A PLC-Based Optical Sub-assembly of Triplexer Using TFF-Attached WDM and PD Carriers

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ABSTRACT—We have fabricated a planar lightwave circuit (PLC) hybrid-integrated optical sub-assembly of a triplexer using a thin film filter (TFF)-attached wavelength division multiplexer (WDM) and photodiode (PD) carriers. Two types of TFFs were attached to a diced side of a silica-terraced PLC platform, and the PD carriers with a 45° mirror on which pin-PDs were bonded were assembled with the platform. A clear transmitter eye-pattern and minimum receiver sensitivity of -24.5 dBm were obtained under 1.25 Gb/s operation for digital applications, and a second-order inter-modulation distortion (IMD2) of -70 dBc was achieved for an analog receiver.

Keywords—Hybrid integration, silica PLC, triplexer, optical transceiver, thin film filter, PD carrier, analog receiver, IMD.

I. Introduction

An optical triplexer that can transmit and receive 1310 nm upload data, 1490 nm download data, and 1550 nm download video signals for cable TV applications is recently gaining much research interest as the key component for realizing fiber-to-the-home (FTTH). Transistor outline (TO)-can packaged triplexers have already been produced, but the cost of the triplexer is still expensive. One realistic way to achieve a cost-effective triplexer is to use a silica planar lightwave circuit (PLC) hybrid integration technology. The conventional wavelength division multiplexers (WDMs) formed on a PLC platform were thin film filter (TFF)-embedded WDMs [1], but generally have some difficulties in forming a narrow trench and embedding the TFF chip into the trench. To overcome this problem, a WDM structure in which the TFF chip is attached to a side of the PLC platform was applied to a diplexer using two wavelength bands [2]. Recently, Tsai and others [3] adopted a silicon (Si) submount with 45° mirror to form an Rx for the diplexer, but the Si submount can cause a restriction of the bandwidth of the Rx because of the parasitic capacitance between the Si and electrical wires [4].

In this letter we report on a PLC hybrid-integrated optical sub-assembly (OSA) of a triplexer. The previously mentioned TFF-attached WDM structure was applied to the triplexer. Also, the photodiode (PD) carriers with 45° mirror, which were made from quartz (Qz) with a low dielectric constant and do not have the aforementioned problem, were used for the Rx parts. Moreover, *pin*-PDs with an 80 μm light-detecting diameter were used to passively assemble the PD carriers with a PLC platform. In the fabricated module, we confirmed the 1.25 Gb/s operation of a digital Tx-Rx and the IMD2 characteristics of an analog Rx.

II. OSA Structure of Triplexer

Figure 1(a) shows a schematic configuration for the OSA of our triplexer. A spot-size-converted Fabry-Perot laser diode (SSC-LD) and a monitoring waveguide PD (M-WGPD) are integrated on a silica-terraced PLC platform [4], [5] to form a Tx, and *pin*-PDs with an 80 μm light-detecting diameter were employed to form a digital/analog Rx. In order to reduce the loss of the Rx parts, we adopt a structure in which received 1490 and 1550 nm signals transmit TFFs to be coupled to the *pin*-PDs. In this OSA, two types of TFFs are used. One of them is a 1490 nm band pass TFF (BP-TFF) that transmits only a 1490 nm wavelength band (1490±10 nm), and the other is a 1550 nm longwave pass TFF (LWP-TFF) that reflects all

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the wavelengths less than a 1550 nm band (1555±5 nm). To guarantee the high responsivity of more than 0.7 A/W of an analog Rx, the 1550 nm channel is first arranged, followed by the 1490 nm channel, as shown in Fig. 1(a). The 1310 nm channel is arranged last since the output power of the Tx can be increased by an injection current. The transmitted 1310 nm signal is reflected by both the 1490 nm BP-TFF and the 1550 nm LWP-TFF in order to be output into a fiber. The 1550 nm signal input from the same fiber transmits the 1550 nm LWP-TFF and is then reflected by the 45° mirror of a PD carrier to be coupled to an analog *pin*-PD. The received 1490 nm signal is first reflected by the 1550 nm LWP-TFF and then transmits the 1490 nm BP-TFF to be coupled to the digital *pin*-PD.

