Multimode fiber devices with single-mode performance

S. G. Leon-Saval and T. A. Birks
Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, UK

J. Bland-Hawthorn
Anglo-Australian Observatory, P.O. Box 296, Epping, NSW 2121, Australia

M. Englund
Redfern Optical Components, Australian Technology Park, Eveleigh, NSW 1430, Australia

Received May 6, 2005; accepted June 2, 2005

A taper transition can couple light between a multimode fiber and several single-mode fibers. If the number of single-mode fibers matches the number of spatial modes in the multimode fiber, the transition can have low loss in both directions. This enables the high performance of single-mode fiber devices to be attained in multimode fibers. We report an experimental proof of concept by using photonic crystal fiber techniques to make the transitions, demonstrating a multimode fiber filter with the transmission spectrum of a single-mode fiber grating. © 2005 Optical Society of America

OCIS codes: 060.2340, 060.2430.

Many optical fiber devices exploit physical interactions that are mode dependent. Although such devices can have high performance in single-mode fiber (SMF), the corresponding multimode fiber (MMF) devices generally perform poorly. For example, simple SMF Bragg gratings are highly reflective over a narrow band of wavelengths, but a grating written directly in MMF reflects each mode at a different Bragg wavelength, giving a response that is spread over a range of wavelengths and depends on the mode spectrum excited in the MMF.[1] (Sun *et al.*[2] demonstrated narrowed MMF gratings, but only for a particular subset of modes in a special fiber incompatible with ordinary MMFs.) This has limited the range of high-performance devices implemented in MMF.

Here we describe how to attain SMF performance in MMF devices by using tapered transitions between an MMF and several SMFs. By way of example, we made an MMF Bragg grating device with the narrow spectral width of an SMF grating. Our work was motivated by applications in astronomy. When a ground-based telescope observes the night sky in the wavelength range 600–1800 nm, the sky background is overwhelmed by bright narrow spectral lines due to atmospheric OH emission. Filtering out these spectral features would greatly enhance contrast in the infrared. Complex Bragg gratings can achieve the required filter response in SMF.[3] However, each pixel of the image is incoherent and highly multimode and can only be efficiently coupled to MMF. The ability to implement the SMF response in MMFs could revolutionize ground-based observations at infrared wavelengths.

The second law of thermodynamics (brightness theorem) prohibits the lossless coupling of light from an arbitrarily excited MMF into one SMF (despite reports to the contrary[4]), but low-loss coupling to another multimode system with at least as many degrees of freedom is possible. If the second multimode system is degenerate, its modes have the same propagation constant and so share the same Bragg wavelength for a given grating. Such a grating therefore behaves like an SMF grating. Reflected light couples back into the original MMF, and a second, reversed, coupling arrangement can similarly couple transmitted light into another MMF. The entire experiment has MMF input and output ports but behaves like an SMF grating.

We implemented this idea using an array of isolated identical SMF cores as the degenerate multimode system. Its spatial modes are the supermodes of the array. Their number equals the number of cores, and their propagation constants equal that of a core on its own.[5] Light can be coupled between the array and an MMF via a gradual taper transition, Fig. 1(a), conceptually like half a multiport fused coupler.[5–7] If the transition is adiabatic, then modes of the MMF core evolve into supermodes of the SMF array, and vice versa. If the number of MMF spatial modes matches the number of SMFs, the transition is a reversible low-loss splitter–combiner between the MMF and the SMFs. Otherwise there are MMF modes that do not evolve into SMF supermodes, or SMF supermodes that do not evolve into MMF modes, causing loss in the forward or reverse direction, respectively, for arbitrary excitation. This is important because inevitable unequal path lengths along the SMFs effectively scramble the supermodes.

The SMF ports of two similar transitions are connected. Identical SMF components in each path perform the same function on all the light. Such a device with Bragg gratings, Fig. 1(b), reflects the same narrow band of wavelengths as each grating and transmits the rest, but other functions could be implemented. Indeed, some functions do not need any SMF devices. For example, connecting the SMF ports of a single transition yields a mode-scrambling mirror. Multicore SMFs could be used as transmission fibers

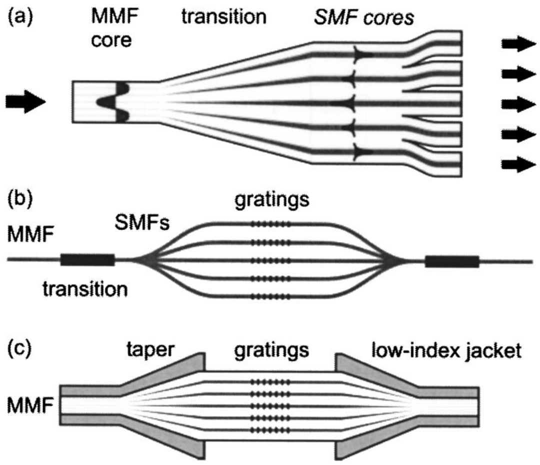

Fig. 1. (a) A taper transition between an MMF and several SMFs. Each MMF mode evolves adiabatically into a supermode of weakly coupled SMF cores and distributed between separate SMFs at the output. The process is reversible (SMFs to MMF). (b) An MMF grating device made by inserting SMF gratings between the SMF ports of two transitions. (c) A more manufacturable form of the device, made by tapering a multicore fiber in two places with a low-index jacket to give MMF ports, and writing gratings in the cores in between.

instead of ordinary MMFs, carrying as many modes while avoiding focal ratio degradation caused by mode-dependent loss.

