Light-current characteristics of vertical-cavity surface-emitting lasers with external optical feedback*

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Abstract: The influence of external optical feedback (OFB) on the light-current characteristics of the vertical-cavity surface-emitting lasers (VCSELs) was investigated theoretically and experimentally. By calculating the OFB sensitivity parameter, the OFB sensibility of the VCSELs was compared with the edge emitting lasers. Based on the compound cavity theory, the light-current characteristic parameters of the VCSELs with external OFB, such as the threshold current and the slope efficiency, were calculated. The experimental results indicated that the threshold current of the VCSELs with different DBR reflectivities decreased to different degrees, accompanied with a decrease of slope efficiency when under 10% feedback ratio of the external OFB, which is in good agreement with the theoretical calculation.

Key words: semiconductor lasers; vertical-cavity surface-emitting lasers; optical feedback; light-current characteristics; feedback ratio

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1. Introduction

Vertical-cavity surface-emitting lasers (VCSELs) have become an important type of semiconductor laser because of the ease with which they couple to optical fibers and two-dimensional array fabrication capability[1−3]. In the VCSEL applications, unwanted optical feedback (OFB) could be induced by various sources, for example, when coupling laser light into fiber for optical communication systems, the fiber facet can create external OFB to the VCSEL laser cavity. External OFB is generally considered to be detrimental to the performance of lasers because under certain conditions, external OFB can cause significant changes in spectrum, power instabilities, relative intensity noise, and polarization switching[4−6].

One significant difference between VCSELs and edge emitting lasers (EELs) is the high cavity mirror reflectivity (> 99%) of the VCSELs. For this reason, it has been regarded that the VCSEL is relatively insensitive to the external OFB. However, the researchers found that the VCSEL can also be affected by the external OFB. The majority of the previous studies focused on the OFB's influence to the dynamic characteristics and the spectral characteristics of the VCSELs[7−9]. In this work, we present a detailed study of the external OFB phenomena in the light-current characteristics of the 980 nm VCSELs. By calculating the optical sensitivity parameters, the OFB sensibility of the VCSELs was compared with the EELs'. Based on the compound cavity theory, the influence of the external OFB on the light-current characteristics of the VCSELs with different DBR reflectivity was evaluated. We found that the light-current characteristic parameters of these VCSELs, such as the threshold current and the slope efficiency, were changed by the external OFB to different degrees.

2. Theory

2.1. OFB sensitivity parameter

The analysis of the external OFB effects typically proceeds from the Van der Pol equation for the electric field of the laser with an additional source term corresponding to the time delayed field. Neglecting the noise terms, the equation can be written as[5]:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \left[-\mathrm{i}\omega_0 + \frac{\Delta G}{2}(1-\mathrm{i}\alpha)\right]E(t) + \kappa E(t-\tau_\mathrm{e}), \quad (1)$$

where ω_0 is the free running laser frequency, ΔG is the gain change due to the external OFB, α is the linewidth enhancement factor, τ_e is the delay time of the external round trip, and $\kappa = \frac{1}{\tau_\mathrm{s}}\frac{1-R_\mathrm{s}}{\sqrt{R_\mathrm{s}}}\sqrt{R}$ is the OFB sensitivity parameter, with τ_s the round trip in the semiconductor chip, R_s the cavity mirror reflectivity, and the feedback ratio R that is defined as the ratio of the power fed back into the laser cavity relative to the output power of the free running laser. It is expressed as $R = \rho^2 R_\mathrm{e}$, where ρ is the coupling efficiency, including coupling losses and attenuation, and R_e is the reflectivity of the source of the external OFB. When the parameter $\kappa > \frac{1}{\tau_\mathrm{e}\sqrt{1+\alpha^2}}$, the calculated laser parameter will have multiple solutions[5], which leads to the rich variety of effects observed.

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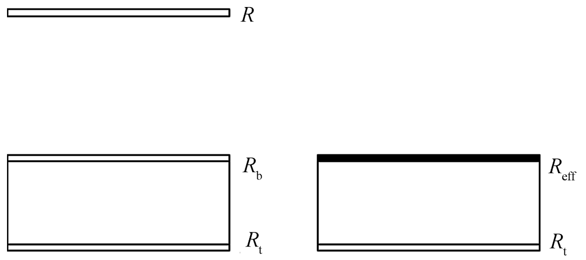

Fig. 1. Schematic diagram of the compound cavity.

