Report on SAIF (A) Grant: *Investigation and Design of Injection Locked Quantum Cascade Laser*

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The research on *Investigation and Design of Injection Locked Quantum Cascade Laser* is very fruitful. We almost have achieved all the goals planed in the proposal. Through the research, we have a deeper understanding on the mode locking mechanism and quantum cascade laser itself. Some innovative device is designed based on the physics understanding. The PI participated in IEEE International Electro Information Technology Conference in Milwaukee, in May, 2014 to present our achievements in the research to colleagues (The paper and oral presentation power-point presented in the conference are attached).

This research activity not only advances the understanding of physics and engineering application on this interesting phenomenon. It also helps to build up the PI’s reputation in optoelectronics domain through the interactions with the researchers of the same interests in the conference, and the communications with the collaborators. Through the research activity, we also find that there are more related topics to be investigated and we will try to seek for possible extramural resources.

In fact, the research also benefits the education in our department. The PI has tailored some research results into his courses such as Introduction to Quantum Electronics. This activity will be continued in the following terms. The research results are going to be shared with the colleagues of our department and EMS. The PI will present a poster on his achievements on the University Research Poster Day.

To conclude, this research has great accomplishments in (1) the understanding of basic scientific principles and engineering applications. (2) the PI’s professional development.
(3) undergraduate education and related curriculum development. The research will be continued if funded by extramural resources such as NSF.

The PI would like to express his great appreciation for the support from Office of Sponsored Program. Hopefully the support will be continued on the other research/teaching activities of PI and lead to more fruitful results.
Spatial Hole Burning Suppression for DFB Laser Diode with Anti-symmetric Grating Gap

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• Fiber to the Home, Office… (FTTH, FTTX)
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Schematic Grating along the cavity

SEM photo

Distributed Feedback (DFB) Mechanism and Mode Selection
Background Information

Single Mode Selection Schemes for DFB Lasers

- **HR/AR coating**: low yield and bad side mode suppression ratio (SMSR)

- **Gain coupling**: super single mode operation, fabrication extremely difficult

- **$\lambda/4$ Phase-shifted**: reliable but sacrifice SHB at high bias
Spatial Hole Burning Effect

Typical Spectrum at low bias →
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Photon concentrated in the center of the cavity; Carrier density drops in the center; Phase change larger than $\lambda/4$
Schemes To Reduce SHB Effect

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(ii) Phase-shift realized by wider/narrower waveguide
(iii) Corrugation-pitch-modulated grating
    - more detailed elegant structure less than half grating period
Anti-symmetric Filter Photon Distribution

Anti-symmetric DFB Laser

Phase-change and anti-symmetric grating  Laser structure
Anti-symmetric DFB Laser

• Models and Key Equations

\[
\frac{1}{v_g} \frac{\partial A}{\partial t} + \frac{\partial A}{\partial z} = \left( \Gamma \frac{g}{2} - \alpha_{\text{mod}} - j\delta \right) A - j k_A B + s_A
\]

\[
\frac{1}{v_g} \frac{\partial B}{\partial t} - \frac{\partial B}{\partial z} = \left( \Gamma \frac{g}{2} - \alpha_{\text{mod}} - j\delta \right) B - j k_A A + s_B
\]

\[
\frac{\partial N}{\partial t} = \frac{I}{eV} - \frac{N}{\tau(N)} - g v_g P
\]

\[P = |A|^2 + |B|^2\]
Anti-symmetric DFB Laser

- Threshold Analysis: grating gap
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The photon plateau in the gap region
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Lasing wavelength is independent of grating gap
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The optimized grating gap is around 20 μm
Anti-symmetric DFB Laser

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I=20 mA
Lasing spectra as bias increases

I=80 mA
Lasing spectra as bias increases

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Photon plateau at high bias
Conclusions

• Anti-symmetric grating with gap: gap range around 20 μm
  - Good SMSR at high bias
  - Fabrication: without a structure less than grating period
  - Efficient, reliable and cost-effective

• Proposed fabrication in near future

• Simulation tool development
Spatial Hole Burning Suppression for the Distributed Feedback Laser Diode with an Asymmetric Grating Gap Structure

