4 hour experiment with irregular temporal light injection, fringe positions did not change to within experimental precision ($\lambda/30000$), the visibility had rms fluctuations smaller than 0.3 %.

Birefringence have been measured in integrated optics waveguides for a long time. For example ion exchange technologies allow to obtain low and high birefringence as for standard and polarization maintaining fibers (normalized birefringence $B \sim 10^{-6}, 10^{-4}$). It has been shown that even when the IO beam combiner is connected with fibers, chromatic differential dispersion can be strongly reduced.[20]

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[*] These conservative numbers are given for silver/glass exchange technology but should remain the similar for IOS_2 or $LiNb0_3$

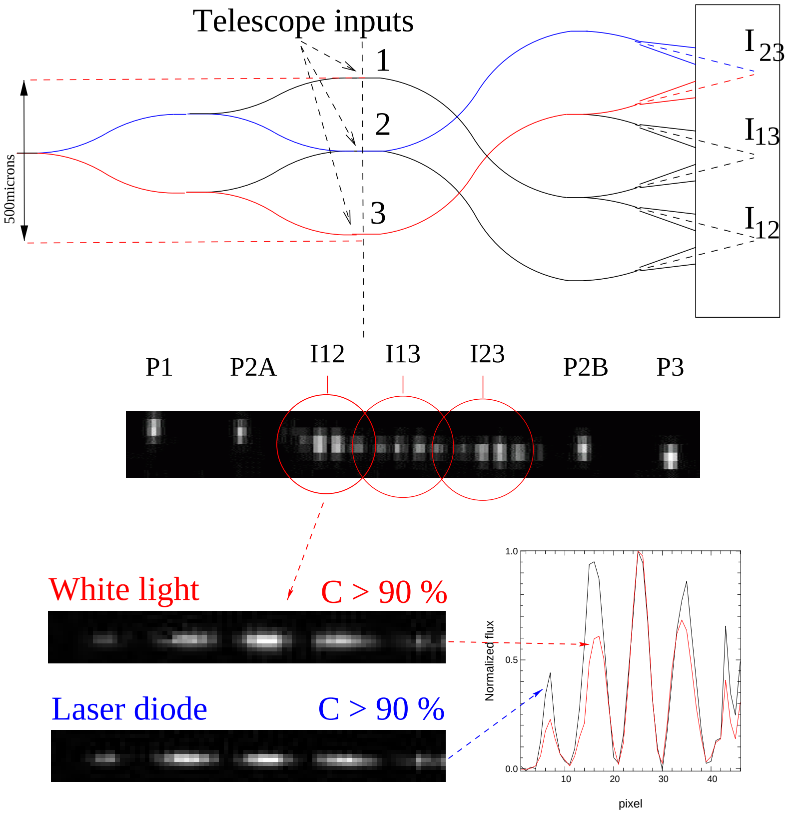

Figure 1. Top: 3-way pairwise multiaxial beam combiner. A common input waveguide allows preliminary tests of the structure. Photometric waveguides have not been drawn for clarity. Bottom: interference figure as seen on the detector when looking from right which figures the photometric channels ($P1, P2A, P2B, P3$) and 3 spatial interferograms($I12, I23, I31$). A zoom on a fringe pattern allows to see the gaussian-shaped interferograms in laser-diode and white-light.

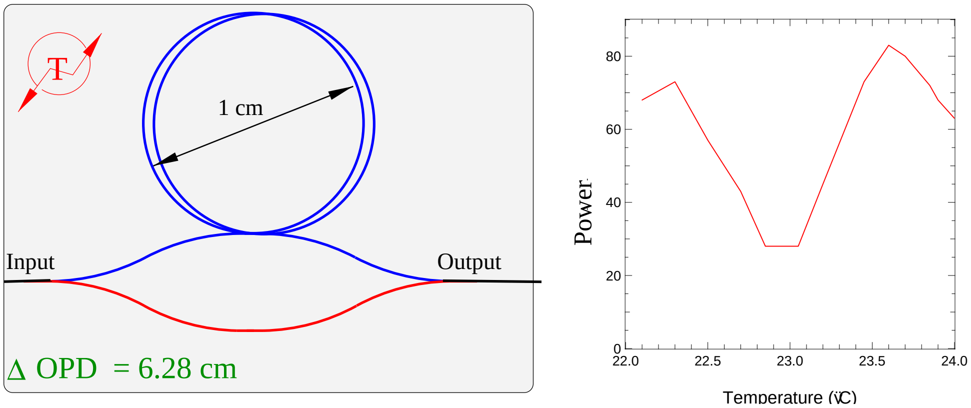

Figure 2. Left: Integrated optics unbalanced Mach-Zehnder interferometer. Optical path difference is $\sim$ 6.28cm. Laser light is used.The whole temperature component can be accurately tuned. Right: Ouput power as function of temperature (see text for details).

