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Optimization Design of Superluminescent Diodes with RWG Structure for High Efficiency Coupling with SMFs

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Abstract: With the aim of achieving high coupling power of RWG SLDs into SMFs, the structure dependences of the output power and the near field pattern are investigated. The thicknesses of the layers between the active region and the ridge waveguide are optimized by taking into account the injected carrier distribution and local material gain in the SLD cross section.

Key words: superluminescent diode; coupling efficiency; injection efficiency
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1 Introduction

Superluminescent diodes (SLDs) are ideal incoherent light sources for optical fiber gyroscopes (OFG)[1], optical coherence tomography (OCT)[2], wavelength-division multiplexing (WDM) systems[3], and low coherence optical time domain reflectors (OTDR)[4]. Coupling high power into single mode fibers (SMFs) is desirable for these applications, in which the output power of the SLD is expected to be high and concentrated within the circular fundamental mode. Recently, ridge waveguide (RWG)[5~7] structures have been widely used in realizing SLDs because of their uniformity and simplicity in fabrication. Thus, schemes for obtaining high power and high quality light beams from RWG SLDs are attractive. To achieve this, proper optical confinement and effective carrier injection, which require avoiding transverse current spreading, are very important. We have noticed that the upper waveguide of the SCH layers and the layer upon it, namely the remnant layer or setback layer, have a significant effect. It has been reported that a thick upper waveguide can achieve high optical confinement[5], while a thin remnant layer can diminish the transverse ("lateral" in Ref. [8]) current spreading[8]. However, how these two layers together influence carrier injection efficiency and optical confinement has not been discussed yet. In this paper, we investigate the effects of these two layers on carrier injection efficiency and optical distribution of RWG SLDs. Accurate modal gain is calculated taking into account the non-uniform carrier distribution in the active region. The optimal thickness is discussed by defining the effective coupled power P_e.

2 Analysis and simulations

Figure 1 shows the simulation model of an SLD with an RWG structure. On n-type InP substrate with $n \approx 1 \times 10^{18} \mathrm{cm}^{-3}$, there is a 1μm thick n-type InP cladding layer with $n \approx 7 \times 10^{17} \mathrm{cm}^{-3}$, followed by a 0.14μm thick down waveguide of separate confinement heterostructure (SCH) layers and four 5nm InGaAsP compressively strained quantum-wells surrounded by 10nm InGaAsP lattice matched barriers. According to the common structure of RWG SLD, there are two layers between the ridge waveguide and the active region: the upper waveguide of the SCH layers and the p-type InP remnant layer. An etch-stop layer is placed on the remnant layer to control the ridge height during the ridge etching process. The doping concentration of the remnant layer and the ridge is $7 \times 10^{17} \mathrm{cm}^{-3}$. The SCH and MQW regions are undoped. The width of the ridge is chosen to be 2μm in order to obtain single mode operation.

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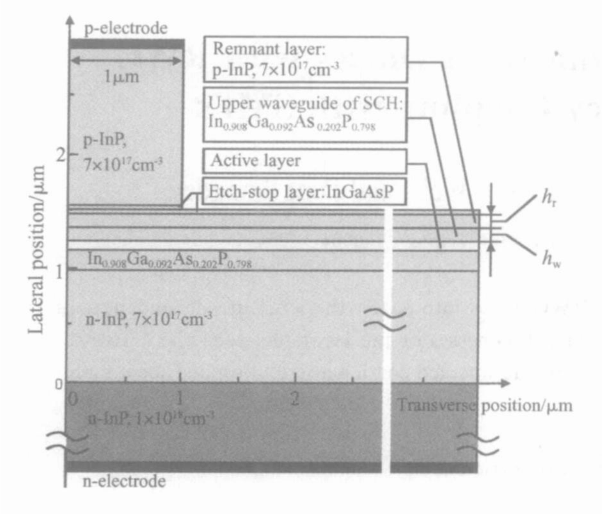

Fig. 1 Cross-section of the SLD used in the simulations Only the right half is shown here. The thicknesses of the upper waveguide and the remnant layer are to be optimized.

In RWG SLDs, the carriers are mostly concentrated beneath the ridge, and the material gain in the active region, which is much wider than the ridge waveguide, is not uniform. We introduce local material gain $g(x,y)$ here for convenient discussion. Together with the optical confinement, which also depends on the RWG structure, $g(x,y)$ will determine different modal gains, output power, and optical field distribution of the SLDs. To investigate the optimal RWG structure for high output power and a high quality light beam, we calculated $g(x,y)$ to obtain the modal gain accurately.

