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INTEGRATED OPTICS APPLIED TO ASTRONOMICAL APERTURE SYNTHESIS:

I. GENERAL CONCEPT FOR SPACE AND GROUND BASED APPLICATIONS

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ABSTRACT: *Space interferometric missions like the American ones, SIM, NMI and TPF, or like the ESA interferometric corner stone from the Horizon2000+ program rise new optical challenges concerning adjustment and stability of optical devices. Beam combination from several telescopes requires angular accuracies better than the spatial resolution expected on the sky λ/B (λ being the wavelength and B the telescope separation), i.e. better than one milliarcsecond for a 100m-baseline in the visible. These accuracies are about 100 times smaller than the ones required for present space telescopes.*

We propose to use planar optics also known as integrated optics on glass substrate to solve most of those new adjustment and stability constraints. For many years embedding of optical waveguides into glass plates has been achieved for telecom applications thanks to chemical ion exchange. By using masking techniques (comparable to the microelectronics ones), one is then able to build complex beam combining instruments on small surfaces well suited for multiple beam combination in astronomical space interferometry.

We discuss the interest of planar optics for beam combining in astronomical interferometric space instruments. We present several instrumental concepts for small and low cost instruments able to combine several beams from different telescopes. Furthermore, in the case of beam combination of three or more telescopes arrays, when compared to bulk optics or fiber optics, planar optics solves a great part of alignment and stability problems and increases in a significant way scientific achievements which are critical aspects for space instrument design.

1 - INTRODUCTION

From the beginning of the 80's it has been proposed to used fiber optics to assure the optical coherent links between the telescopes of an interferometric array [Froe 81]. Several developments have been done to enlight the advantages of optical fibers for this purpose [Reyn 96], [Shak 90], [Fore 94]. Beyond these studies, fiber optics appears to provide a performant solution for two distinct functions of an interferometric set-up (figure 1):

- beam transportation between the telescopes and a combining laboratory
- beam combination in a dedicated instrument

The current expertise acquired from instrument operations have shown the advantages and limitations of the fibers use in an interferometric set-up. From this analysis we have proposed to use guided optics on planar substrates instead of optical fibers for the combining system [Kern 96]. This paper mainly discusses this aspect. First laboratory experiments confirm the interest of this approach.

Section 2 gives the required basic functions of an interferometric combiner and shows how integrated optics can significantly simplify the design.

Section 3 briefly reviews some of the existing technologies for integrated optics components fabrication. It also presents available on-the-shelves integrated functions. Besides an analysis is also proposed in this conference to design the required combining components within the context of our specific applications [Nabi 97].

Section 4 gives a summary of the preliminary results obtained with a laboratory testbed. A detailed description and analysis of these results is presented during this conference [Berg 97].

Finally the concept of IONIC (Integrated Optics Near infrared Interferometric Combiner) is reported and the interest of Integrated Optics for ground and space-based interferometers is discussed (Section 5).

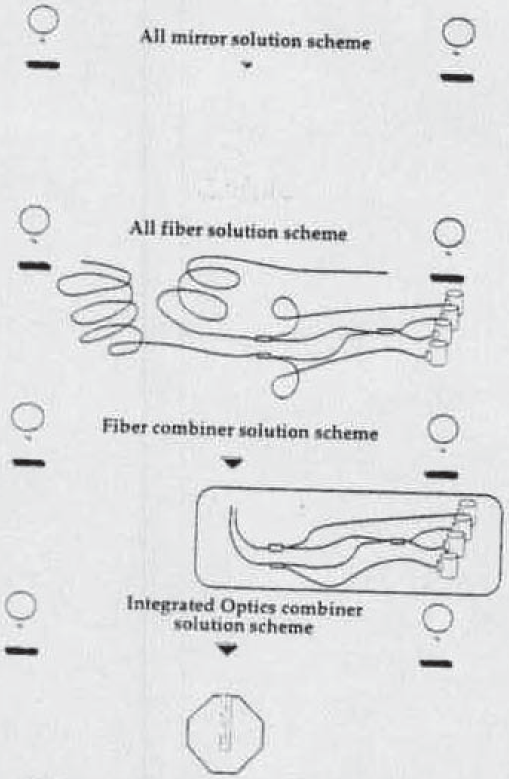

Fig. 1: Various solutions for beam transportation and combination in an coherent telescope array.

