Hard Polymer Cladding Fiber (HPCF) Links for High-Speed Short Reach 1 × 4 Passive Optical Network (PON) Based on All-HPCF Compatible Fused Taper Power Splitter

D. U. Kim, S. C. Bae, J. Kim, T.-Y. Kim, C.-S. Park, and K. Oh

***Abstract*—We report a novel 4 × 4 hard polymer clad fiber (HPCF) splitter fabricated by a fusion and tapering technique showing an excess loss less than 4.58 dB and insertion loss of 10.50 dB, which can be directly applied in short reach (SR) HPCF optical links. The device also showed an excellent uniformity in the power splitting ratio with power fluctuation less than 0.25 dB over a wide spectral range, 600–900 nm, which can significantly alleviate the spectral requirements in transmitters and enable wavelength-division multiplexing. The 1 × 4 passive optical network SR HPCF link for Ethernet communication was experimentally demonstrated over 100 m of HPCF at the data rate of 1.25 Gb/s for the optical signal at 850 nm.**

***Index Terms*—Fusion-tapering technique, hard polymer clad fiber (HPCF), optical power splitter, passive optical network (PON), power budget, short reach (SR) link.**

I. INTRODUCTION

AS OPTICAL communication technologies are finding their applications in access networks and optical interconnections, optical fibers with large core areas have been on focus especially for short reach (SR) or very short reach (VSR) applications. In the field of SR and VSR, new applications of optical transmission techniques are being rapidly developed for applications such as access and customer premise networks, factory automation, traffic control and monitoring, as well as medical image transmission. Conventional silica-based single-mode fibers (SMFs) would be a costly solution for these applications because it requires precise connection and dedicated installation. Robust hard polymer clad fibers (HPCFs) as well as glass multimode fibers (MMFs) and polymer optical fibers (POFs) are being adopted in the SR/VSR environment to overcome the difficulties of glass SMFs.

POF communication technologies have been developed to take the advantages of flexible installation and optical connections [1], [2]. HPCFs, having much larger core than silica SMF and MMFs, are also expected to provide viable solution for SR/VSR applications due to its high source-to-fiber coupling efficiency and tolerance [3], [4]. HPCFs also have merit over plastic optical fiber (POF) in terms of thermal and mechanical robustness. Despite these advantages, HPCFs have been implement only in point-to-point optical links [5], and in order to be applied in point-to-multipoint networks such as passive optical networks (PONs), new power splitters compatible to HPCF should be developed in an analogous manner as planar lightwave circuitry chips and fused taper fiber splitters were developed for glass SMF PONs [6], [7].

In this letter, we experimentally demonstrate a new 4 × 4 HPCF power splitter using a novel fusion-tapering technique and applied it to 1 × 4 HPCF PON link carrying 1.25-Gb/s Ethernet frame, for the first time. The technique can be readily applied in other types of SR links utilized with perfect power uniformity in the output ports, low excess, and insertion losses, along with mass production capability.

II. DEVICE FABRICATION AND CHARACTERIZATION

For SR POF networks, there have been reports on various types of power splitters such as the Y-shaped microoptic type, side polished type, diffused light type, and an active side-polished coupler using a liquid crystal in the intermediate coupling region [8]–[10]. But they all suffer from environmental reliability especially for humidity and temperature cycling, which strongly suggests a great demand in the optical power splitter based on silica glass such as HPCF to expand SR/VSR applications.

In order to secure the inherent environmental advantages of HPCF, we adapted the fusion-tapering technique for glass optical fiber [11], [12] and successfully established a new fabrication process for 4 × 4 HPCF fused taper splitters. The refractive index profile and the structure of fabricated splitter are shown in Fig. 1. The HPCF with a core diameter of 200 μm and an outer diameter of 230 μm had step refractive index of 1.45 and 1.40 for the core and the clad, respectively. In general, spectral and power uniformity of optical splitters strongly depend on the modal distribution in the coupling region. In the case of fused taper splitter, a longer fusion length will provide more uniform power distribution among output ports but excess losses tend to increase. In this work, the optimized fusion and tapering process was obtained to improve both the spectral uniformity and excess loss by *in situ* monitoring of the transmitted power from the output ports using a white light source, a power meter, and an optical spectrum analyzer during the fabrication process.

Manuscript received April 19, 2005; revised July 21, 2005. This work was supported in part by UFON, an ERC program sponsored by KOSEF, in part by BK21 supported by MOE, and in part by ITRC-CHOAN program in Korea.

