Spontaneous emission factor for semiconductor superluminescent diodes

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The spontaneous emission factor β is an important parameter for the characterization of semiconductor light emitting devices. In the analysis of superluminescent diodes, especially in the calculation of the optical intensity using rate equations, most authors have used the estimated value of β taken from laser diodes, despite the conceptual difference involved in each device. In this article, the spontaneous emission factor β for superluminescent diodes is discussed in detail, and a new method in calculating the average value of β is introduced. Based on this method, the values of β for gain-guided and index-guided structures are obtained. [S0021-8979(99)05007-0]

I. INTRODUCTION

Superluminescent diodes (SLDs) are preferred light sources for fiber gyroscopes,[1] wavelength division multiplexers (WDM), acoustic-optic correction systems,[2] and surface imaging technology.[3] Since the structure of a SLD is similar to a laser diode (LD), the local rate equation (or traveling wave rate equation) for analyzing the wave dynamics in a laser diode is often adopted in the analysis and design of SLDs. However, SLD is based on amplified spontaneous emission (ASE) and its emission spectrum is much broader than that of LD. For LD the spontaneous emission factor β is defined as the ratio between the rate of the spontaneous emission coupled into the laser modes divided by the total spontaneous emission rate. Such a definition cannot be applied to SLD, because SLD has no oscillation modes. To our knowledge, most authors still use the value of β related to LD for analyzing the SLD.[4] In this article, the spontaneous emission factor β for the superluminescent diodes are discussed and the use of an average spontaneous emission factor β is suggested. The values of β for the gain-guided and index-guided SLDs are estimated and compared with the β of LD of similar structures. The calculated results show that the β of SLD is considerably larger (in the order of 10^{-2} and 10^{-3} for both gain-guided and index-guided structures, respectively) than that of lasers of similar structures.

II. ESTIMATION OF SPONTANEOUS EMISSION FACTOR β

A. Definition of spontaneous emission factor for SLD

The output of a SLD is amplified spontaneous emission. All spontaneous emission coupled to the waveguide contributes to the light output. Therefore, the spontaneous emission factor β can be defined as[5]

$$\beta=\frac{\text{Rate of spontaneous emission contributed to the output}}{\text{Total spontaneous emission rate}}.$$

Assuming that the rate of spontaneous emission contributed to the output at wavelength λ is $R_{sp}(\lambda)$, the spontaneous emission factor at λ can be written as

$$\beta(\lambda)=\frac{R_{sp}(\lambda)}{R_{sp}}, \tag{1}$$

where R_{sp} is total spontaneous emission rate.

Since the output of a SLD has a broad spectrum, the value of β is

$$\beta=\int \beta(\lambda)d\lambda=\beta_z. \tag{2}$$

β_z denotes the fraction of radiation captured by the waveguide. If the spontaneous emission is isotropic, the factor β can be simply estimated by the relation

$$\beta_z=\frac{\Omega}{4\pi}, \tag{3}$$

where Ω is the solid angle of output emission.

B. Estimation of β for gain-guided SLDs

Light confinement in vertical direction exists in gain guide SLD. Assuming that n_1 is the refractive index of active

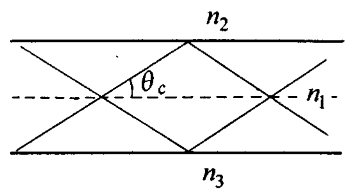

FIG. 1. Light propagation in the gain-guided structure of the superluminescent diodes.

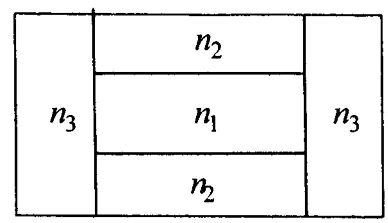

FIG. 3. Cross-section structure diagram of the index-guided superluminescent diodes.

layer, n_2 is the index of cladding layers, θ_c denotes the angle included between the emitted light and the propagation direction (see Fig. 1). When the light satisfies the total reflection condition, the angle θ_c can be written as

$$\theta_c = \arccos \frac{n_2}{n_1}. \tag{4}$$

The spontaneous emission whose direction is less than θ_c in the vertical direction may contribute to β.

Due to the fact that there is no lateral confinement, most of the spontaneous emission will be absorbed after it had escaped the current injection region. Only the spontaneous emission whose direction lies in a certain solid angle along the stripe may contribute to superluminescent output. The coordinate system used in the calculation is shown in Fig. 2. If SLD is a single-pass amplifying device, then

$$\beta = \frac{\int_{-\varphi'}^{\varphi'} d\varphi \int_{\pi/2-\theta_c}^{\pi/2+\theta_c} \sin\theta \, d\theta}{\int_0^{2\pi} d\varphi \int_0^{\pi} \sin\theta \, d\theta}, \tag{5}$$

where φ is the horizontal emitting angle (parallel to junction plane), and θ is the vertical emitting angle.