2 - INSTRUMENTAL REQUIREMENTS FOR AN INTERFEROMETRIC COMBINER AND INTEGRATED OPTICS CAPABILITIES

2.1 - System description

Several analysis of interferometric instruments for ground and space based telescope networks have described the required functions for the whole instrument. The recent AMBER analysis for the near-infrared imaging and spectroscopicVLTI focal instrument [Malb 97] has given the main inputs for our discussion. Figure 2 displays the functional diagram of an interferometer. The beams are collected and then propagated in the instrument through the different functional modules.

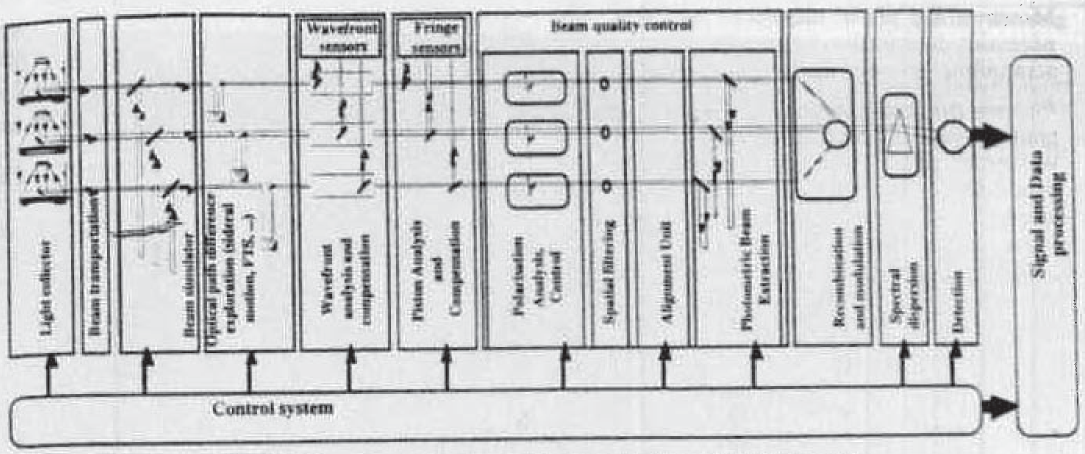

Fig. 2: Functional diagram of an interferometric instrument.

Beam collection and transportation: The module concerns the telescopes network itself and the associated optical links down to a combining station where the interferometric instruments are installed. This function is not discussed in this paper.

Beam simulation: This module provides to the whole instrument a beam suited for instrument calibration and observation simulation.

Wavefront analysis and correction: In many cases an adaptive optics system is required both in ground and space based applications. It enables :

- to correct residual or rough deformations of the incoming wavefront due to disturbances introduced by the instrumental set-up (propagation medium, optics and structures of collecting system and beam tranportation lines).
- to avoid light losses from the first telescope mode (i.e. the diffraction Airy pattern).
- to put the maximum of energy in the fundamental mode of the system leading to the optimization of the flux in the interferometric signal and to a fringe contrast enhancement [Rodd 84].

For single mode interferometric instrumental set-up an adaptive compensation optimizes the coupling efficiency between the telescopes and single mode waveguides [Fore 97].

Such adaptive optics systems improve the efficiency of an interferometric instrument.

Micro-optics technology may be required to solve this wavefront correction, especially when its requirements become harder to implement (number of actuators, overall available space for this module). Such micro-adaptive optics system is the only way to reach very high wavefront flatness in the context of space constraints. Propositions to solve this mode is not in the scope of this paper.

Optical Path difference exploration: this module is an optical delay line dedicated to compensation of optical delays between the different telescopes beams (sideral movement, FTS capabilities).

Optical path difference measurement and compensation: this function measures the interferometric fringes position. If the instrumental design requires a fringe position stabilization, this module can feed a servo loop system returning a suitable signal to an optical delay line. The design of this device is closely related to the design of the recombining instrument.

Spatial filtering: residual disturbance effects are perfectly removed by spatial filtering usually done by an appropriate pin-hole. The light of an image central core is completely phased and gives a fully efficient contribution to the interferences. Any disturbance produce light scattering around the theoretical diffraction pattern and cannot be properly introduced in the single mode guiding structure. The wavefront deformation results only in light level decrease without phase deformation. The efficiency is roughly equal to the Strehl ratio of the image in the so-defined filtering plane.

