Design and fabrication of optical power splitters with large port count

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We design and fabricate compact, low loss, and high port-count optical power splitters of 1 × 128 and 2 × 128 using silica-based planar lightwave circuit (PLC) technology on 6 inch quartz substrate. PLC technology is mainly based on plasma enhanced chemical vapor deposition, photolithography, and etching. The measured results show that the insertion loss, uniformity, and wavelength-dependent loss of 1 × 128 and 2 × 128 optical power splitters are less than 23, 1.43, and 0.92 dB and 23.3, 1.8, and 1.3 dB, respectively, in the wavelength range from 1.26 to 1.65 μm. The polarization-dependent losses are less than 0.16 and 0.2 dB, respectively, in the wavelengths of 1.31, 1.49, and 1.55 μm.

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With the great development of fiber to the home (FTTH), passive optical network (PON), as one important method to attain FTTH, becomes more and more popular. With the increasing need of high speed and huge capacity communication system, the gigabit PON and 10 gigabit Ethernet PON technologies have been widely studied and used. And thus high port count and low-loss optical power splitters are desirable. The dimension of splitters fabricated by conventional fused biconical taper method becomes larger with the increasing output numbers. Splitter fabricated by photonic crystal waveguides is reported because of ultra-compact dimension, but it highly increases the fabrication difficulty[1,2]. Planar lightwave circuits (PLCs) technology, because of the advantages of compact size, low loss, good uniformity, and low wavelength-dependent loss (WDL), has been proved to be a high-efficient splitter fabrication method, especially high port-count splitters. Some high port-count optical power splitters fabricated by PLC technology have been reported. Two kinds of 1 × 128 splitters have been proposed by Takahashi *et al.*[3,4], but the dimension and loss are relatively high. A 1 × 64 splitter has been reported by Tsuda *et al.* in 2008[5], and the insertion loss is less than 19.3 dB for 1.31 μm band and 1.49–1.55 μm band. We have designed and fabricated 1 × 8 and 1 × 64 splitters[6,7], and the insertion loss of 1 × 64 splitter is less than 19.2 dB in the wavelength range from 1.26 to 1.65 μm.

Here in order to obtain compact, low loss, and good uniformity high port-count 1 × 128 and 2 × 128 optical power splitters, 127 Y-branch elements cascaded by sparkle style are used and 2 × 2 wavelength-insensitive coupler (WINC) structure is optimized. These two kinds of high port-count splitters are fabricated using silica-based PLC technology on 6 inch quartz substrate. Compact and good performance high port-count optical power splitters are obtained.

The high port-count splitters are composed of silica waveguide with 0.45% refractive index difference between core and cladding, and the refractive indexes of core n_c and cladding n_s are 1.4515 and 1.445, respectively. The cross-section of waveguide is taken as 6.5 × 6.5 (μm) to ensure single-mode propagation. The bend radius of waveguide is chosen to be 15 mm to achieve low-bend loss and compact dimension.

A 1 × 128 splitter composed of 127 Y-branch elements cascaded by sparkle style is proposed, which is shown in Fig. 1(a), where the output waveguides spacing is 127 μm. The basic structure of 1 × 128 optical power splitter is the tilt Y-branch with different input angles, which is illustrated in Fig. 1(b). The input and output angles of Y-branch are ang_1, ang_2, and ang_3, respectively. The ang_1 is the angle between the input tilt direction and the x-axis. The ang_2 and ang_3 are the angles between the x-axis and tangent line of endings of output_1 and output_2, respectively. The length of straight waveguide is l_t. The straight waveguide lengths of tilt Y-branches of different input angles are optimized by the method proposed in our previous reports[6,7]. Finally, a compact 1 × 128 optical power splitter is obtained, and the dimension is 27.7 × 16.7 (mm), which is nearly 50% shorter than the 1 × 128 optical power splitter reported by Takahashi *et al.*[3]. The simulation results are illustrated in Figs. 1(c) and (d), the insertion loss, uniformity, WDL, and PDL are less than 22.8, 1.40, 0.88, and 0.12 dB, respectively.

