Tunable active chirped-corrugation waveguide filters

Thomas Schrans, Michael Mittelstein, and Amnon Yariv
Department of Applied Physics, 128-95, California Institute of Technology, Pasadena, California 91125

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A novel tunable semiconductor waveguide reflection filter is proposed and analyzed. The filter is based on spatially selective gain pumping of a chirped-corrugation waveguide. This active chirped-corrugation waveguide filter (ACF) is considered for monolithic broadband tuning of semiconductor lasers.

Monolithic waveguide optical filters have the potential of playing a major role in optoelectronics. One of the more immediate applications for such a filter would be as a tuning element for semiconductor lasers. Recently, semiconductor lasers were shown to have tuning ranges exceeding 1000 Å at 0.8 μm,[1-3] and 1350 Å at 1.5 μm.[4] This broad tuning range at 0.8 μm was achieved by operating GaAs/GaAlAs single quantum well (QW) Fabry–Perot lasers near the broad gain flattened condition and using an *external* grating as the tuning element.[1-3,5] Monolithic tunable semiconductor lasers based on distributed Bragg reflection (DBR) have been reported with tuning ranges up to 94 Å at 1.5 μm.[6] The tuning range in this latter case is limited by the relatively small change in Bragg wavelength that can be induced by controlling the refractive index through the injected carrier density. In our proposed scheme, analyzed below, the combination of a chirped grating and inhomogeneous current pumping promises to increase the tuning range by more than an order of magnitude. Therefore, the tuning range of such a laser would fundamentally be limited by the bandwidth of the gain spectrum.

A laser with a monolithic active chirped-corrugation waveguide filter (ACF) is illustrated by Fig. 1. The ACF provides an effective reflectivity R_2 to the otherwise conventional semiconductor laser which occupies the region $z<0$. The wavelength selectivity of the ACF mirror is based on the fact that a given wavelength, say λ_0, is reflected significantly from the immediate neighborhood of the position $z(\lambda_0)$ in the chirped grating, where the grating period $\Lambda(z)$ satisfies the Bragg condition $\lambda_0 = 2n_{\rm eff}\Lambda(z)$ ($n_{\rm eff}$ is the refractive index). The remainder of the grating interacts insignificantly with the optical field.[7] Therefore, the ACF can reflect wavelengths over a range which is equal to the total change in Bragg wavelength over the grating length. The ACF thus acts as a reflector for the gain section, with different wavelengths being reflected from different positions within the chirped grating. By proper tailoring of the gain along the ACF we can favor the effective reflection R_2 at a particular wavelength λ_0.

One way to achieve this wavelength selectivity is to divide the ACF at the position $z(\lambda_0)$ (of Bragg reflection at λ_0) into two functional regions (Fig. 1). The region $0<z<z(\lambda_0)$, denoted as $T(\lambda_0)$, is pumped to *transparency* at the wavelength λ_0, thereby providing lossless propagation, at this wavelength, between the gain section and the region near $z(\lambda_0)$. The remainder of the ACF, region $A(\lambda_0)$, is reverse biased to achieve maximum *absorption*. Operation at a different wavelength, say λ_1, is achieved by moving the boundary between region T and region A from $z(\lambda_0)$ to $z(\lambda_1)$ and by adjusting the pumping in region T to transparency at λ_1. A possible implementation for changing the pumped regions might have multiple contacts along the length of the grating: the contacts corresponding to region $T(\lambda_0)$ would be used to inject the current necessary to pump that region to transparency at λ_0, while the remaining contacts would be used to reverse bias region $A(\lambda_0)$.

The wavelength-dependent gain/loss $g(\lambda)$ of the quantum well structure, which extends over the whole length of the device, was calculated as in Ref. 3; gain spectra for a suitable single QW structure at different pumping levels are shown in Fig. 2. When region $T(\lambda_0)$ is pumped to transparency at λ_0, wavelengths longer than λ_0 will experience gain in $T(\lambda_0)$, while wavelengths shorter than λ_0 will be absorbed (Fig. 2). To prevent oscillation at $\lambda>\lambda_0$, the sign of the chirp is chosen such that the *longer* wavelengths are reflected in region $A(\lambda_0)$.[7] The absorption in this region can then be used to attenuate these wavelengths before they reach their position of reflection. The only question remaining is whether enough absorption can be provided to compensate for the undesired amplification of these wavelengths in region $T(\lambda_0)$. Wavelengths *shorter* than λ_0 will have a lower reflection coefficient as they experience absorption everywhere in the ACF.