In Eq. (5), φ' denotes the maximum horizontal emitting angle within which spontaneous emission may contribute to superluminescent output. It can be written as

$$\varphi' = \operatorname{arctg} \frac{W}{2(L-Z)}, \tag{6}$$

where L is the cavity length and W is the width of current injection region. Thus

$$\beta = \frac{1}{\pi} \sin\theta_c \operatorname{arctg} \frac{W}{2(L-Z)}. \tag{7}$$

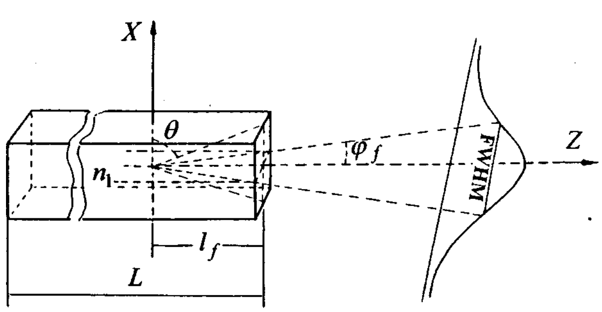

FIG. 2. Schematic diagram of the relationship between output light and the full width at half maximum (FWHM).

This relation shows that β is different at different point along injection current stripe for gain-guided structure. The average value of β may be written as

$$\bar{\beta} = \frac{\sin\theta_c}{\pi L} \left[\int_0^{L-l_f} \operatorname{arctg} \frac{W}{2(L-Z)} dZ + \varphi_f l_f \right]. \tag{8}$$

The second term in the formula is a constant relating to the structure and far field distribution, and it describes the fact that the horizontal emitting angle is larger near the output facet, but the main contribution to the output is the spontaneous emission whose angle is within $2\varphi_f$, which corresponds to the full width at half maximum (FWHM) of the far field.

Supposing that the distance from the light emitting point (denoted by φ_f) to the output facet is l_f, we have

$$l_f = \frac{W}{2 tg \varphi_f}. \tag{9}$$

The spontaneous emission factor in this range can be regarded as constant:

$$\beta' = \frac{1}{\pi} \sin\theta_c \, \varphi_f. \tag{10}$$

The estimation of the value of β using Eqs. (8)–(10) is suitable for a single-pass propagation. In the case of bidirectional propagation, the value of β is multiplied a factor of 2 of that used in Eq. (8) or (10).

C. Calculation of factor β for index-guided SLD

There are confinements in both vertical and parallel directions of the junction plane for an index-guided SLD. In general, the degrees of restriction in the two directions are different. Supposing n_2 is the refractive index of cladding layers, n_3 denotes the refractive index of lateral confinements (see Fig. 3), the total reflection condition can be expressed as

$$\theta_{c\perp} = \arccos \frac{n_2}{n_1}, \tag{11}$$

$$\theta_{c\parallel} = \arccos \frac{n_3}{n_1}, \tag{12}$$

then

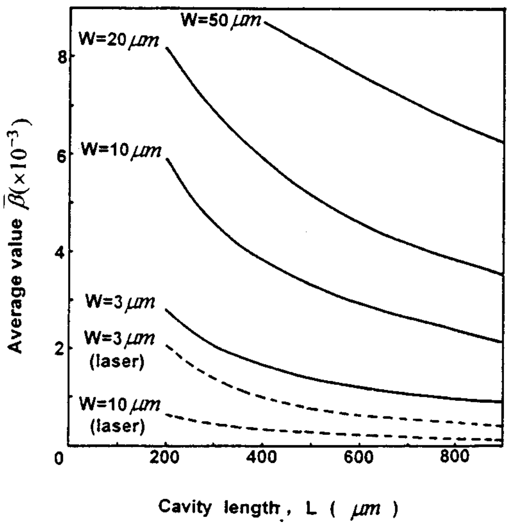

FIG. 4. Relationships of the average value $\bar{\beta}$ with cavity length for gain-guided SLD.

$$\beta=\frac{1}{4\pi}\int_{-\varphi_{c\parallel}}^{\varphi_{c\parallel}} d\varphi \int_{\pi/2-\theta_{c\perp}}^{\pi/2+\theta_{c\perp}} \sin\theta\, d\theta$$
$$=\frac{1}{\pi}\sqrt{1-\left(\frac{n_2}{n_1}\right)^2}\arccos\frac{n_3}{n_1}. \tag{13}$$

Following the same derivation as that in Sec. II B, we get the average spontaneous emission factor for a wide stripe index-guided structure as follows:

$$\bar{\beta}=\frac{\sin\theta_{c\perp}}{\pi L}[\varphi_{c\parallel}(L-l_f)+\varphi_f l_f]. \tag{14}$$

