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K-band integrated optics beam combiners for CHARA fabricated by ultrafast laser inscription

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ABSTRACT

We report the ultrafast laser inscription (ULI) and characterization of 3 dB directional achromatic couplers for K-band between 2 and 2.4 μm. The couplers were fabricated in commercial Infrasil glass using 1030 nm femtosecond laser pulses. Straight waveguides inscribed using optimal fabrication parameters exhibit an average propagation loss of ~1.21 dB over full range of K-band with a single-mode behavior for a length of 17 mm. Directional couplers with different interaction lengths and waveguide widths were fabricated and characterized. We demonstrate that 3 dB achromatic directional couplers for K-band can be fabricated using ULI. These results show that ULI can fabricate high-quality couplers for future applications in astronomical interferometry. Our eventual aim is to develop a two-telescope K-band integrated optical beam combiner to replace JouFLU at CHARA.

Keywords: Astrophotonics, beam combiner, integrated optics, ultrafast laser inscription, long-baseline interferometry, CHARA

1. INTRODUCTION

In recent years, the field of astrophotonics has emerged which aims to develop and exploit the use of photonic devices for astronomy. Astrophotonic devices have already provided recent powerful achievements, such as integrated echelle gratings [1], integrated fibre-fed spectrographs [2-3], and waveguide Bragg-gratings to filter out atmospheric OH-lines [4]. One of the most impressive successes in this scientific field, however, is the development of compact and integrated optic beam combiners, which are a unique resource to build long baseline multiple telescope arrays. Such integrated optic (IO) beam combiners, such as IONIC [5], GRAVITY [6] or PIONIER [7] placed now in the VLTI, have demonstrated and established substantial assets in stellar interferometry by increasing the baseline numbers and achieving the targeted resolution. Despite these demonstrations, existing IO beam combiners can also present key issues with the increase of multiple input baseline telescopes, or for the scalability for future high-volume production. Moreover, the fabrication of the used devices is suitable for the H-band (1.5-1.8 μm) but presents hurdles for other wavelength spans. Indeed, OH contamination in the glass increases unwanted losses in K-band (2.0-2.4 μm) and these IO beam combiners are not able to reach the mid-IR wavelength span (fingerprint region with all the fundamental absorption bands of chemical species from 3 to 12 μm).

To expand the wavelength working span of IO beam combiners to K- or L-bands, ultrafast laser inscription (ULI) with its capacity to inscribe a 3D low loss waveguide in various materials, is a great candidate. These fabrication techniques have recently demonstrated a 3D complex-shape reformatter in H, L, or M-band with experimental lab results as well as on-sky measurement campaigns [8-10].

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In this paper, we report the potential of ULI to develop an IO photonic beam combiner for K-band applications. With the optimum parameters, a straight waveguide presents an insertion loss average of 1.21 dB, fabricated in a 17 mm length of Infrasil bulk material. We use these waveguides as the building block for 3 dB evanescent field couplers, and find that a slight detuning of the core shape of one of the two coupler's arms can results in low loss 3 dB achromatic beam combiner over the entire K-band. A simulation study presents a good agreement with the experimental results when the simulation fits the bending study with an absolute core-cladding refractive step-index difference of $\sim 9\times10^{-3}$. This ULI investigation is part of an ongoing project to develop a fully integrated, fiber-fed two-telescope K-band IO beam combiner to replace JouFLU at CHARA [11-12].

2. FABRICATION AND CHARACTERIZATION

2.1 Optimum waveguide parameters

The waveguides have been fabricated using a PHAROS laser that delivers pulses of 1030 nm light with a duration of 185 fs at a repetition rate of 500 kHz. The polarization was adjusted to circular polarization. The laser was focused into the glass via an anti-reflection coated aspheric lens with a focal length of 6.24 mm and 0.4 NA (Thorlabs C110 TME-B). Infrasil glass with a high transmission over the K-band and a physical length of 17 mm is selected for inscribing the waveguides. An investigation of straight waveguides with different pulse energies and number of scans of the laser focus was performed to find the optimum parameters which can inscribe a symmetric refractive index profile that supports a single mode with low loss over the entire K-band. The waveguide guidance properties were studied using a supercontinuum source (NKT Extreme-K), the light from which was passed through a bandpass filter centered on 2250 ± 250 nm (Thorlabs FB2250-500). The light is coupled into a 2 m commercial SM1950 fiber from Nufern and will be used for the full fiber-fed integrated optic device.