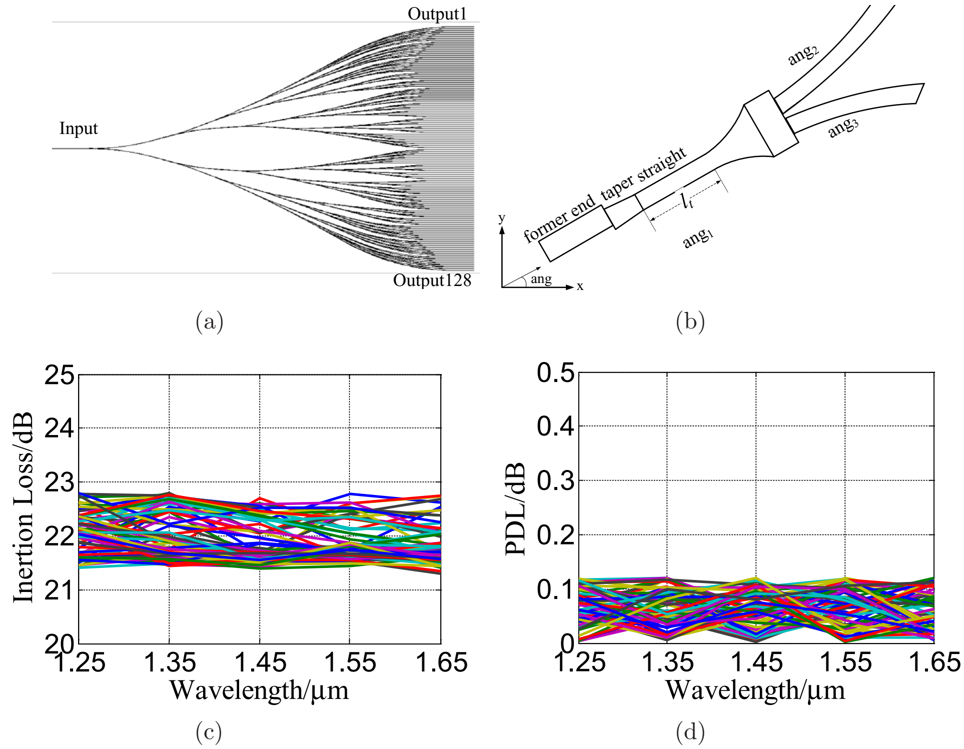


Fig. 1. 1 × 128 optical power splitter: (a) structure, (b) tilt Y-branch, (c) insertion loss, and (d) PDL.

The 2 × 128 optical power splitter is designed by replacing first-stage Y-branch of 1 × 128 splitter with 2 × 2 WINC structure. The WINC is the key structure of 2 × 128 splitter, which is illustrated in Fig. 2. Some WINC structures have been reported. One method introduced dispersive material[8,9]. The other method used the series-tapered coupling structure[10], both these methods introduce additional material or series-tapered structure, and thus increase fabrication difficulty. The WINC structure can also be obtained by multiple-mode interference (MMI) structure[11], because of the wavelength sensitivity of MMI structure, the structure is wavelength dependent. Another WINC structure is composed of two directional couplers and a phase shift structure[3,12]. The parallel lengths and gaps of two directional couplers are larm_1, gap_1 and larm_2, gap_2 respectively. In order to simplify the numerical calculation, gap_1 and gap_2 are chosen equal. Considering the

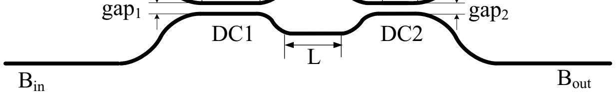


Fig. 2. WINC structure.

coupler effect of bends, the equivalent coupler length (L_e) is introduced, which is defined as equivalent coupler length of the bend waveguide, the parallel length and length difference of phase shift is L and ΔL.

