photovoltaic mode (V ≲ 0). The corresponding detectivity D^* of a heterojunction n^+p photodiode has been evaluated as[13]

$$D^* \simeq \eta\lambda(q/J_0)^{1/2}/(2hc) \qquad (1)$$

where η is the external quantum efficiency, λ the absorbed wavelength, q 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 $V = -0{\cdot}5$ V for the best diodes give D^* ($\lambda = 2{\cdot}2\,\mu$m) $= 8{\cdot}8 \times 10^9$ 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.*[2]

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 $\sim 20\,\mu$A/cm^2 at $-0{\cdot}5$ V, leading to a calculated detectivity D^* ($\lambda = 2{\cdot}1\,\mu$m) as high as 2×10^{11} cm Hz$^{1/2}$ W^{-1}.

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DYNAMIC SPECTRAL BROADENING IN DIGITALLY MODULATED LASERS

Indexing terms: Semiconductor lasers, Modulation

It is demonstrated that Gbit/s digitally 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 high contrast ratio modulation are limited by dynamic spectral broadening which inevitably accompanies carrier density variation during laser switching.[1] The constraints placed on optical transmission systems operating at the fibre attenuation minimum, $\lambda = 1{\cdot}5\,\mu$m, by dispersion in standard singlemode optical fibre (~ 15 ps/km nm) has resulted in considerable efforts to design narrow linewidth $1{\cdot}5\,\mu$m multiple quantum well (MQW) distributed feedback (DFB) lasers.[2,3] A complementary approach, which receives little attention, is to devise modulation schemes which reduce the deleterious effects of linewidth broadening at high bit rates (≥ 1 Gbit/s).[4,5] Previously we suggested that intracavity loss modulation leads to reduced dynamic spectral broadening in comparison to direct (or current) modulation.[6] In this Letter, using singlemode MQW-DFB lasers operating at wavelength $\lambda_0 = 1{\cdot}52\,\mu$m, we experimentally compare spectral broadening resulting from intracavity loss modulation with that resulting from direct or (drive current) modulation. We also calculate the spectrum for each modulation scheme with a rate equation model,[7] using standard semiconductor laser parameters and recently determined data for the voltage and intensity dependence of absorption saturation in InGaAs/InP MQW structures.[8]

The laser structures used to investigate spectral broadening under Gbit/s modulation were InGaAs/InP buried heterostructure (BH) MQW DFB lasers grown by metal organic vapour phase epitaxy (MOVPE) on a ⟨100⟩-oriented n-type InP substrate.[3] 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 Fe-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, on average, ~ 2 mW/facet of optical power was switched in each case. Furthermore, to generate the greatest spectral broadening, the lasers were modulated with a ... 1010 ... bit pattern.

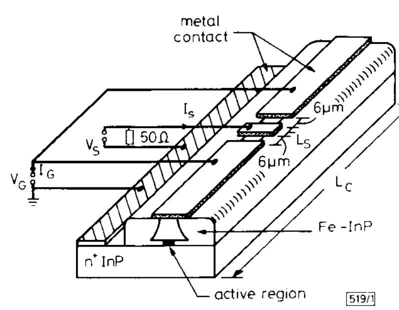

Fig. 1 *Schematic diagram of intracavity loss modulated DFB laser*

Laser gain section is pumped with constant current I_G and laser output is controlled by voltage V_S applied across 50 Ω 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 $I_G = 45$ mA when a ... 1010 ... $-0{\cdot}2\,V \geq V_S \leq 1{\cdot}5\,V$ data

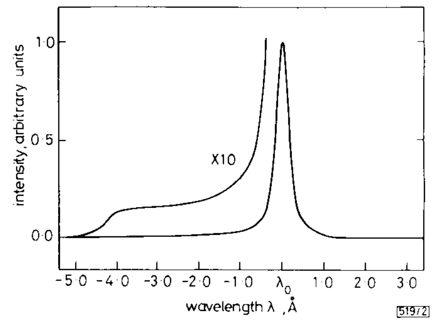

Fig. 2 *Experimental time averaged optical spectra observed when $-0{\cdot}2 < V_S < 1{\cdot}5\,V$ ... 1010 ... bit stream at 1 Gbit/s is applied to absorber section S*

