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2×2 Photonic crystal fiber splitter based on silica-based planar lightwave circuits

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A 2×2 Photonic crystal fiber (PCF) planar lightwave circuit (PLC) splitter, which splits optical power between two PCF channels, has been made by PCF-to-PLC connections. PCF array blocks were lithographically fabricated to have fiber V-grooves and used to firmly hold PCFs and align them to the PLC splitter. The proposed splitter showed a rather flat splitting ratio over a wide wavelength range from 1250 nm to 1750 nm. With the implemented splitter, we obtained a low excess loss of 1.6 dB, a low polarization dependent loss (PDL) of 0.1 dB, and a high return loss of 52 dB. The ultra broadband operation of the proposed splitter is expected to find applications in optical performance monitoring, Ethernet Passive Optical Network (E-PON), and biomedical optics including Optical Coherence Tomography (OCT).

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Photonic crystal fiber (PCF) has been widely studied because of its special spectral characteristics. By adjusting the structure of the air holes running along the fiber length, endlessly single mode propagation [1], very large single-mode area [2], unusual dispersion [3], and ultra wide band WDM transmission [4] have been obtained. A PCF coupler, which couples light from one PCF to another PCF, is one of key devices for a fiber-based OCT system [5], requiring wide spectral band operation for higher axial resolution. The PCF coupler was fabricated by the well known fused biconical tapered (FBT) method [6], and the side-polishing technique [7] were also reported. However, the reported techniques include a high excess loss of 3~6 dB which is due to the damage or contamination of the air holes in the PCF during the fabrication process [7, 8]. The tapering of the PCF involved in the FBT method collapses the air holes due to the high processing temperature; while, the open air holes frequently get contaminated by the polishing powder during the side-polishing process. Further, the un-symmetrically changed air hole configuration causes optical power fluctuation and increases PDL.

Since, directly fabricating a coupler with PCF causes undesirable loss, we can think of coupling PCFs to a conventional single mode fiber (SMF) coupler. However, the coupling loss between PCF and SMF is large (0.2 ~ 4.0 dB) [9] in general. Further, finding optimum splicing conditions to splice PCF and SMF with a conventional fusion splicer is difficult. In addition, SMF and SMF couplers have relatively narrow bandwidth less than 300 nm [10]. In this article, we report a 2×2 PCF PLC splitter, which is implemented by connecting PCFs to a PLC splitter with UV curable adhesive [11]. Besides high reproducibility, the silica-based PLC splitters are well known to have the advantages of low loss, compact size, low PDL and low coupling loss

[12]. The fabrication process and the coupling characteristic of an implemented 2×2 PCF PLC splitter are presented and discussed.

The endless single mode PCF (LMA-8, Crystal Fibre) used for experiments had 7 layers of air holes around a silica core of a 8 μm diameter, and the cladding diameter was 125 μm. As shown in Fig. 1(a), PCFs were placed in the V-grooves of the PCF array block and then covered with a quartz plate. To secure the fixation, UV epoxy was applied between the silicon block and the quartz plate. Figure 1(a) is the schematic and microscopic image of the side view of the PCF array block. The PCF array block was designed for holding two 125 μm fibers separated by 250 μm, and the V-grooves were lithographically fabricated. A photograph and the schematic of the top view of the fabricated 2×2 splitter chip are shown in Fig. 1(b).

As shown in Fig. 2, PCF-installed PCF array blocks were connected at both ends of a 2×2 PLC splitter. The splitter chip (Fi-ra Photonics, Korea) was composed of two 14 mm long straight optical waveguides with a separation of 250 μm between them. The core size was 6 μm×6 μm and the core-cladding index difference was about 0.3 %. The insertion loss and the transmission loss of the splitter chip at 1550 nm wavelength were 3.7 dB per channel and 0.2 dB/cm, respectively; where the insertion loss at a channel was defined as

$$IL_{channel} = -10\log\frac{P_{channel}}{P_{source}} \tag{1}$$

As shown in Fig. 2, the faces of the PCF fiber array blocks and the PLC splitter were polished with a tilt angle of 8°, for reducing PDL and increasing return loss. The bottom photographs of Fig. 2, shows that the fiber blocks and the splitter were well aligned and connected together with the UV curable adhesive. Because PCF array block and PCF PLC splitter were fabricated by conventional method for mass production, we can reproduce PCF PLC splitter easily. We have fabricated five 2×2 PCF PLC splitters and got similar behaviors in the power spectrum and the PDL spectrum.

