Seven-core multicore fiber transmissions for passive optical network

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Abstract: We design and fabricate a novel multicore fiber (MCF), with seven cores arranged in a hexagonal array. The fiber properties of MCF including low crosstalk, attenuation and splice loss are described. A new tapered MCF connector (TMC), showing ultra-low crosstalk and losses, is also designed and fabricated for coupling the individual signals in-and-out of the MCF. We further propose a novel network configuration using parallel transmissions with the MCF and TMC for passive optical network (PON). To the best of our knowledge, we demonstrate the first bi-directional parallel transmissions of 1310nm and 1490nm signals over 11.3-km of seven-core MCF with 64-way splitter for PON.

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OCIS codes: (060.2360) Fiber optics links and subsystems; (060.2310) Fiber optics; (060.4510) Optical communications.

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1. Introduction

Passive optical networks (PONs) are now being deployed in large numbers worldwide for broadband access services [1,2]. The rapid growth in data traffic has recently led to an exponentially growing demand for capacity in access networks [3]. This has driven an increasing need for high counts of feeder fibers, causing congestion problems in some duct

#126920 - $15.00 USD Received 13 Apr 2010; revised 5 May 2010; accepted 5 May 2010; published 11 May 2010

pipes. Hence, low cost, high fiber count, high density cables are necessary to construct practical PON systems for future optical access networks. Multicore fiber (MCF) offers a possible solution to increase the fiber density and overcome cable size limitations and duct congestion problems. Design and fabrication of several types of MCFs have been reported to address this need for high density while maintaining low loss and low crosstalk [4–7]. The crosstalk level, i.e. the maximum power transferred between the cores, is determined by the detailed core and clad index profiles as well as the core-to-core distance. The core density is dominated by the core-to-core distance. The index profile, core geometry, and coating also affect micro- and macro-bending loss. Therefore, a comprehensive design is necessary to optimize overall optical fiber parameters for MCF. Another important problem is connectivity: commercial use of MCF requires low-cost reliable splicing and coupling of signals into and out of the closely-spaced individual cores. Hence, a low-crosstalk and low-loss fiber device that enables coupling to individual cores is important for parallel MCF transmissions.

This paper reports a novel MCF with seven-cores arranged in a hexagonal array, which exhibits low crosstalk at wavelengths between 1310nm and 1490nm. The MCF properties such as low crosstalk and attenuation are described and the practical technical issues in use of MCF including fiber splicing and coupling of individual signals in MCF are discussed. A new tapered multicore fiber connector (TMC) with ultra-low crosstalk and low insertion losses is designed and fabricated for coupling the individual signals in-and-out of the MCF. For the first time, we propose a novel network configuration using MCF parallel transmissions to increase the fiber density and increase the optical network end users at the subscriber premises of a PON. Simultaneous transmissions of seven 1310nm upstream and seven 1490nm downstream signals at 2.5 Gb/s over 11.3-km of seven-core MCF with a split ratio of 1:64 are demonstrated for PON.

2. Seven-core multicore fiber

The MCF is designed for single-mode operation in the 1310nm and 1490nm region and is made of seven 8-μm core diameter cores arranged in a hexagonal array with 38-μm core-to-core pitch. The glass cladding diameter is 130 μm and the acrylate dual coating diameter is 250 μm. The measured cutoff wavelength for each core is about 1200nm, and mode field diameters (MFD) at 1300 and 1490 nm are 8.3 and 9.3 μm respectively. All cores have index about 0.0046 above silica surrounded by cladding index of −0.0012 relative to silica, resulting in a core-clad index difference n_{core}-n_{clad}~0.0058. The dispersion and dispersion slope at 1490 nm are about 10.5 ps/nm-km and 0.059 ps/nm^2-km respectively, and all cores have same dispersion and dispersion slope values.

