2.5-Gb/s hybridly-integrated tunable external cavity laser using a superluminescent diode and a polymer Bragg reflector

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Abstract: We presented a hybridly-integrated tunable external cavity laser with 0.8 nm mode spacing 16 channels operating in the direct modulation of 2.5-Gbps for a low-cost source of a WDM-PON system. The tunable laser was fabricated by using a superluminescent diode (SLD) and a polymer Bragg reflector. The maximum output power and the power slope efficiency of the tunable laser were 10.3 mW and 0.132 mW/mA, respectively, at the SLD current of 100 mA and the temperature of 25°C. The directly-modulated tunable laser successfully provided 2.5-Gbps transmissions through 20-km standard single mode fiber. The power penalty of the tunable laser was less than 0.8 dB for 16 channels after a 20-km transmission. The power penalty variation was less than 1.4 dB during the blue-shifted wavelength tuning.

OCIS codes: (130.5460) Polymer waveguide; (3600) Tunable laser; (1480) Bragg reflectors; (3120) Integrated optics devices; (250.5960) Semiconductor lasers.

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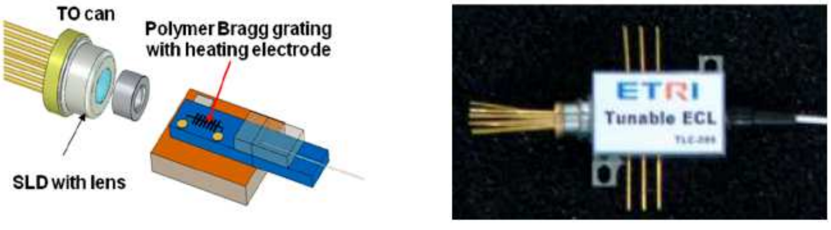
1. Introduction

There has been great interest in applying broad-band, high-speed and low-cost colorless light sources or tunable laser sources to wavelength-division-multiplexing-passive-optical-network (WDM-PON)-based fiber-to-the-home (FTTH) service [1–5]. The colorless light sources such as reflective semiconductor optical amplifiers (R-SOA) and amplifier-spontaneous-emission injected Fabry-Perot laser diodes can flexibly allocate the wavelength to many subscribers but they require additional light sources placed at remote location [6–8]. Monolithically integrated tunable lasers using sampled grating distributed Bragg reflectors (SG-DBRs) and double-ring resonators for wavelength selection and wide wavelength tuning, which use the Vernier effect to extend the wavelength tuning range, can be used as the sources of the WDM-PON system, but they have some problems such as a complicated fabrication process, low fabrication yield and high-cost [9, 10]. Thus a tunable planar lightwave circuit external cavity laser (PLC-ECL) using the hybrid integration technique with a superluminescent diode (SLD) and a polymer Bragg reflector (PBR) [11] is a good candidate for the source of the WDM-PON based FTTH system since this tunable laser has a wider wavelength tuning range due to the large thermo-optic effect of the polymer waveguide and easy fabrication in mass production [12]. We proposed and demonstrated a hybridly-integrated tunable PLC-ECL operating in direct modulation for 1.25-Gbps transmissions [13]. The SLD was used for the gain of the tunable PLC-ECL because it has a wide enough bandwidth to cover the channels of the WDM-PON system at a low operating current [14, 15]. The output power of the tunable PLC-ECL was increased by using the spot-size-converter (SSC)-integrated SLD with a far-field pattern (FFP) of less than 15 deg. On the other hand, PBR was utilized as a tunable filter for the low-cost tunable PLC-ECL because PBR’s large thermo-optic effect causes a wide wavelength tuning range of the tunable laser with consumption of very little electric power [16,17].

In this paper, we study the transmission characteristics of the tunable PLC-ECL with 100 GHz tuning spacing 16 channels successfully operating at directly-modulated 2.5-Gbps over 20-km transmissions. We obtained the tunable PLC-ECL with the modulation speed higher than 2.5-Gbps through the temperature stabilization and the decrease of the total length of the SLD.

