Theoretical Study on the Butt-coupling of Semiconductor Laser and Fiber Bragg Grating*

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Abstract The butt-coupling between a semiconductor laser diode and a fiber Bragg grating external cavity acts a key roll on the laser characteristics. The scatter matrix method considering the butt-coupling efficiency is used to analyze the butt-coupling between them. It is found that the butt-coupling distance and coupling efficiency determine the laser characteristics. For strong feedback, the single lasing wavelength changes in the reflection bandwidth of the effective reflectivity (approximately the Bragg region of the fiber Bragg grating) as the distances change. For weak feedback condition, some different results are obtained. The SMSRs in the two conditions are presented and analyzed. These results can provide important design guidance of device parameters for the practical fabrication.

Keywords Fiber grating; External cavity laser diode; Butt-coupling; SMSR; Lasing wavelength
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0 Introduction

Recently, with the rapid increase in demand for large transmission capacity, DWDM systems have been applied. Successful implementation of DWDM system will depend on the availability of low-coast single-frequency lasers. Fiber grating external cavity lasers are competitive light source, due to their inherent merits such as exactly single oscillation wavelength, narrow linewidth, high SMSR and power output, low chirp under high-speed direct modulation, simple fabrication, high yields and low cost. Currently there are many researches on it theoretically and experimentally[1~5]. In theory, the equivalent external cavity mirror model has been adopted extensively[4~7], in which the fiber Bragg grating serve as a reflecting mirror whose reflectivity is the maximum reflectivity of the fiber Bragg grating[4,5,7]. This model is improved in[6] by taking into account the fiber grating reflectivity spectrum. But these models neglect the air gap between laser diode and the fiber grating and the fiber extended lcavity at the end of the fiber grating caused by the residual facets reflectivity. Then the coupled cavity laser model is introduced in the analysis of the fiber grating external cavity lasers by Zhou[8]. In fact, the butt-coupling between the two separate components play a very important roll on the lasing characteristics, because the key fabrication process is the coupling and packaging after the optimal fabrication of the laser diode and the fiber grating respectively. Zhou's model neglects this factor and needs some modification.

In this paper, we present the theoretical analysis of the butt-coupling using the improved coupled cavity model. We find that the effective reflectivity spectrum determined by the air gap, fiber external cavity and fiber Bragg grating describe the whole characteristics of the device. So the improved analysis of the effective reflectivity spectrum and hereby determined gain spectrum and phase curves can precisely describe the characteristics of the wavelength selectivity and the SMSR. The results of this investigation can provide an important design guidance of device parameters for the practical fabrication.

1 Theory

1.1 Basic butt-coupling model

We consider a fiber grating external cavity laser configuration in Fig. 1. Based on the coupled-cavity laser model, the multiple reflections between the laser diode facet and the fiber external cavity facet is taken into account although AR coatings are usually covered on the two facets to decrease the multiple reflection effect. Coupled-cavity laser model uses the scattering matrix approach[9,10] to describe the electrical field in the active and passive cavities.

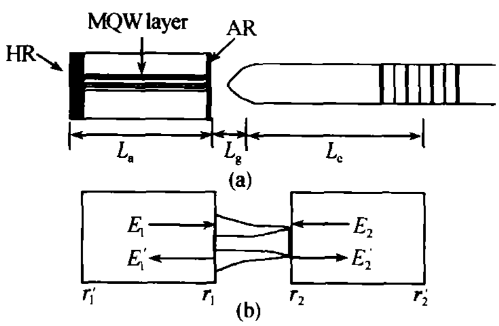

Fig. 1 (a) Fiber grating external cavity laser configuration and (b) Coupled cavity laser model, the butt-coupling efficiency is considered

