Broadband Tuning in Optical-Communication Band Using Fabry-Perot Laser Diodes without Anti-Reflection Coating

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ABSTRACT

A broadly tunable range of 200 nm is achieved in external cavity semiconductor laser using a Fabry-Perot laser diode as an amplifier. The broadband tuning is possible due to two reasons. First, the gain bandwidth is broadened using proper design of nonidentical quantum-well structure. Second, carriers distribute over a broad bandwidth, leading to the reduction of gain over a narrow bandwidth. Thus self-oscillation of uncoated Fabry-Perot laser diodes is suppressed, but there is still gain for external-cavity configuration. A tuning range covering from 1340nm to 1540nm is then achieved.

Keywords: InP, tunable laser, Fabry-Perot laser diode, external-cavity configuration, broadband

1 INTRODUCTION

The information age has created a great demand on data communication, so broadband characteristics are highly desired, leading to the development of optical-fiber communication system. The optical fibers exhibit extremely broad bandwidth. They have the loss less than 0.5dB/km for wavelength from 1200nm to 1600nm. [1] Components and systems for optical-fiber communication are therefore demanded to have similar broadband characteristics. However, even with the bandwidth expanded from C-band (1525nm to 1565nm) to L-Band (1570nm to 1610nm), Er-doped fiber amplifiers and lasers still provide a bandwidth much less than the available range of optical fibers. Semiconductor lasers/amplifiers using multiple-quantum-well (MQW) engineering thus provide another possibility for the broadband purpose.

Conventional semiconductor optical amplifiers (SOAs) have the bandwidth only around 50 nm in the optical-communication band. QW engineering could possibly broaden the bandwidth several times. Several schemes had been used before for this purpose. For example, using a single QW with simultaneous transitions of $n = 1$ and $n = 2$ states [2,3] , the bandwidth is naturally broadened. However, the simultaneous $n = 1$ and $n = 2$ transitions strongly rely on the device length. Nonidentical quantum wells had then been used for the same purpose. [4-8] Because nonidentical multiple quantum wells (MQWs) have less dependence of device length, they were recently used for broadband purposes.

Tunable laser is important for optical-fiber communication. The external-cavity semiconductor lasers so far provide the broadest tuning range. [9] SOA is the key component of the external-cavity tunable semiconductor laser. In addition to the broadband characteristics of the gain media, the elimination of resonance in the Fabry-Perot cavity is also important. Otherwise, the broadband characteristics cannot be realized. A common method to fabricate SOA is applying anti-reflection (AR) coating on a laser diode. This coating increases the threshold of the self-resonance mode, and prevents it from competing with the resonance of external cavity. Normally 30nm to 60nm bandwidth of AR coating could be achieved, but broadband AR-coating with very low reflectivity is challenging. Another methods to get rid of the self resonance are to tilt or bend the waveguide. However, these will change the mode of the SOA, [2] and may reduce the efficiency of external feedback. Here, we introduce another way to fabricate a broad band SOA from a Fabry-Perot LD by simply reducing the cavity length. When the cavity length is reduced below the transition cavity length, the self-resonance moves toward short wavelength region. While this device can still provide gain at long wavelength region. Thus this device is used for a tunable laser with near 200 nm tunable range.

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2 OPERATION OF SHORT CAVITY LASER DIODE

This section describes the theoretical background for using uncoated laser diodes as the gain media in the external-cavity configuration. The conditions for self-oscillation, lasing with feedback, and gain without feedback are analyzed.

Sec 2.1 Input output relation of a LD

To calculate the input-output relation of a laser diode operated as an amplifier, we model the laser diode as the gain media, and two reflective facets as shown in figure 1.

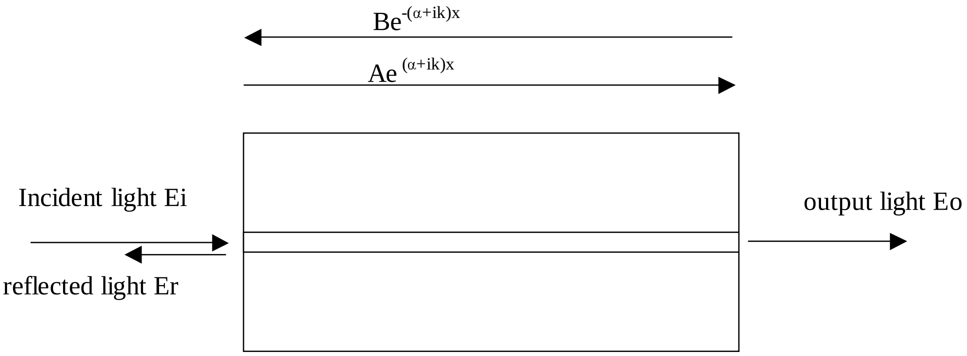

Figure 1. A schematic of the laser diode with two facets.

