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Multi-core fibre–fed integral field spectrograph (MCIFU) – IV: The fiber link

Robert J. Harris[a,b], Fraser A. Pike[c], Mareike Trappen[d], Sebastiaan Y. Haffert*[e,f], Yilin Xu[d], Aurélien Benoît[c], Calum Ross[c], David G. MacLachlan[c], Santiago Barboza[b], Norbert Muench[b], Itan Gris-Sánchez[g,h], Matthais Blaicher[d], Pascal Maier[d], Christian Koos[d], Tim A. Birks[g], and Robert R. Thomson [c]

[a]Zentrum für Astronomie der Universität Heidelberg, Landessternwarte Königstuhl, Königstuhl 12, 69117 Heidelberg
[b]Max-Planck-Institute for Astronomy, Königstuhl 17, 69117 Heidelberg, Germany
[c]SUPA, Institute of Photonics and Quantum Sciences, Heriot-Watt University, Edinburgh EH14 4AS, UK
[d]IMT/IPQ, Karlsruhe Institute of Technology (KIT), Engesserstr. 5, 76131 Karlsruhe, Germany, Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[e]Leiden Observatory, Leiden University, PO Box 9513, Niels Bohrweg 2, 2300 RA Leiden, The Netherlands
[f]Steward Observatory, Unversity of Arizona, 933 North Cherry Avenue, Tucson, Arizona
[g]Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, UK
[h]ITEAM Research Institute, Universitat Politècnica de València,Valencia, 46022,

ABSTRACT

The Multi-Core Integral-Field Unit (MCIFU) is a diffraction-limited near-infrared integral-field spectrograph designed to detect and characterise exoplanets and disks in combination with extreme adaptive optics (xAO) instruments. It has been developed by an extended consortium as an experimental pathfinder for medium resolution spectroscopic upgrades for xAO systems. To allow it to achieve its goals we manufactured a fibre link system composed of a custom integrated fiber, with 3D printed microlenses and an ultrafast laser inscribed reformatter. Here we detail the specific requirements of the fibre link, from its design parameters, through its manufacture the laboratory performance and discuss upgrades for the future.

Keywords: Astrophotonics, Spectroscopy, Integrated optics, Waveguide, Photonic Lantern, Image slicing

1. INTRODUCTION

With each new exoplanet detection and following characterisation, we better understand how planetary systems are formed. After several decades of advancement, the most successful methods of detecting planets are still indirect radial velocity searches and transits, together making up the bulk of detections. These however have difficulty separating the star and planet completely, leaving ambiguity in measurements. In recent years, direct imaging has allowed the discovery of tens of sub-stellar companions at large separations, opening up a new detection parameter space. This success is due to the advances in Adaptive Optics (AO), coronagraphic devices and image processing techniques resulting in the ability to image objects with a contrast of 10^6 with respect to the host star at only a few hundred milliarcseconds from the star. The direct imaging technique is primarily limited by the ability of AO to correct for the atmospheric turbulence and by the other sources of instability

Further author information: (Send correspondence to R.J.H),
E-mail: harris@mpia.de
*NASA Hubble Fellow S. Y. Haffert

in the telescope. Within approximately 10 λ/D the planetary signal is limited by quasi-static speckles induced by residual instrumental aberrations, which are difficult to remove using post processing algorithms. By using a spectrograph of moderate spectral resolving power ($R > 1000$) and spectral differential imaging, the speckles can be removed, as their position and size evolve with wavelength, whereas the planet does not. Taking advantage of this has already lead to the detection of several planets and interest is growing for more instruments that cover this regime.

Currently, the Integral Field Units (IFUs) behind extreme adaptive optics (xAO) systems all use microlenses (e.g Ref. 1–3), however these are limited by the spectral resolving power and bandwidth they can achieve whilst avoiding cross-talk between adjacent spaxels. This is leading to proposals for alternative instruments, using different methods, which interestingly is in line with the older development of conventional IFUs.[4] Recently, several single-mode (SM) fiber-fed instruments have been proposed.[5–8] These take advantage of the spatial filtering properties of SM fibers, increasing the contrast between the star and planet. Here, we introduce the fiber link to the Multi-Core Integral Field Unit (MCIFU), a novel SM IFU, designed as a testbed for photonic technologies for the next generation of high contrast imagers.

In section 2 we define the requirements for our fiber link. In section 3 we describe the current prototype fiber link. In section 4, we define the upgrade and research areas for future improvements to the fiber link and finally we conclude in section 5.