A silica PLC waveguide with an index contrast of super high Δ was adopted to reduce the bending radius and the LD-PLC coupling loss. The PLC has an index contrast of 1.5%, a core size of 4.5 μm×4.5 μm, and a bending radius of 2000 μm. However, the coupling loss between the PLC and a single mode fiber (SMF) is fairly large. To reduce the loss, we use a high numerical aperture fiber (HNAF) with a mode size of 4 μm at 1550 nm. One side of the HNAF is connected to the PLC and the other side is fusion-spliced with the SMF.

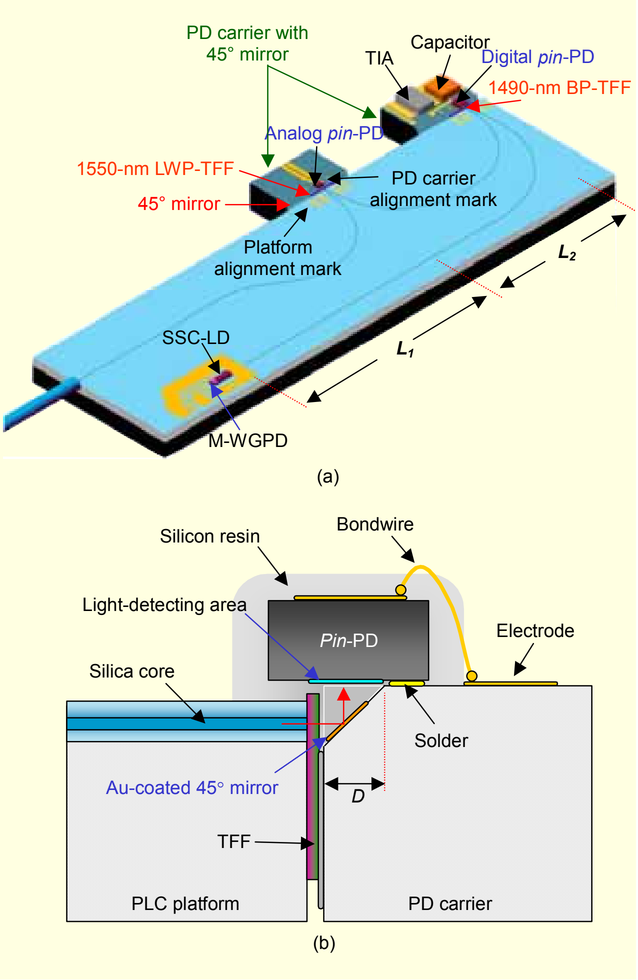


Fig. 1. (a) Schematic configuration for the OSA of the triplexer and (b) cross-sectional view of the Rxs.

Two types of TFFs are attached to a diced side of V-shaped waveguides formed on the PLC platform in order to realize a TFF-attached WDM. The V-shaped angle is 16° and the dicing tolerance at the V-shaped waveguides is precisely controlled to be within ± 2.5 μm. A taper structure of 4.5 to 18 μm, shown in the inset of Fig. 2, is applied at the V-shaped waveguide junctions so that the loss for the light reflected from the TFF can be less sensitive to the TFF-attachment position [1]. Figure 1(b) shows a cross-sectional view of the Rxs. Thanks to the *pin*-PDs with an 80 μm light-detecting diameter, the PD carriers with 45° mirror on which *pin*-PDs are mounted can be passively-assembled with the PLC platform by using platform and PD carrier alignment marks as shown in Fig. 1(a). The mirror width (*D*), as shown in Fig. 1(b), is 150 μm, which roughly corresponds to the distance of the total light path from the TFF to the detecting area of the *pin*-PD. Both horizontal and vertical alignment tolerances of 0.5 dB between the 1.5% Δ waveguide and the *pin*-PD, which are separated from each other by the total path via the reflecting surface of the PD carrier, were calculated by a commercial FullWAVE simulator to be about ±25 μm. This result shows that the passive assembly between the platform and the PD carrier is possible.

To suppress electrical crosstalk, the LD-PDs distances, as shown in Fig. 1(a), are increased to 9 mm (L_1) and 7 mm (L_2) [1], [2]. According to the results calculated by the HFSS simulator, the electrical crosstalk values between the LD and each PD were below about 98 dB, which are generally considered sufficiently low values having little effect on the digital Rx sensitivity of –26 dBm at 1.25 Gb/s and the analog Rx performances for cable TV applications.

