250 mW, 1.5 μm monolithic passively mode-locked slab-coupled optical waveguide laser

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We report the demonstration of a 1.5 μm InGaAsP mode-locked slab-coupled optical waveguide laser (SCOWL) producing 10 ps pulses with energies of 58 pJ and average output powers of 250 mW at a repetition rate of 4.29 GHz. To the best of our knowledge, this is the first passively mode-locked slab-coupled optical waveguide laser. The large mode and low confinement factor of the SCOWL architecture allows the realization of monolithic mode-locked lasers with high output power and pulse energy. The laser output is nearly diffraction limited with M^2 values less than 1.2 in both directions.

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Mode-locked lasers are of interest for a wide range of applications, including laser ranging and imaging, optical communications, nonlinear frequency conversion, arbitrary waveform generation, and optical sampling. To improve system performance, many of these applications require sources with a higher pulse energy and average power than are currently available. Electrically pumped mode-locked semiconductor lasers can be very efficient and compact but have previously been limited to average powers <50 mW and pulse energies <35 pJ without amplification.[1]

In this Letter we report the demonstration of an electrically pumped 1 cm long passively mode-locked slab-coupled optical waveguide laser (ML-SCOWL) operating at a wavelength near 1.5 μm. The laser has an average output power of 250 mW and pulse energy of 58 pJ at a fundamental repetition rate of 4.29 GHz. To our knowledge, the pulse energy reported here is 2 orders of magnitude higher than previously reported for 1.5-μm monolithic mode-locked lasers[2–4] and slightly higher than previously reported for any electrically pumped semiconductor laser.[1]

Average power in semiconductor lasers is often constrained by thermal effects or catastrophic optical damage (COD). For a fixed average power, lower repetition rates will have correspondingly larger pulse energies. Longer cavity lengths (and lower repetition rates) will be limited by mode-locking instabilities that develop when the cavity round-trip time is longer than the upper-state lifetime.[5] Furthermore, pulse energy can also be limited by mode-locking instabilities that develop when the pulse energy is comparable with the saturation energy.[6] This destabilization, due to carrier-induced index nonlinearities on the time scale of a single pulse, can be reduced by designing a device to have a large mode and a low confinement factor.

Multielement arrays,[7] bowtie gain regions,[1] and optically pumped vertical external cavity surface emitting lasers[8] (VECSELs) have all been used to increase the average power and pulse energy of semiconductor mode-locked lasers operating at wavelengths <1.0 μm. A VECSEL has been reported with 2.1 W average power and a 525 pJ pulse energy at 945 nm, but was optically pumped.[8] An actively mode-locked electrically pumped bowtie oscillator generated 36 mW of average power and a 34 pJ pulse energy at 845 nm.[1] Mode-locked semiconductor lasers operating near $\lambda=1.5$ μm typically have much lower pulse energies than those operating at wavelengths less than 1.0 μm. This is due to the shorter upper-state lifetime of the 1.5-μm devices caused by Auger recombination. At 1.5 μm, typical lifetimes in InGaAs/InGaAsP are hundreds of picoseconds,[9] whereas 1.0-μm InGaAs/InAlAs devices have nanosecond lifetimes.[10] Typically pulse energies from 1.5 μm devices are less than 0.5 pJ, average powers are less than 20 mW, and repetition rates are in excess of 40 GHz.[2–4] Longer devices that integrate active and passive waveguide sections have been reported with repetition rates lower than 10 GHz.[11,12]

Slab-coupled optical waveguide lasers (SCOWLs) are capable of generating high pulse energies and average power. SCOWL devices generate large optical modes with nearly circular diffraction-limited beam quality. This is achieved through the filtering of higher-order modes from an otherwise multimode rib waveguide to an adjacent slab region and tailoring the quantum wells (QWs) such that the fundamental mode is the only mode with net gain.[13] The effect is a low confinement factor ($\Gamma_{QW}\sim 0.3\%$) and low waveguide loss ~ 0.5 cm^{-1}.[14] This results in a high saturation energy and allows for centimeter-long device lengths for efficient heat removal and low fundamental repetition rates. These attributes are all favorable for achieving high pulse energies and high average power from a mode-locked semiconductor laser.

