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Multi-core fiber–fed integral field spectrograph (MCIFU) – III: An ultrafast laser inscribed photonic reformatter and mask

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ABSTRACT

We report on the conception and the fabrication of a 3D photonic reformatter of 73 waveguides and its associated opaque mask in a wide collaboration to develop a multi-core fiber-fed integral field spectrograph (MCIFU) centered on the J-band. The reformatter is a 3D structure that light from the input quasi-hexagonal multicore fiber is spread out by rearrangement to avoid individual core spectra overlapping when the light is dispersed. The reformatter is fabricated using ultrafast laser inscription (ULI) in a borosilicate glass of 20 mm length. Using a similar ULI process, a 73-hole mask was fabricated in silica glass that precisely matched the waveguides at the output of the reformatter. The output surface of the mask was coated with a 120 nm layer of chromium to block scattered light generated in the bulk material and enhance the signal-to-noise. All inscribed waveguides, characterized using a stable laser centered at 1310 nm from the multicore fiber to the output mask, present consistent single-mode output behavior with a maximum throughput exceeding 60%. Over the 73 cores, the average throughput was measured at 40%. First observations of the full MCIFU device during on-sky measurements have shown promising results to the potential of this novel fiber integral field unit.

Keywords: Ultrafast Laser Inscription, Multi-core fiber, Astrophotonics, Integral field spectroscopy, Exoplanets, Waveguides, Photonic reformatter, High contrast imaging.

1. INTRODUCTION

Since the discovery of the first exoplanet with 51 Pegasi b in 1995 [1], exoplanet hunting has become one of the most exciting research fields, with the aim of finding Earth-like planets in the habitable zone, utilizing mainly indirect observation techniques such as radial velocity or photometric transit. Despites these impressive results, detecting an exoplanet and characterizing its atmosphere is still highly challenging. Direct imaging instruments employing extreme adaptive optics and coronagraphs can spatially reach the necessary resolution power to resolve the planet orbiting around a star. In recent years, several instruments have been successfully used to characterize exoplanet atmospheres, such as the proto-planet PDS70 b in the visible spectrum detected by MUSE [2], or Beta Pictoris b detected in the infrared range by CRIRES [3].

The authors of this paper are part of wide collaboration that has developed a new multi-core fiber (MCF) fed integral field spectrograph (MCIFU) to overcome these challenges and may enable the detection of exoplanet atmospheric components [4-5]. The complete MCIFU consists of a 3D-printed microlens array on the end facet of Ge-doped single-mode step-index 73-core MCF, connected to the ULI reformatter and accompanying opaque mask. A custom triple stacked Volume Phase Holographic Grating (VPHG) disperses the light into three orders with high efficiency [6-7]. The whole device was then protected using a combination of off-the-shelf components and 3D printed parts. Finally, the

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microlenses were polymer 3D printed on top of an FC/PC connector. Figure 1 presents a schematic representation (Fig. 1(a)) and a photograph (Fig. 1(b)) of the complete MCIFU with the different components from the microlens array (Fig. 1(c)) to the reformatter and mask (Fig. 1(e-h)) passing by the MCF (Fig. 1(d)).

