Optical microfiber coupler for broadband single-mode operation

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Abstract: We present a broadband single-mode bi-conical microfiber coupler (MFC) with a specifically designed transition region that effectively suppresses any higher-order modes present at the input fiber and provides efficient power splitting into the fundamental mode at the two output ports. As a practical example, single-mode 3-dB splitting operation over a broad spectral window (400~1700 nm) was demonstrated for a very thin taper waist (~1.5μm) MFC made from conventional telecom optical fibers.

OCIS codes: (230.1150) All-optical devices; (060.2340) Fiber optics components; (220.4000) Microstructure fabrication; (220.4241) Nanostructure fabrication.

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#106842 - $15.00 USD Received 26 Jan 2009; revised 13 Mar 2009; accepted 13 Mar 2009; published 18 Mar 2009

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1. Introduction

The fabrication of low-loss optical micro-/nanowires (MNWs) has opened up new opportunities for the manipulation of photons in the sub-wavelength domain [1-3]. Due to this sub-wavelength guidance, MNWs can tightly confine an optical beam to a small transverse area and provide for strong interactions with the surrounding medium. These optical properties have been shown to be advantageous for a wide range of applications including high-sensitivity optical sensors, nonlinear optics, atom trapping, micro/nano-scale photonic devices and for evanescent coupling to planar waveguides or microcavities [4-8]. In a recent work [9], the authors have successfully demonstrated that sub-wavelength optical microwires can be used as an efficient element for higher-order mode filtering in multimode waveguides, creating effectively endlessly single mode operation in conventional optical fibers. The stable and low-loss single-mode operation obtained both at short wavelengths and over a wide spectral range is suitable for applications in high performance fiber lasers, sensors, photolithography, and optical coherence tomography (OCT) systems [10-12]. However, single-mode output from a single fiber strand is not sufficient to fulfill all technical demands within these fields making the development of multi-port devices an important requirement.

Here we present for the first time to our knowledge a fused-type bi-conical 2×2 microfiber coupler with an extremely wide single mode operation bandwidth. As introduced in our recent work on single fiber devices [9], the taper transitions are specifically designed to suppress any higher-order mode content present at the input fiber whilst at the same time providing efficient power splitting into the fundamental mode at the two output ports. Further suppression of the higher-order modes can be obtained by controlling the MNW diameter in the uniform waist region [13]. Generally, the practical operational bandwidth in standard single-mode fiber couplers is limited to ~500nm around the third telecom window by higher-order mode cut-offs at short wavelengths and a wavelength-dependant coupling ratio. However, by applying this efficient mode filtering scheme based on sub-wavelength waveguiding, a broad range of single-mode optical operation (400~1700nm) and wavelength-flattened coupling ratios for the two output ports was successfully realized with minimal excess loss.

2. Operating principle and fabrication of fused microfiber coupler

Figure 1 represents an idealized 2×2 microfiber coupler for higher-order mode filtering. The device comprises two conical transition tapers and a central uniform waist region. It is structurally the same as the previously well-established fused-type optical fiber coupler [14-16] other than the extremely small waist diameter (~ 1.5μm). In principle the MFC, made by laterally fusing and tapering two optical fibers, enables an exchange of optical power between two fibers and can be used as a power splitter or combiner. As described in reference 9, however, higher-order modes present at one of the input ports can be effectively suppressed by controlling the taper transition profile and the diameter of the MFC in the uniform waist region, which suppresses propagation of higher-order modes along the entire length of the MFC and constrains the number of guided modes. Therefore, a very thin MFC establishes single-mode operation for multimode waveguide over an extremely wide range of wavelengths and provides efficient power splitting into the fundamental mode at the two output ports (port3, port4). In our experiment, a standard telecom optical fiber (Corning SMF-28) was selected as a simple example of a fiber providing multimode operation at short wavelengths. Low-loss MFCs were manufactured with the aid of the well-established single-stage “flame-brushing” technique [2]. The longitudinal profile of the conical transition tapers was approximated by a decreasing/increasing exponential function and was achieved by

#106842 - $15.00 USD Received 26 Jan 2009; revised 13 Mar 2009; accepted 13 Mar 2009; published 18 Mar 2009

reliable control of the hot zone and precise movement of the translation stages. The diameter of the MFC waist was about 1.5μm and the lengths of tapered region and uniform waist were 25 and 6mm, respectively.