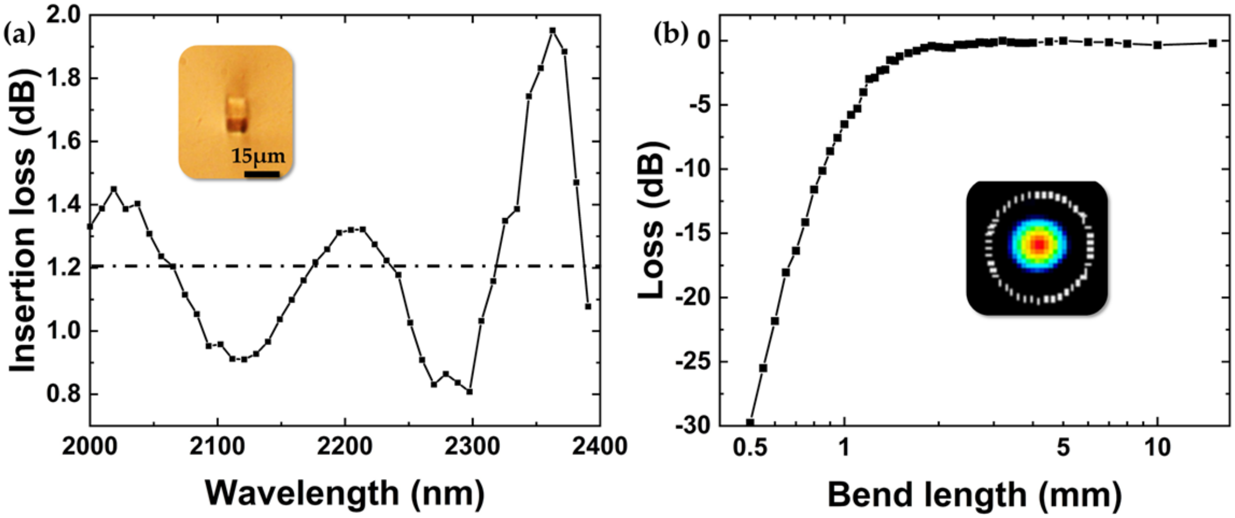

Figure 1. (a) Insertion loss (black squares) of a straight waveguide written with the best set of laser parameters. The dashed black line represents the average loss value at 1.21 dB over the whole K-band span. Inset: micrograph of the ULI waveguide. (b) Evolution of the losses in comparison of the straight waveguide as a function of the bend length with a waveguide offset of 100 μm. Inset: corresponding output near-field intensity distribution.

To properly characterize the insertion loss (IL), a first "reference" measurement was obtained using the 2 m fiber to transport the K-band characterization light into a fiber-coupled optical spectrum analyzer (Thorlabs OSA205). Then, the same fiber was cleaved close to its mid-point and butt-coupled to the waveguide under test. The difference between this second measurement and the reference measurement was defined as the insertion loss spectrum – the loss due to the insertion of the device into the transmission line. The optimum parameters were found to require a pulse energy of approximately 210 nJ corresponding to an average power of 105 mW at the laser focus. The number of scans was found to be 31 with a scan separation of 200 nm. The substrate translation speed was $4\ \mathrm{mm\cdot s^{-1}}$. Figure 1(a) displays the evolution of the insertion loss (black squares curve) as a function of wavelength. The dashed line represents the insertion loss average value of ~1.21 dB measured between 2 and 2.4 μm. The cross section of the waveguide presents the conventional quasi-rectangle shape of inscribed waveguides with a vertical Y-axis longer than the horizontal X-axis. Based on these optimum parameters, we study bend losses by inscribing S-bends with a constant deviation of 0.1 mm, while varying the bend length (along the waveguide axis). Figure 1(b) presents the experimental results representing the well-known logarithmic global shape for bend loss. A microscope image of the substrate end facet is displayed as well as the near field single-mode intensity pattern measured with a microbolometer beam profiler array (DataRay WinCamD).

2.2 Achromatic directional couplers

The full propagation length of the substrate chip is 17 mm enabling waveguides with a deviation of 58.5 µm over a bend length of 2 mm providing negligible additional losses to be written. The power coupling ratios of each coupler were evaluated by measuring output power of the two outputs and using the conventional method defined as $P_{ratio} = Arm_1 / (Arm_1 + Arm_2)$ when coupling light into the input Arm_1.