The transmission spectrum of the fabricated PCF PLC splitter was measured by using a wideband light source and an optical spectrum analyzer (OSA). Figure 3(a) shows the splitting ratio measured at both output channels of the PCF PLC splitter; the through port channel (solid curve) and the cross port channel (dash curve). We can see that the coupling ratio was quite flat over a wide wavelength range from 1250 nm to 1750 nm. The PLC splitter chip was designed to be single mode from 1250 nm to 1750 nm.

To compare the performance of the proposed PCF PLC splitter with the conventional PCF coupler, another PCF coupler was fabricated by the FBT method [6]. A pair of twisted PCFs was elongated together while heating them with a ceramic heater, which has better control over the heating temperature compared to the hydrogen flame heater [13]. The 50/50 coupling ratio at 1550 nm was obtained at a 10.7 mm pulling length. Figure 3(b) shows the splitting ratios measured at both channels of the PCF coupler; the through port (solid curve) and the cross port (dash curve). We can see several ripples, which might be caused by the interference among the cladding modes at the coupling region of the PCF coupler. Figure 4 shows the excess losses of the proposed PCF PLC splitter and the referenced PCF coupler measured in terms of wavelength. The excess loss was calculated with the optical powers measured at both output ports; $P1$ and $P2$.

$$EL = -10\log\frac{P_1 + P_2}{P_{source}} \qquad (2)$$

The excess loss spectrum of the PCF coupler is highly dispersive and ranges from 3 to 6 dB between 1100 nm to 1750 nm. In contrast, the excess loss of the PCF PLC splitter is only 1.6 ~ 4 dB and a monotonic function of wavelength. The excess loss of the PLC splitter chip itself at 1550 nm was less than 0.9 dB. The additional excess loss might be resulted mainly from the contamination in the air holes of the PCF during the 8° polishing process and/or from the intrusion of epoxy during the UV curing process.

Figure 5(a) shows the PDL properties of the PCF coupler and the PCF PLC splitter measured with wavelength. As the figure shows, the conventional PCF coupler had a dramatically varying PDL spectrum with values fluctuating between 1 and 5 dB. Even worse, the PDLs at two output ports were too much different. However, the PDL of the proposed PCF PLC splitter varied within 0.1 ~ 0.3 dB, and no appreciable channel discrepancy was observed. The partial collapsing of the air holes at the fused region of the FBT PCF coupler might be the cause of the large PDL. Of course, the relative orientation of the air hole structures in both PCFs is thought to give appreciable PDL as well. To minimize the PDL of the PCF coupler, PCF couplers were fabricated by aligning the PCFs according to their air hole structures. The return loss of the PCF PLC splitter was about 52 dB, which was about 3 dB better than that of the PCF coupler.

We also examined the transmission performance of the PCF coupler and the PCF PLC splitter. Two single mode XFP (10 Gbps Small Form-Factor Pluggable) transceivers were prepared. The pseudorandom binary sequence (PRBS) length at 2^{23}-1 and 10 Gbps nonreturn-to-zero (NRZ) modulation format were generated by a pulse pattern generator. The two signals transmitted 100 m PCF were guided into the PCF coupler and the PCF PLC splitter, respectively. Figure 5(b) shows the bit error ratio (BER) performance of the PCF PLC splitter (square) and the PCF coupler (circle) measured with respect to the received optical power at 1310 nm. The performance was also confirmed by showing that open eye pattern was maintained after passing the 100 m PCF and the proposed PCF PLC splitter. The power penalty at a BER level of 1×10^{-12}

was about 0.5 dB. We think that the power penalty was mainly caused by the large PDL of the PCF coupler.