Gain section current is $I_G = 45$ mA and $\lambda_0 = 1{\cdot}52\,\mu m$
Also indicated is × 10 expanded view, clearly showing low intensity pedestal extending to short wavelength side of spectrum
Deconvolved spectral width is $\simeq 0{\cdot}2$ Å FWHM

stream at 1 Gbit/s is applied to the absorber section S. Deconvolving the resolution of the scanning Fabry-Pérot interferometer ($\simeq 0{\cdot}3$ Å), the full width at half maximum (FWHM) of the laser emission is $\delta\lambda = 0{\cdot}2$ Å. Also indicated in Fig. 2 is a × 10 expanded view of the spectrum which shows a 4 Å wide, low intensity pedestal extending to the short (blue) wavelength side of the laser line. The peak to pedestal intensity ratio is ~60, and is due to large carrier density changes accompanying a pronounced overshoot in the optical intensity which is characteristic of laser Q switching.[7] We note that, for $I_G =$ 60 mA, the switched optical power increases to 4 mW/facet and the peak to pedestal intensity ratio is >230 (i.e. < −23 dB), giving a −20 dB linewidth of <3 Å.

Fig. 3 shows a calculation of the integrated optical spectrum using a singlemode rate equation model of an intracavity loss modulated laser.[6,7] We use an expression for the intensity

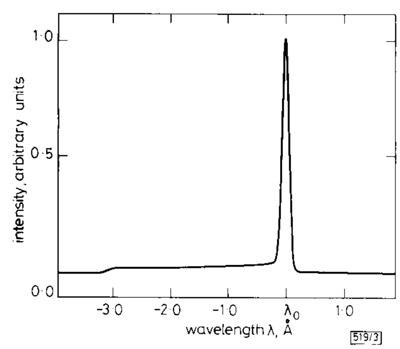

Fig. 3 *Calculated time averaged spectrum of intracavity loss modulated laser*

and voltage dependence of absorption derived from recent experimental data on absorption in InGaAs/InP MQW structures.[8] We model the voltage and intensity dependence of the modulator absorption by

$$\alpha(V_S, I) = \alpha_{US}(V_S) + \frac{\alpha_S^0(V_S)}{[1 + I/I_S(V_S)]} \quad (1)$$

$\alpha_{US}(V_S) = a_1 + a_2 V_S$, describes the above threshold photon extraction efficiency of the absorber section and $\alpha_S^0(V_S)$ 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 sublinearly with V_S. We therefore expect (at least) a quadratic dependence of α_S^0 on V_S. In the forward bias regime, bandfilling due to carrier injection results in an exponential decrease in modulator absorption. Consequently we express α_S^0 as

$$\alpha_S^0(V_S) = a_3 V_S^2 + a_4 V_S + a_5 - a_6 e^{eV_S/\eta kT} \quad (2)$$

where $a_3 - a_6$ are fitted to experimentally determined data.[8] $I_S(V_S)$ is the voltage dependent saturation intensity and is related to low intensity absorption (eqn. 2) by

$$I_S(V_S) = I_{SO} \frac{\alpha_S^0(0)\tau_0}{\alpha_S^0(V_S)\tau(V_S)} F(V_S) \quad (3)$$

I_{SO} is the experimentally determined saturation intensity at $V_S = 0$ V; $\tau(V_S)$ is the voltage dependent carrier lifetime in the MQW, approximated by (see e.g. Reference 9)

$$\tau(V_S) = \tau_0 e^{t_1 \cdot V_S} \quad (4)$$

and, in our approximate model, $F(V_S) = [e^{eV_S/\eta kT} + 1]^{-1}$ allows for a continuous and rapid reduction in saturation intensity under high charge carrier injection ($V_S \gtrsim 0{\cdot}6$ V). We calculate the laser dynamic response with a rate equation model,[7] using an effective absorber segment length, $L_S = 15\,\mu m$, normalising the total modulator loss $= \alpha(V_S, I) \cdot L_S$ to the laser cavity length L_C and mirror α_0 and internal losses α_m. Spectral broadening is calculated assuming a linear dependence of refractive index μ on carrier density n and confinement factor Γ, i.e. $d\mu/dn = -\Gamma\rho$. The result of our calculation (see Table 1 for parameter values), using otherwise standard laser parameters,[6,7] 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