Referring to figure 1, there are two light waves propagating in the wave guide, the forward propagating wave and the backward propagating wave. "A" and "B" are the amplitudes of electric field either end of the device, respectively. "k" is wave number. This is used to describe the effect of phase interference between forward propagating and backward propagating light. "α" is the gain of light propagation in the wave guide. It is a function of injection current density, wave guide shape, and active layer structure. When α is positive, it means gain, and negative means loss. Ei is the electric field amplitude of incident light. Er is the reflected field, and Eo is the output field at another end of the wave guide.

The reflection and transmission of light on cleaving facets is modeled by the following equations.

$$Er = -rEi + tB \qquad (1)$$

$$A = rB + tEi \qquad (2)$$

$$Be^{-(\alpha+ik)l} = rAe^{(\alpha+ik)l} \qquad (3)$$

$$Eo = tAe^{(\alpha+ik)l} \qquad (4)$$

In these equations, "r" is the reflectance of light. "t" is the transmittance of light at the cleaved surface. These two numbers can be calculated by electromagnetic theory.

After some algebraic calculations, we can get the two equations relating Ei, Er and Eo.

$$Eo/Ei = \frac{t^2}{1-r^2e^{2(ik+\alpha)l}}\,e^{2(ik+\alpha)l} \qquad (5)$$

$$\frac{Er}{Ei} = r\,\frac{e^{2(ik+\alpha)l}-1}{1-r^2e^{2(ik+\alpha)l}} \tag{6}$$

the square of Eo/Ei is the gain of transmitted light. When this device is used to amplify optical signals (e.g. an intermediate amplifier for fiber communication), it is the gain of this device. Disregarding the phase factor (i.e assuming $e^{2ikl}=1$), this number can be larger than one, whenever α is positive. It means this device can be used as an amplifier as long as the current is above transparency level.

The square of Er/Ei is the gain of reflected light. This number should be larger than one if this device is used for an external cavity laser shown in figure 2. Also disregarding the phase factor, this number will be larger than one, if $re^{2\alpha l}$ is larger than one. This means that the gain in the waveguide must be large enough to overcome refection loss of one cleaving facet to make an external cavity laser shown in figure 2 lasing.

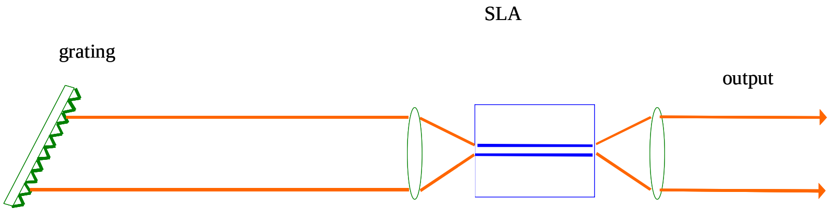

Figure 2 The structure of a tunable laser using a F.P. LD as the gain medium.

From the above consideration, we know the condition under which a laser diode can be used as the gain medium for an external-cavity laser, or communication amplifier. For a commercial laser diode, the threshold of self resonance is achieved at very low injection current density. The carrier can be considered to concentrate at one energy level under low injection current condition. Thus the gain bandwidth is very narrow for injection current below threshold. As a result, the operation current should be very low and tunable wavelength range will be very narrow.

Sec 2.2 Device characteristics

For the broadband device designed, the material gain spectrum varies with injection current density. This can be viewed from the emission spectrum of a device with bended wave guide (figure 3). It shows that at low operation current, the gain at long wavelength region has a maximum value. When the injection current increases, the spectrum is broadened toward the short-wavelength side.

When the Fabry-Perot laser diodes are fabricated on the substrate with the same QW structure and with 300 μm device length, the maximum gain at long wavelength region is below the threshold of the self resonance, resulting in emission spectrum as shown in figure 4. The self resonance threshold is about 160mA. The self resonance wavelength is around 1370nm for this device. If the cavity length is 500 μm, the self resonance wavelength is around 1500nm. The reason is because the required current density at threshold is reduced. Thus at the low injection current, the emission is mainly at the long-wavelength range.