A schematic of the laser device is shown in Fig. 1. The lasers were grown via organometallic vapor-phase epitaxy (OMVPE) on an n-type (100) InP substrate. The material structure is as follows: 0.20 μm n-InP buffer layer, 1.0 μm n-InP cladding layer with graded doping [$n=(1.0–0.2)\times 10^{18}$ cm^{-3}], 4.9 μm lightly doped InGaAsP waveguide ($n=6.0\times 10^{16}$ cm^{-3}, $\lambda_g=1.03$ μm), nominally undoped MQW active region, 0.025 μm p-AlInAs carrier blocking layer ($p=1.0\times 10^{18}$ cm^{-3}, Al $=48\%$), 1.0 μm p-InP cladding with graded doping [$p=(1–8)\times 10^{17}$ cm^{-3}], 0.6-μm p-InP cap layer ($p=1$

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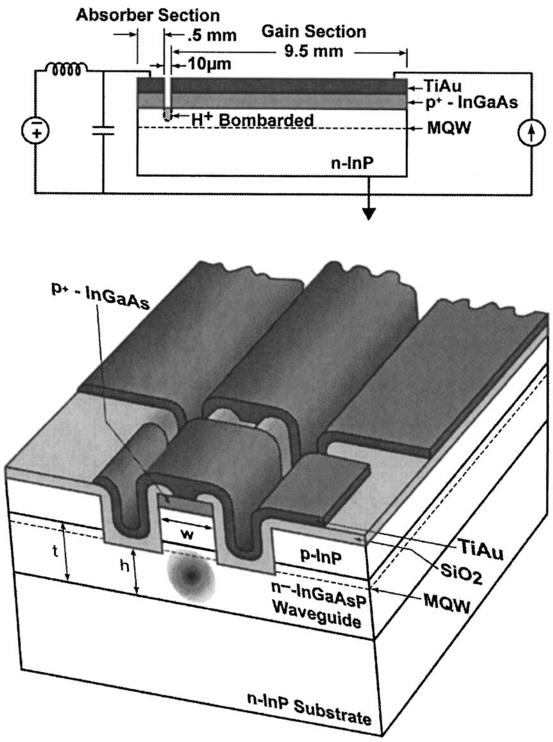

Fig. 1. Schematic of multisection slab-coupled optical waveguide laser device with waveguide dimensions: $w = 5.8\ \mu\text{m}$, $t = 4.9\ \mu\text{m}$, and $h = 4.5\ \mu\text{m}$.

$\times 10^{18}\ \text{cm}^{-3}$), and $0.2\ \mu\text{m}\ p^{+}$ InGaAs contact layer. The MQW active layer contains five 8 nm thick compressively strained (1%) InGaAsP quantum wells with tensile-strained InGaAsP (0.3%, $\lambda_g = 1.21\ \mu\text{m}$) barrier and bounding layers. The peak photoluminescence wavelength was $1.53\ \mu\text{m}$.

Figure 1 illustrates the basic device with its segmented gain and absorber contacts separated by $10\ \mu\text{m}$. The dimensions t, h, and w (4.9, 4.5, and $5.8\ \mu\text{m}$, respectively) are critical to achieving single-spatial-mode operation. The ridge was defined by CH_4–H_2–Ar reactive-ion etching followed by a short wet etch. A wet chemical etch was then used to remove the p^{+} contact layer from the mesa and the region between the contact pads. Silicon dioxide, nominally 290 nm thick, was deposited over the ridge for passivation. A Ti–Au p metallization was sputtered and patterned by wet etching. After thinning the wafers to $\sim 125\ \mu\text{m}$, an evaporated Ni–Ge–Au and sputtered Ti–Pt–Au n metallization was deposited on the wafer backside. Both contacts were alloyed at 450°C for 30 s. Finally, the wafers were proton bombarded to increase isolation between the gain and the absorber with dosages as follows: $1 \times 10^{14}\ \text{cm}^2$ at 210 keV, $5 \times 10^{13}\ \text{cm}^2$ at 120 keV, and $3 \times 10^{13}\ \text{cm}^2$ at 50 keV.

The laser has a total cavity length of 1 cm with an absorber length of $500\ \mu\text{m}$. The laser was mounted junction side up on a CuW submount with an AuSn solder. Dielectric coatings were evaporated on the facets to achieve 95% reflectivity on the facet adjacent to the absorber and 5% reflectivity on the output facet.

Initial measurements of the laser's cw performance were made with the gain and absorber regions electrically connected and forward biased. A maximum cw output power of 580 mW was generated with a drive current of 3.0 A. The laser threshold was 539 mA. The laser's near-field mode-profile $1/e^2$ intensity is $5.3 \times 7.0\ \mu\text{m}$ in diameter and is nearly diffraction limited, with M^2 values in the x and y directions of less than 1.2.

Passive mode locking of the device was obtained by forward biasing the gain section and reverse biasing the absorber section. A maximum average mode-locked output power of 250 mW is obtained with an absorber reverse bias of 1.8 V and a 3.0 A gain-section current. To our knowledge, this is the highest average power directly from a mode-locked electrically pumped semiconductor laser. For these measurements, an inductor and capacitor were incorporated in the absorber circuit to filter transients.