2. FIBER LINK REQUIREMENTS

The fiber link prototype for the MCIFU had the following requirements:

- Each spaxel must be approximately 1.5 times the diffraction-limit of CANARY.
- The microlens array should be fed by an F/22 beam.
- Single-mode over 1-1.6 µm wavelength range.
- Cross-coupling should be less than 10^{-3} between adjacent cores.
- Protected fiber to survive in CANARY/telescope environment.
- As many cores as possible for a large Field of View (FoV).

This set of requirements first informed our choice of fiber, which then allowed us to form the requirements for the reformatter, microlenses and protection scheme.

3. THE SINGLE-MODE MULTI-CORE FIBER LINK

The fibre-link allows us to decouple the spectrograph from the point spread function (PSF) of the AO system, which can then be situated in a stable environment. The prototype fiber link for the MCIFU was assembled by first manufacturing and connectorizing the multi-core fiber (MCF) and v-groove chip. This was then aligned and glued to the reformatter and mask. With this process complete, the system was then packaged using a combination of off-the-shelf and 3D printed components, including an FC-PC connector. This packaged system then had microlenses printed on it. The following sections are arranged in the order of manufacture (not in order of position in the link).

3.1 Fiber

The MCF was selected from a set of pre-existing fibers. The chosen fiber has 73 cores, each of which have an Numerical Aperture (NA) of 0.14 and a diameter of approximately 5.3 µm. The MCF has a outer cladding diameter of 560 µm, which makes it fairly rigid and inflexible. From the NA and core diameter, the SM cutoff of each core is approximately 970 nm. The large core separation of 41 µm ensures negligible cross-coupling across the wavelength range of 1-1.6 µm.

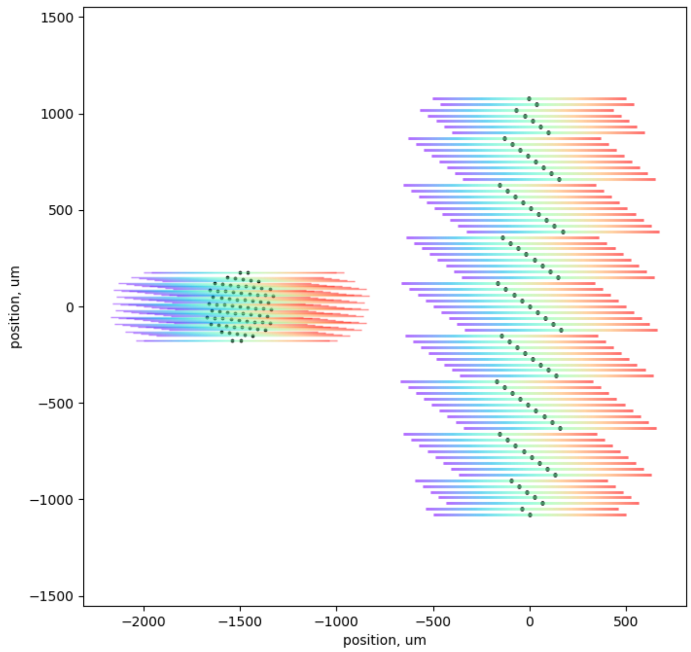

Figure 1. A toy model of a visible Integral Field Unit (IFU) spectra, created with (a) the 73 core hexagonal fiber geometry and (b) The geometry of the reformatter outputs. Here you can see the reformatter slit is elongated, but produces a much more efficient shape for a detector.

3.2 Reformatter and mask

Whilst the fiber and microlens combination allows us to efficiently sample the focal plane, the hexagonal output means that care must be taken to avoid the spectra overlapping. This problem has a geometrical solution (e.g. Ref. 9), though as can be seen from the left hand side of Fig.1, the spectra are still unevenly spaced. We solve this by coupling the end of the fiber to a ultrafast laser inscribed (ULI) reformatter package, similar to Ref. 10. By separating our output waveguides by 30 μm in the vertical direction, we avoid cross-coupling and the ULI process allows us to reformat the waveguides to the desired shape. Whilst we have extra control over the output geometry, the addition of an extra optical element comes at the cost of higher light loss. To minimise this, we optimised parameters to efficiently match the fiber to our ULI reformatter, these included bend radius, overall length and waveguide size. As can be seen in the left hand side of Fig. 1, we chose to retain the hexagonal shape in the horizontal direction, this had two advantages, firstly it required less reformatting in the horizontal direction (minimising loss) and secondly further increasing the distance between cores, reducing the possibility of cross-coupling between adjacent waveguides. Finally, as we require high contrast between adjacent waveguides in the reformatter we made use of a chromium on silica mask to block any uncoupled light. This phenomenon has been observed before in ULI devices (e.g. Ref. 5) and the chosen solution was to use a sidestep in the ULI reformatter. For the MCIFU this is an unfeasible solution as the sidestep in the spatial (horizontal w.r. to chip) direction would be several mm long and in the spectral direction (vertical w.r. to chip), such a large depth difference in the waveguide array would result in very poor ULI waveguides.

