External Cavity Lasers Composed of Higher Order Gratings and SLDs Integrated on PLC Platform

Jang-Uk Shin, Su Hwan Oh, Yoon-Jung Park, Sang-Ho Park, Young-Tak Han, Heekyung Sung, and Kwang Ryong Oh

Very compact 4-channel 200-GHz-spacing external cavity lasers (ECLs) were fabricated by hybrid integration of reflection gratings and superluminescent laser diodes on a planar lightwave circuit chip. The fifth-order gratings as reflection gratings were formed using a conventional contact-mask photo-lithography process to achieve low-cost fabrication. The lasing wavelength of the fabricated ECLs matched the ITU grid with an accuracy of ±0.1 nm, and optical powers were more than 0.4 mW at the injection current of 80 mA for all channels. The ECLs showed single mode operations with more than 30 dB side lobe suppression.

Keywords: High order grating, hybrid integration, external cavity laser (ECL), planar lightwave circuit (PLC), superluminescent laser diodes (SLD).

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I. Introduction

To construct a cost-effective and multi-channel wavelength division multiplexed passive optical network (WDM-PON) system, low-cost wavelength-stabilized light sources are required. External cavity lasers (ECLs) are promising and have been extensively studied [1]. The hybrid integrated form of ECL composed of a UV-written silica waveguide grating and a spot-size converter integrated laser diode (SSC-LD) mounted on a planar lightwave circuit (PLC) platform was proposed in [2]. Recently, PLC-based ECLs have been reported to exhibit better mechanical and thermal stability [3] than ECLs with fiber Bragg gratings [1], [4]. It was reported that PLC-based ECLs can be integrated on a single substrate to fabricate multi-wavelength laser sources. Such multi-wavelength laser sources are the key devices for WDM-PON systems. A 100-GHz-spacing 8-channel ECL light source integrated on a silica PLC platform was reported in [5]. The ECLs were composed of SSC-LDs and silica waveguide gratings on Si substrates. The front facets of the SSC-LDs were coated with dielectric antireflection (AR) films having less than 0.1% reflection. The gratings were formed by irradiating the silica waveguides with UV light through a phasemask.

In this paper, we report the fabrication of a very compact 4-channel ECL light source hybridly integrated on a silica PLC chip. For the first time to our knowledge, we used the higher order gratings patterned by conventional contact-mask photo-lithography and dry etching, which we proved to be applicable to ECL light sources for low-cost WDM systems. The fabrication of ECLs using higher order gratings has several advantages. First, multi-wavelength gratings with different grating periods can be easily fabricated on a small region of the

PLC platform. Second, a standard photomask can be used to form gratings by conventional photo-lithography, which is a well-established reliable process for PLC fabrication, providing higher yields than a process using a holographic interferometer or phasemask. Therefore, the ECL light sources with higher order gratings would be very useful for low-cost WDM-PON systems.

II. Design and Fabrication

Figure 1 shows the schematic configurations of the fabricated 4-channel ECL module. This device consists of a 4-channel superluminescent laser diode (SLD) array, fifth-order reflection gratings with 200 GHz wavelength spacing, and tuning heaters just on the gratings. These components are integrated on a single PLC chip to minimize the size of the module. The device is 5 mm wide and 15 mm long. We formed the etched higher order grating patterns using low-cost conventional photomask instead of writing the gratings using an interferometer or phase mask. The SLD's cavity length was 800 μm including a 340 μm SSC region; the silica waveguide length from LD to grating was about 1520 μm.

Figure 2 shows the schematic diagram of the higher order gratings on the silica waveguide. On the silica underclad layer, which was formed by direct oxidation of the silicon substrate, the higher order gratings were etched by ICP process. Then, the silica waveguide was formed on it by depositing the core layer and the overclad layer one by one as in the usual PLC fabrication processes. The index contrast and physical dimensions of the

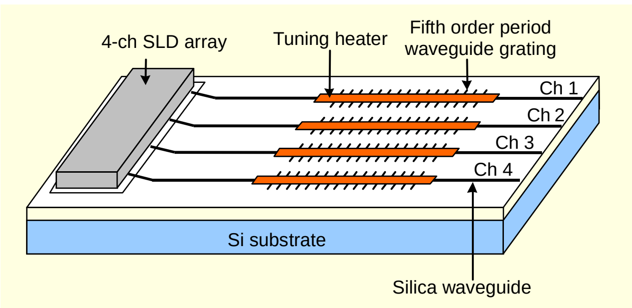

Fig. 1. Configurations of the fabricated 4-channel ECL module.

