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L. CHUSSEAU
J. M. XIE
L. DUVILLARET
J. M. LOURTIOZ

4th June 1990

Institut d'Electronique Fondamentale, URA 22 du CNRS
Université Paris-Sud, Bâtiment 220
91405 Orsay Cedex, France

A. ACCARD
J-P. HEBERT

Centre de Recherches de la CGE
Route de Nozay
91460 Marcoussis, France

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PASSIVE MODE-LOCKING OF MONOLITHIC InGaAs/AlGaAs DOUBLE QUANTUM WELL LASERS AT 42 GHz REPETITION RATE

Indexing terms: Lasers and laser applications, Semiconductor lasers

Pulse trains with a 42 GHz repetition rate were generated by monolithic InGaAs/AlGaAs double quantum well lasers at a wavelength of 9850 Å. The cavity was electrically divided into three regions, one providing gain and the other two providing saturable absorption. The optical modulation has a depth greater than 98% and full-width at half-maximum under 6 ps, and bias conditions for sustained mode-locking are determined.

Monolithic GaAs/AlGaAs semiconductor lasers have been passively mode-locked at repetition rates around 100 GHz by dividing the cavity into regions of gain and saturable absorption, and pumping the lasers with low-frequency electrical sources.[1,2] Such devices may eventually find applications in communications, synchronisation of optoelectronic systems or as sources for spectroscopy and sampling systems. Great stability in the output will be required and devices with various lasing wavelengths will be necessary. Lasers made from strained InGaAs/AlGaAs double quantum wells can be passively mode-locked to produce pulses at 9850 Å. When the repetition rate is reduced to 42 GHz, by cleaving longer devices, the observed pulse trains are substantially more stable than those from a 108 GHz GaAs/AlGaAs triple quantum well laser.[2]

The laser, illustrated in Fig. 1, is grown by molecular beam epitaxy on an *n*-type GaAs substrate and consists of a 1·5 μm *n*-type $Al_{0.5}Ga_{0.5}As$ cladding layer, the graded index and double quantum well region, a 1·5 μm *p*-type $Al_{0.5}Ga_{0.5}As$

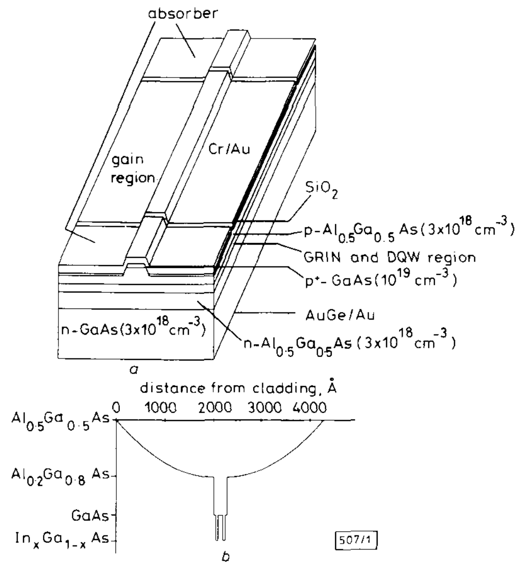

Fig. 1 *Device structure*
a Three-section 42 GHz InGaAs/AlGaAs laser
b Enlargement of graded-index and double quantum well region

layer, and a 2000 Å heavily *p*-doped cap layer. The double quantum well structure consists of two 50 Å InGaAs layers spaced by a 100 Å GaAs barrier, between two 40 Å GaAs layers. Each graded index region is 2000 Å thick.

The laser mesa is formed by etching 3 μm wide stripes to a depth of 1·2 μm. The top metallisation is defined by liftoff, leaving 20 μm gaps between the sections, and electrical isolation of 1 kΩ is effected by etching 7 μm gaps through the cap layer. The gain region is 595 μm long, and the front and rear absorbers are 140 and 180 μm long, respectively. The gain region is driven by 50 μs electrical pulses, while the front absorber is left open-circuited and the rear absorber DC biased through a 100 Ω series resistor, across which the current is measured by sample-and-hold amplifiers while the gain section current is on. Measurements are typically performed 25 μs after the start of the gain section pulse.

