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Low Reflection Optical Coupling for Hybrid Integrated Wavelength Tunable Laser with Silicon Waveguide Ring Resonators

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1. Introduction

Wavelength tunable semiconductor lasers are key devices in metro/core optical networks utilizing wavelength division multiplexing (WDM). There have been intense activities on developing wavelength tunable semiconductor lasers with various schemes such as monolithic cavities and external cavities. External cavity lasers generally offer high optical power, wide tuning range, and narrow linewidth, and produce high yield and reliability because of separately optimizing a gain part and a tunable filter part. These superior advantages have been realized in a waveguide-based external cavity tunable laser composed of a semiconductor optical amplifier (SOA) and a silica-based waveguide tunable filter [1,2]. However, its size and tuning power in the tunable filter part remain to be improved, which makes it difficult to include the laser in TOSA (transmitter optical sub assembly) of XFP (10 Gigabit small form factor pluggable).

For a compact and low tuning power filter, a silicon waveguide filter is attractive. Its compactness originates in the small bend radii of waveguides provided by the strong optical confinement in silicon core. Meanwhile, its low tuning power is based on a highly efficient thermo-optical effect of silicon. The major issue of the hybrid integrated laser using silicon waveguide filter is the optical coupling of an SOA and the waveguide filter. Especially, the reflection at the optical coupling dominantly affects the stability of the tunable laser. Besides, the lower coupling loss enables the higher optical power and the lower threshold of the laser. Thus, the appropriate design of optical coupling with low reflection and low loss is of great importance for the tunable laser performances.

In this paper, we discuss the required specifications of the reflection and the loss at the optical coupling for the stable lasing. Using the structure with a reflection as low as 4×10^{-3} at the optical coupling, stable lasing with a wavelength tunable range of 38 nm is demonstrated.

2. Device Design

Figure 1 shows a schematic of the wavelength tunable semiconductor laser composed of an SOA and a silicon wire waveguide tunable filter. This filter is composed of two ring resonators whose free spectral ranges (FSRs) are 610 and 680 GHz. This slight difference in FSRs gives a Vernier effect in wavelength tuning, and we can choose lasing wavelength (the maximum transmission peak) by varying the transmission peak wavelength of one ring resonator within its FSR by use of a thermo-optical effect. The silicon wire waveguide cross section is 450×220 nm (width × height), and the TE-like fundamental mode is used for lasing.

The transmission spectrum of the filter has one main transmission peak and sub peaks at wavelength intervals equal to the FSR of the ring resonator. Numerically calculated spectrum is shown in Fig. 2 as a typical example. The peak around 1603 nm indicates the maximum transmission corresponding to the lasing wavelength, determined by matching two resonance wavelengths of ring waveguides. The sub peak around 1608 nm has lower transmission caused by the mismatched resonances of two rings. The transmission difference of these peaks suppresses multimode (multi-wavelength) lasing, and improves the single-mode lasing stability (see the red dashed line in Fig. 2). However, the reflection at the optical coupling decreases the transmission difference, because the Fabry-Perot interference fringe originated in this reflection distorts the transmission spectra. The blue line in Fig. 2 indicates the transmission difference of nearly 0 dB (this induces the unstable lasing) when the reflection at the optical coupling is 5×10^{-3}. Therefore, the reflection at the optical coupling should be lower than 5×10^{-3} for this case.

The calculated transmission difference was plotted against the reflectivity at the optical coupling in Fig. 3. The higher reflectivity decreases the transmission difference (accordingly, the stability of the laser operation) as

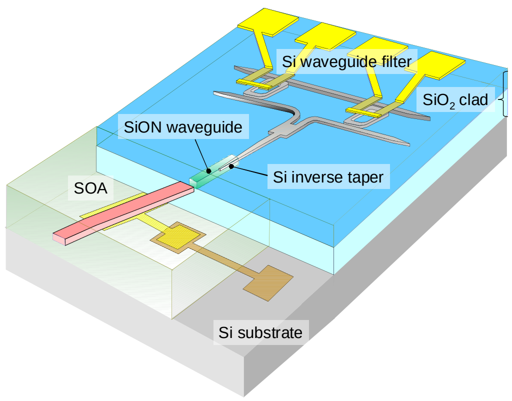

Fig. 1 Schematic diagram of the laser with silicon photonic-wire waveguide filter