The transmission matrix of the WINC structure can be inferred as

$$\begin{bmatrix} A_{\mathrm{out}} \\ B_{\mathrm{out}} \end{bmatrix} = \begin{bmatrix} C_2 & -jS_2 \\ -jS_2 & C_2 \end{bmatrix} \begin{bmatrix} e^{-j\beta L} & 0 \\ 0 & e^{-j\beta L+\Delta L} \end{bmatrix} \begin{bmatrix} C_1 & -jS_1 \\ -jS_1 & C_1 \end{bmatrix} \begin{bmatrix} A_{\mathrm{in}} \\ B_{\mathrm{in}} \end{bmatrix}. \tag{1}$$

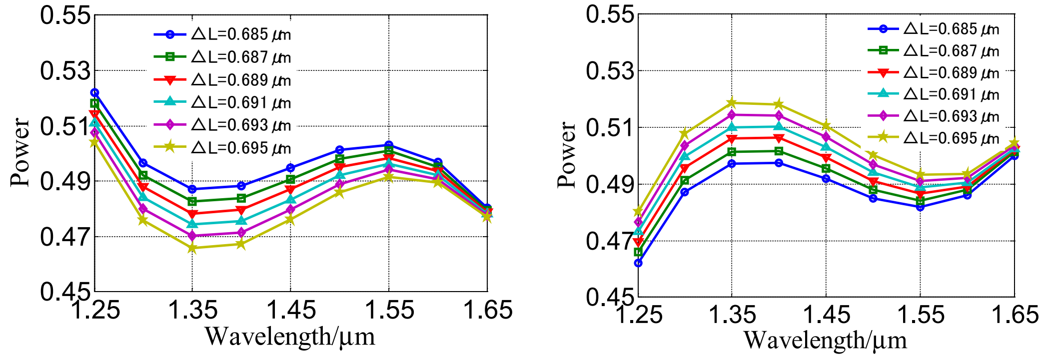
According to Eq. (1), the output power coupler ratio can be expressed as

$$\eta = \frac{\left|B_{out}\right|^2}{\left|A_{out}\right|^2 + \left|B_{out}\right|^2} = a^2 + b^2 + 2ab\cos(\beta \Delta L), \tag{2}$$

$$a = \cos\left[\frac{\pi}{2L_c}(L_{larm1} + L_e)\right]\sin\left[\frac{\pi}{2L_c}(L_{larm2} + L_e)\right],$$

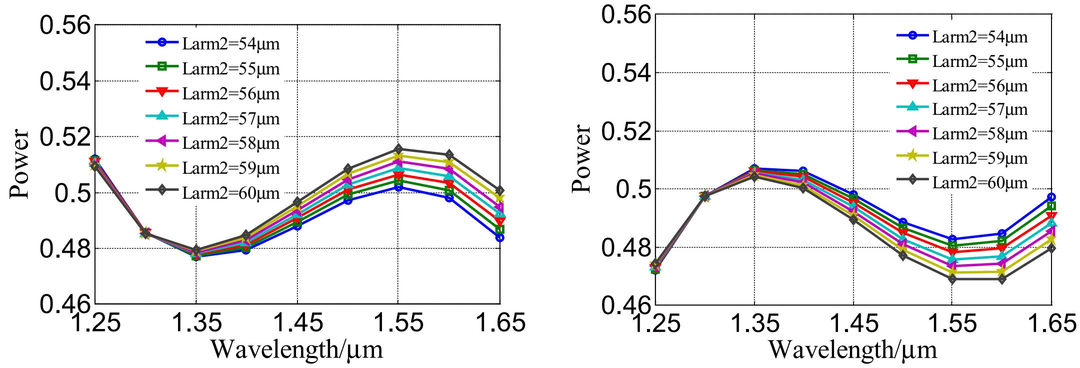
$$b = \sin\left[\frac{\pi}{2L_c}(L_{larm1} + L_e)\right]\cos\left[\frac{\pi}{2L_c}(L_{larm2} + L_e)\right],$$

where β is the propagation constant and L_c is the entire coupler length of directional couplers. The β, L_c, and L_e are fixed when refractive index difference and gaps are given, which is 5.8432, 443.4635, and 1826.8538 μm, respectively, calculated by single coupler[10]. The variations of Eq. (2) are only larm_1, larm_2, and ΔL.



