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Abstract. Bandwidth demand for transferring data among different consumer electronic products is increasing rapidly. Due to issues of high propagation loss, electromagnetic interference, and limited bandwidth-distance product of the present copper-based electrical cables, consumer electronic devices may not provide the bandwidth required for future high-capacity applications. The Intel Corporation has proposed Light Peak technology, allowing data transfer between electronic devices at 10 Gb/s in optical domain. To establish a reliable Light Peak connection, robust optical fiber is highly required. In this paper, we discuss the fabrication and characterization of a new type of 80-μm large-core optical fiber. We perform 10 Gb/s bit-error-rate measurements using 850 and 1550-nm transceivers. The results show that even though we have enlarged the fiber core diameter by 60% (from 50 to 80 μm) in order to increase the laser-to-fiber alignment tolerance, transmission bandwidth and distance required by Light Peak can still be achieved in this new type of large-core optical fiber. [DOI: 10.1117/1.OE.51.1.015006]

Subject terms: large-core optical fiber; fiber design; multimode fiber.

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1 Introduction

It is believed that the present copper-based electrical cables, such as universal serial bus cable and high definition multimedia interface cable, will hit the bandwidth limit soon due to the ever-increasing demand for bandwidth by home customers. Besides, high propagation loss and electromagnetic interference are other issues limiting the reach of present copper-based cable to only a few meters. Hence, using optical fiber to replace copper-based cable in high-capacity and long-distance interconnections is a promising solution. The Intel Corporation has proposed Light Peak technology for high-capacity cable connections, providing information transfer between electronic devices at 10 Gb/s.[1] This means a full length high definition movie can be transferred between consumer devices within 30 s. Light Peak technology will support a direct network of peripheral devices with up to 100 m in length.[1] However, for applications of peripheral devices, wear and tear of the cables is unavoidable. This will produce damage and optical-coupling misalignment to the optical cable, affecting the performance of the peripheral devices.

To establish a high-performance and reliable Light Peak link in hot-plug, robust optical fiber is highly desirable. Thus, recently many efforts have been made to design and manufacture a new type of optical multimode fiber (MMF). Large-core optical fibers can provide important features, such as high tolerance to input optical power, a high optical nonlinearity threshold, and a high tolerance to optical offset launching, among others.[2,3] One of our particular designs for Light Peak application is 80-μm core-diameter large-core optical MMF. Due to the increase in numerical aperture (NA) to ~0.3 of the 80-μm MMF (the NAs of conventional single-mode fiber and 50-μm MMF are ~0.14 and ~0.2, respectively), higher tolerance to offset laser launching is achieved. This means that the alignment accuracy between laser source and fiber can be greatly reduced, which can thus cut down the cost. Besides, if fiber connectors are used, fiber plug-in and pull-out is unavoidable in home electronic devices. And high attenuation due to fiber wear-out and fiber-to-laser misalignment could occur. Large-core MMF can increase the surface area for optical coupling and hence increase the lift time of the optical cable. Although large-core MMF is highly desirable, one concern is that the larger fiber core size (from 50 to 80 μm) may increase intermodal dispersion,

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hence limiting the bandwidth and distance of the connection link.

In this paper, we present our design and successful fabrication of the 80-μm large-core MMF. We performed 10 Gb/s bit-error-rate (BER) measurements using a commercially available 850-nm transceiver, showing that the error-free 100-m connection link can still be achieved in the new type of large-core MMF with negligible power penalty. Error-free 10 Gb/s transmission at 1550-nm wavelength was also performed.

2 Design and Fabrication

To fabricate high bend-radius optical MMF for the Light Peak application, the refractive index difference between the core and the cladding should be increased. Corning Incorporated[4] has proposed using a nanostructure layer surrounding the fiber core to reduce the effective refractive index. However, this technique increases the manufacturing complexity and hence the manufacturing cost. Also used was the Sol-Gel process[5] to deposit a layer of MgF_2-SiO_2 thin film surrounding the core to reduce the refractive index. The process has the advantages of low cost and simplicity. However, it can deposit only a ~1-μm film layer, which may not be thick enough to prevent light escaping from the fiber core during very high bending. Here, we used the modified chemical vapor deposition process[6–8] to introduce SiF_4 for producing the thick layer of low refractive index. Besides, we used a thinner-walled silica support tube to increase the yield. Figure 1 shows the successfully fabricated fiber preform of large-core MMF. It is about 60 cm in length. Then the preform will be drawn into 80/125 MMF for characterization. The refractive index of the core and the tetrafluoride cladding layer of the large-core MMF are 1.4848 and 1.4162, respectively.

