Distributed feedback lasers with multiple phase-shift regions

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(Received 28 March 1988; accepted for publication 16 May 1988)

Phase-shifted distributed-feedback (PSDFB) lasers with multiple phase-shift regions are proposed to reduce the effect of spatial hole burning in conventional PSDFB lasers where a single phase shift leads to a highly nonuniform axial distribution of the mode intensity. We analyze multiple phase-shift PSDFB lasers by solving numerically the coupled-wave equations. Our results show that the use of even two phase-shift regions can substantially reduce the axial inhomogeneity of the mode intensity. Although the gain margin is generally reduced by the use of multiple phase shifts, it is still large enough for most practical purposes if the phase shifts are suitably optimized.

Phase-shifted distributed-feedback (PSDFB) lasers have attracted considerable attention recently[1–5] since they offer the potential of providing semiconductor lasers oscillating stably in a single longitudinal mode over a wide range of operating currents and temperatures. The basic idea[6] consists of introducing a constant phase shift in the middle of the laser cavity either by changing the corrugation phase or by increasing the effective mode index over a small section. The optimum phase shift is $\pi/2$ and can provide a gain margin in excess of 50 cm^{-1} between the neighboring modes. It has been suggested[5] that the performance of a PSDFB laser is affected by spatial hole burning occurring as a result of highly nonuniform intensity distribution of the lasing mode along the cavity length. Since spatial hole burning increases the effective phase shift with an increase in the mode power, one approach consists of designing PSDFB lasers with a less-than-optimum phase shift ($\sim\pi/4$ instead of $\pi/2$) even though it leads to a significant decrease in the gain margin at low powers.

An alternative approach to the hole burning problem would be to make the axial distribution of the mode intensity less nonuniform. In this letter we propose the use of multiple phase-shift regions for this purpose. Using numerical solutions of the coupled-wave equations,[7] we show that the use of two or three phase-shift regions with optimum phase shifts (generally less than $\pi/2$) can provide sufficient gain margin with an axial intensity distribution more uniform than conventional PSDFB lasers. Such modified PSDFB lasers are expected to be less dependent on the operating power than those with a single phase-shift region.

To obtain the threshold gain and the gain margin between the neighboring DFB modes, we solve the coupled-wave equations numerically subject to the appropriate boundary conditions. More specifically, the coupled-wave equations satisfied by the forward and the backward waves are[7]

$$\frac{dA}{dz} = \left(\frac{\alpha}{2} + i\delta\right)A + i\kappa B, \quad (1)$$

$$-\frac{dB}{dz} = \left(\frac{\alpha}{2} + i\delta\right)B + i\kappa A, \quad (2)$$

where α is the mode gain, δ is the mode detuning from the Bragg wavelength, and κ is the coupling coefficient. The boundary conditions for a laser of length L are

$$A(0) = r_1 B(0), \quad B(L) = r_2 A(L), \quad (3)$$

where

$$r_j = \sqrt{R_j}\,\exp(i\phi_j), \quad j = 1,2. \quad (4)$$

R_1 and R_2 are the facet reflectivities, and ϕ_1 and ϕ_2 account for the corrugation phases as the facets.[8] The numerical solution of (1) and (2) is used to obtain the values of α and δ corresponding to the five DFB modes in the vicinity of the Bragg wavelength. The lasing occurs at the mode for which α is lowest. The threshold gain of the lasing mode is obtained using

$$g_{th} = \alpha_{th} + \alpha_{int}, \quad (5)$$

where α_{int} is the internal loss and was taken to be 50 cm^{-1} for a laser length $L = 250\,\mu m$. The gain margin $\Delta\alpha$ is given by the excess gain required by the mode with the next-to-lowest value of the threshold gain.