2. Design and fabrication

Figure 1(a) shows the schematic diagram of the tunable PLC-ECL using the hybrid integration technique for low-cost tunable laser source. Figure 1(b) is the photography of the fabricated PLC-ECL module. The SLD acts as a gain of the tunable laser and the PBR is used as a wavelength selection reflector and a wavelength tuning device. The PBR was actively aligned with the packaged SLD (TO can type) through an aspherical microlens to obtain the high coupling efficiency of about 40%, the low coupling efficiency variation over temperature and high fabrication yield. To increase the modulation speed of the tunable laser, we stabilized the operating temperature of the SLD by using the thermo electric cooler (TEC). The TEC was packaged in TO can, which was not included in Ref [12, 13]. And, the length of the SSC region in SLD was shortened to be 140 μm compared with 300 μm in Ref [14] for high output power and low loss of the SLD. The SSC structure was optimized to obtain the FFP less than 15 degree with circular beam. In this study, we used the SLD chips having the output power of 11mW at injection current of 60mA and the circular divergence beam of 13.6 degree.



(a) (b)

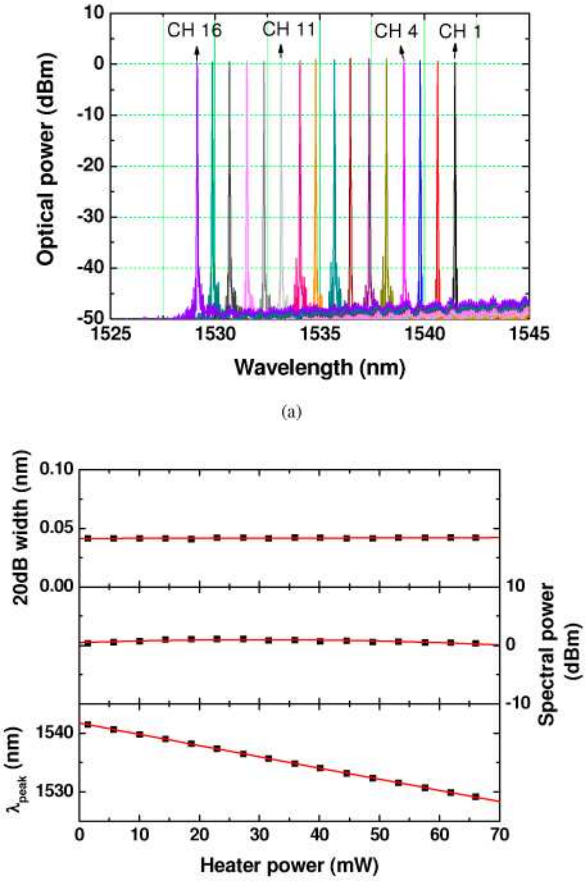
Fig. 1. A tunable PLC-ECL (a) schematic diagram (b) photograph.

The SLD has active straight region, active bending region, tapered SSC region and passive ridge waveguide with lengths of 400 μm, 60 μm, 140 μm, and 50 μm, respectively. The length of the SLD was 650μm, which was reduced by 150μm compared with 800μm in Ref [12–14]. The length of the SSC region was only shortened to decrease the loss of the SLD. The active region is a planar buried heterostructure (PBH) with a multiple quantum well (MQW) composed of seven wells of InGaAsP (λ_w=1.58 μm, thickness=8 nm) and eight barriers (λ_b=1.3 μm, thickness=11 nm) [18]. Separate confinement heterostructure layers (λ_{sch}=1.3 μm, thickness=70 nm) are above and below the MQW. SSC has a double-waveguide-core structure with a lateral tapered upper core (λ_{pu}=1.3 μm, thickness=0.25 μm) and lower core (λ_{pl}=1.15 μm, thickness=0.1 μm) [19,20]. The optical wave emitted from the SLD is expanded by gradually reducing the width of tapered upper core from 1.5 μm down to less than 0.2 μm and the wave is confined by the lower core and the passive ridge waveguide in the vertical and horizontal directions, respectively. The width of the passive ridge waveguide was set to be 4 μm in all SLD regions to obtain the FFP of less than 14 degree with circular divergence beam. The SSC region is butt-coupled to the active region (MQW). To reduce the facet reflection and the spectral ripple of the SLD, the waveguide was tilted 7-degree with respect to the cleaved facet and then the front facet of SLD was anti-reflection (AR) coated (R<0.1%) with two layers of SiO2/TiO2. The rear facet of the SLD was high-reflection coated (R>90%) to increase the output power of the tunable laser.

