Dual mode fused optical fiber couplers suitable for mode division multiplexed transmission

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Abstract: We experimentally demonstrate 2 × 2 and 3 × 3 fused fiber couplers made from dual mode fiber. A unique mode dependent power transfer characteristics as a function of pulling length is obtained that support various optical functionalities. Exploiting this we demonstrate several devices of interest for mode division multiplexed data transmission including LP_{11} mode filter, LP_{11} mode tap coupler, and 50:50 power splitter for both LP_{01} and LP_{11} modes.

OCIS codes: (060.0060) Fiber optics and optical communications; (060.1810) Buffers, couplers, routers, switches, and multiplexers.

References and links

1. B. S. Kawasaki, K. O. Hill, and R. G. Lamont, "Biconical-taper single-mode fiber coupler," Opt. Lett. **6**(7), 327–328 (1981).
2. F. Gonthier, "Fabrication of multiplexing and demultiplexing single-mode fiber optic couplers," U.S. Patent No. 6,763,685 (2004).
3. D. J. Richardson, J. M. Fini, and L. E. Nelson, "Space-division multiplexing in optical fibers," Nat. Photonics **7**(5), 354–362 (2013).
4. V. A. J. M. Sleiffer, Y. Jung, V. Veljanovski, R. G. H. van Uden, M. Kuschnerov, H. Chen, B. Inan, L. G. Nielsen, Y. Sun, D. J. Richardson, S. U. Alam, F. Poletti, J. K. Sahu, A. Dhar, A. M. J. Koonen, B. Corbett, R. Winfield, A. D. Ellis, and H. de Waardt, "73.7 Tb/s (96 x 3 x 256-Gb/s) mode-division-multiplexed DP-16QAM transmission with inline MM-EDFA," Opt. Express **20**(26), B428–B438 (2012).
5. S. Randel, R. Ryf, A. Sierra, P. J. Winzer, A. H. Gnauck, C. A. Bolle, R.-J. Essiambre, D. W. Peckham, A. McCurdy, and R. Lingle, Jr., "6×56-Gb/s mode-division multiplexed transmission over 33-km few-mode fiber enabled by 6×6 MIMO equalization," Opt. Express **19**(17), 16697–16707 (2011).
6. W. V. Sorin, B. Y. Kim, and H. J. Shaw, "Highly selective evanescent modal filter for two-mode optical fibers," Opt. Lett. **11**(9), 581–583 (1986).
7. K. Y. Song, I. K. Hwang, S. H. Yun, and B. Y. Kim, "High performance fused-type mode-selective coupler using elliptical core two-mode fiber at 1550nm," IEEE Photon. Technol. Lett. **14**, 501–503 (2002).
8. A. Li, J. Ye, X. Chen, and W. Shieh, "Low-loss fused mode coupler for few-mode transmission," in Optical Fiber Communication Conference/National Fiber Optic Engineers Conference 2013, OSA Technical Digest (online) (Optical Society of America, 2013), paper OTu3G.4.
9. J. D. Love and N. Riesen, "Mode-selective couplers for few-mode optical fiber networks," Opt. Lett. **37**(19), 3990–3992 (2012).
10. L. Grüner-Nielsen, J. W. Nicholson, K. Jespersen, Y. Sun, R. Lingle, D. Jacobsen, and B. Pálsdóttir, "Measuring distributed mode scattering in few mode fibers with high and low differential group delay," Proceedings of IEEE Photonics Society 2012 Sumer topical meeting, paper TuC1.3.
11. T. A. Birks and Y. W. Li, "The shape of fiber tapers," J. Lightwave Technol. **10**(4), 432–438 (1992).
12. J. D. Love, W. M. Henry, W. J. Stewart, R. J. Black, S. Lacroix, and F. Gonthier, "Tapered single-mode fibres and devices - Part 1: Adiabaticity criteria," IEE Proceedings-J **138**, 343–354 (1991).
13. R. J. Black, S. Lacroix, F. Gonthier, and J. D. Love, "Tapered single-mode fibres and devices - Part 2: Experimental and theoretical quantification," IEE Proceedings-J **138**, 355–364 (1991).
14. Y. Jung, G. Brambilla, and D. J. Richardson, "Broadband single-mode operation of standard optical fibers by using a sub-wavelength optical wire filter," Opt. Express **16**(19), 14661–14667 (2008).
15. Y. Jung, G. Brambilla, and D. J. Richardson, "Optical microfiber coupler for broadband single-mode operation," Opt. Express **17**(7), 5273–5278 (2009).
16. W. J. Miller and D. L. Weidman, "Optical couplers with multilayer fibers," U.S. Patent No. 6,272, 268 (2001).
17. D. L. Weidman and D. R. Young, "Fiber optic couplers exhibiting low nonadiabatic loss" U.S. Patent No. 5,412,745 (1995).
18. S. Moon and D. Y. Kim, "Effective single-mode transmission at wavelengths shorter than the cutoff wavelength of an optical fiber," IEEE Photon. Technol. Lett. **17**(12), 2604–2606 (2005).

