High-Energy Picosecond Pulse Generation by Gain Switching in Asymmetric Waveguide Structure Multiple Quantum Well Lasers

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***Abstract*—A multiple quantum well laser diode utilizing an asymmetric waveguide structure with a large equivalent spot size of ∼3 μm is shown to give high energy (∼1 nJ) and short (∼100 ps) isolated optical pulses when injected with <10 A and ∼1-ns current pulses realized with a MOS driver. The active dimensions of the laser diode are 30 μm (stripe width) and 3 mm (cavity length), and it works in a single transversal mode at a wavelength of ∼0.8 μm. Detailed investigation of the laser behavior at elevated temperatures is conducted; it is shown that at high enough injection currents, lasers of the investigated type show low temperature sensitivity. Laser diodes of this type may find use in accurate and miniaturized laser radars utilizing single photon detection in the receiver.**

***Index Terms*—Semiconductor lasers, quantum well lasers, optical pulses, gain switching, laser radar.**

I. INTRODUCTION

SINGLE isolated short (∼100 ps) and high energy (∼1 nJ) laser pulses can be used in a number of applications including automotive safety devices, 3-D imaging, laser tomography, time imaging, and spectroscopy. Gain switching of semiconductor lasers, known for their high efficiency, compactness, and ease of current pumping, is arguably the best way of producing such pulses [1], [2]. The gain switching regime has been subject to extensive theoretical (see, e.g., [3]–[5]) and experimental (see, e.g., [5]–[13]) studies for a long time. It has been found that in order to maximize both the peak power and the total energy of the optical pulse, the design of lasers for gain switching may need to be different from that used for CW applications. A number of specialist gain-switched or combined gain- and Q-switched [11]–[13] laser designs have been suggested, and pulses with an energy >1 nJ have been demonstrated. Most of the earlier approaches used purpose-built ultrafast GaAs-based current pulse generators providing current pulses with an amplitude *significantly* exceeding 10 A. From the application point of view, and it is desirable that the laser operates with Si-based, CMOS electrical pumping pulse sources which can generate current pulses with a duration down to ∼1 ns and an amplitude up to ∼10 A, at repetition frequencies up to about 1 MHz. We proposed [14] the use of specialized diode lasers for gain switched operation, utilizing a strongly asymmetric waveguide with a large equivalent spot size, defined as the ratio d_a/Γ_a of the active layer thickness to the optical confinement factor. Laser designs with a relatively thick bulk GaAs active layer ($d_a \sim 0.1\ \mu$m) and with $\Gamma_a \ll 0.1$ have been shown theoretically [14] to be capable of producing single short (∼100 ps) optical pulses within the spectral region of $\lambda \sim 0.85\ \mu$m, with energies in excess of 1 nJ, when gain-switched with pulses with an amplitude of about 10 A and a duration of 1–1.5 ns. Experimentally, the characteristics close to those predicted were achieved with current pulses of an amplitude significantly lower than that used in previous work, though still greater than 10 A, due to the lasers used having a modest injection efficiency of about 0.5 [15]–[17]. Gain-switched laser designs with large d_a/Γ_a have also been demonstrated by other teams [18].

To broaden the operating wavelength range, the use of Quantum Well active layers was shown [19] to be beneficial in lasers of this type. We therefore proposed the use of AlGaAs/InGaAs multiple quantum well active layer lasers with an asymmetric waveguide design with extremely small values of Γ_a, adjusted to give $d_a/\Gamma_a \gg 1\ \mu$m. Theoretical studies using phenomenological models with active layer parameters taken from the literature predicted the possibility of generating high energy (>1 nJ) short (∼100 ps) single optical pulses when pumped with an injection current pulse of an amplitude of about 10 A and a duration of 1.5–2 ns. The structures studied in [19] were intended for operation at $\lambda \sim 1\ \mu$m range. We note however that in LIDARs for applications involving automotive safety and imaging, which may use silicon single photon avalanche photodetectors [20], [21], it is beneficial to work at wavelengths $<\sim 0.8\ \mu$m, where the responsivity of the silicon detectors is higher than at longer wavelengths. This wavelength is however shorter than the typical operating wavelength of typical GaAs lasers. In the current paper, we propose and realize a customized asymmetric waveguide laser structure for gain switching, using a GaAs/AlGaAs multiple quantum well active layer, and characterize its performance. Single optical pulses about 100 ps long (FWHM), with an energy of ∼1 nJ at $\lambda \sim 0.808\ \mu$m, have been achieved from