The inhomogeneously pumped chirped-corrugation waveguide can be viewed as a passive reflector with an effective reflection coefficient $R_2(\lambda)$ at $z=0$. To obtain $R_2(\lambda)$ we assume that the electric field in the grating is given by

$$E(\lambda,z) = A_+(\lambda,z)e^{-i\beta z} + A_-(\lambda,z)e^{i\beta z}, \qquad (1)$$

where $A_+(\lambda,z)$ and $A_-(\lambda,z)$ are the complex amplitudes of the forward and backward propagating modes, respectively, and $\beta = (2\pi/\lambda)n_{\rm eff}$ is the propagation constant in the wave-

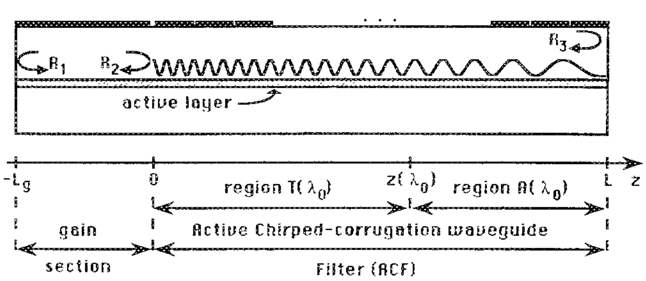

FIG. 1. Schematic diagram of the monolithic tunable laser structure.

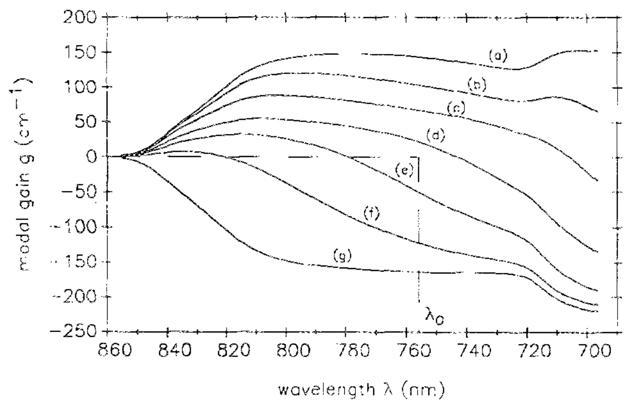

FIG. 2. Gain spectra of a single QW structure for several pumping levels. The gain section is operated in the range of curves (b) and (c); region $T(\lambda_0)$ between (c) and (f); and region $A(\lambda_0)$ is operated at curve (g).

