Merz, A. C. Gossard, and L. A. Coldren, *IEEE Photon. Technol. Lett.*, vol. 3, p. 585, 1991.
[11] P. K. York, K. J. Beernink, G. E. Fernandez, and J. J. Coleman, *Appl. Phys. Lett.*, vol. 54, p. 499, 1989.
[12] K. M. Dzurko, E. P. Menu, C. A. Beyler, J. S. Osinski, and P. D. Dapkus, *Appl. Phys. Lett.*, vol. 54, p. 105, 1989.
[13] K. M. Dzurko, E. P. Menu, C. A. Beyler, J. S. Osinski, and P. D. Dapkus, *IEEE J. Quantum Electron.*, vol. 25, p. 1450, 1989.
[14] C. Shieh, J. Mantz, H. Lee, D. Ackley, and R. Engelmann, *Appl. Phys. Lett.*, vol. 54, p. 2521, 1989.
[15] W. Rideout, B. Yu, J. LaCourse, P. K. York, K. J. Beernink, and J. J. Coleman, *Appl. Phys. Lett.*, vol. 56, p. 706, 1990.
[16] K. J. Beernink, J. J. Alwan, and J. J. Coleman, *Appl. Phys. Lett.*, vol. 58, p. 2076, 1991.
[17] P. K. York, C. J. Kiely, G. E. Fernandez, J. N. Baillargeon, and J. J. Coleman, *J. Crystal Growth*, vol. 93, p. 512, 1988.
[18] T. R. Chen, Y. H. Zhuang, W. K. Marshall, Y. J. Xu, and A. Yariv, *IEEE Photon. Technol. Lett.*, vol. 3, p. 694, 1991.
[19] Y. Zou, P. Grodzinski, J. S. Osinski, and P. D. Dapkus, *Appl. Phys. Lett.*, vol. 58, p. 717, 1991.

Long-Wavelength InGaAsP/InP Distributed Feedback Lasers Incorporating Gain-Coupled Mechanism

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Abstract—**We demonstrate successful operation of long-wavelength InGaAsP low-threshold-current gain-coupled DFB lasers. This is accomplished by using a InGaAsP quaternary grating that absorbs the DFB emission. The amount of gain (loss)-coupling is controlled by the composition (bandgap) and thickness of the grating quaternary, and the InP-spacer layer between the grating and the active layer. With optimally designed lasers, CW threshold currents were 10–15 mA (250 μm cavity, as-cleaved), slope efficiency of ~0.4 mW/mA (both facets) and SMSR was as high as 52 dB. The laser operated in the same DFB mode with SMSR staying ~50 dB throughout the entire current range. At 100°C, the CW threshold current stayed low, ~50 mA, and SMSR was ~40 dB. Results also indicate that the presence of gain-coupling removes the degeneracy in lasing wavelength.**

THE oscillation wavelength degeneracy at the edges of the Bragg reflection band is a major problem in index-couples DFB [1]–[5] lasers. One solution to this problem is the use of antireflection/high-reflection (AR/HR)-coated facets. This, however, causes a yield problem associated with the uncertainty of the facet phases [1]. Another solution is the incorporation of a $\lambda/4$ or corrugation-pitch modulated phase shift [2], [3], [6]. For perfect AR coatings, these lasers show a high yield, while deteriorating rapidly for reflectivities only a few percent [2]. Other drawbacks include that half of the power practically being wasted from the back facet and the high spatial hole burning caused by the $\lambda/4$ phase shift [3] (this is reduced by the corrugation-pitch modulation scheme [6]). The high-spatial hole burning gives rise to optical nonlinearity in the light-current (L-I) curves, increased spectral linewidth, and a less flat frequency-modulation response.