For the same feedback level, we can obtain the ratio of κ between VCSEL and EEL to be about 0.6 using the typical values of laser parameters. The parameters used in the calculation are: R_s for VCSEL and EEL are 99.7% and 30%, cavity lengths are 1 μm and 300 μm, respectively. The α for both lasers are assumed to be the same. This result suggests that VCSELs have almost the same OFB sensibility as EELs although their structures differ significantly[1]. This is because the sensibility of a semiconductor laser to external optical feedback depends mainly on the stored energy in the cavity and the coupling of the laser mode to the external field. The extremely short cavity lengths of VCSELs cancel out the effect of the highly reflective cavity mirrors.

2.2. Analysis of threshold current variation

The threshold current of the VCSEL can be written as[10]:

$$I_{\text{th}} = I_{\text{s}} \exp\left\{\frac{2}{g_{\text{N}}\Gamma}\left[\alpha_{\text{i}} + \frac{1}{L}\left(\alpha_{\text{diff}}d + \ln\frac{1}{R_{\text{t}}R_{\text{b}}}\right)\right]\right\}, \quad (2)$$

where $I_{\text{s}} = \frac{qV_{\text{s}}BN_{\text{tr}}^2}{\eta_{\text{i}}}$, q is the quantity of the electron charge, V_{s} is the volume of the active region, B is the bimolecular recombination coefficient, N_{tr} is the transparent carrier concentration; η_{i} is the internal quantum efficiency; g_{N} is the material gain coefficient, Γ is the confinement factor, α_{i} is the intracavity absorption coefficient, α_{diff} is the diffraction loss coefficient, L is the cavity length, d is the thickness of the active region, and R_{b} and R_{t} is the bottom and the top DBR reflectivity. The bottom DBR is the output mirror of the 980 nm VCSEL.

Based on the compound cavity theory, when the length of the external cavity is much longer than that of the laser diode itself[11], the threshold current is determined by:

$$I'_{\text{th}} = I_{\text{s}} \exp\left\{\frac{2}{g_{\text{N}}\Gamma}\left[\alpha_{\text{i}} + \frac{1}{L}\left(\alpha_{\text{diff}}d + \ln\frac{1}{R_{\text{t}}R_{\text{eff}}}\right)\right]\right\}, \quad (3)$$

where $R_{\text{eff}} = \left(\frac{\sqrt{R_{\text{b}}} + \sqrt{R}}{1 + \sqrt{R_{\text{b}}R}}\right)^2$ is the effective reflectivity of the external OFB, which is shown in Fig. 1. The normalized threshold current is given from Eqs. (2) and (3) by

$$\frac{I'_{\text{th}}}{I_{\text{th}}} = \exp\frac{\ln\frac{1}{R_{\text{t}}R_{\text{eff}}} - \ln\frac{1}{R_{\text{t}}R_{\text{b}}}}{L\Gamma g_{\text{N}}}. \quad (4)$$

From Fig. 1 and Eq. (4), we can see that while the VCSEL is under external OFB, the reflectivity of one of the cavity mirrors becomes a little higher. The decrease of the threshold current of the VCSEL can be expected because of the increase of the cavity mirror reflectivity.

2.3. Change of slope efficiency

While under lower injection current level, the thermal effect of the high power VCSELs can be neglected. The expression of the VCSEL output power P_{out} is:

$$P_{\text{out}} = \frac{hv}{q}\eta_{\text{i}}\eta_{\text{d}}\left(I - I_{\text{th}}\right), \quad (5)$$

where hv is the power of the photon, η_{d} is the differential quantum efficiency, and I is the injection current. The expression of η_{d} is

$$\eta_{\text{d}} = \frac{\ln\frac{1}{R_{\text{b}}R_{\text{s}}}}{2\alpha_{\text{i}}L + \ln\frac{1}{R_{\text{b}}R_{\text{s}}}}. \quad (6)$$

Because the active region diameter of the VCSEL is relative large, the diffraction loss can be ignored[10]. When the VCSEL is under external OFB, η_{d} can be rewritten as:

$$\eta'_{\text{d}} = \frac{\ln\frac{1}{R_{\text{b}}R_{\text{eff}}}}{2\alpha_{\text{i}}L + \ln\frac{1}{R_{\text{b}}R_{\text{eff}}}}. \quad (7)$$

And the expression of the output power of the VCSEL with external OFB goes as follows:

$$P'_{\text{out}} = \frac{hv}{q}\eta_{\text{i}}\eta'_{\text{d}}\left(I - I'_{\text{th}}\right), \quad (8)$$

where I'_{th} follows Eq. (3).

