# Development of Hard Plastic Clad Fiber (HPCF)-Compatible Devices and Demonstration of HPCF-PON

J. K. Kim, D. U. Kim, T.-Y. Kim, C.-S. Park, B. H. Lee, and K. Oh

***Abstract*—We report implementation and packaging of a whole line-up of hard plastic clad fiber (HPCF)-compatible devices: HPCF pigtailed 850-nm vertical-cavity surface-emitting lasers, HPCF pigtailed GaAs PIN photodiode, and 4 × 4 HPCF power splitter. Using these devices, an all-HPCF 4 × 4 passive optical network (PON) link suitable for short reach optical networks was successfully constructed. The PON link was operating well at a data rate of 1.25 Gb/s. The structures of the devices and their fabrication processes are discussed in detail along with characterizations of transmission performance by measuring the eye diagrams.**

***Index Terms*—Hard plastic clad fiber (HPCF), lensed fiber, passive optical network (PON), pigtailed photodetector (PD), pigtailed vertical-cavity surface-emitting laser (VCSEL), very short reach (VSR).**

## I. Introduction

In order to cope with demands for high-speed short reach (SR)/very short reach (VSR) networks, low-cost and robust optical components are being developed so that they are compatible to large core fibers such as hard plastic clad fiber (HPCF) as well as the conventional glass multimode fiber (MMF) and polymer optical fiber (POF) [1]. HPCF has drawn intensive attention in the notions that 1) the large core and high numerical aperture (NA) can relieve constraints in transmitter and receiver coupling compared with glass MMF [2], and 2) HPCF can sustain higher reliability against thermal and humidity changes compared with POF [3].

Despite these advantages, HPCFs have been implemented mainly for point-to-point optical links [4]. In order to be further applied in point-to-multipoint networks such as passive optical networks (PONs), power splitters compatible with HPCF are required in a similar manner as the planar waveguide and fused taper fiber splitters were developed for glass fiber PONs [5]. Recently, the authors reported successful development of 4 × 4 fused taper HPCFs [6], with a high uniformity in the power splitting ratio and low insertion loss.

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J. K. Kim, D. U. Kim, T.-Y. Kim, C.-S. Park, and B. H. Lee are with the Department of Information and Communications, Gwangju Institute of Science and Technology (GIST), Gwangju 500-712, Korea.

K. Oh is with the Institute of Physics and Applied Physics, Yonsei University, Seoul 120-749, Korea (e-mail: koh@yonsei.ac.kr).

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In this letter, we report further development of a whole line-up of HPCF-based optical components for SR/VSR optical communication, which includes an HPCF pigtailed vertical-cavity surface-emitting laser (VCSEL), PIN photodiode, and 4 × 4 fused taper HPCF splitter, all terminated with FC-type connectors. These components were assembled, then, to construct a 1 × 4 1.25-Gb/s PON network. Fabrication processes of individual devices and the transmission performances of the implemented PON link are discussed.

## II. Device Fabrication and Characterization

VCSELs have been regarded as highly potential light sources for MMF-optical data links in the 850-nm range due to their low threshold current, narrow circular beam divergence, and a low-cost packaging. However, a major problem with VCSELs is that they tend to lase in multiple transverse modes at high currents because of the spatial hole burning of the carriers in the active layer [7]. Direct VCSEL-to-fiber coupling was reported to be highly dependent on the driving current [8], showing fluctuations in far-field emission pattern at a higher current. Therefore, for the VCSEL-to-fiber coupling, the large core and high NA of HPCF can be utilized to suppress coupling variations along with an optimal focusing optics between the HPCF and the VCSEL.