The transmission loss spectra of 11.3-km MCF, measured by cutback technique, are shown in Fig. 1 (a). The center core has 0.39 dB/km and 0.30 dB/km attenuation at 1310nm and 1490nm respectively. Average losses for 6 outer cores are 0.41dB/km and 0.53dB/km at 1310nm and 1490nm respectively. The loss of the center core and the short-wavelength (~1310nm) loss of the outer cores are close to the losses in conventional standard single mode fiber (SSMF). In comparison, the losses of conventional SSMF at wavelength 1310nm and 1490nm are about 0.35dB/km and 0.24dB/km, respectively. The loss for outer cores at 1490-nm is higher than loss in conventional SSMF, due to micro-bending loss and interactions with the coating at close proximity (for example core-coating effective index matching [8]). This loss of outer cores at longer wavelength can be reduced by optimized design of the cutoff wavelength and/or increasing the outer clad diameter [5]. In particular, we calculated the tunneling loss using a two dimensional finite difference vector model solver using a perfectly-matched non-reflecting boundary layer [9]. This tunneling loss introduces an excess attenuation in the outer cores above that in the center core. Figure 1 (b) shows the calculated tunneling and macrobend losses (15 cm diameter bend) for the 130 um clad diameter fiber in which the outer core centers are 27 um from the coating are similar to the measured excess loss. This indicates that this tunneling loss can be made negligible by increasing the fiber clad

#126920 - $15.00 USD Received 13 Apr 2010; revised 5 May 2010; accepted 5 May 2010; published 11 May 2010
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diameter to 140μm such that the outer core centers will be 32 um from the coating while keeping the same 38 μm core pitch.

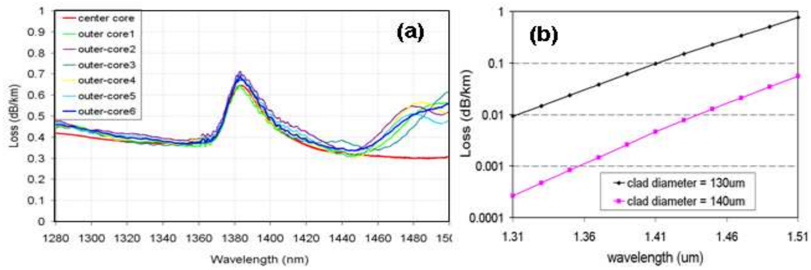

Fig. 1. (a) Measured attenuation spectra of 7-core MCF, (b) Calculated tunneling loss versus wavelength for clad diameter of 130μm and 140μm. This tunneling loss introduces an excess attenuation in the outer cores above that in the center core.

The optical crosstalk between adjacent cores is an important problem. The optical crosstalk from the centre core to adjacent outer cores is measured by scanning the optical power intensity distributions at the output endface of the fiber using 1 meter of SSMF. A MCF with 11.3-km length is reeled in a 28cm-diameter spool and the centre core is spliced to 1-meter of SSMF launching 1310nm or 1490nm signals. The crosstalk is defined by the ratio of optical power detected at 6 outer cores to the optical power detected at center core at end of 11.3-km MCF. Figure 2 shows an example of optical power distribution vs. radius. The local maximum crosstalk occurs at about 38-μm radial position that is the center of the adjacent core. The crosstalk for the 6 outer cores from center core after 11.3-km are shown in Table 1. Maximum crosstalk is less than −38dB at 1310nm, and less than −24dB at 1490nm, consistent with the expected increased evanescent penetration through the cladding at longer wavelengths [10], where the mode effective index is smaller, and MFD is larger. Note that compared with the case of signal transmission through one core, the worst-case crosstalk would be 6 times for center core and 3 times for outer cores when all 7 cores carry signals simultaneously. It should also be pointed out that the characteristics of crosstalk in MCF not only depend on the fiber design such as index, core diameter and core-pitch but also on fiber length [6] and the fiber layout (e.g. bending, twist) along the optical links [10].