Directional couplers were fabricated to understand how the ratio of power in each arm varied across the wavelength span as a function of two main parameters of the couplers, the interaction lengths and core-to-core separation. It is important to consider the specified interaction length does not encompass the entire section of waveguide that interacts since the ends of the bends also contribute. It is not possible to present all the data acquired from the dozens of couplers we fabricated with interaction length from 0.1 to 1.6 mm and a core-to-core separations ranging from 9 to 15 µm, but Fig. 2 presents 2D maps of the power ratios measured on Arm_1 (remains in input waveguide) and Arm_2 (couples to other waveguide) for a coupler with a core-to-core separation of 10 µm. In the maps, the color pattern was chosen to readily identify two points: (i) a horizontal color line represents achromatic behavior; (ii) a perfect white horizontal line represents an achromatic 3 dB behavior. One can clearly see in Fig. 2, the impact of the interaction length on the coupling behavior - by increasing the interaction length, an oscillation pattern of the coupling behavior appears. A more achromatic behavior over the full working wavelength span is demonstrated for the shorter interaction length.

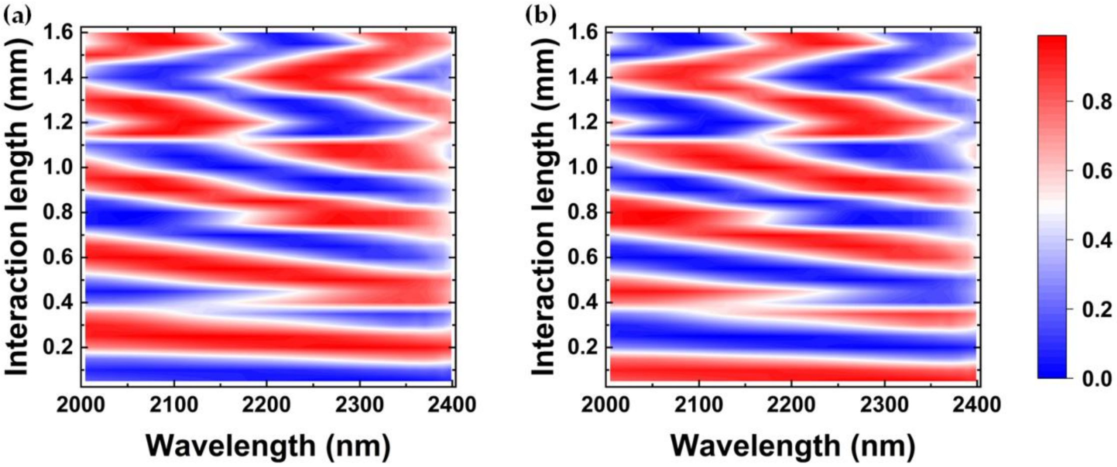

Figure 2. 2D representation maps describing the power ratio of Arm_1 (a) and Arm_2 (b) as a function of the interaction length and the propagated wavelength for a core-to-core separation of 10 µm.

Nevertheless, even if Fig. 2 seems to present good achromatic behavior over the whole span with a “white line” around 0.2 mm of interaction length, to obtain achromatic 3 dB directional couplers we have focused our investigation on the 10 µm separation over the shortest interaction lengths with a detuned core study. The detuning study consisted of slightly changing the optimum ULI parameters and fabricating a different waveguide shape for one of the two waveguides. The detuned waveguide presents a narrower size on the X-axis in order to correctly adjust the propagation constant of one of the modes and to obtain the wanted coupling behaviour with a 3 dB achromatic beam coupling. A large detuning parameter was used from 0 to 25% by 5% steps, meaning the X-axis of the detuned waveguide is shorter by the same percentage in comparison of the optimum X-axis size of straight waveguide. Figure 3(a-b) shows the same 2D maps power ratio representation for Arm_1 and Arm_2 with a core-to-core separation of 10 µm and a detuned core of 25%. The dashed grey squares highlight the relevant interaction length that ensures a 3 dB achromatic behaviour over the K-band. Figure 3(c) represents the evolution power ratio for the two arms of the couplers, Arm_1 in red points and Arm_2 in blue diamond, over the working wavelength span.