The authors are with the Department of Information and Communications, Gwangju Institute of Science and Technology (GIST), Gwangju 500-712, Republic of Korea (e-mail: koh@gist.ac.kr).

Digital Object Identifier 10.1109/LPT.2005.857598

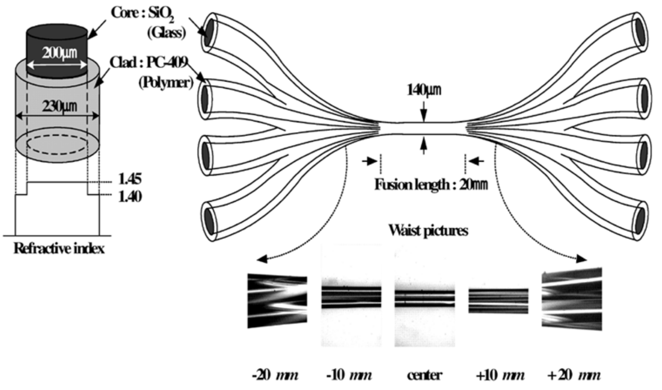
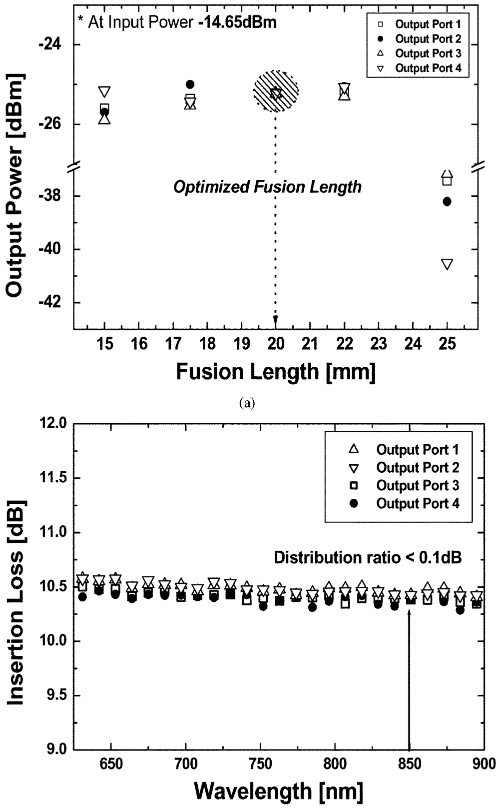


Fig. 1. Refractive index profile of HPCD and fabricated 4 × 4 HPCF fused taper splitter.



(a)

(b)

Fig. 2. Characterization of the fabricated 4 × 4 HPCF. (a) Output power versus fusion length at 850 nm. (b) Insertion loss versus wavelength of signal at fusion length 20 mm.

Optical transmission characteristics of a power splitter are generally described by the following parameters such as:

$$\begin{aligned}\text{Excess loss [dB]} &= -10\log(\text{sum}[P_{\text{output}}]/P_{\text{input}})\\ \text{Insertion loss [dB]} &= -10\log(P_{\text{output}}/P_{\text{input}})\\ \text{Distribution ratio [dB]} &= \text{MAX}_{\text{insertion loss}}\\ &\quad - \text{MIN}_{\text{insertion loss}}.\end{aligned}$$

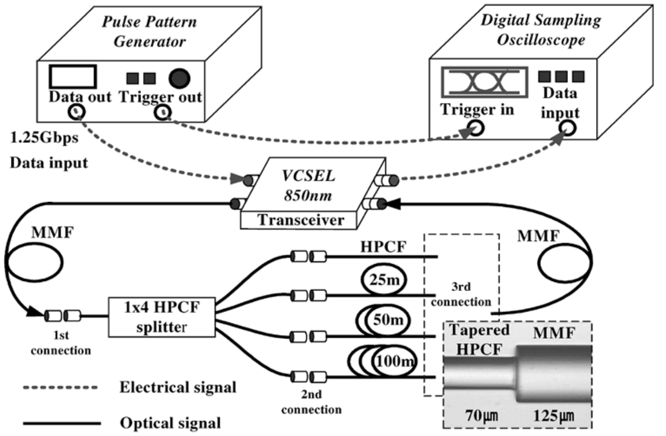


Fig. 3. Setup for optical transmission over HPCF with the proposed 1 × 4 power splitter.