Wei Li, Senior Member, IEEE, S. M. Sadeghi

Abstract—We propose and design an asymmetric grating distributed feedback (DFB) laser with a grating gap at its center. The below and above threshold analyses show that this kind of laser will be lasing at the Bragg wavelength independent of the grating gap length with an output spectrum similar to those of $\lambda/4$ phase-shifted DFB lasers. However, the proposed structure shows a uniform photon and carrier distribution in the grating gap region, and therefore, spatial hole burning, which is the bottle-neck for the phase-shifted DFB laser design, is greatly suppressed. By simulation, it is demonstrated that with the same grating coupling efficiency, the proposed laser will share similar threshold current and efficiency as those of $\lambda/4$ phase-shifted DFB lasers, but as the biased current increases, reaching 100 mA, the former keeps the single mode operation with more than 30 dB side mode suppression ratio while the $\lambda/4$ phase-shifted laser becomes multi-mode. Fabrication of the proposed laser structure does not involve extra complexity. It is much easier to implement compared to the other techniques used to suppress the spatial hole burning effect.

Index Terms—single mode distributed feedback laser diode, asymmetric grating gap, spatial hole burning, modeling and simulation.

I. INTRODUCTION

SINGLE mode laser diodes are key components in the optic communication system and optical signal sensing, processing and detection [1,2]. $\lambda/4$ Phase-shifted DFB lasers are one of the well-known approaches to satisfy this demand [3]. However, due to the spatial-hole burning (SHB) effect, it is found that such laser diodes sacrifice side mode suppression ratio (SMSR) if the grating coupling is strong and bias current is high [4]. To overcome this side-effect, many schemes have been proposed in order to smooth the photon distribution in the phase-shifted region and suppress SHB effect. For example, instead of using a $\lambda/4$ phase-shifted grating in the center, two $\lambda/8$ multi-phase-shifted regions were applied in the cavity design [5]. Other attempts include using a phase-shifted section at the center with a wider or narrower waveguide structure compared to the grating regions. This can change the effective refractive index of this section from the other parts of the waveguide, inducing 90° phase change for the propagation wave. This approach is equivalent to the corrugation-pitch-modulated grating structure [6]. Some optimized position dependent grating strength along the laser cavity was also investigated [7-9]. All these schemes are trying to generate a relatively uniform photon distribution around the phase-shifted region in order to avoid the strong photon accumulation. Such a photon accumulation results in carrier depletion and larger phase change than desired, causing red shift of lasing wavelength and multi-mode operation. However, it is also obvious that all schemes are introducing various fabrication complexities such as multi-etching/regrowth.

To suppress SHB, in this work, we apply an asymmetric grating structure with a gap at its center to an index-coupled DFB laser. By simulation, it is demonstrated that this laser is lasing at the Bragg wavelength independent of the grating gap length at the threshold. Its output spectrum is similar to that of a $\lambda/4$ phase-shifted DFB. However, in this structure, the photon distribution shows a flat plateau at the grating gap region instead of a sharp peak. Therefore, while biased current is increased, the SHB effect is suppressed. It is also shown that even with a strong grating coupling strength, this laser diode can still maintain single mode operation with large SMSR at very high bias while the $\lambda/4$ phase-shifted DFB fails under the same condition. In general, the proposed laser diode excels in every respect over its peer device. It is noted that we are not claiming that our approach is superior to the other schemes in order to suppress SHB. However, this realization does not introduce any fabrication complexity such as duty cycle variation of the grating or multi-electrode control, that were commonly proposed in the previous designs, but experimentally are difficult to implement or expensive to fabricate [6-12].

In this paper, we will first present the proposed laser...
structure and its threshold analysis. In this part, we will systematically investigate the mode characteristics for the different grating gap lengths and predict the optimized gap length. Then in section III, we will first briefly review the above threshold analysis simulation theory. Based on this, using the optimized grating gap length, we will demonstrate both static state and dynamic operation of this laser diode. As a comparison with \( \lambda / 4 \) phase-shifted DFB lasers, we also show the photon distribution along the cavity and output spectrum at various biased currents in order to explain the SHB suppression mechanism. Finally, we will give a brief conclusion in section IV.