Figure 1 shows the threshold gain g_{th} and the gain margin $\Delta\alpha$ as a function of the phase shift ϕ_{sh} for PSDFB lasers with one, two, and three phase-shift regions. In each case the phase-shift regions are equispaced and have identical phase shifts. Thus, for $N_{sh} = 3$, a phase shift of ϕ_{sh} occurs at $z = L/4$, $z = L/2$, and $z = 3L/4$. The coupling coefficient κ was chosen such that $\kappa L = 2$. In order to avoid complications resulting from the corrugation phases ϕ_1 and ϕ_2 (which may vary from device to device), Fig. 1 is drawn for an ideal PSDFB laser with $R_1 = R_2 = 0$. The effect of residual facet reflectivities is to replace each curve in Fig. 1 by a band resulting from variations in the corrugation phases ϕ_1 and ϕ_2. The qualitative behavior, however, remains unchanged for typical facet reflectivities of 1% or less. The main conclusion drawn from Fig. 1 is that multiple phase shifts can provide significant gain margin in the range of 20–30 cm^{-1} for optimum values of ϕ_{sh}. Although the gain margin is roughly reduced by a factor of 2 compared with that obtained for conventional PSDFB lasers with $\phi_{sh} = \pi/2$, it is still sufficient to suppress the side modes by 30 dB or more as long as $\Delta\alpha > 8$–10 cm^{-1}. Note also that the threshold gain is generally larger for $N_{sh} > 1$.

Figure 2 compares the axial distribution of the mode intensity inside the laser cavity for the three PSDFB lasers of Fig. 1 with the optimum value of the phase shifts for each N_{sh}. More specifically, Eqs. (1) and (2) were solved using

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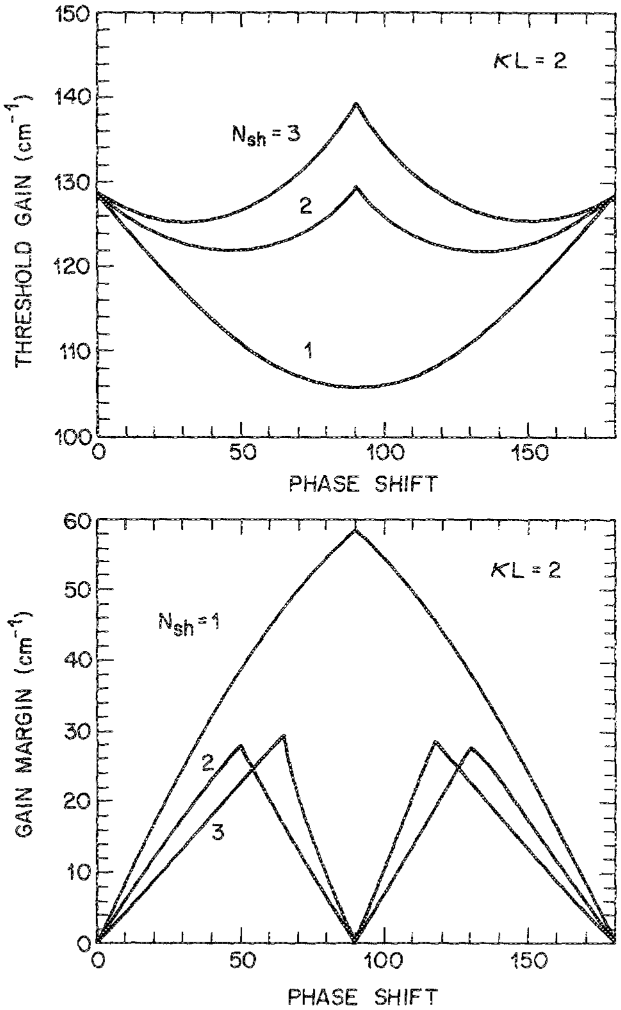

FIG. 1. Variation of the threshold gain g_{th} and the gain margin $\Delta\alpha$ with the phase shift ϕ_{sh} for PSDFB lasers with $N_{sh} = 1$–3 phase-shift regions. The device parameters are taken to be $\kappa L = 2$ and $R_1 = R_2 = 0$.

