Advanced Photonic Technologies for Optical Interferometry

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Abstract

We review photonic technologies which may find applications for future optical interferometers or upgrades on the VLTI facility. We show the results presented with different technologies and their application to different observing bands of astronomical interest encompassing near and mid-IR wavelengths. We focus in particular on 1) the usage of optical fibers to deliver metrology and/or links for the elescopes and 2) three dimensional photonic components for integrated beam combiners including micro-spectral analyzers, suitable for the combination of an arbitrary large number of telescopes. Possible related science cases are put forward. While this instrumental research is turned towards future interferometers, it relies on more than 10 years of development work with proven scientific return. This certainly reinforces the potential and originality of the approach.

Science cases and requirements

Advanced photonics technologies help to simplify the implementation of large interferometric, imaging or spectroscopic instruments. The requirements imposed by varied science cases such as the study of distant galaxies or the detection of exoplanets have been explored in details by our group in Allington-Smith et al. (2010, SPIE Proc 7739, 925). In the more specific field of optical spectro-interferometry, photonics technologies provide reliable and low-cost solutions for:

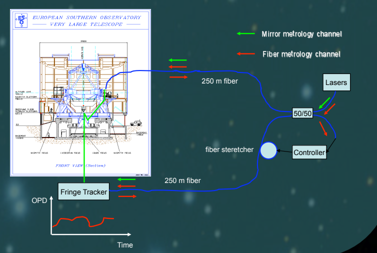
- Imaging of astrophysical objects such as giant star surfaces, young circumstellar disks, distant AGNs, tight binaries in SF regions, interacting and cataclysmic binaries. These science cases rely on the high –angular resolution and good UV plan coverage offered by the multi-aperture interferometer.
- Spatially resolved observations of gas lines thanks to high-spectral resolution photonics modules to identify the origin of warm gas in massive systems or to perform spatially localised kinematics studies .

For high-contrast science cases (sub-stellar objects companions, planets, debris disks), high-precision interferometry and high throughput are required, for which photonics still need some improvement. But we think that in the coming years , photonics technologies will also enable the calibration and metrology techniques necessary to the realisation of those last difficult science cases (fringe tracking, high-precision metrology of vibration, phase control for nulling interfereometry etc…)

The MAMMUT system

Fast mechanical vibrations in the optical train of the interferometer limit the sensitivity of the instrument by reducing the visibility of fringes. Accurate real-time metrology of the optical path of light is necessary to compensate actively the vibrations and improve the performance of the interferometer.

Photonics can provide solutions to deliver laser metrology beams even in the moving parts of the telescopes. An example is MAMMUT, the Mirror vibrAtion Metrology systeM for the Unit Telescope, an actively stabilized fibre interferometer [Minardi et al. 2009, Astr. Nach. 330, 518] designed to deliver phase referenced laser beams for metrology purposes anywhere in the VLTI facility. MAMMUT could be used to inject light at the level of M4 in the UT's and measure the position of mirrors up to M8 with 10 nm precision at kHz rate, by means of an ultrafast fringe tracker [Spaleniak et al. 2010, SPIE Proc. 7734, 3Y]. MAMMUT is currently undergoing validation tests at Paranal.



Photonics spectrometry

Low, mid and high resolution spectroscopy is a key investigation technique to be associated to interferometry, in particular for imaging of spectral-line related phenomena. Ideally, miniaturized integrated spectrographs would be inserted in the optical design. Different options exist:

AWG spectrographs: originally developed for optical telecom networks, AWG exploit wavelength multiplexing within a phased array of SM fibres, then connected to outside world through an input and output port. Cvetojevic et al. (2009, OpEx 17, 18643) have demonstrated on-sky the operation of AWG spectrometers for OH-lines suppression (see Fig. 1). Extension of the concept to 3D structures has been proposed to reduce the size of high resolution spectrometers (Fig. 2 -Thomson et al. 2009 Opt.Exp. 17, 1963).

SWIFTS spectrographs (see Kern et al. 2009, OpEx 17, 1976): based on theory of standing waves in SM, integrated Fourier-Transform spectrographs can be produced on the mm/cm scale (see Fig. 3). Fully operational components have been produced. This solution offers routinely high-spectral resolution and an extension of the concept towards the mid-infrared bands is under study.