(a) (b)

Fig. 3. Wavelength response of different ΔL: (a) output channel 1 and (b) output channel 2.



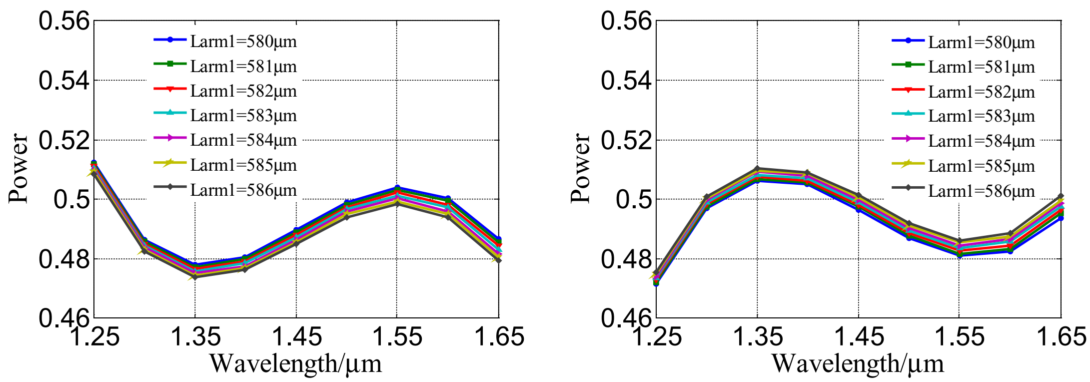
(a) (b)

Fig. 4. Wavelength response of different larm$_2$: (a) output channel 1 and (b) output channel 2.

Based on fixed L_c and L_e, larm$_1$, larm$_2$, and ΔL are obtained using Matlab by choosing series of values. The calculated values of larm$_1$, larm$_2$, and ΔL are 581, 44, and 0.69 μm, respectively. In order to obtain the optimized structure, larm$_1$, larm$_2$, and ΔL are optimized around the calculated values using three-dimensional beam propagation method. The ΔL is first optimized. Figure 3 shows the two output powers of different ΔL in the wavelength range from 1.25 to 1.65 μm. From Fig. 3 we can see that ΔL has an impact mainly on the output powers in the wavelength range from 1.25 to 1.55 μm. The optimized ΔL is 0.689 μm.

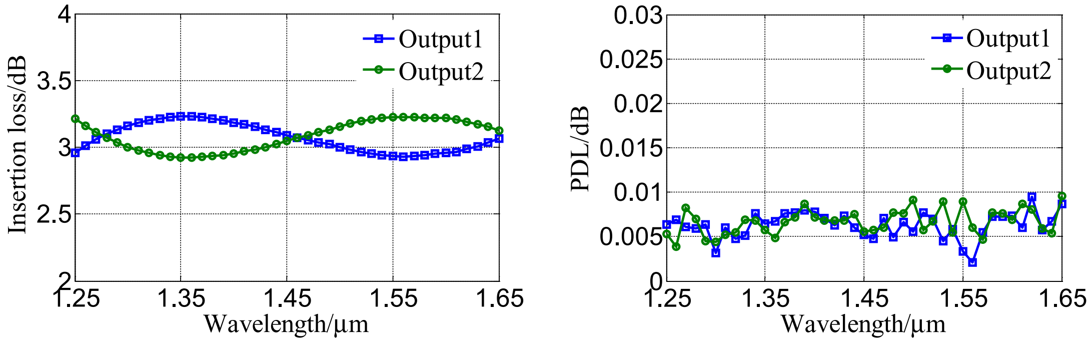
Figure 4 illustrates the two output powers of different larm$_2$ in the wavelength range from 1.25 to 1.65 μm. From Fig. 4 we can see that larm$_2$ has an impact mainly on the output powers in the wavelength range from 1.55 to 1.65 μm. The larm$_2$ is chosen to be 58 μm.

