LETTER

Performance improvement of optical negative feedback laser by reducing feedback loop length

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Abstract The Optical path length of an input/output optical waveguide in a Si ring filter is reduced to shorten the feedback loop length of an optical negative feedback laser. Thanks to the increase in phase margin in the optical negative feedback system, the spectral linewidth of a single-mode semiconductor laser can be reduced to 99.8 kHz.

Keywords: semiconductor laser, spectral linewidth, negative feedback, Si filter, integration

Classification: Integrated optoelectronics

1. Introduction

Compact and narrow spectral linewidth semiconductor lasers are required for digital coherent optical transmission systems [1]. Many studies have been conducted to develop such lasers [2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23], and almost all of them have focused on increasing the laser cavity quality factor (Q-factor) by lengthening the laser cavities via the addition of external cavities. As a result, the cavity sizes of these lasers become long. Moreover, frequency noise increases at the repetition frequency coincident with round trip frequency of the external cavity modes, which makes it difficult to use the lasers in optical transmission systems. While a current feedback technique that does not rely on increasing the cavity Q-factor has been proposed [24, 25], it requires large feedback electrical circuits and the size of the laser system consequently becomes too large. To achieve a compact and very narrow spectral linewidth semiconductor laser, we have previously proposed an optical negative feedback semiconductor laser [26, 27, 28, 29] that features a simple structure consisting of a single mode semiconductor laser and an optical filter. The optical filter acts as an optical frequency discriminator and converts the frequency noise of the semiconductor laser into electrical field amplitude modulated feedback light that is then fed back to the single-mode semiconductor laser. In the optical negative feedback laser, the optical filter does not constitute the laser cavity, so the laser is free from the issue of frequency noise increase. By using a ring optical filter with a Si optical waveguide, a compact optical negative feedback laser with

Fig. 1. Schematic structure of Si ring filter with reduced feedback loop length.

the spectral linewidth of 160 kHz has been achieved [30]. The value of the reduced spectral linewidth, however, is limited by the small phase margin of the negative feedback system. In this paper, we report a new Si ring filter with a shorter input/output optical waveguide that helps reduce the feedback loop length and enlarge the phase margin of the negative feedback system. By applying the Si ring filter to a single-mode semiconductor laser, the spectral linewidth can be reduced to 99.8 kHz.

2. Si ring filter and feedback characteristics

Fig. 1 shows the schematic structure of the proposed ring filter with the Si optical waveguide. A single-mode semiconductor laser is coupled to the Si ring filter at left in the figure by mean of a butt coupling technique. In order to increase the coupling efficiency between the two, a SiO_x slab buffer region and taper Si waveguide are located at the facet of the filter. The dimensions of the Si waveguide are set to 400 nm (width) and 220 nm (thickness) to satisfy the single-mode condition for 1550-nm transverse-electric polarized light. Propagation loss of the Si waveguide is assumed to be 3.6 dB/cm. Input light from the laser is coupled to the ring waveguide and re-coupled to the laser via input/output waveguide. The radius of the wrapping waveguide of the input/output waveguide r is set to 20 μm to avoid the increase in propagation loss at the curved waveguide. The total round trip waveguide length (feedback loop length) is reduced to $L_{\text{FBL}} \sim 828 \mu\text{m}$, which corresponds to the feedback loop delay time of $\tau_{\text{FBL}} \sim 9.9 \text{ ps}$. The value can be reduced to almost half the value of the previous Si ring filter ($L_{\text{FBL}} \sim 1226 \mu\text{m}$ and $\tau_{\text{FBL}} \sim 18.8 \text{ ps}$) [30]. The radius of the ring waveguide is set to 220 μm and the free spectral range of the filter is 50 GHz. The power transition efficiency of optical coupling between the input/output and ring waveguides σ is set to 0.2 by setting the gap between the two waveguides to 420 nm. The

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Fig. 2. Calculated feedback gain and phase of the optical negative feedback system of the laser as a function of noise frequency.

waveguide at the right of the ring waveguide is attached in order to monitor the condition of the butt joint between the single-mode semiconductor laser and the Si ring filter. The finesse of the Si ring filter is estimated to be 13.9, which is the same as the filter in the previous report [30]. The maximum conversion efficiency from frequency change to electrical field reflection coefficient of the filter is estimated to be $1.02 \times 10^{-10} \text{ Hz}^{-1}$. We estimate the feedback gain and phase delay of the optical negative feedback system of the laser by calculating the transfer function of the system [27]. Fig. 2 shows the calculated result. We found that the feedback gain of the optical negative feedback system of the laser could reach 11.3 dB at the noise frequency range below several hundred mega hertz even when the phase margin of the system was set to 45 degrees. This indicates that the spectral linewidth of the optical negative feedback laser using the Si ring filter proposed here can reduce the value to two orders of magnitude narrower than the value under the free running condition. The laser's spectral linewidth can be reduced to less than 100 kHz when a semiconductor laser with 10 MHz spectral linewidth under a free running condition is used.

3. Experiment

We tested the optical negative feedback laser by integrating a distributed feedback (DFB) laser and the fabricated Si ring filter as a hybrid. Cavity length and threshold current I_{th} of the DFB laser were 300 μm and 9 mA, respectively. The dimensions of the fabricated Si ring filter are the same as the one explained in the previous section. The characteristics of the filter are almost the same as the previous one [30] as predicted from the numerical analysis mentioned above. Fig. 3(a) shows a photograph of the integrated optical negative feedback laser. The gap between DFB laser and input/output waveguide of the Si ring filter is filled with refractive index matching gel to reduce the reflections from the facets of the two. Fig. 3(b) show the near field beam pattern of the output from the Si ring filter. It exhibits a clear single transverse mode pattern and indicates that the butt coupling between the DFB laser and the Si ring filter is done sufficiently. The spectral linewidth of the laser is measured using a delayed-heterodyne method [31]. A delay optical fiber of 20 km is used and the resolution of the measured system is estimated to be 5 kHz. Fig. 4(a) shows the measured beat spectra of the laser under free running and feedback conditions. Bias current to the DFB laser is set to $10I_{th}$. The spectral line-

Fig. 3. (a) Photo of optical negative feedback laser consisting of DFB laser and Si ring filter. (b) Near field pattern of the output from Si ring filter's monitor waveguide.

Fig. 4. (a) Measured beat spectra of lasing mode under free running (gray curve) and optical negative feedback (black curve) conditions. (b) Magnified beat spectrum of the optical negative feedback laser. Dotted curve is a fitted one by using Lorentz function.

width of the DFB laser is estimated to be around 10 MHz under the free running condition. This can be reduced dramatically by performing optical negative feedback with the Si ring filter. Fig. 4(b) shows the magnified beat spectrum of the laser under the optical negative feedback condition. The dotted curve in the figure is a fitted one of the measured data using the Lorentz function. The reduced spectral linewidth is estimated to be reached to 99.8 kHz, which is two orders of magnitude narrower than the value under the free running condition (~ 10 MHz). The reduction ratio of the spectral linewidth is almost identical to the predicted value from the numerical calculation.

4. Summary

In this work, we improved the spectral linewidth reduction ratio in an optical negative feedback laser with a Si ring filter by reducing the optical path length of the input/output waveguide of the Si ring filter. Thanks to the increase in phase margin of the optical negative feedback system, the spectral linewidth of the optical negative feedback laser was reduced to 99.8 kHz, which is two orders of magnitude narrower than the value for the free running DFB laser used in this experiment.

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