A tuneable multi-core to single mode fiber coupler

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***Abstract*—We demonstrate a low loss, wide-band multi-core to single-mode fiber coupler using a modified side-polishing technique. The coupler was designed to access light from a single core of the multi-core fiber without disrupting the signal propagation in the remaining cores. The coupling ratio between the two fibers can be continuously tuned over the entire spectral band via a simple mechanical displacement method. We expect that such couplers will be of use for monitoring, splitting and multiplexing applications in future multi-core communication and sensing systems.**

***Index Terms*—Fiber coupler, multi-core fiber, fiber optics.**

I. INTRODUCTION

Multi-core fiber (MCF) research is currently undergoing a renaissance due to heightened interest in space-division multiplexing (SDM) technologies. This surge in activity is primarily fueled by the need to increase the capacity of the networks that modern day life has come to depend on [1]. Although many important MCF devices have been demonstrated, including multi-core erbium doped fiber amplifiers [2], MCFs with reduced cross-talk [3], and spatial division multiplexers [4], [5], several of the key elements required to build a complete multi-core fiber network are still missing. In particular, one of the most ubiquitous components in fiber systems is the passive optical coupler, which is used to combine, split or monitor light within the system.

Today, the most common types of optical fiber couplers are fabricated using the fused biconical-tapering method or, more specifically for MCFs, photonic lantern technologies [6], [7]. However, when applied to MCFs, both of these methods result in simultaneous coupling to multiple cores, so that it is not possible to independently control the relative coupling [8]. The alternative is to make use of a side-polishing technique, where part of the cladding is removed from the MCF to allow access to the evanescent field of the desired core mode [9]. Using this method it is straightforward to fabricate a four port coupler by placing two side-polished fibers in contact. Compared to their tapered counterparts, side-polished fiber couplers offer a number of advantages as they are mechanically robust, can be designed to operate over a broad wavelength region (several hundreds of nanometers), and can be continuously tuned by simply adjusting the evanescent field overlap [10].

In this letter, we report the first MCF to single-mode fiber (SMF) coupler fabricated using a modified side-polishing approach. The coupler was designed to split light from a single core of a 7-core MCF, without disrupting the signal propagation in the remaining fiber cores. The MCF to SMF coupler exhibits a low ($\sim 1\,\mathrm{dB}$) insertion loss over the entire telecommunications band and a tuneable coupling ratio of up to $\sim\ 30\,\%$ at $1550\,\mathrm{nm}$. The results are in good agreement with numerical simulations, which confirm the high precision of our fabrication approach. We anticipate that side-polished MCF devices that can split, monitor and multiplex signals in a spatially controlled manner will become critical components in future SDM networks.

II. DEVICE DESIGN AND FABRICATION

The MCF used in this work was designed so that the individual cores support single mode operation across the telecom band. It consists of seven $8\,\mu$m diameter cores that are arranged in a hexagonal array with a $50\,\mu$m core-to-core pitch to limit crosstalk [11]. The resulting outer diameter of the MCF is $198\,\mu$m. The single-mode fiber is standard SMF-28 with an $\sim\ 8\,\mu$m core and $125\,\mu$m outer diameter. The refractive index contrast of the core/cladding is $0.36\,\%$ for both the MCF and the SMF. Prior to polishing, the fibers were stripped of their acrylic coating and mounted in separate aluminum polishing blocks that help to maintain mechanical stability, both during and after the processing. To ensure that the polishing plane of the MCF allowed access to just one core, a red light source was coupled into the fiber during the mounting process and the orientation checked by monitoring the output pattern. A portion of the cladding material was then removed from each mounted fiber using a standard polishing technique. To facilitate optimal coupling, the aluminum blocks were custom-made to produce a flat, $1\,\mathrm{cm}$ long, coupling region and an adiabatic transition from the fiber's full circular geometry to the D-shaped uniform polished region, as shown in the schematic of Fig. 1(a) [12]. This coupling length was chosen to allow for controllable and efficient coupling between the two fibers as the overlap is tuned, though the polishing process can be easily adapted for either longer or shorter lengths. Fig. 1(b) displays a scanning electron micrography (SEM) image of the smooth, flat region of the polished fiber. Confirmation of the excellent surface quality was obtained via measurements with a ZeScope profilometer, which revealed a roughness of less than $< 1\,\mathrm{nm}$ RMS. The quality of the polished surface is critical since surface abnormalities such as scratches scatter light from the fiber, which will increase the fiber losses. Thus the resulting polished fibers have negligible transmission loss ($< 0.1\,\mathrm{dB}$ insertion loss), though it is possible to access the core guided light through their exposed surface. The target distance between the core and the polished

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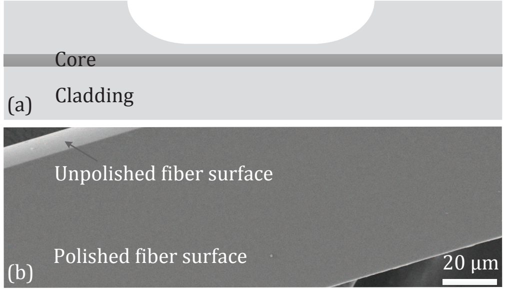

