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Design and optimization of frequency tunable semiconductor laser used in resonator integrated optic gyro

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ABSTRACT

Frequency tunable semiconductor laser has potential applications in resonator integrated optic gyro (RIOG) for its small size and easy to be integrated. An alternative construction of frequency tunable semiconductor laser with planar waveguide external cavity is proposed in this paper. The frequency tuning section, which is placed between the active section and Bragg grating section, is designed to be one part of the waveguide external cavity. The slab etched grating, based on the silicon-on-isolator ridge waveguide, is adopted to narrow the width of reflectivity spectrum. After the theoretical analysis and simulations, the frequency modulation coefficient of 2.1 MHz/mA is obtained, and the power change is less than 3.6×10^{-4} dB/1.6 GHz. The proposed configuration combines the advantages of wavelength tunable laser and external cavity laser, and it can realize precision frequency tuning, ignored power fluctuation and narrow linewidth, which contribute much to RIOG.

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1. Introduction

Resonator integrated optic gyro (RIOG) has been widely investigated for its excellent advantages such as high reliability, wide dynamic range, small size, and low cost [1–3]. In order to realize higher sensitivity, the light source used in RIOG should satisfy several requirements. Firstly, the spectral linewidth must be sufficiently narrow for high-sensitivity detection [4]. Then, the light source must be tunable continuously over one free spectral range of the resonator to set the center frequency of the laser to the resonance frequency of the resonator [5]. Furthermore, there should better no accompanying amplitude changed during frequency modulation [6]. To satisfy almost all the requirements, single-frequency He–Ne lasers [7], Nd:YAG lasers [8,9] and fiber lasers [10] have been selected as the laser source. The linewidth has been narrowed to less than 5 kHz by enlarging the cavity length, and the frequency-tuning range over several tens of GHz has been obtained. The amplitude can be constant because the current in the gain material is not changed. However, the lasers mentioned above are too large to realize the miniaturization of the RIOG system. Along with the development of opto-electronic integration technology, semiconductor lasers have been proposed to be used in RIOG for it's much more compact and easy to be integrated [11,12].

Ultra narrow linewidth emission of semiconductor lasers has been obtained by using several kinds of external cavities, such as bulk diffraction grating external cavity [13], fiber Bragg grating external cavity [14] and waveguide Bragg grating external cavity [15]. The bulk diffraction grating and fiber Bragg grating are hard to be integrated because of their discrete elements. The semiconductor lasers with planar waveguide Bragg grating external cavity (PW-ECL) has been considered to be the best choice for its butterfly package is smaller, simpler and lower cost than lasers of similar performance. The ECL uses a planar Bragg reflector on a planar silica or silicon waveguide to form a distributed Bragg reflector laser cavity [16,17]. The linewidth can be narrowed to be less than 10 kHz through lengthening the external cavity. For the commercial PW-ECL, the frequency can be tuned continuously by modifying the bias current of the gain part when the temperature is stable [18]. However, there may be some drawbacks about this approach. One is that the frequency modulation coefficient is not small enough for the application of high sensitivity of RIOG. For example the RIOG with waveguide resonator, whose cavity length is only 12.8 cm, the free spectral range (FSR) and full width at half maximum (FWHM) are 1.6 GHz and 28 MHz, respectively [2]. While the modulation coefficient of the PW-ECL is larger than 50 MHz/mA [6], which is too large to achieve high performance of RIOG. The other is that the frequency modulation of the laser produces an accompanying amplitude modulation, resulting in attenuation distortion of the

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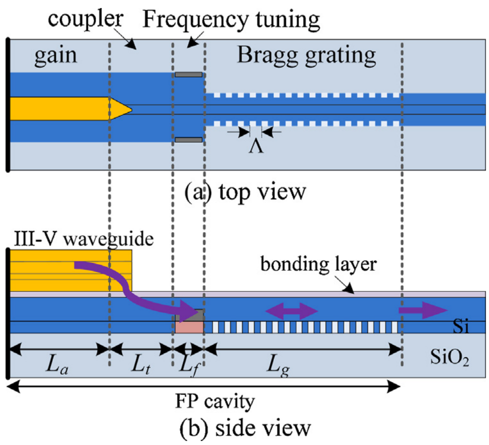

Fig. 1. The schematic diagram of the frequency tunable laser with waveguide external cavity. (a) The top view. (b) The side view. Where Λ is the period of Bragg grating, L_a, L_t, L_f and L_g are the lengths of the gain section, the coupler, the frequency tuning section and the Bragg grating section, respectively.

resonance valley [12]. That is because when the injection current in gain material is changed, both of the refractive index and the carrier density are modified, and then affecting the gain material loss and efficiency at the same time. In order to realize high sensitivity of RIOG, the current of the gain part in the laser should not be changed when the frequency is modulated.