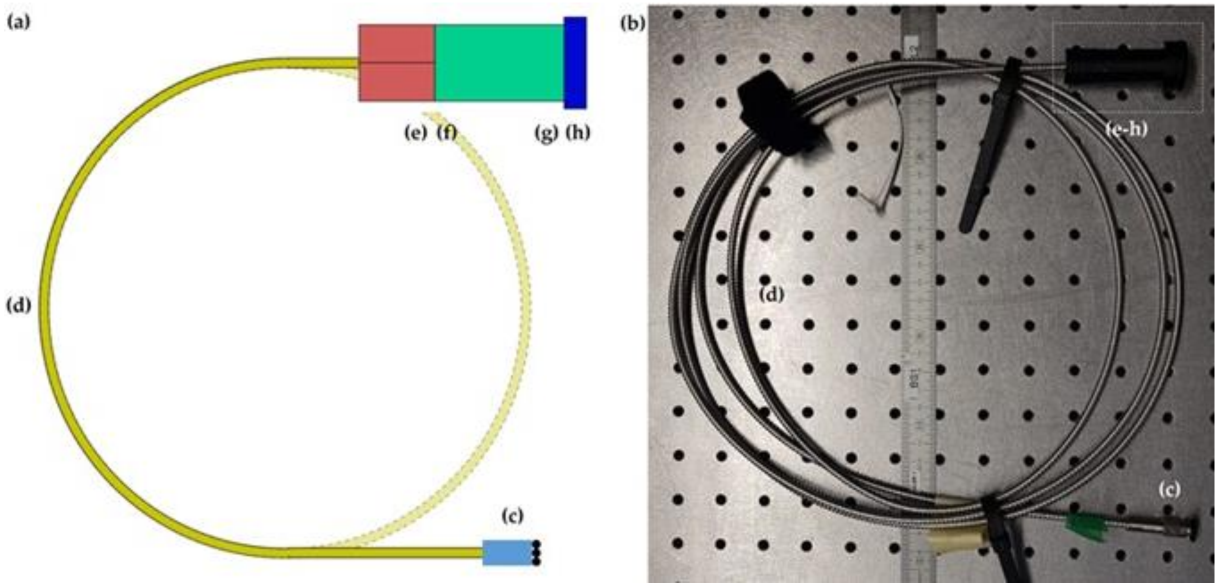

Figure 1. (a) Schematic representation and (b) photograph of the full MCIFU device composed by the input microlens array (c), the multicore fiber (d), and the full reformatter with the fiber chip support (e), the input (f) and the spread output (g) of the reformatter and the mask (h).

In this paper, the authors report the fabrication of the waveguide reformatter and its associated opaque mask in the collaborative project of the MCIFU. The reformatter is ULI fabricated in a 20 mm long borosilicate glass substrate, reshaping the quasi-hexagonal MCF by spreading the light out via 3D waveguide structures to avoid overlapping the spectra in the spectrograph. This reformatter is connected to an opaque mask coated with a 120 nm layer of chromium that enables increased signal-to-noise by eliminating much of the scattered light inside the reformatter. From the MCF to the mask, the end-to end throughput was measured at an average of 40 % over the 73 cores, exceeding 60 % for some individual cores. The characterization was performed with an ultra-stable laser at 1310 nm. At the conference, we will present all the fabrication processes and characterization results.

2. ULTRAFAST LASER INSCRIPTION REFORMATTER

The fiber support components of the MCIFU, including the chip, reformatter and mask, were fabricated using ULI [8-9]. During inscription, the glass substrates were translated through the laser focus to inscribe the desired structures. Within the beam focus, non-linear absorption processes excite the material and produce a partial free-electron plasma, which results in a permanent modification to the material upon relaxation. The material surrounding the laser focus remains unaffected and so three-dimensional structures with feature sizes on the order of the beam focus can be inscribed. The modification manifests in two distinct ways: firstly, the local refractive index may be altered due to material densification and secondly, the rate at which laser inscribed material is dissolved in certain chemical etchants can be significantly increased. A Menlo Systems BlueCut fiber laser that delivered 350 fs pulses centered at a 1030 nm wavelength was used for inscription. Figure 2 presents the different illustrations of the reformatter components: the fiber support chip (Fig. 2(a)), the input quasi hexagonal shape of the inscribed reformatter (Fig. 2(b)), a schematic representation of the spread 3D design (Fig. 2(c)), the reformatter output (Fig. 2(d)), the mask output (Fig. 2(e)) and finally the full scaled reformatter with the MCF (Fig. 2(f1)), the chip (Fig. 2(f2)), the reformatter (Fig. 2(f3)) and the mask (Fig. 2(f4)).