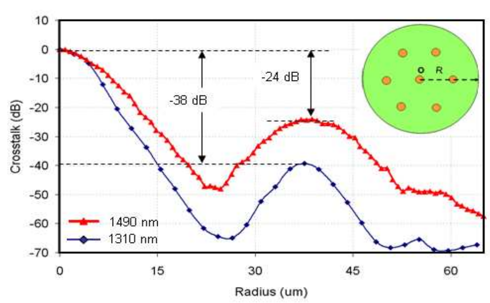

Fig. 2. Examples of the relative power versus the radius for crosstalk measurements.

Table 1. Crosstalk Characteristics

Core #	Crosstalk 1310 nm (dB)	Crosstalk 1490 nm (dB)
Outer core 1	−38.0	−24.0
Outer core 2	−39.8	−25.5
Outer core 3	−39.1	−24.7
Outer core 4	−40.2	−25.4
Outer core 5	−38.3	−24.0
Outer core 6	−38.5	−25.1

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3. MCF connectivity

Because several cores are densely packed in a small region, the connectivity of each individual core between MCF becomes very difficult. For example, splicing of the MCF requires careful precision alignment. Practical use of MCF requires coupling of signals into and out of each core independently. To overcome this problem, a new TMC is designed and fabricated and the structure of TMC is illustrated in Fig. 3. The TMC preserves individual cores at both ends of the connection. Seven single core fibers are tapered together to match the MCF spacing. One end of the resulting taper can then be connected to the 7-core MCF via fusion splicing, while the other end consists of seven individual single-core fibers. It should be noted that the TMC is different from tapered fiber bundle (TFB) [11] which is often used for coupling pump light sources into cladding pumped fiber lasers and amplifiers [12]. As shown in Fig. 3, the TMC keeps the individual cores at both ends of the connection, and so prevents cross-talks or optical power coupling between cores. In contrast, a TFB merges lightfrom multiple cores into a single core [11]. In order to achieve a low crosstalk and low insertion loss in TMC, a special single-mode fiber is used. Experimental results for insertion loss and crosstalk of two seven-core TMCs are shown in Table 2. The insertion loss for each connector of the TMCs ranges from 0.38 dB to 1.8 dB, and the crosstalk between cores is less than −38 dB. The slightly high coupling loss of some cores can be readily reduced by improving core matching.

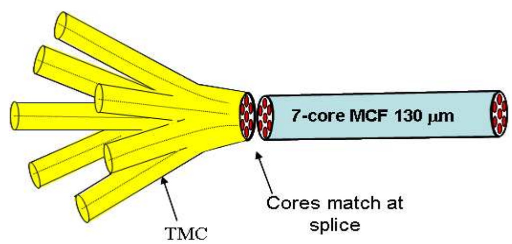

Fig. 3. Schematic diagram of tapered multicore fiber connectors.

Table 2. Insertion Loss and Crosstalk of TMCs

	TMC #1		TMC #2	
Core #	Loss (dB)	Crosstalk (dB)	Loss (dB)	Crosstalk (dB)
Center core	1.6		0.38	
Outer core 1	1.8	−37.9	1.6	−40.8
Outer core 2	1.1	−39.0	0.9	−39.3
Outer core 3	1.4	−41.1	1.2	−43.8
Outer core 4	1.8	−39.6	1.0	−41.8
Outer core 5	1.3	−42.1	1.3	−41.8
Outer core 6	1.4	−38.7	0.9	−43.8
Average	1.48	−39.8	1.17	−41.8

Splicing of MCF is also an important consideration, and each core of the MCF should have precision alignment to achieve low splicing loss. Hence, it is necessary to perform rotational fiber core alignment in addition to lateral alignment. An experimental set-up for investigation of splicing properties of MCF is shown in Fig. 4. A stable laser source at 1310 nm is divided into seven outputs and connected to a TMC. Another TMC is connected to seven power meters. Two meters of seven-core MCF are connected to the TMC via fusion splicing (Fig. 4 (a)) using a polarization maintaining (PM) splicer (Ericsson FSU995PM). The optical power meters are carefully calibrated and the optical powers are recorded. After optimizing the splicing parameters, it is found that the precise alignment of each core can be obtained by automatic alignment. Low loss splicing between the MCF can be achieved by

#126920 - $15.00 USD Received 13 Apr 2010; revised 5 May 2010; accepted 5 May 2010; published 11 May 2010
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conventional PM splicer. Figure 4 (b) shows the recorded splicing loss for 10 repeated fusion splices. The average splice loss is about 0.10 dB which is similar to the splicing loss of conventional PM fiber.