II. DEVICE STRUCTURE AND THRESHOLD ANALYSIS

A. Grating and Device Structure

In the investigation, we use InGaAsP/InP ridge waveguide structure as an example. In general, however, the model is material and waveguide structure independent. The proposed asymmetric grating gap is schematically shown in Figure 1 (a). The laser side view is shown in Figure 1(b) with both facets anti-reflection (AR) coated.

![Grating and Device Structure](image)

The proposed grating structure shows 180° grating phase difference between its front and rear sections. Here, however, instead of a sudden phase flap at the center, as in the case of the \( \lambda / 4 \) phase shifted DFB lasers, a uniform gap region without grating is sandwiched between two grating sections with opposite phases. From Figure 1 (a), we can see that, similar to the \( \lambda / 4 \) phase-shifted DFB, the proposed laser grating coefficient is also asymmetric relative to the cavity center, but the gap region grating coefficient is zero. It is noted that if the gap length is zero, the proposed laser structure is the same as a \( \lambda / 4 \) phase-shifted DFB laser. Considering the asymmetric nature of both \( \lambda / 4 \) phase-shifted and asymmetric gap laser diodes, we are expecting that these two structures should show similar longitudinal lasing mode selection, which is confirmed by the following threshold analysis. Here, however, without changing such a spectral property we can control the photon distribution of the lasing mode along the cavity by changing the length of the gap region. As shown in the following, this allows us to have a uniformly distributed photon density, instead of sharply peaked one, as happens in \( \lambda / 4 \) phase-shifted DFB lasers.

Finally, the new grating structure does not introduce any fabrication complexity, compared with the standard techniques used for phase-shifted DFB lasers. This is because of the fact that this asymmetric grating gap can be fabricated by creating a photomask as shown in Figure 1 (a) or by using a uniform grating photomask but with positive and negative photoresists in the front and rear grating regions respectively [6, 13]. Therefore, to suppress the SHB effect, unlike the other schemes described in the introduction, the proposed laser needs no additional processing steps such as multi-etching/regrowth or multi-electrode [6-12]. In other words, the standard \( \lambda / 4 \) phase-shifted DFB laser diode fabrication procedures will well satisfy our requirements. As we will show in the following, from the design point view, since lasing modes are similar to \( \lambda / 4 \) phase-shifted DFB lasers independent of the grating gap length, it is also very easy to optimize the laser performance.

B. Threshold Analysis

The threshold analysis is a standard approach in the frequency domain. We only consider the TE mode. The optical field propagating in the waveguide can be expressed as [14,15]

\[
\vec{E}(X, z) = [A(z)e^{-j \frac{\pi}{\Lambda} z} + B(z)e^{j \frac{\pi}{\Lambda} z}] \Phi(X)e^{j \omega t},
\]

where \( \vec{E} \) is the optical field, \( X \) is the cross sectional coordinates \((x, y)\), and \( z \) is the longitudinal direction along the waveguide. \( A \) and \( B \) are the forward and backward optical wave envelop functions respectively. \( \Lambda \) is the grating period and \( \Phi(X) \) is the cross sectional optical field profile function. Here the waveguide has been designed to support only one single cross sectional mode. \( \omega \) is the angular frequency of the propagating field.

Using the perturbation theory, we found the coupled mode equations [14 -17]

![Fig.1](image)
\[
\frac{dA}{dz} = (G - j\delta)A - jk_+ B \\
\frac{dB}{dz} = -(G - j\delta)B + jk_- A . \\
G = \Gamma (g / 2) - \alpha_{\text{mod}}
\] (2)

In Eqn. 2, \( G \) is the net modal gain, \( \Gamma \) is mode confinement factor, \( g \) is the material gain and \( \alpha_{\text{mod}} \) is modal loss. \( \delta = (2\pi / \lambda)n_{\text{eff}0} - \pi / \Lambda \) is the detuning factor and here \( n_{\text{eff}0} \) is the effective refractive index of the waveguide for a cold cavity. \( \lambda \) is the wavelength. \( k_\pm \) is the coupling coefficient. Since here we only consider the index coupling case, we have

\[
k_+ = e^{i\theta} k \\
k_- = e^{-i\theta} k
\] (3)

\( k \) is a real index coupling coefficient and \( \theta \) is the grating phase. For the asymmetric grating gap case, if the front grating section phase is chosen as zero that actually is arbitrary. The rear grating section phase has 180° difference to the front section and should be 180°. It is apparent that \( k \) at the grating gap region is zero.