First, we have designed a VCSEL-HPCF coupling package, as shown in Fig. 1. The HPCF with a core diameter of 200 $\mu$m and an outer diameter of 230 $\mu$m had step refractive indexes of 1.45 and 1.40 for the core and clad, respectively. The package structure is composed of a ferruled HPCF, a ferrule housing, a can housing, and a canned VCSEL as in Fig. 1. The specifications of the VCSEL were also listed in the table of Fig. 1. A ball lens having a 2-mm diameter and an effective focal length of 1.4807 mm at 850 nm was assembled with a VSCEL chip in a conventional TO-46 Can package. The tight focusing of the VCSEL beam with the ball lens enabled very stable coupling performances against the bias current changes. The HPCF-pigtailed VCSEL showed a low variation of 0.4 dB in the coupled power for different bias currents, from 3 to 7, and 8 mA, as shown in Fig. 2. The minimum coupling loss was 2 dB and the 1-dB tolerance was about 29 $\mu$m for both axial and transverse fiber displacements.

The polymer cladding was removed and the 200-$\mu$m silica core of HPCF was assembled with the ferrule, which was subsequently mounted on the metal ferrule housing by using a thermally curable epoxy. All components were aligned in an automated packaging assembly and then welded using a pulsed Nd : YAG laser. Finally, the pigtailed HPCF was then connectorized using the same ceramic ferrule with FC-type termination.

Second, we have designed a lensed HPCF-PIN photodetector (PD) coupling package, as shown in Fig. 3. The conventional

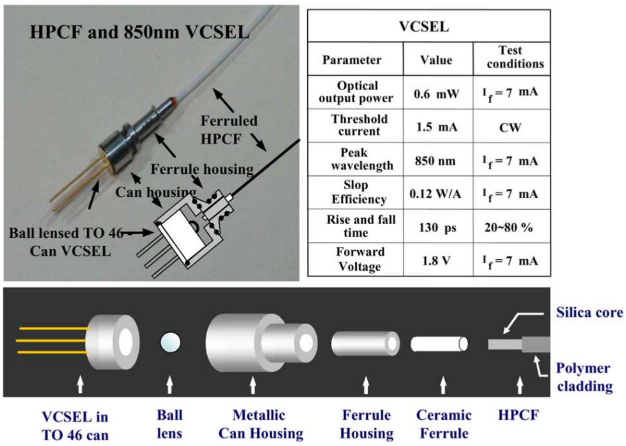


Fig. 1. Exploded diagram showing the different parts of the assembly of a pigtailed VCSEL and VCSEL specification.

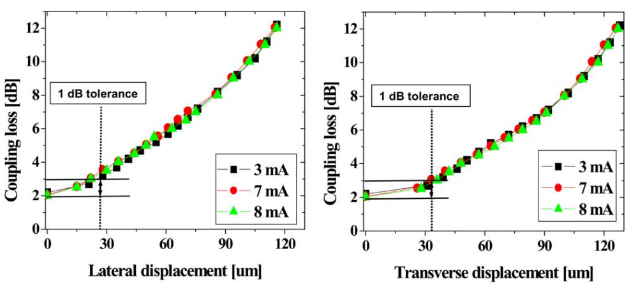


Fig. 2. Coupling loss versus lateral and transverse displacement between VCSEL and HPCF.

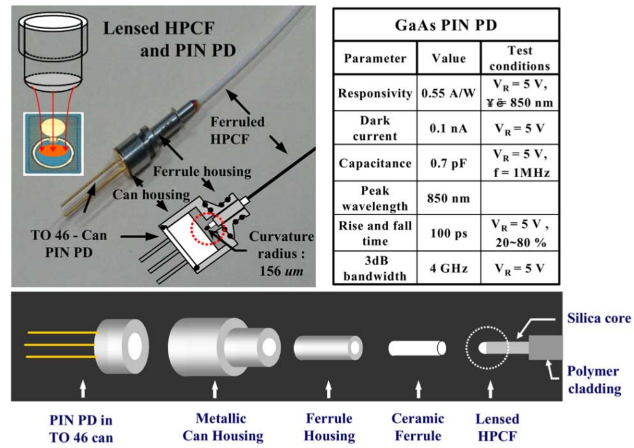


Fig. 3. Exploded diagram showing the different parts of the assembly of a pigtailed PIN PD and PD specification.

