Hybrid sol-gel technology for fast prototyping in astronomical interferometry

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ABSTRACT

Hybrid sol-gel technology was used for fabrication of prototypes of coaxial two, three and four telescopes beam combiners for astronomical applications. These devices were designed for the astronomical J-band and have been characterized using an optical source with emission centered at 1265 nm and with a spectral FWHM of 50 nm. Interferometric characterization of the two, three and four beam combiners, showed average contrasts respectively higher than 98%, 96% and 95%. Interferometric spectral analysis of the beam combiners revealed that the chromatic differential dispersion is the main contributor to the observed contrast decay in the latter cases. The laser direct writing technique was used for fabrication of a coaxial two beam combiner on sol-gel material; it showed a contrast of 95%. The measured high contrast fringes confirm that the procedures used lead to performant IO beam combiners. These results demonstrate the capabilities of the hybrid sol-gel technology for fast prototyping of complex chip designs for astronomical applications.

Keywords: Hybrid Sol-Gel technology, fast prototyping, UV laser direct writing, integrated optics, beam combiner, astronomical interferometry

1. INTRODUCTION

Guided optics is undertaking more roles in modern astronomy leading to the emergence of the new field of astrophotonics [1]. It has contributed almost in all blocks of an astronomical interferometer. From the beam transportation part where large mode area photonic crystal fibers have been proposed for broadband light transportation [ref] till beam combination part where several experimental and on the sky demonstrator of the integrated optics beam combiners have been characterized [2,3,4,5]. A new four beam combiner, based on pairwise combination was characterized recently [6] to be used in PIONEER and in GRAVITY, both VLTI second generation instruments. For each pair of beams, four signal outputs in quadrature are produced (ABCD like), so the amplitude and the phase of the fringes are both retrieved using appropriate processing. The most efficient design, in terms of signal-to-noise ratio for combination of six or more telescope beams is a spatial all-in-one beam combiner [7]. For combination of six telescope beams a multiaxial combiner was suggested [8]. The Swift-Gabor principle was proposed for combination of eight and more telescope beams [9].

In this rapidly evolving field of research, a fast prototyping technique would help to test new ideas and optimize designs. After the design goals have been met, the results obtained employing such technology could be easily transferred to the production of a final device fabricated using highly performant silica technologies. A demonstration of one such fast prototyping technique was reported previously [10], with a UV laser direct-write fabrication of a silica-on-silicon two telescope beam combiner for the H-band. In this paper, the hybrid sol-gel technology was used for fabrication of prototypes of coaxial two, three and four telescopes beam combiners for astronomical applications. Also for the first time

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we have used laser direct writing technique on sol-gel material for fabrication of a coaxial two beam combiner. These devices were designed for the astronomical J-band and have been characterized using an optical source with emission centered at 1265 nm and with a spectral FWHM of 50 nm. Interferometric characterization of the two, three and four beam combiners, showed average contrasts respectively higher than 98%, 96% and 95% for them. Interferometric spectral analysis of the beam combiners revealed that the chromatic differential dispersion is the main contributor to the observed contrast decay in the latter cases. However the measured high contrast fringes confirm that the procedures used lead to performant IO beam combiners. These results demonstrate the capabilities of the hybrid sol-gel technology for fast prototyping of complex chip designs for astronomical applications.

In the following, first the fabrication technology is explained then there is a very brief discussion about the design of the beam combiners and in the end the results of the interferometric characterization is presented.

2. HYBRID SOL-GEL TECHNOLOGY

2.1 Sol-gel technology

The hybrid sol-gel technology used to produce IO devices is based on a low temperature process, which results in thick photo-patternable optical layers from a single deposition step, and avoids relatively complex and costly processing steps, such as ion etching. The organic-inorganic material is synthesized from the precursor MAPTMS by hydrolysis and polycondensation and then addition of zirconium (IV) propoxide mixed with methacrylic acid [11]. The refractive index control is required to create the waveguide index profile; this is achieved by two methods: firstly tuning the MAPTMS-ZrO2 molar ratio; secondly by selecting different curing methods including photocuring and thermalcuring. The solution is deposited on a glass substrate by spin-coating, and the films are pre-baked to evaporate the solvent. Channel waveguides and integrated optic devices have been fabricated in our group using MAPTMS-ZrO_2 and UV laser patterning by standard mask lithography or direct-write technique, without recourse to a photoinitiator, and employing a standard photolitographic technique. Single mode channel waveguides were fabricated with a square core cross section (typically 4×4 μm^2) and step index profile with refractive index contrast of 0.001. The propagation loss measured in the single mode channel waveguides is typically 0.4 dB/cm at 1.3 μm, which is fully acceptable from the point-of-view of rapid prototyping.

