Bulletin de la Société Royale des Sciences de Liège, Vol. 74, 5-6, 2005

Single mode beam combination for interferometry

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Abstract: This paper presents the capability of single mode instruments for interferometry, mainly for the beam combination. Guided optics is identified as a unique way to provide the required single mode behavior for the most demanding applications in terms of measurement accuracy. We give a brief description of existing technologies, and present typical developments in progress on this subject, which benefits from the properties of guided optics.

1 Introduction: beam combination in interferometry

Among possible beam combination concepts, single mode ones bring some essential behaviors related to the modal filtering capabilities. Such a filtering is critical to improve the performances on the contrast measurement in interferometry. For applications that require high contrast measurement as nulling interferometry, or high accuracy on the contrast measurement, it may even become mandatory. It has been demonstrated that only single mode wave guides are able to provide the filtering at a sufficient level to meet the required performances for such applications (Mege 2002). Two kinds of wave guide devices can be considered, optical fibers and integrated optics wave guides. Major developments of the existing products were conducted for telecom applications, mainly at .8, 1.3 and 1.5 μm. We first give some elements on existing technologies for single mode propagation at optical and infrared wavelengths in the cases of optical fibers and of integrated optics. In each case we consider main applications, beam transportation for fiber optics and beam combination for integrated optics. The last part presents existing developments and investigated concepts.

2 Guided optics and modal filtering

Introduced in early 80's as a convenient tool for beam transportation and combination in interferometric networks of telescopes (Froehly 1981), guided optics brings along convenient additional functionalities. Among them it provides single mode propagation with corresponding capabilities and drawback.

The fundamental behavior of single mode propagation is to provide perfectly coherent wavefront independently of the injected beam at the input. Then, while dealing with corrugated wavefront coming from an unresolved source, a 100 % contrast is theoretically achievable with a single mode wave guide. The perturbations of the incident wavefronts turn into intensity fluctuations through the single mode wave guides. An a posteriori correction of these intensity fluctuations allows correcting the resulting fringes, in order to keep only flux fluctuation resulting from interferometric process. Wavefront filtering greatly improves the fringe reconstruction efficiency and provide a precision enhancement of the measured parameters. This becomes a real advantage when phase determination is critical. For sharp imaging reconstruction it brings significant improvements, as in phase closure and astrometry.

For nulling interferometry it becomes mandatory, for faint object detection in the vicinity of a bright star. No sufficient central star extinction can be considered without a very efficient modal filtering, able to clean any stray-light that directly affects the nulling capabilities (Mennesson 2002). An accurate analysis has demonstrated that spatial filtering allows a significant relaxation on the required specifications on the incident wavefront flatness to achieve the considered extinction (up to 10^{-6} in the $[4-20\mu m]$ spectral band). For instance, thanks to this analysis it appears that the $\lambda/4400$ requirement on the wavefront flatness in the case of bulk optics without any spatial filtering became $\lambda/400$ thanks to a spatial filtering using an adapted pinhole and $\lambda/63$ thanks to modal filtering using an optical wave guide.

3 Fiber optics

3.1 Available Technology

Apart from their beam transportation capability on long distance (attenuation $< 0.1 dB/km$ for telecom fibers @ $1.5\mu m$) , fibers provide an important instrument flexibility to manage the injection of large number of beams. Single mode fibers are commercially available for the $.5-5\mu m$ range. One of the drawback of the use of optical fibers are their high sensitivity to environmental constrains (thermal, mechanics) with induced birefringence effects.

R&D programs are in progress to obtain single mode fibers for longer wavelengths ($\lambda > 5\mu m$) as TNO TPD / The Netherland, Le Verre Fluor / France. To date, no operational product exists at these wavelengths with sufficient transmission and demonstrating single mode behavior at required efficiency. One of the difficulty for efficient modal filtering is the capability of the fiber structure to manage the rejected light which is not guided in the core of the fiber, but may still be guided by its cladding which acts as an other external wave guide. In some developments it is considered to apply an external coating on the cladding of the fiber to manage a suitable leakage of rejected light.