Figure 5 illustrates the two output powers of different larm$_1$ in the wavelength range from 1.25 to 1.65 μm. From Fig. 5 we can see that larm$_1$ has an impact on the



(a) (b)

Fig. 5. Wavelength response of different larm$_1$: (a) output channel 1 and (b) output channel 2.



(a) (b)

Fig. 6. Simulated results of WINC: (a) insertion loss and (b) PDL.

output powers in the whole wavelength range from 1.25 to 1.65 μm. The best larm$_1$ is 584 μm.

Low loss and flat-wavelength WINC structure is finally obtained. The simulated wavelength response is illustrated in Fig. 6. From Fig. 6 one can see that the optimized insertion loss, uniformity, WDL, and PDL are less than 3.25, 0.35, 0.3, and 0.01 dB, respectively, in the wavelength range from 1.25 to 1.65 μm.

Finally, compact 2 × 128 optical power splitter is obtained by replacing first-order Y-branch of 1 × 128 with 2 × 2 structure, which is illustrated in Fig. 6 and the dimension is 32.7 × 16.7 (mm).

Based on the above discussion, we fabricated 1 × 128 and 2 × 128 optical power splitters on 6 inch quartz substrate in the PLC platform of Henan Shi Jia Photons Technology Co., Ltd, China. First, SiO_2–GeO_2 core layer with 6.5 μm thickness are directly deposited on quartz substrate using plasma enhanced chemical vapor deposition (PECVD). Then, these two kinds of splitter circuits are patterned on photoresist by photolithography. Splitter waveguides are etched using induced coupler plasma (ICP) system. The micro-photo of 2 × 128 optical power splitter after ICP is illustrated in Fig. 7(a), and the waveguide cross-section and the minimum gap are about 6.6 × 6.6 (μm) and nearly 2.8 μm, respectively, which is similar to our design. In order to reduce the stress birefringence, 18 μm thick SiO_2 upcladding layer doped with B and P is formed using PECVD six times, and scanning electron microscope (SEM) photograph of 2 × 128 optical power splitter after depositing the upcladding layer is shown in Fig. 7(b).

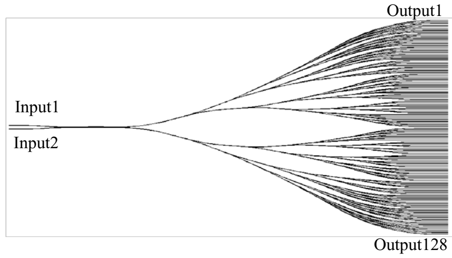


Fig. 6. 2 × 128 optical power splitter.

After slicing, 1 × 128 and 2 × 128 optical power splitter chips are obtained. In order to reduce the couple loss to fiber and the return loss, the end surface is polished at 8°. The fabricated optical power splitters were tested by an optical spectrum analyzer and a wideband light source with a wavelength range from 1.26 to 1.65 μm. The PDL are measured at the wavelengths of 1.31, 1.49, and 1.55 μm.

The measured results of 1 × 128 splitter are shown in Fig. 8, and from Fig. 8 we can see that the insertion loss, uniformity, and WDL are less than 23, 1.43, and 0.92 dB, respectively, in the wavelength range from 1.26 to 1.65 μm. We can conclude that the insertion loss is 2.5 dB lower than that of the structure proposed by Takahashi *et al.*[4,5]. The PDL is less than 0.16 dB in the wavelengths of 1.31, 1.49, and 1.55 μm. The result completely satisfies the commercial needs[13,14].

The measured results of 2 × 128 splitter are illustrated in Fig. 9, and from Fig. 9 we can see that the insertion loss, uniformity, and WDL are less than 23.3, 1.8, and 1.3 dB, respectively, in the wavelength range from 1.26 to 1.65 μm. The PDL is less than 0.2 dB in the wavelengths of 1.31, 1.49, and 1.55 μm.