Thermal stability Accurate phase closure measurements requires strong optical path stability in particular with temperature. Stability lowers periodic calibration constraints. Left of Fig. 2 shows an integrated optics unbalanced MachZehnder interferometer[†]. The input waveguide is splitted thanks to a "Y" junction. A double loop is introduced in one of the arms that leads to an optical path difference (OPD) between the two arms which is $\sim$ 6.28cm. A reverse "Y" junction allows the two splitted beams to interfere. A laser source (1.3μm) is used. The output power is a function of the interference state between the two arms. When the whole chip temperature varies the OPD is scanned and the fringe pattern is recorded (as can be seen in Fig. 2 right). A 2π phase shift is obtained for temperature amplitude of 1.3°. When considering the OPD measured in our IO component (see 3) whis is roughly $\sim$ 1 micron this leads to the striking result that phase drift for a 1° temperature variation is remarkably small ($\sim 2\pi/90000$).

4. A MULTIAXIAL BEAM COMBINER.

Previous results have shown that IO instruments have optical properties that (closely) match beam combining requirements. Using laboratory measurements and simulation tools we can propose a concept for an IO N-way multiaxial beam combiner and then estimate roughly its performances.

Figure 3 displays a concept for a 8-way beam multiaxial beam combiner. The IO beam combiner inputs have been omitted here but are located about 3cm away from the beam combination. This component is about 5mm wide (without photometric channels). We suppose here that eight beams have been focused onto 8 fibers or directy onto 8 waveguides in the chip. After a $\sim$ 1cm propagation inside the chip to obtain an efficient spatial filtering the eight waveguides are adiabatically enlarged end reach a planar waveguide where light can diffract. Adiabatic transitions ensure planar beams. Their direction converges to a common point where the eight gaussian beams can interfere. A non-redundant set of angles allows to disentangle all possible pairs of interference by attributing a particular spatial frequency to each. The final interferogram size is defined by optical considerations i.e how to image and sample it correctly on a detector. One must notice that bulk optics beam combiners require anamorphosis optics to compress light in the vertical direction in order to maximize light flux, this is a technical issue, here, as propagation occurs in a planar waveguide there is not longer need for anamorphosis. From a technical point of view the trickiest issue is the waveguide tapering that allows to obtain large ($\sim 100\mu$m) planar wavefronts. Table 2 displays typical parameters computed for different number of input waveguides (of telescopes). These parameters have been optimized for an optical layout made of an IO beam combiner, a doublet and an infrared array with a 40μm pixel size. Figure 4 displays simulated 4 and 8 beams interferograms and their corresponding modulus. We can see respectively 6 and 28 fringe peaks corresponding to each possible combination. Optical throughput of the eight beam combiner should be better 70%. As there are no major technical difference between our previous 3T multiaxial beam combiner (see section 3) and this one we can predict that instrumental constrast should be better than 90%[‡].

Number of beams	W (microns)	M	$i_{min}(\mu\text{m})$	θ_{max}	throughput
3	48	× 10	16	3°	70 %
4	96	× 10	16	5°	70 %
5	88	× 20	8	10°	70 %
6	136	× 20	8	15°	70 %
7	100	× 40	4	20°	70 %
8	132	× 40	4	30°	70 %

Table 2. W gives the interferogram size (width at $1/e^2$), M is the optical magnification required for an optimized sampling of 4 pixels per smallest fringe (pixel size 40 μm), i_{min} gives the smallest fringe period (in microns) and θ_{max} the maximum output beam angle.

5. A COAXIAL BEAM COMBINER.

Couplers have been proposed for a long time as building blocks for a larger coaxial beam combiner. Succesful application by Shaklan[11] (see also Huss et al.[22]) have demonstrated the interest of this concept. However, fiber beam

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[†] Ion exchange technology is used here.

[‡] A slight decrease in the contrast could be the consequence of photometric unbalance between each interfering beam.

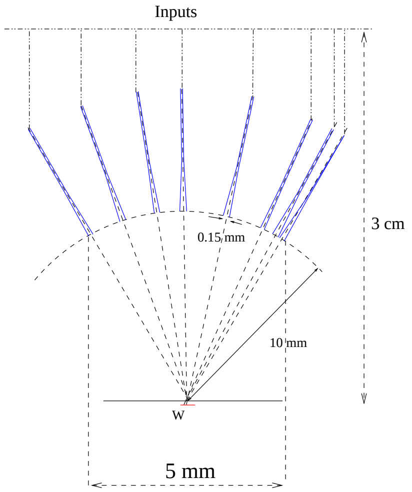

Figure 3. Schematic representation of a multiaxial 8 beam combiner with typical sizes (see text for details).

