Improvements in Mode-Locked Semiconductor Diode Lasers Using Monolithically Integrated Passive Waveguides Made by Quantum-Well Intermixing

F. Camacho, E. A. Avrutin, *Member, IEEE*, P. Cusumano, A. Saher Helmy,
A. C. Bryce, *Member, IEEE*, and J. H. Marsh, *Senior Member, IEEE*

Abstract—**By using the technique of quantum-well intermixing (QWI), monolithically integrated passive, and active waveguides can be fabricated. It is shown that mode-locked extended cavity semiconductor lasers with integrated low-loss passive waveguides display superior performance to devices in which the entire waveguide is active: the threshold current is a factor of 3–5 lower, the pulsewidth is reduced from 10.2 ps in the all active laser to 3.5 ps in the extended cavity device and there is a decrease in the free-running jitter level from 15 to 6 ps (10 kHz–10 MHz).**

Index Terms—**Integrated optics, mode-locked lasers, pulse generation, quantum-well lasers, semiconductor lasers.**

I. INTRODUCTION

THE ABILITY to generate short optical pulses using semiconductor lasers is crucial for high bit-rate optical systems. There are various techniques for short pulse generation, but passive modelocking (ML) generates the shortest optical pulses, and is achieved simply by introducing a saturable absorber into the laser cavity. Monolithic semiconductor lasers working at frequencies of 10–30 GHz have recently attracted considerable attention but very long cavities ($\sim$ millimeters) are required to achieved such "low" repetition rates. Several device constructions have been studied [1], [2]; in this letter, we report the improvements obtained when using *extended cavity mode-locked semiconductor lasers* (ECL), made by quantum-well intermixing (QWI) instead of *all-active mode-locked semiconductor lasers* (AAL).

The AAL configuration is simple to fabricate but, as will be shown in the following sections, has some drawbacks in comparison with the ECL such as emission of broader pulses and self-pulsations behavior [3]. The passive section of the ECL was fabricated using an initial QWI step to widen selectively the bandgap of the extended cavity [4] giving a low-loss passive waveguide section. This fabrication technique is much easier and has a higher yield than those involving material regrowth [2]. Furthermore, the use of QWI ensures perfect alignment between the active and passive sections of the device and results in a negligibly small reflection at the interface. The particular intermixing technique used, impurity free vacancy disordering (IFVD), allows controlled and reproducible blue shifts in the QW bandgaps. The sample is encapsulated by dielectrics, using SiO_2 to enhance and phosphorus doped SiO_2 ($P{:}SiO_2$) to suppress disordering, followed by rapid thermal annealing (RTA) of the sample. The SiO_2 is porous to out-diffusion of Ga atoms, so generating group III vacancies which results in diffusion of Al atoms from the barrier to the well and hence a widening of the material bandgap. QWI is suppressed in the active regions because the $P{:}SiO_2$ is impermeable to Ga atoms [4].

II. DEVICE CONSTRUCTION AND FABRICATION

Ridge waveguides 3.5 μm wide and 0.8 μm deep were fabricated using a self aligned reactive ion etching (RIE) technique [4]. For the experimental work of this letter, a 5-mm-long AAL and a 4-mm-long ECL were studied, the former working at around 8 GHz and the latter at around 10 GHz. The AAL had a 4910-μm-long gain section and an 80-μm-long saturable absorber, and the ECL had a 440-μm-long gain section, a 50-μm-long saturable absorber and a 3500-μm-long extended cavity, as shown in Fig. 1. To assist construction optimization, we performed numerical simulations using a distributed time-domain model [5], taking into account gain and group-velocity dispersion, self-phase modulation (with gain section linewidth enhancement factor 4.0) and fast gain, absorption and refractive index nonlinearities. The simulations predicted that ECL lasers with shorter absorber sections than those used in experiment (30 μm) may not reach complete ML, whereas longer absorber sections (70 μm) lead to very strong self-pulsing modulation up to currents 2.5–3 times above threshold. Although the simulated situation for the AAL was similar, devices fabricated with 10-, 20-, 30-, and 50-μm-long saturable absorbers did not show well developed ML, and therefore an 80-μm-long absorber was used. Thus, both configurations were optimized in the sense that they were fabricated with the minimum saturable absorber length required to obtain well developed ML. The contacts were separated by a 10-μm gap, which gave an isolation resistance of 5–6 kΩ.

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The authors are with the Department of Electronics and Electrical Engineering, University of Glasgow, Glasgow G12 8QQ, Scotland, U.K.

