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Passively mode-locked diode-pumped surface-emitting diode laser

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We demonstrate to our knowledge the first passively mode-locked surface-emitting semiconductor laser. We used a 2-W high-brightness diode laser as pump source and a semiconductor saturable absorber mirror (SESAM [1, 2]) as modelocker. The laser generates two stably mode-locked output beams with 11 mW average power each, 26 ps pulse duration, and a repetition rate of 4.4 GHz. In contrast to edge-emitting semiconductor lasers, optically pumped semiconductor vertical external cavity surface emitting lasers (OPS-VECSELs) allow one to scale up the mode area in order to generate a high average power and high pulse energies, while the external cavity enforces a diffraction-limited output. A diffraction-limited output with >0.5 W in cw operation has been demonstrated for a similar kind of device [3]. Thus our concept promises to be scalable to much higher average and peak powers than can be obtained from electrically pumped surface-emitting mode-locked diode lasers or from edge emitting diode lasers. Only synchronously pumped surface emitting semiconductor lasers have generated pulses with high average power and pulse energy, but these require a powerful pulsed pump source [4]. Compared to mode-locked lasers based on ion-doped crystals or glasses, mode-locked semiconductor lasers can generate high repetition rate (multi-GHz) pulse trains without Q-switching instabilities [5]. Their broad amplification bandwidth is sufficient for pulse durations in the femtosecond regime.

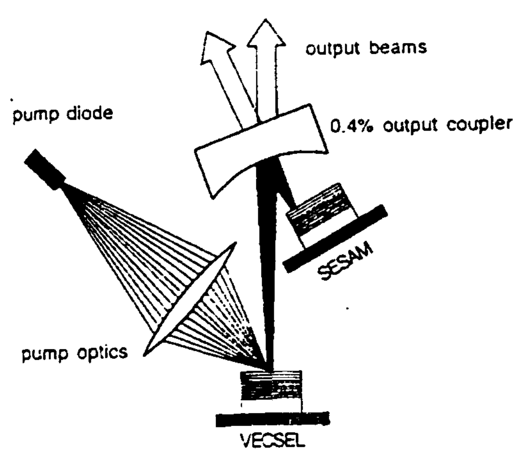

Fig 1. SESAM-mode-locked OPS VECSEL laser cavity

For our experiments we used the V-shaped laser cavity shown in Fig. 1. The optically pumped quantum well structure 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, folded the cavity.

The quantum well gain structure, grown by MOCVD on a GaAs substrate, is similar to that described in Ref. 3. It consists of an array of 12 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 $GaAs_{0.94}P_{0.06}$ layers are separated by GaAs layers which space the wells at intervals of $\lambda/2$, and 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 on the substrate face down to a thickness of ~100 µm, and soldered to a copper heat sink with indium. The spectrum of photoluminescence emitted from a cleaved platelet edge showed a strong peak at the design wavelength of ~980 nm, on which the Bragg mirror was centered, and at which the $\lambda/2$ spacing of adjacent quantum wells was set. There was, however, sufficient variation in layer thickness towards the edge of the wafer to allow us to select a platelet lasing at ~1030 nm, a wavelength at which SESAMs were readily available to us.

The SESAM consists of a 25-repeat AlAs/GaAs mirror and a low-finesse antiresonant $\lambda/2$ cavity hosting a single 20 nm thick $In_{0.2}Ga_{0.8}As$ quantum well. The absorber was grown with low temperature (300°C) molecular beam epitaxy (MBE). The low-intensity losses of the SESAM are about 1.3%, and the bleaching response is bitemporal with a 130-fs fast component and 4 ps recovery time.

A 2-W broad stripe diode laser emitting at 810 nm was used to pump the VECSEL continuously. Up to 1.6 W of pump power was focused into a region of dimensions ~ 90 x 90 µm^2 on the surface of the platelet at an angle of 45° with p polarization. The sample absorbed 60% of the incident pump power.