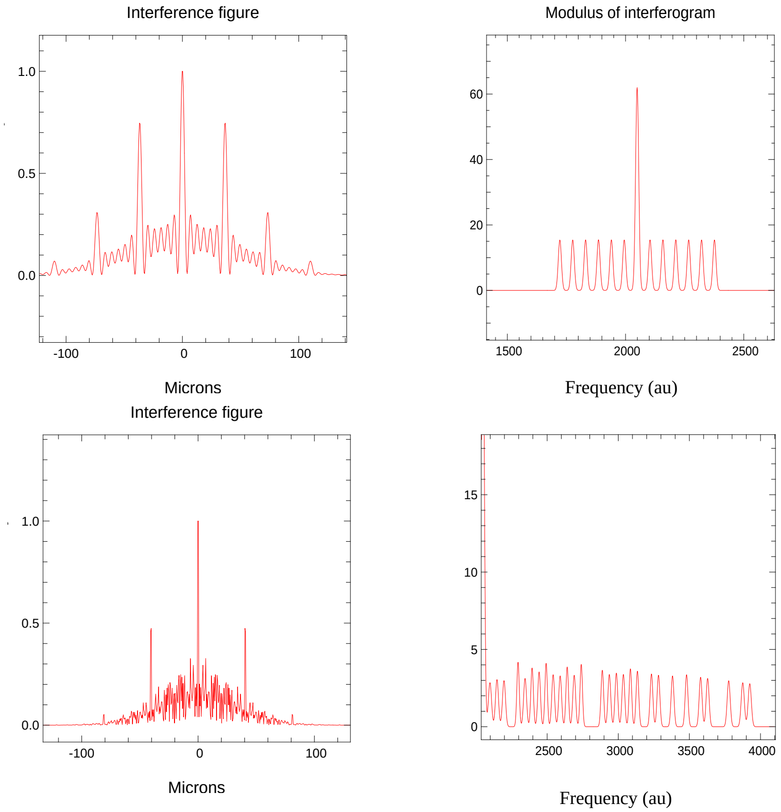

Figure 4. Left column: Simulated interferograms for a 4 and 8-way beam combiner. OPD are given in x axis (microns). Right column: corresponding Fourier amplitude.

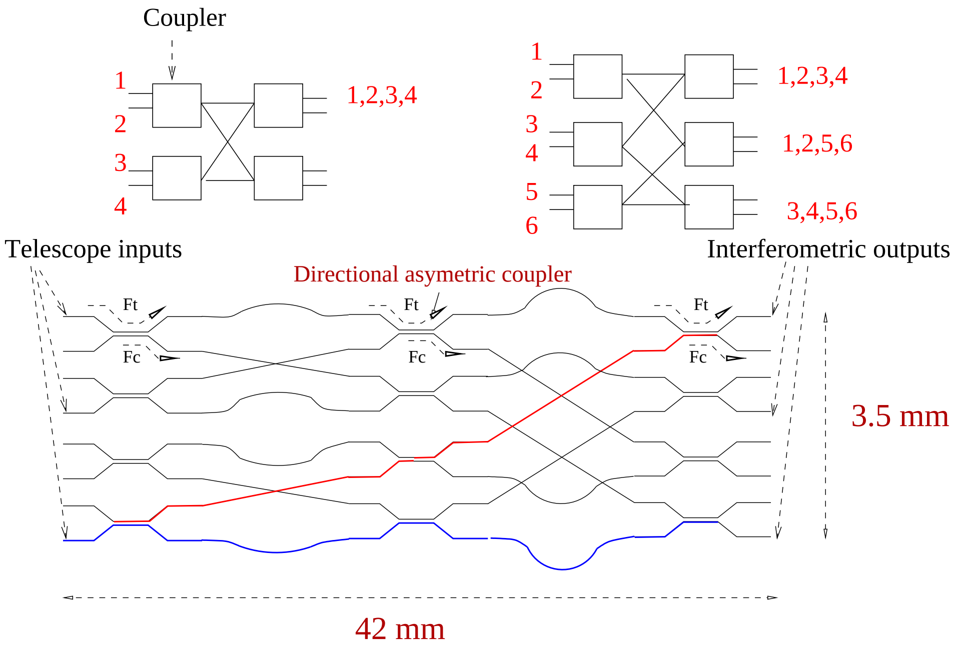

Figure 5. Top: schematic drawing of coaxial 4 and 6-way beam combiners composed with several coupler stages. Beams are labelled with numbers. Bottom: a 8-way beam combiner made of 3 coupler stages. All incoming beams are splitted 3 times and consequently are present at each ouput.
thb

Throughput	45%
OPD maximum error	10μm
C_{max}	6%

Table 3. Main properties of a coaxial 8-way beam combiner.

combiners require carefull thermal and mechanical stabilisation. Integrated optics offer a similar solution but add its own natural stability and polarisation maintaining capability (see section 3).