The devices were fabricated and assembled during the spring of 2019, for full details of the manufacture of the reformatter and mask, see Ref. 11.

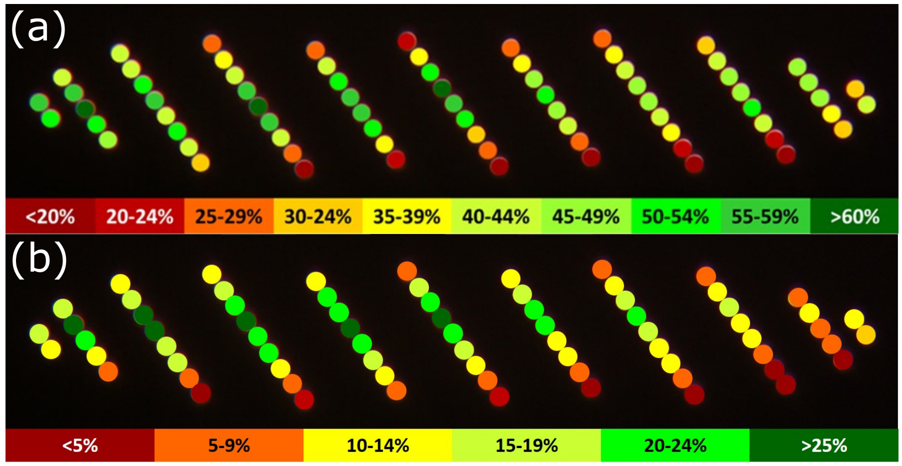

Figure 2. The measured monochromatic (1310 nm) throughput results for the prototype fiber link. (a) throughput for the fiber plus reformatter and mask(b) for the full fiber link. Note the colour bars are different for each figure. Reproduced from[12]

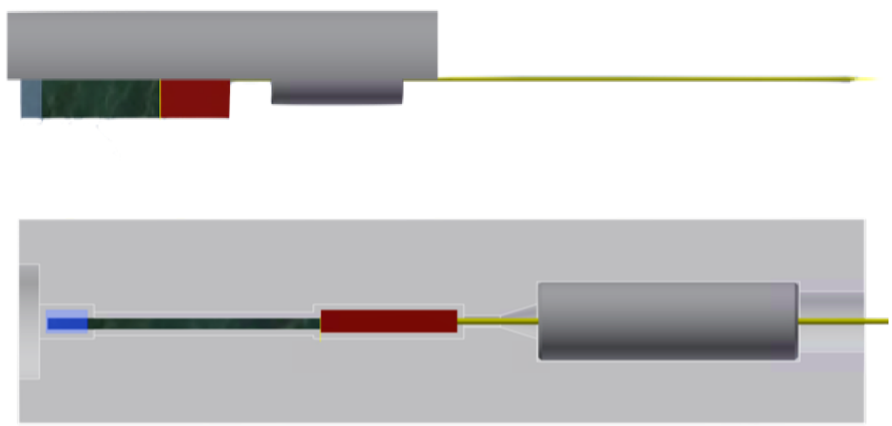

Figure 3. A CAD model of the 3D printed fiber holder (light grey), containing the silica/chromium mask (blue), ULI chip (marble green), connector (red) and mating tube (dark grey). The fiber (yellow) can be seen exiting the rear of the holder and was encased in stainless steel furaction tubing (not shown). The top image shows the chip from above, whilst the bottom image shows the encased chip from the side, both images only show one half of the holder.

3.3 Packaging

With the fabrication of the ULI reformatter and mask complete the device was packaged. For simplicity and to reduce cost the fiber itself was packaged within standard furcation tubing (Thorlabs FT05SS) and connected to an FC-PC connector (Thorlabs 30640G3) using mating tube (Thorlabs FTS50D). The mismatch between the fiber diameter (560 µm) and the ferrule bore (640 µm) led to a decentering of the fiber within the ferrule. This however, was compensated for during the microlens fabrication and subsequent alignment processes. At the other end of the fiber the ULI reformatter was placed within a 3D printed housing (see Fig 3). The housing is printed in two parts from PLA, with pins and holes to allow the device to be held together. To minimise strain on the reformatter join, the two halves of the housing were oriented such that any pressure during assembly was put on the width of the reformatter chip. At the entrance, the chip was slightly recessed to provide additional protection.