An ideal SLD is a traveling wave optical amplifier with zero input signal into the amplifying region[9]. Concerning only forward propagating waves, SLDs can be modeled by the simplified stationary TWA equation

$$c\frac{\mathrm{d}S(\lambda)}{\mathrm{d}z} = c[g_m(\lambda) - \alpha]S(\lambda) + \beta\gamma_{sp}(\lambda) \tag{1}$$

where S is the photon number, g_m is the modal gain at this wavelength, γ_{sp} is the sum of the spontaneous photons within the range of the fundamental mode, all of which are functions of wavelength λ, and β is the factor of spontaneous emission, which is coupled into the fundamental mode. For an ideal SLD with zero reflection at both ends, $S(\lambda)$ is obtained as follows:

$$S(\lambda) = \frac{\beta\gamma_{sp}(\lambda)}{c} \times \frac{\exp[(g_m(\lambda) - \alpha)L] - 1}{g_m(\lambda) - \alpha} \tag{2}$$

The output power can be calculated as

$$P = \int \frac{hc}{\lambda} S(\lambda)\,\mathrm{d}\lambda \tag{3}$$

For an active region with a uniform material gain g, the modal gain g_m is simplified as a product of the material gain g and the optical confinement factor Γ, where Γ is defined as the ratio of the optical field in the active region to the total optical field. However, in an RWG structure, due to the non-uniform carrier distributions in the transverse direction, the modal gain has to be calculated by taking local material gain to be

$$g_m(\lambda) = \iint g(x,y,\lambda)\,W(x,y)\,\mathrm{d}x\mathrm{d}y \tag{4}$$

Here, the Cartesian coordinate x represents the transverse position, y represents the lateral position, $g(x,y,\lambda)$ is the local gain spectrum, which is determined by the carrier concentration, and $W(x,y,\lambda)$ is the normalized local light power function, which is given by

$$W(x,y) = \frac{|E(x,y)|^2}{\iint |E(x,y)|^2\,\mathrm{d}x\mathrm{d}y} \tag{5}$$

Here, $E(x,y)$ is the local optical field magnitude.

2D distributions of current spreading and carrier concentration within the cross section of the SLD can be calculated by implementing Poisson's and the current continuity equations. Using the carrier concentration distribution, the 2D optical distribution can be calculated using the wave equation[10]. Then, using Eqs. (1～5), the modal gain of the SLDs and the output power can be obtained taking into account the non-uniform carrier distributions. Variation of the RWG structure will change carrier and optical distributions, namely change $g(x,y,\lambda)$ and $W(x,y)$ in the equations. As a result, g_m and P are changed. Therefore, we can investigate how the RWG structure affects the output power and light beam quality with this method.

3 Results and discussion

The total thickness of the layers between the ridge waveguide and the active region h includes the upper waveguide of the SCH layers h_w and the p-type InP remnant layer h_r, which not only affects the optical confinement but also critically affects the injected carrier distributions. Figure 2 (c) shows the simulated results of the carrier distribution in the transverse direction for two structures with different h using commercial software; Figures 2(a) and (b) are the calculation results of the optical field for these two structures considering the carrier distributions.

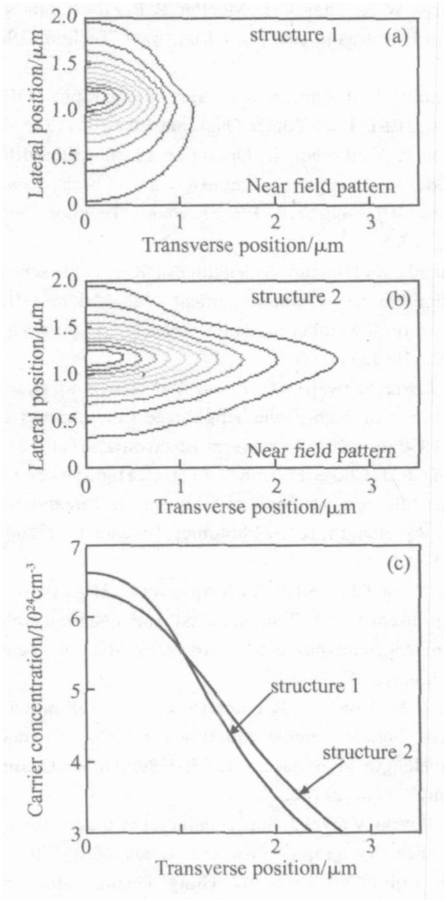

Fig. 2 (a) Optical field of the fundamental mode of structure 1 ($h_w = 0.05\mu m$, $h_r = 0.05\mu m$); (b) Optical field of the fundamental mode of structure 2 ($h_w = 0.15\mu m$, $h_r = 0.40\mu m$); (c) Carrier distributions in the active regions of structures 1 and 2

It can be seen that for structure 2, a larger h broadens the transverse channel for current spreading and decreases the current flowing through the area where the fundamental mode is concentrated. It decreases the carrier concentration in this area and reduces the material gain for the fundamental mode. Together with the weaker optical confinement due to the larger h, the optical field spreads more than that in structure 1. According to Eq. (4), the modal gain will be reduced in this case.