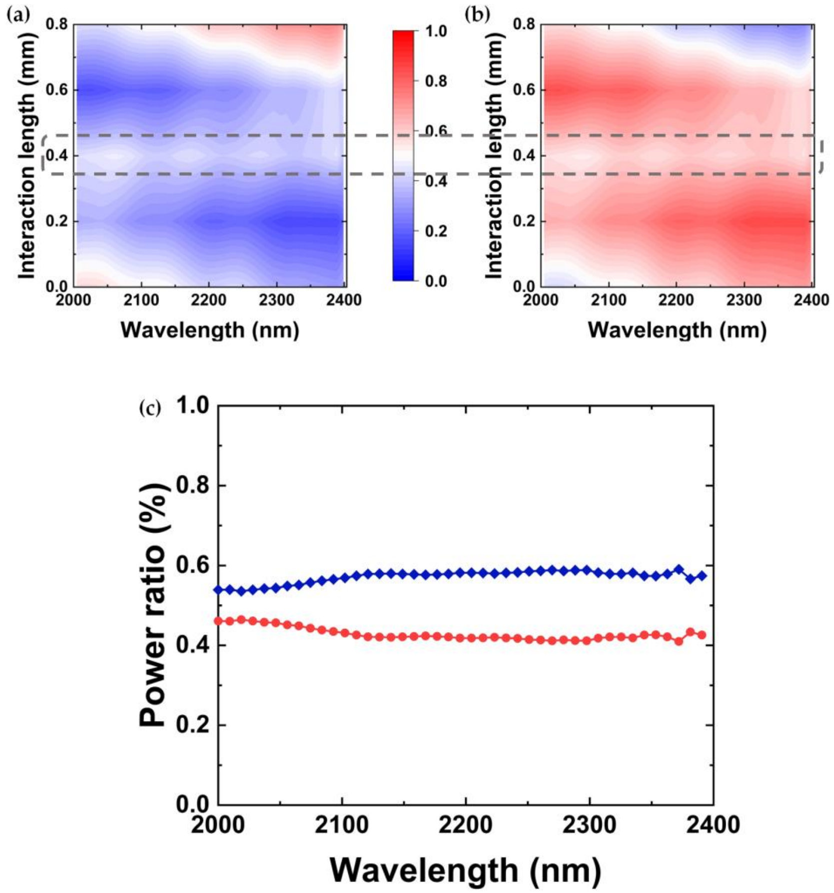

Figure 3. 2D map representation of the full investigation of the 2-arms power ratio versus the interaction length and the wavelength with a detuned core of 25% Arm_1 (a) and in Arm_2 (b). The dashed grey square highlights the interaction length with a white horizontal power ratio line for the two arms that represents a 3dB achromatic directional coupler. Power ratio evolution of the 2 output arms. (c) Arm_1 in red points and Arm_2 in blue diamonds for a detuned core of 25 % and interaction length 0.4 mm.

One interesting feature that we can observe in Fig. 3(a-b) is the fact the couplers lose the conventional oscillation behavior along the interaction length, observed in Fig. 2, between the two arms of the couplers as a result of the detuned core.

3. NUMERICAL INVESTIGATION

To corroborate the experimental results, we have developed a numerical model with CodeSeeder software. The simulated waveguide is a square of 7 µm, matching with the physical core size of the Nufern SM1950 fiber. The fabricated ULI waveguides are slightly rectangular in the Y-axis (7.35×6.65 µm), corresponding to an estimated value of 5% difference between the Y and the X-axis, based on microscope images. The first step was to calibrate our numerical model by finding the refractive index difference of the step-index waveguide. For that, we have used the experimental data from the bend study with a deviation of 100 µm. For all the simulations, the resolution of the numerical data is ~$\lambda/10$ with an axis propagation step of 20 µm. Figure 4 presents the loss evolution as a function of the bend length for the experimental data (black squares) and for the numerical model (orange line) with a refractive index difference of 9×10^{-3}.