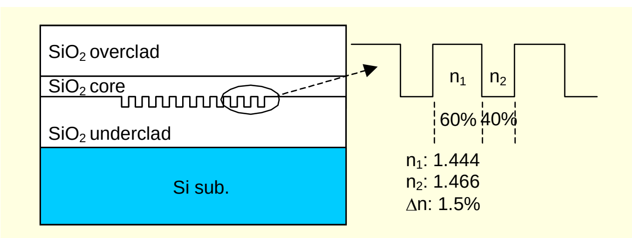

Fig. 2. Schematic diagram of the higher order grating on silica optical waveguides.

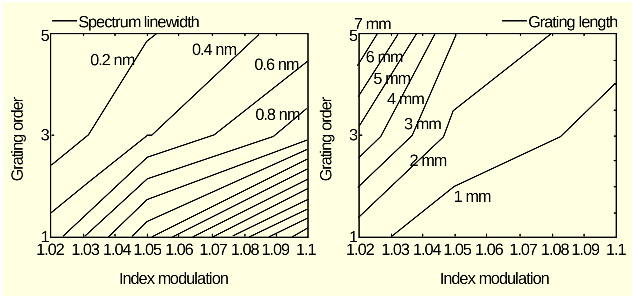

Fig. 3. Calculated grating properties: (a) the spectrum linewidth and (b) the grating length for 60% reflectance.

silica waveguide were 1.5%Δ and 4.0 μm ×4.5 μm, respectively. Using a commercial simulation tool (R-Soft GratingMOD), we calculated the reflection properties of light from the higher order gratings in the silica waveguide to obtain the optimized grating conditions. In the calculation, the index modulation was assumed to have a periodic stepwise function as in Fig. 2, and the target reflectance was fixed at 60% for each grating condition. The calculated spectrum linewidth and grating length for the given grating order and index modulation are shown in Fig. 3(a) and Fig. 3(b), respectively. The index modulation is the normalized variation of the effective index of the silica waveguide in the grating region.

To obtain the spectrum linewidth below 0.4 nm or a quarter of the wavelength spacing, the index modulation was set to below 5% for the third-order grating and below 8.5% for the fifth-order grating. If the index modulation is below 5%, the grating length should be longer than 2 mm and 3 mm for third- and fifth-order gratings, respectively, to have 60% reflection. For index modulation above 5%, the grating length can have shorter values but the spectrum linewidth would be widened, which may cause negative effects, such as multimode lasing. Therefore in this study, we restricted our grating conditions as follows: 1) odd numbers (first, third, fifth, and so on) in the grating orders for back reflection, 2) a grating length shorter than 4 mm for compact integration, and 3) a spectrum linewidth narrower than 0.4 nm, a quarter of the wavelength spacing. We designed a set of gratings with third and fifth orders for C-band wavelength channels equal to ITU grids of 200 GHz spacing. Grating periods were about 1.5 μm and 2.5 μm for third- and fifth-order gratings, respectively. As the groove depth deepens, the reflectivity grows and the reflection bandwidth widens as well. Therefore, the groove depths of etched gratings were carefully controlled in the range around 1 to 2 μm corresponding to the target index modulation, and from the experimental data we set the groove depth as 1.1 μm. The gratings were patterned by conventional photolithography using a contact photomask. The fifth-order gratings showed good performance as reflection gratings, but the third-order