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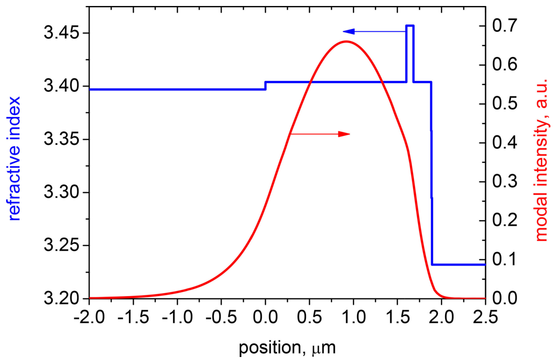

Fig. 1. Schematic of the refractive index profile and the corresponding transverse mode intensity distribution in the structure analyzed. The active region is represented as a single layer with an averaged refractive index.

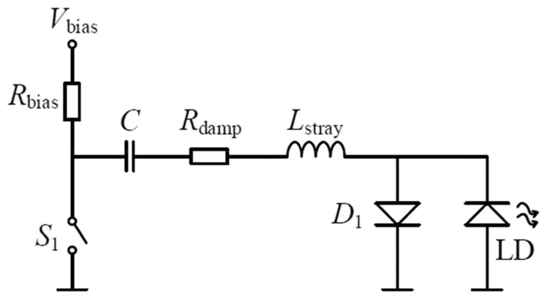

Fig. 2. *LCR* transient-based laser diode driver scheme.

lasers with a stripe width of 30 μm, using pumping pulses with an amplitude of a few Amps and a duration of $\sim$1 ns from a compact MOS driver. Temperature performance of the laser has been investigated experimentally and theoretically. It has been shown that the inevitable performance degradation at high temperatures (either due to ambient temperature or Joule heating in the CMOS source) can be to a significant extent overcome by a relatively modest current increase. A prototype compact source with a hybridly integrated electrical pulse generator and laser has been manufactured and characterized.

II. LASER STRUCTURE

The quantum well laser structure has been grown using Molecular Beam Epitaxy by Innolume GMBH, Dortmund. Fig. 1 shows schematically the refractive index profile in the structure and the calculated transverse mode intensity profile (the structure supports a single transverse mode only). The structure belongs to the broad asymmetric waveguide category [14], [22] in the sense that the mode overlap with the optical confinement layer is larger than that with the *n*-cladding. This may lead to slightly higher internal losses than the alternative narrow asymmetric waveguide [22], but offers a higher tolerance to fabrication imprecision (particular as regards the composition of the *n*-cladding and hence its refractive index, see Fig. 1) and hence more reproducible design due to the waveguide operating further away from the cutoff condition. The active layer consisted of five thin (4 nm thick) GaAs/Al$_x$Ga$_{1-x}$As ($x \approx 0.3$) Quantum Wells, providing the operating wavelength of 808 nm. To help achieve a large $d_a/\Gamma_a \approx 3$ μm, the position of the active layer was shifted away from the mode peak towards the *p*-cladding. The injection efficiency of the laser was measured as $\approx$0.75, and the internal loss, as ≈ 1.5 cm^{-1}.

The stripe width was chosen as 30 μm, as a compromise between the need for high power pulse generation and the need to keep the source dimension small. The ratio of the stripe width and the focal length of the transmitter optics defines the field-of-view of the transmitter and this should be kept small (e.g., $\sim$1 mrad) to improve the spatial accuracy and reduce the level of background radiation seen by the receiver. The lasers were mounted *n*-side down on a ceramic sub-mount, which then was fastened onto the driver board at a right angle with no heat sink.

III. EXPERIMENTAL

The laser diode driver was based on an LCR transient-based pulse shape control. The principle of the driving scheme is shown in Fig. 2. In this driver, a capacitor *C* is first charged to the V_{bias} voltage (20 . . . 150 V) and then rapidly discharged with a switch S_1 realized with a MOS transistor [23]. In this configuration the current pulse width is determined by the capacitance and the stray inductance of the current loop ($\propto (LC)^{1/2}$). The peak amplitude of the current pulse is proportional to the bias voltage. Pulses with a width of $\sim$1 ns and peak current of $\sim$10 A are available with a MOS transistor switch as explained in more details in [24]. As the current pulses driven through the laser diode are short, the average current at a pulsing rate of, say, 100 kHz, is only 0.5 mA. Thus a pulsing rate of 100 kHz to about 1 MHz can be achieved.