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It can be derived from [9 ~ 11] that the characteristics of effective reflectivity R_{eff} reflect the threshold gain of the laser and the lasing wavelength. So by controlling the parameters of the effective reflectivity the laser characteristics can be determined directly. Fig. 2 shows the gain-wavelength curve. In the real fabrication process, after the fabrication of laser diode and the fiber grating, the important process is the coupling. Commonly the coupling efficiency is rather low, which is about 20% ~40%, so there have been many fiber end fabrication methods to increase the coupling efficiency up to nearly 100%[12]. In this analysis we only consider the plane fiber end facet. When the laser diode facet and the fiber facet are both uncoated, it is called weak feedback[7] ($R_1=0.545$, $R_2=0.187$), and if both are coated with AR coatings, strong feedback[7] (say, $R_1=0.006$, $R_2=0.076$). We change the distance of the butt-coupling and find in the situation of weak coupling, the effective reflectivity spectrum shows the periodical change because of the multiple reflections between the two facets. Compared with Fig. 3, Fig. 4 shows the effective reflectivity spectrum of the strong feedback. We can find that due to the small residual reflectivity of the two facets, the reflectivity spectrum is relatively more smooth and more independent on the distance.

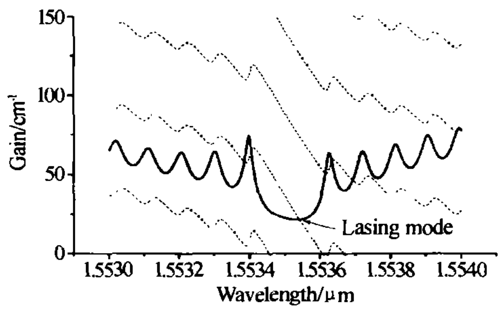

Fig. 2 Gain-wavelength spectrum, the crossing points represent the possible lasing modes

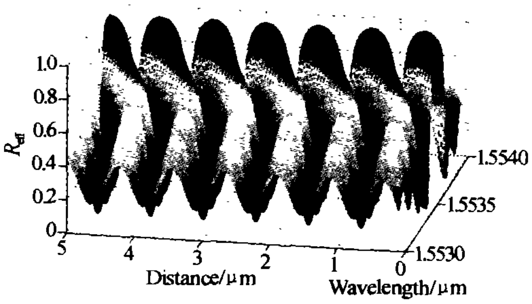

Fig. 3 Effective reflectivity spectrum of weak feedback

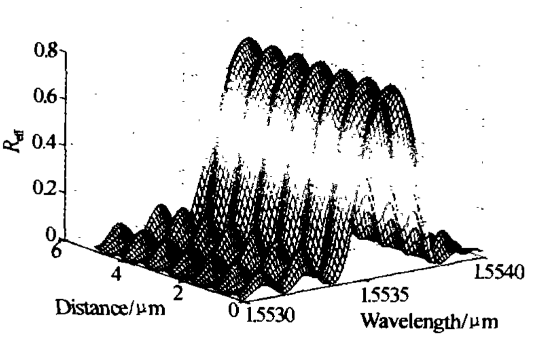

Fig. 4 Effective reflectivity spectrum of strong feedback

1.2 Improved butt-coupling model

The model above neglects the diffraction loss in the air gap and the mode mismatch, we consider them as coupling efficiency, that is, the light coupling efficiency from the laser facet to the fiber and from fiber to the laser. In the multiple reflection process, we should consider a different coupling coefficient[13] in each reflection. Here based on the simple approximation in [14], we add the coupling efficiency into the phase factor t, and suppose the 1, 2, ⋯ round-trips amplitudes of the light field that propagating from the laser diode, $|t_g|$, are equal. The same situation is for the amplitudes $|t_{fg}|$ when the light propagates round-trips from the fiber facet. Although this approximation is not so precise when the multiple reflections are strong (that is, there are many times of multiple reflections), but in fact only several reflections can be formed in the gap, so many models only take consideration of one reflection[4]. In [13], the different coupling coefficients are considered as we discussed above, but they computed several round-trips, which is equivalent to our consideration. We rewrite the expressions of phase factors as

