200 GHz-spacing 8-channel multi-wavelength lasers for WDM-PON optical line terminal sources

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Abstract: We have fabricated modules of 8-channel multi-wavelength lasers (MWLs) with a wavelength separation of 200 GHz for the wavelength division multiplexed-passive optical network (WDM-PON) optical line terminal sources. The variation in the output power is minimized by inserting silicone between the superluminescent diode (SLD) and the silica waveguide. The wavelength shift of each channel is less than 0.21 nm from the ITU grid and can be controlled in the range of 0.36 nm without any reductions of the output power by a tuning heater. MWLs operated successfully in the direct modulation for 1.25 Gbit/s transmissions over 20 km.

OCIS codes: (060.4510): Optical communication, (230.1480): Bragg reflectors, (130.3120): Integrated optics devices.

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1. Introduction

The wavelength division multiplexed-passive optical network (WDM-PON) is a promising approach to meet a number of requirements of access networks such as large capacity, network security, protocol transparency, and upgradeability. Various PON architectures incorporating the wavelength division multiplex (WDM) features into access networks have been proposed [1-5]. Broad-band optical gain media such as Fabry-Perot laser diode (FP-LD) [3-5], semiconductor optical amplifier (SOA) [6], and reflective SOA (RSOA) [7] have been widely studied for optical network units (ONUs). However, there have been few studies for cost-effective optical line terminal (OLT) sources. In previous reports [8-10], we have shown that multi-wavelength lasers (MWLs) are promising candidates for multi-channel OLT sources, because they could replace multiple discrete laser arrays and reduce the management overhead. All channels were combined into an output waveguide with a fiber-pigtail and an isolator [11]. However, the MWLs fabricated for our previous studies [8, 10] revealed a large variation in the output power, which was due to passive alignment and flip-chip bonding.

In this paper, we propose a new 8-channel MWLs module with reduced variations in the output power and wavelength of lasers. High-order reflection gratings were formed by using photolithography [12], which provides a low-cost fabrication method of WDM-PON OLT modules. The center wavelength of the MWL was about 1.54 μm. The MWLs operated successfully at 1.25-Gbit/s transmission over 20 km.

2. Design and fabrication

The schematic configuration of the MWLs module for the present study is shown in Fig. 1 [8]. The module consists of an array waveguide grating (AWG) transmitter, 8-channel SLDs, tuning heaters, and high-order reflection gratings for external cavity laser (ECL). The center of the AWG pass band was designed to match the lasing wavelength of ECL. The 3dB line width of the AWG pass band was 0.8 nm. The fifth-order planar lightwave circuit (PLC) gratings with a wavelength separation of 200 GHz corresponding to those of the 8-channel silica AWG were fabricated by using photolithography [12]. These components are integrated on a single PLC chip to minimize the size of module. The module is 10 mm wide and 30mm long. The reflectivity and internal loss of each grating was 60% and 1~1.5dB, respectively. The 3dB line-width of the grating stop band was less than 0.2 nm, and the wavelength shift from the target wavelength was within ± 0.2nm. The fabrication procedure of the MWLs is detailed elsewhere [8]. We formed a tuning heater on top of the specific grating area to eliminate the mode hopping and to tune the wavelength of each channel for an accurate wavelength control. It was possible to tune the wavelength by 1nm with an applied power of 1W into the heater. MWL has long cavities of 6.345 mm from SLD to grating region.

Superluminescent diode (SLD) is the light source of MWLs, and its structure and

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performance are detailed in [13]. The cavity length of SLD is 800μm. For an efficient coupling between the silica waveguide and SLD, the far field pattern (FFP) of the SLD must be less than 15°. Our SLD was designed to have the lasing beam in a circular shape at the front facet and was fabricated in the ridge waveguide (RWG) type which was better than the buried RWG [14] in making a circular-shaped laser beam. The front facet of the SSC-SLD was antireflection (AR) coated to obtain a reflectivity of less than 0.01%, whereas the rear facet was high reflection (HR)-coated, yielding a reflectivity of 98%. The center wavelength of the SLD was about 1.54 μm. The 3 dB spectral width of the emission spectrum was 45nm at an operating current of 60 mA, which covers the full c-band. The slope efficiency measured at the front facet was about 0.21 mW/mA. The SLD array was precisely mounted on the terraced silicon by flip-chip bonding and a passive alignment technique using marks on both the SLD and the terraced silicon platform. The accuracy of the passive alignment was better than 1.5 μm.