The average output power as a function of current is shown in Fig. 2 for two bias conditions. In Fig. 2*a*, all three sections of the laser are driven in parallel, and the threshold current is 28 mA. There is a linear dependence of output power on current above threshold and a differential external quantum efficiency of 60%. When the rear absorber is reverse biased, a light jump ocurs at threshold. At higher gain currents, where the absorber is more saturated, there is another large differen-

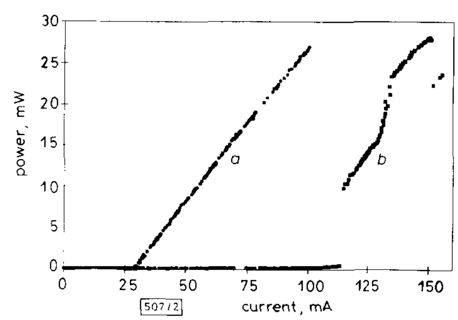

Fig. 2 *Light output against current for three-section laser*
a All three sections connected in parallel
b Centre section pumped, rear absorber with −2·2 V bias through 100 Ω series resistance, front absorber open-circuited

tial increase in light output, after which conditions where passive mode-locking can be observed are reached. At gain section currents above 145 mA, the power drops, and streak camera measurements show self-pulsations.

The output from the front facet is measured using a Hamamatsu C1537 streak camera, with an S-1 photocathode, in its single-shot mode. Fig. 3 shows typical pulse trains near optimum bias conditions on the two fastest streak scales. The

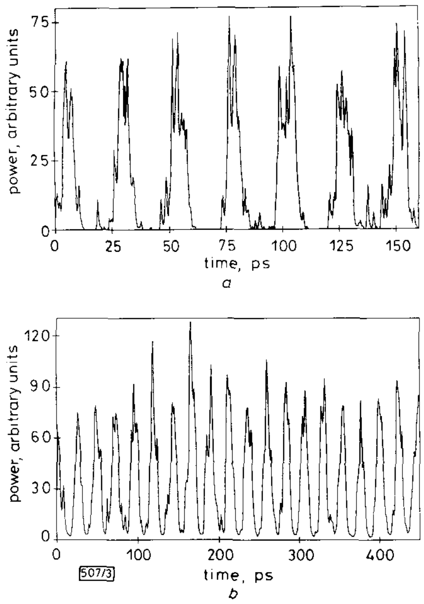

Fig. 3 *Output from front facet*
a Time resolution better than 2 ps
b 450 ps streak

pulsewidths average 5·9 μs and have a 42 GHz repetition rate. The average peak power is estimated to be 80 mW, and the modulation depth exceeds 98%. Integrating under the peaks in Figs. 3*a* and 3*b* gives standard deviations in the pulse energies of 9% and 14%, respectively. Photocathode shot noise can account for about a 3% deviation. Other sources of the variations include lower frequency intensity relaxation oscillations, spontaneous emission noise and inhomogeneities in the streak camera system. Only a small number of pulses are compared, and more accurate noise characterisation will require measurements over longer time periods, possibly using a very fast photodetector and spectrum analyser. The optical spectra were typically very broad, with full-widths at half-maximum of 400 GHz or higher, and centred near 9850 Å.[3]

The ranges of both gain and absorber current where mode-locking is consistently observed are shown in Fig. 4. To perform these measurements, the gain section current is fixed, while the absorber bias is swept in the negative direction. The output is unmodulated or shows some unstable structure at

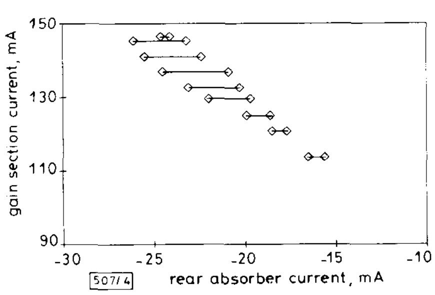

Fig. 4 *Absorber currents for sustained mode-locking at fixed gain section currents*

frequencies near the cavity resonance. At stronger bias, the current flowing out of the absorber continues to increase and the output appears similar to that in Fig. 3. The sustained pulse train remains until the absorber bias is increased to where the laser self-pulsates, at which point the absorber current drops by several milliAmperes. A second laser on the same cleaved bar had almost the same locking ranges. The locking ranges are qualitatively consistent with those predicted from a three mode coupling theory.[4]