Polarization control: the two polarizations of the light contribute separately to the interferometric fringe construction. The *s* polar can rotate with respect to the *p* polar in a different way for each beam.

Moreover the phase difference between s and p status may be substantial. For this reason it is necessary to control the light polarization status through the whole instrument to avoid any signal scrambling between the two polarizations status.

Photometric calibration: Accuracy on fringe contrast is highly improved when one performs photometric calibrations of each telescope incoming beam [Fore 97]. We have seen above that wavefront phase perturbations induce light reduction after a spatial filtering module. An accurate measurement of these light level fluctuations significantly improves the interferometric signal error estimation. This function requires extracting a part of the signal between the spatial filtering and the beam combination.

Beam combination: it can be done either in a multi-axial mode or in a co-axial mode (cf figure 3).

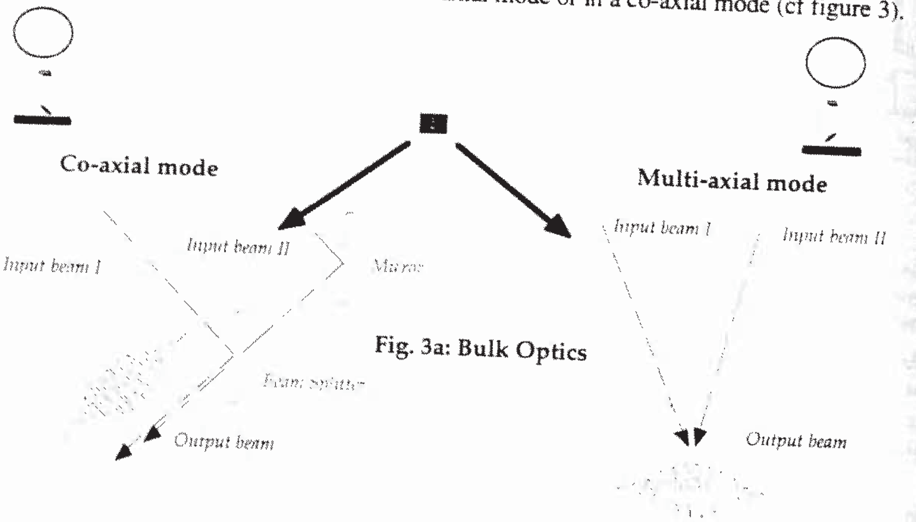

Fig. 3a: Bulk Optics

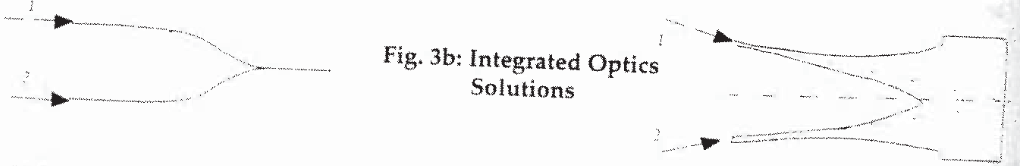

Fig. 3b: Integrated Optics Solutions

Fig 3: Beam combination modes using bulk optics (figure 3a) or integrated optics (figure 3b).

Beam alignment capabilities: this point concerns all the necessary optomechanical structures with tuning capabilities for beam alignments able to remain stable all over the fringe detection.

Spectral dispersion: depending on the scientific purpose of the instrument, having a spectral resolution of the detected interferometric fringes may be required. Traditional bulk optics design of spectrograph in multi-axial modes implies cylindrical optics components for proper slit illumination.

Detection: the requirements depend on the recombining mode and the dispersing arrangement for spectroscopic modes. For co-axial modes, a single detector per channel output is sufficient. InSb highly sensitive single detectors have been used in the past. For multi-axial modes, an array detector is required to sample the fringes. The number of needed pixels grows up significantly with the increase of the dispersing requirements. Rockwell HgCdTe detector arrays (Nicmos, Picnic, Hawaï) or SBRC InSb detectors (Aladin) seem to be the best suited choice for near infrared detection sensitivity requirements [Malb 96].

2.2 - Integrated Optics capabilities for each basic functions

Integrated optics components are a good solution for many of the above functions.