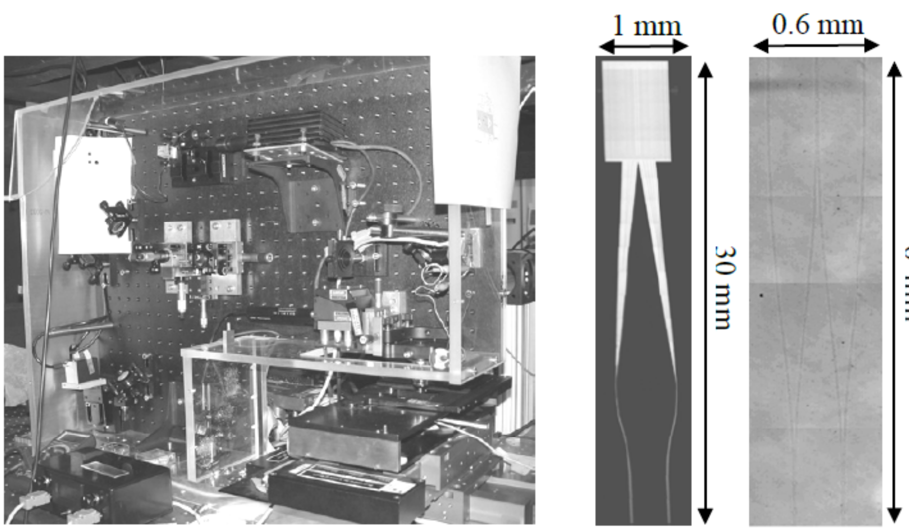

Figure 1. Left: photograph of the laser direct writing unit. Center - picture of a multiaxial two beam combiner written in mask photoblanks. Rigth: a coaxial two beam combiner written on hybrid sol-gel.

2.2 Laser direct writing unit

A laser photopatterning system has been developed (Fig. 1, left) which can produce masks on special plates with a focused laser beam at 532 nm (Fig. 1, middle), or write directly the integrated optic hybrid sol-gel device using a UV laser at 244 nm (Fig. 1, right). The machine is composed of four main blocks: the laser beam processing optics and power control section, the autofocus and power monitoring block, the precision sample positioning system and the real-time vision system. The laser processing optics is composed of a few mirrors, beam splitters and a high-quality microscope objective lens. The laser beam power control is achieved with an acousto-optic cell which is a fast and efficient shutter. The cell is positioned in such way that the first diffracted order is aligned with the optical axis, and therefore a truly on/off regime is attained. To ensure a constant incident power on the substrate, the signal generated by a photodetector is applied to a feedback system, which produces small corrections to the amplitude of the acoustic wave in the acusto-optic cell. The samples are positioned by two orthogonally mounted high-precision translation stages with minimum displacement of 2 nm. The maximum traveling distance in both directions is 100 mm. The laser writer is computer controlled, uses the output CAD files from an integrated optics simulation package, and the pattern is written by X-Y displacement of crossed precision translation stages under the dynamically focused laser beam.

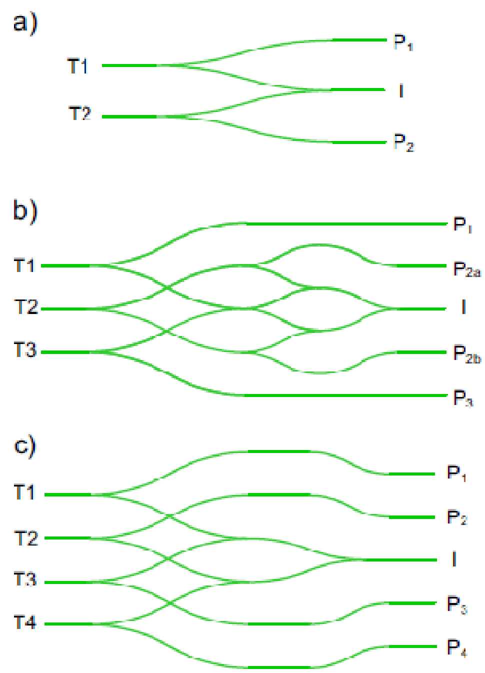

Figure 2. Schematic layouts of 2T, 3T and 4T combiners.

