where $q$ is the external quantum efficiency, $\lambda$ the absorbed wavelength, $e$ the elementary charge, $J_0$ the dark current density, $h$ the Planck constant and $c$ the speed of light in a vacuum. Our results at $V = -0.5$ V for the best diodes give $D^* (\lambda = 2.2 \mu m) = 8 \times 10^{-18}$ cm Hz$^{1/2}$/W$^{-1}$ at room temperature. This value is quite comparable to detectivity evaluation from the noise measurements of Srivastava et al.$^4$

A great improvement in device performance is obtained when the photodiode is cooled. As an example, at 200 K, which is the lowest temperature attainable using a Peltier cooling system, the dark current density is reduced to $\sim 20 pA$ at -0.5 V, leading to a calculated detectivity $D^* (\lambda = 2.1 \mu m)$ as high as $2 \times 10^{12}$ cm Hz$^{1/2}$/W$^{-1}$.

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References


14. DYNAMIC SPECTRAL BROADENING IN DIGITALLY MODULATED LASERS

Indexing terms: Semiconductor lasers, Modulation

It is demonstrated that GaInAs/GaInP modulated, voltage controlled singlemode multiple quantum well semiconductor lasers with an intracavity saturable absorber show reduced spectral broadening compared to conventional high contrast modulation schemes. The intracavity loss modulated laser linewidth is also calculated using experimentally determined voltage and intensity dependence of absorption in MQW modulators and excellent agreement with experiment is found.

Data rates and transmission distances for lightwave systems that use digital (on-off) or higher order modulations are limited by dynamic spectral broadening which inevitably accompanies carrier density variation during laser switching. Constraints placed on optical transmission systems operating at the fibre attenuation minimum, $z = 1.5$ $\mu$m, by dispersion in standard singlemode optical fibre (~15 ps/km nm) have resulted in considerable efforts to design narrow linewidth 1.5-$\mu$m multiple quantum well (MQW) distributed feedback (DFB) lasers. A complementary approach has been presented by Srivastava et al.\(^4\), using standard semiconductor laser parameters and recently determined data for the voltage and intensity dependence of absorption saturation in InGaAs/InP MQW structures.\(^6\)

In this Letter, we present a simple model of MQW-DFB lasers operating at wavelength $\lambda = 1.52$ $\mu$m, where experimental results are compared with those obtained using $n$- and $p$-layer structures. The lasers were modulated with a 100 MHz modulation of the $n$-layer carrier density, resulting in reduced spectral broadening in comparison to direct or (drive) current modulation. We also calculate the spectrum for each modulation scheme with a rate equation model, using standard semiconductor laser parameters and recently determined data for the voltage and intensity dependence of absorption saturation in InGaAs/InP MQW structures.

The laser structures used to investigate spectral broadening under GaInAs modulated InGaAs/InP buried heterostructures (BH) MQW DFB lasers grown by metal organic vapour phase epitaxy (MOVPE) on semi-insulating InP substrate. After crystal growth, BH lasers were formed by mesa stripe etching, reduction of the width of the active region using a selective etch and finally regrowth of semi-insulating InP, again using MOVPE. Front-side electrical contact to the $n$- and $p$-layers was achieved using standard metallisation techniques, resulting in DFB lasers with intracavity loss modulators, shown schematically in Fig. 1. To ensure fair comparison between modulation schemes, the experimental parameters were set so that, averaged, $\sim 2$ $\mu$m of available power was switched in each case. Furthermore, to generate the greatest spectral broadening, the lasers were modulated with a ...101... bit pattern.

Fig. 1 Schematic diagram of intracavity loss modulated DFB laser

Laser gain section is pumped with constant current $I_L$ and laser output is controlled by voltage $V_i$ applied across 920 $\Omega$ resistor across high impedance, small absorber section $S$. Conventionally operated laser may be recovered by connecting absorber section to gain section.
In Fig. 2 we show the measured optical spectrum of an intracavity loss modulated laser for a gain section current \( I_g = 45 \text{ mA} \) when a \( -0.2 \leq V_s \leq 1.5 \text{ V} \) at 1000 MHz. A beam stream at 1 Gbit/s is applied to the absorber section S. The gain section current is \( I_g = 45 \text{ mA} \) and \( \lambda_0 = 1.52 \mu\text{m} \). Also indicated is a 10 expanded view, showing short wavelength extended to short wavelength side of spectrum. Deconvolved spectral width is \( 0.2 \text{ A} \) FWHM.