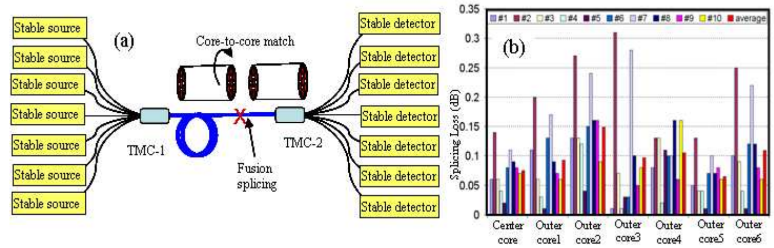

Fig. 4. (a) experiment set-up for study the splicing property of MCF, (b) splice losses of each core of seven-core MCF using PM fusion splicer.

4. Seven-core MCF parallel bidirectional transmission experiment

We propose a novel network configuration using MCF parallel transmissions to increase the fiber density and increase the optical network end users at subscriber premises of a passive optical network (PON). Figure 5 shows a schematic diagram of a PON employing a 7-core MCF and two TMCs which are used to couple the individual signals in-and-out of the MCF. At a central office (CO), seven optical line terminals (OLT), each comprised of PON transceivers [1490nm downstream (DS) signal transmitter and 1310nm upstream (US) receiver], are connected to the TMC via seven single-core fibers, and the TMC is connected via fusion splice to the 11.3-km seven-core MCF. At the remote node (RN), a second TMC is connected via fusion splice to the MCF, and each of seven pigtail fibers at the other end of the TMC is connected to optical fiber splitters (e.g. with 1:64 splitting ratio). Each splitter is then connected to optical network units (ONU) at the subscriber premises.

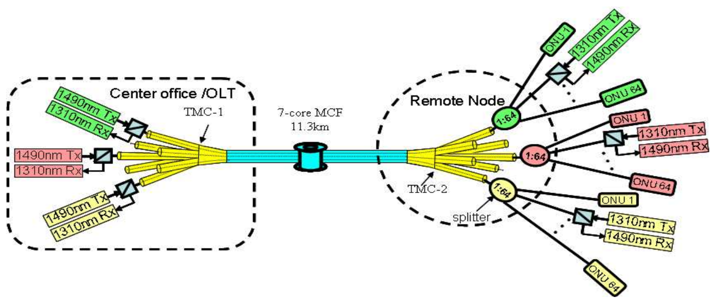

Fig. 5. Schematic diagram of a PON system using a 7-core MCF and two TMCs, 1310nm and 1490 nm DFB diodes as transmitters, APD as receivers.

Table 3. Total Link Losses

	Fiber loss (dB/km)	Loss (dB) 11.3 km MCF	Loss (dB) TMC #1	Loss (dB) TMC#2	Loss (dB) 1:64 splitter	Total link loss (dB)
Center core (1310 nm)	0.39	4.41	1.64	0.38	21.0	27.4
Outer cores-averaged (1310 nm)	0.41	4.63	1.48	1.16	21.0	28.3
Center core (1490 nm)	0.30	3.39	1.64	0.38	21.0	26.4
Outer cores-averaged (1490 nm)	0.53	5.99	1.48	1.16	21.0	29.6

The experimental set-up to demonstrate our novel PON configuration for parallel bidirectional transmissions using 7-core MCF is illustrated in Fig. 5. Seven commercially available un-cooled DFBs at 1310nm and 1490nm with 3 dBm output power are used as the