3. DESIGN OF INTEGRATED OPTIC BEAM COMBINERS

The design of the beam combiners was developed for operation in the astronomical J-band (1.1-1.4µm), using BPM-CAD commercial software packages (Optiwave and Rsoft). Specific aspects of design optimization dealt with Y-splitter/combiner and X-crossing sections, and overall optical path equalization in order to obtain high contrast broadband interferences. Figure 2 shows the schematic layout of the coaxial two, three and four telescope beam combiners (hereafter denoted as 2T combiner, 3T combiner and 4T combiner). The interference fringes resulting from the combination of all of the input beams are simultaneously present in the single interferometric output channel.

The design of a coaxial all-in-one beam combiner for an even number N of input beams follows almost directly from the design of the simple 2T combiner as follows from inspection of the examples of Fig. 2. However, in the case of an odd number N, the design is more complex, as it is of fundamental importance to ensure that all the interfering light paths have the same optical length in order to achieve correct broadband operation.

4. INTERFEROMETRIC CHARACTERIZATION

The experimental setup which was used for interferometric validation of the beam combiners is shown in Fig. 3. A superluminescent diode (SLD), with emission centered at 1265 nm and with a spectral FWHM of 50 nm, was used as a broadband source for a full characterization of the combiners. Due to some limitations in the setup, only two inputs could

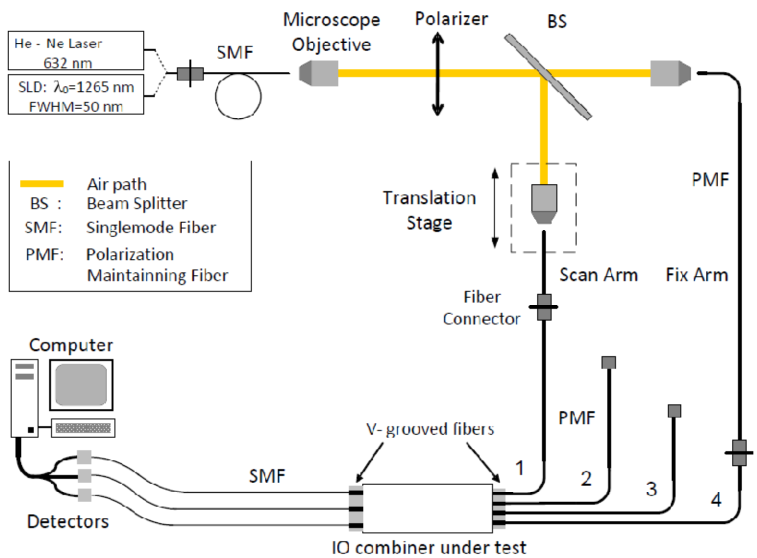

Figure 3. Laboratory interferometric set-up based on a Mach-Zehnder interferometer used for characterization of the IO chips.

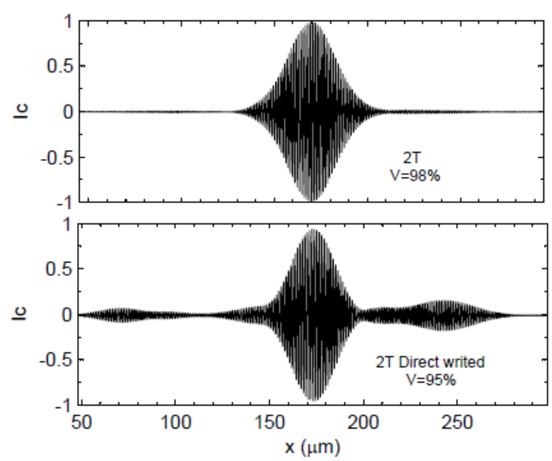

Figure 4. Photometry corrected interferograms of a 2T combiner made by standard photolithographic techniques (top), and a 2T combiner made by UV direct writing unit (bottom), the radiated light decrease the visibility.

be simultaneously launched into the chip. Hence, for the 3T combiner and 4T combiner devices, the visibilities were measured for all possible input pairs. The data reduction process is not discussed here and can be found in [12]. The interferogram which is corrected from the photometric unbalance is refered as corrected interferogram or normalized interferogram throughout this paper. All the devices reported here are produced in sol-gel, using standard photolithographic technique, the only exception is a 2T combiner fabricated by laser direct writing technique.