Self-sustained pulsation and large relaxation oscillations greatly limit the range of stable passive mode-locking in this and othr devices. A shorter, two-section laser, whose output is shown in Fig. 5, displays a 4 GHz, 80% modulation in the envelope of the mode-locked pulse train, indicating that the modes remain coupled while their amplitudes oscillate. The

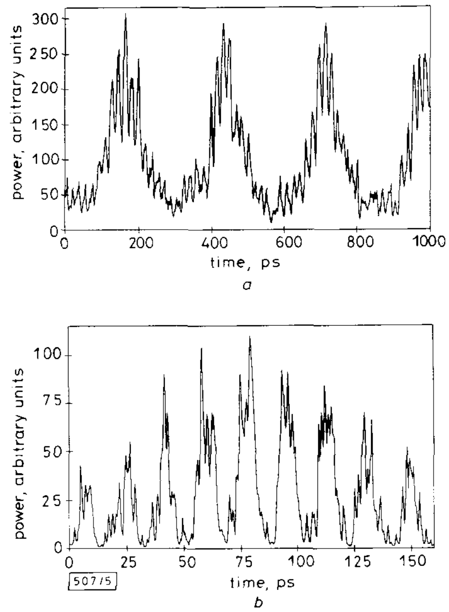

Fig. 5 *Strong 4 GHz modulation of mode-locked pulse amplitudes*
$L_{gain} = 545\,\mu m$; $L_{abs} = 135\,\mu m$; $I_{gain} = 84$ ma; $I_{abs} = -13{\cdot}9$ mA
a 12 ps resolution, 1 nanosecond streak
b 2 ps resolution, 160 ps streak

conditions for self-sustained pulsation and passive mode-locking of inhomogeneously pumped lasers are similar, since lower saturation intensity of the absorption than the gain and short carrier lifetimes in the absorber facilitate both processes.[5,6]

InGaAs/AlGaAs double quantum well lasers have been passively mode-locked at 42 GHz. The output wavelength is centered around 9850 Å, and large current ranges exist where sustained mode-locking is observed. Instabilities in the form of large modulation at a few gigaHertz severely limit the conditions where stable passive mode-locking can be achieved.

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S. SANDERS
L. ENG
A. YARIV

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Department of Applied Physics, 128-95
California Institute of Technology
Pasadena, California 91125, USA

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INFLUENCE OF LEAKAGE CURRENTS BETWEEN ELECTRODES IN TUNABLE DBR-LASERS

Indexing terms: Semiconductor lasers

Wavelength tunable multi-section DBR lasers have been fabricated on a *p*-doped InP substrate by LPE. Maximum output power is 10·5 mW and largest step-wise tuning range is 5·1 nm for a single-sided DBR laser. A double-sided laser has a continuous tuning range of 1·4 nm. It is shown that the low electrical isolation between the top contacts causes lower output power and a significantly larger laser linewidth.

Wavelength tunable distributed Bragg reflector lasers are attractive as transmitters in optical fibre communication systems. They are also suitable as tunable local oscillators for channel selection in coherent frequency multiplexed systems or as tunable wavelength filters[1] in direct detection systems. A wide tuning range together with a narrow spectral linewidth are important parameters.

The BIG-DBR[2] laser is shown in Fig. 1. The fabrication includes four steps of liquid phase epitaxy. Reactive ion etching and wet chemical etching are used to form the mesas, and the transverse current confinement is achieved using the FBH structure.[3] We have chosen to fabricate the lasers on a *p*-doped InP substrate because of better control of the *pn*-junction position. The electrical isolation between the top contacts is increased by etching 1 μm deep and 15 μm wide grooves in the top contact and cladding layers and implanting He^{++} ions. We have chosen helium ions instead of protons because of their better thermal stability in the subsequent processing steps. Due to the limited resistivity achievable in the *n*-type cladding and waveguide materials,[4] the resulting electrode separation resistance is only about 50 Ω in the present structure. Without the helium ion implantation the isolation is less than 20 Ω.

