980-nm Monolithic Passively Mode-Locked Diode Lasers With 62 pJ of Pulse Energy

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***Abstract*—Passively mode-locked 980-nm slab-coupled optical waveguide lasers have been demonstrated with pulse energies as high as 62 pJ and average powers of 489 mW at 7.92 GHz from a 5-mm device with a 300-μm absorber. Mode-locking has been observed with devices ranging from 3 to 10 mm in length.**

***Index Terms*—High-power diode lasers, mode-locked lasers, quantum-well devices, semiconductor lasers, single-mode semiconductor lasers.**

I. INTRODUCTION

MODE-LOCKED semiconductor lasers are attractive sources due to their potential for compactness, efficiency, and wavelength flexibility. They are promising for a number of applications including frequency metrology [1], light detection and ranging, Raman spectroscopy [2], and communications. In particular, frequency-converted semiconductor lasers show great potential as suitable deep ultraviolet sources for sensors and nonline-of-sight communications [3], [4].

However, to date, mode-locked semiconductor lasers have generally been demonstrated only at low powers and pulse energies. Typical reported pulse energies from sources operating between 800 and 900 nm are 1–10 pJ, with corresponding average powers ranging from 1 to 5 mW [5]. In this work, we report on passively mode-locked electrically pumped 980-nm slab-coupled optical waveguide lasers (SCOWLs) with record-breaking pulse energies and powers. Passive mode-locking has been demonstrated with a large range of device lengths incorporating an integrated saturable absorber. An average power of 489 mW with 62 pJ of pulse energy has been achieved from a 5-mm-length device, with a 0.3-mm absorber.

The power and pulse energy from semiconductor lasers are limited by their saturation energy, $h\nu A/a\Gamma$, where $h\nu$ is the photon energy, A is the active region area, a is the differential gain, and Γ is the confinement factor. Thus, by increasing the active-region area, or decreasing the confinement factor, one can increase the average power and pulse energy. The active area of a semiconductor laser can be increased by adding a flare to a waveguide or using a vertical-cavity surface-emitting geometry. With flared waveguides, including an integrated saturable absorber for passive mode-locking, 6.8 pJ and 9.1 mW of average power has been demonstrated [6] at 940 nm. An inverse bow-tie amplifier, operated in an external cavity with a separate saturable absorber, produced 36 pJ with 36 mW of average power at 1 GHz [7]. An optically pumped vertical-cavity surface-emitting laser generated 2.1 W of average power with 0.5 nJ of pulse energy [8]. However, optical pumping is complex and inefficient. Using a combination of two devices, a flared and a straight amplifier, and through active mode-locking, Goldberg *et al.* were able to achieve 12-ps pulses at a repetition rate of 1 GHz, with pulse energies of 0.5 nJ [9].

Our approach to this problem is to combine an electrically pumped SCOWL with a low confinement factor, 0.003, and an integrated saturable absorber for passive mode-locking. The SCOWL has been demonstrated CW with diffraction-limited single-mode output of >1 W at 980 nm, and >0.8 W at 1550 nm [10]–[12]. Passive mode-locking has been demonstrated with 250 mW of average power and 58 pJ of pulse energy at 1550 nm [13], and active mode-locking producing 40 mW of average power [14]. This work reported here is focused on passive mode-locking of 980-nm electrically pumped SCOWLs, suitable for frequency conversion to ultraviolet wavelengths.

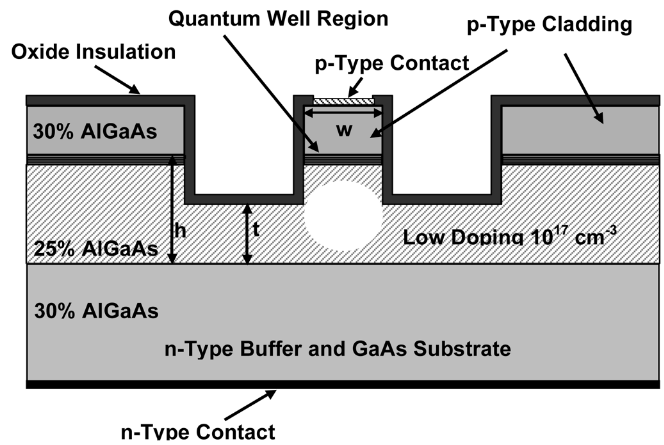

Fig. 1. Schematic of a typical monolithic mode-locked 980-nm SCOWL. Several parameters critical for single spatial mode operation are indicated: $w = 5.8$ μm, $h = 5.0$ μm, and $t = 4.4$ μm.