Figures 2(a) and 2(b) show the mode-locked output pulse train and optical spectrum under typical operating conditions (2.9 A gain-section current and 1.8 V saturable-absorber reverse bias). The 4.29 GHz pulse train, measured with a 45 GHz photodetector, is shown in Fig. 2(a). The optical spectrum, centered at 1544 nm, is shown in Fig. 2(b). It was measured with a resolution bandwidth of 0.1 nm and has a 3 dB bandwidth of 5.7 nm.

Figure 3 shows pulse-width measurements obtained by second-harmonic-generation (SHG) auto-

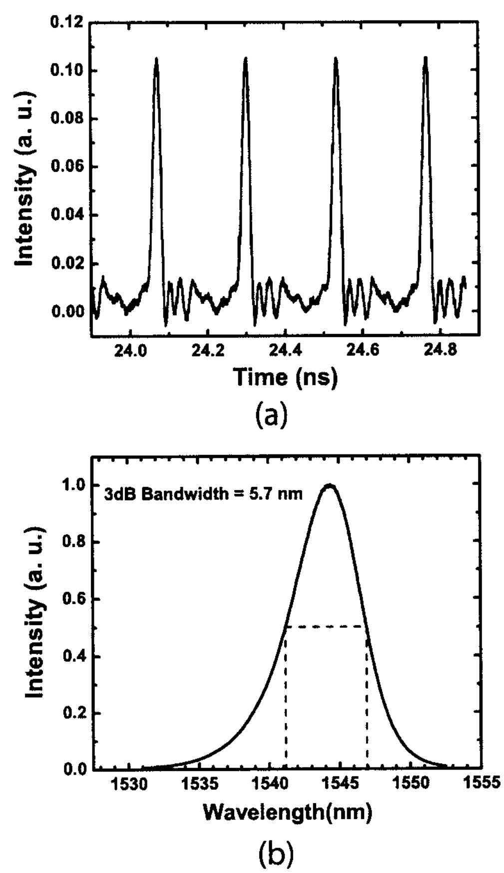

Fig. 2. (a) Sampling scope trace of pulse train. (b) Optical spectrum of mode-locked device measured with 0.1 nm of resolution.

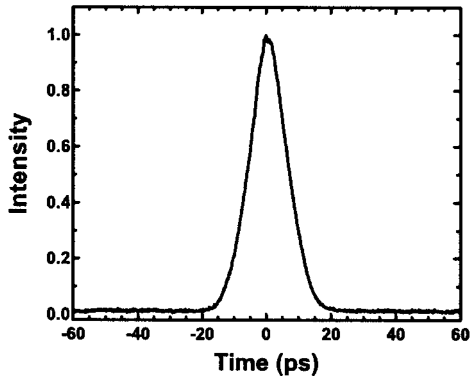

Fig. 3. Autocorrelation of mode-locked output.

correlation. The pulses were measured to have a width of 10 ps, assuming a Gaussian-shaped pulse, which corresponds to a time–bandwidth product of 7.5. Pulse compression to 4 ps was achieved with 200 m of single-mode 1550-nm fiber (SMF-28). It is possible that nonlinear chirp on the pulses prevents further compression. Blueshifting the absorber band edge or using an intracavity spectral filter may mitigate the chirp by controlling the laser wavelength and bandwidth.

We anticipate that the repetition rate of similar mode-locked SCOWL devices could be varied to fit applications. Continuous-wave-SCOWL devices at 1550 nm have been previously demonstrated with lengths ranging from 0.4 to 1.2 cm (corresponding to repetition rates from 10.7 to 3.6 GHz).[14] Devices shorter than 0.4 cm lase in a higher-order transverse mode due to gain guiding at higher current densities. Longer devices will be limited by mode-locking destabilization when the round-trip time exceeds the upper-state lifetime of the gain medium. It is also possible to tailor the center wavelength through material choice.

In conclusion, we have fabricated and demonstrated a 1.5 μm InGaAsP mode-locked slab-coupled optical waveguide laser producing 10 ps pulses at 4.29 GHz with an average output power of 250 mW. The 58 pJ pulses had a corresponding peak power of 5.8 W. These results represent an order-of-magnitude higher average power and 2 orders-of-magnitude higher pulse energy compared with previously reported semiconductor mode-locked lasers operating in the 1.5-μm wavelength range.[2–4] To the best of our knowledge, this is the first demonstration of a passively monolithically mode-locked slab-coupled optical waveguide laser.

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