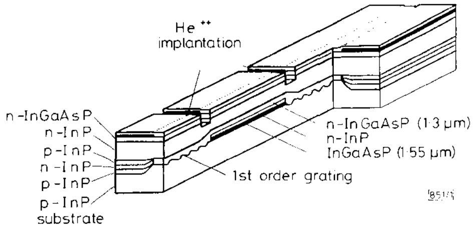

Fig. 1 *Double-sided BIG-DBR laser*

The threshold current of a three-electrode DBR laser having a 140 μm long front grating region, a 300 μm long active region, and a 360 μm long rear grating is measured to a low value of 19 mA. The light-current characteristic is shown in Fig. 2*a*, where the discontinuities in the curve are caused by mode-jumps. The low maximum output power of 0.9 mW can be explained by the high reflectivity ($\kappa L \approx 1{\cdot}8$) of the output grating, and also by leakage currents from the active region to the passive grating regions which cause absorption losses.[5]

A way to eliminate the leakage currents through the passive waveguides is to short-circuit the grating contacts to the common bottom electrode. The leakage currents from the active region will in this case increase since once the current has passed the electrode separation region, it is directed straight to the bottom contact and not through the *pn*-junction in the grating regions. This results in an increased threshold current; for this laser it increases from 19 to 46 mA. In spite of this, the maximum output power increases to 1·3 mW because of the reduced number of free carriers in the passive waveguides and thereby the reduced waveguide absorption (Fig. 2*a*).

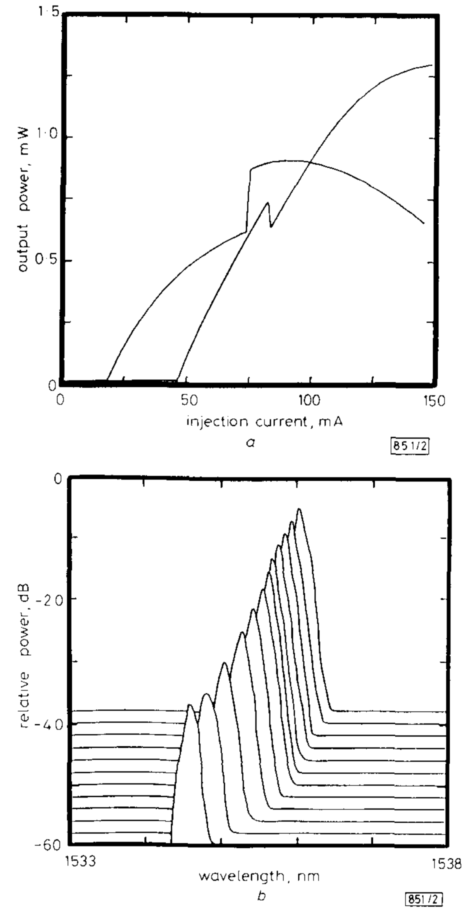

Fig. 2 *Characteristics of three section DBR laser*

a Light–current

b Continuous tuning range

By increasing the resistance between the grating contacts and the bottom contact the leakage current is redirected to pass through the grating regions so that the refactive index in the passive waveguides is lowered due to the plasma effect. This results in a continuous tuning of 1·4 nm towards shorter wavelengths when the total leakage current from the two grating electrodes is reduced from 47 to 6 mA (Fig. 2*b*). At the same time the output power is reduced from 1·15 to 0·45 mW due to the increased waveguide absorption.

Two-electrode DBR lasers are obtained from the same wafer by cleaving the front grating region away. The best sample has a threshold current of 21 mA and a maximum output power of 10·5 mW, without any mode-jump. The quantum efficiency is 21% for the front facet. Continuous tuning is not possible with this configuration, having two sections only. The output wavelength can be reduced in a stepwise manner by increasing the current through the grating