The PBR with core dimension of 6×6 cm^2, refractive index of 1.38, index contrast of 0.01, and thermo-optic coefficient of -2.547×10^{-4}/°C was used as a tunable filter for the tunable PLC-ECL. To reduce the fabrication cost of the PBR, the PBR was fabricated by conventional process methods such as spin coating, UV-curing, photolithography using silicon photoresist, and e-beam evaporation of Ti-Au for metal heater. The fabrication process and reflection characteristics of PBR were detailed in [12].

3. Results and discussion

Figure 2 (a) and 2(b) show the spectrum characteristics of the tunable PLC-ECL with 100 GHz spacing 16 channels. The lasing wavelength of the tunable PLC-ECL was blue-shifted linearly over a 12 nm wavelength range (16 channels) due to the thermo-optic effect of the polymer waveguide when the electric power was applied to the PBR from 0 mW to 65 mW. The SLD current was set to be 50 mA and the temperature of the tunable laser was 40°C. The spectral peak power was higher than 0 dBm, a 20-dB bandwidth was less than 0.05 nm and a side-mode suppression ratio (SMSR) was larger than 40 dB, as an optical spectrum analyzer (OSA) with a resolution of 0.01nm was used.



(a)

(b)

Fig. 2. Spectral characteristics of tunable PLC-ECL (a) Superimposed spectra (b) Peak wavelength, spectral power and 20-dB bandwidth of each channel for various electrical powers applied to PBR.

Figure 3 shows L-I characteristics of the tunable PLC-ECL at the temperatures of 25°C [Fig. 3(a)] and 40°C [Fig. 3(b)]. The maximum output power at the SLD current of 100 mA, the power slope efficiency and the minimum threshold current were 10.3 mW, 0.132 mW/mA and 8 mA, respectively, for Ch1 (1546.01 nm) at the temperature of 25°C. The maximum variations of the threshold current, the output power and slope efficiency among the channels were 2.5 mA (2.5 mA), 0.8 mW (1.7 mW) and 0.01 mW/mA (0.019 mW/mA), respectively, at the temperature of 40°C (25°C). As the temperature of the tunable laser was increased from 25°C to 40°C, the channels of the tunable laser were shifted to the shorter wavelength by about 4.5 nm due to the thermo-optic effect. The increase of the temperature of the tunable laser caused the decrease of the output power and the increase of threshold current because the increase of the temperature in the SLD induces a reduction of the net modal gain of the SLD. As compared with the previous results at the same temperature of 25°C [13], the maximum output power at the SLD current of 100 mA and the power slope efficiency were increased by 1.7 mW and 0.03 mW/mA, respectively. And the threshold current was decreased by 1 mA. There occurred kink because the increase of the SLD current causes the mismatch between the round-trip time of the SLD and that of tunable PLC-ECL by a change in the effective index of the tunable laser, which is known as mode-hopping [21].

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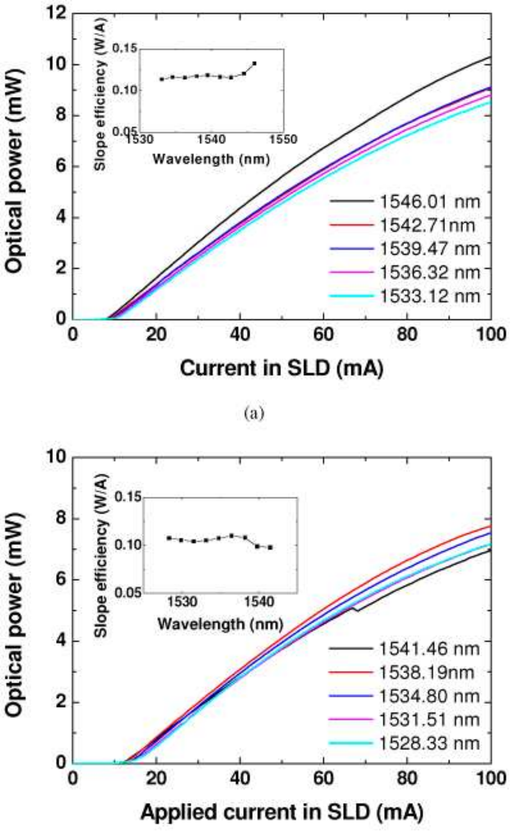

(a)

(b)

Fig. 3. L-I characteristics of tunable PLC-ECL at the temperatures of (a) 25°C and (b) 40°C. The inset is slope efficiency in each channel.