III. Fabrication and Performance

For a vertically passive alignment between the PLC platform and PD carrier, both a 15 μm oxidized Si wafer for the platform and Qz wafer for the carrier were polished up to a thickness calculated previously in consideration of the structure shown in Fig. 1(b), where the polishing accuracy was ± 1 μm. After the fabrication of the PLC waveguide on the Si wafer by using a flame hydrolysis deposition process, a two-step etching technique [5] was applied for the fabrication of the PLC platform. The etched structure of a silica terrace and a trench surface can be confirmed from the scanning electron micrograph shown in the inset of Fig. 3(a). The fabrication process of our silica-terraced PLC platform was described in detail elsewhere [5].

Prior to the module fabrication, we did preliminary experiments to check the characteristics of the TFF chips and the TFF-attached WDM. The TFF chips (Central Glass Co., Japan) had a size of 0.5 mm×1 mm and a thickness of about 22 µm. Each TFF chip was sandwiched and bonded between 8° angled polished fiber blocks using a UV-curable epoxy with a refractive index of 1.46 at 1550 nm. As can be seen from Table 1, it is thought that the epoxy did not have much influence on the TFF's performance and that the isolation characteristics of the TFFs are proper to be used as a WDM for the triplexer. Figure 2 shows the reflection optical spectra of the TFFs that were attached to the diced side of a test chip shown in the inset of Fig. 2. The spectra, which were obtained by subtracting the spectrum of a straight waveguide from those of a V-shaped and tapered waveguide, show that the losses for the light reflected from each TFF including a bending loss were below 1 dB at the wavelength bands of 1310, 1490, and 1550 nm. These values could be repeatedly acquired for the test chips with a dicing tolerance of +4/-2.5 µm, which means that the TFF-attached WDM can be applied to the triplexer.

V-grooves for a 45° mirror were formed on the Qz wafer by using a dicing saw with 90° blade, and Cr-Ni-Au film was deposited and patterned by liftoff to simultaneously form the reflecting surface for the mirror, the electrodes, and the PD carrier alignment marks for horizontally passive alignment. Au-Sn solders were also formed on the wafer, and the PD carriers were completed by dicing the center of the V-groove. Then, the *pin*-PDs were flip-chip bonded on the PD carriers. When the HNAF was about 30 µm apart from the lower edge of the 45° mirror and best-aligned with the PD carrier, a responsivity of around 0.96 A/W was obtained, meaning that the mirror well-reflected the input lights to be coupled to the *pin*-PD.

Table 1. Transmission characteristics of TFF chips sandwiched between 8° angled polished fiber blocks.

TFF	Transmitted isolation
1490-nm BP-TFF	< –45 dB @ 1310 ± 50 nm
	< –38 dB @ 1555 ± 5 nm
1550-nm LWP-TFF	< –48 dB @ 1310 ± 50 nm
	< –34 dB @ 1490 ± 10 nm

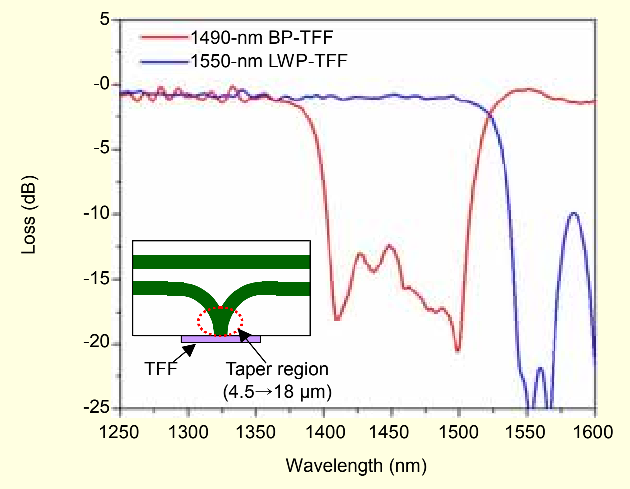
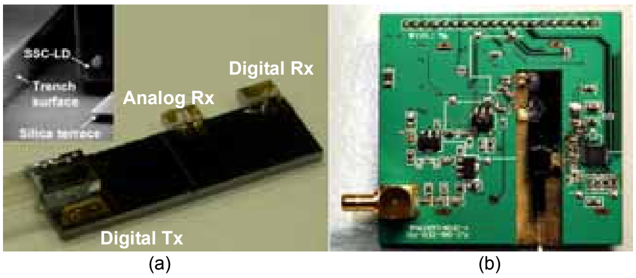


Fig. 2. Reflection optical spectra of the TFF chips that were attached to the diced side of a test chip shown in the above inset.