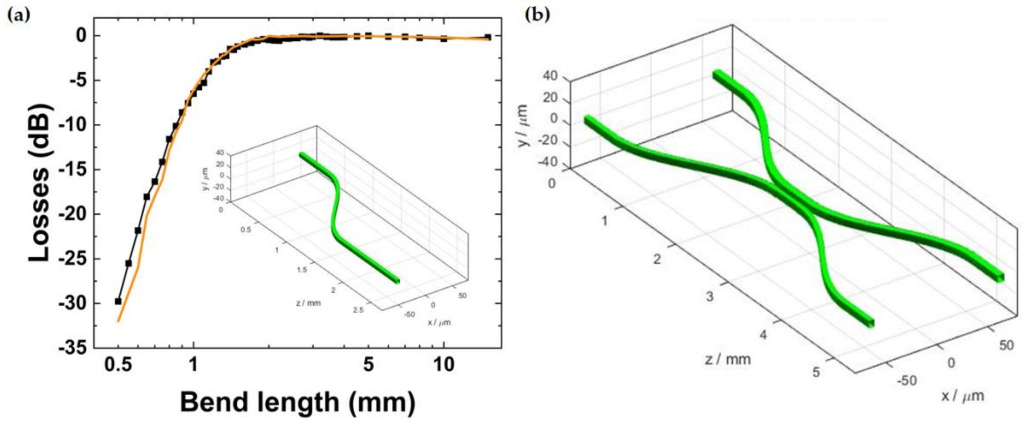

Figure 4. (a) Comparison of the losses versus the bend length between the experimental data (black curve) and the simulation obtained data (orange curve) for a refractive index difference of 9×10^{-3}. Inset: 3D representation of the numerical bending waveguide (b) Numerical 3D representation of the directional couplers with the right physical specifications.

Simulation and measured values are in good agreement for a refractive index difference of 9×10^{-3}, which makes a fair comparison with a typical step profile. After considering the calibration of our numerical model, the physical specifications of the fabricated achromatic couplers were implemented in the model: a bending length of 2 mm, a deviation of 58.5 µm, an interaction length of 400 µm and a detuned core size of 25 % in the x-axis. In this case, the shape of the detuned core is a rectangular 5×7.35 µm waveguide. Figure 5 presents the main numerical results for a detuning core of 25% represented by two 2D power intensity maps at 2 µm (Fig. 5(a)) and 2.4 µm (Fig. 5(b)), and the comparison with the experimental data over K-band in Fig. 5(c). The numerical data corroborates with a nice agreement the experimental data over the whole K-band by simply adding the real optomechanical waveguide properties.

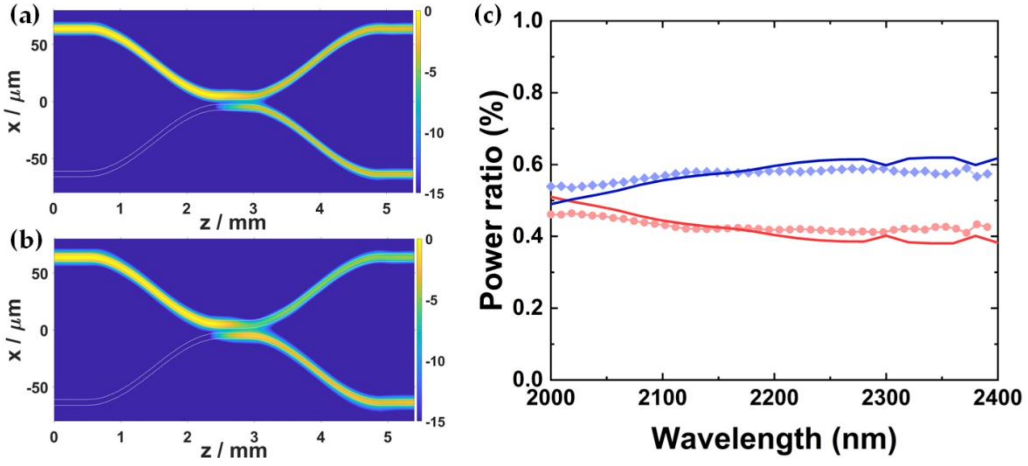

Figure 5. 2D simulated results of the propagated light in the directional couplers with a detuned core of 25 % and an interaction length of 0.4 mm at a wavelength of (a) 2 µm and (b) 2.4 µm. Full comparison of the evolution of the power ratio in Arm$_1$ (red) and Arm$_2$ (blue) as a function of the wavelength between the experimental data (transparent points) and the computed data (lines).

4. CONCLUSION

We report the ultrafast laser inscription and characterization of 3 dB directional achromatic couplers for K-band between 2 and 2.4 µm. The couplers were fabricated in a commercial Infrasil glass substrate using femtosecond laser pulses of 1030 nm light. Straight waveguides inscribed using optimal fabrication parameters were found to exhibit an average propagation loss of ~1.2 dB over the whole K-band with single-mode behavior. An intensive series of directional couplers was studied with different interaction lengths and with different narrower waveguides inscribed by slightly decreasing the scan separation. These demonstrate the capability to obtain a closed 3 dB achromatic directional coupler over the whole K-band spectrum span. These results clearly prove that ultrafast laser inscription can fabricate high-quality couplers for future applications in astronomical interferometry to develop a two-telescope K-band integrated optical beam combiner to replace JouFLU at CHARA.

5. ACKNOWLEDGEMENTS

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