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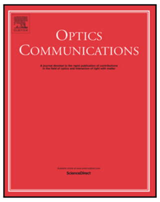

Research of asymmetric waveguide on surface emitting distributed feedback semiconductor lasers

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ABSTRACT

Surface emitting distributed feedback (SE-DFB) semiconductor lasers with second-order grating have become one of research hotspots due to be in terms of high beam quality, narrow linewidth and so on. The diffraction and feedback of the second-order grating are utilized to achieve wavelength stabilization and surface emitting. In the paper, SE-DFB laser with asymmetric waveguide is designed, and the effect of waveguide structures on slope efficiency is discussed. The results show that the slope efficiency of SE-DFB laser with P-asymmetric waveguide is 1.04 W/A which enhances 0.12 W/A than the device with symmetric waveguide. It provides an idea for SE-DFB laser research.

1. Introduction

Surface-emitting distributed feedback (SE-DFB) semiconductor lasers have become the research hotspot due to their advantages of high beam quality, narrow linewidth and stable wavelength, and they have attained various of applications in pumping sources, optical communications, chemical sensors and environmental monitoring [1–3].

In 1987, American scientist Macomber firstly demonstrated the electric pump 840 nm SE-DFB semiconductor laser without any facet reflections [4]. Power output as high as 70 mW was obtained by cooling the heatsink to 0 °C, and slope efficiency was 0.05 W/A. In the same year, Kazumasa Mitsunaga developed for the first time continuous waves (CW) lasing SE-DFB laser at room-temperature [5] with top surface power of 3 mW, slope efficiency of about 0.05 W/A and diffraction-limited narrow beam divergence in DFB transverse junction stripe of 0.13°. The early SE-DFB semiconductor lasers had an asymmetric-mode of exiting beams, double-lobe in far field, unevenly distributed waveguide field, space burning holes by multi-mode lasing and so on.

In order to improve the light output characteristics of the SE-DFB laser, researchers have carried out extensive research on the beam quality, the emission wavelength, narrow linewidth, slope efficiency and other aspects of the SE-DFB lasers. In 2005, Li Shuang et al. proposed resonant-optical-waveguide SE-DFB arrays [6]. In the device, second-order DFB grating and distributed Bragg reflector (DBR) grating are combined to achieve single mode operation. 20 units arrays had been demonstrated diffraction-limited-beam operation to very high pulsed (10 W) and CW (1.6 W) output powers. The calculated slope efficiency was 0.78 W/A. In 2009, G. Masions et al. developed 5.65 μm surface emitting quantum cascade lasers using biperiodic top metal grating to obtain a low beam divergence (12° × 3.1°) and mid-infrared wavelength [7]. The threshold current was 1.8 A, corresponding to threshold current density of 3 kA/cm^2 and the peak power was measured above 10 mW. In 2010, M. Kanskar et al. in Alfalight company proposed 975 nm SE-DFB laser [8]. The curve grating is used to achieve high power and stable wavelength. A single emitter producing 73 W of CW power, over 50% power conversion efficiency, and 0.07 nm/°C thermal drift. In the lateral direction the divergence is approximately 8° at full angle. In 2013, Tan Shao-Yang et al. proposed 1064 nm ridge waveguide DFB laser [9]. The output power of laser was 90 mW at single mode up to 255 mA, and slope efficiency was 0.42 W/A. In 2015, Yinghui Liu et al. developed 4.8 μm SE-DFB quantum cascade lasers with second order metal/semiconductor grating at room temperature [10]. The grating allowed efficient surface emission for the transverse-magnetic-polarized light. The CW output power was 94 mW at 25 °C, with a low threshold current density of 1.21 kA/cm^2. The slope efficiency was about 0.32 W/A.

In the above researches, researchers have been working hard to explore unique methods to improve the light output characteristics of SE-DFB lasers. Researches indicate that asymmetric waveguide structures can improve the efficiency in edge-emitting semiconductor lasers [11–13], so we choose this method to explore the effect of asymmetrical

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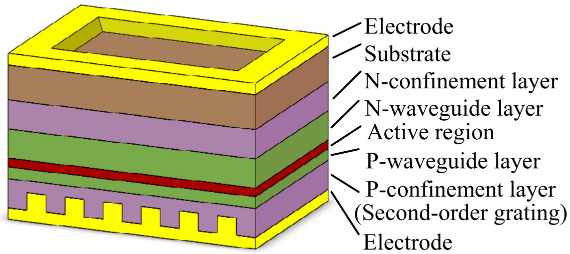

Fig. 1. Schematic diagram of SE-DFB laser structure.

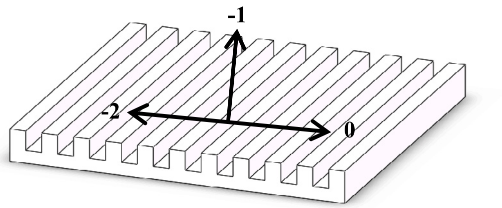

Fig. 2. Diagram of second-order grating diffraction principle.

waveguide structures on the light output characteristics of SE-DFB lasers. In this paper, the SE-DFB laser with asymmetrical waveguide structures is studied, and the influence of asymmetric waveguide in SE-DFB laser on the slope efficiency is researched. Meanwhile the parameters of second-order grating are designed for 976 nm SE-DFB laser with Matlab software. The results show asymmetric waveguide structures can improve the slope efficiency in SE-DFB semiconductor lasers. The output power of 976 nm asymmetric waveguide SE-DFB laser is 100 mW when inject current is 100 mA, the slope efficiency is 1.04 W/A., which enhances 0.12 W/A than the device with symmetric waveguide.