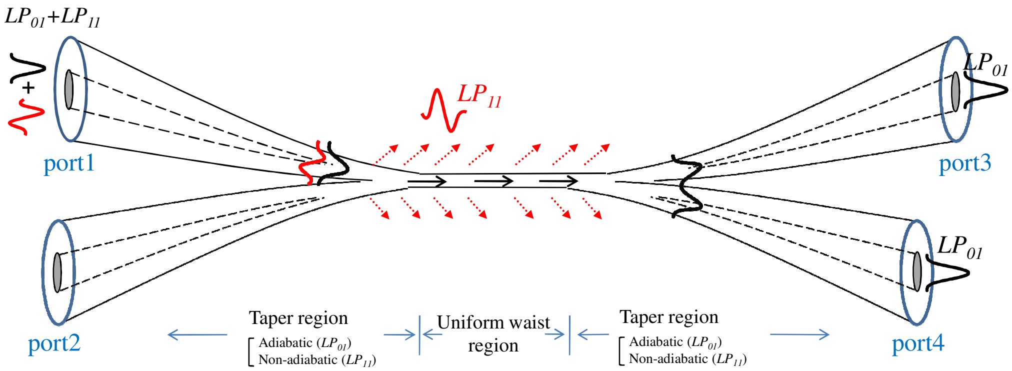
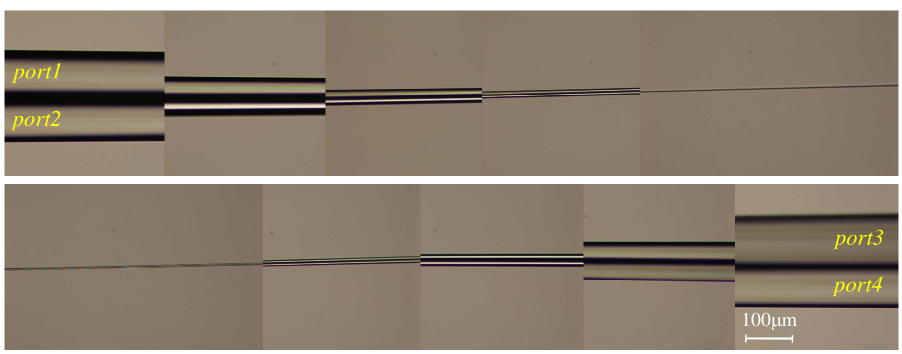
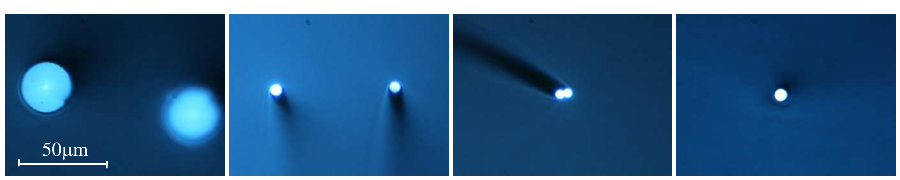


Fig. 1. A schematic diagram of the microfiber coupler (MFC). The biconical MFC with specially designed transition taper and very-thin taper waist effectively suppress any higher-order modes at the input fiber and provides efficient power splitting into the fundamental mode at the two output fibers.

Figure 2(a) and (b) show microscopic top- and cross-sectional views of the fibers along the MFC. The two fibers were fused together into a biconical taper and their cross-sectional shape gradually changed from dumbbell to circular at different positions along the taper. The geometric parameters characterizing the resulting structure and the coupler behaviors are determined by the overlapping part of the cladding (i.e. degree of fusion) [14, 15].



(a)



(b)

Fig. 2. Microscopic (a) top- and (b) cross-sectional view of the fibers along the microfiber coupler.

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3. Coupling characteristics of the MFC and stability of single mode operation

To investigate the modal guidance, *in-situ* transmission spectra of the MFCs were recorded for various outer diameters during a single tapering process. An incoherent white light source was used in conjunction with an optical spectrum analyzer to measure the wavelength characteristics of the MFC. Figure 3 shows the spectral output of a coupler made from telecom optical fiber for different diameters of the uniform waist region. Just as in similar previous experiments on high-order mode filtering in a single strand of microfiber [9], intermodal interference appears in the multimode spectral region (<1250nm) when the waist diameter is decreased from 125 to 35μm, whilst no such effects are seen in the single-mode operation range (1250~1700nm). However, in the two fiber case, coupling of optical power commences once the outer diameter is reduced to approximately 20μm. As the optical power in the output port P_3 (Fig. 3a) starts to decrease the power in output port P_4 is seen to increase (Fig. 3b). As the coupler is stretched further, the coupling coefficient increases and the overcoupling state is soon reached [15, 17]. Beyond this the optical power oscillates back and forth between the two coupler arms due to modal interference in the coupling region, i.e. mode coupling between the lower-order symmetric and anti-symmetric supermodes. Both the period and strength of the sinusoidal modulation in the transmission spectrum decreased as the waist diameter was further decreased from 20 to 4μm. Moreover, a slow modulation of the spectral envelope was also observed, which can be well explained by considering the different coupling properties of the device's two polarization eigenstates [18, 19]. Finally, we note that for the 1.5μm diameter MFC there was no higher-order mode cut-off (~1250nm) observed in the untapered input fiber; this is mainly due to the efficient mode filtering effect as described in Ref. 9. The strength of oscillation is significantly decreased and the total optical excess loss is negligible (excess loss <0.1dB at λ=1.55μm). An increased excess loss (~3.3dB) was observed in the multimode spectral region (<1250nm) due to the filtering effect of higher-order modes in the input fiber.