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19. D. Donlagic, "In-line higher order mode filters based on long highly uniform fiber tapers," J. Lightwave Technol. **24**(9), 3532–3539 (2006).
20. D. B. Mortimore, "Wavelength-flattened fused coupler," Electron. Lett. **21**(17), 742–743 (1985).
21. D. W. Stowe, "Wide band coupler," U.S. Patent No. 4,997,248 (1991).
22. R. Ryf, M. A. Mestre, A. Gnauck, S. Randel, C. Schmidt, R. Essiambre, P. Winzer, R. Delbue, P. Pupalaikis, A. Sureka, Y. Sun, X. Jiang, D. Peckham, A. H. McCurdy, and R. Lingle, "Low-loss mode coupler for mode-multiplexed transmission in few-mode fiber," in *National Fiber Optic Engineers Conference*, OSA Technical Digest (Optical Society of America, 2012), paper PDP5B.5.
23. N. K. Fontaine, R. Ryf, J. Bland-Hawthorn, and S. G. Leon-Saval, "Geometric requirements for photonic lanterns in space division multiplexing," Opt. Express **20**(24), 27123–27132 (2012).
24. T. A. Birks, "Effect of twist in 3 x 3 fused tapered couplers," Appl. Opt. **31**(16), 3004–3014 (1992).
25. D. B. Mortimore and J. W. Arkwright, "Theory and fabrication of wavelength flattened 1 x N single-mode couplers," Appl. Opt. **29**(12), 1814–1818 (1990).

1. Introduction

Fused fiber optic couplers [1, 2] are widely used in optical communications, sensing (e.g. to build interferometer and gyroscopes etc.) and fiber lasers for splitting optical signals between two fibers or combining optical signals from two fibers into one fiber. Fused fiber couplers can be made from various optical fibers, e.g. single mode, multimode and polarization maintaining fibers. Recently, few-mode fibers have been used for Mode Division Multiplexing (MDM) transmission [3–5] where information is transmitted simultaneously on several spatial modes in a single fiber, and a record data transmission capacity [4] has recently reported over a 110km length link of three-mode fiber incorporating an inline few-mode amplifier. However, current MDM systems are implemented with the aid of numerous free-space optical components and consequently suffer considerable excess loss for each mode added to the system. To realize a stable and practical MDM system, an all-fiber solution will inevitably be strongly preferred ultimately and the fabrication of few-mode fiber couplers is a potential way forward. In Ref [6, 7], an efficient mode selective fiber coupler formed between a single mode fiber (SMF) and a dual mode fiber (DMF) was demonstrated by using an asymmetric coupler approach (dissimilar fiber coupler), where the SMF was pre-tapered or etched to achieve the desired phase-matching condition at the coupler waist. Most of the work reported so far has focused on the mode selective coupler [8, 9] for multiplexing/demultiplexing the individual modes of a few-mode fiber. However, from the practical MDM application standpoint, it will be necessary to develop other devices such as mode insensitive power splitters, mode selective filters and wavelength division multiplexing (WDM) couplers with appropriate designs/functionality similar to conventional fused single mode fiber couplers used so successfully in single-mode systems to date. In this paper, we experimentally present 2 × 2 and 3 × 3 fused directional fiber couplers using identical dual mode fibers (i.e. symmetric couplers). By employing a mode multiplexer with more than 20dB extinction ratio between the LP_{01} and LP_{11} modes, the mode dependent coupling characteristics are investigated as a function of taper time/pulling length. By choosing an appropriate pulling length (i.e. control of the taper geometry), various interesting optical devices have been obtained; e.g. an LP_{11} mode filter, an LP_{11} mode tap coupler (1:99), and a 50:50 mode insensitive power splitter for both LP modes.