2. Working principle

In SE-DFB laser structure, the idea of integrated optics is used. The second-order grating is etched on the *P*-confinement layer to avoid secondary growth. The schematic diagram of SE-DFB laser structure is shown in Fig. 1. In the active region, electrons and holes recombine to generate photons, and the photons oscillate in the waveguide layer. At the same time, part of the photons pass through the waveguide layer and interact with the second-order grating to change the exit direction [6–8] The second order grating has two diffraction directions as shown in Fig. 2, the output coupling provided by the first-order diffraction makes the beam exit from the surface, and the second-order diffraction light is used for optical feedback and mode selection. Meanwhile, the grating also has the effect of stabilizing the laser wavelength.

3. Numerical calculation of second order grating

Grating cycle is expressed by the Bragg formula, which is defined as Eq. (1)

$$\Lambda = \frac{m\lambda_B}{2n_{\mathrm{eff}}} \tag{1}$$

where Λ is grating cycle, λ_B is incident wavelength, n_{eff} is effective refractive index, m is diffraction series.

For the rectangular thin film grating, the coupling coefficient is approximately expressed by coupling coefficient formula [14], which is defined as Eqs. (2) and (3).

$$\kappa_2 = k_0 \cdot \Delta n \cdot \Gamma_g \frac{\sin(2\pi\sigma)}{2\pi}. \tag{2}$$

$$\kappa_1 = \frac{2 \cdot \Delta n \cdot d_g}{\lambda} \cdot \tan(\pi\sigma) \cdot \kappa_2. \tag{3}$$

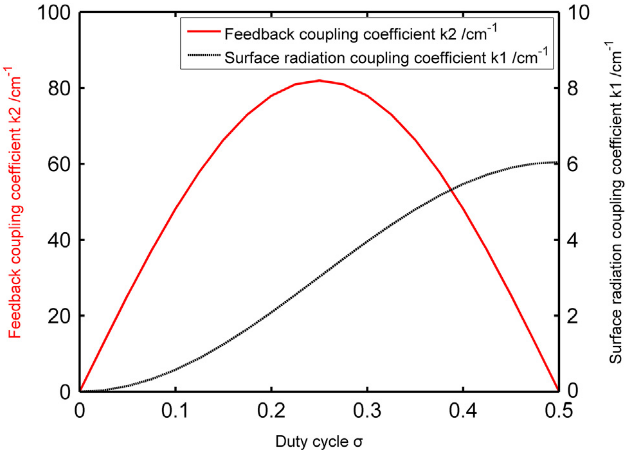

Fig. 3. The variation of coupling coefficient $k1$, $k2$ and duty cycle σ.

where $k_0 = 2\pi/\lambda$, Δn is the difference of refractive index of waveguide layer and confinement layer; Γ_g can be the restriction factor of grating; σ is the duty cycle.

According to Eq. (1), the grating period of 976 nm wavelength is 300 nm. The relationship between coupling coefficient and duty cycle is obtained with Matlab software using Eqs. (2) and (3), the result is showed in Fig. 3. The red solid line and black dashed line represent the change that feedback coupling coefficient and surface radiation coupling coefficient as a function of the duty cycle, respectively. The red solid line rises firstly and then drops, reaching the maximum value is 80 cm^{-1} at $\sigma = 0.25$. The result indicates that the second-order diffracted light of the second-order grating is strongest at the same σ point, providing stable optical feedback to the device and generating laser. The black dashed line is rising with the increasing the value of σ. When the value of σ is reaching 0.5, the surface radiation coupling coefficient $k1$ is maximum value 6 cm^{-1}. The result indicates that the first-order diffracted light of the second-order grating is the strongest at $\sigma = 0.5$, which can change the light exit direction of the device and achieve the surface emission. In the SE-DFB lasers, feedback coupling and surface radiation coupling are both indispensable. The feedback will decide to produce laser, and the surface radiation coupling will achieve the surface of the light. In Fig. 3, the feedback coupling efficiency and the surface emission coupling efficiency are taken into account when the value σ is approximately 0.4. Therefore, the duty cycle of the second-order grating is about 0.4. According to Eq. (3) the surface radiation coupling coefficient is proportional to the grating depth, so the depth of the grating is determined by the thickness of the confinement layer. Meanwhile the depth is easy to process.

4. Design and simulation of SE-DFB laser structure

4.1. Asymmetric waveguide structure

For the traditional semiconductor lasers, the symmetrical waveguide structure is main structural features. The optical distribution of the waveguide structure is symmetrically distributed around the active region, and most of the optical field is confined in the waveguide layers. In the SE-DFB laser, second-order grating is etched on the confinement layer. The asymmetric waveguide structure can change the optical field distribution, effectively increase the optical area of confinement layer and the probability of photons interacting with second-order gratings, and then enhancing the efficiency [15].

In order to study the influence of the asymmetric waveguide structure on the optical field distribution, the model of the semiconductor laser waveguide structure is built using CrossLight software. The total