Some fiber based instruments have been realized or are under construction for several interferometric facilities: IOTA (Fluor , Thisis) , Chara, PTi, VLTi (VINCI, AMBER), Mauna Kea (OHANA).

3.2 Application: Beam transportation

Optical fibers are identified as powerful tools to bring the light from the telescopes to the combination instrument, leading to significant infrastructure simplification. It has been demonstrated that the attenuation due to the propagation through the fibers is comparable to the losses introduced by the mirrors (aberrations and diffraction) of conventional optical trains. Thanks to the flexibility of optical fibers, a set of existing telescopes can be used as an interferometric network. This is the purpose of the Ohana project (Perrin 2000 and 2003) on the Mauna Kea in Hawaii, using 3 to 10 meters telescopes. The instrument takes the beams from each telescope to the beam combination unit through single mode fibers. Some of the major concerns of the program, apart beam injection in the fibers thanks to the adaptive optics system on each telescope, are related to fiber performances, mainly the chromatic dispersion in the fibers on the considered bandwidths (J, H and K bands) (Vergnole 2004).

The impact of the use of fiber optics on the accessible interferometer FOV is also addressed in Guyon 2003. First encouraging results have been obtained just a few days before this conference with the OHANA instrument between the two 10 meter telescope Keck 1 and Keck 2. Some further investigations in progress are related to the possibility to provide delay line using fiber optics, mainly at IRCOM-Limoges/France. Once again, the main issue is the dispersion of the fibers.

Crystal photonic fibers (PCF) is also considered as a promising solution for beam transportation, allowing single mode propagation through a wider spectral band, but also as a good candidate to improve the dispersion behaviors. Specific developments were conducted to provide interferometric measurement at four wavelengths respectively in the R, I, J, and H bands, with the same couple of PCFs (Vergnole 2005). Further investigations must be continued, in consideration to the encouraging obtained results.

4 Integrated optics

4.1 Available Technology

Integrated optics also issued from telecom developments is commercially available in a similar spectral range ($.8 - 1.7\mu m$). Various technologies are available with achieved performances suitable for an application in interferometry. For most of the technology the propagation losses are larger that the one of the fibers, but the required lengths of the components is much shorter as only a few centimeter guides are required for most of the cases.

A first review of the IO capabilities has been proposed thanks to a dedicated workshop by Kern and Malbet in 1996 (Kern & Malbet 1996). The most interesting behavior of this technology is to allow an integrated instrument with several optical functions made of complex optical circuitry on a single tiny chip of a few mm^2. It turns in very compact instruments, and allow an high instrument stability , with a low sensitivity to vibrations and temperature fluctuations. A lot of convenient optical functions can be implemented on the same chip, for light deflection, beam separation and combination, modulation, light dispersion (Kern 2001). Using these capabilities it is even possible to consider an integrated interferometric instrument including scientific beam combiner and metrology facilities working at different wavelengths, implemented on the same chip. It is the purpose of the MAFL program (AAS, IRCOM, IMEP, GeeO) that provide beam combining and metrology for a three telescope imager.

One drawback of this planar technology is the fact that IO is not adapted for 2D beam arrangement in the output plane.

Operational instruments are available and under exploitation using IO technology: IOTA (IONIC), VLTi (VINCI/IONIC). Other developments in progress consider the use of IO components as beam combiners: VLTi (VITRUV, Gravity), Chara (MIRC). The proven capabilities for astronomical applications either from laboratory demonstration or thanks to on-sky measurements are the following:

- The filtering properties for single-mode interferometry as been demonstrated and nulling