$$t_g(2d)=\sqrt{2w_0w(2d)/[w^2(2d)+w_0^2]}\cdot \exp(\mathrm{i}2\beta d)=t_g(4d) \quad (1)$$

$$t_g'(d)=\sqrt{2w_0'w(d)/[w^2(d)+w_0'^2]}\exp(\mathrm{i}\beta d) \quad (2)$$

$$w^2(d)=w_0^2[1+(\lambda d/\pi w_0^2)^2] \quad (3)$$

$$t_{gf}(2d)=\sqrt{2w_0w'(2d)/[w'^2(2d)+w_0^2]}\cdot \exp(2\beta d)=t_{gf}(4d) \quad (4)$$

$$t_{gf}'(d)=\sqrt{2w_0w'(d)/[w'^2(d)+w_0^2]}\exp(\mathrm{i}\beta d) \quad (5)$$

$$w'^2(d)=w_0'^2[1+(\lambda d/\pi w_0'^2)^2] \quad (6)$$

w_0 is the Gaussian mode waist spot size of the laser diode, w_0' is the fiber fundamental mode waist spot size. We set $w_0=1.2\ \mu m$, $w_0'=2.5\ \mu m$.

At the meanwhile, the scattering matrix elements should be rewritten as

$$S_{11}=r_1-\frac{r_2(1-r_1^2)t_g(2d)}{1-r_1r_2t_g(2d)}$$

$$S_{22}=r_2-\frac{r_1(1-r_2^2)t_{gf}(2d)}{1-r_1r_2t_{gf}(2d)}$$

$$S_{12}=\frac{[(1-r_1^2)(1-r_2^2)]^{1/2}t_{gf}'(d)}{1-r_1r_2t_{gf}(2d)}$$

$$S_{21}=\frac{[(1-r_1^2)(1-r_2^2)]^{1/2}t_g'(d)}{1-r_1r_2t_g(2d)} \quad (7)$$

2 Simulation results

Fig. 5 and Fig. 7 show the effective reflectivity spectrums of the strong and weak feedback considering the butt-coupling efficiency. The maximum reflectivity decreased with the increasing of the butt-coupling distance, compared with Fig. 3. and Fig. 4. The gain-wavelength curve is showed in Fig. 6. We can find the threshold gain (loss) increased due to the increasing of distance. The similar results are shown in Fig. 8, but the gain (loss) increases rapidly and oscillates dramatically. Fig. 9 (a) shows the single mode oscillation wavelength with the distance. We find that the lasing wavelengths shift with the distance, and the periodic mode hopping occurs by increasing the distance, and the lasing modes are all in the wavelength region determined by the effective reflectivity spectrum of Fig. 5. (also approximately equal to the fiber grating reflectivity spectrum). It can be seen the wavelengths are not always in the lowest Bragg region. Based on Henry's theory[11], the different lasing position in the Bragg reflection region

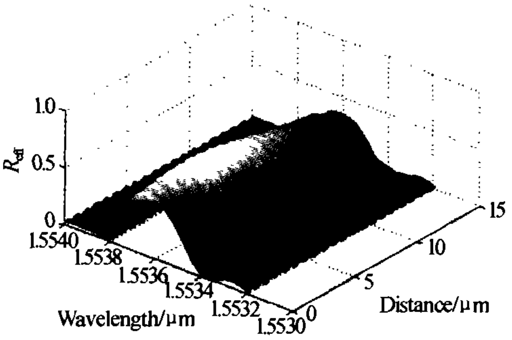

Fig. 5　Effective reflectivity spectrum with the strong feedback condition, butt-coupling efficiency is considered

