Extended Abstracts of the 1992 International Conference on Solid State Devices and Materials, Tsukuba, 1992, pp. 234-236 **PC1-8**

Fabrication of an Absorptive-Grating Gain-Coupled DFB Laser with an Optimized Duty Factor

H. L. Cao, Y. Luo*, Y. Nakano, K. Tada, M. Dobashi*, and H. Hosomatsu*

Department of Electronic Engineering, University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo, 113, Japan
* Optical Measurement Technology Development Co., Ltd.
2-11-13 Naka-cho, Musashino-shi, Tokyo, 180, Japan

We discuss an optimum range in grating duty cycle for the gain-coupled (GC) distributed-feedback (DFB) semiconductor laser of absorptive grating type. The minimum threshold gain achievable within the optimum range is found to be almost independent of the order of the grating. According to this prediction we have fabricated GaAlAs/GaAs GC DFB lasers with a third-order absorptive grating, where the grating duty factor has been made close to the theoretical optimum value. In 200μm-long devices, CW threshold current of 20mA, external efficiency of 0.5mW/mA, and SMSR as high as 45dB have been obtained.

1. INTRODUCTION

Gain-coupled (GC) distributed-feedback (DFB) semiconductor lasers possess several uncommon features over conventional DFB lasers[1-4] One way of realizing GC DFB in semiconductor lasers is by placing an absorptive grating along the active layer to obtain a periodic change in net gain[1,5-7]. This GC DFB laser of absorptive grating type has a merit that the gain-coupling coefficient can be prescribed through the absorption coefficient of the grating. However, the excess absorption near the active layer, at the same time, tends to badly affect the threshold and external efficiency of the lasers. Although this problem can be lessened if a small duty factor is used for the absorptive grating, the duty factor should not be too small in order to retain a significant amount of gain coupling.

In this paper, our numerical analysis will show that low threshold operation is possible if the duty factor of the grating is properly selected. According to this prediction, we fabricate a GaAlAs/GaAs GC DFB laser using an absorptive grating with a near-optimum duty factor, and demonstrate high-quality single-longitudinal-mode oscillation with low threshold current.

2. METHOD OF ANALYSIS

A schematic of the model used for theoretical analysis here is shown in Fig.1. The periodic absorptive region (absorptive grating) placed near the active layer gives rise to periodic change in the gain coefficient, so that the gain coupling is obtained. The corrugation on the waveguiding layer acts as an antiphase index grating to cancel (partly) the index perturbation generated by the absorptive grating. Reflectivity of both facets is assumed to be zero.

Since refractive index and loss are periodically perturbed along the z direction, the complex relative

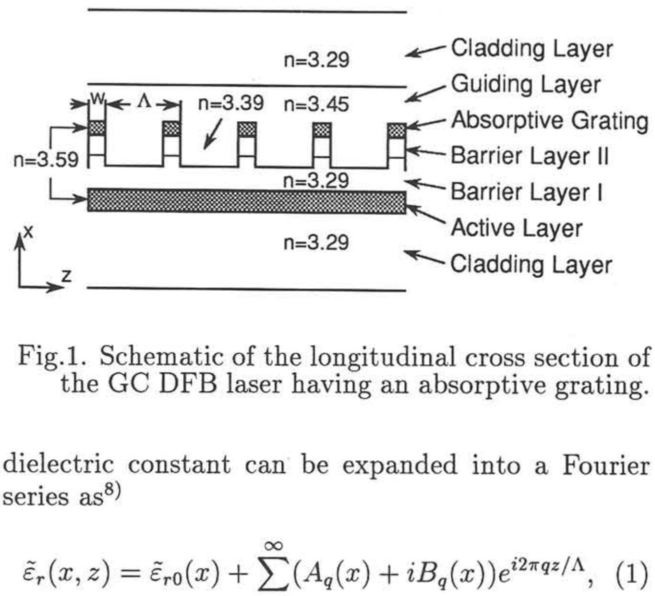


Fig.1. Schematic of the longitudinal cross section of the GC DFB laser having an absorptive grating.