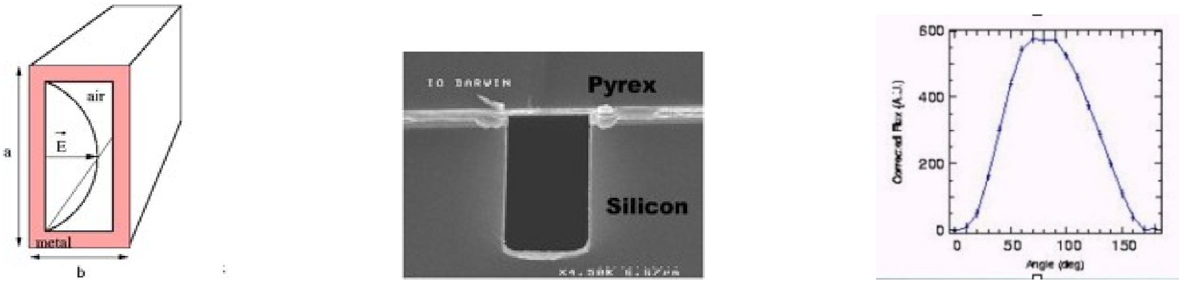

Figure 1: Left: Hollow metallic wave guide structure, Middle: MEB pictures of the output of the guide, Right: measurement of the polarization behavior of the guide at $10.6 \mu m$, the 0 deg axis corresponds to the direction b on the guide (Labadie 2005). For this orientation, the signal is at the noise level, comparable to the polarizer extinction capability, close to 1:200

extinction as low as 10^{-5} have been obtained at $1.5 \mu m$(weber 2004) on a dedicated bench at Alcatel Alenia Space.

- Self Alignment is provided and no alignment maintenance has to be considered (especially if adaptive optics is provided for injection). As soon as the light is injected in the component, no misalignment is any more possible.
- Easy installation when fiber optics connection is properly managed. The installation in the VINCI instrument takes a few minutes in the VLTi focal laboratory.
- Reliable beam splitters / combiners
- Demonstrated excellent fringe contrast with on-sky experiments (Lebouquin 2006)
- Routine science is performed on equipped interferometer (VLTi/VINCI) (IOTA/IONIC: Kraus 2005, Monnier 2004)
- Improved resolution of the interferometer, thanks to the reduction of the measurement errors.
- Improved stability phase of the instrument for imaging purposes.

Dedicated developments are in progress in astronomy to extend the technology and achieve single mode operation in the $3 - 20 \mu m$ range. First interesting results have been obtained using hollow metallic wave guides (Labadie 2005). Developments of chalcogenide glass guides are also in progress (Vigreux 2005). The single mode behavior of hollow metallic wave guide has been demonstrated thanks to polarization analysis of the device, showing an obvious extinction when a polarizing device blocks the light along the polarization direction of the guide (see figure 1 right). The considered guide for this analysis presents a rectangular geometry, with a dedicated design for electric field propagation only for one orientation of the polarization (along the smaller dimension of the guide) at the considered wavelength. For the tested component the dimensions of the guide are $4.7 \times 10 \mu m$ to obtain a single mode behavior at $10.6 \mu m$.

For modal filtering the geometry of IO components is much more efficient that the geometry of the fibers to properly reject parasitic light filtered by the wave guide thanks to the absence of axi-symetric geometry. The substrate dimensions are large enough in most of the cases to avoid efficient guidance up to the optical guide output, or even re-injection in the guide. Furthermore, in the case of the hollow metallic wave guides, no electromagnetic field is transmitted in the substrate, as the interface between the core and the cladding act as a metallic mirror. In this case the rejection of unexpected higher modes is theoretically perfect.

