Passively Mode-Locked Diode-Pumped Surface-Emitting Semiconductor Laser

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***Abstract*—A surface-emitting semiconductor laser has been passively mode locked in an external cavity incorporating a semiconductor saturable absorber mirror. The gain medium consists of a stack of 12 InGaAs/GaAs strained quantum wells, grown above a Bragg mirror structure, and pumped optically by a high-brightness diode laser. The mode-locked laser emits pulses of 22–ps full-width at half maximum duration at 1030 nm, with a repetition rate variable around 4.4 GHz.**

***Index Terms*—Diode-pumped laser, semiconductor laser, ultrashort pulses.**

OPTICALLY pumped vertical-external-cavity surface-emitting lasers (VECSELs) have generated both high average powers and circular diffraction-limited output beams [1]. In this type of semiconductor laser, both the beam quality limitations of edge-emitting diode lasers and the power restrictions of electrically pumped surface-emitting lasers are overcome. In addition, optical pumping of VECSELs allows scaling of the output power into the multiwatt range simply by increasing the laser mode area at higher pump powers. In this letter, we describe what we believe to be the first passively mode-locked surface-emitting semiconductor laser. The device is pumped optically by a high-brightness diode laser, and mode locked by a semiconductor saturable absorber mirror (SESAM) which forms part of an external cavity (Fig. 1). Previously, SESAMs have been extensively used to mode lock diode-pumped solid-state lasers [2], [3]. However, optically pumped VECSELs offer a number of advantages over those solid-state lasers.

There is a rapidly growing requirement for gigahertz repetition rate pulsed lasers for application in high-energy physics, in optical testing of semiconductor electronics and telecommunication components, in optical clocking of integrated circuits, and in optoelectronic performance enhancements of analog-to-digital converters. Recently, $Nd:YVO_4$ has been passively mode locked with pulse repetition rates as high as

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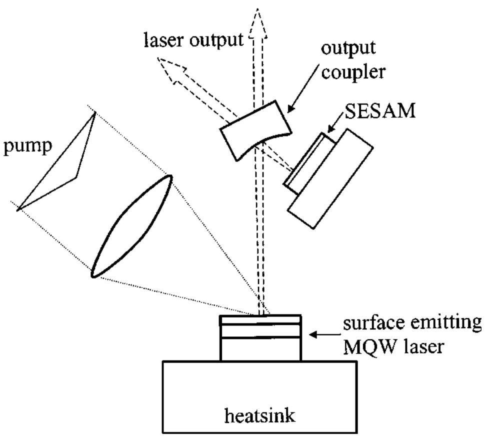

Fig. 1. Mode-locked diode-pumped VECSEL cavity with SESAM.

~30 GHz producing 6.8-ps pulses at a center wavelength of 1.064 μm with a maximum average output power of 80 mW [4]. However, extension of this result to subpicosecond pulses is unlikely because the large gain saturation fluence of broader band gain media such as Nd-doped glass leads to *Q*-switch instabilities at gigahertz repetition rates [5]. In contrast, the relatively small gain saturation fluence of semiconductor quantum-well lasers implies that they can be passively mode locked at repetition rates of several gigahertz with no tendency to *Q*-switching. A single quantum well exhibits a gain bandwidth of ~30 nm, sufficient to support subpicosecond pulses; moreover, laser structures incorporating wells of different widths have been used to demonstrate tunability over 80 nm [6]. A semiconductor quantum-well structure pumped by optical absorption in the barriers additionally offers great freedom in the selection of pumping and lasing wavelengths.

Saturable absorber mode locking of semiconductor diode lasers has been widely investigated before, both in an external cavity and in monolithic devices [7]. However, compared with other mode-locked solid-state lasers, mode-locked diode lasers are still low in output power and brightness, with the most powerful examples emitting only a few tens of milliwatts [8]. Thus, the power scaling potential of passively mode-locked diode-pumped VECSELs is attractive.