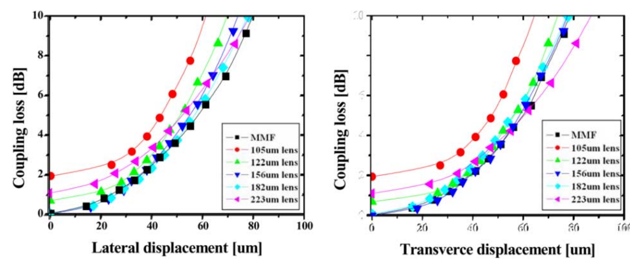


Fig. 4. Coupling loss versus lateral and transverse displacement between lensed HPCF and PIN PD.

photosensitive area of these PDs is around 70 $\mu$m or smaller, which is suitable to the conventional glass fibers not to the HPCF fiber. Since the core diameter is around 200 $\mu$m, a PD with a larger photosensitive area is indispensable for the HPCF-based data link. The large photosensitive area in a PD, however, tends to induce a high parasitic capacitance to result in a significantly low response time. In order to provide a solution to these challenges in the HPCF-compatible receiver package, we propose the HPCF having a micropolymer lens tip which focuses its output to the small area of a conventional GaAs PIN PD, as shown in the inset diagram of Fig. 3. Detailed fiber lens fabrication processes were reported by the authors elsewhere [9]. Fig. 3 illustrates the packaging structure of the HPCF-pigtailed PIN PD and the PD's specification along with the schematic of the packaging procedure.

In order to evaluate the coupling performance of the proposed lensed HPCF packaging, its coupling loss was measured and compared with the case of a conventional glass MMF. An MMF having a core diameter of 62.5 $\mu$m and a GaAs PD designed for glass MMF coupling were used. As shown in Fig. 4, by adjusting the radius of curvature, the coupling loss could be reduced as small as the but-coupled MMF case. With the radius of curvature from 156 to 182 $\mu$m, the coupling loss of the lensed HPCF-PD was minimized to near 0.3 dB, and the 1-dB tolerance was measured as 27 and 30 $\mu$m for axial and transverse displacements, respectively. With a 156-$\mu$m curvature radius, the packaging process, similar to the VSCEL case, was made and then the packaged lensed HPCF was applied to the following transmission test.

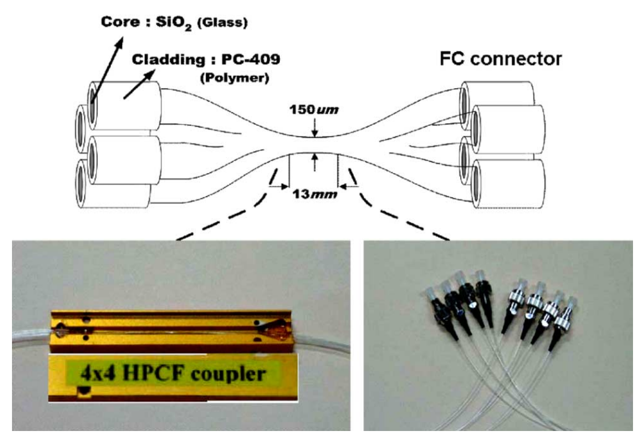


Fig. 5. Fabricated 4 × 4 HPCF fused taper splitter and the real images of the HPCF coupler and FC-type connectors.

Finally, we fabricated the HPCF splitter with FC-type ferrule as in Fig. 5. Adapting the fused tapering technique for glass optical fiber, we successfully fabricated a 4 × 4 HPCF fused taper splitter [6] as shown in Fig. 5. The flame brush technique was used to provide a variety of taper shapes. By controlling of flame temperature and pulling speed, the tapering length and splitting ratio could be flexibly adjusted.