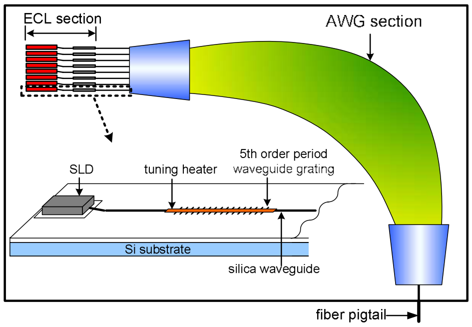

Fig. 1. Schematic configuration of the fabricated 8-channel MWLs.

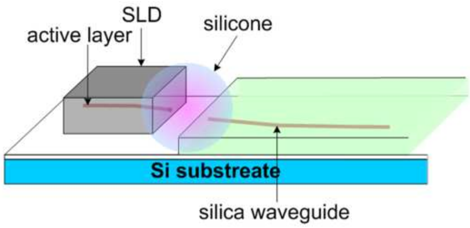

Fig. 2. Schematic diagram at the interface between a SLD and silica waveguide

The coupling of a laser beam between SLD and silica waveguide is shown schematically in Fig. 2. The distance between the SLD and the waveguide was set to be 20 μm. To avoid multiple reflections at the interface, the SLD and the silica waveguide were tilted by 7 and 23 degree, respectively, with respect to the cleaved facet [8]. The reflection of laser at both interfaces was reduced by inserting silicone in the gap [15-16], as shown in Fig. 2. We used the commercial silicone gel, which has a similar reflective index with the silica waveguide. The silicone was poured into the gap and thermally set. With use of a silicon index matching medium, the tilt angle of the silica waveguide was reduced to 15 degree, which improved the coupling efficiency.

3. Characteristics of MWL

We measured the oscillation characteristics of the fabricated 8-channel MWLs with silicone. All measurements were performed at a mount temperature of 25°C. Figure 2 shows the output

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power versus current characteristics of the 8-channel throughout fiber pigtail. The threshold current is from 10 to 18mA, which was not only 10mA lower than those of using monolithic integration scheme in ref [11], but also those of previous report in ref [8]. And our threshold current was a similar to ECLs of using hybrid integration scheme on silica PLC in ref [16]. In our MWL, mode hopping occurs only when there is a large sharp kink in five channels (ch1, ch3, ch5, ch6, ch8) among the all channel. Although the optical power of other channels was not linear with the injection current, there was no mode hopping in the threshold to 80mA range. We measured the mode hopping of 0.1~0.12nm at five channels, which was matched the calculating result of 0.11nm. This seems to be typical for this type laser having long cavity such as ref [11], [17]. And optical power is from 0.25 to 1.3mW at an injection current of 80mA. The slope efficiency was 0.009~0.015mW/mA.

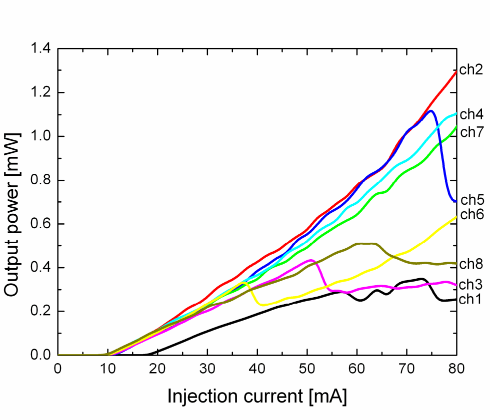

Fig. 3. Optical power dependence on injection current of 8-channel MWLs.