The slope efficiency of the VCSEL with external OFB is defined as:

$$\frac{\text{d}P'_{\text{out}}}{\text{d}I} = \frac{hv}{q}\eta_{\text{i}}\eta'_{\text{d}}. \quad (9)$$

From this, the external OFB exerts the same influence on the differential quantum efficiency and the slope efficiency of the VCSEL. We can get:

$$\frac{\frac{\text{d}P'_{\text{out}}}{\text{d}I}}{\frac{\text{d}P_{\text{out}}}{\text{d}I}} = \frac{\eta'_{\text{d}}}{\eta_{\text{d}}}. \quad (10)$$

3. Calculation results

Based on the theoretical model above, we can evaluate the influence external OFB exerts on the light-current characteristics of the VCSEL with different DBR reflectivities. The parameters we chose during the calculation are listed in Table 1.

Let a equals $I'_{\text{th}}/I_{\text{th}}$, the relationship between the a and the feedback ratio is shown in Fig. 2. The bottom-DBR reflectivities of the VCSELs are 99.7% and 99.2%, respectively.

In the same way, we assume b to be equal to $\eta'_{\text{d}}/\eta_{\text{d}}$. The relation of the factor b versus feedback ratio R is shown in Fig. 3. The bottom-DBR reflectivities of the VCSELs are 99.7% and 99.2%, respectively.

Table 1. Parameters of lasers and materials.

Parameter	Name	Value
λ	Laser wavelength	980 nm
R_t	Top-DBR reflectivity	99.9%
R_{b1}	Bottom-DBR reflectivity 1	99.7%
R_{b2}	Bottom-DBR reflectivity 2	99.2%
L	Cavity length	1 μm
η_i	Internal quantum efficiency	1
Γ	Confinement factor	0.12
g_N	Material gain coefficient	2000 cm^{-1}
α_i	Intracavity absorption coefficient	10 cm^{-1}

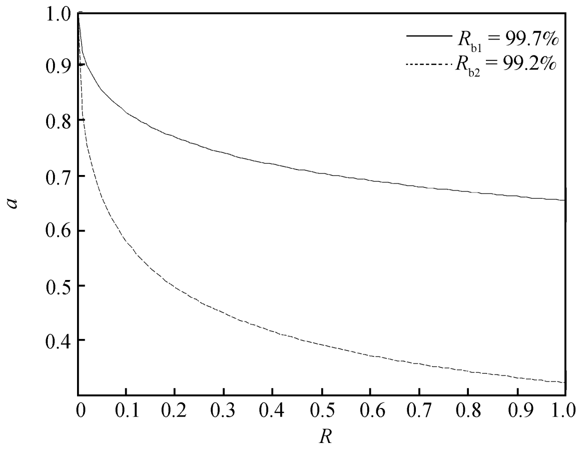

Fig. 2. Calculated relationship of a versus feedback ratio R. The real line and the dashed represent the 99.7% bottom-DBR reflectivity VCSEL and the 99.2% bottom-DBR reflectivity VCSEL, respectively.

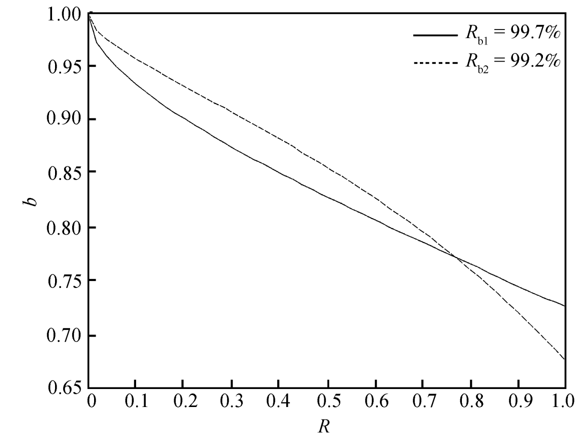

Fig. 3. Calculated relationship between b and feedback ratio R. The N-DBR reflectivity of the VCSELs is 99.7% and 99.2%, respectively.

4. Experimental results and discussion

The schematic diagram of the experimental setup is shown in Fig. 4. Two CW (continuous wave) VCSELs operating at 980 nm at room temperature were used in the experiment. Both of the VCSELs have an aperture of 300 μm in diameter. The bottom-DBR reflectivity of the VCSELs was 99.7% and 99.2%, respectively. We called the VCSEL with 99.7% bottom-DBR reflectivity VCSEL-A and the other one VCSEL-B for simplicity. VCSEL-A and VCSEL-B were mounted on microchannel water coolers to keep the temperature constant at 25 °C. The collimated laser beam was reflected back to the laser cavity using a flat mirror placed 60 mm away. The flat mirror was coated to provide 70% reflectivity at 980 nm. Taking the loss of the beam splitter and the absorption of the substrate of the VCSEL into account, the feedback ratio was calculated to be about 10%, which is much lower than the reflectivity of the flat mirror. The power meter was used to measure the power variation.