2. Fabrication of dual mode 2 × 2 fused coupler and coupling characteristics

Figure 1(a) represents an idealized dual mode 2 × 2 fused fiber coupler. A pair of identical DMFs is twisted in order to make a close contact along the longitudinal direction and fused/stretched together to form a common taper waist in which light can be coupled from one waveguide to the other. If the taper transitions are adiabatic, guided core modes (i.e. LP_{01} and LP_{11}) of the DMF are continuously mode converted to guided cladding modes surrounded by air along the down-taper section and which are then coupled back into core modes of the DMF at the up-taper section. DMF couplers were manufactured with the aid of the well-established "flame-brushing" technique [14] and step index DMFs (core diameter = 19.7μm, NA = 0.12) [10] were used to investigate the mode dependent coupling characteristics. The longitudinal profile of the conical transition tapers was approximated by a decreasing/increasing exponential function and was achieved by reliable control of the hot zone and precise movement of the translation stages. The lengths of tapered region and uniform waist were 25 and 6mm, respectively. To selectively launch two individual modes at the input end of the DMF, a tight-bend mode stripper and binary LP_{11} phase plate were employed offering more than 20dB modal extinction ratio between the LP_{01} and LP_{11} modes [4]. The optical coupling ratio for each mode at λ = 1550nm was individually recorded as a function of the pulling length and is plotted in Fig. 1(b). It is clear that each guided mode experiences a significantly different power transfer curve and the unique mode coupling signature can be used for realizing different optical devices; 1) LP_{11} mode filter, 2) LP_{11} mode tap coupler, 3) power splitter for both LP_{01} and LP_{11} modes.

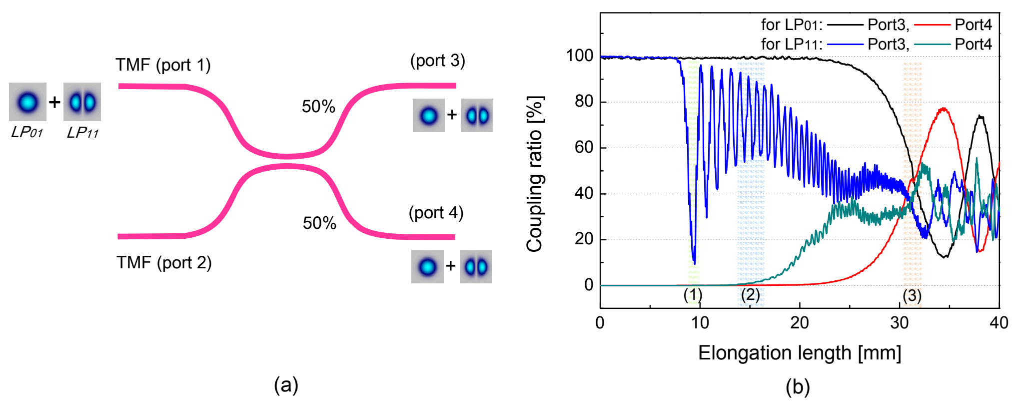

Fig. 1. (a) Schematic of a dual mode 2 × 2 fused fiber coupler and (b) evolution of the coupling ratio for pure LP_{01} and LP_{11} modes at λ = 1.55μm as a function of the pulling length.

