Numerical Optimization of DFB LD Grating Structure for Uniform Longitudinal Intensity Distribution

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1. Introduction

The DFB LD is one of the most important devices in optical communication systems, so much effort has been devoted to enhance its performance. The coupling coefficient (κ) is critical in achieving high performance DFB LDs for narrow linewidth[1] and/or high output power applications. It is well known that conventional DFB LDs with a $\lambda/4$ shift exhibit relatively strong longitudinal spatial hole burning (SHB). The lasing probability is guaranteed by introducing the $\lambda/4$ phase shift or a multi-phase structure that yields the same result. From the viewpoint of low-threshold operation, we would like to efficiently use photons in the cavity by adopting a high κL value, where L is cavity length. However, a large κL value and the phase shift enhance the concentration of the optical power and the related carrier concentration in the vicinity of the phase shift. In most practical situations, this is undesirable and limits performance. Chirped gratings[1] and multi-phase shift structures[2] have been demonstrated to be effective in reducing the SHB-related degradation.

In the conventional approach, initial design parameters are incrementally changed by measuring the parameters of fabricated devices and/or using a simulation program based on coupled mode theory[3]. Moreover designing the optimum grating structure is time consuming, and the manner in which the design parameters are modified depends on the engineer's experience. While analytical approaches have been proposed for designing grating coupling coefficients[4-5], they are limited in that they are valid only when $\kappa L=1$. Therefore, it has been impossible to design high κL structures for low threshold lasing. Under these circumstances, it is a need for an overall grating coupling coefficients design approach that automatically outputs the optimum structure to allow novice engineers to design high-performance DFB LDs. One should note that parameter extraction and the optimization of electron devices and their fabrication conditions have been employed for VLSIs [6].

2. Numerical Optimization Approach

This study focuses on optimizing the grating structure via parameter tuning to yield a uniform longitudinal intensity distribution. Our overall grating design program consists of an analysis part and a parameter updating part that uses a cost function and derivatives. The cost function is defined as

$$f = \sum_{i=1}^{kn} \frac{w_i}{L} (I(z) - I_{av})^2 \cdot \Delta z, \qquad (1)$$

where, $I(z)$ is the intensity distribution along the cavity, I_{av} is the average value, and w_i is a weighting function. The gradients for the parameters (x_i) are calculated by the following manner.

$$g_i = \frac{\partial f}{\partial_{x_i}} = \frac{f\ (x_i + \Delta_{x_i}{}') - f\ (x_i)}{\Delta_{x_i}{}'} \qquad (2)$$

Figure 1 shows a schematic of the grating structure along the cavity. The whole region is divided into k sections, and a section dependent coupling coefficient and phase shift are assigned to each. These are chosen as the parameters to be tuned. The analysis program is iterated to evaluate Eqs. (1) and (2).

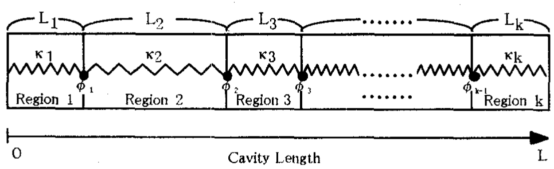

Figure 1. Schematic grating structures under investigation.

3. Results and Discussion

First, the program was applied to a device with L=1500μm. The cavity was divided into six sections and a λ/4 phase shift was placed at the center. In this first example, the normalized coupling coefficient (κiL) in the six sections was determined to realize uniform optical intensity along the cavity. Using a symmetrical structure, we saved treated tuning variables by setting $\kappa_1L=\kappa_6L$, $\kappa_2L=\kappa_5L$, and $\kappa_3L=\kappa_4L$. All initial values were 2.0, the convergence criteria for the cost function defined in (1) were sufficiently small, and the iteration limit was set at 35. Figure 2 shows the iteration process. The final optical intensity distribution together with the corresponding initial distribution is summarized in Fig. 3. The cost function value was improved from 0.14798 to 0.0019869. From both this numerical value and Fig. 3, it is concluded that the final results show sufficiently flat optical distribution and that the program achieves its intended goal.