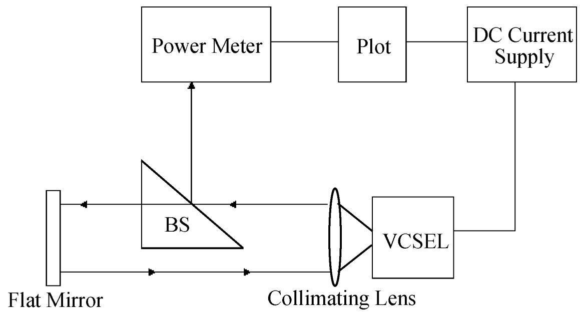

Fig. 4. Schematic diagram of the experimental setup.

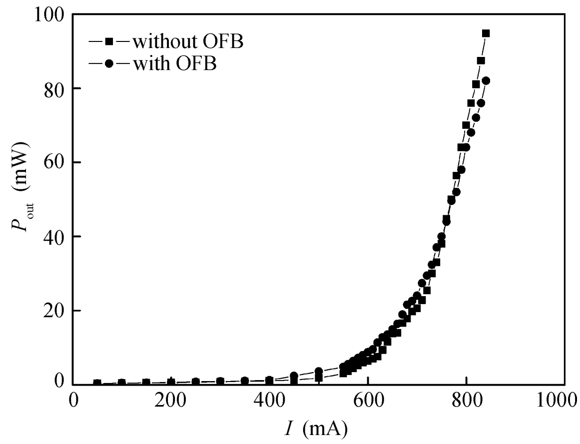

Fig. 5. P–I curve of VCSEL-A with and without external OFB. The feedback ratio is 10%.

Figure 5 shows the P–I curve of the VCSEL-A with and without external OFB. It can be seen from this figure that the threshold current of the VCSEL-A decreased from 630 to 590 mA while under the external OFB of 10% feedback ratio. When the injection current was 800 mA, the output power of the VCSEL-A with external OFB decreased by 8%, compared with the VCSEL-A without external OFB. This means the decrease of the slope efficiency of the VCSEL-A.

Figure 6 shows the P–I curve of the VCSEL-B with and without external OFB. This figure indicated that the threshold current of VCSEL-B decreased from 780 mA to about 500 mA. The slope efficiency also decreased, but not significantly. When the injection current was 1500 mA, these two curves did not cross, but the value of the output power was growing closer together

The results indicated that while under external OFB, the threshold current of the VCSEL decreased, as well as the slope efficiency. These light-current characteristic parameters of the VCSELs with different bottom-DBR reflectivities changed to different degrees.

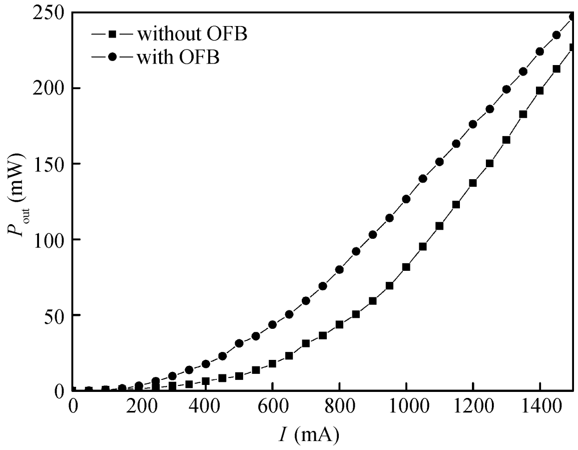

Fig. 6. $P-I$ curve of VCSEL-B with and without external OFB. The feedback ratio is 10%.

5. Conclusion

The influence of external optical feedback (OFB) on the light-current characteristics of the vertical-cavity surface-emitting lasers (VCSELs) was investigated in this study. The results show that VCSEL and EEL possess similar external optical feedback sensibility. The theoretical calculation indicated that, when external optical feedback exists, the threshold current and slope efficiency of the VCSEL would decrease. For the VCSEL with different DBR reflectivity, the degree of the change of the light-current characteristics was different. The results of the experimental investigation indicated that the threshold current of the VCSEL with 99.7% DBR reflectivity was decreased from 630 to 590 mA, and the threshold current of the VCSEL with 99.2% N-DBR reflectivity was decreased from 780 to 500 mA, when the feedback ratio of the external OFB was 10%, and the slope efficiency was changed to different degrees, which is in good agreement with the theoretical calculation.

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