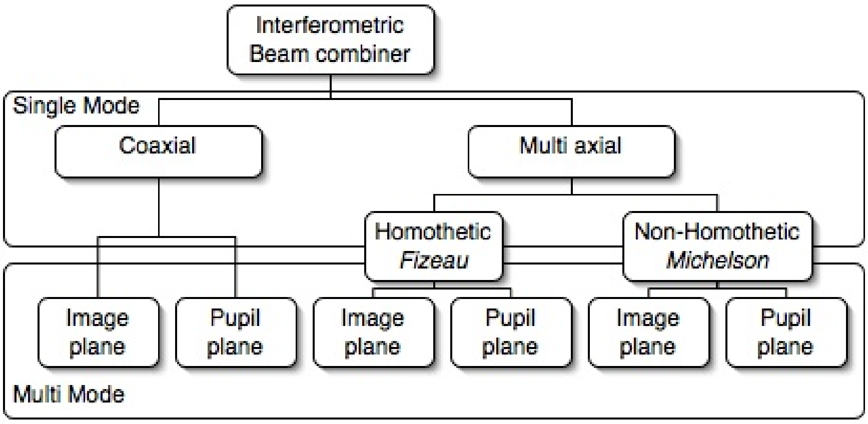

Figure 2: Possible schemes for interferometric beam combination (adapted from Mariotti 92)

4.2 Beam combination

Beam combination concepts have been fully described in the frame of the preparation of the large interferometric facilities. Mariotti (Mariotti 1992) proposes a classification of the possible concepts that can be summarized in figure 2: Interference measurements can be obtained either using co-axial or multi axial combination of beams coming from a network of telescopes. In the first case the interferometric fringes are detected along the optical axis thanks to a temporal modulation of the optical path, leading to a temporal sampling of the signal detected on a single detector. In the multi axial case, the beams coming with different incident angles interfere on a focal plane, where a suitable array detector samples the interferometric signal. In the multi-axial modes, it can be considered to re-arrange the beams leading to non-homothetic configurations. For instance in the Michelson mode, the output pupil of the interferometer doesn't respect the scale ratio between the diameter of the individual sub-apertures and the sub-aperture separation of the input pupil, as the Fizeau mode does.

For all cases the detection can be done either in the pupil plane or in the image plane.
Pupil densification (Labeyrie 1996) is an application of the Michelson mode. Note that the IRAN mode dedicated to coronagraphy (Vakili 2004) is a particular case of beam arrangement in the image plane.
When only the spatially coherent part of the incident wavefront is considered, one can speak of single mode beam detection, as the beam étendue is limited to $\approx \lambda^2$. In that case the notion of images and pupils are not any more meaningful. This type of detection is the only one that applies in radio-interferometry.
We are speaking of multi mode beam detection when the beam étendue is $>> \lambda^2$, in other words when the field of view is much larger than the diffraction patch of individual telescopes. It turns that when the incident wavefront is not limited by the diffraction of the individual sub-apertures, but by all the aberrations introduced by the optical system, and even more by atmospheric turbulences, each aperture images a speckled pattern from ponctual sources. Single mode beam combiners will select only one of the speckles issued from each telescope beam for the interferometric interferences. In that case it is highly mandatory to feed the wave guide using adaptive optics system to reduce the number of speckles and improve the injection efficiency. In any case this efficiency is theoretically limited to 78% due to the adaptation of the field distribution at the output of the telescope (Airy pattern) to the gaussian mode of the wave guide (Foresto 1994).

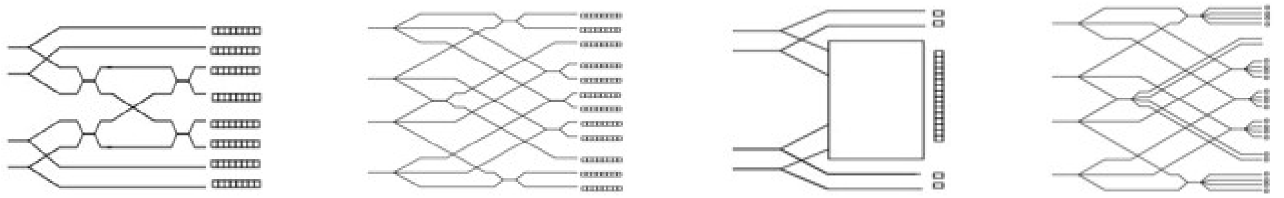

Figure 3: Possible beam combination schemes for an array of 4 telescopes using integrated optics technology : a. Temporal all in one beam combiner, b. Temporal pairwise combiner, c. Multiaxial combiner, d. Matricial combiner

Single mode detection through a single dish reduces the field of view (FOV) to a single point defined by the diffraction pattern of the telescope. In any case, using single mode beam combination will reduce the largest accessible FOV of the whole interferometer to the diffraction Airy disk of the largest telescope. Then the maximum number of sampling points in the reconstructed images is limited by the ratio of the maximum baseline length to the largest telescope diameter. It must be pointed out that in many cases the FOV is rather limited by other instrumental parameters as telescope configurations and pupil rearrangement. For instance pupil densification has a strong impact on the FOV.