Laser diode characterization measurements were performed to determine the injection current pulse amplitude, the corresponding optical pulse power and their relative positions in the time domain. The current pulse amplitude was determined by measuring a voltage drop over a damping resistor in series with the laser diode. The optical power of the laser pulse was determined by measuring the pulse shape emission in time domain in relation to the measured optical average power. For the time domain presentation, the optical energy was collected with a graded index optical fiber using a lens pair to collect the total emission of the laser diode. An OE-converter and a real-time oscilloscope with a bandwidth of 24 and 12 GHz, respectively, were used in the measurements, and the given results are produced directly from the oscilloscope results without any BW correction.

Fig. 3 shows the measured temporal optical pulse profiles alongside the corresponding current pulses (note that the negative part of the current pulse was channeled to the shunting diode and not applied to the laser, see Fig. 2). Note also that the results are from separate measurements and combined on the same graph for convenience.

The optical pulses are about 100 ps at half maximum; the peak power reaches about 9 W for a peak current of 6 A, corresponding to a pulse energy of about 1 nJ. At the current pulse amplitude in excess of 3–4 A, the optical pulses show

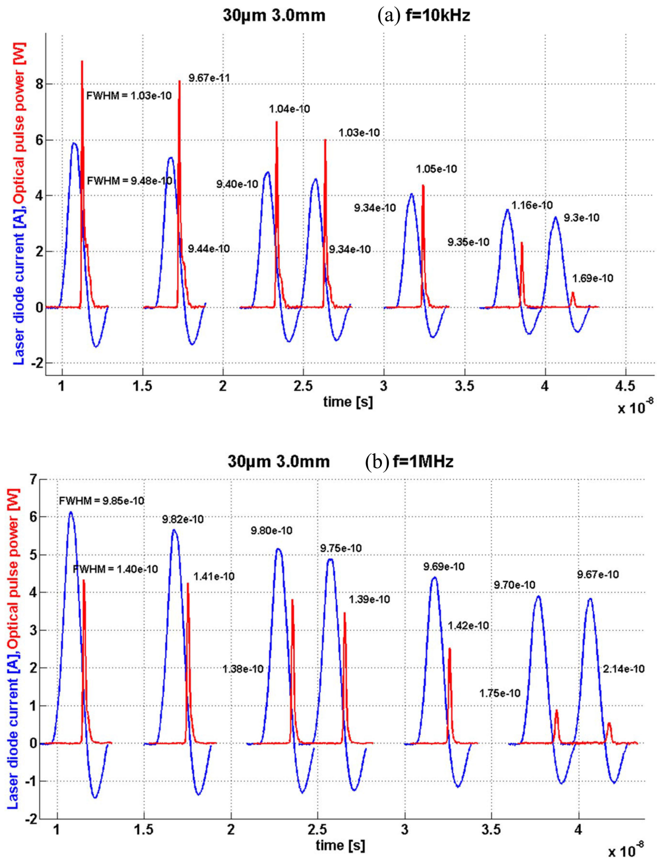

Fig. 3. Output pulse (red curve) versus injection current pulse (blue curve) for a QW laser diode with 30 μm stripe width and 3 mm cavity length; (a) pulsing rate is 10 kHz, (b) pulsing rate is 1 MHz.

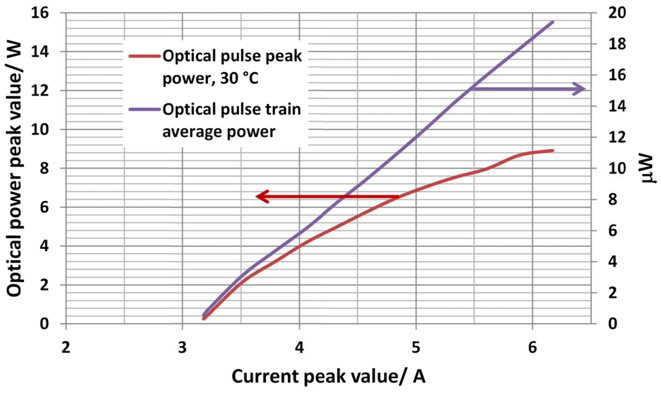

Fig. 4. Peak and average powers of the 30 μm/3 mm QW laser diode as a function of the peak pumping current.

some relatively weak trailing pulse structure that does not affect the FWHM pulse duration. The dependence of the peak power and total optical output energy (including the afterpulsing structure if any) on the current amplitude can be seen more clearly in Fig. 4.

It is seen that, while the total energy shows a relatively linear dependence on the peak current, the current dependence of the peak optical power is markedly sublinear. This difference can be attributed to the emergence of the afterpulsing structure, taking on some of the pulse energy; the measured FWHM duration of the main pulse does not increase substantially with current.