Optical Path length difference compensation: For small excursions, up to 100µm, it is possible to modulate the optical path with on-the-chip electro-optics, thermo-optics or magneto-optics actuators.

Spatial filtering: A single mode waveguide, as a filtering hole, securely insures the spatial filtering function.

Polarization control: Almost all integrated optics components (IOC) provide intrinsic polarization maintained waveguide. Further more active IOC can also provide active polarization control.

Photometric calibration: a simple so-called Y-junction (1-to-2 beam divider) allows to extract the needed part of the light for the calibration.

Beam combination: Both co- and multi-axial combining modes can be implemented on a single integrated optics chip for any telescopes array arrangement (figure 3b). These two kinds of components are commonly used for other laboratory applications like chemistry or telecom, including hydrology and metrology.

Beam alignment capabilities: this function is not any more required as soon as an instrument is integrated on a stiff substrate.

Spectral dispersion: several designs associated with IOC have been proposed [Kern 96]. The IOC output is equivalent to the input slit of a spectrograph and is able to directly feed the spectrograph grating avoiding cylindrical optics components.

Detection: one can illuminate an array detector directly with the IOC output or with the output of a set of IOC dedicated to several wavelength bands detection or spectrograph arrangements [Kern 96]. It is possible to provide a complete instrument on the same detector including fringe sensor capability. Another solution consists in matching single-detectors with each IOC output leading to a completely integrated design on chip detector concept. In this scheme, when the STJ (Supraconducting Tunnel Junction) detector technology will be available [Paec 97], [Feau 96] it will be possible to build a powerful instrument with photon counting capacity on a large spectral range with an excellent quantum efficiency. Furthermore the intrinsic low spectral resolution capability (R~50 at 1µm) of the STJ technology can be directly applicable for dispersing fringes. This resolution ability provides an interesting tool for on-line instrument chromatic effects calibration, especially when fibers or component chromatic effects are important. A spectrograph arrangement in the interferometric multi-axial mode can also give a powerful and robust fringe sensor taking into account the fringes positions according to the spectral defined channels.

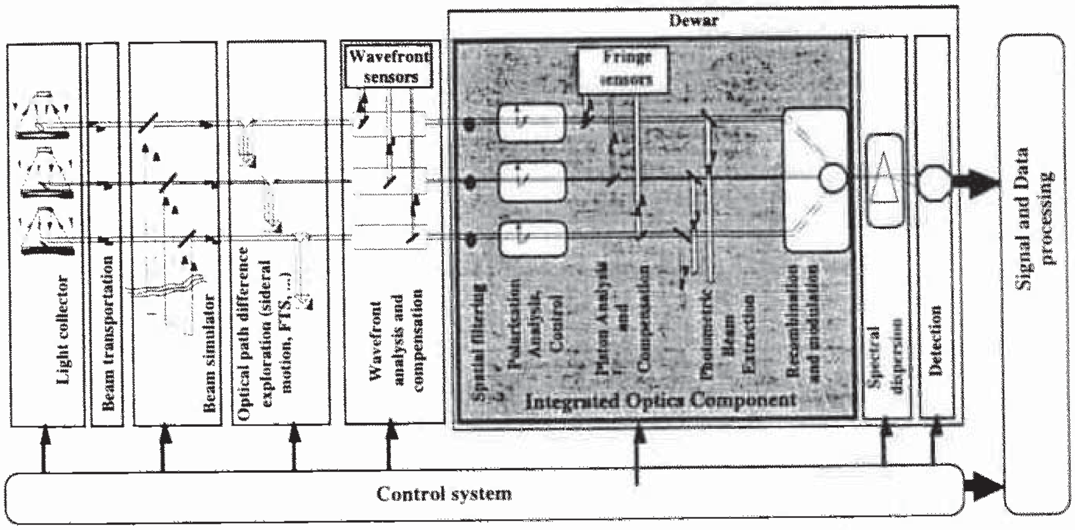

Fig. 4: Integrated Optics solutions for interferometric instrument functions. The Dewar box marks the possible contents of a cryogenic instrument. The Integrated Optics Components box marks the possible single chip integrated instrument.

2.3 - Discussion of integrated Integrated Optics solution

Up to now we have commented the capabilities of integrated optics only for single function design. However the main advantage of this technology is its ability to integrate a large part of the described functions on single chips for any number of telescopes (figure 4).