3 Experiments and Characterization

We test the bending loss of the fiber using an 850-nm light source. The fiber was wrapped around a metal rod with diameter of 10 mm. The bending loss was measured at different numbers of turns, as shown in Fig. 2. We can observe that the bending loss of the fiber was <0.03 dB when the fiber was wrapped around the metal rod by ten turns.

We then characterize the differential mode delay (DMD) of 3-km-long, 80-μm large-core MMF. In the DMD

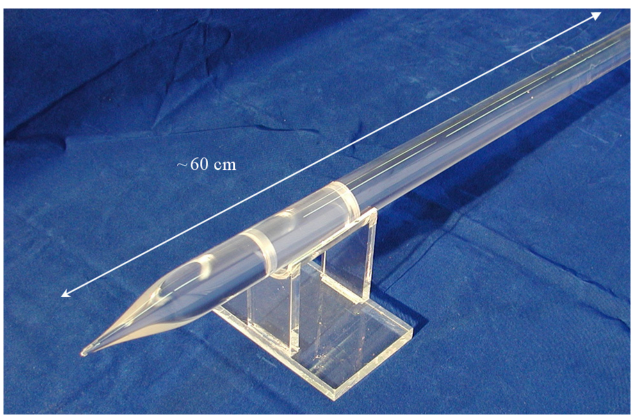

Fig. 1 The successfully fabricated preform of the 80-μm large-core optical MMF. (Color online only.)

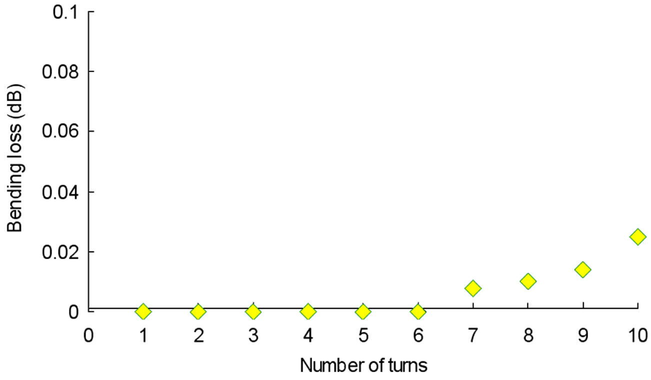

Fig. 2 Bending loss of the large-core MMF. (Color online only.)

measurement, a short optical pulse was launched at one of the facets of the MMF, and the optical signal was measured at the output fiber facet. The DMD measurement was repeated, starting at the axis of the MMF core and moving outward to the core/cladding interface. For a given offset launching, only a weighted subset of all the possible mode groups was excited in the MMF. At the next offset launching location, a different weighted subset of mode groups was excited. The different mode groups will have different propagation times. By measuring the time difference between 25% of the leading edge of the fastest pulse and 25% of the trailing edge of the slowest pulse, divided by the total fiber length, the DMD values can be calculated.[9] The measured DMD value of 80-μm large-core MMF was 0.16 ps/m when using an 850-nm laser source. The attenuation at 850 nm was 4.64 dB/km. DMD is an industrial standard measuring the maximum difference between the delays of optical pulse propagating in one mode group compared with others within the MMF. It is a fast estimation method of fiber bandwidth.

BER measures (number of bits in error)/(total bits transmitted). It is the most accurate method to evaluate the performance of the fiber link. We performed 10 Gb/s BER measurements (a pseudorandom binary sequence of $2^{31} - 1$) using a commercially available 850-nm transceiver. Figure 3 shows the experimental setups of the BER measurements: The pattern generator of the BER tester (BERT) was directly connected to the 850-nm transmitter (Tx) to generate the 10 Gb/s optical signal. A variable optical attenuator (VOA) was used to vary the input power to the 850-nm receiver (Rx) for the BER measurements. Figure 4 shows that error-free ($BER < 10^{-9}$) 100-m transmission can be achieved with negligible power penalty.