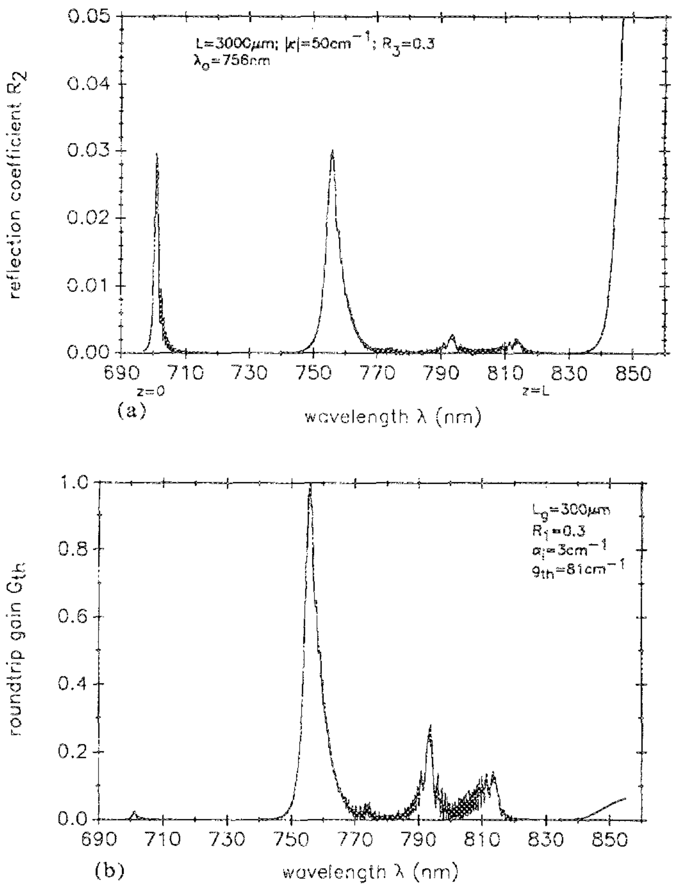

FIG. 3. (a) Reflection spectrum of the chirped grating at the operational conditions listed in the figure. (b) Round-trip gain spectrum at threshold.

guide neglecting the grating. The fields $A_+(\lambda,z)$ and $A_-(\lambda,z)$ at a given λ are given by the coupled wave equations

$$\frac{dA_+}{dz} = \kappa^* e^{2i\Delta\beta(z)z} A_-(\lambda,z) + \frac{g(\lambda,z)}{2} A_+(\lambda,z) \qquad (2)$$

$$\frac{dA_-}{dz} = \kappa e^{-2i\Delta\beta(z)z} A_+(\lambda,z) - \frac{g(\lambda,z)}{2} A_-(\lambda,z) \qquad (3)$$

with κ the coupling constant of the grating, $\Delta\beta(z) = \beta - \beta_B(z)$, $\beta_B(z)$ the Bragg wave vector of the grating at z $[\beta_B(z) = \pi/\Lambda(z)]$, and $g(\lambda,z)$ the wavelength and z-dependent modal gain. Equations (1)–(3) were solved numerically using a matrix method to describe propagation and coupling.[8] In this method the chirped grating is approximated as a cascade of uniform gratings. Once the reflection spectrum $R_2(\lambda)$ of the ACF, defined as

$$R_2(\lambda) = \frac{|A_-(\lambda,0)|^2}{|A_+(\lambda,0)|^2} \qquad (4)$$

is known, the round-trip gain spectrum $G(\lambda)$ of the whole structure at a fixed pumping level in the gain section can be calculated from

$$G(\lambda) = R_1 R_2(\lambda) \exp\{2[g_g(\lambda) - \alpha_i]L_g\}, \qquad (5)$$

where R_1 is the front facet reflectivity, α_i the internal losses, L_g the length of the gain section, and $g_g(\lambda)$ the gain in the gain section.

Calculations were performed for a grating with a linear chirp $\beta_B(z) = \beta_{B0} - a_\beta z$. The parameter values used were $\lambda_B(0) = 700$ nm, $\lambda_B(L) = 820$ nm, $n_{\rm eff} = 3.5$, $L = 3000$ μm (giving a chirp $a_\beta = 1.5 \times 10^{-3}$ μm^{-2}) and $|\kappa| = 50$ cm^{-1}. A facet reflectivity $R_3 = 0.3$ at $z = L$ was included; it will be shown that this reflectivity does not affect the performance of the device. The main results, illustrating the feasibility of this novel scheme, are shown and discussed below. A more detailed analysis of the modeling will be published elsewhere.

Results of the calculated spectra for $\lambda_0 = 756$ nm are shown in Fig. 3. Figure 3(a) shows the wavelength dependence of the reflectivity $R_2(\lambda)$ of the ACF, while Fig. 3(b) shows the corresponding round-trip gain spectrum $G_{\rm th}(\lambda)$ at threshold, as given by Eq. (5). The reflection spectrum $R_2(\lambda)$ shows several peaks, one of which is at the desired wavelength λ_0. The steep increase in R_2 for wavelengths longer than 840 nm is due to reflection at the end of the grating (R_3) and the relatively low absorption at these wavelengths near the band edge. At these wavelengths, however, the gain section does not provide significant gain, so lasing is excluded [Fig. 3(b)]. The peak in R_2 at the shorter wavelengths ($\lambda \simeq 700$ nm) corresponds to reflection at the beginning of the grating, where propagation in the grating before reflection is very short, so that no strong absorption is encountered. The wavelength dependence of the gain in the gain section is used to discriminate against this peak. The small peaks at $\lambda \simeq 795$ nm and $\lambda \simeq 815$ nm correspond to the wavelength region of maximal gain in region $T(\lambda_0)$. Again the gain section can discriminate against these peaks.