3.4 Microlens array

The microlens array was designed to sample an F/22 beam, which is roughly twice the F/ratio of CANARY, allowing a simple 2-1 magnification system in the injection optics. For simplicity we chose a singlet microlens array design, with the core spacing setting each spaxel to approimately 1.5 times the diffraction limit at 1.3 μm. The microlens array was created by *in-situ* printing on the flat facet of the FC-PC connector. The lenses were printed in one run, using two-photon lithography with a commercial negative-tone photoresist IP-Dip. The fabricated structure was developed, flushed with isopropanol, and subsequently blow dried.

3.5 Performance of the fiber link

The recorded throughput of the fiber system is shown in Fig. 2. For the whole system the maximum is approximately 25%, which is slightly less than half the theoretical limit. The figure also shows a clear difference between the best performing central cores, due to mismatches in the reformatter waveguides and microlenses at the edges of the device.

4. FUTURE UPGRADES

With the MCIFU now assembled as a fully working test-bed we are in the position to trial new photonic technologies. Due to the size and relative lack of complexity of the spectrograph, we plan to embark on a series of upgrades over the next few years, slowly optimsing the device and exploring new ideas to improve performance.

As we increase the performance by replacing components, we hope that this will lead to us showing the technique is viable for future high contrast instruments such as planetary camera system (PCS) for the Extremely Large Telescope (ELT). **MORE**

4.1 Fiber

The fiber we selected was one from a list of previously manufactured fibers. Whilst it fulfilled our requirements, it was not optimal. For future upgrades we wish to optimise the following parameters:

- **Number of cores:** Increasing the number of cores will allow us to observe a greater FoV, competing with conventional instrumentation.
- **Core spacing:** By optimising the core spacing we can increase the number of cores per fiber, this also has the effect of reducing the size of the microlenses, easing manufacture and improving performance.
- **Core NA and size:** By optimally matching the core NA and size to the ULI waveguides we can reduce coupling losses.
- **Number of fibers:** We are investigating using multiple fibers feeding multiple replicated spectrographs for future upgrades, which will increase our field of view and allow us to mix different types of fibers (e.g. for novel wavefront sensing methods[13–15]).

4.2 Lenslets

The lenslets we manufactured for the protoype were early stage devices, these can be further optimised through the following:

- **Size of lenslets:** With the fiber core spacing optimised we will aim to reduce the size of the lenslets, as mentioned above, this increases performance.
- **Number of lenses:** Using multiple lenses within the microlens array (e.g. doublets instead of a singlet) has the possibility to give increased performance when the AO performance degrades. This has been shown in single printed lenses, but the difficulties in arrays are yet to be overcome.
- **New types of lens:** We wish to investigate new designs of microlenses to reduce the scatter from diffraction at the edges of each lens into adjoining lenses.
- **AR coating:** AR coating our lenslets would give an increase in performance, by reducing losses due to reflection.

4.3 Reformatter and mask

The reformatter and mask were ambitious in terms of size and complexity. For future upgrades we wish to increase the performance, this will be done as follows:

- **Waveguide optimisation:** There are many areas that can be optimised to reduce uncoupled light, including glass type, waveguide size and refractive index profile. We also noted the difficulty in creating such large structures, resulting in bad positioning at the edge waveguides, this can be corrected by improved manufacturing tolerances. In addition, due to the depth difference between the upper and lower waveguides the beam profile changes shape between them, this will be compensated for in future iterations.
- **Mask optimisation:** We wish to further test the optimisation parameters for the mask, reducing the size of the holes as much as possible, whilst retaining throughput.

5. CONCLUSIONS

We have developed a novel fiber link for the Multi-Core Integral Field Unit (MCIFU) project. This project aims to develop the photonic Integral Field Units (IFUs) technologies for direct imaging. To create the fiber link we developed a ultrafast laser inscribed (ULI) reformatter, which formed the entrance slit to our spectrograph. We joined this to a 73 core multi-core fiber (MCF), allowing us to decouple from the telescope. The fiber/reformatter system was packaged using custom and off-the-shelf compontents and then a microlens array was 3D printed on the opposite end to the ULI reformatter. This built on previously developed techniques, brought together for the first time, requiring additional research to combine everything effectively.

Our fiber link met our requirements and has room for improvement. We will use our test-bed instrument to explore upgraded versions of the instrument and new photonic concepts.

The instrument itself will be taken to MagAO-X in 2021, allowing us to test it with a full extreme adaptive optics (xAO) system. We wish to show its potential for the third generation of direct imaging Extremely Large Telescope (ELT) instrumentation.

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