We can summarise as below the advantages and drawbacks of a IOC system:

Pros

- very compact solution (less than 1cm^2 for a complete instrument)
- completely stable (while embedded in a substrate)
- low sensitivity to external constraints (temperature, pressure)
- no need of opto-mechanical mounts, except for light coupling with the waveguides, and no other alignments requirements
- very low cost components and instrumentation set-up
- intrinsic polarization capabilities
- only one single component for any number of telescopes and for any instrumental concept complexity
- facility to implement the whole instrument in a dewar for cooled applications. No relay optics is needed, the guide can be very close to the detector and the dewar window size significantly reduced
- concerning the instrument construction all efforts are shifted on the design phase.

Cons

- chromaticity (a separate device is required for each wavelength band)
- R&D still in progress
- completely sealed structure (no 'real time' instrument modification capabilities)
- not convenient for long path components, such as delay lines waveguides longer than 10 cm may lead to unacceptable losses (typically around 0,1dB/cm, down to 0,02dB/cm for the best materials).

3 - CURRENT TECHNOLOGIES

3.1 - Processes

Through the relatively high number of technologies for IOC fabrication, it is possible to distinguish diffused technologies and etched technologies. In the first class guiding structures are obtained by modification of the chemical structure of the propagating medium. Such a technic developped at LEMO (Laboratoire d'Electromagnetisme Micro-ondes et Optique) consists in ion exchanges inside a glass substrate (figure 5) [Scha 96].

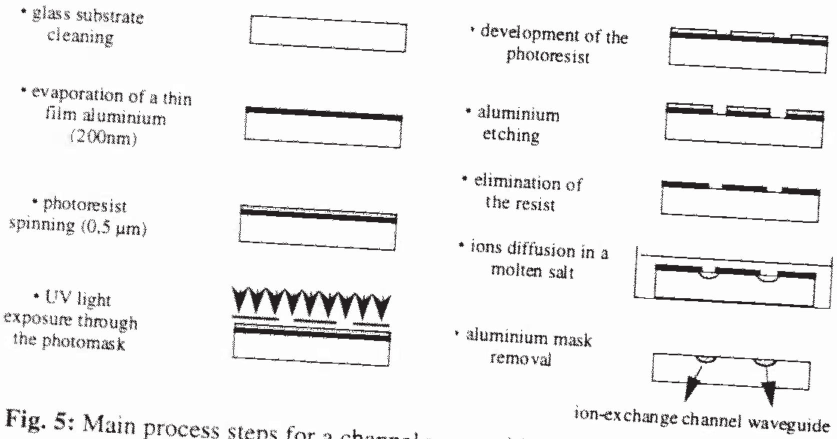

Fig. 5: Main process steps for a channel waveguide in a glass wafer [Scha 96].

In the second class, a micro-structure is made by etching processes. LETI-CENG [Mott 96] has developped Integrated Optics on Silicon (IOS) processes (figure 6) where it is possible to integrate on the same components optical and electronic functions. For passive IR functions, III-V or II-VI or IV-VI materials can be used for etched multilayer structures with the possible implementation of the detectors and optical sources. A planar guiding multilayer structure is obtained by CVD or sol-gel processes. The multilayer is lateraly etched to ensure confinement of the light.

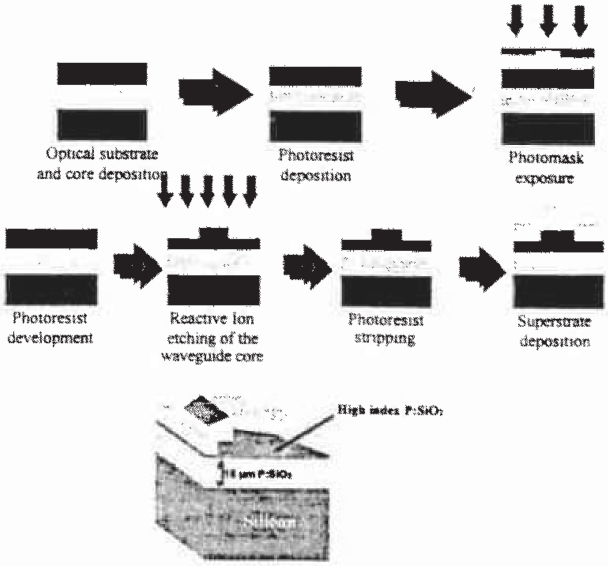

Fig. 6: Technological process flow chart for OIS_2 channel waveguide achievement and perspective view of a waveguide [Mott 96].