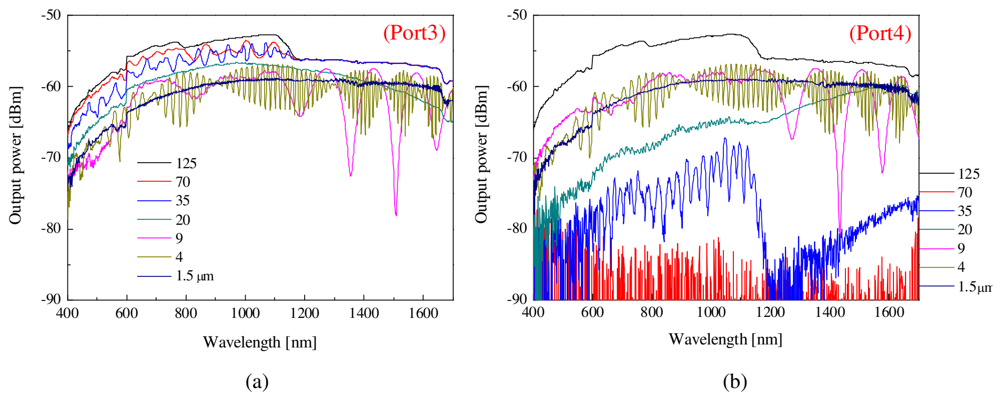

Fig. 3. Spectral response of microfiber coupler: Transmission spectra of the MFC at (a) output port3 and (b) port4 for different MFC outer diameters during a single taper fabrication process. Both higher-order modes filtering effect [refer to figures of Ref. 9] and coupling characteristics between two optical fibers can be observed during the MFC fabrication process. A 50:50 power splitting ratio was obtained for the whole range of scanned wavelengths for the MFC with 1.5μm diameter. In (b) the spectrum at 125μm represents the fiber transmission when light is launched into port4 before the MFC fabrication and which is reported only as a reference to identify the maximum transmission level.

Figure 4(a) shows the spectral response of the two output ports of the fabricated 1.5μm MFC at a 50:50 coupling ratio. The output ports have very uniform spectral characteristics over a wide wavelength range, extending from 400 to 1700 nm, which makes the device suitable as a broadband power splitter. Figure 4(b) shows the normalized output power variation from both arms as a function of the elongation length (this plot is called the "pull signature") at a wavelength of 1.55μm using a single wavelength Fabry-Perot laser (EXFO

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FLS-2100) and optical power meter (EXPO IQS-505P). At first there is no coupling since the light is still guided in the core and the overlap integral of the modes of the two cores is zero. After a 10mm elongation of the fiber, mode coupling between the lowest order coupler supermodes begins. As the coupler is further elongated, both the spectral oscillation and amplitude modulation (due to the polarization effect) appear but this then decreases in strength. Once the elongation reaches ~55mm, equal splitting of the output power into the two output fiber is achieved, resulting in a 50:50 coupler. It appears therefore that the maximum diameter for efficient higher order filtering is about 1.5um. The single-mode operational bandwidth is generally limited at short wavelengths in standard single mode fibers by a higher-order mode cut-off (λ_c_LP_{11}, λ_c_LP_{21} and λ_c_LP_{02}). However, by applying this efficient mode filtering scheme based on a sub-wavelength waveguide, a broad range of single-mode optical operation (400~1700nm) in two output ports was successfully realized with minimal excess loss. This key feature of the proposed MFC is directly applicable to the high-performance fiber lasers, fiber sensors, optical coherence tomography (OCT) and fiber test & measurement systems requiring single mode operation over a broad spectral range.

