We present the results of our work on developing fully integrated devices (photonic dicers) for reformatting multimode light to a diffraction limited pseudo-slit. These devices can be used to couple a seeing limited telescope point spread function to a spectrograph operating at the diffraction limit, thus potentially enabling compact, high-resolution spectrographs that are free of modal noise. © 2015 Optical Society of America

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Future AO systems may enable SM coupling efficiencies in the near infrared approaching 100% [4]. The situation becomes considerably more difficult as either the wavelength of light is reduced and/or the size of the telescope aperture is increased, as revealed by Eq. (1). Given the significant engineering challenges in developing AO systems for 8 m class telescopes, it is unlikely that AO systems will be able to provide high SMF coupling efficiencies on extremely large telescopes (ELTs) with apertures ≥30 m, such as the European-ELT and Thirty Meter Telescope.

The photonic lantern is a guided-wave device that was developed to enable the efficient implementation of SM photonic functionality on seeing limited telescopes. It is formed by a guided-wave transition between a multimode (MM) waveguide or fiber supporting $M$ modes and a set of $N$ individual spatial modes. If the transition is sufficiently gradual, and $N \geq M$, then the system can, in principle, couple the $M$ incoherently excited modes at the MM input to the $N$ output SMs with low loss.

To date optical-fiber-based photonic lanterns have demonstrated the highest throughput in MM-to-SM conversion. Birks et al. [5] recently demonstrated a MM-to-SM-to-MM transition based on photonic lanterns fabricated using a 120-core multicore fiber exhibiting a throughput loss of <0.5 dB. Photonic lanterns have also been fabricated using stack-and-draw techniques, and Noordegraaf et al. [6] demonstrated a 61 fiber-based MM-to-SM-to-MM device with a transmission loss <0.76 dB.

In 2011, we demonstrated [7] that photonic lanterns could also be fabricated using a laser writing technique known as ultrafast laser inscription (ULI), where focused ultrashort laser pulses are used to directly inscribe localized refractive index modifications inside a transparent dielectric material. We later demonstrated [8] that ULI could be utilized to create a monolithic integrated device capable of reformatting a MM telescope PSF to a diffraction-limited pseudo-slit, a device that we named a photonic dicer (PD). Figure 1 shows a schematic diagram of a PD component, where it can be seen that the MM end of the device is formed from a $6 \times 6$ array of SM waveguides that are
tightly stacked in the $z$- and $y$-axis (as seen in Fig. 1). These waveguides split up along the $x$-axis via a photonic lantern transition into a 2D array of loosely coupled SM waveguides. These waveguides are then routed through a series of transitions, to eventually form a planar waveguide that is SM across the waveguide ($z$-axis), and MM along the waveguide ($y$-axis). As originally proposed in the PIMMS (Photonic Integrated Multimode Micro-Spectrograph) instrument concept [9], the use of photonic lantern-based devices for this purpose could revolutionize high-resolution astronomical spectroscopy by enabling spectrographs that combine the high efficiencies associated with a MM fiber-fed spectrograph with the precision and stability of a SMF-fed spectrograph. In this Letter, we present the results of detailed studies on the development of PD devices.

The PD fabrication was performed using a 500 kHz train of 460 fs pulses at a wavelength of 1064 nm (Fianium Femtopower 1060 fs laser). The pulse energy was set to 251 nJ and the polarization to circular. The pulses were focused with a numerical aperture of 0.3 to a depth of $\approx 200 \mu$m below the surface of a borosilicate substrate (Corning EAGLE2000). The substrate was mounted on high precision $x$−$y$−$z$ crossed-roller bearing stages (Aerotech ANT) and translated through the laser focus at a speed of 8 mm/s.

The cross section of the SM waveguides was controlled using the well-established multiscan technique [10], which enables the fabrication of waveguides with an almost square cross section that can be positioned in close proximity to each other. Each SM waveguide was constructed by translating the substrate through the laser focus 21 times, with each scan laterally offset from the previous by 0.4 $\mu$m. These square waveguides can then be stacked on top of and adjacent to each other with a center-to-center separation of 8.4 $\mu$m to form either a large MM waveguide, or a pseudo-slit, that is SM across the slit ($z$-axis in Fig. 1) and MM along the slit ($y$-axis in Fig. 1).

If the MM input to the device is formed by a $K \times K$ array of SM waveguides, we fabricated PDs of six different sizes, where $K$ was varied between 2 and 7 in steps of 1. For each size of the PDs, we inscribed two 30 mm long devices (PD1 and PD2) back-to-back, seamlessly connected at their slit-ends. At one end of this structure, we also inscribed a 10 mm long “MM-state-preparation” section; a schematic of the design for a $3 \times 3$ full device is shown in Fig. 2. The state-preparation input consisted of an $K \times K$ array of SM waveguides separated by a center-to-center distance of 25 $\mu$m that approach each other along the length of the section to form a MM waveguide matched to the MM end of PD1. Microscope images of the facets of the input, MM, and pseudo-slit ends of a $7 \times 7$ PD, together with near-field images of 1550 nm light emitted from these structures are shown in Fig. 3.