Fig. 1: (a) Schematic design of the side-polished fibers. (b) SEM image of the flat section of a polished fiber.

surface is chosen to permit access to more than 30 dB of the light propagating through the core. The point at which this occurs is determined by dropping a high refractive index liquid onto the polished region and monitoring the change in transmitted power [12]. Using this method, the polishing process was terminated when the polished surface reached a distance of approximately $1\,\mu$m from the target core. Fig. 2(a) shows a cross-sectional image of a polished MCF that has been optimized for coupling to and from a single core. The coupler was then formed by mating the respective polishing blocks, thus bringing the relevant cores into the proximity required to achieve evanescent coupling. Fig. 2(b) shows a schematic image of the coupler cross-section illustrating the geometry and orientation of the polished fibers.

Positioning of the polished fibers and optimization of the coupling was achieved by holding the polished MCF block in a fixed assembly and mounting the second SMF block in a kinematic mount with sub-micron positioning accuracy. The kinematic mount was also used to adjust the position of the fibers with respect to each other so that the coupling ratio could be tuned by longitudinally or vertically displacing the relative positions of the fibers, as shown in Fig. 3, which amounts to changing the effective coupling length and coupling strength, respectively. The relative position is quantified by calculating the longitudinal or vertical distance traveled by the kinematic mount. A liquid with a refractive index equal to the fiber cladding ($n \sim 1.4468$) was applied to improve the coupling efficiency and lubricate the surfaces of the optical fibers [13].

III. MEASUREMENT RESULTS AND DISCUSSIONS

When optimized, a maximum coupling percentage of $\sim$33 % was obtained for the telecommunication wavelength 1550 nm, and this coupling position was fixed as the zero offset for the remaining measurements. The spectral response of the MCF-SMF coupler was then measured by coupling in a broadband ASE (amplified spontaneous emission) source and monitoring the output on an optical spectrum analyzer across the wavelength range $1535-1615$ nm. The results of this measurement are shown as the top curve ($0\,\mu$m) in Fig. 4(a), where it can be seen that the coupled power only varies by 10 % over the spectral range, i.e. the entire telecommunications C-band. This measurement was then repeated for different coupling lengths by adjusting the longitudinal displacement $\triangle L$ in intervals of $\sim 15\,\mu$m, as illustrated in Fig. 3(b). As expected, reducing the interaction length reduced the coupled power at each wavelength correspondingly, so that the device retained its spectral flatness. Thus these results serve to highlight the excellent broadband nature of this type of coupler.

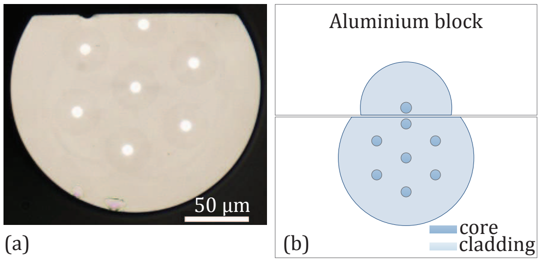

Fig. 2: (a) Microscope image of the polished MCF cross-section. The dip on the top surface is due to a marker for identification. (b) Schematic of the mated MCF-SMF coupling blocks.

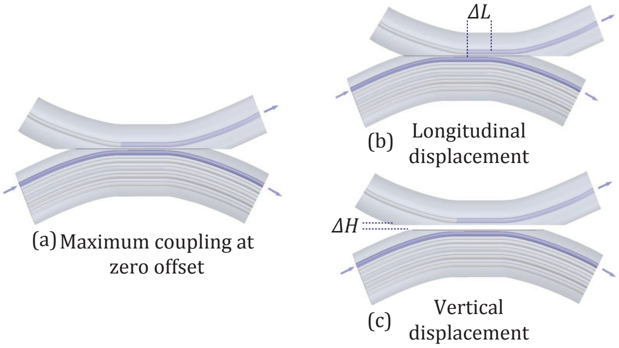

Fig. 3: (a) Illustration of the MCF-SMF coupler position for maximum coupling. Arrows show the flow of light into and out of the device. Schematics showing (b) longitudinal and (c) vertical adjustments of the coupling ratio.

The throughput loss for this device was estimated by comparing the total output power from both fibers to the input power. Fig. 4(b) shows the results obtained across the entire spectral band, where it can be seen that the losses vary by less than 10% around the value of $\sim$ 1 dB. Although this is a reasonable device loss for a first iteration, there is no physical reason to prevent the losses being reduced to values commensurate with standard (SMF-SMF) polished couplers ($<$ 0.5 dB). We attribute the low loss of this coupler both to the ultra-smooth surface (nanometer-scale roughness) and the adiabatic transmission from the full fiber to the coupling region, which ensure the polished fibers' negligible losses. Also, no polarization dependent loss was observed in the side-polished couplers during our experiments.