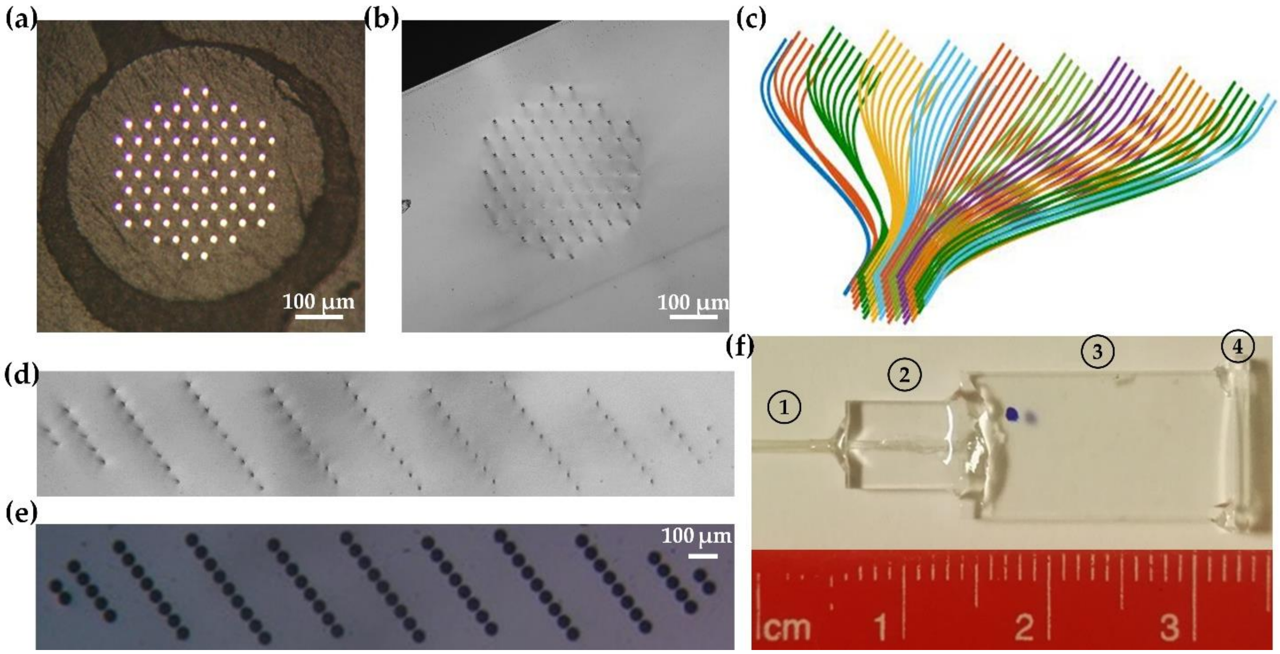

Figure 2. Representation of the different parts of the MCIFU. (a) Photographs of the bare multicore fiber in the fiber chip and the input of the chip reformatter (b). (c) Schematic representation of the 3D complex structure of the reformatter to properly avoid overlapping spectra. (d) Photograph of the output of the bare reformatter associated to the mask (e). (f) Scale picture of the full MCIFU device with the fiber (1), the chip (2), the reformatter (3) and the mask (4).

2.1 The fiber support

A fiber support was developed to house the MCF and provide a large gluing surface to bond the fiber to the reformatter. The support consisted of a hollow cylindrical through-hole embedded in an 8 × 6 × 2 mm thick fused silica substrate to which the stripped input fiber was inserted (Fig 2(a, f2)). The fiber support chip was inscribed in UV grade fused silica using a pulse repetition rate of 250 kHz. The energy of each pulse was set to 220 nJ and the beam was focused to a diffraction limited spot with a theoretical spot diameter of 2.19 µm using a 0.3 NA aspheric lens. The inscribed material was removed via wet chemical etch in 8 $mol.L^{-1}$ potassium hydroxide (KOH) solution heated to 85˚C.

The fiber was inserted into the tunnel and rotated manually to the desired orientation before being UV cured in place with Norland optical adhesive 61. The end facet was then ground back to a flat but rough surface, ideal for bonding to the reformatter. The large gap between the MCF and the bulk glass, as seen in Fig 2(a), is due to the larger amount of material removed by etching near the edges of the chip – the fit is much tighter in the center. A narrow slot runs along the length of the through-hole, which aided etching in the center.

2.2 The reformatter

The reformatter is designed to properly separate each core (and associated spectrum) from the quasi hexagonal shape of the MCF and avoid any overlaps after dispersion by the VPHG. To achieve this spread design, the reformatter was inscribed with a 500 kHz-train of 350 fs pulses in a 20 × 10 × 1 mm borosilicate Eagle XG glass. The laser was focused on the substrate with a 0.55 NA aspheric lens and the substrate translated at 8 $mm.s^{-1}$ with 19 laser scans separated by 0.2 µm inscribing each waveguide. The complex 3D structure requires an evolution of the pulse energy as a function of the inscription depth in the material. At the initial depth of 470 µm, the pulse energy which provided the highest throughput waveguides was measured at 128 nJ and then the pulse energy was varied to determine a set of parameters for various writing depths in the substrate, with the pulse energies ranging from 105 nJ to 128 nJ.