For beam combination, several schemes have been proposed using either fibers or integrated optics components. Integrated optics brings a suitable flexibility, to choose the appropriate beam combination according to the applications or the number of telescopes. All of the single mode beam combination concepts can be implemented using integrated optics. In many cases it offers a way to reduce the complexity of the instrument. A complete analysis of the best beam combination strategies according to the configuration of the telescope network and to the observed targets has been conducted at LAOG (Lebouquin 2005). Figure 3 shows the various proposed concepts in the case of a 4-telescope array. The two first one (a. and b.) are extrapolations of the concept used for the IONIC/IOTA instrument installed on IOTA (Monnier 2004) for the 3 telescope beam combination or for the VINCI/IONIC instrument installed on the VLTI for 2 telescope beam combination (Lebouquin 2006). It corresponds to the co-axial concept presented in figure 2. In the second concept (c.) the multiaxial fringes produced at the output of the component are images on an array detector. It might be the convenient scheme for large number of telescopes, as for the whole VLTi array with 8 telescopes. The last one, the matricial concept (d.) is an integrated ABCD fringe detector. Fixed phase shifts introduced within the guides make it possible to obtain directly at the four outputs of the component 4 statuses of the considered fringes without any external phase modulation. With such a design no more temporal modulation is required. The optimized configuration is a trade off considering the minimum number of pixels, the required spectral resolution, the sensitivity to the turbulence. The feasibility of the component must be considered as some proposed solutions have not yet been manufactured with all the required constrains (number of telescope, working wavelength, wavelength range). Schemes a. b. and c. have been realized for H band and are under tests in laboratory. An interesting behavior of IO beam combiner is the arrangement of the outputs on a single line. This line can act as the entrance slit of the instrument spectrograph, avoiding any cylindrical optics. The width of this line made of single mode guide outputs is diffraction limited.

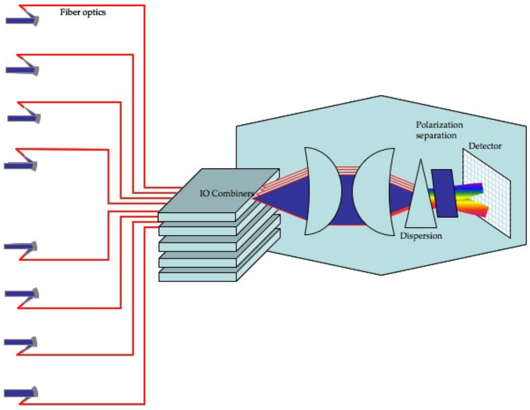

Figure 4: Concept of the Vitruv instrument proposed to ESO as an imager instrument managing the beams coming from 4 to 8 telescopes. Beam combiner chips can be chosen according to the observation requirements.

5 Some of the current developments

5.1 VITRUV developments

The LAOG team proposes a concept based on IO capabilities for the 2nd generation of interferometric instrument for the VLTi. The so-called VITRUV concept (figure 4) aimed to provide imaging capabilities using 4 to 8 telescope of the site, allows choosing between several beam combiners schemes according to the interferometer configuration. In such a concept several beam combiner IO chips can be available. The user can select one of the beam combiners according to the optical bandwidth, the number of telescopes, the required performances. The proposed instrument working in the JH or K band is designed to provide a spectral resolution up to R $\sim$ 30 000.
A complete development program is in progress at LAOG to prepare such an instrument, including all the required analysis :

- Full simulation of the IO part of the instrument: feeding optical fibers and integrated optics components
- Theoretical analysis of considered IO components
- Realization and characterizations of prototype components
- Complete laboratory demonstration bench for image reconstruction validation. It provides a scaled simulation of the VLTi telescope arrangement for up to 8 telescopes. Complex objects can be injected in the bench to validate and qualify the reconstruction capabilities of the IO based instrument.