III. RESULTS ANALYSIS

Figure 4 shows the average spontaneous factor $\bar{\beta}$ of SLDs as a function of the cavity length for a gain-guided structure calculated by Eqs. (8), (9), and (10). We assume $n_1=3.55$, $n_2=3.35$, and $\varphi_f=5°$. The values of β corresponding to a stripe laser is also plotted in the same figure for comparison. The formula that we used in the calculation of β in a laser diode is as follows:[6]

$$\beta=K\frac{\lambda^4}{4\pi^2 n_r^3 V\Delta\lambda}, \tag{15}$$

where $K=2$, $\lambda=0.83$ μm, $n_r=3.55$, $\Delta\lambda=0.03$ μm, $d=0.015$ μm, respectively.

Figure 4 indicates that the spontaneous emission factor β of SLDs are considerably larger than that of lasers with the same structures. The typical value of β for SLD is in the order of 10^{-2}–10^{-3}. It increases with the width W of the current injection stripe. For LD, the value of β decreases with the width, since the percentage of the spontaneous emission coupled into oscillation modes decreases. For SLD, there is no oscillation, and the total amplified spontaneous emission in a certain range may contribute to β. Therefore β increases with the width of the stripes.

For an index-guided SLD, when L is long enough, namely, $L\gg l_f$, the value of β is approximately constant. If $n_2=n_3=3.35$, $\beta=3.56\times10^{-2}$, and it is 7.1×10^{-2} in the case of bidirectional propagation. From Eqs. (13) and (14), we know that β depends on the degree of lateral restriction. This dependence is calculated and plotted in Fig. 5. It is evident that the spontaneous emission factor β of an index-guided SLD is about one order of magnitude larger than that of a gain-guided SLD. But for an index-guided LD, $K=1$ in Eq. (15), and the value of β is less than that of a gain-guided structure. For a SLD, the wider the stripe, the less the value of β. This result is the opposite for a gain-guided structure. With a decrease of the lateral confinement, the value of β reduces notably. When the refractive index $n_3\rightarrow n_1$, the value of β is reduced to 10^{-3}. Thus it becomes gain-guided structure.

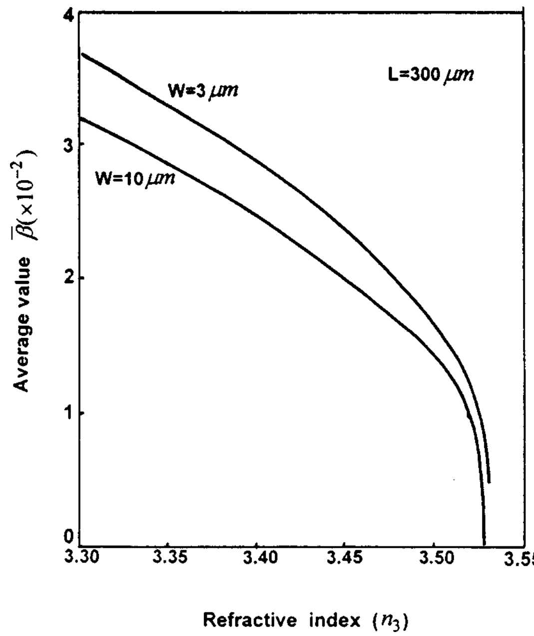

FIG. 5. Relationships of the average value $\bar{\beta}$ with refractive index n_3 for index-guided SLD.

IV. DISCUSSION

The output light versus to the spectral width (FWHM) λ_s above the lasing threshold in a LD can simply given by[7]

$$\lambda_s=\lambda_h P_s/P_t \quad (P_t>2P_s). \tag{16}$$

Here λ_h is the homogeneous spontaneous emission linewidth, P_t is the output power transmitted through the facet, and P_s is on the order of the power output just below threshold. This relation indicates that a higher output power P_s leads to a larger λ_s. However, P_s depends on the reflectivities of the facet. An increase of P_s and λ_s due to a decrease of the facet reflectivity by antireflection coating or angling the stripe were demonstrated both theoretically and experimentally.[7,8] Furthermore, λ_s increases rapidly with the astigmatism factor K (Ref. 7) or the spontaneous emission factor β.[9] Because a SLD has a larger λ_s (or higher P_s), it should have a large K or β.

V. CONCLUSION

The spontaneous emission factor β of SLDs have different physical meaning from that of semiconductor lasers. Its value is also very different from that of lasers with similar structures. The large value of β is a notable characteristics of the broad emission spectra of SLDs. The typical value of β for an index-guided SLD is about 10^{-2}. For a gain-guided SLD, the value of β is on the order of 10^{-3}. However, the value of β for both structures are larger than that of lasers with similar structures.

ACKNOWLEDGMENTS

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