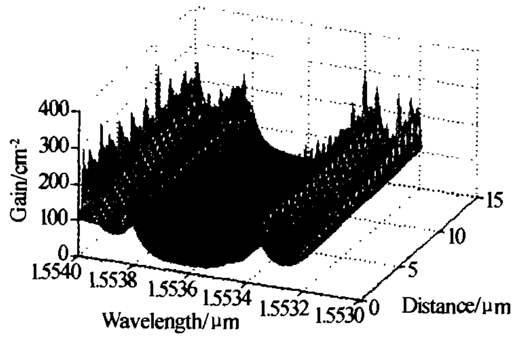

Fig. 6　Threshold gain (loss) spectrum with strong feedback condition, the loss increased along the distance due to the coupling efficiency decreased

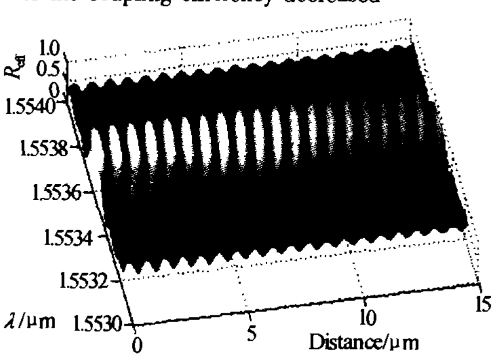

Fig. 7　Effective reflectivity spectrum with the weak feedback condition, butt-coupling efficiency is considered

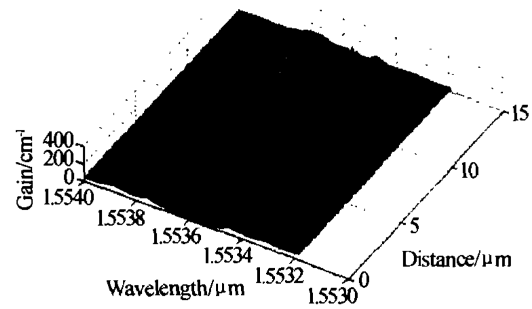

Fig. 8　Threshold gain (loss) spectrum with weak feedback condition, the lowest loss increased along the distance due to the coupling efficiency decreased

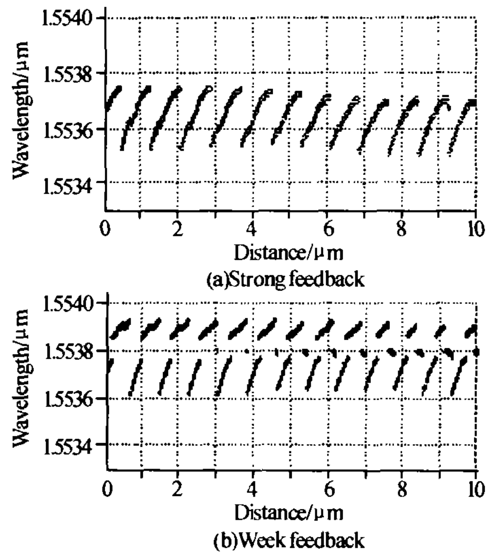

Fig. 9　Lasing wavelength change with the butt-coupling efficiency

results in the different linewidth narrowing. For the weak feedback condition, we show the single mode oscillation in Fig. 9(b). It can be seen that compared to Fig. 9 (a), (b) shows some uncertainty of oscillation wavelengths and the lasing modes are not always in the Bragg region, which means the lasing modes are more sensitive to the butt-coupling distance compared to the strong feedback condition.

Fig. 10 shows the simulated SMSR with the butt-coupling distance by assuming the injection current I_f is