Output spectra of the MWL modules with and without silicone were measured at a SLD injection current of 60 mA at 25^{o}C. The wavelength interval of MWLs matches the AWG channel spacing quite accurately. Figure 4(a) shows the measured output spectra of the MWL without silicone with a resolution of 0.1 nm for each channel [10]. The lasing wavelengths are summarized in Table 1 and compared with the ITU grid. Differences of lasing wavelengths from the ITU grid were between -0.07 nm are -0.25 nm. The output power was between -9.05 and -1.96 dBm with a maximum variation of 7.09dBm. The single mode operation of the MWLs was obtained at more than 60 dB output power range in all channels, indicating that we have a good SMSR (side mode suppression ratio). The output spectra of the MWLs with using silicone are plotted in Fig. 4(b) and summarized in Table 1. The difference between the laser wavelength and the ITU grid was between -0.01 nm and -0.21 nm, in good agreement with a target wavelength shift of less than ± 0.2nm. This result is better than that of MWLs without silicone, demonstrating that silicone provides a good coupling of the laser beam between the SLD and the silica waveguide. The output power was -3.36 ~ -1.15dBm, which was 0.24~7.90 dBm higher than that obtained without silicone and shown in Fig. 4(a). If the AWG is excluded, the output power of the present device was 2 dBm, similar to that of ECLs in ref [18]. The variation of the output power was 2.21 dBm which was 4.78 dB lower than 7.09 dBm obtained by the device without silicone. We also obtained a SMSR of 35 dB, which is similar to the performance of the device without silicone. Considering that the output powers of the bare SSC SLDs are about 9.3 mW (9.68 dBm) at the injection current of 60 mA, and fiber coupling loss including the propagation loss of the silica waveguide is 0.5 dB, and the internal loss of grating is 1.5 dB. The AWG propagation loss is 4dB, and the coupling loss between the silica waveguide and the SSC SLD is estimated to be about -7.04 ~ -4.83 dB with silicone and -12.73 ~ -5.64dB without silicone. These results indicate that the uniformity of the output power and the wavelength accuracy was improved by using silicone. Therefore, we believe that the present device is suitable for 200GHz-spacing WDM-PON systems.

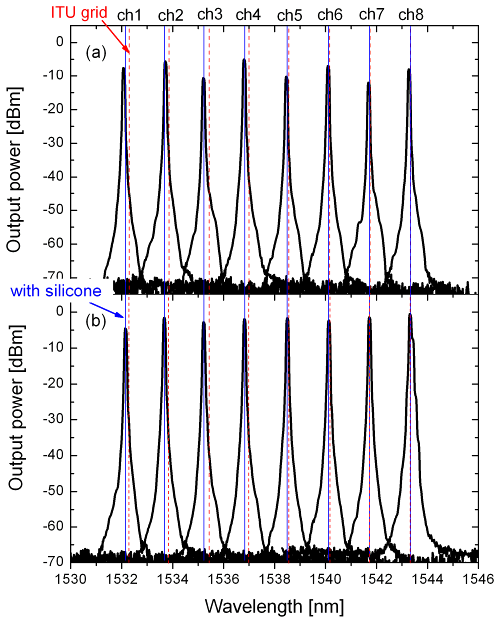

Fig. 4. Output spectra of the fabricated MWL at the SLD injection current of 60mA.

Table 1. Lasing Wavelengths of 8-Channel MWLs

channel	ITU grid (nm)	without silicone			with silicone		
		λ_{LASING}	$\Delta\lambda$	P_{output} (dBm)	λ_{LASING}	$\Delta\lambda$	P_{output} (dBm)
Ch1	1532.59	1532.10	- 0.19	-4.54	1532.14	- 0.15	-3.36
Ch2	1533.86	1533.70	- 0.16	-2.53	1533.66	- 0.2	-1.27
Ch3	1535.43	1535.18	- 0.25	-8.62	1535.22	- 0.21	-2.41
Ch4	1537.00	1536.80	- 0.20	-1.96	1536.82	- 0.18	-1.72
Ch5	1538.56	1538.46	- 0.10	-7.21	1538.50	- 0.06	-1.48
Ch6	1540.16	1540.10	- 0.06	-3.96	1540.12	- 0.04	-2.15
Ch7	1541.75	1541.68	- 0.07	-9.05	1541.72	- 0.03	-1.15
Ch8	1543.33	1543.26	- 0.07	-4.96	1543.32	- 0.01	-1.56

Figure 5(a) is shows the variation of output spectra with injection power of heaters when a SLD injection current is fixed at 60 mA. We found that the pattern of output spectra was a similar within AWG pas band, the pattern of AWG pass band and lasing spectra of ECL is simultaneously showed without AWG pass band at injection power of 713mW. And, the SMSR of ECL was higher than 35dB. The laser wavelength shows a red shift with increasing the injection power since the index of silica waveguide is varied by the injection power. The variation of the wavelength and output power with respect to the injection power is shown in Fig. 5(b). The tuning range was 0.48 nm at an injection power of 713 mW. There was no mode-hopping with a variation of the injection power in the tuning region. When the injection power was 300 mW, the laser wavelength was matched to the ITU grid of 1537.00 nm. The wavelength tuning range was 0.36 nm at the injection power of about 500 mW, but the output