To demonstrate tuneability of the coupler, our next set of measurements investigated the effect of altering the coupling strength by vertically displacing the SMF, as shown in Fig. 3(c). Starting from the zero offset position, the core to core spacing $\triangle H$ was increased in steps of 600 nm, thus decreasing the modal overlap. Fig. 5 shows the measured change in coupled power relative to the displacement $\triangle H$ for two wavelengths, 1550 nm (triangles) and 1600 nm (circles). These results show the expected trend of decreasing coupling ratio with increasing core to core spacing. Due to the nature of the evanescent coupling condition, the coupling ratio decreases much faster for vertical displacements than for longitudinal displacements of the same size. The initial coupling ratio is slightly higher for the longer wavelength, in agreement with

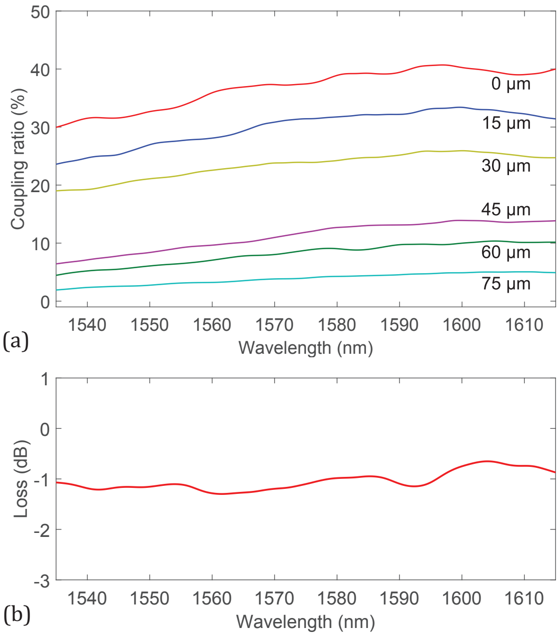

Fig. 4: (a) Spectral response of the coupler for different longitudinal tunings $\triangle L$, in increments of $\sim 15\,\mu$m. (b) Spectral response of the throughput loss when set at the maximum coupling for an operation wavelength of $1550\,$nm.

the results in Fig. 4(a), but drops rapidly for $\triangle H > 3\ \mu$m. Noticeably, in both cases, the rate of decrease in the coupling was slightly slower than the expected exponential rate for two identical fiber cores, thereby suggesting the MCF-SMF coupler is slightly asymmetric. To investigate this further, we modeled the system using the well-known coupled mode theory [14]. Iterative simulations were performed to obtain the best match to the experimental results, starting with a symmetric coupler system comprising of two SMF fibers, and gradually introducing asymmetry in the geometrical parameters. Mismatch between the refractive index profiles of the MCF and SMF was ruled out following refractive index profile measurements, indicating that any discrepancy should be in the core size. From the best fit simulations we found that there is most likely a small difference of $\sim$2% between the core radii of the MCF and the SMF, which is reasonable considering that the core diameter of SMF-28 is typically around $8.2\,\mu$m (i.e., $2\,\%$ larger than our MCF cores). Thus, the maximum coupling of $\sim$33 % in Fig. 4(a) can now be understood as a limitation imposed by the asymmetry in the coupler system in which there is a slight mismatch in the propagation constants of the fundamental modes in each fiber. This core mismatch means that we will not achieve $100\,\%$ coupling for this system, but this could easily be addressed through careful selection of the starting fibers. Overall, the observed trends in the experimental measurements match well with the simulation results for most displacements in Fig. 5.

IV. CONCLUSION

In conclusion, we have demonstrated the first MCF to SMF coupler by using a modified side-polishing technique. The coupler offers key benefits in that it is low loss, capable of operating over a broad bandwidth, and it can be tuned continuously using simple displacement methods. As in the case of the standard polished coupler, the coupling characteristics, such as the spectral response and the coupling ratio, can be varied quite dramatically by altering the polishing depth and interaction length. We predict that the side-polishing technology will also be suitable for other MCF fibers that may have doped cores or suppressed index contrast. Furthermore, it would also be possible to replace the SMF in this coupler with a second MCF to expand the potential application scenarios. We expect that robust and low loss MCF-SMF couplers will form a critical component of future MCF networks, providing lateral access to the propagating light for monitoring, splitting and multiplexing applications.

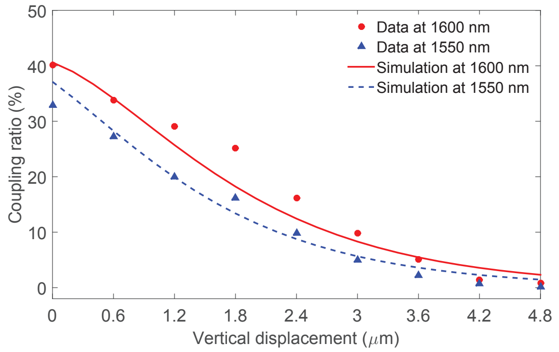

Fig. 5: Coupling throughput as a function of vertical displacement $\triangle H$ at wavelengths of $1550\,$nm (triangles) and $1600\,$nm (circles). The fitted curves are the numerical simulations at $1550\,$nm (dashed) and $1600\,$nm (solid).

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