In this paper, a construction of frequency tunable semiconductor laser with waveguide external cavity is proposed. The characteristics of the laser are designed and optimized to realize narrow linewidth and frequency tunable. The gain part and the coupler section are designed to be the same structure of hybrid silicon lasers for further integration [19]. The difference is the frequency tuning section that placed between the gain section and the Bragg grating section. The modulation performance is analyzed in detail. After theoretical analysis and simulations, the proposed construction of laser can realize high precision of frequency tuning and the power fluctuation is small enough to be ignored simultaneously, which can well satisfy the RIOG system.

2. Theory and structure

The schematic structure of the frequency tunable laser with waveguide external cavity is shown in Fig. 1. It consists of a gain section, a coupler section with a taper, a frequency tuning section for precisely tuning and a distributed Bragg grating reflector section. The gain section is composed of a stack of strained-layer multiple quantum wells emitting at a 1550 nm wavelength and hybrid integrated with silicon ridge waveguide by the taper coupler [19]. The grating and frequency tuning sections are fabricated on SOI substrate. The laser Fabry-Pérot (FP) cavity extends from the cleaved facet at the left-hand side of the gain section to the Bragg grating section. The frequency tuning region, whose reflective index can be changed through free carrier electrooptic effects, is used to shift the frequency with high precision and it can also lengthen the cavity of the whole lasing cavity to achieve narrow-linewidth.

2.1. Single wavelength output characteristics of laser

The mode spectra of the laser based on FP cavity can be illustrated as in Fig. 2. The output wavelength of the FP cavity is decided by the cavity length [20], which can be express as

$$\frac{2(n_aL_a + n_tL_t + n_fL_f + n_gL_{geff})}{\lambda_0} = m, \quad m = 1, 2, 3, \ldots \tag{1}$$

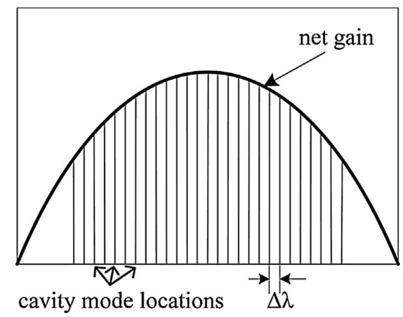

Fig. 2. The illustration of the gain and cavity mode spectra of the FP cavity.

where $n_a = 4.1$ is the reflective index of the active material, n_t, n_f, n_g are reflective index of the coupler, frequency tuning section and the Bragg grating section, respectively. λ_0 is the center wavelength of the FP cavity. L_{geff} is the effective length of the Bragg grating.

The range between two continue cavity mode (which also called the mode spacing) is given by

$$\Delta\lambda = \frac{\lambda_0^2}{2(n_aL_a + n_tL_t + n_fL_f + n_gL_{geff})} \tag{2}$$

$\Delta\lambda$ is decided by the value of $L_f + L_{geff}$ when the lengths of active section and taper coupler section have been fixed. The lengths of the active region and coupler section are designed to be 300 μm and 170 μm, respectively, which are in accordance with the structure characteristics of silicon hybrid integrated lasers [19]. Fig. 3 shows the range $\Delta\lambda$ with different sum length of $L_f + L_{geff}$. Obviously, $\Delta\lambda$ decreases as the $L_f + L_{geff}$ increases and it is larger than 0.1 nm when $L_f + L_{geff}$ is smaller than 4 mm. For the waveguide resonator fabricated by our research group, the FSR and FWHM are 1.6 GHz and 28 MHz, respectively [2], which corresponding to wavelength variation of $0.0128–8 \times 10^{-6}$ nm by Eq. (3) when the working optical wavelength λ is 1550 nm. It is obviously that, $\Delta\lambda = 0.1$ nm contains about eight FSR of resonator, so that mode hopping would not happen when the frequency modulation is less than eight FSR.

$$\frac{df}{d\lambda} = -\frac{c}{\lambda^2} \tag{3}$$

2.2. The filter characteristics of Bragg grating

The Bragg gratings are formed by a periodic corrugation on the slab of the SOI ridge waveguide to achieve narrow linewidth [21,22] (see Fig. 4(a)). The SOI waveguide is with a 0.22-μm-thick Si layer and 2-μm-thick buried oxide layer. The waveguide width and slab thickness are 0.42 μm and 0.07 μm, respectively. The single mode characteristics simulated by 3D beam propagation method (BPM) is shown in Fig. 4(b). Fig. 4(c) describes

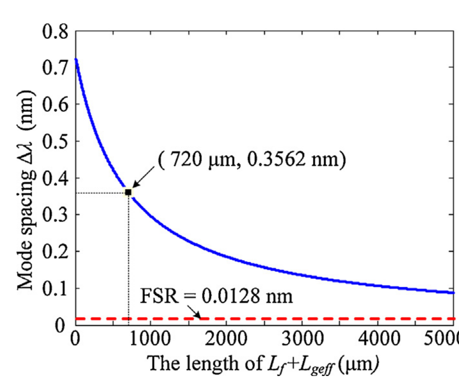

Fig. 3. The mode spacing $\Delta\lambda$ varies with different sum length of $L_f + L_{geff}$. The point in the figure is in the condition that the L_{geff} equals 690 nm and L_f equals 30 nm.

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