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Novel Tunable Ladder-Type Filter for Widely Tunable Laser Diodes

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1. Introduction

High-speed tunable lasers are key components for future fiber-optic communication systems [1-4]. Recently, we reported a novel widely tunable laser, consisting of a ladder-type filter, a ring resonator, and an optical amplifier [4]. In this laser structure, the oscillation wavelength is determined by the resonant wavelength of the ring resonator, and the ladder filter selects one channel from the periodic resonant peaks. However, because of the relatively long cavity lengths, we have to make the bandwidth of the ladder filter narrow to stabilize the oscillation wavelength [4]. The bandwidth can be narrowed by increasing the number of arrayed waveguides (***N***) or by increasing the diffraction order (***m***). Table 1 summarizes the characteristics of the ladder filter when ***N*** and ***m*** are increased, with regard to loss, longitudinal mode spacing ($\Delta\lambda^{LM}$), free-spectral range (FSR), and tunable range ($\Delta\lambda$).

Table 1. Characteristics of the ladder filter by increasing ***N*** and ***m***

	Loss	$\Delta\lambda^{LM}$	FSR	$\Delta\lambda$
N	**High**	**Narrow**	Constant	Constant
m	Constant	Constant	**Narrow**	**Narrow**

Although increasing ***N*** assures a narrow bandwidth, the insertion loss becomes large and $\Delta\lambda^{LM}$ becomes narrow due to the relatively long cavity length. A large ***N*** also requires a larger number of optical couplers, which normally makes the filter characteristics more wavelength sensitive. Meanwhile, increasing ***m*** makes both FSR and $\Delta\lambda$ narrow. Thus, when the gain bandwidth of the optical amplifier is broader than the FSR, the laser operation could be unstable. The drawback of the narrow FSR can be overcome by using a chirping technique [3]. However, the reduction of $\Delta\lambda$ would be unavoidable when ***m*** is increased. As a result, in either case, it is quite difficult to satisfy all conditions required for a widely tunable laser. In this paper, we report a ladder filter design in which the bandwidth narrowing is achieved without increasing ***N*** and ***m*** and discuss the measured spectral and tuning characteristics of the fabricated devices both theoretically and experimentally.

2. Novel ladder filter design for widely tunable laser

Figure 1 shows a schematic drawing of the proposed ladder filter. The device is composed of lower and upper waveguides, crossing waveguides, and optical couplers. Each crossing waveguide is connected to the lower and upper waveguides via optical couplers. As shown in Fig. 1, the proposed ladder filter has a cascaded-connected structure composed of multi-stage ladder interferometers with a relatively low ***m*** and a single-stage ladder interferometer with a relatively high ***m***.

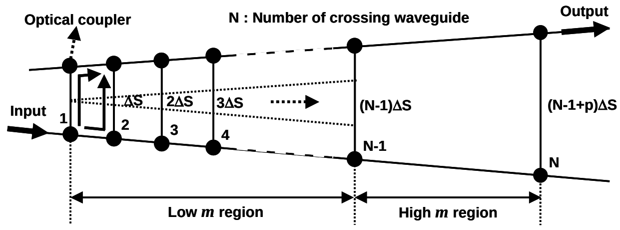

Fig. 1. Schematic drawing of the proposed ladder filter

The lightwaves passing through the upper waveguide and the crossing waveguides interfere at every optical coupler located at the upper waveguide side. In the low ***m*** region, the length of the crossing waveguide changes by the same amount, ΔS, which is defined as ($\boldsymbol{m}$*λ_0) / n_{eff}, where ***m***, λ_0, and n_{eff} are the diffraction order, filtering wavelength, and effective refractive index, respectively. In the high-***m*** region, the length of the crossing waveguide is set to ($\boldsymbol{N}$–1+$\boldsymbol{p}$)*ΔS (***p*** is a positive integer). In the proposed device, the peak transmittance and the FSR are determined by the low-***m*** region, while the bandwidth narrowing is achieved by the high-***m*** region.

Figure 2 shows the calculated wavelength spectra for a conventional and the proposed ladder filters, respectively.