These potential advantages motivated an investigation of the device shown schematically in Fig. 1. A 2-W broad stripe diode laser emitting at 810 nm was used to pump the VECSEL continuously with up to 1.6 W focused onto a region of dimensions $\sim 90 \times 90\ \mu m^2$ on the surface of the platelet. The sample absorbed ~60% of the incident pump power. The optically pumped wafer and the SESAM formed the cavity end mirrors, and a spherical output coupler mirror, with radius 10 mm and transmission 0.4% at the laser wavelength, was used to fold the cavity.

The MOCVD-grown quantum-well gain structure used in this laser (Fig. 1) is similar to that described in [1]. It consists of an array of 12 compressively strained $In_{0.2}Ga_{0.8}As$ quantum wells between $GaAs_{0.94}P_{0.06}$ tensile-strained barriers, of thickness adjusted to balance the net strain in the structure to zero. The quantum wells are spaced by GaAs layers to intervals of $\lambda/2$. Underneath the multiple quantum well section lies a 27-repeat AlAs–$Al_{0.1}Ga_{0.9}As$ Bragg mirror. A window layer of 450-nm-thick $Al_{0.43}Ga_{0.57}As$ was grown over the multiple quantum well section to keep carriers away from the surface, and this was finished with a capping layer of 10 nm of GaAs. Platelets approximately 5-mm square were cleaved from this wafer, lapped, and polished to reduce the GaAs substrate to a thickness of $\sim$200 μm, and attached to a copper heat sink using indium. The spectrum of photoluminescence emitted from a cleaved platelet edge showed a strong peak at $\sim$980 nm. Platelets exhibited lasing at wavelengths over the range 1000–1040 nm, governed by the temperature of the pumped surface, and also by variation in layer thickness across the wafer.

The SESAM used in this laser (Fig. 1) consisted of an AlAs–GaAs Bragg mirror with 25 layer pairs and a low-finesse antiresonant $\lambda/2$ cavity incorporating a single 20-nm-thick $In_{0.2}Ga_{0.8}As$ quantum well grown by low-temperature (300 °C) molecular beam epitaxy (MBE). The low-intensity loss of the SESAM was $\sim$1.3%, and the bleaching response was bitemporal, with a 130-fs fast component and a 4-ps recovery time. As shown in Fig. 1, the V-cavity was made asymmetric, with cavity legs containing the SESAM and the gain wafer of length 6 and 28 mm, respectively. The cavity mode was, thus, focused more tightly on the SESAM than on the gain wafer, with a mode area $\sim$40 times smaller. The absorber saturation pulse energy was, therefore, sufficiently small relative to the gain saturation pulse energy to ensure fast absorption saturation and strong pulse shaping.

With 1.4 W of pump power incident on the wafer, the VECSEL emitted a total power of 21.6 mW divided equally between two beams. Further increase of the pump caused the output power to decrease due to thermal effects. Fig. 2 shows the fundamental peak observed in the radio-frequency spectrum of the photocurrent from a fast diode monitoring the laser output, corresponding to the cavity round-trip repetition rate of 4.43 GHz. The trace is free from sidebands down to the level of -70 dBc, demonstrating that the VECSEL exhibited stable, mode locking with no *Q*-switching instabilities. A measured pulse autocorrelation trace is shown in Fig. 3 (solid curve), with a best fit assuming a hyperbolic secant pulse (dashed curve), for which the full-width at half-maximum (FWHM) pulse duration is 22 ps.

Fig. 4 shows the optical spectrum of the laser, with a bandwidth of 0.25-nm FWHM. This laser bandwidth is consistent with the free spectral range of an etalon formed by the distributed Bragg reflector (DBR) and the back surface of the GaAs substrate, which is soldered to a copper mount with indium. In continuous-wave (CW) operation, with a highly reflecting mirror replacing the SESAM, jumps in the laser wavelength of $\sim$0.3 nm were typically observed. It therefore appears probable that, at resonant wavelengths of this substrate étalon, the DBR reflectivity is spoiled, restricting the bandwidth of the mode-locked laser within one free spectral range, a value smaller by an order of magnitude than the intrinsic bandwidth of the wells. In future work, roughening or angle polishing of the back surface will eliminate this effect.