(a) (b)

Fig. 3. (a) Hybrid-integrated PLC platform and (b) packaged triplexer.

SSC-LDs and M-WGPDs were flip-chip bonded on the PLC platforms. A far-field pattern of the LDs was about 10° and 13° in horizontal and vertical directions, respectively. The alignment accuracy of the flip-chip bonding was better than ±1.5 µm, and the height alignment accuracy between the centers of the LD and PLC core was less than 1 µm [5]. Two TFFs were attached to a diced side of the V-shaped waveguides formed on the platform, and the PD carriers were assembled with the platform using the UV-curable epoxy. While the LD was on, the platform chip was pig-tailed with the HNAF using the slant-polished fiber block. Figure 3(a) shows the hybrid-integrated PLC platform. A pre-amplifier and a capacitor were placed on the digital PD carrier, and the integrated PLC platform was then bonded on a metal block by using a silver epoxy that was attached to a printed circuit board (PCB) and connected with the PCB through short bondwires. The active devices were encapsulated with a silicone resin, and the surfaces of the platform chip were then covered with an opaque resin to suppress the optical crosstalk caused by the stray light from the LD [1], [2]. The packaged triplexer is shown in Fig. 3(b), where the opaque resin was only partially applied to the platform chip and a metal case is not shown.

Figure 4(a) shows the light-current (*L-I*) curve of the fabricated Tx. The threshold current was 10 mA, and the continuous-wave (CW) output power at 30 mA was 1.9 mW. The *L-I* curve shows the linear increase of the power without any saturation, indicating that the thermal properties of the integrated LD were acceptable for low power Tx [4]. Figure 4(b) shows the optical waveform at a power of 1 dBm. A clear eye-pattern was observed at 1.25 Gb/s.

The responsivity of the digital Rx and that of the analog Rx were about 0.56 and 0.8 A/W at 1490 and 1555 nm, respectively.

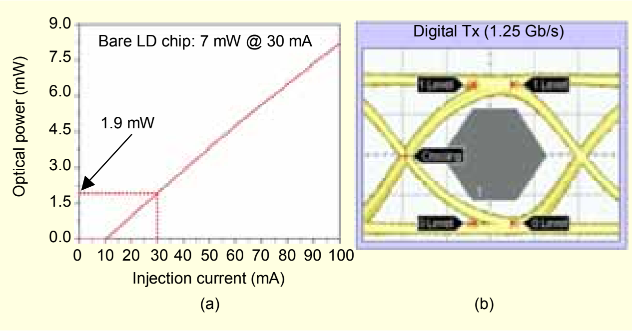


Fig. 4. (a) *L-I* curve of Tx and (b) eye-pattern of Tx.

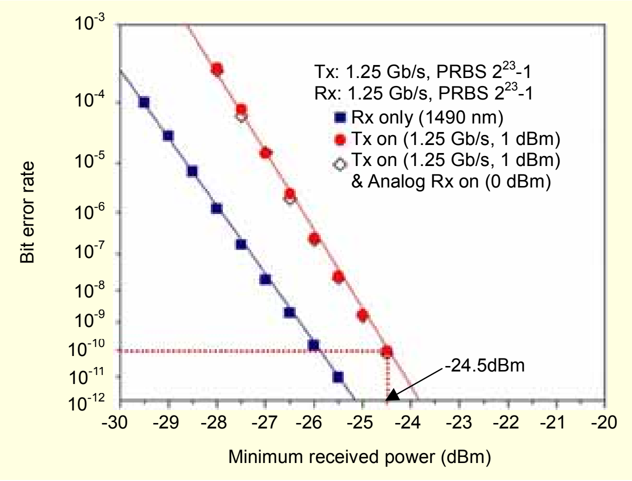


Fig. 5. BER characteristics of digital Rx.