dielectric constant can be expanded into a Fourier series as[8]

$$\tilde{\varepsilon}_r(x,z) = \tilde{\varepsilon}_{r0}(x) + \sum_{-\infty}^{\infty}(A_q(x) + iB_q(x))e^{i2\pi qz/\Lambda}, \quad (1)$$

where

$$\tilde{\varepsilon}_{r0}(x) = n_0^2(x) + i\alpha_0(x)n_{abs}/k_0, \quad (2)$$

$$A_q(x) = \frac{1}{\Lambda}\int_{-\Lambda/2}^{\Lambda/2} n^2(x,z)e^{-i2\pi qz/\Lambda}dz, \quad (3)$$

and

$$B_q(x) = \frac{1}{\Lambda}\int_{-\Lambda/2}^{\Lambda/2} \frac{n_{abs}\alpha(x,z)}{k_0}e^{-i2\pi qz/\Lambda}dz. \quad (4)$$

In the above expression, $k_0 = 2\pi/\lambda$ is the free space wave number, q the order of the grating, and Λ the pitch of the grating. $n_0(x)$ and $\alpha_0(x)$ are the refractive index and the loss corresponding to DC term of the Fourier expansion, and n_{abs} and α_{abs} are bulk refractive index and absorption coefficient of the absorptive grating, respectively. The complex coupling coefficient $\tilde{\kappa}$ is expressed as

$$\begin{aligned}\tilde{\kappa} &= \kappa_{index} + i\kappa_{gain} \\ &= \frac{k_0^2}{2\beta_0 P}\int_{-\infty}^{\infty} E_0(x)(A_q(x) + iB_q(x))E_0^*(x)dx,\end{aligned} \tag{5}$$

where $\beta_0 = q\pi/\Lambda$ is the propagation constant in the z direction, $E_0(x)$ the electric field distribution in the x direction, and $P = \int_{-\infty}^{\infty} E_0(x)E_0^*(x)dx$ the integrated intensity in the x direction. By substituting $\tilde{\kappa}$ into the coupled wave equations[9], the reflection loss α is determined.

In the GC DFB laser with absorptive grating, the average absorption composes the majority of the internal loss. It is calculated for the model shown in Fig.1 as

$$\alpha_0(x) = \Gamma_{abs} \cdot duty \cdot \alpha_{abs}, \tag{6}$$

where

$$\Gamma_{abs} = \frac{1}{P}\int_{abs} E_0(x)E_0^*(x)dx \tag{7}$$

is the confinement factor in the absorptive grating layer, and $duty = W/\Lambda$ is the duty factor defined as the ratio of the length of the absorptive region (W) to the grating period (Λ). Then, normalized threshold gain $g_{th}L$ is obtained by

$$g_{th}L = \alpha L + \alpha_0 L. \tag{8}$$

Radiation coupling in the higher-order gratings is not taken into account in this calculation.

3. RESULTS OF NUMERICAL ANALYSIS

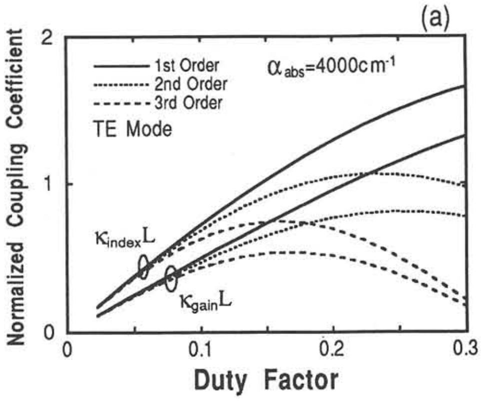
Assuming cavity length of 300μm, and absorption coefficient of 4000cm^{-1}, we calculated normalized coupling coefficients $\kappa_{index}L$ and $\kappa_{gain}L$, average absorption $\alpha_0 L$, and normalized threshold gain $g_{th}L$.

The results are shown in Figs.2(a) and (b). When the duty factor increases from zero, the coupling coefficients increase accordingly in Fig.2(a), which causes the decrease in $g_{th}L$ in Fig.2(b). However, $\alpha_0 L$ increases at the same time as shown in Fig.2(b) to lift $g_{th}L$. Therefore, $g_{th}L$ takes its minimum at a certain value of the duty factor. The minimum values of $g_{th}L$ for the first-, second-, and third-order gratings are at the duty factor of 0.15, 0.13 and 0.11, respectively, and they are between 66 $\sim$ 100cm^{-1} for 300μm cavity length. Thus, low threshold current operation is possible in the GC DFB laser with an absorptive grating.

Furthermore, our analysis has shown that the value of the minimum threshold gain appearing around the duty factor of 0.11 is almost independent of the order of the grating, which allows us to use higher-order gratings in actual devices. Although the results above are calculated for TE modes, those for TM modes can readily acquired in a similar manner.