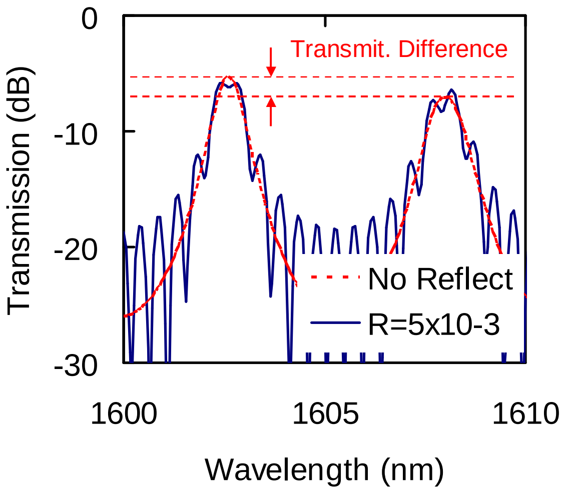

Fig. 2 Typical example of transmission characteristics of silicon photonic-wire waveguide filter

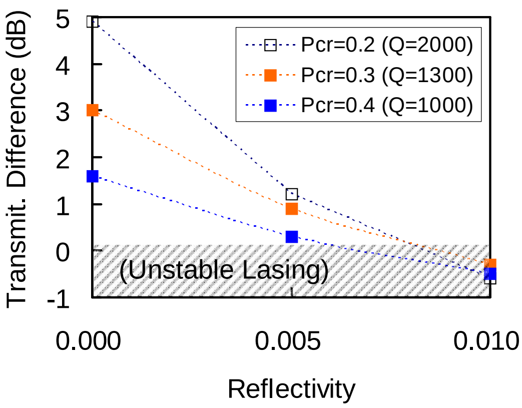

Fig. 3 Simulated transmission difference depending on reflectivity at the optical coupling and power coupling ratio (P_{cr}) of the ring resonators

discussed above. For the fixed FSRs of ring resonators, the transmission difference is also dependent on the power coupling ratio (P_{cr}) between ring and the bus waveguides (or the quality factor of the ring resonators). As shown in Fig. 3, the reflectivity lower than 5×10^{-3} gives the transmission difference larger than 0 dB and enables the stable lasing for P_{cr} of 0.2 to 0.4 (this range is reasonable for the laser stability and the output power). Thus, this reflectivity (5×10^{-3}) can be regarded as a criterion for the stable lasing.

For optical coupling of the SOA and the silicon waveguide filter, SiON waveguide is formed for butt-coupling to the SOA. Additionally, SiON and silicon waveguides are connected with the structure of the inversely tapered silicon core doubly surrounded by SiON inner cladding and SiO_2 outer cladding. Although SiON waveguide contributes to reducing the reflection (because it provides the small discontinuity of the effective refractive index of the guided lightwave), the major residual reflection is obtained at the silicon taper tip. This reflection needs to be evaluated considering the above-mentioned required specification.

We fabricated waveguides including tapered silicon and SiON to measure the reflection. OCDR (optical coherence domain reflectometry) was used for the measurement, and the reflection at the silicon taper tip was measured to be less than 4×10^{-3}. This satisfies the required reflection less than 5×10^{-3} at the optical coupling for the stable operation of the wavelength tunable laser.

In this structure, the spot size of the waveguide mode is also adiabatically converted along the silicon taper. The spot size conversion loss was also measured to be less than 0.5 dB for TE-like mode, which does not influence the stability of lasing so much.

3. Tunable Laser Experiments

The silicon wire waveguide filter was fabricated with thin film heaters on the silica cladding at the ring resonators. The resonance wavelengths of rings were tuned by thermo-optic effect via heating silicon core. The waveguide structure at the optical coupling was fabricated as described in Sect. 2. As a result, the stable wavelength tunable lasing was obtained at the wavelength range of 38 nm (1567-1605 nm), and the superimposed lasing spectra are shown in Fig. 4. The injection current in the SOA gain section was kept to be 50 mA, and the SMSR (side mode suppression ratio) was about 30 dB.

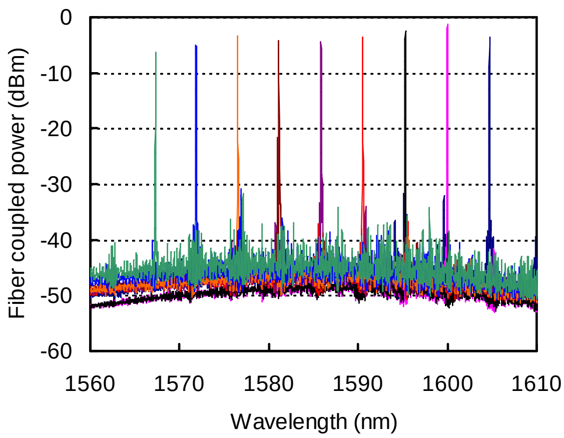

Fig. 4 Superimposed lasing spectra

4. Conclusions

The compact wavelength tunable laser composed of the SOA and the silicon wire waveguide filter was proposed and demonstrated. For the stable laser operation, we showed that the reflection was required to be less than 5×10^{-3} at the optical coupling. This specification was confirmed to be satisfied. Using the low reflection scheme at the optical coupling, the stable tunable lasing was achieved.

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