The required transitions superficially resemble integrated-optic mode splitters,[8,9] where each mode of a multimode waveguide is channeled into a different single-mode waveguide. However, for our purposes it is enough that each MMF mode evolves adiabatically into a supermode distributed across all the SMFs, rather than into just one SMF. The SMFs can then be identical, simplifying fabrication and avoiding a limitation to ~5 SMFs.[8]

We made 1×19 transitions by using a technique[10] for interfacing SMFs to photonic crystal fibers (PCFs), Fig. 2(a). A silica cane, or ferrule, with an array of holes was made, Fig. 2(b). Conventional SMFs (diameter 125 μm, cutoff wavelength ~1250 nm) were inserted into 19 of the holes. Each SMF was coated for ~2 cm inside the ferrule, to prevent accidental cleaving, but the rest of the fiber in the ferrule was uncoated. The filled ferrule was treated as a preform and drawn to a length of multimode PCF, Fig. 2(c). The MMF core incorporated material from the 19 SMFs and was supported in an air cladding by a network of silica webs.[11] (The irregular shape that was due to distortion of the holes could be avoided by using a ferrule with more holes.) By preserving the neck-down region in the furnace when drawing stopped, the MMF remained connected via a continuous transition to the SMF pigtails protruding from the ferrule, Fig. 2(d).

Nineteen nominally identical SMF Bragg gratings were fusion spliced between two such transitions as depicted in Fig. 1(b). Light from an erbium-doped fiber amplifier continuum source was launched via a conventional MMF into one MMF port. The output from the other MMF port was fed via another conventional MMF into an optical spectrum analyzer. The measured spectrum is plotted in Fig. 3(a), along with the average of the 19 SMF gratings. There were no other features outside the 2 nm range shown. The ~0.07 nm ripples are weak Fabry–Perot fringes from the coupling optics and not a feature of the device. The zero on the vertical axis was adjusted for comparison with the SMF gratings and does not represent zero loss.

The shape of the spectrum closely matched that of the SMF gratings, with a similar notch width and depth. In contrast, the response of a grating in an MMF with a numerical aperture (NA) of 0.2 would be spread over ~15 nm. Heating 9 of the 19 gratings by 60°C shifted the Bragg wavelength of those gratings and gave a spectrum with two 3 dB (50%) notches separated by 0.4 nm, Fig. 3(b). Their similar depths indicate the expected distribution of light between the two roughly equal sets of SMFs.

The measured transmission away from the grating notch was only 3.4% (−14.7 dB), but this high loss can be accounted for by the mode-number mismatch between the MMF and the SMF array. We made no attempt to match mode numbers in this proof-of-principle experiment. The number of MMF modes was estimated from SEM images like Fig. 2(c). The core is approximately a disc of diameter 34.5 μm, and the supporting webs were 0.5 μm thick. Hence the effective NA was[12] 0.75, and the fiber supported ~710 spatial modes.[13] If these modes were equally excited at the input, the transmission of an otherwise ideal device would be 19/710, or 2.7% (−15.7 dB).

There are large uncertainties in comparing these two transmission values: the measured value in-

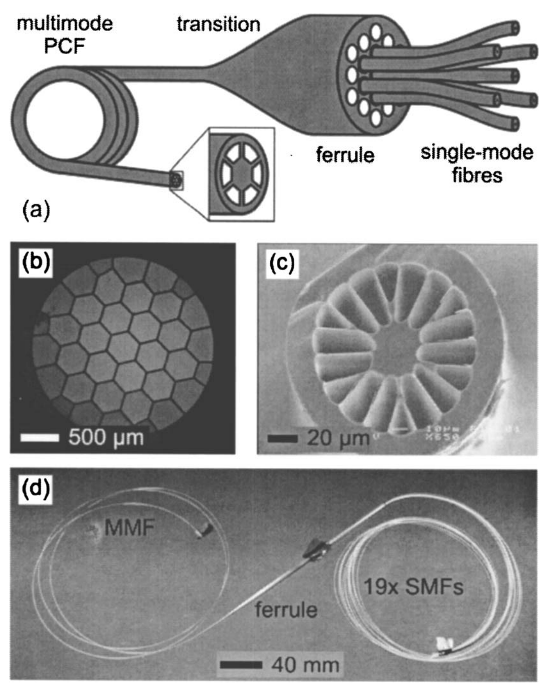

Fig. 2. (a) An MMF–SMF transition made by drawing a holey ferrule filled with SMFs. (b) Optical micrograph of the ferrule. The solid outer jacket was ~260 μm thick. (c) SEM image of the multimode PCF drawn from the ferrule after the central 19 holes were each filled with an SMF. (d) Photo of a complete transition.