Figure 4 shows the interferogram of a 2T combiner with V=98%. In the lower part of the same figure, the corrected interferogram of a 2T coaxial combiner made by the laser direct writing on sol-gel material is displayed. This device was our first try in the direct writing process. In its present form it suffers from a low index contrast which decreases the light confinement, resulting in radiation of the light in the bends. The unwanted radiated light can reach the interferometric output and interfere there and consequently decrease the visibility value to 95% and also create spurious

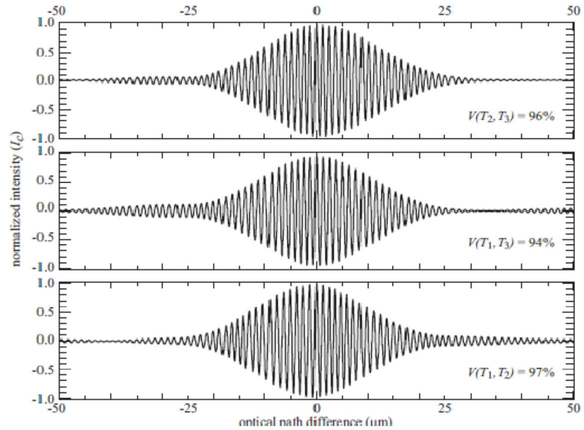

Figure 5. Photometry corrected interferograms of the 3T combiner with fringe visibilities of 96%, 94% and 97% respectively for the combination pairs (T2,T3), (T1,T3) and (T1,T2).

side lobes as shown in the lower interferogram of Fig. 4. Further study is ongoing to achieve a correct index contrast for sol-gel devices made by laser direct writing unit.
Figure 5 shows the corrected interferograms and the measured visibilities of all combination pairs of a 3T combiner. Fringe visibilities of 94%, 96% and 97% have been measured, respectively for the combination pairs (T1,T3), (T2,T3) and (T1,T2). A 4T combiner results in six combination pairs, Fig. 6 displays interferograms of the pairs with respectively the best and the worst visibility values. They respectively resulted from combination pairs, (T2, T4) with V =97.5 and (T1, T4) with V = 92.1. The full table of the pairs and their corresponding visibility values can be found in [13].
The comparison of the V values from 3T and 4T combiners with the value from the 2T combiner shows some degradation. In general terms, there are several mechanisms which can cause the observed visibility decay: spatial mode mismatch, polarization mismatch, radiated light inside the chip, or chromatic differential dispersion between the two interfering fields. As only single mode waveguides are used in this work, spatial superposition of the interfering lights is achieved perfectly, so this factor can be dropped. Spectral analyses were performed [13] to evaluate the contribution of the differential chromatic dispersion in this process, revealing that it was the main contributor.

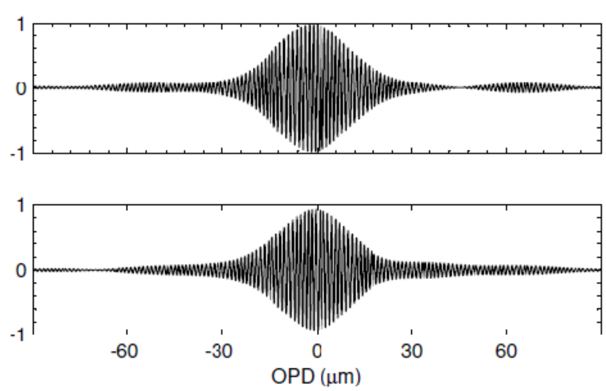

Figure 6. Photometry corrected interferograms of the 4T combiner with best and worst visibilities, for combination pairs (T2, T4) with V = 97.5, and (T1, T4) with V = 92.1.