We can estimate the wavelength-tunable range in which a 300 μm device can be used for a tunable laser according to the self resonance wavelengths of 300 μm and 500 μm devices. The gain of a 300 μm device at short wavelength region can exceed the threshold condition mentioned in section 2.1, so the short wavelength limit of the laser should be shorter than 1370nm. In addition, the short wavelength limit of operation wavelength will not greatly differ from 1370nm because self-resonance mode will compete with the feedback mode from the external cavity.

The limit of operation wavelength range at long wavelength region should be longer than the resonance wavelength of a 500 μm F-P. LD, around 1500nm, because the maximum gain of the 300 μm device at this wavelength can overcome the transmission loss of one cleaved facet. Assuming the maximum gain provided by the 300 μm wave guide at this wavelength is Gm300. The maximum gain provided by the 500 μm wave guide at this wavelength be Gm500. According to the following relations

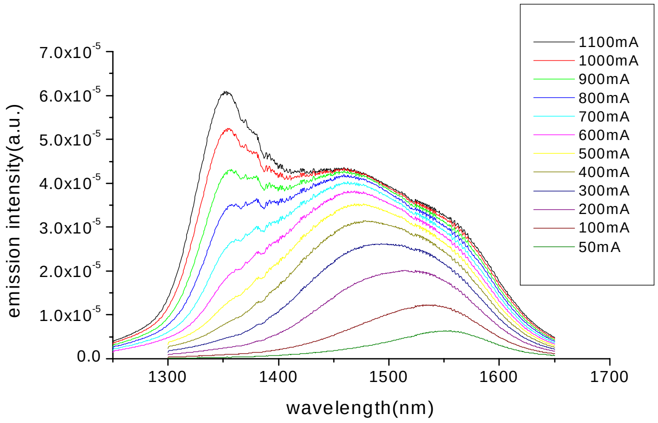

Figure 3 The emission spectrum of the designed broadband SOA with bended waveguide[3]

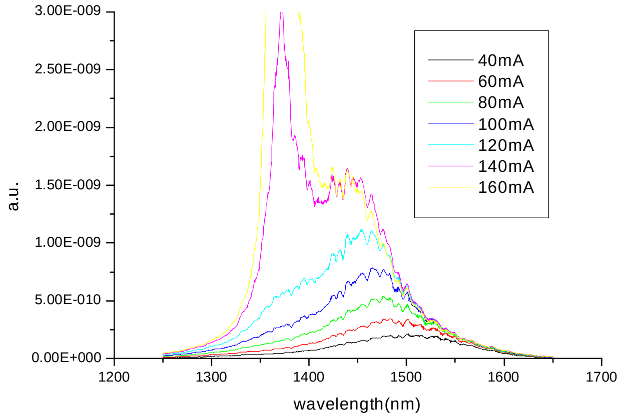

Figure 4 The emission spectrum of the designed LD with 300 μm device length.

$$Gm300 = e^{\alpha_{max} * 300 \mu m} \tag{7}$$

$$Gm500 = e^{\alpha_{max} * 500 \mu m} \tag{8}$$

$$Gm500 * r^{2} > 1 \tag{9}$$

$$\rightarrow Gm500 > r^{-2} \quad (10)$$

$$Gm300 * r = Gm500^{3/5} * r > r^{-1/5} > 1 (r < 1) \quad (11)$$

$$\rightarrow Gm300 * r > 1 \quad (12)$$

Equation 12 indicates that the maximum gain of a 300 μm device at 1500nm is above the threshold condition mentioned in section 2.1, so the operation waelength range of this device will cover the self resonance wavelength of both 300 μm and 500 μm devices.

3 EXPERIMENT

Sec 3.1 OPEREATION WAVELENGTH RANGE

The experiments are done on the 300 μm Fabry-Perot devices mentioned in section 2 by the cavity configuration as shown in Figure 2. Figure 5 shows the relative resonance intensity for different feedback wavelength and current. At 80mA injection current, the tuning range of this external-cavity laser is between 1446nm and 1537nm. When the current increases to 120mA, the tuning range extends to 1366nm and the resonance intensity increased with current. The tunable range is 170nm wide already. The threshold of the LD’s self resonance is 160 mA. When the injection current increasesto this point, the peak self-resonance intensity is is at 1370nm. This self resonance is suppressed by 15dB when the external feedback is applied between 1350 nm and 1510nm. The resonance intensities of the feedback mode are all stronger than the peak self-resonance intensity at 160mA injection current when the feedback wavelength is between 1350nm and 1525nm. Thus, the total usable gain bandwidth of this device is between 1350nm and 1537nm, about 187nm wide.