Because the air holes of a PCF were easily contaminated with the polishing powder and the UV curable adhesive, the excess loss was measured over 3 dB at 1550 nm as shown in Fig. 4. By adjusting the refractive index structure of the PLC splitter chip and minimizing the contamination of the PCF air holes, a practical PCF PLC splitter can be easily realized. Thus with these efforts we might have ultra wideband single mode operation, even at short wavelengths, which is definitely required in the field of biomedical imaging applications such as OCT [5]. We can design PLC, much more easily than drawing a specialty fiber, to have the wide single mode bandwidth and/or proper mode field diameter well matched with that of PCF at least in principle.

It has been presented that a 2×2 wideband fiber splitter was successfully implemented by connecting PCF with PLC. By using lithographically fabricated V-grooves, PCFs were fixed at PCF array blocks first and then connected with a PLC splitter. The optical performance of the proposed device, including low PDL, high return loss, and low excess loss, were concluded as better than those of the conventional PCF coupler fabricated with the FBT method. The proposed scheme might be used in the optical performance monitoring system that measures optical power, wavelength, and optical signal to noise ratio (OSNR) at ultra wideband WDM transmission systems. It also might be used as the key device for the PCF-based Ethernet Passive Optical Network (E-PON). We can think of application in the medical imaging field represented by OCT.

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List of Figure Captions

Fig. 1. PCF array block structure by using lithographically fabricated fiber V-grooves and microscope end surface image of the PCF array block (a). Schematic of the top view of 2 by 2 splitter chip and microscope image (b).

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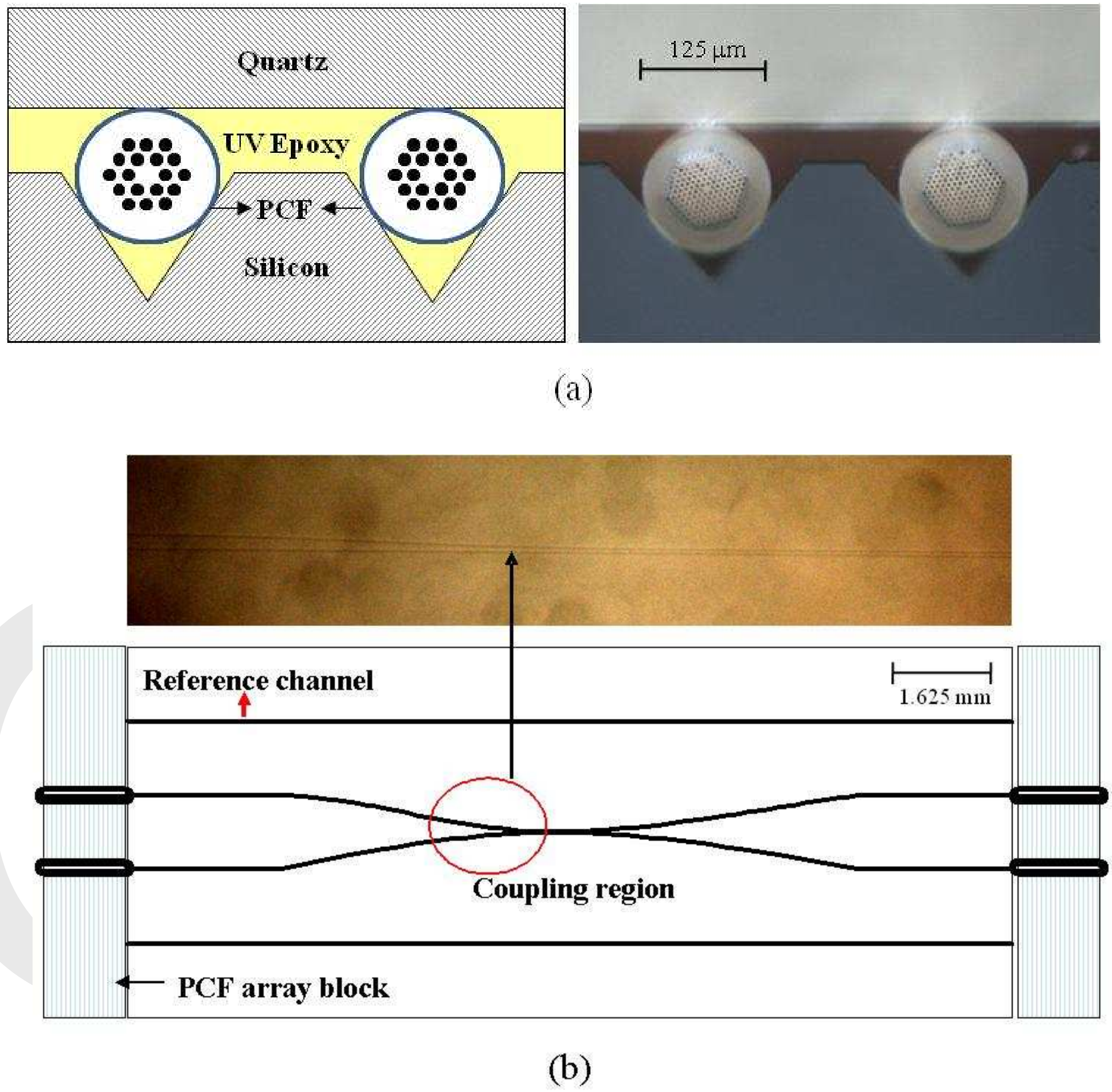