An alternative approach is the introduction of gain coupling [5], [7], [8]. Purely gain-coupled lasers theoretically should have one lasing mode exactly at the Bragg wavelength for AR-coated facets, thereby solving the degeneracy problem [5]. It is shown theoretically [9], [10] that even a small degree of gain coupling enhances the performance considerably in terms of threshold gain difference (side-mode-suppression ratio) and removes the degeneracy of an AR-coated DFB laser. Moreover, a complete elimination of spatial hole burning is possible [10]. This, in turn, will further increase the laser yield. For non-AR-coated lasers, it is shown [11], [12] that there is a relevant improvement in yield even for a small amount of gain coupling. In addition, results also show a potential for lower feedback sensitivity compared to other DFB lasers [13]. The validity of the gain-coupled approach for semiconductor DFB lasers has been demonstrated recently in GaAs/AlGaAs lasers [7], [8]. Very recently, 1.5 μm gain-coupled DFB lasers were also demonstrated using varying active layer thickness [14] and in AlGaInAs systems [15]. In this letter, we propose and demonstrate the use of loss-coupled (since the resultant effect is a periodic gain modulation, we will refer in the following as gain-coupled in accordance with the convention) InGaAsP quaternary grating for long wavelength DFB lasers. The amount of gain-cou-

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pling coefficient κ_g is controlled by the composition (bandgap) of the grating quaternary chosen.

In Fig. 1, we show schematically the proposed DFB laser structure. As an illustrative example, a 1.5-μm InGaAs/InGaAsP multiquantum well (MQW) with a InGaAsP quaternary grating is shown. The grating grooves have etched through the InGaAsP layer to form isolated InGaAsP grating lines buried in InP. This yields the largest possible gain modulation since the burying InP is lossless. To fabricate this, a uniform layer of 20 nm n-type InGaAsP (bandgap wavelength $\lambda = 1.56$ μm, for convenience, it will be referred to as $Q_{1.56}$) was grown on a 2-in diameter (100)-oriented n-InP substrate capped by a 5-nm InP top layer. This ensures that there is optical absorption at the lasing wavelength, 1.55 μm. Other alloy compositions have also been tried in order to adjust the amount of optical absorption independent of the grating thickness. It is a concern that too much absorption many cause self-pulsation, although we have not verified this. Our present lasers do not show self-pulsation behavior. It has been shown previously that the present CBE system is capable of producing layers having a thickness uniformity of $\leq \pm 1\%$ and a photoluminescence (PL) peak wavelength uniformity of $\leq \pm 5$ nm (as good as ± 1.5 nm) [16], [17]. Recent results from other research groups also obtained thickness variations $\leq 0.75\%$ and bandgap wavelength variations of InGaAsP quaternaries $\leq \pm 1$ nm over 3-in diameter wafers with CBE [18]. First-order gratings were prepared by standard holographic techniques and wet etching, and had an amplitude of ~ 50 nm. No precise grating depth control was exercised here as long as the QW's were completely etched through. After cleaning, the sample was reintroduced into the CBE system for MQW laser regrowth. The substrate was heated up to $\sim 545°$C under phosphorus over-pressure from precracked phosphine (PH_3). Under such low-temperature conditions, no grating erosion was observed. The detailed shape of the grating was well preserved as examined by the transmission electron microscopy (TEM). An n-type InP spacer layer of the desired thickness (65 nm in the present laser) was grown. The thickness of this layer will also affect the value of both the index- and the gain-coupled coefficients. Because the $Q_{1.56}$ is thin and the top surface is capped with InP layer, subsequent regrowth of InP over such a grating is essentially the same as growing InP on InP. This makes regrowth over grating a trivial task and guarantees defect-free as examined by TEM. This was then followed by the standard strained-layer 6-QW separate confinement heterostructure (SCH). The quaternary, $Q_{1.25}$, waveguide layers were 52.2 nm each. The strained-layer $In_{0.6}Ga_{0.4}As$ QW's and $Q_{1.25}$ barriers were 5 and 18.6 nm, respectively. In these experiments, all-vapor-sources were used including the p- and n-type dopants [19]. Diethylzinc and tetraethyltin were employed as the p- and n-type doping sources, respectively. These laser wafers were further processed into buried heterostructure employing MO-VPE regrowth of Fe-doped InP at 630°C.