The time-bandwidth product for these pulses is $\sim$1.5, indicating the presence of strong phase modulation effects. This is reminiscent of the behavior reported for synchronously pumped mode-locked VECSELs, for which time-bandwidth products more than two orders of magnitude larger than the diffraction limit have been observed [9]. Such pulses could, moreover, be compressed externally almost to the diffraction limit using only a diffraction grating pair [10]. Future work will establish whether the passively mode-locked VECSEL exhibits similarly linear chirp characteristics.

In summary, we have demonstrated the first passively mode-locked surface-emitting semiconductor laser. The compact, all-semiconductor device generates 22-ps pulses with 21.6-mW average power at a repetition rate of >4 GHz. There is scope for substantially increasing the output power from this device,

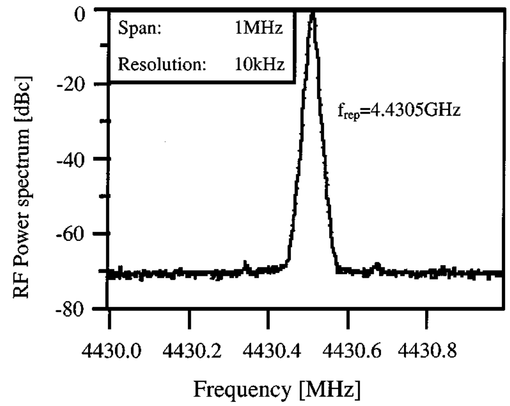

Fig. 2. Radio-frequency spectrum of the VECSEL power output showing mode locking without *Q*-switching instabilities at a repetition rate of 4.43 GHz. The signal was obtained with a 50-GHz photodiode and a 26-GHz amplifier and spectrum analyzer.

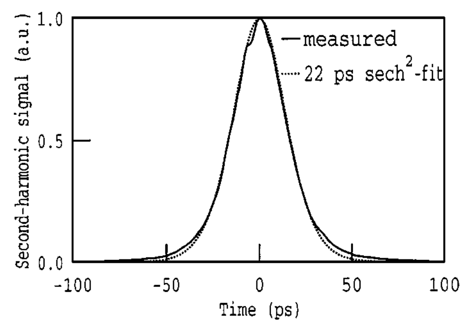

Fig. 3. Autocorrelation trace of the mode-locked pulses (solid curve). The dashed line represents a fit to the data assuming a hyperbolic secant pulse profile with 22-ps FWHM.

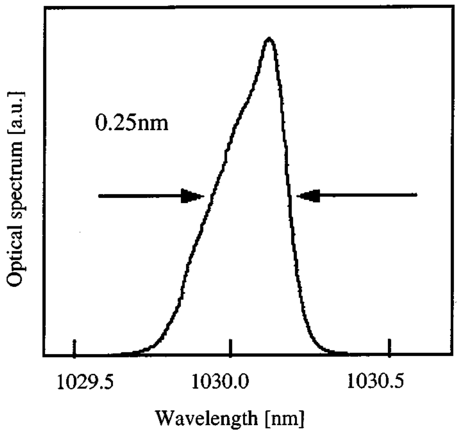

Fig. 4. Measured spectral profile of the mode-locked laser output.

firstly, because with better fabrication the thermal impedance can be greatly reduced [11], and secondly, because an improved wafer design, for example, based on an antiresonant cavity, can extend the operating temperature range. We propose to investigate the feasibility of achieving subpicosecond pulse durations by eliminating substrate étalon effects, and by external pulse compression. Such devices will be free of the *Q*-switching tendency that is inherent in passively mode-locked dielectric laser systems with high repetition rates. It is additionally interesting to consider the extent to which band-gap engineering can be used to shape the pulses, or even integrate gain and saturable absorption within the same wafer. We believe that this concept will lead to rugged, efficient pulsed laser sources with high average power in a diffraction-limited beam, subpicosecond pulse durations, and multigigahertz repetition rates.

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