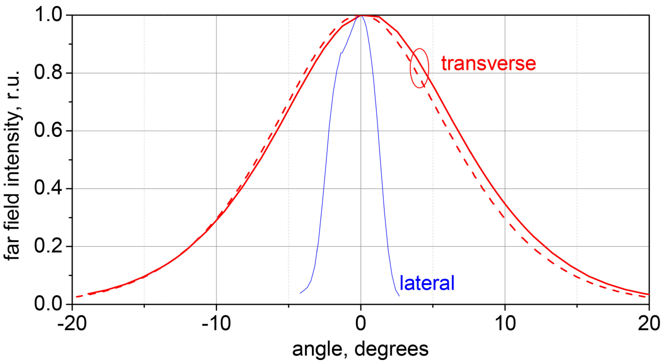

Fig. 5. Far field distribution of the 30 μm/3 mm QW laser diode in the transverse direction (solid-measured, dashed-calculated) and in the lateral direction (measured).

Fig. 5 shows the far field of the laser emission in the transverse (a) and lateral (b) directions. As usual in laser structures of this type, the transverse field (the broader, red, solid curve in Fig. 5) is determined by the profile of the single transverse mode and relatively narrow ($\sim$15° FWHM) in good agreement with the calculations (the dashed curve), thus allowing the use of a relatively compact lens in the laser transmitter design. The lateral field is more complex, due to the multimode nature of the emission from the simple rectangular 30 μm stripe, but still narrower than the transverse field, with the FWHM of about 3°–4°.

The curves shown in Figs. 3(a), 4, 5 have been measured for low pulse repetition frequencies (10 kHz). Experimentally, frequencies up to 1 MHz have been used (see Fig. 3(b). In the latter case, which is preferable for realistic acquisition systems such as a LIDAR, the behavior of the laser is qualitatively similar but the pulse amplitudes are lower due to the current heating in the power supply. In addition, a realistic LIDAR for automotive applications must be capable of operating in broad range of ambient temperatures.

We have therefore investigated the temperature dependence of the laser performance by controlling the temperature explicitly.

Shown in Fig. 6 are the pulse shapes and the corresponding (identical) current pulses, for different values of ambient temperature and measured at low repetition rate (10 kHz) to substantially eliminate the effects of current heating. Unsurprisingly, the well-known gain decrease with temperature is seen in the dynamics, resulting in a decreased power and energy of the pulses generated. The measurements in this figure correspond to a relatively high value of the current amplitude, so the optical power decrease is noticeable but not drastic.

The effect of temperature on the laser performance is more important at modest currents, as illustrated in Fig. 7 which shows the dependences of the peak optical power on current peak measured at different temperature values (the middle curve, corresponding to $T = 30°$, is identical to the one in Fig. 4). Clearly, for peak current values of less than 4–5 A, an increase in

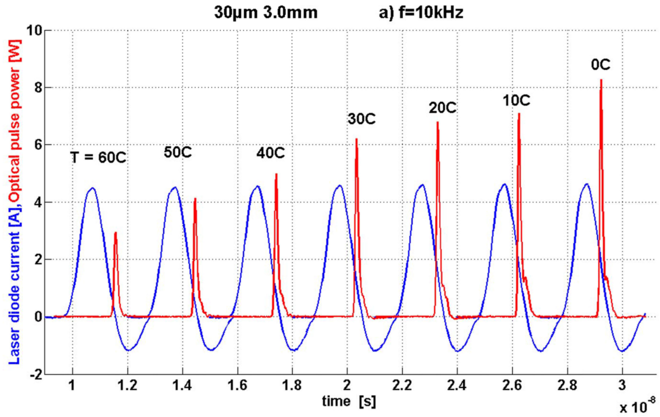

Fig. 6. Dependence of the peak power of the 30 μm/3 mm QW laser diode on the temperatures at a constant injection current amplitude.

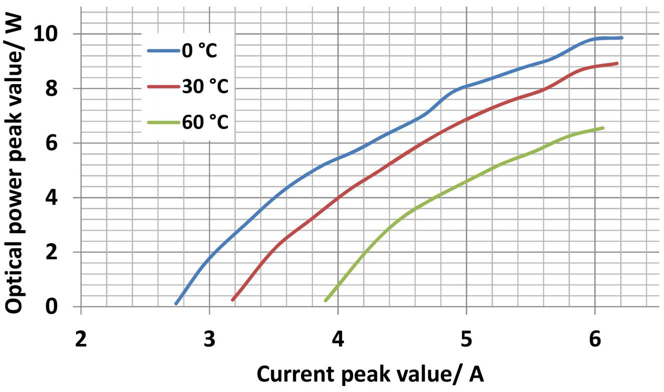

Fig. 7. Dependence of the peak power of the 30 μm/3 mm QW laser diode on the injection current at the temperatures of 0° (blue), 30° (red) and 60° (green).

temperature of 30° can shut the laser down. In practice however, the laser is intended for operation at high currents to maximize the output pulse energy, which simultaneously minimizes the temperature influence.