3.2 - Functions

Both technologies, available in Grenoble either in research center (LEMO, LETI) and through industrial structures (CSO, GeeO), give a lot of standard on-the-shelves functions for wavelengths between 0.5 μm and 1.8 μm (close to standard telecom bands). Figure 7 illustrates some of the classical available functions [Scha 96].

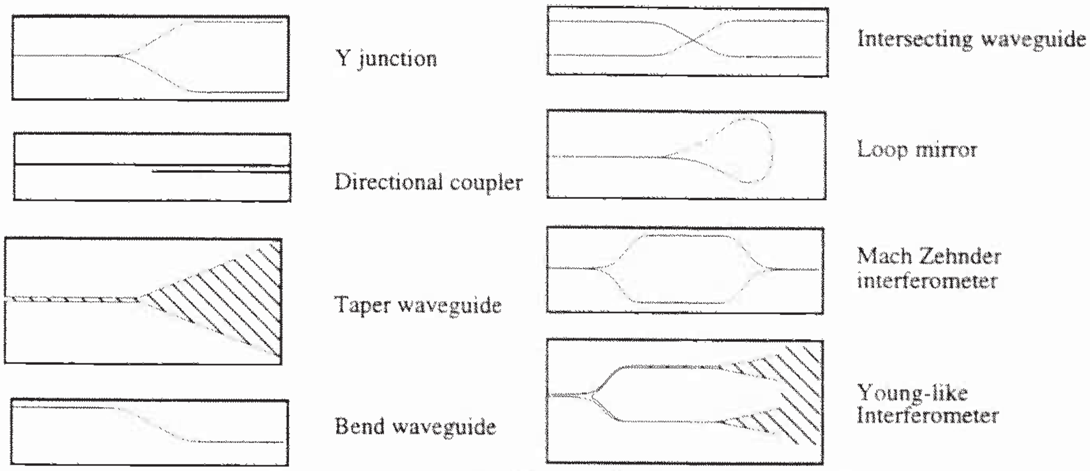

Fig. 7: typical basic function fabricated in Integrated technology.

Moreover, besides these basic functions, some parts of more complex instruments, originally designed for specific applications are able to provide components for stellar interferometers. Some LEMO existing masks gave us the possibility to build both co-axial and multi-axial demonstrators [Berg 97].

3.3 - R&T in progress

Our current investigations are developed toward two directions. The first one concerns wavelength extension of the available technologies, the second one is related to the optimization of a suitable design dedicated to our specific astronomical applications [Nabi 97].

In the first case we are testing the possibility to obtain components for wavelengths up to 2.7 µm by ions exchange technics. The limitation is given by the losses of the usable glasses. For longer wavelengths, especially in the context of the DARWIN project [Lége 97] (i.e. at 10.6 µm), preliminary investigations look into the possibility to use LETI technology with appropriate IR materials or structures.

A significant advantage of integrated technology is the relative independence between the function construction and the material choice. Mostly all of the functions are available for any material as soon as it is possible to create single mode guiding structure in these materials.

4. EXPERIMENTAL LABORATORY TESTS (see [Berg 97] in this conference for a detailed description).

First lab tests have been performed to analyse IOC in term of polarimetric, photometric, interferometric and dispersion properties. This test bench will allow to prepare an instrument dedicated to astronomical measurements on the sky in the near infrared band (1-2.5 µm).

The tested component (figure 8) is a two-telescope combiner with two photometric and one interferometric outputs. The tested components carried out with the LEMO facilities used potassium doped structures.

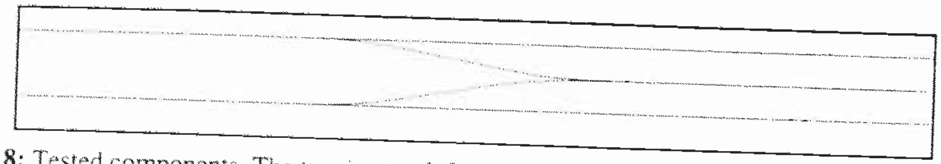

Fig. 8: Tested components. The two inputs (left side) are fed by the telescopes. The central output (right side) gives the interferometric signal, while the two lateral ones give the photometric signals.