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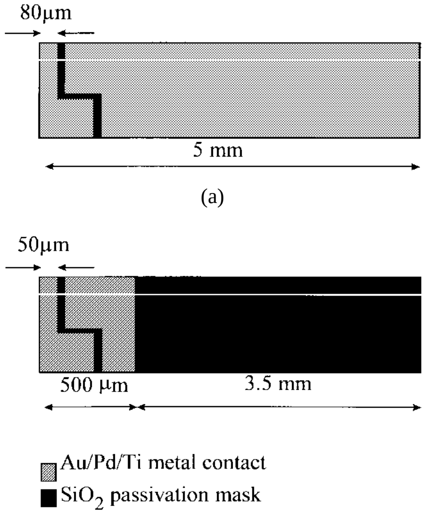
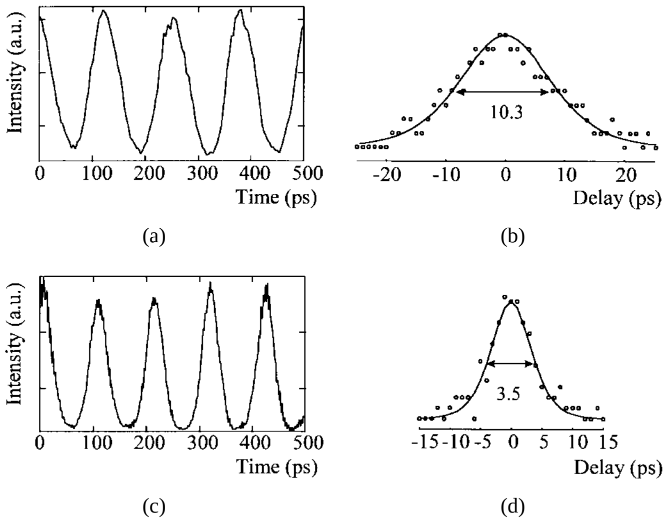


(a)

(b)

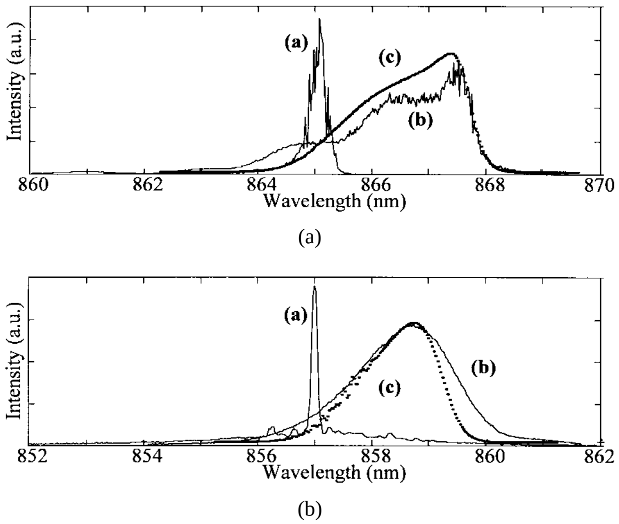
Fig. 1. Diagram of the (a) All-active mode-locked semiconductor laser. (b) Extended cavity mode-locked semiconductor laser.



(a) (b)

(c) (d)

Fig. 2. Temporal measurements from the AAL (a) and ECL (c), and autocorrelation data and fittedtraces and fitting curves for the AAL (b) and ECL (d).



(a)

(b)

Fig. 3. Lasing spectra: Spectral measurements taken with (a) measured with the saturable absorber floating; (b) measured with the saturable absorber reversed biased from the AAL at $I/I\mathrm{th} = 2.0$ (upper graph) and ECL at $I/I\mathrm{th} = 2.9$ (lower graph) and; (c) simulated at the same bias.

III. Experimental Results

From the light versus current (*L–I*) characteristics, taken under pulsed excitation with the saturable absorber floating, the threshold current for the ECL was 32 mA, less than a third of that of the AAL which was 105 mA. The increase in threshold current under CW operation, due to heating effects, was less than 10% in both cases. *L–I* characteristics of the ECL were very similar when measured from the active or from the passive end of the laser, which indicates that the passive waveguide losses are very low [4]. With both sections forward biased, the ECL threshold current was reduced to 18 mA, and the AAL threshold current only to 100 mA, more than five times that of the ECL.

Besides the improvement in threshold current, using the optimized ECL construction eliminates self-pulsations (SP) regimes accompanying ML. Depending on the negative bias on the absorber and the current in the gain section, the AAL operated in several distinct dynamical regimes, which included pure ML, pure SP, and ML combined with a deep SP envelope [3]. For all bias conditions investigated, the ECL showed no SP modulation of the ML pulse train.

