A Stable Widely Tunable Laser Using a Silica-Waveguide Triple-Ring Resonator

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Abstract: A tunable laser consisting of a silica-waveguide triple-ring resonator connected directly to a semiconductor optical amplifier is presented. Stable single-mode, grid-hopping free and full-L-band wavelength-digitally-tuning operations with 50-GHz channel spacing are successfully demonstrated.

OCIS codes: (140.3600) Lasers, tunable, (160.6030) Silica, (230.7370) Waveguides, (250.5980) Semiconductor optical amplifiers

1. Introduction

A stable, widely-wavelength-tunable laser is strongly demanded for wavelength-division-multiplexing (WDM) and reconfigurable-optical-add/drop-multiplexing (ROADM) networks. Several types of tunable lasers have been proposed and demonstrated [1-3]. However, unstable lasing operation has been observed in external cavity lasers, distributed Bragg reflector (DBR) lasers and sampled grating DBR (SG-DBR) lasers. To obtain stable single-mode operation of a tunable laser, a large threshold-gain difference between main mode and sub-mode is necessary. We have proposed a novel laser structure that consists of a silica-waveguide ring resonator connected directly to a semiconductor optical amplifier [4]. This laser structure has several advantages, such as a simple laser structure suitable for mass production and high reliability due to having stable thermo-optic phase shifters and no moving parts.

In the present study, we developed a stable tunable laser consisting of a silica-waveguide triple-ring resonator connected directly to a semiconductor optical amplifier (SOA). To realize stable single-mode operation, each ring length is optimized to obtain large threshold-gain difference between main mode and sub-mode. The laser attains grid-hopping-free operation by optimum design of ring resonators. And it successfully demonstrated full-L-band wavelength-digitally-tuning operation with 50-GHz channel spacing and fiber-coupled power of more than +7 dBm.

2. Ring resonator design

The triple-ring resonator is schematically shown in Fig. 1. Ring 1 has a FSR of 50 GHz adjusted to an ITU-T grid, and Ring 2 and Ring 3 have FSRs slightly different from below 50 GHz. The relationship between Ring 1 and the other rings is defined by

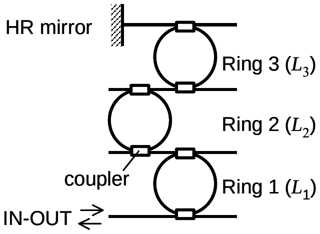

Fig. 1. Schematic design of triple-ring resonator

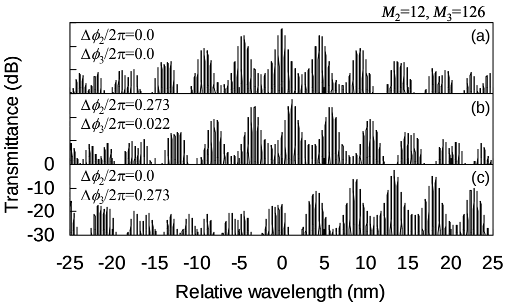

Fig. 2. Calculated transmittance spectra of the triple-ring resonator. (a) initial condition, (b) fine tuning, (c) coarse tuning

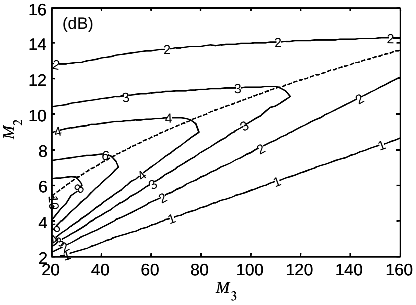

Fig. 3. Calculated threshold-gain-difference contour plot as a function of *M*-parameters

$$L_i = \frac{M_i}{M_i - 1} L_1 \quad (i = 2, 3), \tag{1}$$

where L_i is ring length, M_i is a wavelength-tuning enhancement factor [5], and subscript i is the number of rings.

Wavelength tuning is performed by controlling the phase $\Delta\phi_i$ corresponding to a change of ring length L_i. The transmittance was calculated taking into account the six-cascaded rings in the laser cavity. Figure 2 shows the calculated transmittance spectra under several phase conditions. In the calculation, 3-dB couplers were assumed to act as ring resonators, and M-parameters of M_2=12 and M_3=126 were selected for Ring 2 and Ring 3, respectively. Fine wavelength tuning is possible by controlling $\Delta\phi_2$ as shown in Fig. 2(b). On the other hand, controlling $\Delta\phi_3$ enables coarse wavelength tuning as shown in Fig. 2(c). Although the phase $\Delta\phi_i$ is only tuned from 0 to 2π, the wavelength-tuning range covers the full C- or L-band.