II. DESIGN AND FABRICATION

The SCOWL is based on a principle developed by Marcatili [15] in which single-mode operation in a multimode waveguide

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TABLE I
CHARACTERISTICS OF DEVICES TESTED

Device	Device Length (mm)	Absorber Length (mm)	Maximum Average ML* Power
A	3	0.3	195 mW @ 658 mA,-0.22V
B	5	0.3	489 mW @ 1589 mA, -0.56V
C	10	0.3	218 mW @ 1200 mA, -0.81V
D	10	0.5	97 mW @ 1000 mA, -0.66V
E	10	0.8	322 mW @ 1500 mA, -0.5V

*ML = Modelocked

can be achieved by coupling the multimode waveguide to a slab. The SCOWL is a rib waveguide structure in which the higher order modes are coupled to a slab. The SCOWL devices studied are AlGaAs–InGaAs-based lasers with a confinement factor roughly an order of magnitude lower than conventional semiconductor lasers. The 980-nm SCOWL structure, shown in Fig. 1, has three compressively strained InGaAs quantum wells, and consists of an upper cladding of 30% AlGaAs, with a 5-μm-thick waveguide of 25% AlGaAs, and a 30% AlGaAs lower cladding. Tensile-strained $GaAs_{0.92}P_{0.08}$ is used as the barrier and the bounding layer material. The near-field mode size was measured, by imaging the laser facet, to be 4.8×3.9 μm.

The ridge is defined with a $SiCl_4$ inductively coupled plasma etch and a short wet-chemical etch to remove sidewall damage and reach the desired final depth. This is followed by a p^+-GaAs cap etch, which enhances the isolation between the gain and absorber sections. Next, a layer of SiO_2 is deposited, a p-contact opening is etched with CF_4 RIE, and the top is metallized with Ti–Au. Bond pads are defined with wet chemical etching. The backside of the wafers is lapped to 140 μm, polished and metallized with Ni–Ge–Au alloy and a Ti–Pt–Au bonding layer. Finally, a proton implant is performed between the gain and absorber sections to increase the electrical isolation between the sections. Photoresist is used to protect the gain and absorber regions from the protons, and only a 10-μm section between the sections is exposed to bombardment. The facets on each side were cleaved perpendicular to the direction of propagation and were passivated with 1-nm/20-nm layer of Gd/GGG. The lasers are mounted junction-side up on copper-tungsten submounts. The absorber section was located on the device back facet, which had a 95% reflectivity coating. The output was taken from the front facet, which had an 8% reflectivity coating.

III. RESULTS AND DISCUSSION

The mode-locked devices studied in this letter are in the early stages of development and the full parameter space has not been completely mapped out. Thus, we investigated multiple devices of different lengths. Table I delineates the characteristics of the lasers were tested with lengths ranging from 3 to 10 mm, and absorber sections ranging from 0.3 to 0.8 mm. The devices were first characterized quasi-CW at a 1% duty cycle (100 Hz, 100 μs) at modest drive currents. Mode-locking was achieved with a variety of device lengths: 3-mm/0.3-mm absorber; 5-mm/0.3-mm absorber; and 10-mm device lengths with 0.3-, 0.5-, and 0.8-mm absorber sections. The mode-locked devices were characterized with a power meter, noncollinear autocorrelator with a scan range of 200 ps, sampling oscilloscope, optical spectrum analyzer, and RF spectrum analyzer.