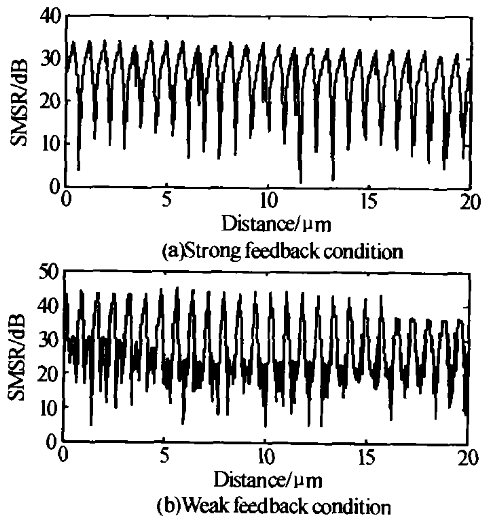

Fig. 10　SMSR curves

twice the threshold I_{th}, and by using the approximate expression (3.77) in[10]. The SMSR is not always kept high with different butt-coupling distances, even for the strong feedback condition (see Fig. 10(a)). This can explain why the SMSR is not high in some experimental results[15], although the well-known AR coating facets condition is satisfied for the single mode oscillation. In the actual fabrication process, the distance between the diode and the fiber facet should be controlled more precisely to obtain higher SMSR.

It can be seen from Fig. 10(b) that the SMSR changes more dramatically than Fig. 10(a), which means some modes instability. In certain distances the SMSRs are rather high, and sometimes rather low, even result in multimode oscillation. This can be seen directly from the gain spectrum: along the distance the gain spectrum shows "resonance enhancement" and "attenuation" due to the multiple reflections. In the attenuation regions, the gain curve is more "smooth" along the wavelength, which shows poor mode selection mechanism and the reflection function of the fiber Bragg grating is weaken by the "non-resonance enhancement" effect. In these regions the low SMSR, even dual or multi-modes occur. The contrary results occur in the "resonate enhancement" condition, which shows high SMSR. Compared to the Fig. 9(b), we find the high SMSR occurs in the Bragg region (middle region of Fig. 10) and the "resonate enhancement" region in distance (air gap length), whereas the low SMSR occurs in the "non-resonate enhancement" region and the modes apparently deviate from the Bragg wavelength region. So it is lucky to see that by carefully adjusting the coupling distances, the single mode with high SMSR is possible to be obtained in the desired wavelength region. From above analysis we can see that the butt-coupling distance tolerance of strong feedback condition is greater than week feedback condition.

From Fig. 10 we also find that the SMSR curve of the strong feedback is generally smaller than that of the weak feedback condition. The "resonate enhancement" effect can explain it and experiments are needed to validate this phenomenon.

3 Conclusion

By using the improved coupled cavity laser model, the fiber grating external cavity semiconductor laser is analyzed. The butt-coupling distance (distance between the diode and the fiber facets), coupling efficiency and the facets reflectivity play important rolls in the laser characteristics. For strong feedback condition, the single lasing wavelength shifts linearly with the distance in the reflection bandwidth of the effective reflectivity (also approximately the Bragg region of the fiber Bragg grating), and periodical mode hopping happens. For weak feedback condition, the lasing wavelengths shifts are not so regular as the strong feedback condition. In the weak feedback condition, the SMSR changes dramatically as the increasing of the distance, in some distances the SMSR is even higher than the strong feedback condition. Future experiments should be done to validate this phenomenon. So the weak feedback fiber grating semiconductor laser is more sensitive than the strong feedback configuration. These results can provide important design guidance of device parameters for the practical fabrication.

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半导体激光器与光纤光栅对接耦合研究

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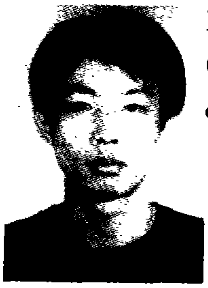
摘 要 半导体激光器管芯与光纤光栅的对接耦合对光纤光栅外腔激光器的特性起到关键作用。利用散射矩阵分析了激光器管芯与光纤光栅外腔的对接耦合，发现对接的距离以及对接的耦合效率决定了光纤光栅外腔激光器的性能。在强反馈情况下，激射波长在光纤光栅外腔有效反射率决定的布喇格波长内随对接耦合距离周期性的变化，对弱反馈情况则有些不同。同时对比了两种情况的边模抑制比。该分析为实际制作器件提供了指导。

关键词 光纤光栅；外腔激光器；对接耦合；边模抑制比；激射波长



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