![Graph](image1)

**Fig. 2** Experimental time averaged optical spectra observed when \(-0.2 \leq V_s \leq 1.5 \text{ V} \) at 1000 MHz. A beam stream at 1 Gbit/s is applied to the absorber section S. Deconvolving the resolution of the scanning Fabry–Perot interferometer \((0.3 \text{ A})\), the full width at half maximum (FWHM) of the laser emission is \( \beta L = 0.2 \text{ A} \). Also indicated is a 10 expanded view of the spectrum which shows a 4 A wide, low intensity pedestal extending to the short wavelength side of the laser line. The peak to pedestal intensity ratio is \( 80 \), and is due to large carrier density changes accompanying a pronounced overshoot in the optical intensity which is characteristic of laser Q switching. We note that, for \( I_g = 60 \text{ mA} \), the switched optical power increases to 4 mW/facet and the peak to pedestal intensity ratio is \( 800 \) (i.e., \( < -23 \text{ dB} \)), giving a 20 dB linewidth of \( < 3 \text{ A} \).

Fig. 3 shows a calculation of the integrated optical spectrum using a singlemode rate equation model of an intracavity loss modulated laser. We use an expression for the intensity and voltage dependence of absorption derived from recent experimental data on absorption in InGaAs/InP MQW structures. We model the voltage and intensity dependence of the absorber section and the absorption coefficient by

\[
\alpha(V_s) = \frac{\alpha_0 + \alpha_1 V_s + \alpha_2 V_s^2}{1 + I_g I(V_s)}
\]

\( \alpha_0 + \alpha_1 V_s \) describes the threshold photon extraction efficiency of the absorber section and \( \alpha_2 V_s^2 \) is the voltage dependent low intensity absorption in the quantum wells. In the reverse bias regime, changes in the depletion width of the absorber region with increasing bias result in the electric field applied across the quantum wells varying sub-

![Graph](image2)

**Fig. 3** Calculated time averaged spectrum of intracavity loss modulated laser.

and, in our approximate model, \( F(V_s) = \left[e^{\pi V_s/\lambda} + 1\right]^{-1} \) allows for a continuous and rapid reduction in saturation intensity under high charge carrier injection \( (V_s \gtrsim 0 \text{ V}) \). We calculate the laser dynamic response with a rate equation model, using an effective absorber segment length, \( L_a = 15 \mu\text{m} \), normalising the total modulator power \( = a(V_s, I) \), to the laser cavity length \( L_c \) and mirror \( \alpha_m \) and internal losses \( \alpha_{in} \). Spectral broadening is calculated assuming a linear dependence of refractive index \( \mu \) on carrier density \( n \), and confinement factor \( \Gamma, \) i.e. \( \rho_d \mu \Delta n \rightarrow \Gamma \rho \Delta n \). The result of our calculation (see Table 1 for parameter values), using otherwise standard laser parameters, shows excellent agreement with the experimental spectra, in both the magnitude and shape of the spectral broadening and the peak to pedestal intensity ratio.

### Table 1: Parameters Used to Model Voltage Controlled, Singlemode BH Grinsch MQW InGaAs/InP Laser Diode

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_1 )</td>
<td>227^{-1} cm^{-1}</td>
</tr>
<tr>
<td>( a_2 )</td>
<td>-725^{-1} cm^{-1} V^{-1}</td>
</tr>
<tr>
<td>( a_3 )</td>
<td>420^{-1} cm^{-1} V^{-2}</td>
</tr>
<tr>
<td>( a_4 )</td>
<td>672^{-1} cm^{-1} V^{-1}</td>
</tr>
<tr>
<td>( a_5 )</td>
<td>15^{-1} cm^{-1}</td>
</tr>
<tr>
<td>( \eta )</td>
<td>4.5</td>
</tr>
<tr>
<td>( \Gamma )</td>
<td>48^{-1} cm^{-1}</td>
</tr>
<tr>
<td>( \mu_0 )</td>
<td>48^{-1} cm^{-1}</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>24^{-1} cm^{-1}</td>
</tr>
<tr>
<td>( L_{q,1} )</td>
<td>170^{-1} cm^{-1} kV cm^{-1}</td>
</tr>
<tr>
<td>( L_{q,2} )</td>
<td>15^{-1} cm^{-1}</td>
</tr>
<tr>
<td>( \Gamma )</td>
<td>500^{-1} cm^{-1}</td>
</tr>
<tr>
<td>( \mu_0 )</td>
<td>1^{-1} \times 10^{-21} cm^{-3}</td>
</tr>
<tr>
<td>( \rho_0 )</td>
<td>4.5</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>1.5 \mu m</td>
</tr>
</tbody>
</table>