Using the transfer matrix or Green’s function methods [15-17], it is easy to obtain the lasing mode wavelength \( \lambda \) and its corresponding net modal gain \( G \). Here to emphasize the SHB effect, we have chosen a very large coupling coefficient. For the total laser cavity length \( (L=300 \mu m) \), in the simulation we have considered \( kL = 4 \). Normally, for index coupling laser, \( kL \) is around 2 and 3. The other simulation parameters are listed in Table 1. It is noted that to keep \( kL \) the same, our laser has even larger coupling coefficient \( k \) compared with that of the \( \lambda / 4 \) phase-shifted DFB laser.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Cavity length (( \mu m ))</td>
<td>300</td>
</tr>
<tr>
<td>Grating coupling strength ( kL )</td>
<td>4</td>
</tr>
<tr>
<td>Grating period (( \mu m ))</td>
<td>0.24</td>
</tr>
<tr>
<td>Active layer thickness ( d ) (nm)</td>
<td>40</td>
</tr>
<tr>
<td>Active layer width ( w ) (( \mu m ))</td>
<td>2</td>
</tr>
<tr>
<td>Carrier life time ( \tau ) (ns)</td>
<td>0.5</td>
</tr>
<tr>
<td>Modal absorption coefficient ( \alpha_{\text{Mod}} ) (cm(^{-1}))</td>
<td>10</td>
</tr>
<tr>
<td>Differential gain ( g_N ) (10(^3) cm(^{-1}))</td>
<td>1.5</td>
</tr>
<tr>
<td>Effective refractive index without pumping ( n_{\text{eff}0} )</td>
<td>3.22</td>
</tr>
<tr>
<td>Effective group refractive index ( n_g )</td>
<td>3.67</td>
</tr>
<tr>
<td>Transparent carrier density ( N_T ) (10(^{18}) cm(^{-3}))</td>
<td>1.0</td>
</tr>
<tr>
<td>Line-width enhancement factor ( \alpha_m )</td>
<td>2</td>
</tr>
<tr>
<td>Gain saturation coefficient ( \xi ) (10(^{-17}) cm(^{-3}))</td>
<td>3.0</td>
</tr>
<tr>
<td>Spontaneous radiation coefficient ( B ) (10(^{-10}) cm(^3)/s)</td>
<td>1.0</td>
</tr>
<tr>
<td>Spontaneous coupling coefficient ( \beta )</td>
<td>5x10(^{-5})</td>
</tr>
<tr>
<td>Petermann’s factor ( K )</td>
<td>1.0</td>
</tr>
</tbody>
</table>

We change the grating gap length from zero, which is corresponding to \( \lambda / 4 \) phase-shifted DFB laser, up to 50 \( \mu m \). Because of the large \( kL \) and hence relatively wide stop band, within the grating gap range considered, there are only three major modes: two around the edges of the stop band and one dominant mode around the Bragg wavelength. Using the above simulation parameters, we find that as the grating gap length \( L_{\text{Gap}} \), is changed, there is almost no visible wavelength variation for these modes. The dominant mode wavelength is 1545 nm and symmetrically there are two side modes at 1548 nm and 1542 nm as shown in Figure 2.

![Fig. 2. Threshold mode positions and their corresponding net gain. Here \( L_{\text{Gap}}=0 \), which is corresponding to \( \lambda / 4 \) phase-shifted DFB. For other \( L_{\text{Gap}} \), the feature is similar (a). The mode wavelength at different grating gap lengths (b).](image)

In Figure 2 (a), we only show the mode wavelengths and threshold gains for the case where \( L_{\text{gap}}=0 \), i.e., identical to the \( \lambda / 4 \) phase-shifted DFB lasers. As shown in Figure 2(b), for asymmetric grating gap lasers with \( L_{\text{Gap}} \) less than 50 \( \mu m \), there is no visible change in the mode positions. However, as shown in Figure 3, when \( L_{\text{Gap}} \) increases, the main lasing mode...
threshold gain decreases while the threshold gain difference between this mode and the side modes gets smaller.