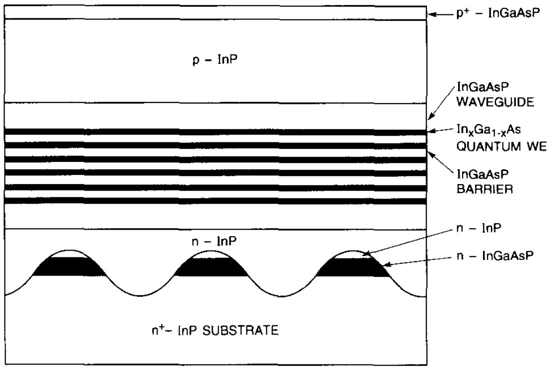

Fig. 1. A schematic diagram of the MQW DFB laser structure with a bottom buried loss-coupled quaternary grating.

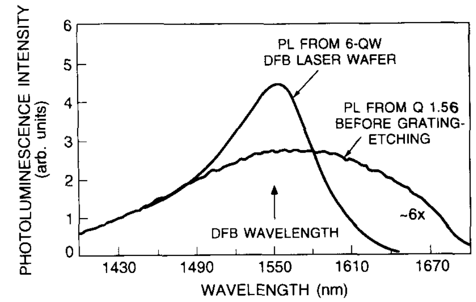

Fig. 2. The photoluminescence spectra from the grating $Q_{1.56}$ measured before grating-etching and the 6-QW $In_{0.6}Ga_{0.4}As/Q_{1.25}$ active-layer DFB laser wafer after regrowth over the $Q_{1.56}$ grating.

In Fig. 2, we show photoluminescence (PL) spectrum of the grating $Q_{1.56}$ measured before grating-etching together with the PL spectrum from the 6-QW $In_{0.6}Ga_{0.4}As$(5nm)/$Q_{1.25}$(18.6 nm) active-layer DFB laser wafer after regrowth over the $Q_{1.56}$ grating. It is seen that optical absorption has extended well beyond 1550 nm. This suggests that the present $Q_{1.56}$ grating will produce a gain-coupled component in addition to the index-coupled component due to index refraction difference between InP and $Q_{1.56}$. It is important to point out that this index refraction difference increases as the quaternary bandgap decreases. Thus, thinner quaternary layer is needed for the same index refraction difference. This facilitates the regrowth over the grating.

The resulting DFB lasers (250 μm long cavity and both facets as-cleaved) operated at 1.55 μm with CW threshold currents 10–15 mA and slope efficiences up to 0.4 mW/mA (both facets). Side-mode suppression ratios (SMSR) as high as 52 dB have been obtained in as-cleaved lasers without facet coatings. These performance values are among the best DFB lasers. A typical light-current characteristic is shown in Fig. 3. The inset shows the spectrum obtained at output power of ~ 20 mW/facet. A very large SMSR of 52 dB was obtained. The laser operated in the same DFB mode with SMSR above 45 dB starting above threshold and stayed at ~ 50 dB throughout the entire current range as shown in Fig. 4. No mode jumps were observed in the threshold crossing. For comparison, the SMSR is also shown for a similar structure as described in [20] but with purely index-coupled DFB laser ($\kappa L \sim 2$). It is important to point out that of the seven lasers CW-bonded for checking the spectra, all have

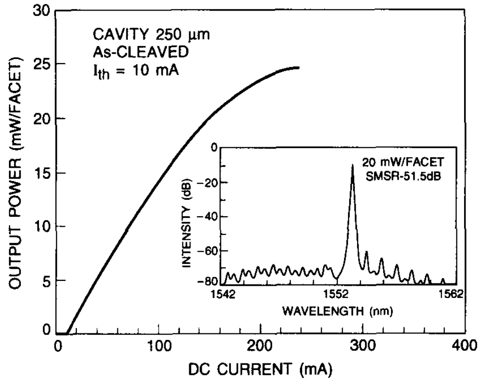

Fig. 3. The light-current characteristic of a typical as-cleaved CBE-grown buried heterostructure gain-coupled MQW DFB laser. The inset shows the spectrum obtained at an output power of ~20 mW/facet. A SMSR of 52 dB was measured.