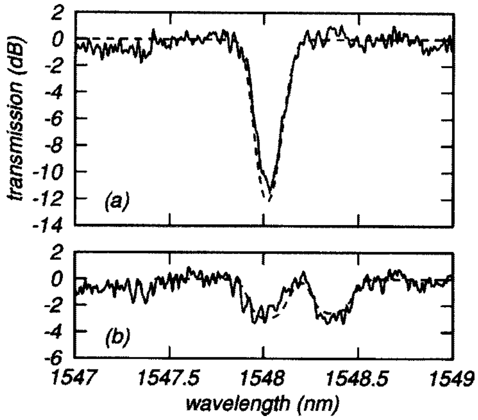

Fig. 3. (a) Transmission spectrum of the MMF grating device measured when all 19 gratings were at room temperature (solid curve), together with the average (dashed curve) of the 19 SMF gratings as calculated from their data sheets. (b) Same as (a) but measured when 9 of the gratings were heated by 60°C (solid curve), together with the calculated average with 9 of the gratings shifted in wavelength by the measured amount (dashed curve).

cluded unknown coupling losses to the conventional MMFs at input and output; the grating and device SMFs were not identical, giving splice losses of ~0.8 dB; and the MMF modes would not have been equally excited. Nevertheless, the similarity between the measured transmission and that estimated by mode counting suggests that the device would be low loss if the mode numbers were matched. Unoptimized ferrule transitions between PCFs and SMFs exhibit losses[10] of ~0.6 dB, and analogous 1×19 fused couplers with losses of 0.3 dB have been reported.[7] Mode numbers can be matched by including enough SMFs to match a given number of MMF modes or by adjusting the MMF core diameter or NA to match a given number of SMFs: 50 SMFs would have matched our MMF if its NA were 0.2.

In our experiment the SMF cores were separate SMFs and the MMF was a multimode air-clad PCF. The device was therefore cumbersome to make, but more manufacturable implementations can be conceived. An example is shown in Fig. 1(c): the SMF cores are contained in a multicore fiber, the gratings are written in one shot across all the cores (researchers studying multicore gratings believe this to be possible[14]), and the fiber is tapered down either side (perhaps on a tapering rig) and cleaved to yield multimode ports. Jacketing with low-index cladding glass makes them conventional MMFs. Construction would involve far fewer process steps (e.g., no splicing) and be more scalable to higher mode counts, making it applicable to cost-sensitive applications such as MMF communication and sensing.

We have shown how transitions between one MMF and several SMFs can give an MMF device with the same characteristics as the SMF components within it. We illustrated this with transitions made by using PCF techniques, and we implemented an MMF filter with the response of an SMF grating. The high loss can be explained by the mismatch between the number of MMF modes and the number of SMFs, suggesting that a mode-number matched device should be low loss, and we have described how such devices could be more readily manufactured.

J. Bland-Hawthorn dedicates this paper to his brother Simon, who died in December 2004.

References

1. T. Mizunami, T. V. Djambova, T. Niiho, and S. Gupta, J. Lightwave Technol. **18**, 230 (2000).
2. Y. Sun, T. Szkopek and P. W. E. Smith, Opt. Commun. **223**, 91 (2003).
3. J. Bland-Hawthorn, M. Englund, and G. Edvell, Opt. Express **12**, 5902 (2004).
4. Y. Yang, J. Lee, K. Reichard, P. Ruffin, F. Liang, D. Ditto, and S. Yin, Opt. Commun. **249**, 129 (2005).
5. F. Ladouceur and J. D. Love, Opt. Quantum Electron. **22**, 453 (1990).
6. D. B. Mortimore and J. W. Arkwright, Appl. Opt. **30**, 650 (1991).
7. J. W. Arkwright, D. B. Mortimore, and R. M. Adnams, Electron. Lett. **27**, 737 (1991).
8. R. N. Thurston, E. Kapon and Y. Silberberg, IEEE J. Quantum Electron. **23**, 1245 (1987).
9. B.-T. Lee and S.-Y. Shin, Opt. Lett. **28**, 1660 (2003).
10. S. G. Leon-Saval, T. A. Birks, N. Y. Joly, A. K. George, W. J. Wadsworth, G. Kakarantzas, and P. St. J. Russell, Opt. Lett. **30**, 1629 (2005).
11. R. P. Espindola, R. S. Windeler, A. A. Abramov, B. J. Eggleton, T. A. Strasser, and D. J. DiGiovanni, Electron. Lett. **35**, 32 (1999).
12. W. J. Wadsworth, R. M. Percival, G. Bouwmans, J. C. Knight, T. A. Birks, T. D. Hedley, and P. St. J. Russell, IEEE Photonics Technol. Lett. **16**, 843 (2004).
13. W. Snyder and J. D. Love, *Optical Waveguide Theory* (Chapman & Hall, 1983).
14. I. Bennion (Aston University, Birmingham, UK, February 2005), G. A. Miller (SFA, Inc., Largo, Md., February 2005), separate personal communications.