We used a 12.5-Gbps pulse pattern generator (PPG: Anritsu cop.), a digital communication analyzer (DCA: Agilent corp.), a bit error rate (BER) tester (Anritsu cop.), and a 10-Gbps avalanche photo detector (APD) for data transmission experiments of the tunable PLC-ECL. The PPG was set to generate a 2.5-Gbps nonreturn-to-zero (NRZ) pseudorandom bit stream (PRBS) with pattern length of 2^7-1. A bias current of 43 mA and a peak-to-peak modulation current of 41 mA were applied at the SLD for direct modulation. Figure 4 shows the BER performance and the filtered eye diagram for back-to-back (BTB) and 20-km single-mode fiber (SMF) transmissions. Error-free operation was successfully obtained at all channels. The power penalty after a 20-km SMF transmission was less than 0.8 dBm due to the chromatic dispersion of SMF. The effective reflectivity difference of the PBR among the channels caused BER variation and output power variation during the blue-shifted wavelength tuning. The extinction ratios (ER) were larger than 6 dB after 20-km transmission. Figure 5 shows the BERs of 16 channels for 20-km SMF transmission. The power penalty variation over 16 channels was less than 1.4 dB.

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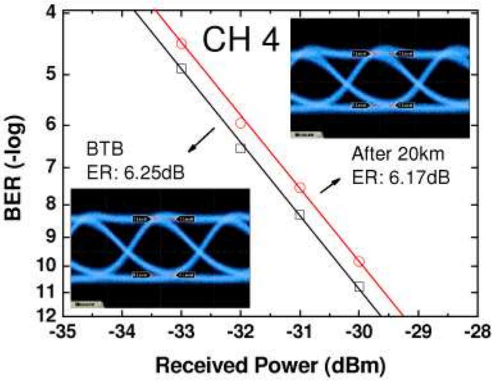

Fig. 4. BER of tunable PLC-ECL for back-to-back and 20-km SMF transmission. The SLD of the tunable PLC-ECL was directly modulated at 2.5-Gbps. The insets are the eye diagrams.

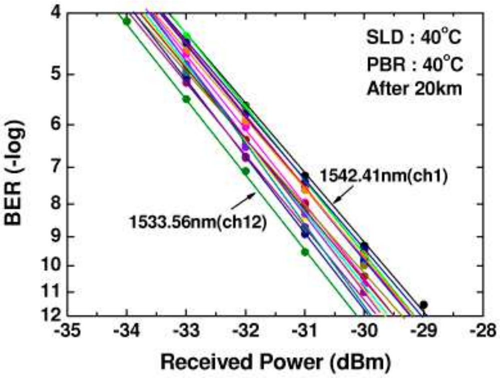

Fig. 5. BERs of the tunable PLC-ECL with the 0.8 nm wavelength spacing 16 channels for 20-km SMF transmission.

3. Conclusion

A 2.5-Gbps directly-modulated tunable PLC-ECL using an SLD and a PBR was demonstrated as a low-cost and broad-band source of a WDM-PON-based FTTH system. We stabilized the temperature of the SLD by using TEC in SLD TO can for over 2.5 Gbps modulation speed of the tunable laser. Although the wavelength tuning range of the tunable laser was 12 nm, which can be used for a 100GHz spacing 16 channels WDM-PON system, the tuning range of the tunable laser can be easily extended by increasing the tuning range of the PBR because the SLD had wide bandwidth. The 2.5-Gbps directly modulated tunable laser had a power penalty of less than 0.8 dB during blue-shifted tuning and a power penalty variation of less than 1.4 dB after transmission through 20 km of SMF.

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