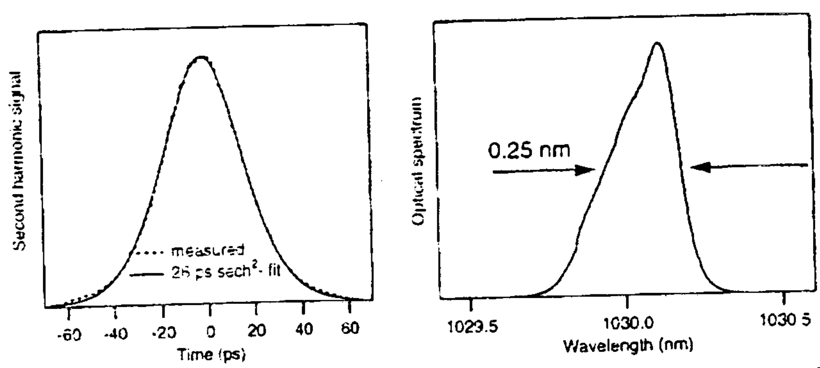

Fig. 2 a) Autocorrelation trace of the mode-locked laser. The solid line is a fit assuming sech^2-pulse shape. b) The optical spectrum is measured with a resolution of 0.1 nm.

The gain saturation fluence of the VECSEL is rather small, even smaller than the saturation fluence of the SESAM because the latter is an antiresonant structure while the VECSEL is resonant at the operation wavelength. Therefore we designed the laser cavity (Fig. 1) so that the mode area is ≈40 times smaller on the SESAM compared to the VECSEL, so that the gain saturation energy is larger than the saturation energy of the SESAM. Indeed we obtained mode locking in this operation regime, which is reminiscent of the regime in which mode-locked dye lasers are usually operated. For 1.4 W of pump power, the mode-locked OPS-VECSEL laser emitted a total power of 21.6 mW, divided equally between two near-diffraction-limited output beams. At higher pump powers we observed a decrease of output power due to heating effects. Fig. 2a shows the autocorrelation, from which we calculated the pulse width to be 26 ps. The spectral width (Fig. 2b) is 0.25 nm (full width at half maximum) and the time-bandwidth product is 1.8, indicating a chirp. The RF spectrum of the photocurrent from a fast photodiode is shown in Fig. 3 and demonstrates stable mode locking at 4.43 GHz repetition rate. Spans with a smaller resolution bandwidth reveal a jitter with ≈10 kHz width which probably arises from weak fluctuations of the cavity length in the order of 80 nm.

The 0.25-nm bandwidth of the mode-locked OPS-VECSEL is restricted not by the gain bandwidth (which is about an order of magnitude larger) but by coupled-cavity effects arising from the residual transmission of the Bragg mirror and reflection from the back side of the GaAs substrate which is soldered to the copper mount with indium. These effects are also apparent from fringes with ≈0.3 nm spacing in the optical spectrum for continuous operation (without SESAM). Thinning down the substrate further or roughening its back side should eliminate this effect. There is also an interference with the Fresnel reflection from the top surface of the device: the spacing of the corresponding fringes is tens of nanometers. The chirp of the pulses arises from gain saturation [6] and may in the future be reduced by external pulse compression which has lead to dramatic pulse shortening in synchronously pumped VECSELs [7].

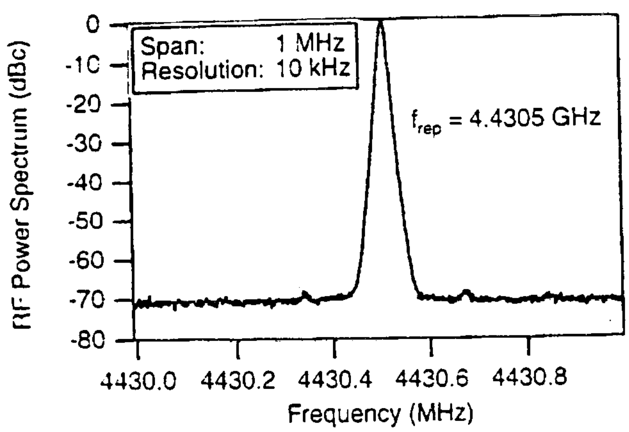

Fig. 3. Radio frequency spectrum of the photocurrent indicating mode locking at a repetition rate of 4.43 GHz. The signal was measured with a 26-GHz amplifier and spectrum analyzer and a 50-GHz photodiode.

In conclusion, we demonstrated the first passively mode-locked surface emitting semiconductor laser. Using a SESAM as modelocker, we obtained 26-ps pulses with 21.6 mW average power at 4.4 GHz repetition rate. We envisage substantial increases of output power from improved cooling schemes, improved VECSEL designs and a higher pump power (applied to a large spot), generated with high-power diode bars. Sub-picosecond pulse durations should be achievable by eliminating the mentioned coupled-cavity effects and by external pulse compression. 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 compact, reliable, cost-effective and efficient pulsed laser sources with high average power in a diffraction-limited beam, sub-picosecond pulse durations, and multi-GHz repetition rates.

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