4. DEVICE FABRICATION

The results of the analysis showed that, if the duty factor is optimized, it is possible to achieve low threshold current operation. However, in practice, it is difficult to make first-, and second-order gratings with a small duty factor ($\leq$ 0.2) in GaAlAs/GaAs lasers, we here use a third-order absorptive grating.



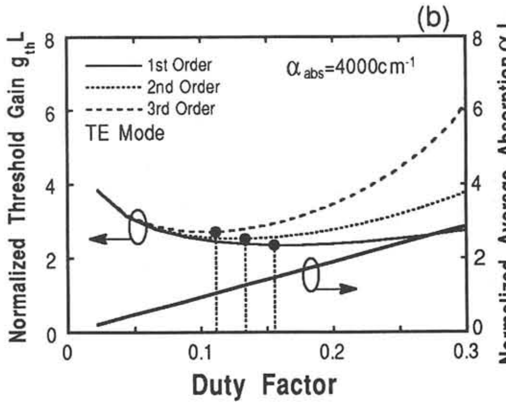


Fig.2. (a)Normalized index- and gain-coupling coefficients versus the duty factor of the grating; (b)normalized averaged absorption (α_0L) and threshold gain (g_{th}L) versus duty factor of the grating.

Fortunately, as shown in the previous section, the third-order grating similarly will give us low threshold as the first- and second-order ones.

For device fabrication we used two-step organometallic vapor phase epitaxy (OMVPE). During the first step epitaxy, n^+-GaAs buffer, n-super lattice buffer, n-$Ga_{0.55}Al_{0.45}As$ cladding, 0.1μm thick undoped GaAs active, p-$Ga_{0.55}Al_{0.45}As$ barrier, p-$Ga_{0.7}Al_{0.3}As$ barrier, and 0.05μm thick p-GaAs absorptive layers were grown on an n^+-GaAs (100) substrate, successively. A third-order grating with a 394nm period and a duty factor of approximately 0.15 was formed on the photo-resist film spin-coated on the epitaxial wafer by holographic exposure and over development. To accomplish TE-mode oscillation[10], the depth of the grating grooves was controlled to $\sim$0.12μm by using wet chemical etching.

During the second step epitaxy, p-$Ga_{0.75}Al_{0.25}As$ waveguiding, p-$Ga_{0.55}Al_{0.45}As$ cladding, and p^+-GaAs contact layers were grown. A scanning electron micrograph of the cross section is shown in Fig.3, where we observe the absorptive grating with a duty factor being $\sim$0.15. The wafer was made into a ridge waveguide structure. Then it was cleaved into 200μm long devices whose both facets were left as-cleaved.

Under CW operation at room temperature, the lasers exhibited threshold current of 20mA and total external efficiency of 0.5mW/mA. The typical spectrum below threshold is shown in Fig.4 (a). The stop-

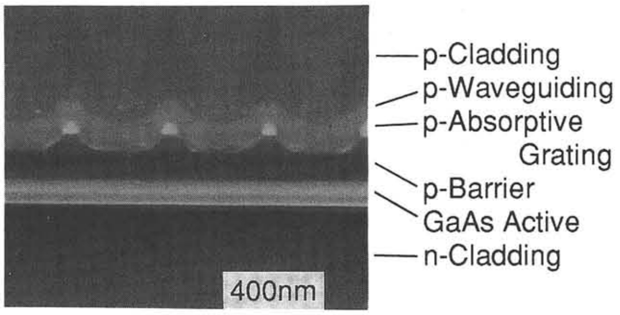


Fig.3. Scanning electron micrograph of the epitaxial layers showing the absorptive grating with a small duty factor (~0.15).

band near the Bragg wavelength is not observed, as is common to gain-coupled oscillation [9,10]. Figure 4(b) shows the spectrum at 8mW output power (per facet) where the side-mode suppression ratio (SMSR) as high as 45dB is obtained. As expected, almost 100% in hundreds of measured devices oscillated in a TE single longitudinal mode. If SMSR greater than 30dB at 5mW or larger is chosen as a criterion of single mode operation, the yield was 61%. This high yield of single mode operation without any facet coating is probably due to the gain-coupled optical feedback in the lasers.

5. CONCLUSION

The GC DFB laser of absorptive grating type is thought to confront a threshold rise due to excess absorption. From our analysis, it has been found that low threshold operation with sufficient gain coupling is possible in this type of lasers if the duty factor of the absorptive grating is controlled to be 0.1~0.2. Furthermore, our analysis has shown that the value of the minimum threshold gain appearing around the duty factor of 0.11 is almost irrelevant to the order of the grating, thus allowing us to use higher-order gratings in actual devices.