The modal gain g_m was calculated for structures with different h. Figure 3 shows the results at the gain peak wavelength. Here, the ratio $h_w : h_r$ was fixed at 5 : 3. It can be seen that the modal gain decreases as h increases when $h > 3.5\mu m$. In the region of $h < 3.5\mu m$, the tendency is the opposite because a smaller h will weaken the lateral optical confinement. The same effect in the transverse direction will also reduce the modal gain. Therefore, there is an optimal h for obtaining the largest g_m.

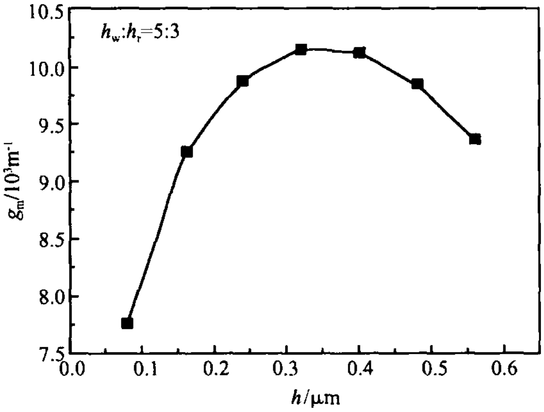

Fig. 3 Comparison of h versus calculated modal gain

A high modal gain g_m can result in a high output power. However, not all the output power can be launched into the SMF because of the shape of the near field, and therefore the far field pattern, determines the coupling efficiency. The more circular the optical field is, the more easily it can be launched into SMFs[11]. Here we defined effective coupled power, P_e, as the power in the circle where the power drops to 10% of the peak value, as shown in the inset of Fig. 4. A higher P_e means a more circular optical field or a higher output power, which therefore means more power can be launched into SMFs. Using the calculated results of g_m shown in Fig. 3, we calculated P_e as a function of h, where the ratio $h_w : h_r$ was chosen to be 2 : 5, 1 : 1, and 5 : 3. It shows that P_e changes with different h with the same tendency as that of g_m. When h increases, P_e increases at first and then decreases. The optimum h, which is insensitive to the ratio $h_w : h_r$, is around 0.3~0.4μm in these cases. It should be noticed that the effects of h_w and h_r are quite different. Figure 4 shows that for the same thickness of h, a large h_w and a small h_r are better for a high P_e, namely for high coupling power to SMFs due to a better optical confinement effect of the upper waveguide. This implies that the composition of these two layers also affects the coupling power, which will be investigated in the future.

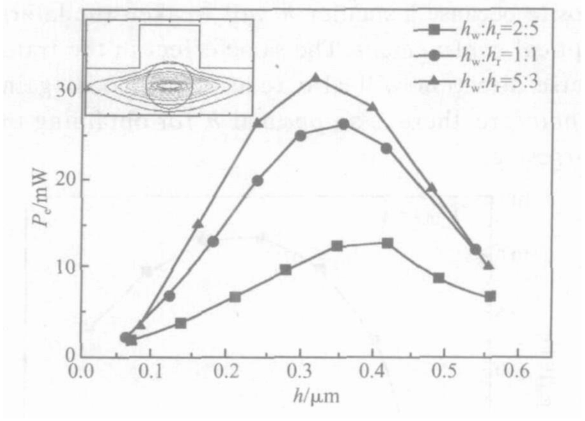

Fig. 4 Effective coupled power P_e as a function of h for different h_w : h_r The inset shows the definition of effective coupled power.

4 Conclusion

We have analyzed the structure dependences of the output power and the near field pattern in SLDs considering the injected carrier distributions. The modal gain was calculated based on the local material gain and optical field distribution. It is found that the thicknesses of the layers between the active region and the ridge waveguide are critical for effectively coupling power into SMFs because they simultaneously affect the injected carrier distribution and the optical confinement. The simulation results show that the optimal thickness is 0.3～0.4μm, and a structure with a thick upper waveguide and a thin remnant layer is preferable.

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与单模光纤高效耦合的超辐射二极管优化设计

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摘要：为了提高脊波导结构的超辐射二极管(SLD)与单模光纤的耦合功率，研究了有源区与脊之间的残留层和上光限制层的厚度对 SLD 输出功率和近场光斑的影响. 考虑了注入载流子横向分布的不均匀，较准确地计算了模式增益. 结果表明，通过对残留层和上光限制层厚度的优化，可以有效提高 SLD 与单模光纤的耦合功率.

关键词：超辐射二极管；耦合效率；注入效率

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