Our preliminary measurements showed that IOC are well suited to obtain interference fringes with high contrast (more than 70% with a 1,55µm He-Ne laser). With no special care on polarisation control, contrast variations over 7 days are smaller than 8%. Photon losses reach 70% of the total incoming flux but have been clearly identified and seem to be easily avoidable. "Near field" analysis show natural birefringence of potassium waveguides, which means that polarisation maintaining is a natural by-product of this technic.

5. CONCEPT OF IONIC AND FUTURE GROUND AND SPACE APPLICATIONS

The construction of a first stellar interferometer with integrated optics technology is in progress at LAOG. For the so-called IONIC (Integrated Optics Near infrared Interferometric Camera), various optical configurations are possible (figure 9). To discuss the performances of each of them, we have considered several requirements (Table 1).

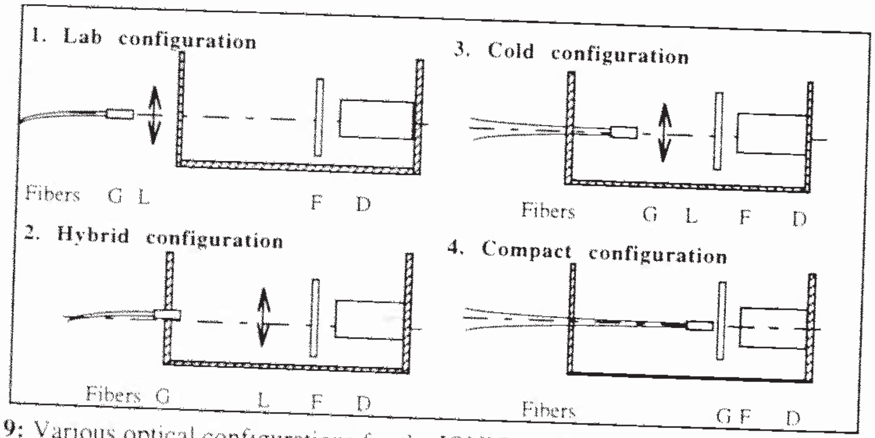

Fig. 9: Various optical configurations for the IONIC Project. G denotes the guide, L the relay optics, F the spectral filter and D the detector.

Placing optical components in the dewar reduces the thermal noise and improves the mechanical stability of the device. Since the components accessibility is not a decisive requirement, Configs 3 and 4 are much better for scientific applications. For these solutions, research on cold fiber/guide coupling is necessary. Some tests have shown that there are glues compatible with low temperature operation (77 K) and keeping their transmission properties for $\lambda \leq 2$ µm [Bert 96]. For larger wavelengths (up to 10.6 µm), studies need to be carried out. Nevertheless, Config. 3 can be foreseen without cooling the guide and then provides an efficient trade-off between reducing thermal noise and providing a mechanically stable device. That is why the latter solution has been chosen for the IONIC project.

Finally, Config. 4 is the most interesting long term solution. There is no optics, the guide is cooled, the dewar is blind (input by fibers) and besides one can contemplate to deposite a thin-film spectral filter or photo-sensitive cells at the guide output. Thus the whole interferometric instrument lies inside a single camera dewar, which is particularly adapted to spatial applications.

Config.	Reduced thermal noise	Accessible optics	Optical surfaces	Hard points
1	No	guide and lens	4 + Filter	None
2	No	guide	2 + Filter	Vibrations of the guide w.r.t. the detector
3	Yes	None	2 + Filter	If cold coupling is needed
4	Yes	None	Filter	- Cold coupling - Critical proximity of the detector

Table 1: Main requirements for the possible optical configurations of the IONIC project (Fig. 9).

6. CONCLUSION

We have shown in this paper that Integrated Optics Technology used up to now for telecom and laboratory sensor applications offers an attractive solution for the design and the fabrication of a stellar interferometer. This allows to shift the instrument complexity to its design phase.

With such a technology it is possible to provide very compact, stable and robust combining instrument whose price can be substantially low. Moreover with such a compactness, the whole interferometric instrument can lie inside a single camera dewar, which is very attractive for future spatial missions.

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