The left side of Eqn. 4 is propositional to the mirror loss from the right and left facets respectively and right hand side of Eqn. 4 is corresponding to the net cavity gain. At the threshold, the net modal gain $G$ is independent of $z$, the net cavity gain can be written as

$$2G_0^2(|A(z)|^2 + |B(z)|^2)dz$$

(5)

In Figure 4, we have normalized the mirror loss to be the same for each configuration. It is obvious that larger grating gap will lead to more efficient cavity gain, i.e., larger field distribution integral along the cavity in Eqn. 5. From Eqns 4 and 5, we conclude that longer gap results in the lower net threshold gain $G$. The threshold gain difference for various gap lengths can be explained in the similar way by considering the side mode field distribution.

Figure 4 also shows that as Lgap increases a flat plateau appears in the longitudinal mode intensity profile. Therefore longer grating gap length will result in better SHB suppression if the laser is highly biased. However, Figure 3 (b) presents the limit of this process, i.e., as grating gap becomes longer, the threshold gain difference between the main mode and two side modes is degraded. To maintain the SMSR, these two effects should be compromised. Based on the results shown in Figure 3 and 4, to have a large enough threshold gain difference (larger than 20 cm$^{-1}$) and reasonable long photon distribution plateau, for $kL=4$ L$_{Gap}$ should be between 10 to 20 μm. This conclusion is confirmed by the following above threshold analysis.

III. ABOVE THRESHOLD ANALYSIS

A. Simulation Methods

We use the time domain traveling wave model to study the above threshold characteristics of the proposed laser. This is done by calculating the carrier and photon distribution followed by application of the Green’s function method to obtain the above threshold spectrum. Since the details of the approach have been reported before in [16, 18-20], here we just briefly review the key formula related to this work. Similar to Eqns. (1) and (2), but here $A$ and $B$ are now both position and time dependent instead of depending on the wavelength only. The coupled mode equations are:

$$\frac{1}{v_g} \frac{\partial A}{\partial \tau} + \frac{\partial A}{\partial z} = (\Gamma - \frac{g}{2} - \alpha_{mod} - j\delta)A - jk_+ B + s_A$$

$$\frac{1}{v_g} \frac{\partial B}{\partial \tau} + \frac{\partial B}{\partial z} = (\Gamma - \frac{g}{2} - \alpha_{mod} - j\delta)B - jk_- A + s_B$$

(6)

Here $v_g$ is group velocity, $s_A$ and $s_B$ are the driving spontaneous noise term satisfying the following correlation
Here $\beta$ is spontaneous noise coupling coefficient, $K$ is Petermann’s factor, $B$ is bimolecular recombination coefficient and $N$ is local carrier density. It is noted that in Eqn. (6) detuning factor is defined by $\delta = (2\pi / \lambda_0)n_{eff} - \pi / \Lambda$, where $\lambda_0$ is the reference wavelength chosen as Bragg wavelength in the simulation, and $n_{eff} = n_{eff0} - \Gamma a_m\lambda_0 / 2\pi$. Here $a_m$ is the line-width enhancement factor. The material gain is related to the carrier density as

$$g = g_N \ln\left(\frac{N}{N_T}\right) \frac{1}{1 + B P}.$$  \hspace{1cm} (8)

Here we assume the active layers are quantum wells. $g_N$ is gain coefficient and $N_T$ is the transparent carrier density. $g$ is the gain saturation coefficient and $P$ is local photon density defined by

$$P = |A|^2 + |B|^2.$$  \hspace{1cm} (9)

These optical equations are coupled with the carrier equation

$$\frac{\partial N}{\partial t} = \frac{I}{eV} - \frac{N}{\tau(N)} - g v g P,$$  \hspace{1cm} (10)

where $I$ is the bias current, $e$ is the free electron charge, and $V$ is the active region volume. $\tau(N)$ is the carrier life time defined by

$$\frac{1}{\tau} = A + BN + CN^2.$$  \hspace{1cm} (11)

A, B and C are the non-radiative, bimolecular and Auger recombination coefficients, respectively. In the simulation, we assume the carrier life time is a constant.