In conclusion, we design and fabricate high port-count 1 × 128 and 2 × 128 optical power splitters using silica-based PLC technology on 6 inch quartz substrates. The splitters have low loss, good uniformity, and low WDL. To the best of our knowledge, this is the first report in China, and the results completely satisfy the needs of commercialization application.

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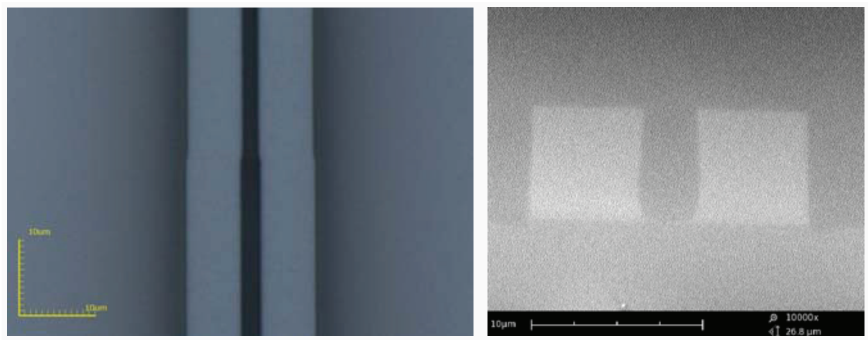
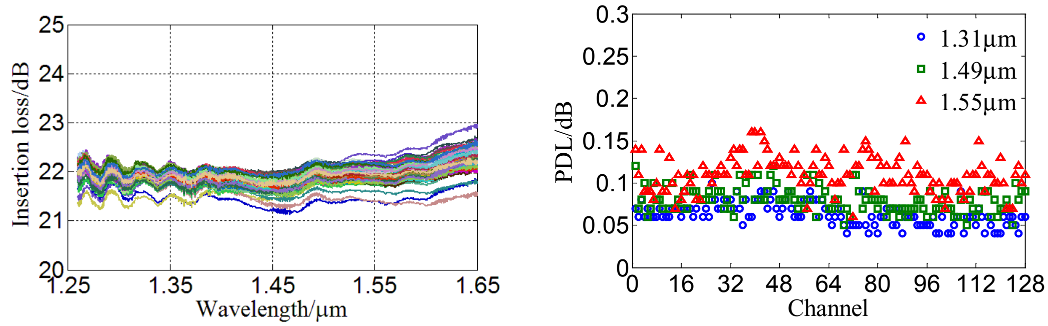


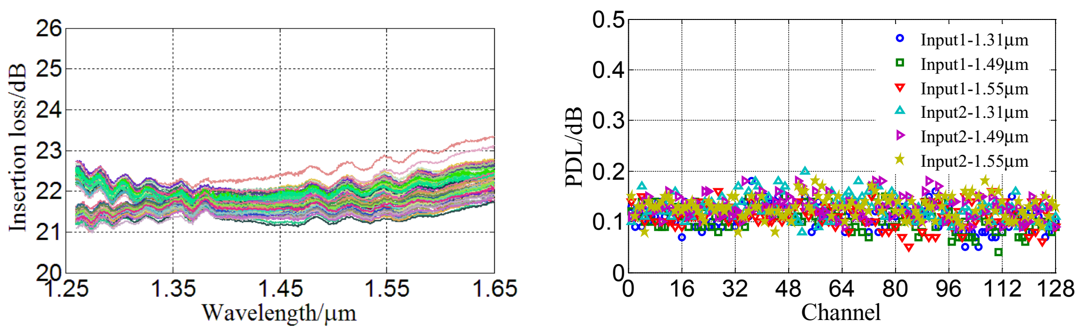
(a) (b)

Fig. 7. Photographs of 2 × 128 optical power splitter: (a) micro-photograph after ICP and (b) SEM after top cladding layer.



(a) (b)

Fig. 8. Performances of 1 × 128 optical power splitter: (a) insertion loss and (b) PDL.



(a) (b)

Fig. 9. Optical performances of 2 × 128 optical power splitter: (a) insertion loss and (b) PDL.

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