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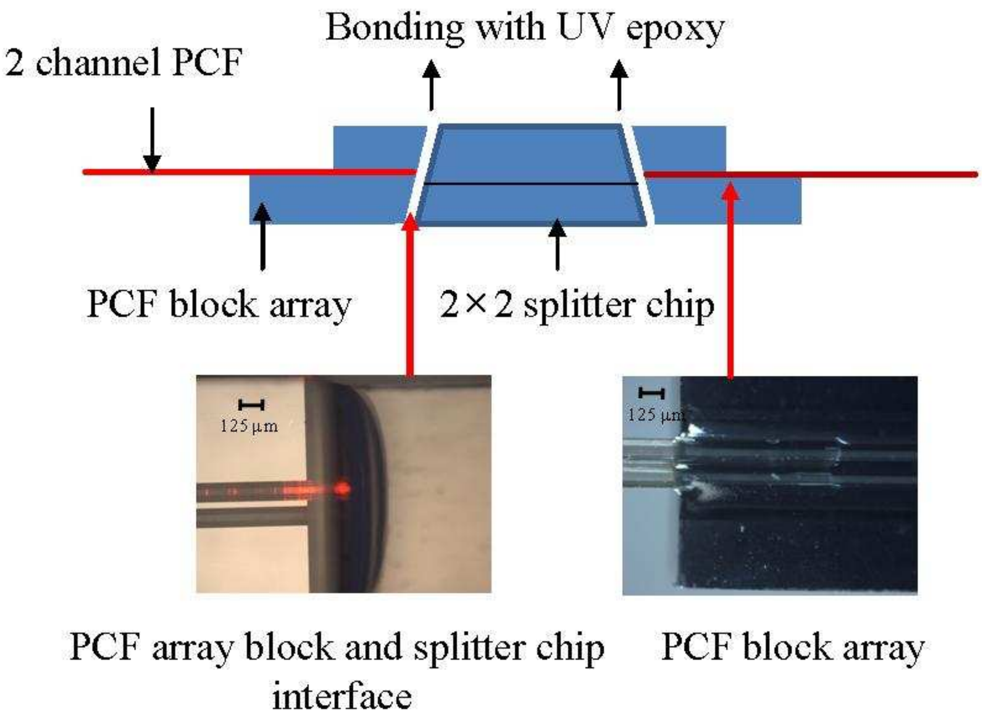