Using several stages of 2-way couplers one can design N-way beam combiners. Top of Fig. 5 shows two schematic examples of 4 and 6-way beams combiners. In the first one, 2 coupler stages are required for the 4 beam interference, in the second the combination is not “all-in-one” but allows each beam to interfere with each other at least once. Of course this kind of beam combination requires a nonredundant OPD temporal modulation. Bottom of Fig. 5 shows a more detailed study of a 8-way beam combiner. It is about 4 cm long and 4 mm wide (without photometric channels). It uses three stages of four asymmetric couplers. These couplers have been described by Berger et al.[23] and Severi et al.[21] They have a reduced chromaticity when compared to standard couplers. Curved waveguides between the couplers are designed to match the optical path equality requirement in particular for the “critical” lengths[24] that can not be compensated by the 7 delay lines. The trickiest issue is to manage crossings and curves that have opposite consequences. Short curvature radius leads to high photon losses but high angle crossings. Small angles (obtained with low loss high curves) lead to cross-talk and coupling undesirable effects.

From our current knowledge, we can estimate main properties for a 8-way beam combiner (see Table 3). C_{max} is the chromatic maximum contrast loss due to coupler chromaticity. It is the consequence of the cumulated photometric unbalance between each coupler arm. It can be written as:

$$C_{max} = \frac{2\sqrt{F_c^3 Ft^3}}{F_c^3 + F_t^3} \tag{1}$$

where F_c and F_t are respectively coupled and transmitted fluxes in one coupler for the worse asymmetric coupling.

6. DISCUSSION

6.1. Preliminary comparison

Common properties Both multiaxial and coaxial beam combiners will have high instrumental contrast and high thermal stability. Stability leads to precise visibility measurements (recall: 0.3% rms variation over 4 hour in a 3-way beam combiner) but also phase variation ($< \lambda/10000$ for the worse case.). As for bulk optics signal to noise ratio considerations lead to similar performances. Also, both are well optimized for a specific number of beams but can be used for a lower number. The temporal OPD modulation for coaxial BC should in principle provide sampling reconfiguration capability.

Multiaxial properties. The multiaxial beam combiner has the highest thoughput as it avoids crossings and couplers. The key technological point is the waveguide taperisation which has to be smooth enough to ensure planar wavefronts. The extension to a great number of telescopes will be limited by the adiabatic transition length ($\sim 1cm$ for a 160μm beam width and the non-redundancy requirement that will lead to high numerical apertures. We think that from a technological point of view it will be the easiest to manufacture.

Coaxial properties. Cascade of couplers will lead to an unavoidable chromaticity and crosstalks. Resulting output interferograms should have different spectra but this should remain stable and consequently allow calibration[§]. Moreover, increasing N requires decreasing the bandwidth (to enlarge coherence length and allow nonredundant fringe detection) this should reduce chromaticity influence. Its complexity lowers its thoughput. Also it is only well optimized for a number of beams which is a power of two. However it seems that it will be the easiest concept to extend to a larger number of telescopes as it only requires to double the number of couplers per stage and a to add new stage which is technically possible.

6.2. Future prospects

"All in one" integrated beam combiners seem a realistic possibility. Futher researches can be envisioned that will increase IO attractivity.

1. **Beam combiner passive and active reconfiguration.** IO low cost allows to use several beam combiners that combine different sub-arrays of telescopes ("all-in-one", "pairwise", "intermediate"). By just changing fiber connection it should be possible to adapt observational mode to the observed objects complexity. In a further step using integrated optics switches can be envisioned for active reconfiguration.
2. **Integrated or fiber[25] active fast path compensators:** to provide temporal encoding capability in order to avoid external mechanically active optics;
3. **Integrated spectral dispersion for group delay tracking.** Modest spectral resolution can be achieved with current technologies;
4. **Integrated metrology combination.** This should allow get a precise end to end metrology information.

7. CONCLUSION

We have described two types of "all in one" integrated optics eight beam combiners. Both show that IO offer an unique solution for the beam combination function of a large array. Moreover, this technology allows beam combination flexibility as several beam combiners designs (corresponding to a particular strategy) can be integrated on the same chip. The multiaxial beam combiner seems the easiest to manufacture but the coaxial requires further studies as it should be the easiest concept to extend to a large number of telescopes. These beam combiners are expected to have the following properties:

- combining with flexibility any number of telescopes
- stability with time
- acceptable optical losses
- ease of upgrade configuration
- high instrumental contrast
- ease of alignment
- complexity independant cost
- small size ($\leq$ 5cm $\times$ 5cm)

[§] Provided that starlight coupling fluctuations are achromatic.

We are actively working on laboratory demonstrators. Using our IONIC experience[26] we are also working of a global instrumental concept for a large array combination.

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