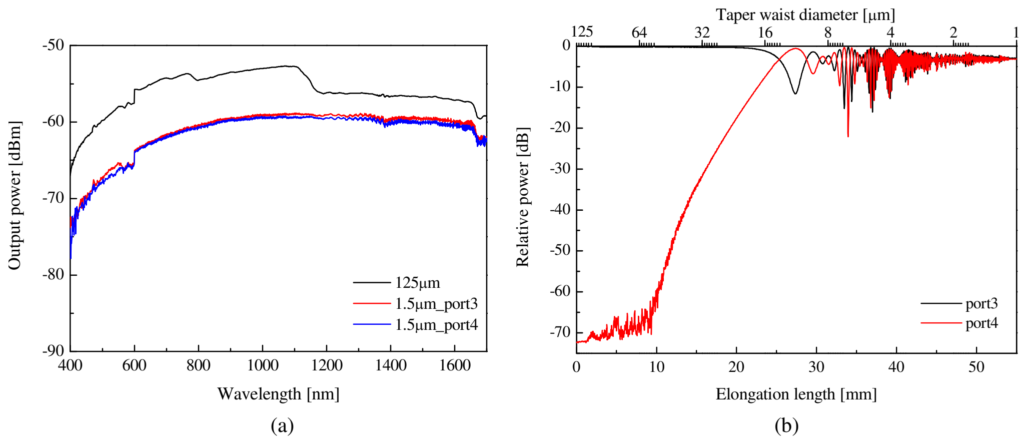

Fig. 4. (a) Comparison between the transmission spectra of the 1.5μm MFC at: the input (in black) and two output ports (in red, blue). (b) Relative coupled power at λ=1.55μm as a function of the pulling length and taper waist diameter.

To investigate the robustness of single-mode guidance, the far-field patterns were measured with a 50× microscope lens and a CCD camera at a wavelength of 632.8nm.

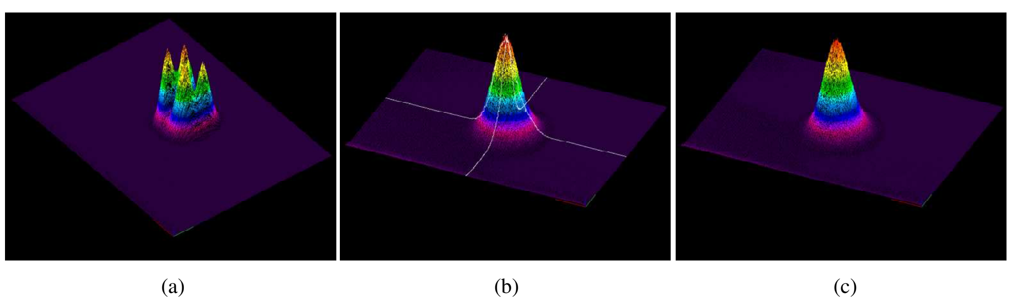

Fig. 5. Far-field imaging of MFC at an input (a) and two output ports (b: port3, c: port4).

As shown in Fig. 5(a), the conventional telecom fiber (cutoff wavelength ~1.26μm) is multimode at this wavelength and suffers severe modal interference when applying bends. Sensitivity of the output beam to environmental factors limits many applications in high-performance fiber lasers, sensors and optical coherence tomography systems. However, on launching light into the input port of the MFC, high-quality single-mode beams were obtained

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at the output ports as shown in Figs. 5b and 5c. Further external bends and multi-point splices were applied to the output fibers but no form of optical degradation was detected in the mode profile and/or in the transmission spectrum.

4. Conclusions

We have demonstrated and validated for the first time a broadband single-mode 2×2 fused microfiber coupler using the single stage "flame brushing" technique. Broadband single-mode operation of the multimode fiber coupler was successfully realized by combining the fabrication technique of fused-fiber couplers with the higher-order filtering characteristics of sub-wavelength diameter optical wires. A standard telecom optical fiber was tested as a simple example of a fiber providing multimode operation at short wavelengths. A very thin (waist diameter ~1.5µm) microfiber coupler establishes single mode operation over an extremely wide range of wavelengths (400~1700nm) with minimal excess loss (<0.1dB at λ=1.55µm) and provides efficient power splitting (50:50) into the fundamental mode at the two output ports. We believe that the microfiber coupler provides many potential applications in and beyond the field of high performance fiber lasers, fiber sensors and optical coherence tomography systems.

Acknowledgements

The authors thank the Engineering and Physical Sciences Research Council UK (EPSRC) for financial support; GB gratefully acknowledges the Royal Society (London, UK) for his Research Fellowship; the work was partially supported by the Korea Research Foundation Grant funded by the Korean Government (KRF-2008-357-C00040)

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