2.1 LP_{11} mode filter

First, the LP_{11} mode experiences a non-adiabatic transition (fast power oscillation due to excitation of higher-order cladding modes) starting at an elongation of 9mm. Generally, the adiabatic criteria [11–13] between the fundamental mode and high-order modes are significantly different and the higher-order modes need a smaller well-controlled taper angle and a relatively longer taper transition length [14, 15]. The DMF used for this experiment has a depressed index trench in the cladding, which makes it more challenging to achieve an adiabatic transition for higher order modes [16, 17]. However a non-adiabatic transition can be used for LP_{11} mode stripping without deformation of the LP_{01} mode shape (generally a tight-bend mode stripper deforms the fundamental mode). At 9mm elongation length, about 10dB rejection was achieved. In this region there is no coupling to the second fiber which is essentially redundant, light is simply coupled into the fiber cladding and lost. This higher-order mode filtering effect can also be observed in a single fiber taper and the rejection efficiency can be further improved by applying a high index jacket to strip out any light in the cladding at the tapered section [18, 19]. Figure 2(a) is a schematic of a tapered DMF, encapsulated within a silica capillary with a UV curable polyacrylate coating (n = 1.5), providing a robust packaged format. Near 25dB LP_{11}-mode rejection was achieved over a wide wavelength range (1500~1600nm) as shown in Fig. 2(b) and the insertion loss of the fundamental mode was less than 0.2dB.

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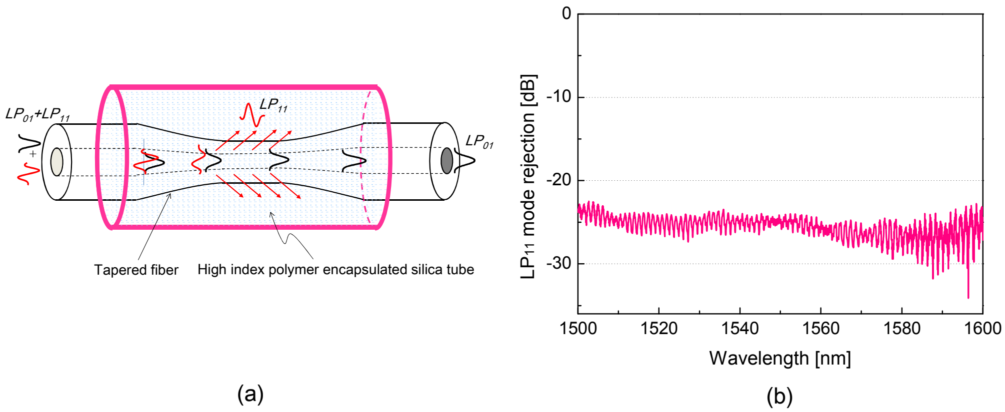

Fig. 2. (a) Schematic of tapered dual mode fiber mode stripper and (b) measured mode suppression ratio for LP_{11} mode.

2.2 LP_{11} mode tap coupler

The LP_{11} mode starts to couple at a pulling length of around 13mm where the LP_{01} mode power transfer happens only after a pulling length of 22mm. This means that the power of the LP_{01} mode does not change while the power of the LP_{11} mode transfers into the other branch, which offers the possibility to realize an LP_{11} mode tap coupler. This behavior is due to the fact that the evanescent tail of the higher-order mode profiles extends further into the cladding during stretching and light begins to couple into another arm at an earlier pulling stage. As an example of an LP_{11} mode tap coupler, a 1% tap coupler (20dB tap coupler) was fabricated by stopping the tapering process around 15mm elongation length. As shown in Fig. 3, a reasonable 1% tap coupler was obtained over a spectral range of 1500nm to 1550nm. The excess loss was measured to be less than 0.1dB at 1510nm, which is comparable to that of a single mode fused coupler, although this increased at longer wavelengths (up to 2dB at 1590nm). The wavelength dependent excess loss is mainly due to the non-adiabatic taper transition of the LP_{11} mode and could be improved by using a DMF with an index-matched cladding.