5. CONCLUSION AND PERSPECTIVE

The hybrid sol-gel technology was used for the fabrication of prototypes of coaxial two, three and four telescopes beam combiners for astronomical applications. Also for the first time we have used laser direct writing technique on sol-gel material for fabrication of a coaxial two beam combiner. These devices were designed for the astronomical J-band and have been characterized using an optical source with emission centered at 1265 nm and with a spectral FWHM of 50 nm. Interferometric characterization of the two, three and four beam combiners, showed average contrasts respectively higher than 98%, 96% and 95% for them. Interferometric spectral analysis of the beam combiners revealed that the chromatic differential dispersion is the main contributor to the observed contrast decay in the latter cases. However the measured high contrast fringes confirm that the procedures used lead to performant IO beam combiners. These results demonstrate the capabilities of the hybrid sol-gel technology for fast prototyping of complex chip designs for astronomical applications.

The laser direct writing technique 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. This unit, combined with recently presented result of direct writing by visible light on appropriate material, which results in the formation of waveguides operating in mid-IR [14] can have interesting applications in astronomical context. Another interesting application is to use the termo-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.

REFERENCES

[1] Bland-Hawthorn, J., and Kern, P., "Astrophotonics: a new era for astronomical instruments," Opt. Express 17, 1880-1884 (2009).

[2] Berger, J.P., et al., "Integrated optics for astronomical interferometry - II. First laboratory white-light interferograms". Astronomy & Astrophysics Supplement Series, 139(1): p. 173-177. (1999)

[3] Haguenauer, P., et al., "Integrated optics for astronomical interferometry. III. Optical validation of a planar optics two-telescope beam combiner". Applied Optics, **39**(13): p. 2130-2139 (2000)

[4] LeBouquin, J.B., et al., "First observations with an H-band integrated optics beam combiner at the VLTI". Astronomy & Astrophysics, 424(2): p. 719-726. (2004)

[5] LeBouquin, J.B., et al., "Integrated optics for astronomical interferometry VI. Coupling the light of the VLTI in K band". Astronomy & Astrophysics, 450(3): p. 1259-1264. (2006)

[6] Benisty, M., Berger, J. P., et al. "An integrated optics beam combiner for the second generation VLTI instruments." Astronomy & Astrophysics 498(2): 601-613 (2009).

[7] LeBouquin, J. B., Berger, J. P., Labeye, P., Tatulli, E., Malbet, F., Perraut, K. A., and Kern, P., "Comparison of integrated optics concepts for a near infrared multi-telescope beam combiner," in New Frontiers in Stellar Interferometry, A. Traub, ed., Proc. SPIE 5491, 1362-1369 (2004).

[8] Jocou, L., Berger, J. P., et. al., "System overview of the VLTI Spectro-Imager," in Optical and Infrared Interferometry, M. Scholler,W. Danchi, and F. Delplancke, eds., Proc. SPIE 7013, 70132Y- 70132Y-12 (2008).

[9] Kern, P., Le Coarer, E., and Benech, P., "On-chip spectrodetection for fully integrated coherent beam combiners," Opt. Express 17, 1976-1987 (2009).

[10] Olivero, M., Svalgaard, M, Joucou, L., Berger, J.-P., "Direct UV-written integrated optical beam combiner for stellar interferometry", J.Ligh.Tech., vol.25, p.367, (2007)

[11] Moreira, P. J., Marques, P. V. S., Leite, A. P., "Hybrid sol-gel channel waveguide patterning using photoinitiator-free materials", Phot. Technol. Lett. 17, 399-401 (2005)

[12] Ghasempour, A., Leite, A. M. P., et. al., "Hybrid sol-gel planar optics for astronomy," Opt. Express 17, 1970-1975 (2009).

[13] Ghasempour, A., Leite, A. M. P., et. al., "Performance of astronomical beam combiner prototypes fabricated by hybrid sol-gel technology," Opt. Express 18, 9413-9422 (2010).

[14] Hô, N., Phillips, M. C., and et. al. "Single-mode low-loss chalcogenide glass waveguides for the mid-infrared," Optics Letters, 31:18601862, (2006).