The length L_g of the gain section is restricted by the following limits. If the gain section is too short, the high threshold gain requires a pumping level in the gain section for which discrimination against the shortest wavelengths is not possible. At these pumping levels the gain spectrum shows increasing gain for decreasing wavelengths [Fig. 2: curve (a)]. If the gain section is too long, the gain spectrum corresponding to threshold at the desired wavelength shows so much gain at $\lambda \simeq 795$ nm and $\lambda \simeq 815$ nm, that their round-trip gain is higher than 1. Therefore, discrimination against these longer wavelengths is lost. Calculations for different gain section lengths L_g showed that there is a wide

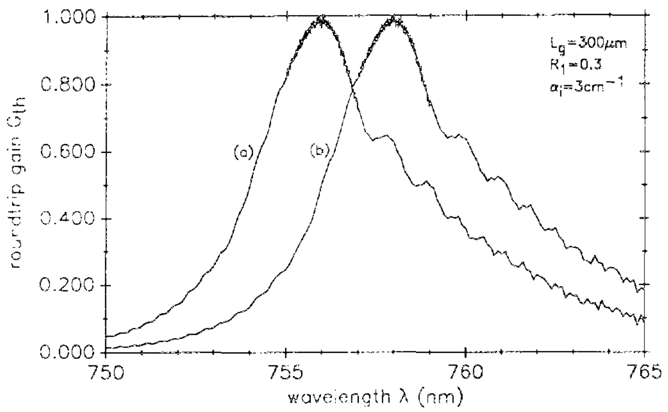

FIG. 4. Round-trip gain spectrum at threshold for two different tuning wavelengths λ_0: (a) $\lambda_0 = 756$ nm and (b) $\lambda_0 = 758$ nm.

range, $200\ \mu m < L_g < 500\ \mu m$, for which lasing will occur only at the desired wavelength.

Tuning can be achieved by changing the length of region $T(\lambda_0)$ and by adjusting its pumping level to transparency at the desired wavelength. Figure 4 shows the round-trip gain $G_{th}(\lambda)$ at threshold ($R_1 = 0.3$, $L_g = 300\ \mu m$, $\alpha_i = 3$ cm^{-1}) for two different tuning wavelengths, (a) $\lambda_0 = 756$ nm and (b) $\lambda_0 = 758$ nm. Curve (a) is an expanded portion of Fig. 3(b), while curve (b) is obtained by increasing the length of region $T(\lambda_0)$ by $50\ \mu m$ (which could be the length of one of the multiple contacts) and by adjusting the pumping level to transparency at $\lambda = 758$ nm. The peak is shifted by 2 nm corresponding to the change in Bragg wavelength over $50\ \mu m$ along the chirped grating. The two peaks are clearly resolved, indicating that tuning is possible.

In conclusion, a novel scheme for a tunable semiconductor waveguide reflection filter, combining an active chirped grating and inhomogeneous pumping, has been introduced. This new scheme (ACF) was considered as a tunable reflector for a monolithic tunable semiconductor laser, allowing for tuning over the entire bandwidth of the gain medium. The optical field in the ACF was calculated using the coupled mode formalism and theoretical gain spectra for a single QW structure. The resulting reflection spectrum of the ACF and the round-trip gain spectrum at threshold were presented. It was shown that lasing occurs at the desired wavelength and that tuning of this wavelength over a wide range seems possible. Other scenarios of inhomogeneous current pumping of the ACF, leading to multiple wavelength oscillation and to wavelength switching, are easily suggested and will be considered.

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