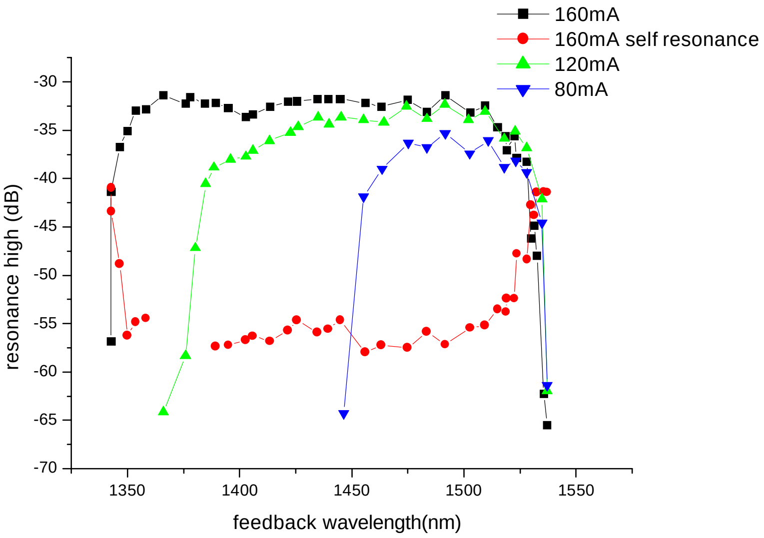

Figure 5 Relative resonance strength for different feedback wavelength and current.

Sec 3.2 THERMAL EFFECT AT LONGWAVELENGTH REGION

Figure 6 shows the threshold current at different feedback wavelength. It shows that the tuning range could be from 1340 nm to 1540nm. The minimum threshold is 40mA and occurred at 1525nm. The threshold current increase when feedback wavelength increases from 1525nm to 1550nm. This is the edge of the quantized transition wavelength of this device. Because the maximum gain of this region decrease rapidly with increasing wavelength, the threshold significantly increases at the wavelength beyond 1550nm.

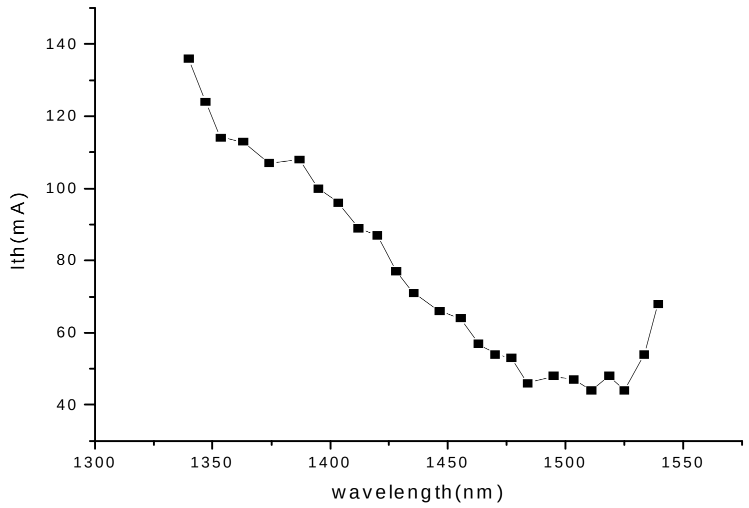

Figure 6. Threshold current vs. feedback wavelength

Except increased threshold current, the device cannot provide so much output when operated at wavelength longer than 1527 nm. This situation is shown in Figure 7. When we attempt to output more power by increasing the injection current, the tunable wavelength range at long wavelength region shrinks because current heating decreases the available gain. Thus the operation wavelength range at long wavelength region is reduced with increased current.