Fig. 2 shows temporal measurements taken with a high-speed streak camera, and autocorrelation data with fitted curves. Fig. 2(a), measured from the 5-mm-long AAL, depicts a ML pulse train at approximately 8 GHz, while Fig. 2(c), measured from the 4-mm-long ECL, shows a ML pulse train at around 10 GHz. Although not resolved by the streak camera, the ECL pulse width varied from 3.5 to 6.5 ps (FWHM assuming hyperbolic secant square shape), depending on the biasing conditions, while the AAL pulsewidth varied from 10.2 to 13.8 ps, again depending on the biasing conditions. The pulsewidth was measured with a two-photon absorption semiconductor waveguide autocorrelator [6], which is sensitive enough to allow us to acquire autocorrelation measurements under pulse excitation, Fig. 2(b) and (d). The decrease in the pulsewidth in the ECL as opposed to the AAL is expected since all the nonlinear phenomena (slow and fast gain saturation) and all the dispersive effects (gain and group velocity dispersion) that broaden the ML pulse are much stronger in the active parts of the cavity.

Fluctuations in mode-locked lasers include variations in both pulse intensity and pulse timing. Carrier density fluctuations modulate the round-trip time for the optical pulses inside the laser cavity, and cause jitter in ML devices. The root-mean-square (rms) timing jitter, under continuous-wave (CW) operation, was estimated by the frequency-domain technique [8]. The AAL jitter (10 kHz–10 MHz) was found to be around 15 ps, while the ECL jitter (10 kHz–10 MHz) was just 6 ps. The ECL shows the expected reduction in jitter levels predicted by Derickson *et al.* [7]. The jitter levels are larger for all-active waveguide configurations than for extended cavity configurations due to the fact that, for similar carrier density levels in each active waveguide, the phase noise level will be

TABLE I

	Active section length (mm)	ML frequency (GHz)	I Threshold (mA)	Pulse FWHM (ps)	Time-bandwidth product	Timing jitter (ps)	Wavelength (μm)
AAL [7]	6.1	5.5	116	10	4	12.5 (150 kHz-50 MHz)	0.85
External cavity [7]	0.5	5	13	2.5	1.8	12.2 (1.5 kHz-50 MHz)	0.85
ECL [2]	0.65	8.6	50	5.5	7		1.55
Our AAL	5	7.6	105	10	7	15 (10 kHz-10 MHz)	0.86
Our ECL	0.5	9.3	18	3.5	2.5	6 (10 kHz-10 MHz)	0.86

larger in the AAL than in the ECL roughly by the ratio of the active waveguide lengths, the former being 5 mm long and the latter being 500 μm long.

Optical spectra were taken with an optical spectrum analyzer with a resolution of 0.1 nm. Fig. 3 shows spectra taken from the AAL and ECL when (a) the saturable absorber was not biased and (b) the devices were mode-locked. For both constructions, the optical spectra suffer a shift of more than 2 nm to longer wavelengths when the laser in ML, become very asymmetric and the spectral width changes from 0.4 nm at zero absorber bias to almost 2 nm when the saturable absorber is reverse biased for the AAL and from 0.2 to 2 nm for the ECL. Also shown (c) are the simulated spectra for the same construction and bias conditions. Both the asymmetry and the shift of the spectra (the zero frequency of the simulated spectra was aligned to the experimental CW lasing wavelength) are readily reproduced by the theory. The modeling thus shows that both effects may be explained almost entirely by the self-phase modulation (SPM) [9] in the gain section.

The time-bandwidth product for the AAL was calculated to be 7, while for the ECL it was just 2.5. Previously reported extended cavity mode-locked lasers, made using regrowth techniques [2], show similarly large time-bandwidth products to that of the AAL, around 20 times larger than the theoretical value, which was attributed [2] to reflections between the active and passive section. According to our simulations, such reflections result in pulse broadening and the formation of trailing pulses when the active/passive interface reflectance is about 10^{-3} or higher. In our case, the reflectance is much smaller (estimated as $<10^{-6}$) which may be one of the reasons why the time-bandwidth product is reduced to 2.5.

The measured ML parameters are summarized in Table I, along with the best previously reported values. The performance of our IFVD ECL is better than that of previously reported monolithically integrated Fabry–Perot constructions. Only external cavity constructions have shown better ML parameters, however external cavity constructions have major disadvantages, such as mechanical instabilities and difficulties in eliminating secondary pulses.

IV. CONCLUSION

We have reported the fabrication of mode-locked semiconductor lasers with active and passive waveguides. By using the IFVD technique to fabricate the low-loss waveguide, the ECL are simple to make. Improvements over the AAL are seen in terms of the threshold current, pulsewidth, timing jitter, and the time-bandwidth product, resulting in a set of mode-locking parameters which is, to the best of our knowledge, the best achieved so far with a monolithic Fabry–Perot diode laser at repetition frequencies around 10 GHz.

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