B. Simulation Results

As we explained in section II, the optimized grating gap length is around 10 to 20 \(\mu m\). We will use 20 \(\mu m\) in the following simulation. For the sake of comparison, we present in parallel the results of a \(\lambda/4\) phase-shifted laser with the same simulation parameters as in Table I. As shown in Figure 3(a), compared with the \(\lambda/4\) phase-shifted DFB (gap length is zero), since the 20 \(\mu m\) gap length shows lower main mode threshold net gain, we are expecting that the asymmetric grating gap laser should also have lower threshold current. The laser efficiency for both cases should be similar due to the same coupling strength $kL=4$. The L-I curves are presented in Figure 5.

Fig. 5. L-I curves for the asymmetric grating gap DFB laser and \(\lambda/4\) phase-shifted DFB laser with the same $kL$.

It is clear that these two type laser configurations have the similar thresholds and efficiencies. Although smaller threshold current effect is not clearly visible due to the long carrier life time, our proposed laser shows better performance in term of output power. For the strong grating coupling condition considered here ($KL=4$), it is well-known that \(\lambda/4\) phase-shifted DFB becomes multi-mode when current injection is high, due to the strong SHB effect. From the threshold analysis in section II, we are expecting that the asymmetric grating gap can smooth the photon concentration even at higher bias and therefore result in the desired single mode performance. In the simulation, after the time domain output power reaches the static state at a specific bias current, using the Green’s function approach, we calculate the output spectra above the threshold and present the results in Figures 6-8 for currents equal to 20 mA, 80 mA and 100 mA respectively.

Fig. 6. Output spectra at 20 mA for the asymmetric grating gap DFB laser and \(\lambda/4\) phase-shifted DFB laser.
Figures 6-8 demonstrate that while the current is below 20 mA, where the SHB effect is not severe, the SMSR for both $\lambda/4$ phase-shifted and asymmetric grating gap DFB lasers are very high. The $\lambda/4$ phase-shifted one should even show more advantage due to its large threshold gain difference between the main mode and side modes. As current increases, however, the SHB effect becomes dominant. In the $\lambda/4$ phase-shifted case, while biased current is above 50 mA, the SMSR will be less than 30 dB, at 80 mA the SMSR is below 20 dB as shown in Figure 8, and finally at 100 mA the side mode even surpasses the main mode as shown in Figure 9. However, for the proposed asymmetric grating gap DFB, although the SMSR degrades as the bias current increases, the laser still keeps single mode operation with more than 30 dB SMSR even at 100 mA. The reason for such a resistance against SHB can be rooted back to the flat photon distribution in the gap region under current injection levels, as shown in Figures 9.

Finally, it is noted that because of the time averaging and collective effect of all frequency components for the static state power, the L-I curve doesn’t show any kink while the $\lambda/4$ phase-shifted DFB goes to multimode operation at high bias. However, the time domain output power really shows great fluctuation and mode beating effect. On the contrary, the asymmetric grating gap DFB laser is very stable due to the dominant single mode. We compare the output power as a function of time for these two types of lasers in Figure 10. Here the current jumps from 0 to 100 mA at t=0 ns.

IV. CONCLUSIONS

In this paper, we proposed an asymmetric grating gap DFB laser diode. Independent of the grating gap length, the lasing modes are similar to the $\lambda/4$ phase-shifted DFB at the threshold. It was demonstrated that in such a laser, the lasing modal photon distribution at the grating gap region would be flat. We showed that this could make such a laser resistance against SHB effect to a large extent. It is shown that for very strong coupling strength (KL=4) and very high bias, if we leave 10-20 $\mu$m asymmetric grating gap at the laser cavity center, the laser can maintain single mode operation up to 100 mA with SMSR more than 30 dB while $\lambda/4$ phase-shifted laser fails at much lower bias. Since the design procedures are well prescribed, it is easy to extend the results to the other cases with different coupling strength and laser cavity length. The proposed laser structure does not introduce any extra
experiment complexity and, therefore, standard procedures to fabricate a $\lambda/4$ phase-shifted DFB are well enough for our case. Due to the simpler fabrication procedures compared with the other schemes to suppress SHB, we believe that this low cost asymmetric grating gap laser will be more applicable in the optic communication system for the optical signal generation and detection.

REFERENCES