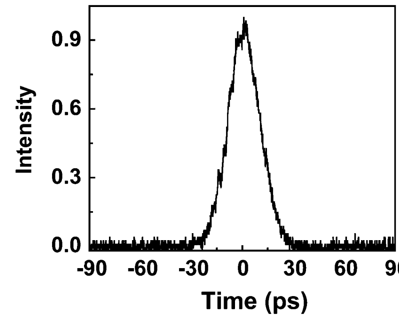

Fig. 2. Autocorrelation of pulses from a 5-mm laser with a 300-μm absorber at 1589 mA and 0.56 V of reverse bias.

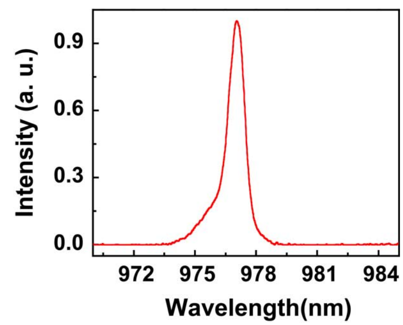

Fig. 3. Optical spectrum of a mode-locked 5-mm laser with a 300-μm absorber at 1589 mA and 0.56 V of reverse bias.

Device B, with a 5-mm length and 0.3-mm absorber length, had a threshold of 440 mA and a slope efficiency of 0.73 W/A with an unbiased absorber. Free running, the device had a wavelength of 975 nm. Mode-locked operation was then investigated. Figs. 2 and 3 show an autocorrelation and optical spectrum from Device B. At 1589 mA and 0.56 V of reverse bias, stable mode-locking was observed at 7.92 GHz. The pulsewidth was 16 ps, the spectral width was 0.96 nm, and the average power was 489 mW. This translates to 62 pJ of pulse energy, to our knowledge a record pulse energy and average power from a mode-locked electrically pumped monolithic semiconductor laser. Mode-locking was achieved for currents from 600 to 1600 mA and biases ranging from 0.3 to 1.2 V. We have compared the locking regime of Device B (5-mm length with 0.3-mm absorber) with Device E (10-mm length with 0.8-mm absorber). While the mode-locked power from Device E is not as large as that from Device B, the locking regime is comparable. Fig. 4 shows the mode-locking stability regime for Device E. The stability regime is quite large, but we believe that the second stability area starting at 1200 mA is due to double pulsing. A maximum of 322 mW of average power was measured from the device under mode-locked operation. The laser's wavelength under mode-locked operation ranged from 973 to 985 nm.

To investigate the beam quality of the devices, we measured the M^2 of Device A, a 3-mm laser with a 0.3-mm absorber

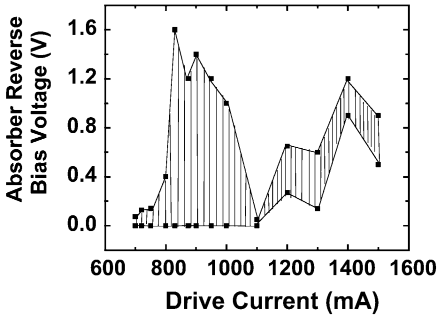

Fig. 4. Range of currents and biases that allow mode-locking in a 1-cm device with a 0.8-mm absorber section.

under both CW and mode-locked conditions, with a Shack–Hartmann wavefront sensor. Under CW conditions at a current of 658 mA, we measured an M^2 of 1.4 (vertical direction) $\times 1.93$ (horizontal). To mode-lock the laser, we reverse biased the absorber with 0.22 V, and then remeasured the beam quality. The laser had M^2 values of 1.16 and 1.61. The beam quality between CW and mode-locked operation does not vary significantly, and the device displays close to diffraction-limited operation. The beam quality of this device was most likely limited by fabrication errors. The typical beam quality of 980-nm and 1550-nm SCOWLs under CW operation is nearly diffraction limited [10], [11].

IV. Conclusion

We have achieved 62 pJ of pulse energy and 489 mW of average power from an electrically pumped passively mode-locked 5-mm monolithic 980-nm SCOWL. By placing these lasers in external cavities, we hope to obtain nanojoule-class pulse energies with kilowatt-peak powers, with the potential for as much as 10% conversion to the ultraviolet. A frequency-converted SCOWL that is compact, efficient, and wavelength-tunable is attractive for ultraviolet applications such as sensing, nonline of sight communications, and spectroscopy.

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