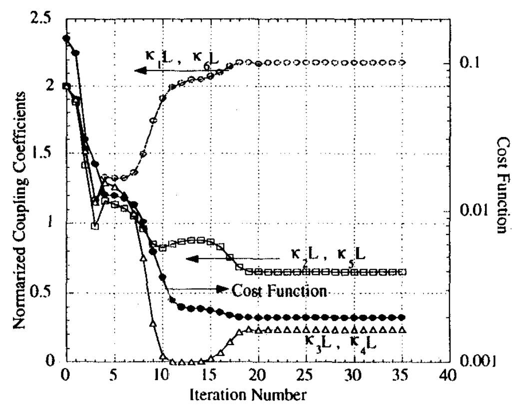

Figure 2. The iteration process for cost function, and tuning parameters for six sections.

The second example shows the effectiveness of the program even when the tuning variables are restricted. There were two constraints. One was total κL and the other was the upper limit of κL in each section. Whenever we design a flat optical distribution without constraining the total κL, the value converges to 1.0. This is because the flattest distribution is realized at κL=1.0. This is not always what we want. As mentioned before, the total κL is related to photon recycling in the cavity and a large value is desirable, if possible. The grating is fabricated by chemical etching, so some constraint is placed on the depth, especially considering the yield. Taking into account practical cases, we set the following constraints in this study: the total κL should be kept at 4/3 and the maximum κL in each section should be less than 2.5.

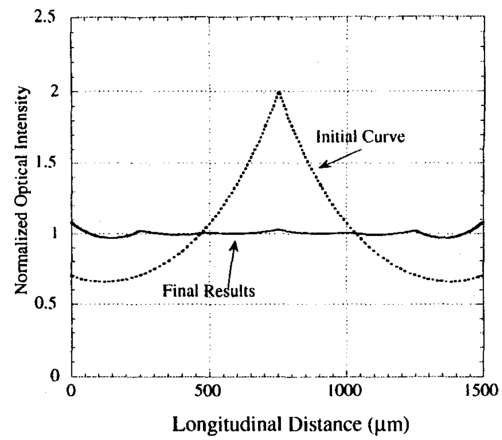

Figure 3. Final Optical intensity distribution along the cavity (solid line), and the initial characteristics (dotted line).

The cavity length was the same as in the first example, and the cavity was divided into 12 sections in this example. We also placed the λ/4 phase shift at the center and the initial conditions were $\kappa_1L=\kappa_2L=\kappa_3L=\kappa_4L=\kappa_9L=\kappa_{10}L=\kappa_{11}L=\kappa_{12}L=2.0$ and $\kappa_5L=\kappa_6L=\kappa_7L=\kappa_8L=0.0$. The final results were $\kappa_1L=\kappa_{12}L=2.500$, $\kappa_2L=\kappa_{11}L=0.206$, $\kappa_3L=\kappa_{10}L=0.730$, $\kappa_4L=\kappa_9L=0.455$, $\kappa_5L=\kappa_8L=0.0$, and $\kappa_6L=\kappa_7L=2.253$; the optical distributions for the initial and the final values are shown in Fig. 4. Please note that the obtained value for the first (twelvth) section reached the upper limit. In addition, the final curve was much better than the initial curve, as shown in Fig. 4. Further improvement can be expected by using the weighting function defined in Eq. (1).

The corresponding lasing conditions were obtained by solving complex the eigenvalue problem. Figure 5 shows the results which satisfys the threshold resonance conditions. The vertical axis shows the imaginary part of ΔαL which is related to threshold gain, and the horizontal axis is the real part of

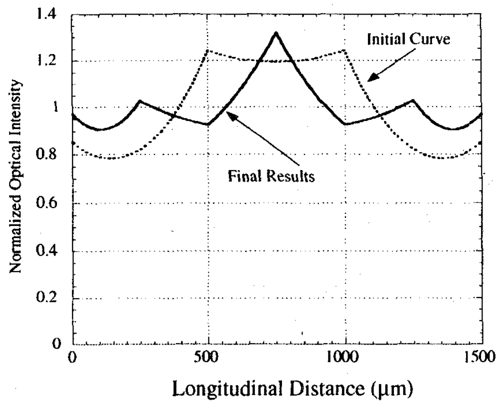

Figure 4. Optimized results under constraints, i.e., κL=4/3 and $\kappa_i L < 2.5$. The final characteristics (solid line) and initial curve (dotted line).