the values of α and δ corresponding to the lowest threshold mode and

$$P(z) = |A(z)|^2 + |B(z)|^2 \quad (6)$$

was calculated. The peaks in $P(z)$ occur at the location of the

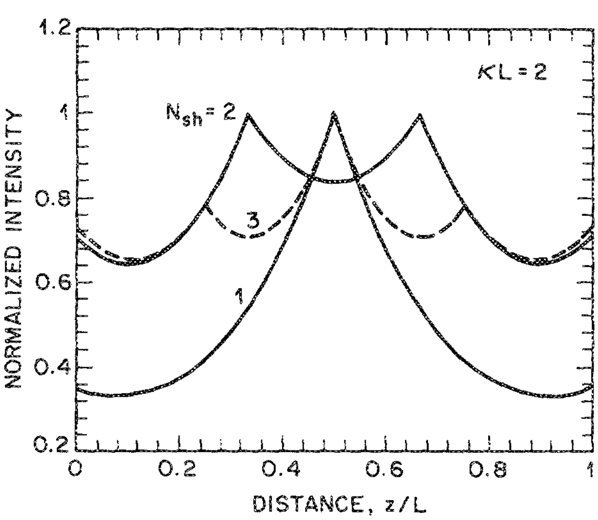

FIG. 2. Axial distribution of the mode intensity inside the laser cavity of PSDFB lasers with $N_{sh} = 1$–3 phase-shift regions. In each case the phase shift is obtained from Fig. 1 such that the gain margin $\Delta\alpha$ is maximum.

phase shifts. The important point to note is that the use of multiple phase shifts reduces considerably the range over which $P(z)$ varies inside the laser cavity. As a result, spatial hole burning is less effective, and the performance of such PSDFB lasers is expected to be less dependent on the operating power. Note from Figs. 1 and 2 that even two phase-shift regions are enough to take the advantage of the concept of the multiple phase shifts.

For $\kappa L = 2$ and $R_1 = R_2 = 0$, the optimum values of ϕ_{sh} in Fig. 1 are about 50° and 70° for $N_{sh} = 2$ and 3, respectively. We have performed a number of calculations to study the sensitivity of these optimum values of ϕ_{sh}^{opt} to variations in κL, R_1, and R_2. For $R_1 = R_2 = 0$, the values of ϕ_{sh}^{opt} vary by less than 5° when κL is varied in the range 2–3, indicating that the performance of PSDFB lasers with multiple phase shifts will not be adversely affected by nominal variations in values of the coupling coefficient. The dependence of ϕ_{sh}^{opt} on the facet reflectivity is more complicated because of the corrugation phase ϕ_1 and ϕ_2 which may vary randomly from device to device. Our numerical results show that the dependence on the corrugation phases is not of much consequence as long as R_1 and R_2 are $\lesssim 0.1\%$. For larger values of the facet reflectivities, the device performance can be characterized only in a statistical sense. In general as R_1 and R_2 increase, the fraction of devices with a high gain margin reduces below unity even for the optimum phase shifts when all possible phase combinations are considered.

In conclusion, we have proposed PSDFB lasers with multiple phase-shift regions as a possible candidate for high-performance single-frequency semiconductor lasers. The use of multiple phase-shift regions leads to a more uniform axial distribution of the mode intensity inside the laser cavity than that occurring in a conventional PSDFB laser. As a result, spatial hole burning is less effective in destabilizing the single-mode operation, and the performance of such modified PSDFB lasers should be less dependent on the operating power. In order to present the main qualitative features as simply as possible, we have considered the case where all phase-shift regions are equispaced from each other. In practice, both the location and the magnitude of the phase shifts can be independently chosen to tailor the device characteristics. Thus PSDFB lasers with multiple phase-shift regions offer a greater design flexibility than the conventional PSDFB lasers. It was recently shown[9] that the use of an odd number of equispaced $\pi/2$ phase shifts can reduce the linewidth of PSDFB lasers.

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