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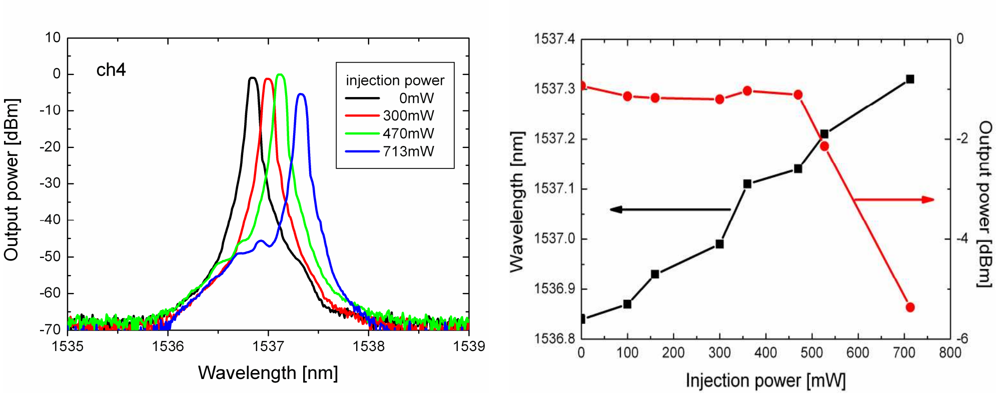
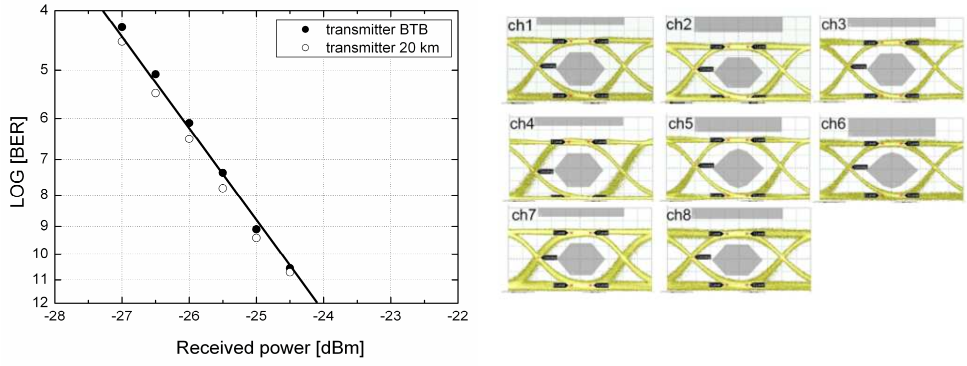
power for the wavelength tuning range of 0.36 nm was not varied. It is possible to tune the wavelength without the reduction of output power at the center region of AWG. The 3dB line width of the AWG pass band was about 0.92 nm, approximately matched the designing value of 0.8 nm.



(a) (b)

Fig. 5. (a). the variation of output spectra with injection power at the SLD injection current of 60mA. (b) the variaction of the wavelength and output power with the injection power of the channel 4.

It is important to know the channel-to-channel crosstalk when all channels of the MWLs are on. Figure 6(a) shows the measured bit-error rates (BERs) for both back-to-back and 20-km transmission of channel 1. Error-free operation was confirmed when the lasing current was modulated at a 1.25 Gbit/s with a pseudo random bit sequence (PRBS) of 2^{23}-1 (non-return-to-zero). No power penalty was observed at a bias current of 60 mA and amplitude of 40 mA (± 20 mA). And, the measured eye diagram of the 8-channel MWLs with 20-km transmission was shown in Fig 6(b). A clear eye pattern was obtained with the mask margin of 10%, confirming the simultaneous operation of all channels in the MWLs. From this result, we confirmed that the optical crosstalk was not observed in our MWLs.



(a) (b)

Fig. 6. (a). Bit-error rate (BER) curves, (b) Eye diagram of an optical signal generated from 1.25 Gbit/s direct modulation of the MWLs.

4. Conclusion

We have successfully demonstrated 200-GHz spacing 8-channel MWLs for very low-cost compact WDM-PON systems using a PLC technology. We improved the uniformity of output

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power and reduced the variation of lasing wavelength for the ITU grid by inserting silicone because of this gel provides a good coupling of the laser beam between the SLD and the silica waveguide. The wavelength shift of MWLs from the ITU grid was within -0.21 nm for all the 8-channels, well matched to the target wavelength shift of less than ±0.2nm. The output power was more than -3.36 dBm and the variation of output power was less than 2.21 dBm at an injection current of 60 mA for each channel. We also confirmed that the 8-channel MWLs operate successfully with 1.25-Gbit/s transmission over 20 km when all channels simultaneously were operated. Therefore, the proposed technique would be promising for a light source of WDM-PON systems.

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