Moreover, experiments show that the temperature induced deterioration of the laser performance can be reversed, at the high enough operating currents, by a relatively modest increase in the current pulse amplitude (e.g., as can be seen in Fig. 8, an increase in the current from 4.5 to 6 A largely recovers the peak power deterioration caused by heating the laser by about 30 K). As shown in the experimental result of Fig. 8, this happens with only a modest penalty in the pulse shape.

All the qualitative tendencies seen in the experiments are readily reproduced by rate equation simulations, using gain dependence on carrier density and temperature from [25].

As an example of a practical laser diode transmitter realization, Fig. 9 shows a module using a 30 μm/1.5 mm (note cavity length difference compared to the 3 mm long laser discussed above) QW laser diode and a full-custom CMOS driver described in [23], and its output at the pulsing rates of 10 kHz and 1 MHz, respectively, driven with a ~2.5 A/1ns current pulse.

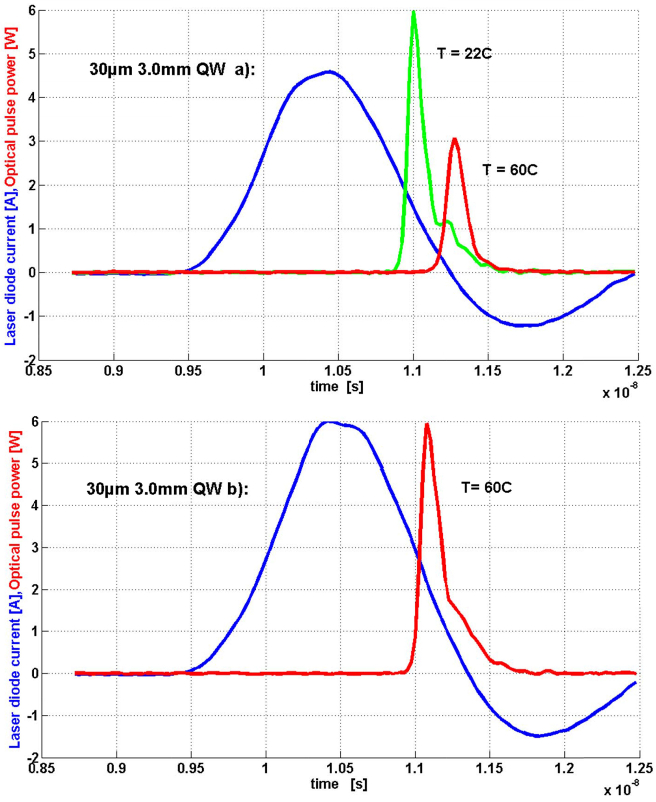

Fig. 8. Optical output of the 30 μm/3 mm QW laser diode (a) at the temperatures of 22° and 60° with the same injection current pulse amplitude, and in (b) at the temperatures of 60° with ~30% increased pumping current amplitude.

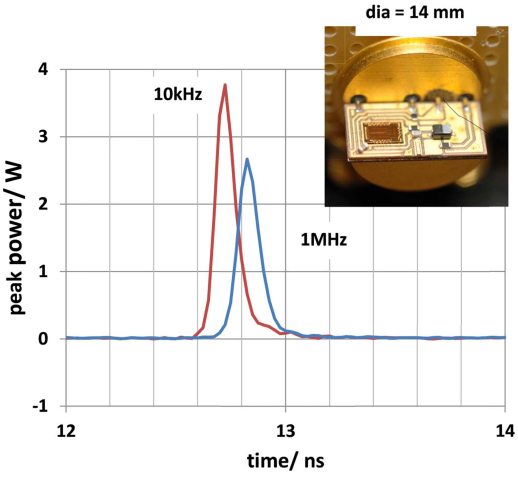

Fig. 9. Construction and optical output of the 30 μm/1.5 mm QW laser diode at 10 kHz and 1 MHz pulsing rates, respectively.

IV. CONCLUSION

To conclude, we have shown that lasers with an active layer utilising thin GaAs Quantum Wells and a strongly asymmetric waveguide allow for the generation of high energy (~1 nJ) picosecond pulses at 808 nm, with a modest current pumping pulse amplitude (<10 A) and a reasonably good tolerance to ambient temperature. A prototype integrated transmitter for operating in a laser radar scheme has been demonstrated.

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