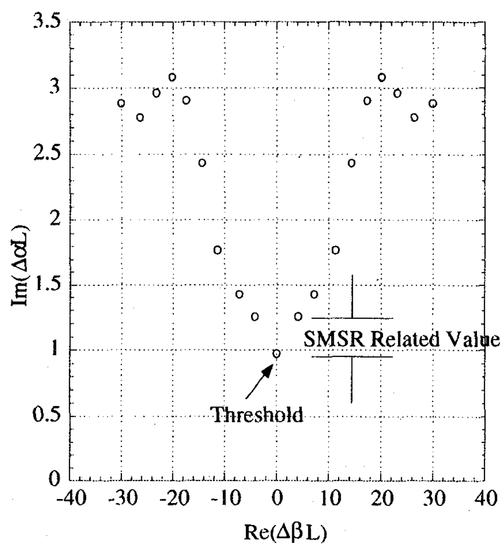

Figure 5. Solutions for the threshold resonance conditions corresponding to the results in Fig. 4.

ΔβL, which indicates the deviation from the Bragg condition (detuning). Among them, the lowest threshold gain condition (shown by the arrow in the figure) is chosen as the threshold. The threshold difference between the next oscillation condition gives the SMSR (Side Mode Suppression Ratio). When the difference is large, it means that the first mode lasing is stable. It can be seen from the figure that the threshold takes place at the Bragg condition and the SMSR is sufficient.

The final example shows the availability of the current program for multi-phase shift structures. In this example, a uniform grating of κL=2 was assumed for a 1200-μm-long cavity. This is the largest κL value in the present study, and with it, effective photon recycling can be expected. We assumed 12 uniform sections along the cavity. Between the sections, 11 phase shifs were placed as shown in Fig. 1. The obtained final phase shift values were $\phi_1=\phi_{11}=0.0°$, $\phi_2=\phi_{10}=14.04°$, $\phi_3=\phi_9=17.07°$, $\phi_4=\phi_8=21.22°$, $\phi_5=\phi_7=18.82°$, and $\phi_6=11.15°$. The final optical intensity distributions are shown in Fig. 6. It is also concluded that the results indicate sufficiently flat optical distribution and our intended design goal is achieved.

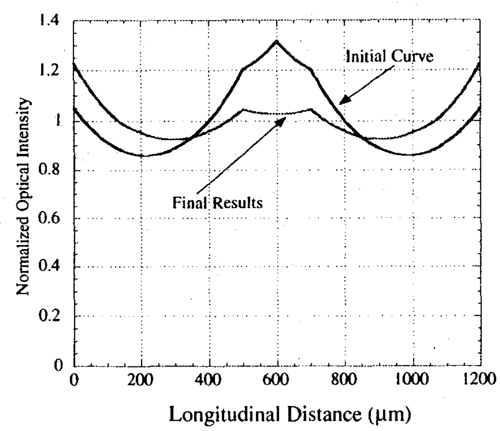

Figure 6. Optimized results for a muiti-phase shift structure. The final characteristics (solid line) and initial curve (dotted line).

4. Summary

We have developed a numerical optimization program that uses a region-dependent grating structure and/or multi-phase shift DFB LDs with uniform longitudinal intensity distributions. The effectiveness of the program was confirmed by calculating longitudinal optical intensity distributions, and its effectiveness has been demonstrated for restricted tuning variables conditions. Since the restriction arising from our fabrication conditions is included in the optimization procedure, the obtained tuning parameters take into account the actual fabrication.

It is concluded that an overall grating coupling coefficient design for high performance DFB LDs can be automatically achieved by using the current program.

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