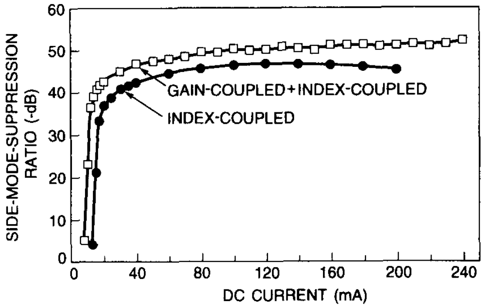

Fig. 4. The SMSR as a function of injection current for a 1.5 µm wavelength gain-coupled and an index-coupled DFB laser.

the same single DFB mode (the longer wavelength one). Since the $Q_{1.56}$ grating segments have higher refractive index and are optically absorbing, the Bragg mode, which has its standing-wave peaks aligned with these $Q_{1.56}$ segments will suffer more loss and has a shorter wavelength than the other Bragg mode which aligns with the InP troughs of the grating. This explanation is consistent with our experimental observation. Although this result is rather preliminary, it appears to agree with the theoretical expectation that even a small degree of gain coupling enhances the performance considerably in terms of threshold gain difference, and removes the degeneracy. Our estimated κ_g is ~ 4 cm^{-1} using an absorption loss of $\sim 2 \times 10^4$ cm^{-1} for $Q_{1.56}$. The κ_i is less than ≤ 50 cm^{-1}. Furthermore, the present lasers showed that with optimal design, the presence of the loss-coupled grating did not noticeably increase the threshold currents. In fact, the threshold currents are quite similar to index-coupled DFB lasers obtained previously [20].

We also investigated the device performance as a function of heat-sink temperature. Keeping the operating current constant, the SMSR and lasing wavelength were measured as a function of temperature. The DFB laser stayed stably in the same DFB mode and with high SMSR even at high temperatures (100°C checked here). Fig. 5 shows an example with the operating current maintained at 160 mA. SMSR decreased from 52 dB at 20°C to 41 dB at 100°C, while the lasing wavelength increased at a rate of 0.095 nm/°C. The threshold-temperature dependence coefficient T_o is ~ 80 K between 20-40°C. At 100°C, the CW threshold current is still very low, 50 mA. As measured previously, the temperature behavior of DFB lasers depends on the relative position of the DFB mode with respect to the gain peak. A detailed discussion can be found in [21]. For actual system applications, antireflection/high-reflection (AR/HR) coatings are needed in order to increase the slope efficiency and the output power from the output facet. It will also improve the high-temperature operation of the diode.

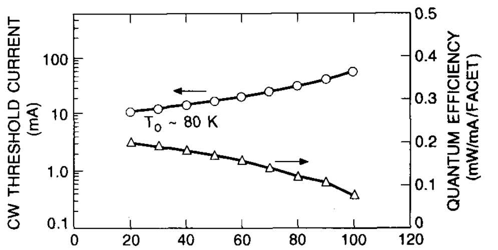

Fig. 5. The SMSR and lasing wavelength were measured as a function of temperature keeping the operating current constant at 160 mA.