In Fig. 2(a), the experimental results obtained for the output power of the four ports are shown for various fusion lengths. Here we used a laser diode power of −14.65 dBm. Very uniform output power splitting was obtained for the optimal fusion length about 20 mm and the difference in optical power among four output ports was less than 0.1 dB, which are the lowest values ever reported among HPCF compatible 4 × 4 splitters [6]. For this optical fusion length, the device showed the excess loss of 4.58 dB and the insertion loss of 10.50 dB.

The spectral distribution of the insertion loss over 600 to 900 nm at fusion length 20 mm is shown in Fig. 2(b). We could find that the device, indeed, had an excellent spectral uniformity with distribution ratio less than 0.25 dB over the whole spectral range, which has not reported thus far. The minimum power distribution ratio was less than 0.1 dB at 850 nm. The excellent uniformity strongly implies this device could be further applied in wavelength-division multiplexing over HPCF PONs.

III. OPTICAL LINK TRANSMISSION EXPERIMENTS AND RESULTS

Fig. 3 shows the setup for a optical transmission experiment over HPCF. A 1 × 4 HPCF power splitter was made by truncating three input ports of the fabricated 4 × 4 HPCF splitter with Subminiature version A (SMA) receptacles. One input port and four output ports were connected with an SMA-type connector with a large inner diameter ceramic ferrule. An 850-nm vertical-cavity surface-emitting laser transceiver was directly modulated by 1.25-Gb/s nonreturn-to-zero pseudorandom binary sequence $(2^{23} - 1)$ signals from the pulse pattern generator. In order to measure the transmission performance of this 1 × 4 HPCF PON link, eye diagrams and jitters over various HPCF lengths of 25, 50, and 100 m were observed by the digital sampling oscilloscope. Detection threshold and delay were optimized manually. There were two connections between 200-μm core HPCF and 62.5-μm core MMF. The coupling loss from MMF to the larger core HPCF was negligible yet the coupling from HPCF to MMF required a special tapering technique. The photograph shown in the inset of Fig. 3 shows fusion splicing between the down tapered HPCF and MMF. The outer diameter of HPCF silica core was adiabatically tapered down to 70 μm with a low tapering loss of 0.8 dB. The taper was then cleaved and fusion-spliced to MMF, which gave a coupling loss about 4 dB. The impact of transverse and longitudinal misalignments

TABLE I
ANALYSIS OF POWER BUDGET FOR A SHORT REACH NETWORK

Attenuation of 100m HPCF	0.6dB
Coupling loss from HPCF to HPCF	1.2dB
Coupling loss from Tapered HPCF to MMF	4.0dB
1x4 HPCF coupler insertion loss	10.5dB
Needed power budget	**16.3dB**
Output power of transmitter	-2.2dBm
Sensitivity of receiver @ BER of 10^{-12}, PRBS 2^7-1,NRZ	-20dBm
Available power budget	**-17.8dBm**
System margin	**1.5dB**

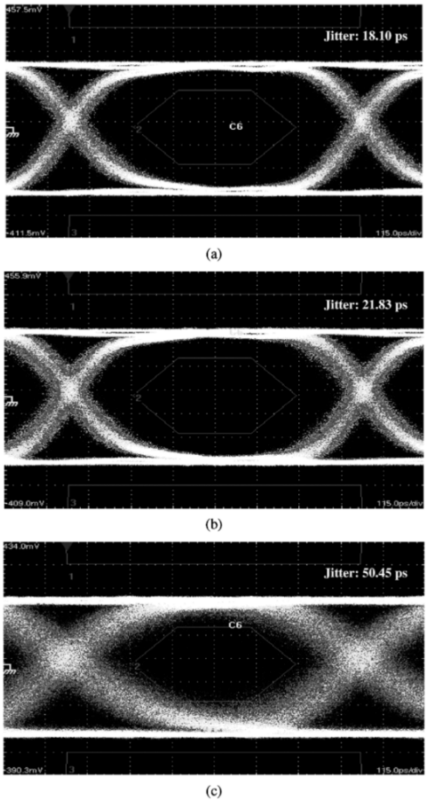


Fig. 4. Eye diagrams and jitters for HPCF transmission of 1.25 Gb/s at 850 nm, (a) 25 m, (b) 50 m, (c) 100 m.

were also measured for both HPCF to HPCF, and tapered HPCF to MMF coupling. In the case of HPCF to HPCF coupling, the transverse and longitudinal offsets were 33 and 313 μm at 1-dB penalty, respectively. In the other case, the transverse and longitudinal offsets were 16 and 155 μm at 1 dB penalty, respectively. The power budget for the experimental PON link setup is listed in Table I. A total power budget of 16.3 dB was required to compensate the total loss. For the given transmitter and receiver, we could obtain the power budget of 17.8 dB to result in the system margin of 1.5 dB. It is noteworthy that the system power budget can be significantly improved if the transceivers are directly pigtailed by HPCF, decreasing the coupling loss between the tapered HPCF and MMF.