For future applications, the capability of working at the 1550-nm wavelength is also required. Hence, a 10 Gb/s BER measurement at 1550 nm was also performed. In this measurement, shown in Fig. 3(b), a continuous wave generated by a distributed feedback (DFB) laser was modulated by a Mach-Zehnder modulator (MZM), which was electrically driven by 10 Gb/s non-return-to-zero data from the BERT. A 10-GHz, 1550-nm PIN photodiode (PD) was used at the Rx [Fig. 3(d)]. Figure 5 shows that error-free 100-m transmission can also be achieved with negligible power penalty at 1550-nm. The differences between the Rx sensitivities shown in Figs. 4 and 5 are due to different sets of Tx and Rx used for the 850 and

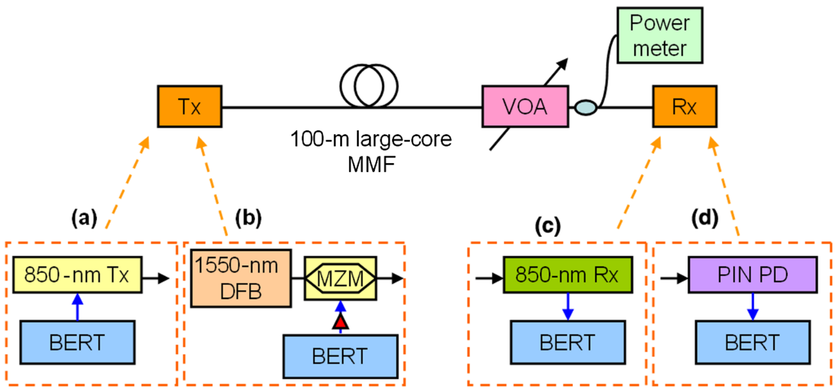

Fig. 3 Experimental setup of the BER measurements at (a) and (c) 850 nm and (b) and (d) 1550 nm. (Color online only.)

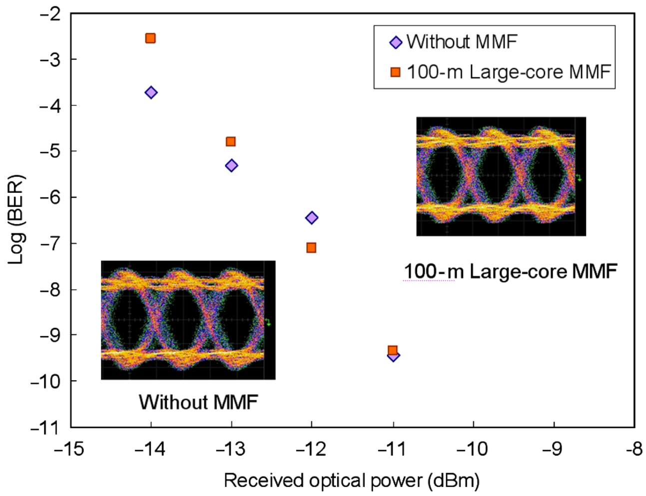

Fig. 4 Measured 10 Gb/s BER at 850-nm wavelength without and with the MMF. (Color online only.)

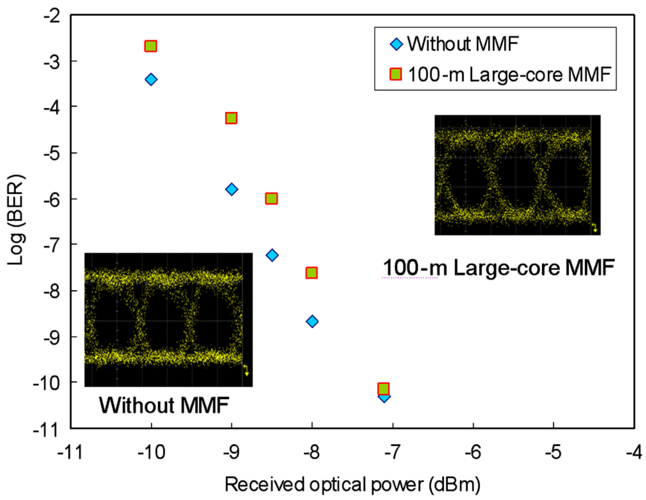

Fig. 5 Measured 10 Gb/s BER at 1550 nm wavelength without and with the MMF. (Color online only.)

1550-nm measurements. The measured bandwidth-distance product of the large-core MMF at 850 nm is 3067 MHz · km, which has the same order of magnitude when compared with commercially available 50-μm-diameter MMF. However, by using a mode-field matched center-launching technique[10] or an incoherent input light source,[11] >10 Gb/s data rates and over 1-km MMF transmission are possible.

4 Conclusion

We discussed the fabrication and characterization of a new type of 80-μm large-core optical fiber for Intel Light Peak. We performed 10 Gb/s BER measurements at 850 and 1550 nm, showing that error-free ($BER < 10^{-9}$) 100-m transmission can be achieved with negligible power penalty. All the experimental results confirm that even though we have enlarged the core diameter by 60% (from 50 to 80 μm) in order to increase the laser-to-fiber alignment tolerance, the transmission bandwidth and distance required by Light Peak can still be achieved in this new type of MMF.

Acknowledgments

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Gary Chou: biography and photograph are not available.