The waveguides were characterized by two different laser sources: a stable 1310 nm laser and a supercontinuum with an 1100 nm ± 10 nm bandpass filter. The two different sources were coupled into an SMF-28 optical fiber and characterization performed by butt-coupling the SMF28 output to a single core of the MCF. The MCF was then butt-coupled to each individual waveguide of the reformatter with the aid of an index matching fluid. By this way, we ensure to work with the matched mode field diameter to characterize the waveguides rigorously. Single-mode behavior over the whole span in the J-band, between 1.1 and 1.3 µm was observed for all the waveguides. The waveguides show an MFD of ~7.3 µm at $1/e^2$ of the beam size at 1310 nm with an NA of ~0.11. The throughput was characterized with the stable laser at 1310 nm. With this optimized set of parameters, the throughput of the straight waveguides can attain 67 %. An investigation was performed to study optimal bend radius and minimize transmission losses, and then the full reformatter was fabricated. Figure 3 presents the full output spread shape of the reformatter with a color scheme that illustrates the corresponding throughput of each core. The color bar on the bottom shows the different span of throughputs. Over the 73 cores, the average throughput was measured at 40 %. Unfortunately, a slight offset in the depth writing of the waveguides had affected the mode mismatch between the MCF and the reformatter that implies coupling losses. These losses are shown in Fig 3 by a lower throughput on the top and bottom cores of the reformatter.

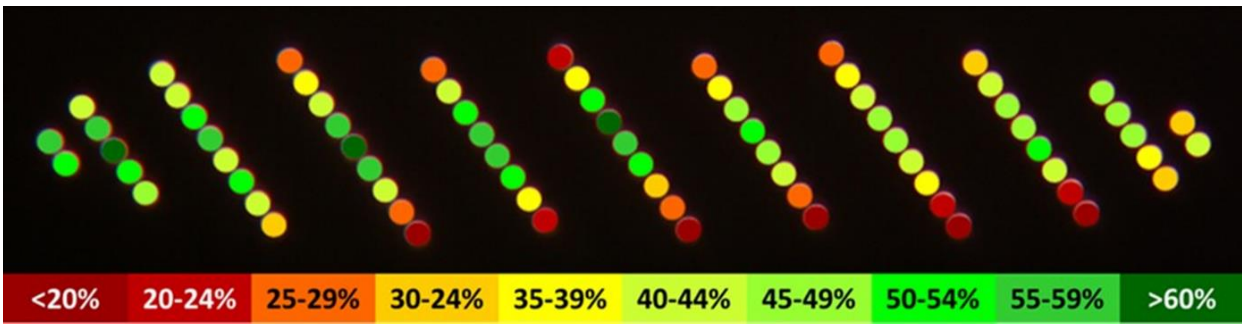

Figure 3. Representation of the output measured throughputs for the 73 individual cores of the reformatter with the opaque chromium mask attached. The throughput range of the results is represented in the color bar at the bottom.

2.3 The output opaque mask

We expected issues such as coupling losses between the MCF and the reformatter to generate a certain amount of light in the reformatter glass substrate [10-11]. Due to a high contrast between the star and its orbiting planet, any background light presents a real hurdle for astronomical observations and instrumentation. To block this background scattered light, a mask was designed at the reformatter output while preserving the output light from the individual waveguides. The mask, presented in Fig. 1(h), was fabricated by the same process of femtosecond laser inscribed chemical etching (FLICE) in a 2 x 12 x 2 mm fused silica substrate [12]. For each output waveguide, a hole with a 30 µm diameter was fabricated and a rectangular slot was inscribed to fit precisely over the reformatter output. This high-level process is challenging and needs high precision translation stages. Then, a 120 nm layer of chromium metal was deposited on the outer surface of the mask by electron-beam physical vapor deposition. In this way, the light from the waveguide should perfectly pass through the holes while scattered light in the bulk should be reflected by the metallic layer. Figure 4(a) presents a photograph showing the accurate alignment between the waveguide output of the reformatter and the mask holes. To characterize the mask's impact on the scattered light, we have selected the pixel power as a straight line along one of the same rows of the reformatter with and without the opaque chromium mask. These two extracted line data were normalized to be compared fairly depending on the input coupling.