We have also measured the optical spectrum of an MQW DFB laser when digitally (on-off) current modulated with a 1 Gbit/s ... 1000 MHz beat pattern (Fig. 4). To achieve the high optical intensity contrast ratio required for digital transmission, the laser is switched from below to above threshold. The applied bias current \( I_g = 14 \text{ mA} \) and modulation current \( I_m = 20 \text{ mA} \) were chosen so that the average switched power \(~2 \text{ mW/facet}\) is similar to the intracavity loss modulated case. The deconvolved FWHM of the laser emission \( \beta L = 1 \text{ A} \) is clearly far broader than that observed in the intracavity loss modulated case. Furthermore, a pronounced peak to shoulder ratio \(~4 \text{ dB} \) spectral feature extends \(~3 \text{ A} \) to the short (blue) wavelength side. The spectrum also shows considerable broadening on the long wavelength (red) side. This clearly shows that significantly greater spectral broadening...
occurs with conventional current modulation than with intracavity loss modulation. In Fig. 5 we show the calculated spectrum for a laser conventionally modulated with a 1-GBits/s data stream. For this calculation, the terms in the

![Fig. 4 Experimental time averaged spectrum for conventionally modulated DBR laser](image)

Applied bias current ($I_a = 14 mA$) and modulation current ($I_m > 20 mA$) were chosen to give similar average switched optical power as in Fig. 2. Spectrum extending pronounced pedestal extending to short wavelength side and large (deconvolved) spectral width of 1.4 A FWHM

![Fig. 5 Calculated time averaged spectrum of conventionally current (directly) modulated laser](image)

Same device parameters are used as in Fig. 3. Photon rate equation describing voltage controlled intracavity loss are set to zero. The agreement with experiment is reasonable. We note that, experimentally, when the bias point was set for above threshold (i.e. on-on) modulation, a broad double peaked spectrum with ~1.8 A peak separation was observed. We also observed for direct laser modulation, when the high frequency electrical signal was improperly terminated, the resulting ringing in the laser intensity also manifested itself by distorting and further broadening the laser spectrum. It is to be noted that the high impedance of a voltage controlled intracavity absorber lends itself to a correctly terminated high frequency electrical load.

In conclusion, we have experimentally investigated spectral broadening occurring in high bit rate, digitally modulated MQW-DFB lasers. We have confirmed our previous suggestion, that intracavity loss modulation of singlemode semiconductor lasers leads to reduced spectral broadening in Gbit/s digitally modulated lasers. We have calculated the laser linewidth using experimental data which characterises the voltage and intensity dependence of absorption in MQW modulators and have found good agreement with experiment.

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ULTRALOW THRESHOLD STRAINED InGaAs-GaAs QUANTUM WELL LASERS BY IMPURITY-INDUCED DISORDERING

**References**

**Indexing terms:** Semiconductor lasers, Lasers

Stripe-geometry strained InGaAs-GaAs quantum well lasers were fabricated by impurity induced disordering. Threshold currents as low as 2.2 mA at room temperature continuous operation (RT CW) were obtained for uncoated lasers having 1.2-µm wide, 710-µm long active stripes. The authors believe that this ultralow threshold is mainly due to the very small active stripe width and the excellent electrical confinement of the laser.

Low threshold current is of essential importance for semiconductor lasers, and continuous efforts have been made toward achieving this low threshold current since the invention of semiconductor lasers. In past years, a number of low-threshold stripe-geometry semiconductor lasers have been developed. Among them, impurity-induced disordering (IID) lasers are attractive because their fabrication procedures are relatively simple and repeatable, and their configurations are planar. The best IID lasers reported so far have threshold current as low as 3 mA for uncoated devices at room temperature continuous (RT CW) operation. However, this number is considerably higher than that of the best buried heterostructure (BH) lasers by second growth, which have threshold current as low as 2.5 mA, the lowest threshold current reported so far for any kind of uncoated stripe-geometry lasers at RT CW operation. Moreover, the BH lasers are much more complicated than those of IID lasers. Therefore, it would be interesting to produce IID lasers that have threshold current equal to or less than that of BH lasers. We report on uncoated IID lasers that have RT CW threshold current as low as $I_{th} = 2.2$ mA, fabricated using a simple selfaligned process.

The material used for the laser fabrication was strained In$_{x}$Ga$_{1-x}$As-GaAs-$Al_x$Ga$_{1-x}$As quantum well (InGaAs-QW)