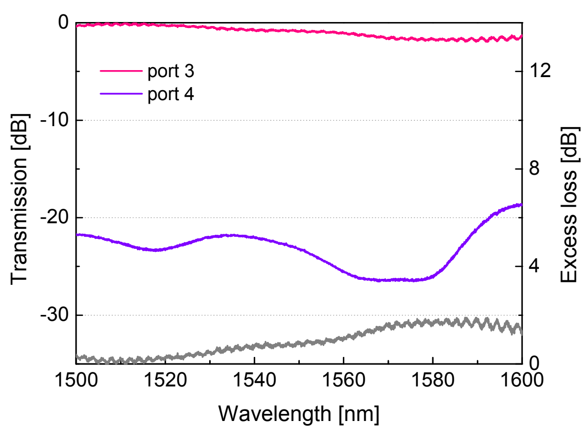

Fig. 3. LP_{11} mode tap coupler (splitting ratio = 1/99); total excess loss (grey line).

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2.3 50:50 power splitter for both LP modes

Thirdly, we can realize a 50/50 power splitter (3dB coupler) for both modes around 31mm elongation length, which represents the first modulation intersection point of the LP_{01} power transfer curve in Fig. 1(b). For the LP_{01} mode (Fig. 4(a)), it is evident that the coupler exhibits relatively equal (50%) power splitting at 1500nm but the coupling ratio at 1600nm is increased to 58%. The coupling ratio generally increases linearly with wavelength but the wavelength sensitivity can be mitigated by using an asymmetrical fiber coupler. By using dissimilar fibers (pre-tapering one of the identical DMFs), the difference in the propagation constants leads to incomplete power transfer between the fibers and a wavelength insensitive 3dB coupler can be realized [20, 21]. For the LP_{11} mode (Fig. 4(b)), the splitting ratio was roughly equal but the spectral response is oscillatory because the fusion process was stopped after two or three coupling cycles (highly over-coupled). Generally, the rate of change in splitting ratio with wavelength becomes faster with an increase in the pulling length (with decrease in size of the coupler waist). The excess loss in this case was less than 0.2dB for LP_{01} but ~3dB for LP_{11} due to the non-adiabatic transition. Clearly, a 3dB power splitting for both modes was achieved with a reasonable excess loss which is comparable to that associated with free space optics solutions used in current mode division multiplexed system. The excess loss and wavelength flatness of the dual mode coupler can be further enhanced by making the taper transition mode adiabatic and employing an asymmetric coupler approach. To place the utility of this device in context we note that in recent MDM systems research, photonic lantern or multi-spot based mode multiplexers [22, 23] have been introduced as a low loss signal multiplexers and have attracted much attention as a means to extending to a larger number of spatial channels. In contrast to the phase plate based mode-multiplexer, this mode-multiplexer does not excite particular modes of the fiber but launches the signal power into a linear combination of spatial modes, resulting essentially in mode-insensitive performance. As a consequence a mode-insensitive power splitter is likely to become a critical passive device in MDM transmission link and networks.