The value of 0.8 A/W corresponds to a loss of 0.8 dB from the reference responsivity of 0.96 A/W in the case of the best alignment between the HNAF and the PD carrier. This means that the PLC-carrier coupling loss was about 0.3 dB, excluding a fiber coupling loss of 0.5 dB. We can also infer from the digital Rx responsivity of 0.56 A/W that the loss for the light reflected from the LWP-TFF was roughly 1.55 dB. This value is a little larger than the result (below 1 dB) of the preliminary experiment, which we thought came from a slantly diced position and a high-order mode loss at the V-shaped and tapered waveguides. If we assume that the total loss for the light reflected from the TFFs was 3.1 dB at two points, the LD-PLC coupling loss is estimated to be roughly 2 dB because the output power of the bare LD chip was 8.45 dBm (7 mW), that of the Tx was 2.78 dBm (1.9 mW), and the fiber coupling loss was 0.5 dB.

Figure 5 shows the bit error rate (BER) characteristics of the digital Rx. The minimum Rx sensitivity at a BER of 10^{-10} was -24.5 dBm under the operation of the digital Tx and analog Rx. A power penalty of about 1.3 dB was exhibited under the Tx operation at 1.25 Gb/s, and an additional power penalty was not observed even when the analog Rx was turned on. It is thought that this penalty came from the electrical crosstalk caused by the Tx because the optical isolation characteristics of the TFFs were enough to obtain an Rx sensitivity of –26 dBm and because the opaque resin was applied to the platform surface, and that the penalty would be reduced by optimizing the circuits of the PCB.

We measured the IMD2 characteristics of the analog Rx by performing a two-tone test of 400 and 450 MHz. The analog Rx showed an IMD2 value of -70 dBc at an optical modulation index of 40%, and it is believed that this value is further lowered by improving the non-linear characteristics of the analog *pin*-PD. Recently, we have been taking efforts to raise the responsivity of the digital Rx by optimizing the dicing condition and taper structure at the V-shaped waveguides, and suppress the power penalty below 0.5 dB.

IV. Conclusion

Using a TFF-attached WDM and PD carriers, we have fabricated an OSA of the triplexer. A PLC hybrid integration technology was employed to bond the SSC-LD and the M-WGPD on the silica-terraced PLC platform, and the *pin*-PDs on the PD carriers with 45° mirror. Two types of TFFs were attached to a diced side of the platform, and the PD carriers were assembled with the platform. Digital Tx-Rx operation at 1.25 Gb/s was successfully demonstrated and an IMD2 value of -70 dBc was obtained for the analog Rx.

References

[1] T. Hashimoto, A. Kanda, R. Kasahara, I. Ogawa, Y. Shuto, M. Yanagisawa, A. Ohki, S. Mino, M. Ishii, Y. Suzuki, R. Nagase, and T. Kitagawa, “A Bidirectional Single Fiber 1.25 Gb/s Optical Transceiver Module with SFP Package Using PLC,” *Proc. ECTC 2003*, vol. 53, May 2003, pp. 279-283.

[2] M. Oguro, A. Goto, N. Kitamura, Y. Sakamoto, T. Masuta, and T. Tamura, “1.25 Gb/s WDM Bi Directional Transceiver Module Using DFB-LD and PLC with Spot-Size Conversion Region,” *Proc. ECTC 2002*, vol. 52, May 2002, pp. 305-310.

[3] M. L. Tsai, C. H. Ko, M. J. Chou, W. S. Lin, J. S. Chang, B. C. Tsai, Y. T. Chiou, and C. H. Chu, “Fiber-Based Bidirectional Transceiver Module Using Optical Subassembly with an Injection Molded Polymer Optical Bench,” *Proc. ECTC 2005*, vol. 2, May 2005, pp. 1629-1633.

[4] D.-J. Kim, Y.-T. Han, Y.-J. Park, S.-H. Park, J.-U. Shin, and H.-K. Sung, “Thermal Characteristics of a Laser Diode Integrated on a silica-Terraced PLC Platform,” *ETRI J.*, vol. 27, no. 3, June 2005, pp. 337-340.

[5] Y.-T. Han, S.-H. Park, J.-U. Shin, D.-J. Kim, Y.-J. Park, S.-W. Park, J. Kim, and H.-K. Sung, “A Two-Step Etching Technique for Silica Terraces in the PLC Hybrid Integration,” *IEEE Photon. Technol. Lett.*, vol. 16, no. 11, Nov. 2004, pp. 2436-2438.