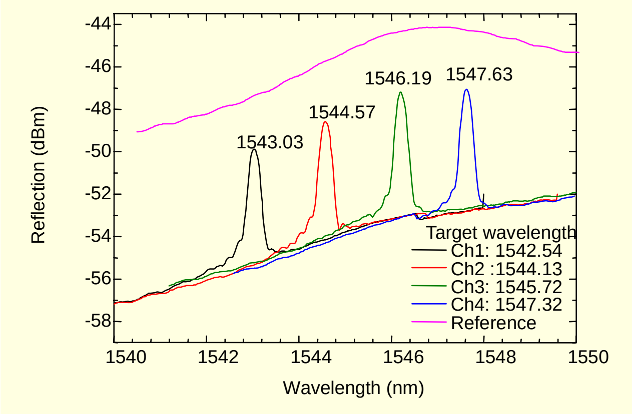

Fig. 4. Reflection spectra of the fabricated 4-channel gratings.

Table 1. Reflection wavelengths of 4-channel PLC grating.

Channel	ITU grid (nm)	Reflection wavelength (nm)	Δ (nm)
1	1542.54	1543.03	0.51
2	1544.13	1544.57	0.43
3	1545.72	1546.19	0.47
4	1547.32	1547.63	0.31

gratings showed poor grating properties, such as high insertion losses and uncertain reflection peaks, even though, in theory, they should have higher reflectivity than fifth-order gratings. We also obtained better reflectivity for 60:40 grating duty than 50:50. We think that a certain amount of diffusion occurs in the core and over-cladding processes. This diffusion alters the shape of the index profiles of the third-order gratings and 50:50 duty gratings from a step-function-like profile to a more sinusoidal-function-like shape, which causes less reflectivity.

The reflection spectra of the fabricated 4-channel gratings are shown in Fig. 4. The measured reflectivity of the gratings was about 60% for all channels. The reflection wavelengths are shown in Table 1, together with the related ITU grids for comparison. The wavelength shift from the target wavelength varied from wafer to wafer, but the channel spacing rather accurately matched the desired values for all times.

To control the overall shift (offset) of wavelengths which depends on the waveguide parameters, the process conditions of the silica waveguide, such as core thickness and refractive index, should be carefully controlled. For well-stabilized manufacturing processes, the wavelength shift could be easily eliminated by putting the compensating offset in the grating wavelength design. The insertion loss of the 4 mm-long gratings was between 1 and 1.5 dB. The 3 dB linewidths of the gratings' reflection spectra were less than 0.2 nm. For the wavelength adjustment of the gratings, we attached a tuning heater onto each grating. The wavelength tunability was about 0.9 nm/W and the maximum tuning range without heater failure was about 0.5 nm.

The 4-channel LD array was composed of buried ridge stripe (BRS) SSC-SLDs. The waveguide in the SSC region was tilted by 7 degrees with respect to the cleaved facet vertical. The AR coating was formed on the front facet by depositing SiN_x film. We estimate the reflectivity on the front facet to be less than 10^{-4} by the combined effect of both the AR coating and the waveguide tilting. The rear facet was HR-coated with multilayers of SiO_2/TiO_2 to obtain a high gain. The SLD's output powers were about 4 to 5 mW at a 60 mA injection current. The ripples in the emission spectra were less than 3 dB.

The SLD array was precisely mounted on the terraced silica platform by a flip-chip bonding technique [6], in which the SLD chip was passively aligned with the alignment marks on both the SLD and the terraced silica platform. The positioning accuracy was within 2 μm [7]. The gap between the flip-chip bonded SLD and the PLC waveguide was 15 μm, and the coupling loss was measured to be less than 3 dB.

III. Result and Discussion

We measured the lasing properties of the hybrid integrated ECLs. Figure 5 shows the measured output power versus the injection current of the 4-channel ECLs. As shown in the figure, the threshold currents were 15 to 18 mA, and the optical powers were from 0.4 mW to 0.5 mW at an injection current of 80 mA. Mode hopping occurred at an injection current of about 73 mA for channel 1 and at around 90 to 100 mA for other channels. Figure 6 shows the measured output spectra of the fabricated ECLs at an injection current of 60 mA without using tuning heaters. The peak wavelengths are summarized in Table 2 and are compared with the ITU grid. We found that we could adjust the channel wavelengths to the ITU grid to within 0.1 nm accuracy by putting a wavelength offset into the grating design and carefully controlling the waveguide processes. We measured the optical power dependence on the injection current at 25°C. There was no mode-hopping at the injection current in the modulation range from 40 to 80 mA (60±20 mA) except for channel 1. We obtained optical power ranging from -9.3 to -7.5 dBm at an injection current of 60 mA.