5.2 MIRC Chara program

This instrument is designed to provide imaging capabilities combining the 6 CHARA telescopes in the $1.45 - 2.5\mu m$ range with milliarcsecond resolution. The design is aimed to allow good calibration and efficient synthesis aperture imaging thanks to spatial filtering with fiber optics, a low-resolution spectrometer (R $\sim$100 to 300) and a synthetic densified pupil. First results on the sky have been obtained using Chara facilities (Monnier 2004).

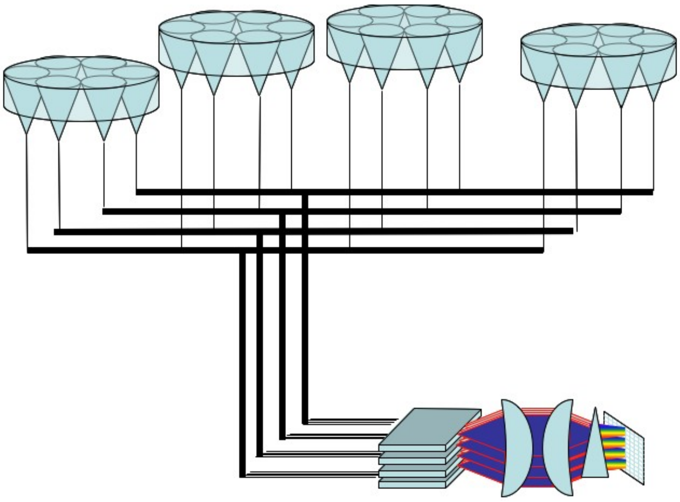

Figure 5: Possible concept where a fragmentation of the main interferometer pupils allows to reduce the turbulence constrains on each individual fiber injection, to enlarge the field of view of the interferometer and to provide larger number of baseline for a better u-v plane coverage

5.3 Pupil re-mapping and Pupil densification

Some interesting concepts also have been proposed using fiber optics to re-arrange either monolithic or diluted pupils for different purposes. In some case it is considered for pupil densification concepts (Patru 2005 in these proceedings) or to enhance specific spatial frequencies (Lacour 2005 in these proceedings). In some cases, one can consider a fragmentation of individual interferometer apertures. A suitable modal filtering associated to the generated sub-apertures, allows reducing the effects of atmospheric turbulence if the sub-aperture size is close to ro value. A tip tilt actuator on each fiber injection device allows a correction of the incident wavefront, as with an adaptive optics system. In addition this method turns in an enlargement of the interferometer field of view, as the FOV limit is given by the diffraction pattern of the defined sub-aperture. An additional interest of the method is to have access to a lager number of baselines, and to provide a better u-v plane coverage.

6 Conclusion

Many concepts of multi beam combination can take benefit of single mode operation at least using fiber optics. A lot of elementary functions are available for JH & K bands thanks to huge telecom funding, including sources and detectors, dichroic separator or active components as phase modulator or beam switches.

One can consider that one of the major limitations for the use of integrated optics is the availability of the involved teams to explore the complete domain for its application to stellar interferometry. Some specific developments must be considered to extend the domain to shorter and longer wavelengths (visible and thermal IR). It may require, especially for thermal infrared heavy technology developments.

The new photonics crystal domain must be accurately considered, mainly in short term for photonics crystal fibers, regarding to its very promising potential.

Many current investigations for instruments dedicated to interferometry consider the use of single mode devices when the technology is available. It shows the great potential of the domain.

Acknowledgements

This research was supported at LAOG in part by contract with CNES, INSU/CNRS, ESA and Université Joseph Fourier (Grenoble France).

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