Figure 4(b) presents the mask impact by describing the light output of the reformatter with (green area) or without the mask application (blue area). The stray light contrast shows the difference of normalized pixel power along the same extracted line. We can clearly see that the mask has removed a significant amount of scattered light between the waveguide outputs, from blue to green areas. This innovative opaque mask presents an elegant solution to increase the signal-to-noise of the ULI fabrication by removing observed scattered light.

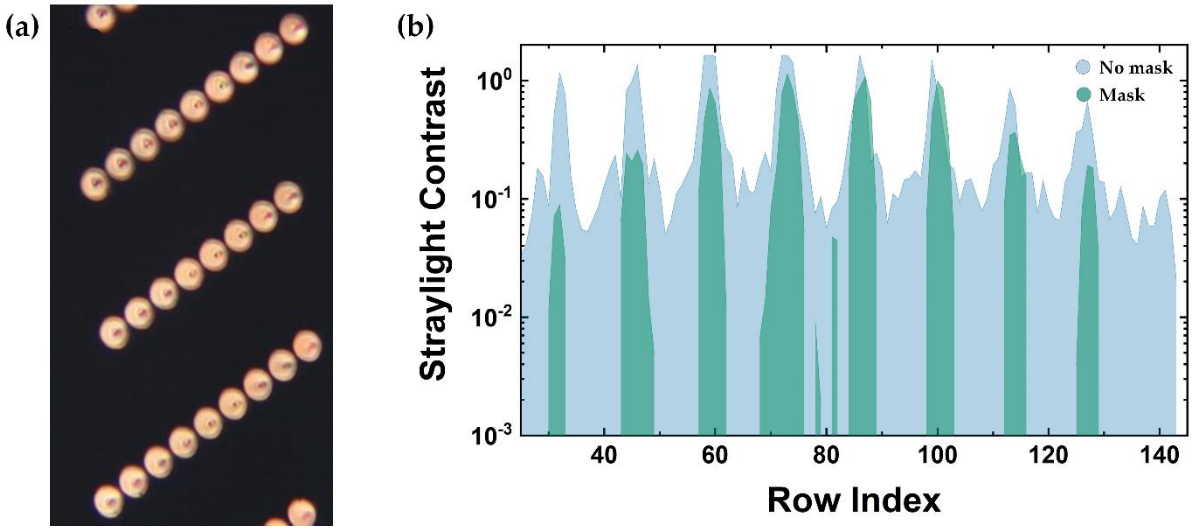

Figure 4. (a) Photograph showing the alignment between the output of the reformatter and the holes of the mask. (b) Representation of the area of output detected light between a reformatter associated without (blue area) or with its associated opaque mask (green area).

3. CONCLUSIONS

We report the conception and the characterization of a 3D photonic reformatter composed of 73 waveguides and a corresponding opaque metallic mask that represents a part of a wide collaboration to develop multi-core fiber–fed integral field spectrograph centered in the J-band. The reformatter functions to re-route the light path coming from a 73-multicore fiber to a spread-out arrangement that avoids any spectrum overlap in a spectrograph, and is fabricated by femtosecond ULI in a 20 mm borosilicate glass substrate. The mask is composed of 73 holes fabricated by ULI in a fused silica substrate with a 120 nm chromium film deposed onto the surface to block scattered light and increase the signal-to-noise. By coupling an ultra-stable laser at 1310 nm in a core of the multicore fiber, we demonstrated single-mode behavior for all cores with an average throughput measured at 40 % from the multimode fiber to the output mask. The throughput difference between the cores comes from a slight fabrication mismatching that induces coupling losses, especially visible on the top and bottom of the reformatter. First on-sky observations [4-5] have demonstrated that the MCIFU is an innovative and promising prototype to characterize exoplanets by direct imaging instruments.

4. ACKNOWLEDGEMENTS

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