In summary, we have demonstrated successful operation of long wavelength InGaAsP low threshold-current gain-coupled DFB lasers. This is accomplished by using a InGaAsP quaternary grating that absorbs the DFB emission. The amount of gain (loss)-coupling is controlled by the composition (bandgap) and thickness of the grating quaternary, and the InP spacer layer between the grating and the active layer. With optimally designed lasers, CW threshold currents were 10-15 mA (250 µm cavity, as-cleaved), slope efficiency of ~0.4 mW/mA (both facets) and SMSR was as high as 52 dB. The laser operated in the same DFB mode with SMSR staying ~50 dB throughout the entire current range. At 100°C, the CW threshold current stayed low, ~50 mA, and SMSR was ~40 dB. Results also indicate that the presence of gain-coupling removes the degeneracy in lasing wavelength.

REFERENCES

[1] J. Buss, "Mode selectivity in DFB lasers with cleaved facets," *Electron. Lett.*, vol. 21, pp. 179-180, 1985.

[2] J. Kinoshita and K. Matsumoto, "Yield analysis of SML DFB lasers with an axially-flattened internal field," *IEEE J. Quantum Electron.*, vol. 25, pp. 1324-1332, 1989.

[3] H. Soda, Y. Kotaki, H. Sudo, H. Ishikawa, S. Yamakoshi, and H. Imai, "Stability in single longitudinal mode operation in GaInAsP/InP phase-adjusted DFB lasers," *IEEE J. Quantum Electron.*, vol. 23, pp. 804-814, 1987.

[4] K. David, G. Morthier, P. Vankwikelberge, R. G. Baets, T. Wolf, and B. Borchert, "Gain-coupled DFB lasers versus index-coupled and phase-shifted DFB lasers: A comparison based on spatial hole burning corrected yield," *IEEE J. Quantum Electron.*, vol. 27, pp. 1714-1724, 1991.

[5] H. Kogelnik and C. V. Shank, "Coupled-wave theory of DFB lasers," *J. Appl. Phys.*, vol. 43, pp. 2327-2335, 1972.

[6] M. Okai, T. Tsuchiya, K. Uomi, N. Chinone, and T. Harada, "Corrugation-pitch modulated MQW-DFB lasers with narrow spectral width," *IEEE J. Quantum Electron.*, vol. 27, pp. 1767-1772, 1991.