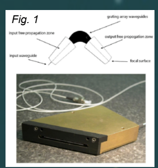


Fig. 1

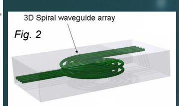
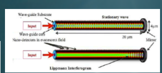


Fig. 2



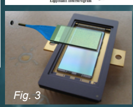
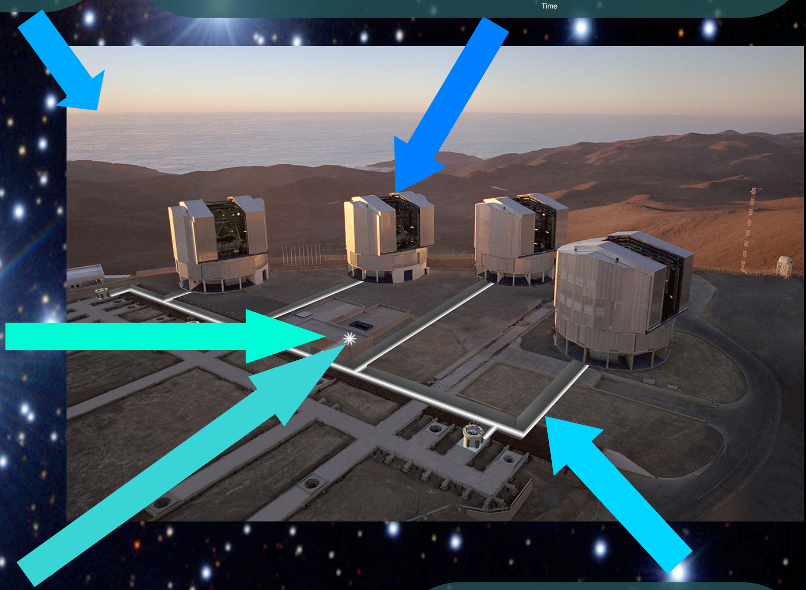


Fig. 3



Beam Combiners

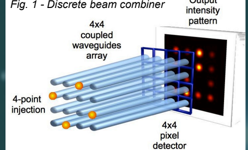
Integrated optics has influenced beam combination in the field of astronomical interferometry delivering miniaturized, monolithic components which deliver highly stable and reproducible visibility measurements. Silica on silicon technology has been used so far to manufacture optical chips combining up to 4 telescopes at a time in H band [Benisty et al. 2009, A&A 498, 601], used presently on the PIONER instrument (see scientific program). Scaling of such components to combine even more telescopes for all possible baselines is constrained by the growing complexity of the design imposed by their planar geometry, which reflects into tighter manufacturing tolerances.

A possible solution to this problem can be provided by three dimensional (3D) photonic components manufactured by means of ultra short laser inscription [Rodenas et al., 2011, CLEO Europe 2011, Opt. Tech. Digest, paper JSIII_P2]. The addition of a dimension enables the elimination of the waveguide crossovers, resulting in a simplified design. 3D ULI applies also well to mid-IR chalcogenide waveguide, with which 2D components have already been demonstrated in the lab [Labadie et al. 2011, A&A 531,A48L].

The simplification can be pushed even further by combining the light of N telescopes with just an array of NxN evanescently coupled wavveguides. The scheme, named Discrete Beam Combiner [Minardi, Pertsch 2010, Opt. Lett. 35, 3009], allows the retrieval of the visibilities over all possible baselines by measuring the power carried by each waveguide of the array at the end of the sample. A laboratory demonstration of the concept has been carried out and plans for initial tests on sky are in progress.

The images below show different components, geometries, and results: DBC cartoon concept (1), and phase retrieval (2); 3–dimensional 3T telescope chalcogenide beam combiner (3) and resulting broadband fringes filtered in the 9-11 μm range (4).

Fig. 1 - Discrete beam combiner



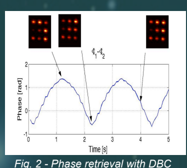


Fig. 2 - Phase retrieval with DBC

Fig. 3 - 3D+3T beam combiner

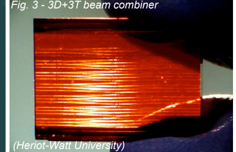
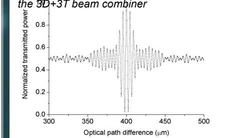


Fig. 4 - 9-11μm filtered 2T fringes using the 3D+3T beam combiner



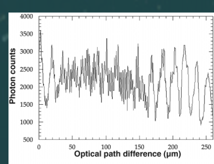
Fiber Links

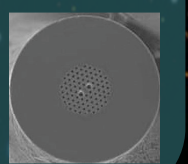
Optical fibers may deliver in the future a cost effective solution for linking telescopes in interferometers over baselines far exceeding the ones available today. A proof of principle for fiber links was successfully carried out at the Keck interferometer [Perrin et al. 2006, Science 311, 194] in the frame of the OHANA project.

Critical issues are insuring a broadband single mode and low dispersion performance of the optical fibers.

Both goals can be accomplished by suitably designed Photonic Crystal Fibers (PCF), where the complex geometry of the hole distribution in the cladding can be used to Taylor precisely the properties of the fibers [Russell 2003, Science 299, 358]. The potential of these fibers for interferometry was demonstrated recently in the laboratory [Vergnole et al. 2006, Appl. Opt. 44, 2496].

Advances in fabrication of PCFs with chalkogenide glasses opens interesting perspectives for fiber links in mid-infrared.





Left: first fringes of the fiber link interferometer (Perrin 2006). **Right:** cross section of a photonic crystal fiber.