Parameter	Value
a_1	$227{\cdot}0\,cm^{-1}$
a_2	$-725{\cdot}0\,cm^{-1}V^{-1}$
a_3	$42{\cdot}0\,cm^{-1}V^{-2}$
a_4	$672{\cdot}0\,cm^{-1}V^{-1}$
a_5	$19{\cdot}7 \times 10^3\,cm^{-1}$
a_6	$15{\cdot}0\,cm^{-1}$
η	5·5
t_1	$0{\cdot}46\,V^{-1}$
α_0	$48{\cdot}4\,cm^{-1}$
α_m	$24{\cdot}1\,cm^{-1}$
I_{SO}	$17{\cdot}0 \times 10^3\,kW\,cm^{-1}$
L_S	$15{\cdot}0\,\mu m$
L_C	$500{\cdot}0\,\mu m$
Γ_ρ	$-1{\cdot}8 \times 10^{-21}\,cm^3$
μ	4·5
λ	$1{\cdot}52\,\mu m$

We have also measured the optical spectrum of an MQW DFB laser when digitally (on-off) current modulated with a 1 Gbit/s ... 1010 ... bit 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 $I_b = 14$ mA and modulation current $I_m =$ 20 mA, were chosen so that the average switched power (~2 mW/facet) is similar to the intracavity loss modulated case. The deconvolved FWHM of the laser emission $\delta\lambda =$ 1·1 Å is clearly far broader than that observed in the intracavity loss modulated case. Furthermore, a pronounced (peak to shoulder ratio = 4·6) spectral feature extends ~3 Å 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 Gbit/s ... 1010 ... data stream. For this calculation, the terms in the

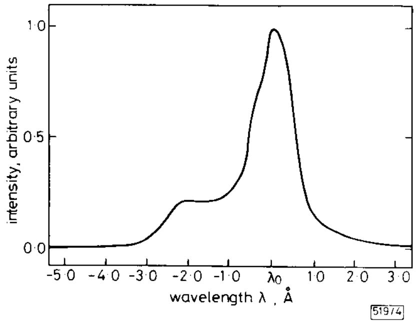

Fig. 4 *Experimental time averaged spectrum for conventionally modulated DFB laser*

Applied bias current ($I_b = 14$ mA) and modulation current ($I_m \simeq 20$ mA) were chosen to give similar average switched optical power as in Fig. 2
Spectrum exhibits pronounced pedestal extending to short wavelength side and large (deconvolved) spectral width of 1·1 Å FWHM

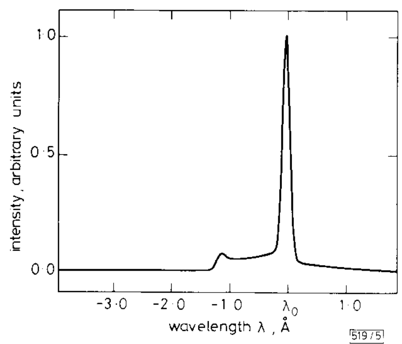

Fig. 5 *Calculated time averaged spectrum of conventionally current (directly) modulated laser*

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 laser bias point was set for above threshold (i.e. on–on) modulation, a broad double peaked spectrum with ~1·8 Å peak separation was observed. We also observed for direct laser mdoulation, 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

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, 215 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.[1–7] 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.[3,5] However, this number is considerably higher than that of the best buried heterostructure (BH) lasers by second growth,[1] 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. Because the second growths were made on wafers having etched ridge structures, the fabrication procedures of such 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 $In_yGa_{1-y}As$–GaAs–$Al_xGa_{1-x}As$ quantum well (InGaAs-QW)