According to the analysis, we have fabricated GaAlAs/GaAs GC DFB lasers having a third-order absorptive grating with a small duty factor. In 200μm-long devices with as-cleaved both facets, low CW threshold current of 20mA, external efficiency of 0.5mW/mA, and SMSR as high as 45dB have been obtained. High yield of single mode oscillation without any facet coating is an indication that the gain coupling has come into effect in the actual devices.

ACKNOWLEDGMENT

The authors would like to acknowledge the support of Dr. M. Morimura and Dr. H. Iwaoka to this study. The research of H.-L. Cao, Y. Nakano, and K. Tada was supported by the Grant-in-Aid for Developmental Scientific Research (#03505001) from the Ministry of Education, Science, and Culture of Japan.

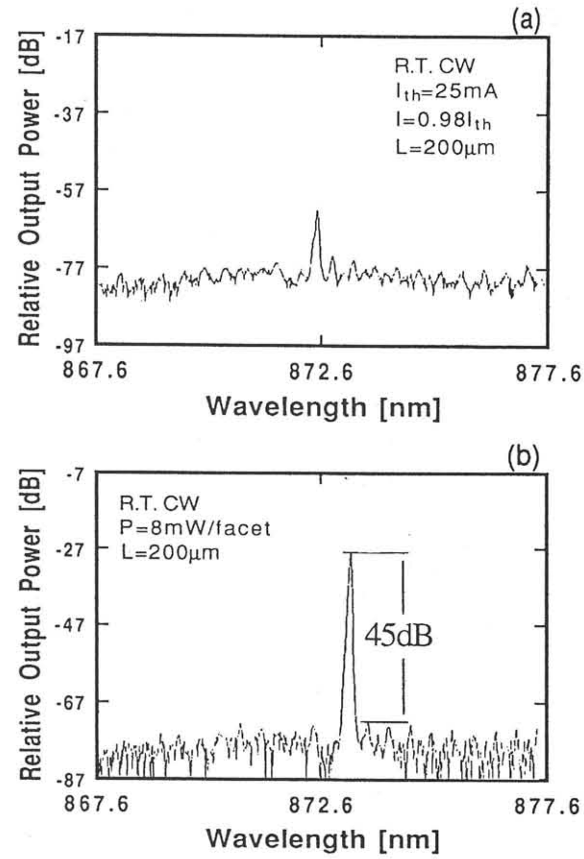


Fig.4. Spectra of the GaAlAs/GaAs GC-DFB laser fabricated (200μm-long with both facets as cleaved); (a) below threshold and (b) at the output of 8mW.

REFERENCES

1) Y. Nakano, Y. Luo, and K. Tada, Appl. Phys. Lett. 55 (1989) 1606.
2) K. David, G. Morthier, P. Vankwikelberge, and R. G. Baets: Electron. Lett. 26 (1990) 238.
3) Y. Nakano, Y. Deguchi, K. Ikeda, Y. Luo, and K. Tada, IEEE J. Quantum Electron. 27 (1991) 1732.
4) Y. Luo, R. Takahashi, Y. Nakano, K. Tada, T. Kamiya, H. Hosomatsu, and H. Iwaoka, Appl. Phys. Lett. 59 (1991) 37.
5) Y. Luo, Y. Nakano, and K. Tada, SSDM, Tokyo, D-4-4 (1988) 327.
6) B. Borchert, K. David, B. Stegmuller, R. Gessner, M. Beschorner, D. Sacher, and G. Franz, IEEE Photon. Technol. Lett. 3 (1991) 955.
7) W. T. Tsang, F.S. Choa, M. C. Wu, Y. K. Chen, R. A. Logan, A. M. Sergent, and C. A. Burrus, IEEE Photon. Technol. Lett. 4 (1992) 212.
8) W. Streifer, D. R. Scifres, and R. D. Burnham, IEEE J. Quantum Electron. 13 (1977) 134.
9) H. Kogelnik and C. V. Shank, J. Appl. Phys. 43 (1972) 2327.
10) H. L. Cao, Y. Luo, Y. Nakano, and K. Tada, to be submitted.
11) Y. Luo, Y. Nakano, K. Tada, T. Inoue, H. Hosomatsu, and H. Iwaoka, Appl. Phys. Lett. 56 (1990) 1620.