Hybrid sol-gel planar optics for astronomy

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Abstract: Hybrid sol-gel planar optics devices for astronomy are produced for the first time. This material system can operate from the visible (0.5 μm) up to the edge of astronomical J-band (1.4 μm). The design, fabrication and characterization results of a coaxial three beam combiner are given as an example. Fringe contrasts above 94% are obtained with a source with spectral bandwidth of 50 nm. These results demonstrate that hybrid sol-gel technology can produce devices with high quality, opening the possibility of rapid prototyping of new designs and concepts for astronomical applications.

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1. Introduction

Guided optics is a key domain in modern astronomical instrumentation. Multi-mode fibers are common place in single object, multi-object and integral field spectrographs. Mono-mode fibers are used as spatial filters in the focal instrumentation of optical interferometers (e.g. [1]), and as couplers in interferometers [2]. Photonic crystal fibers can be used to transport the laser light to the launch telescope of laser guide stars [3], or to build interferometers [4]. Aperiodic Bragg gratings on fibers were proposed for atmospheric OH emission suppression [5].

In contrast to fiber research, the application of integrated optics (IO) components to astronomy is very recent. A seminal paper described the potential of IO in the context of optical interferometry, namely for fringe tracking, photometric calibration, beam combination, spectral dispersion and detection [6]. The first prototypes of beam combiners soon followed. Two telescope co-axial beam combiners (Y-junction design) produced using silver-ion exchange on glass substrate were qualified in the laboratory, achieving a contrast of 93% with a He-Ne laser at 1.54 μm [7, 8]. Then, the first astronomical measurements in the H-band (1.43-1.77 μm) with two telescopes beam combiners on the IOTA interferometer were obtained [9]. No difference in the astronomical visibility measurements was detected between the beam combiners fabricated with silver-ion exchange (Y-junction design) and silica etching (asymmetric directional coupler design). As the ground based interferometers sensitivity strongly increases with...
wavelength, the next step was to build combiners for K-band (2.0-2.4 μm). Initially, the asymmetric directional couplers developed for the H-band were tested on sky [10], then a dedicated beam combiner for the K-band was commissioned at the Very Large Telescope Interferometer, with a total instrument broad-band contrast of 89% [11]. Beam combiner design in the near infrared is an active field with the emphasis on large number of telescope combination, including alternative designs such as multimode interference [12], ABCD [13] and SWIFTS-Gabor [14]. Further to beam combination, the compactness of integrated optics devices was used to combine in a single chip both a three-telescope co-axial beam combiner as well as metrology interferometers and beam dividers [15].

Recent developments in integrated optics devices for astronomy in the near-infrared are upward frequency conversion and spectroscopy. The use of Ti-diffused periodically poled lithium-niobate waveguides to upward frequency conversion from 1.5 μm to 0.63 μm was demonstrated [16]. The main advantage of upward frequency conversion is the possibility of using the superior properties of optical detectors, especially their low-read-out noise and high quantum efficiency, when compared to near-infrared arrays. The SWIFTS-Lipmann concept opens the possibility of optical spectroscopy with an integrated optics chip [17].

The recent boom of ideas and concepts in integrated optics for astronomy described in the previous paragraphs is a strong driver for rapid and cheap prototyping of integrated optics components. A UV-written silica-on-silicon two telescopes beam combiner for the H-band was reported [18]. In the present paper we report the first qualification for astronomy of a polymeric device, namely a hybrid sol-gel three telescopes beam combiner for the J-band (1.1-1.4 μm). The fabrication and design of the device are described in Section 2. The interferometric validation is presented in Section 3 where we report contrasts above 94%. We conclude in Section 4 and discuss the new possibilities opened by rapid prototyping of new ideas and concepts with UV-written hybrid sol-gel waveguides.

2. Methods

2.1. Hybrid sol-gel technology

Hybrid sol-gel uses a low temperature process which results in thick optical layers in a single deposition. This technique allows the fabrication of channel waveguides and devices, using MAPTMS-ZrO2 and UV laser patterning, without recourse to photo-initiator, as demonstrated in our group [19]. The steps involved in the waveguide fabrication are as follows: after substrate cleaning, a uniform layer of sol-gel (n_{core} = 1.5096) is deposited by spin-coating; after drying, the layer is exposed through a photomask and by chemical development, the unexposed area is removed. A cladding consisting of sol-gel (n_{clad} = 1.4998) matching the substrate refractive index is then deposited in the last step of the fabrication process. The refractive index profile of the channeled waveguides is nearly square and uniform (step-index waveguide). The propagation loss measured on single mode sol-gel channel waveguides is typically 0.4 dB/cm at 1.300 μm [19], which is acceptable from the frame of rapid prototyping. The waveguides have high transmission from 0.5 μm to the edge of the astronomical J-band (1.4 μm), except for an absorption band from C-H overtone at 1.15 μm [19]. The photomask was produced in a fused silica substrate using standard photolithographic methods and wet-etching.

2.2. Design considerations

The design of the all-in-one coaxial three beam combiner for the astronomical J-band was done using BPM-CAD commercial software packages (Optiwave and Rsoft). The separation between each of the three telescope inputs was set to 0.25 mm. Channel waveguides were designed with a square core (typically 4 × 4 μm²) to guide a single mode. Elements such as S-bends, X-junctions, Y-junctions and waveguide tapers were individually studied and optimized.
In the design of the beam combiner it was ensured that all the interfering optical paths have the same length in order to achieve correct broadband operation.