#126920 - $15.00 USD Received 13 Apr 2010; revised 5 May 2010; accepted 5 May 2010; published 11 May 2010
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US and DS transmitters and APDs are used as the receivers. The 64-way splitters are set to be 21 dB and total link losses are shown in Table 3. For the center core, total link losses are 27.4 and 26.4 dB at wavelength 1310nm and 1490nm respectively. For outer cores, the averaged link losses are 28.3 and 29.6 dB at 1310nm and 1490nm wavelength respectively. The DFB LDs at 1310nm and 1490 nm are directly modulated at 2.5 Gbit/s (2^{31}-1 PRBS) by electrical signals generated by a pattern generator, amplified and divided with different lengths of microwave cables.

Figure 6 shows the bit-error-ratio (BER) performance for 7-core parallel bi-directional transmission over 11.3-km MCF with 1:64 splitter, with all cores operating through the system simultaneously. It can be seen in Fig. 6 (a), that there is virtually no penalty for 1310nm US when all 7 cores simultaneously operate (core#-all) vs. one core transmits only (core#-only); this means there is no impact from crosstalk between cores. When all cores operate, the 1490nm DS BER performance (see Fig. 6 (b)) is degraded by about 0.8dB and 1.7 dB (at BER 10^{-11}) for outer cores and center core (dashed blue line) relative to that when only one core operates, respectively. It should be pointed out that the center exhibits −17.4 dB crosstalk when all six outer cores are simultaneously transmitted signals, in comparison that the outer core has about −24 dB crosstalk when center core operates only (see Table 1). This is because the center core has 6 times (~7.8dB) nearest neighbors. However, there is no indication of error floors, and error free 7-core MCF transmission is obtained for both 1310-nm US and 1490-nm DS, demonstrating parallel multi-core fiber transmission of 11.3-km fiber with 1:64 way splitter ratio for PON applications

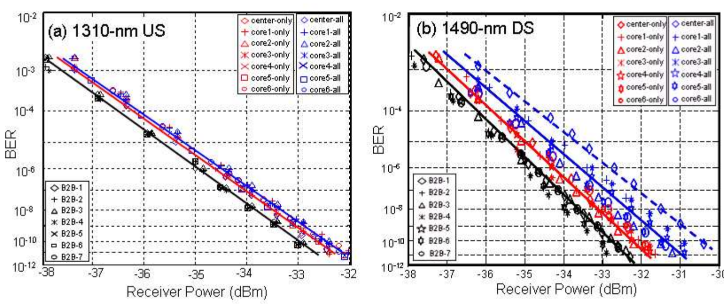

Fig. 6. BER performance for 1310nm US (a) and 1490nm DS (b) for all 7-core parallel transmission with 1:64 splitter for three cases: back-to-back (B2B, black), one core transmits only (core#-only, red) and all cores operate through the MCF simultaneously (core#-all, blue).

5. Summary

We designed and fabricated a novel 7-core MCF for construction of high density and high count optical fiber cables. The fiber properties of MCF including low crosstalk, attenuation and splicing loss are reported. A new TMC with ultra-low crosstalk for coupling the individual signals in-and-out of the MCF was also designed and fabricated. By using TMCs, we have demonstrated simultaneous transmissions of 1310nm US and 1490nm DS signals at 2.5 Gb/s over 11.3-km of 7-core MCF with a split ratio of 1:64 for PON, thus it can serve a total of 448 end-users at the subscriber premises from a single fiber. Further reduction in cost and power consumption of PON can be realized by using a 2-D VCSEL/PIN array which can be butt-coupled with MCF as the transmitter and receiver in a CO OLT [13], where each VCSEL can be directly modulated for DS and be transmitted through MCF and RN to ONUs at the subscriber premises.

Acknowledgements

We thank David DiGiovanni at OFS Labs for his encouragement and support, and we also thank Dr. Russell Davey at BT for his inspiring discussion on multicore fiber for access network applications.

#126920 - $15.00 USD Received 13 Apr 2010; revised 5 May 2010; accepted 5 May 2010; published 11 May 2010
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