The calculated threshold-gain difference decreases with increasing M-parameter, as shown in Fig. 3. Although large M-parameters tend to wide wavelength-tuning, the optimum threshold-gain difference can be achieved when the M-parameters approximately satisfy the following simple equation,

$$M_3 - 1 = (M_2 - 1)^2. \tag{2}$$

The combinations of the M-parameters calculated from Eq. (2) are represented as a dashed line in Fig. 3. We selected the simulation parameters M_2=12 and M_3=126 in Fig. 2. First, M_3 was determined by the wavelength-tuning range of 50 nm, which was calculated from $(M_3-1)\cdot\mathrm{FSR}_{\mathrm{Ring\ 1}}$, to fully cover the C- or L-band. Next, optimum M_2 was calculated from Eq. (2). As a threshold-gain difference of 2.8 dB was estimated by optimum design of the triple-ring resonator, we can expect stable single-mode operations with wide wavelength-tuning range.

3. Device fabrication

The tunable laser consists of a triple-ring resonator fabricated by a planer lightwave circuit (PLC) and a SOA, as schematically shown in Fig. 4. Both are connected directly to each other through anti-reflection (AR) coatings. The rear facet of the ring resonator is coated with 95% high-reflection film. Thin metal heaters are formed along the ring waveguides to control the phases of each ring by thermo-optic effect.

In the triple-ring resonator, a ring length of about 4 mm and a minimum curvature radius less than 0.6 mm are necessary to realize a 50-GHz FSR. We employed a nitride-doped-silica (SiON) core for a low-excess-loss waveguide with small curvature [6]. The SiON core deposited by plasma-enhanced chemical vapor deposition (PE-CVD) was buried in a silica cladding layer. We achieved a minimum curvature radius of 0.25 mm at a refractive index difference of 6%, which is enough for the ring resonators of a 50-GHz FSR.

Figure 5 shows the measured one-way transmittance spectrum of the triple-ring resonator. Both the calculation result mentioned in section 2 and the measurement result are in good agreement. The minimum loss difference between the main transmission peak and sub-peaks estimated from Fig. 5 is more than 1.0 dB

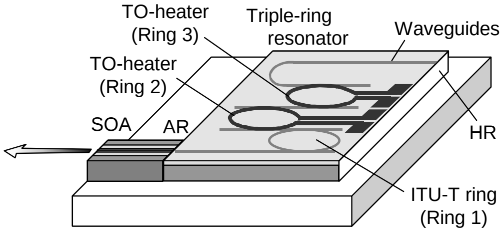

Fig. 4. Schematic structure of the proposed tunable laser

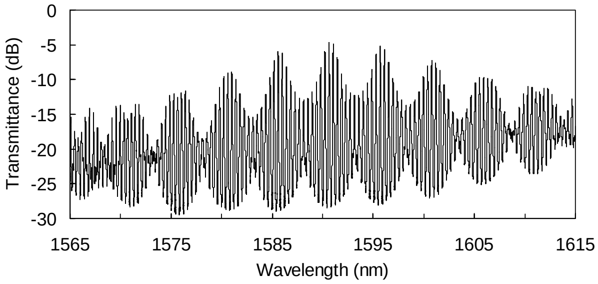

Fig. 5. One-way transmittance spectrum of the fabricated triple-ring resonator

4. Laser performance

Figure 6 shows the superimposed spectra from the laser with 50-GHz channel spacing over the L-band (97 channels). The injection current of the SOA was 300 mA at the maximum. Temperature of the triple-ring resonator and the SOA were stabilized at 25°C by a thermo-electric cooler (TEC). Wavelength tuning was performed by applying the electric power to the phase shifters. We achieved wide wavelength-tuning range of 40 nm (from 1570 to 1610 nm), fiber-coupled power of +5 to +7 dBm, and side-mode suppression ratio (SMSR) of more than 50 dB for all channels.

The wavelength-tuning characteristics are shown in Fig. 7. The lasing channels are tuned linearly as a function of the power applied to the phase shifters of Ring 2 and Ring 3.