Eye diagrams and jitters for 1.25-Gb/s Ethernet frame transmission through the proposed 1 × 4 HPCF PON links were measured for different HPCF lengths and the results are shown in Fig. 4. The eyes adequate for the Gigabit Ethernet mask were wide open after 25- and 50-m HPCF transmission and no significant power penalty was observed. Even for 100 m of HPCF, we could find that the eye diagram did not significantly deteriorate but jitter increased from 21.83 to 50.45 ps due to the modal dispersion in HPCF. Through the transmission experiments, we could confirm the proposed power splitter indeed works for 1 × 4 HPCF Gigabit PON link in the SR/VSR communication range.

IV. CONCLUSION

We successfully fabricated 4 × 4 and 1 × 4 HPCF optical power splitters using a fusion-tapering technique, which showed perfect power uniformity among output ports over wide wavelength range 600–900 nm with a low excess loss of 4.58 dB and insertion losses of 10.5 dB. Up to the link distance of 100-m HPCF, transmission of data rate of 1.25 Gb/s was demonstrated through the 1 × 4 splitter. Reduction in coupling loss from the better tapered HPCF to MMF or using an HPCF pigtailed transceiver would further improve the transmission performance within a reasonable power budget. Experimental results strongly indicate that the device can be readily applied to SR point-to-multipoint HPCF or POF links.

REFERENCES

[1] J. Zubia *et al.*, “Plastic optical fibers: An introduction to their technological processes and applications,” *Opt. Fiber Technol.*, vol. 7, pp. 101–140, 2001.

[2] Y. Koike *et al.*, “High-bandwidth graded index polymer optical fiber,” *J. Lightw. Technol.*, vol. 13, no. 7, pp. 1475–1489, Jul. 1995.

[3] S. Furusawa *et al.*, “Low-cost and high-speed optical transceiver using 850 nm VCSEL and hard polymer clad fiber,” presented at the Optical Fiber Communication Conf. (OFC 1998), San Jose, CA, Feb. 1998, Paper WI6.

[4] T. Ouchi *et al.*, “Direct coupling of VCSELs to plastic optical fibers using guide holes patterned in a thick photoresist,” *IEEE Photon. Technol. Lett.*, vol. 14, no. 3, pp. 263–265, Mar. 2002.

[5] S. Poferl *et al.*, “New physical layer concepts for optical data buses in automobiles,” presented at the LEOS’99, San Francisco, CA, Nov. 1999, Paper ThT1.

[6] T. Kibler *et al.*, “Planar star couplers for 200 μm multimode PCS fibers,” presented at the LEOS 2003, Tucson, AZ, Oct. 2003, Paper WX5.

[7] T. Kibler *et al.*, “Optical data buses for automotive applications,” *J. Lightw. Technol.*, vol. 22, no. 9, pp. 2184–2199, Sept. 2004.

[8] C. Chaudhari *et al.*, “A new technique for the reduction of the power loss in the Y-branch optical power splitter,” *Opt. Commun.*, vol. 193, pp. 121–125, Jun. 2001.

[9] O. Takanashi *et al.*, “High-uniformity star coupler using diffused light transmission,” *IEICE Trans. Electron.*, vol. E84-C, no. 3, pp. 339–345, Mar. 2002.

[10] J. Zubia *et al.*, “Design and measurement of a plastic optical fiber active couplers,” *IEEE Photon. Technol. Lett.*, vol. 10, no. 11, pp. 1578–1580, Nov. 1998.

[11] I. Yokohama *et al.*, “Fiber-coupler fabrication with automatic fusion-elongation processes for low excess loss and high coupling-ratio accuracy,” *J. Lightw. Technol.*, vol. LT-5, no. 7, pp. 910–915, Jul. 1987.

[12] T. A. Birks *et al.*, “The shape of fiber tapers,” *J. Lightw. Technol.*, vol. 10, no. 4, pp. 432–438, Apr. 1992.