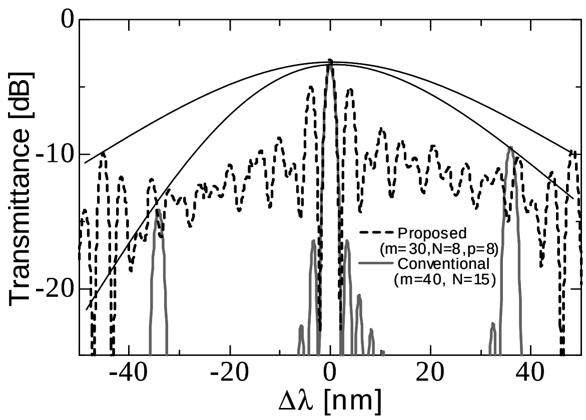

Fig. 2. Calculated wavelength spectra

In the calculation, a MMI coupler was considered as the optical coupler, and its wavelength dependence was also considered by using the beam propagation method. λ_0 was 1550 nm ($\Delta\lambda$=0). The number of crossing waveguides and the diffraction order were set to ***N***=15 and ***m***=40 for the conventional device and ***N***=8 and ***m***=30 (***p***=8) for the proposed device, respectively. The coupling ratio of the 2x2 MMI coupler was set to 15:85 in power (κ=0.85), except κ of the coupler connected to the ***N***th crossing waveguide for the proposed device (κ=0.5). Here, we assume a lossless medium. As shown in Fig. 2, the proposed device exhibits the same bandwidth in spite of the relatively low ***m*** and small ***N***, which leads to a wider tuning range, as shown by the envelops in Fig. 2. In addition, the proposed device is advantageous for achieving low insertion loss and weak wavelength sensitivity due to the low number of MMI couplers. Compared with the conventional device, the proposed device shows relatively large crosstalk. However, the crosstalk level is low enough to discriminate the lasing mode and suppress the lasing at unwanted spectral region due to the difference in gain [4]. The crosstalk could be further decreased by an optimized design.

3. Experimental results

Conventional and proposed ladder filters were fabricated on an InP wafer with a 1.5-µm-thick p-*InP* cladding layer, a 0.3-µm-thick *InGaAsP* core layer (λ_g=1.3 µm), and a 0.5-µm-thick n-*InP* cladding layer. The deep-ridge waveguide structures were formed by Cl_2-based ICP-RIE. Figure 3 shows the fabricated (a) conventional and (b) proposed ladder filters. The conventional device is 2.9 x 0.68 mm^2 in size and the proposed device 2.9 x 0.61 mm^2. For each device, the values of ***m***, ***N***, ***p***, and the power splitting ratio of the MMI coupler were the same as those used in the calculation.

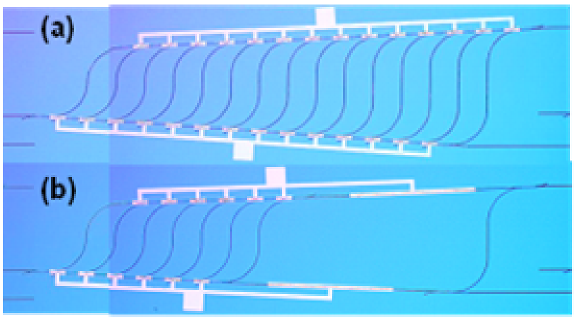

Fig. 3. Top-view photographs of the fabricated (a) conventional and (b) proposed ladder filters

The width and height of the waveguides are 1.6 and 4.0 µm, respectively. As shown in Fig. 3, current injection structures were formed to achieve wavelength tuning. Each electrode was 90-µm long. For the proposed device, the electrode length of the high-***m*** region was set to be ***p*** (=8) times longer than that of the low-***m*** region to remove the spectrum distortion caused by the tuning operation.

Figure 4 shows the fiber-to-fiber transmission spectra for the two fabricated devices (no current injection). An amplified spontaneous emission was used as an optical source. The input polarization was adjusted to be TE-mode. The measured 3-dB bandwidths were nearly the same, 2.04 (conventional) and 2.08 nm (proposed). As shown in Fig. 4, we achieved a relatively broad FSR in the proposed device without increasing the device size, the bandwidth, and the diffraction order.

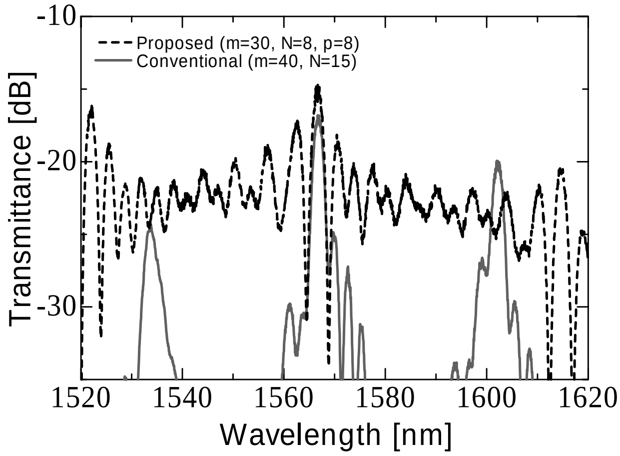

Fig. 4. Measured wavelength spectra

The transmittances, including fiber coupling losses, at λ_0 (=1566.7 nm) were measured to be 14.8 dB for the proposed device and 16.8 dB for the conventional one, respectively. We speculate that the loss of the proposed device is lower because of the reduced number of MMI couplers. It is evident that the proposed device has weaker wavelength-dependent spectral characteristics than the conventional one. When the same current of 40-mA was injected to the lower-side electrode (Fig. 3), the peak wavelength shifted to a shorter wavelength by 5.7 and 4.6 nm for the proposed and conventional device, respectively. Hence the proposed device based on our novel design has the potential to enhance oscillation intensity and tuning range without degrading the laser characteristics.

4. Conclusion

We have designed and demonstrated a novel ladder-type filter for widely tunable laser diodes. Results for a fabricated device show that the design enables us to achieve a wide tuning range and a low insertion loss without increasing bandwidth and device size.

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