We used non-linear third harmonic generation (THG) to obtain cross-sectional images through a ULI fabricated lantern manufactured on a different system, though with similar parameters to those used in the manufacture of the PDs, with full details reported in [7]. The system used for the THG
imaging was based on a Cr:forsterite laser producing a 76 MHz train of 65 fs pulses at a wavelength of 1235 nm, and is similar to the system reported in Ref. [11] that has previously been used to image ULI fabricated optical waveguides with 3D resolution [12]. For a focused beam in a homogenous medium, the detected THG is zero because the Gouy phase shift causes destructive interference between the THG from either side of the focus. The interferometric cancellation is disrupted only when a boundary between different materials is present near the focus [13], for example between the modified and unmodified regions within the substrate. The images shown in Fig. 4 are therefore highly informative. The double horizontal line structure of the SM waveguides in images (a) to (d) strongly suggest that the SM waveguides exhibit a close to top-hat refractive index profile, as has been confirmed previously in multiscan fabricated waveguides [14]. A much weaker THG signal is obtained at interfaces along the optical axis than those normal to the optical axis, hence the double horizontal line appearance for a square area of modified material. Images (e) and (f) demonstrate that as the SM waveguides approach each other, the THG signal becomes progressively weaker until almost no contrast in the image can be seen within the MM waveguide in Fig. 4(f). This is what we would expect if the MM waveguide exhibited an essentially top-hat refractive index profile. Previous refractive index profiling measurements of this structure, reported in [7], strongly support this conclusion. This is exactly the evolution one would require for an efficient and adiabatic MM-to-SM transition. A rendered 3D image of the full photonic lantern transition is provided as Visualization 1.

Coherent MM states were generated to test the throughput of the PDs in a similar technique to that employed in [15], by butt-coupling SMF28 fiber into each of the SM input waveguides on the state preparation section, and the output from the MM end of PD2 measured by free space coupling to a photodiode (Measurement Set 1). PD2 was then diced from the device (along line A in Fig. 2), and the output of the PD1 slit was measured (Measurement Set 2). Finally PD1 was diced from the device (along line B in Fig. 2), and the measurement repeated for light emitted from the MM end of the state preparation section (Measurement Set 3). These measurements effectively form a series of cutback measurements, where differences in signal between Measurements 1 and 2 provide the throughput losses of PD2, and the differences in signal between Measurements 2 and 3 provide the throughput losses of PD1.

The throughput of each PD was measured at 1550 nm for horizontal and vertical polarizations and the average determined. A single straight waveguide written with the same parameters was measured to have a 75% ± 3% throughput between 1500 and 1580 nm and to be single mode throughout the 1320 to 1580 nm region. The 2 × 2 PD structure was also investigated for 1500 and 1580 nm light, in both cases the throughput was found to be within 3% to that measured for 1550 nm light, so we expect that the PD devices will work with a similar performance across this range. The average throughput at 1550 nm (Fig. 5) is seen to decrease steadily from a maximum of 70% to a minimum of 50% as the number of modes supported by the PD increases. This is due to the fact that waveguides forming higher $K$ devices exhibit greater radiation losses, as for the same transition length these waveguides must undergo bends with smaller radii in order to construct a longer slit. It is also interesting to note that the average throughputs for PD1 and PD2 are very close to each other, despite the fact that the light was propagating in the MM-to-slit direction for PD1, and the slit-to-MM direction for PD2. This observation would tend to indicate that the photonic-lantern and slit-forming transitions are close to adiabatic, with the number of modes being supported along these transitions remaining roughly constant.

Fig. 4. Cross-sectional images of a 16-core, 4 × 4 ULI fabricated lantern, obtained using a THG microscope. Bright areas indicate a material boundary. (a) is furthest from the MM end, while (f) is within the MM end of the device. Main image scale bars indicate 20 μm. Inset in (c) shows a high-resolution image of a single square waveguide with 4 μm scale bar.

Fig. 5. Average throughputs measured at 1550 nm for PD1 (MM-to-slit) and PD2 (slit-to-MM) for each $K$ by $K$ PD.
due to optical path length differences within the PD, as discussed previously in Refs. [5,16].

We have presented a body of work on the development of PD devices using ULI, and used THG microscopy to image a ULI fabricated photonic lantern transition. The results of this clearly demonstrate that the multiscan technique enables the fabrication of a well-controlled transition, where individual step index waveguides can be slowly combined to create a single, near step-index MM waveguide. We have performed detailed throughput characterization experiments for PD devices of different sizes. We observed that the throughput steadily reduced as the size of the PD increased, a property that we attribute to higher radiation losses as the routing waveguides are forced to perform increasingly severe bends as the PD size increases. Furthermore we recently reported a $6 \times 6$ PD device that exhibited a maximum in-laboratory throughput of 66% (in-line with results presented here) and an on-sky throughput of 20% [8].

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