The uniformity of coupling devices strongly depends on the modal distribution in the fusion region. The optimized fusion length was about 13 mm and the length of the tapered waist was 150 $\mu$m. Here all the fiber inputs and outputs were terminated with FC-type connectors using the special HPCF-compatible

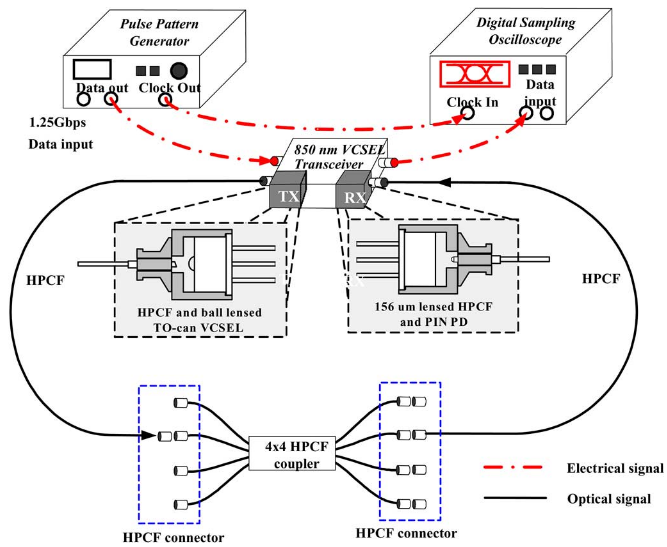


Fig. 6. Practical network composition of the fabricated components.

ceramic ferrules. The fabricated $4 \times 4$ HPCF splitter had a low insertion loss of about 7 dB. The uniformity in the output power splitting ratio was less than 0.5 dB, the power deviation among four output ports over a wide spectral range of 600–900 nm.

The special HPCF-compatible ferrule could make a very efficient connectorization between the HPCFs with FC-type terminations, whose connection loss was measured to be below 0.2 dB. Employing these low-loss HPCF connectorizing techniques, the optical power budget in the HPCF links can be significantly improved to realize the HPCF PON.

## III. PON Transmission Experiments and Results

Utilizing the HPCF-compatible devices, VCSEL, GaAs-PD, and $4 \times 4$ splitter, a $1 \times 4$ PON HPCF network was constructed as shown in Fig. 6. Here all the connections were made using the special HPCF-compatible FC-type connectors.

The HPCF length between the VCSEL transmitter and the splitter was 15 m, and the one between the splitter and GaAs PD was 10 m. The 850-nm VCSEL was directly modulated to provide 1.25-Gb/s nonreturn-to-zero signals using a pulse pattern generator. The modulated signal was transmitted over the HPCF and then split uniformly over the four output ports of the fused taper HPCF splitter. One of outputs from the splitter was then further carried over the HPCF and then toward the PD. The detection threshold and the delay in the receiver were optimized manually. In order to measure the transmission performance of the all-HPCF link, eye diagrams and jitters of the transmitted signal were observed by a digital sampling oscilloscope.

Fig. 7 shows the eye diagram for the transmission performance of the proposed HPCF PON. For the data rate of 1.25 Gb/s, the eye mask was obtained whose area was wide enough for the gigabit Ethernet standard, and no significant power penalty was observed. The jitter and $Q$-factor were 30.74 ps and 45.54, respectively. The transmission experiment enables us to confirm that the proposed HPCF PON using the whole line-up of HPCF-compatible devices can be readily applied to gigabit SR/VSR point-to-multipoint HPCF links.

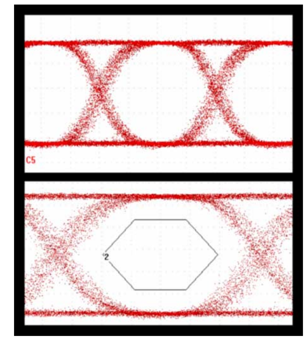

Fig. 7. Eye diagram for back-to-back transmission with 30.74-ps jitter and 45.54 $Q$-factor.

## IV. Conclusion

We successfully fabricated a whole line-up of optical components that are compatible to HPCF: the HPCF pigtailed VCSEL with a coupling loss of 2 dB, the lensed HPCF-PIN PD package with a 0.3-dB coupling loss, and the $4 \times 4$ HPCF coupler having an insertion loss of 7 dB. Using a special ceramic ferrule compatible to HPCF, all the fiber ends were terminated with FC-type connectors with the connection loss of less than 0.2 dB. Utilizing these HPCF-compatible components, a $1 \times 4$ HPCF PON link was constructed. We experimentally confirmed that the link could carry 1.25 Gb/s while satisfying the Gigabit Ethernet transmission qualifies.

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