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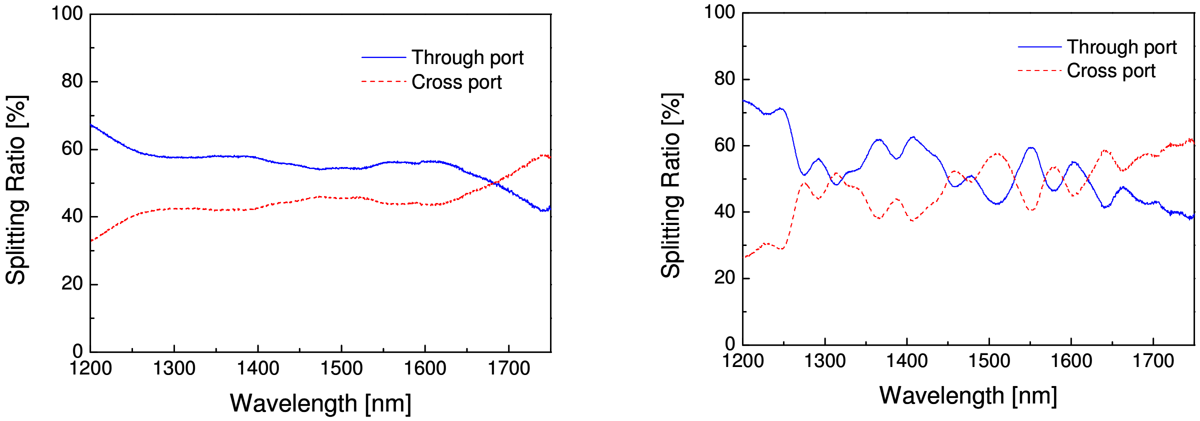
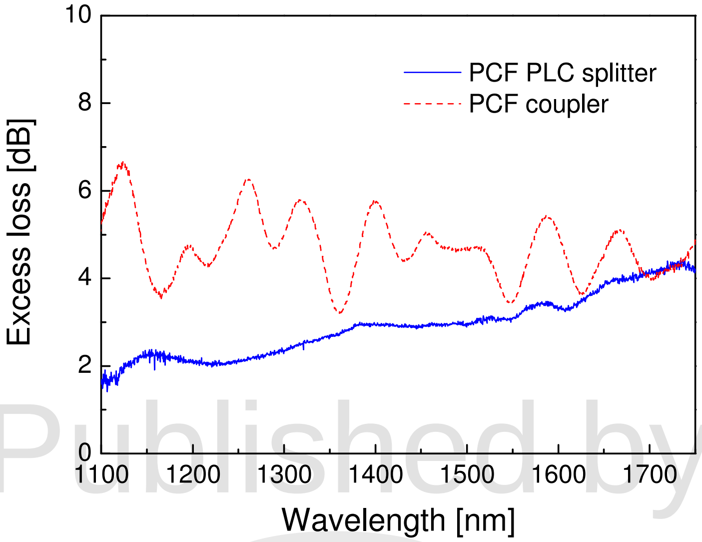


(a) (b)

Fig.3. J. B. Eom *et. al.,* Optics Letters



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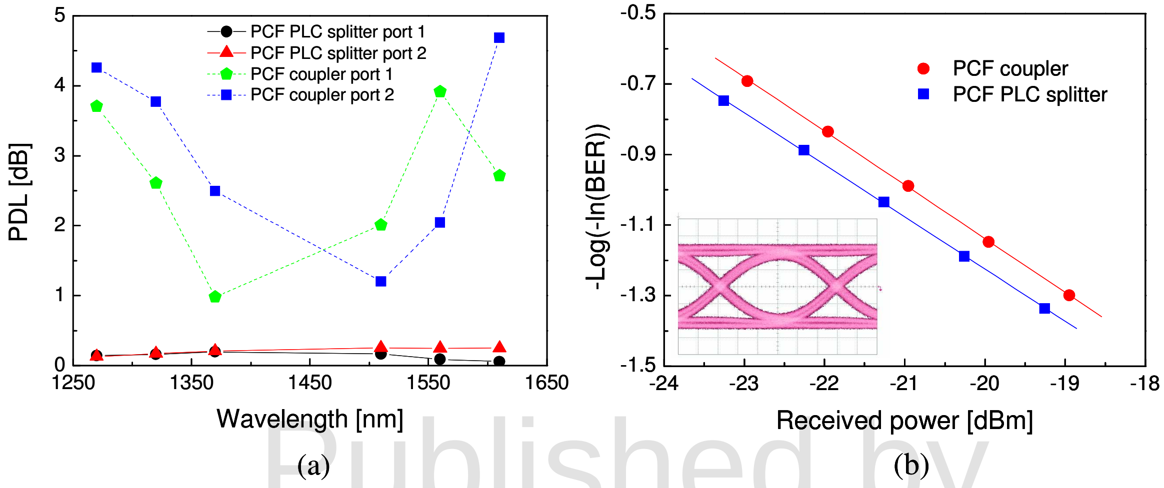

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