The ECLs showed single mode operations in all channels with more than 30 dB side lobe suppression. We also measured the wavelength tunability of the ECLs. We changed the lasing wavelength from Ch1 to Ch1′, as shown in Fig. 6, by heating the grating with a heater power of 500 mW, and we obtained a wavelength change of 0.45 nm, showing about 0.9 nm/W tunability. The tuning heater was designed to control the grating wavelengths individually, but it is unnecessary if the wavelength shift is removed by stabilizing the process conditions. In conclusion, as shown in Fig. 6, we proved experimentally that our fifth-order gratings formed by conventional contact-mask photo-lithography can provide ECL light sources which are highly applicable to low-cost WDM-PON systems.

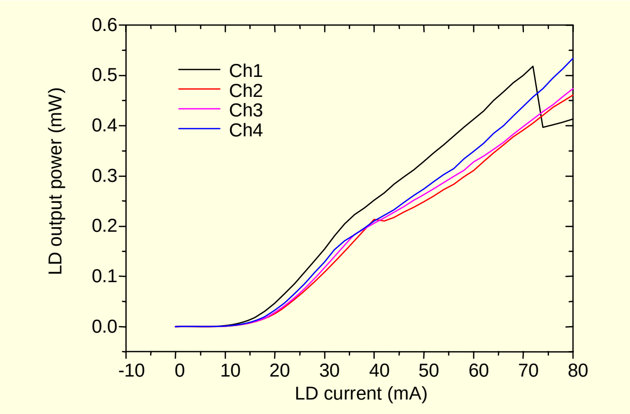

Fig. 5. Optical power dependence on injection current of 4-channel light source.

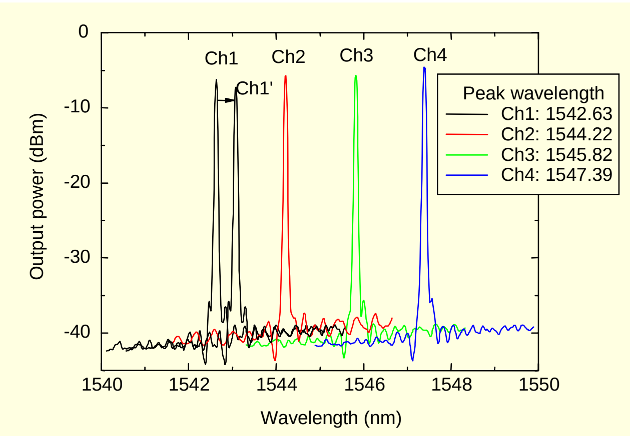

Fig. 6. Measured output spectra of the fabricated ECL source, the SLD injection current of 80 mA, and the wavelength shift of the ECL using a tuning heater.

Table 2. Oscillation wavelengths of 4-channel ECLs.

Channel	ITU grid (nm)	Oscillation wavelength (nm)	Δ (nm)
1	1542.54	1542.63	0.09
2	1544.13	1544.22	0.09
3	1545.72	1545.82	0.1
4	1547.32	1547.39	0.07

IV. Conclusion

We developed a very compact 200-GHz-spacing 4-channel ECL light source using silica PLC hybrid integration technology. To achieve low-cost fabrication, fifth-order gratings were formed using conventional contact-mask photo-lithography, and SLDs were hybridly integrated with the fifth-order gratings on a PLC platform to construct the 4-channel ECL light sources. We experimentally confirmed that we could control the lasing wavelengths with 0.1 nm accuracy by carefully controlling the waveguide process conditions. We expect the results shown in this study to provide a promising solution for low-cost light sources for WDM-PON systems.

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