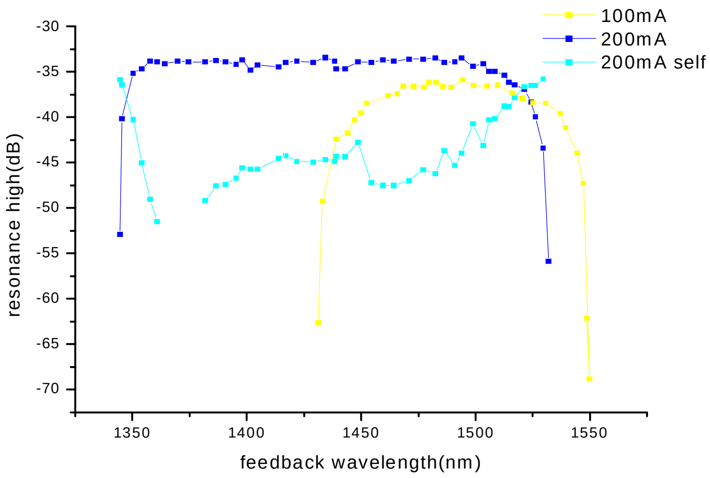

Figure 7. Effect of current heating on resonance intensity

Sec 3.3 COMPETITION EFFECT AT SHORT WAVELENGTH REGION

Because the gain competition from the LD's self resonance, this device cannot be operated at wavelength above 1350nm. Short wavelength operation requires band-filling effect to fill up all empty states below the feedback wavelength. To operate at wavelength shorter than 1350nm, all empty states with longer transition wavelength need to be filled, including the empty states that have 1370nm transition wavelength. However, the gain of this device at 1370nm is high and it will begin to have self-resonance at 1370nm before carriers can fill up states with shorter transition wavelength. Thus, increasing injection current results in the increased intensity of the self-resonance mode, but does not deliver carriers to higher energy states.

Although gain competition limits the short wavelength operation range, competition is not completely an undesired effect for this device. Gain competition is important for high current density operation, especially at short wavelength region. This device can still operate at 20nm above the self-resonance wavelength. For this wavelength range, the operation current is high. Under high injection current, the spontaneous emission intensity is high if feedback is not applied. Thus, gain competition is needed to reduce the intensity of spontaneous emission and make the output power concentrate on the resonance of the external-feedback mode.

Sec 3.4 VARIATION OF SELF-RESONANCE INTENSITY ON FEEDBACK WAVELENGTH

The peak intensity of the self-resonance mode versus feedback wavelength in Figure 7 also indicates some interesting phenomena. At 200mA injection current, gain competition cannot suppress the self-resonance mode completely. Under the effect of the Fabry-Perot cavity, small variation of gain at 1370nm can be easily observed from the measured emission intensity. In figure 7, the self resonance has a minimum when feedback is approaching 1370nm because the resonance of the external-cavity mode and the self resonance of the Fabry-Perot mode share almost the same pool of carriers, leading to strong gain competition. When feedback wavelength increases from 1370nm and 1450nm, the self-resonance intensity increases while the intensity of external-cavity resonance does not vary much. This indicates that the effect of gain competition is decreasing. Then, the self-resonance intensity exhibits sharp change when the feedback wavelength moves across 1450nm. When feedback wavelength is between 1450nm and 1550nm, the self-resonance intensity increased with increasing feedback wavelength again. The same trend can be observed in Figure 5 for 160mA injection current. These behaviors may provide some information about the carrier transition inside the devices because carrier transition between different energy levels is the main cause of gain competition at large wavelength separation. If carriers can move between two energy levels more easily, the effect of gain competition should be stronger. Thus, we may conclude that there exists some mechanism that makes carriers with 1370nm transition wavelength fall to quantized levels with 1450nm transition wavelength more easily.

4 CONCLUSIONS

The experiments demonstrate the possibility of using Fabry-Perot laser diodes as gain media for the external-cavity lasers with broad tunable range. By reducing the cavity length, we can have near 200nm broad tuning range without any AR-coating, because the peak gain in the device is reduced below the self resonance threshold.

Because of high current density and low gain, these devices always suffer some thermal effect at long wavelength region. This should be compensated by using quantum well of lower transition energy or utilizing temperature control. On the other hand, the self-resonance wavelength of the LD limits the short wavelength edge and the device cannot provide too much gain above the natural lasing wavelength of the diode. Gain competition between self-resonance and resonance of external cavity is observed here.

Different from the gain competition usually observed with small wavelength separation, competition between modes with large wavelength separation must occur through the transition of carriers between different energy levels or quantum wells. Thus, the strength of competition should depend on how fast carriers can go from one energy level to another energy level or from one QW to another. From the curve relating self resonance intensity and feedback wavlength, the carriers with 1370nm transition wavelength seems to fall into energy levels with 1450nm transition wavelength easily.

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