The tunable laser achieved grid-hopping free operation because of the large threshold-gain difference, as shown in Fig. 8. Although the lasing wavelength was slightly shifted with increasing SOA current from threshold to 280 mA, no changes between other grids were observed. The wavelength shift was less than 15 pm (about 1.9 GHz) across the whole range of injection current of the SOA. This result indicates that the developed tunable laser has excellent stability and tunability.

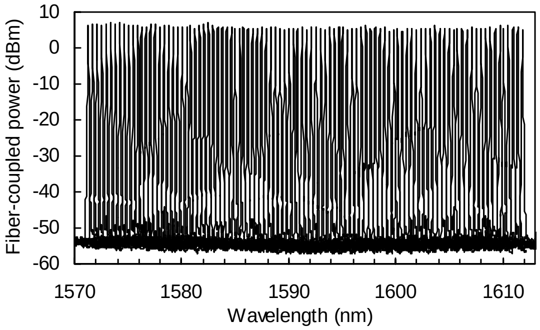

Fig. 6. Superimposed spectra at 50-GHz channel spacing over the L-band

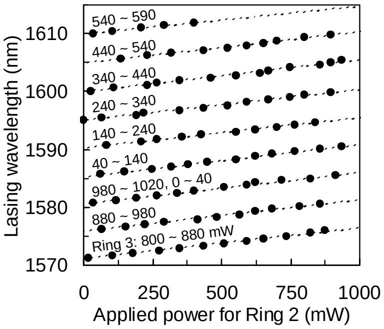

Fig. 7. Tuning characteristics at various lasing wavelengths

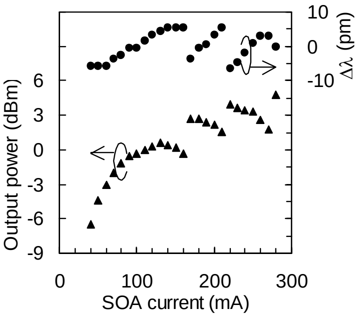

Fig. 8. Grid-hopping free operation against injection current of SOA

5. Conclusion

We developed a widely-wavelength-tunable laser consisting of a novel triple-ring resonator based on silica waveguides connected directly to a SOA. The excellent wavelength stability of the laser is due to sufficient threshold-gain difference between the main mode and sub-mode. And it achieved stable single-mode operation, at 50-GHz channel spacing covering the L-band, with a tuning range of more than 40 nm, fiber-coupled power of more than +7 dBm, and SMSR of more than 50 dB. We believe that this tunable laser is promising for application to WDM and ROADM networks because it attains stable single-mode and digitally wide wavelength-tuning operations.

References

1. J. D. Berger, Y. Zhang, J. D. Grade, H. Lee, S. Hrinya, H. Jerman, A. Fennema, A. Tselikov and D. Anthon, “Widely tunable external cavity diode laser using a MEMS electrostatic rotary actuator,” ECOC2001, F.3.3.
2. Y. A. Akulova, C. Schow, A. Karim, S. Nakagawa, P. Kozodoy, G. A. Fish, J. DeFrance, A. Dahl, M. Larson, T. Wipiejewski, D. Pavinski, T. Butrie and L. A. Coldren, “Widely-Tunable Electroabsorption-Modulated Sampled Grating DBR Laser Integrated with Semiconductor Optical Amplifier,” OFC2002, ThV1.
3. B. Pezeshki, E. Vail, J. Kubicky, G. Yoffe, S. Zou, J. Heanue, P. Epp, S. Rishton, D. Ton, B. Faraji, M. Emanuel, X. Hong, M. Sherback, V. Agrawal, C. Chipman and T. Razazan, “20-mW Widely Tunable Laser Module Using DFB Array and MEMS Selection,” IEEE Photon. Technol. Lett., **12**, 1457-1459 (2002).
4. H. Yamazaki, M. Ishizaka, M. Takahashi, S. Watanabe, K. Suzuki, K. Sato and S. Sudo, “Widely Tunable Laser Consisting of a Silica Waveguide Double Ring Resonator Connected Directry to a Semiconductor Optical Amplifier,” ECOC2004, post-deadline paper 4.2.4.
5. B. Liu, A. Shakouri and J. E. Bowers, “Wide Tunable Double Ring Resonator Coupled Lasers,” IEEE Photon. Technol. Lett., **14**, 600-602 (2002).
6. T. Shimoda, K. Suzuki, S. Takaesu and A. Furukawa, “Low-Loss, Polarization-Independent Silicon-Oxynitride Waveguides for High-Density Integrated Planar Lightwave Circuits,” ECOC2002, 4.2.2.