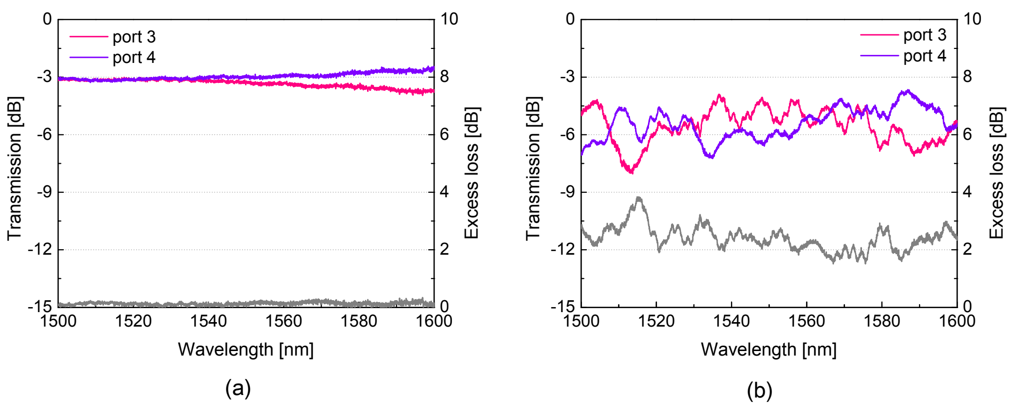

Fig. 4. Spectral dependence and excess loss (grey line) of dual mode 2 × 2 3dB power splitter (50/50) at pure (a) LP_{01} and (b) LP_{11} mode excitation.

3. Dual mode 3 × 3 fused fiber couplers

To demonstrate a larger port count coupler, we fabricated a 3 × 3 fused fiber coupler [24, 25]. The fabrication process used to produce a dual mode 3x3 fused fiber coupler is similar to that used for producing a 2 × 2 coupler and a 31mm elongation length was used to achieve an equal power splitting ratio. As depicted in Fig. 5, the powers in the three output ports are split reasonably equally however a strong wavelength dependency is observed. The wavelength

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flatness could be improved once again by employing an asymmetric coupler whilst the high excess loss could be minimized by using a DMF with index-matched cladding.

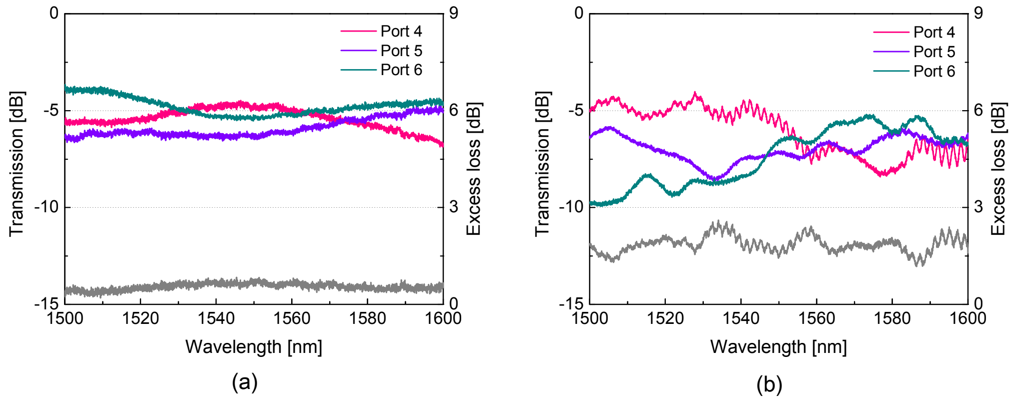

Fig. 5. Spectral dependence and excess loss (grey line) of dual mode 3 × 3 3dB power splitter (50/50) at pure (a) LP_{01} and (b) LP_{11} mode excitations.

4. Conclusion

We have fabricated both dual mode 2 × 2 and 3 × 3 fused fiber optic couplers and investigated their mode dependent coupling characteristics as a function of pulling length. The LP_{11} mode starts to couple first compared to the LP_{01} mode and various optical functions can be realized by choosing an appropriate pulling length. The most important characteristics of the dual mode fiber coupler were classified into three categories: i) an LP_{11} mode filter, ii) an LP_{11} mode tap coupler (1:99), and iii) a 50:50 mode insensitive power splitter for both LP modes. All-fiber fused components offering various optical functions could play an important role in developing practical mode division multiplexing systems.

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