Figure 1 shows the design of the all-in-one coaxial three beam combiner following the layout given by [20]. $T_i$ are the telescope inputs, $I$ the interferometric output and $P_i$ the photometric outputs. In an all-in-one combiner all the baselines are multiplexed on the same output channel. This will result in a complex interferogram shape. The visibility and phase information of each combination pair can be extracted by Fourier analysis of the time dependent interferogram. To separate information in the Fourier space, the input beams should be time modulated using a non-redundant configuration.

3. Results

Interferometric validation of the coaxial three beam combiner was performed using the laboratory set-up described in Fig. 2. Feeding all the three inputs simultaneously was not possible due to set-up limitations, so each pair of inputs was tested individually. Hence the visibility information of each combination is accessible in direct space and there is no need for calculation in the Fourier space.

In the interferometric set-up several optical sources were used: a He-Ne laser ($\lambda_0 = 632$ nm) for alignments; a narrow spectral bandwidth (< 1 nm) laser diode at 1.3 $\mu$m; as a broadband source a Super Luminescent Diode (SLD) at 1.265 $\mu$m (FWHM 50 nm) was used.

The source collimated beam, after passing through a polarizer is split into two beams which are injected into polarization maintaining (PM) fibers. The same principal axes (slow or fast) of both PM fibers are aligned with the polarizer direction. In one arm of the interferometer, a translation stage is used to cancel the optical path difference and to perform path scanning. Light is injected into the beam combiner with V-grooved PM fibers. The outputs of the chip are coupled to single mode fibers, which feed single-pixel detectors.

The normalized interferogram intensity ($I_c$), for a given pair of telescope inputs $T_i$ and $T_j$ is given by

$$I_c = \frac{I_{ij} - \alpha P_i - \beta P_j}{2\sqrt{\alpha P_i \beta P_j}}$$

where $I_{ij}$ is the interference of the two inputs and $\alpha$, $\beta$ are the interferometric to photometric ratios inputs $i$ and $j$. This expression allows the correction of the bias induced by the photometric unbalance over the different interferometric arms. The normalized interferogram intensity calculation for each combination pairs consists on the following steps [8]:

$$I_c = \frac{I_{ij} - \alpha P_i - \beta P_j}{2\sqrt{\alpha P_i \beta P_j}}$$
Fig. 2. Laboratory interferometric set-up based on a Mach-Zehnder interferometer, used for characterization of the IO chips.

• Measure the raw outputs photometry $P_i$, photometry $P_j$ and interferometry $I_{ij}$, by feeding two different inputs $T_i$ and $T_j$. For input $T_2$ just one of the photometric channels is used.

• Compute the interferometric to photometric ratios $\alpha$ and $\beta$. This is achieved by feeding only one input ($T_i$) at a time and measuring the interferometric ($I_{i0}$) and the photometric ($P_{j0}$) intensities. $\alpha = I_{i0}/P_{j0}$ is computed when input $i$ is fed and $\beta = I_{j0}/P_{j0}$ when input $j$ is fed.

Once the normalized intensity ($I_c$) is obtained by the previous procedure, the fringe visibility is estimated through

$$V = \frac{\max(I_c) - \min(I_c)}{2}$$  \hspace{1cm} (2)

Figure 3 shows the normalized interferogram and the measured visibilities for each combination pair. Fringe visibilities of 94%, 96% and 97% have been measured, respectively for the combination pairs ($T_1$, $T_3$), ($T_2$, $T_3$) and ($T_1$, $T_2$). The different visibility values can possibly be related to different lengths of the input fibers, which can lead to residual different chromatic differential dispersions. The same effect also modifies the fringe envelope by creating a small side lobe.

The cross-talk in the X-junction between inputs $T_2$ and $T_3$ was determined by measuring $P_{2b}$ (see Fig. 2) while only $T_3$ was fed, obtaining a value less than -27 dB (0.2%).

4. Conclusions and perspectives

In this paper, the results of design, fabrication and characterization of a coaxial three beam combiner for astronomical interferometry, using hybrid sol-gel technology, were reported. High contrast ($\geq 94\%$) fringes have been obtained, demonstrating the high performance of the devices made by hybrid sol-gel for astronomy.
This technology combined with a UV direct writing unit allows the rapid prototyping of devices. We have recently developed a laser photopatterning system that already allows the writing of photomasks. We are currently calibrating the system for sol-gel direct writing, without making use of a photomask. Such a rapid prototyping system has interesting applications in integrated optics for astronomy, in particular at the research/design phase where the comparison and testing of different concepts is addressed. Multimode interference power splitters have been fabricated using hybrid sol-gel technology (e.g. [21]). The properties of astronomical beam combiners based on such components [22] could be compared with more classical designs such as the one presented in this paper. Another interesting application is to use the thermo-optic or electro-optic effects to control directly, on the device, the optical path modulation. Applications to metrology, in particular dichroic functions, could be tested, with recourse to Bragg gratings, for example.

Finally, 3D writing of waveguides in sol-gel has recently been demonstrated (e.g. [23]). This result opens the possibility of escaping the planar world of present astrophotonics into tridimensional concepts and ideas.

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