[7] Y. Luo, Y. Nakano, K. Tada, T. Inoue, H. Hosomatsu, and H. Iwaoka, "Fabrication and characteristics of gain-coupled DFB lasers with a corrugated active layer," *IEEE J. Quantum Electron.*, vol. 27, pp. 1724-1731, 1991.
[8] ——, "Purely gain-coupled DFB laser," *Appl. Phys. Lett.*, vol. 56, pp. 1620-1622, 1990.
[9] E. Kapon, A. Hardy, and A. Katzir, "The effects of complex coupling coefficients on DFB lasers," *IEEE J. Quantum Electron.*, vol. 18, pp. 66-71, 1982.
[10] G. Morthier, P. Vankwikelberge, K. David, and R. Baets, "Improved performance of AR-coated DFB lasers by the introduction of gain-coupling," *IEEE Photon. Technol. Lett.*, vol. 2, pp. 170-172, 1990.
[11] K. David, G. Morthier, P. Vankwikelberge, and R. Baets, "Yield analysis of non-AR-coated DFB lasers with combined index and gain coupling," *Electron. Lett.*, vol. 26, pp. 238-239, 1990.
[12] Y. Nakano, Y. Luo, and K. Tada, "Facet reflection independent, single longitudinal mode oscillation in a GaAlAs/GaAs DFB laser equipped with gain-coupling mechanism," *Appl. Phys. Lett.*, vol. 55, pp. 1606-1608, 1989.
[13] Y. Nakano, Y. Deguchi, K. Ikeda, Y. Luo, and K. Tada, "Reduction of excess intensity noise induced by external reflection in a gain-coupled DFB laser," *IEEE J. Quantum Electron.*, vol. 27, pp. 1732-1735, 1991.
[14] T. Inoue, S. Nakajima, T. Oki, H. Iwaoka, Y. Nakano, and K. Tada, "High-performance InGaAsP/InP Gain-coupled DFB laser," presented at 17th European Conf. Opt. Comm., Paris, France, 1991, post-deadline paper 5.
[15] B. Borchert, K. David, B. Stegmuller, R. Gessner, M. Beschorner, D. Sacher, and G. Franz, "1.55 μm gain-coupled quantum well DFB with high single-mode yield and narrow linewidth," *IEEE Photon. Technol. Lett.*, vol. 3, pp. 953-955, 1991. During the reviewing process of our manuscript, this reference appears in print.
[16] T. K. Koch, P. J. Corvini, U. Koren, and W. T. Tsang, "Wavelength uniformity of 1.3 μm GaInAsP/InP distributed Bragg reflector lasers with hybrid beam/vapour epitaxial growth," *Electron. Lett.*, vol. 24, pp. 822-823, 1988.
[17] W. T. Tsang, M. C. Wu, T. Tanbun-Ek, R. A. Logan, S. N. G. Chu, and A. M. Sergent, "Low threshold and high power output 1.5 μm InGaAs/InGaAsP separate confinement multiple quantum well lasers grown by CBE," *Appl. Phys. Lett.*, vol. 57, pp. 2065-2067, 1990.
[18] H. Heinecke, B. Baur, N. Emeis, and M. Schier, "Growth of highly uniform InP/GaInAs/GaInAsP heterostructure by CBE for device integration," 3rd Internat. Conf. Chemical Beam Epitaxy, Oxford, UK, paper D3 1991.
[19] W. T. Tsang, F. S. Choa, R. A. Logan, T. Tanbun-Ek, and A. M. Sergent, "All-gaseous doping during chemical beam epitaxial growth of InGaAs/InGaAsP multi-quantum well lasers," *Appl. Phys. Lett.*, vol. 59, pp. 1008-1010, 1991.
[20] W. T. Tsang, F. S. Choa, M. C. Wu, Y. K. Chen, R. A. Logan, T. Tanbun-Ek, S. N. G. Chu, K. Tai, A. M. Sergent, and K. W. Wecht, "1.5 μm wavelength InGaAs/InGaAsP distributed feedback multi-quantum well lasers grown by chemical beam epitaxy," *Appl. Phys. Lett.*, vol. 59, pp. 2375-2377, 1991.
[21] W. T. Tsang, N. A. Olsson, and R. A. Logan "Threshold-wavelength and threshold-temperature dependences of GaInAsP/InP lasers with frequency selective feedback operating in the 1.3- and 1.5-μm regions," *Appl. Phys. Lett.*, vol. 43, pp. 154-156, 1983.

5.5-mm Long InGaAsP Monolithic Extended-Cavity Laser with an Integrated Bragg-Reflector for Active Mode-Locking

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***Abstract*—We have fabricated a 5.5-mm long monolithic extended-cavity laser with an integrated Bragg-reflector in the InGaAsP system for active mode-locking at low repetition rates at a wavelength of 1.55 μm. The device, which is designed to be employed as a pulse source in long-distance soliton systems and optical time division multiplexed systems, generates 20-ps wide transform-limited pulses with a time-bandwidth product of 0.34 at a repetition rate of 8.1 GHz.**

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ULTRALONG distance soliton transmission experiments have emphasized the need for a reliable and stable pulsed laser source to generate transform-limited pulses at repetition rates of 2-10 GHz with squared hyperbolic secant (sech^2) shape. Actively mode-locked external cavity lasers, which are typically used as the source for soliton demonstrations, suffer in their performance due to mechanical instabilities and poor intra cavity coupling efficiency which accompany bulk-optic or hybrid designs. Recent advances in monolithic integration techniques have resulted in the fabrication of several long cavity mode-locked lasers [2]-[6]. All of the

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