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Hoogland, S., Garnache, A., Sagnes, I. et al. (2 more authors) (2005) 10-GHz train of sub-500-fs optical soliton-like pulses from a surface-emitting semiconductor laser. IEEE Photonics Technology Letters, 17 (2). pp. 267-269. ISSN 1041-1135

https://doi.org/10.1109/LPT.2004.839464

10-GHz Train of Sub-500-fs Optical Soliton-Like Pulses From a Surface-Emitting Semiconductor Laser

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***Abstract*—We report sub-500-fs operation of a passively mode-locked diode-pumped external-cavity surface-emitting semiconductor laser at a repetition rate of 10.014 GHz. For an incident pump power of 706 mW, the laser produced 486-fs soliton-like pulses, with an average output power of 30.3 mW. The role of the ac Stark effect in shaping subpicosecond pulses is demonstrated.**

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

COMPACT optical sources of ultrashort transform-limited pulses, operating at repetition rates of many gigahertz with high average power, are potentially of importance for applications such as optical interconnection, sampling, and signal processing. The vertical-external-cavity surface-emitting semiconductor laser (VECSEL) is capable of high average power in a diffraction-limited beam, and can readily be passively mode-locked using a semiconductor saturable absorber mirror (SESAM) [1]. These lasers have been operated with average power of almost 2 W in the 1-μm region [2]; they have also been realized at 1.5 μm using phosphide-based material [3]. Most implementations to date have used optical pumping; however, diode VECSELs have also recently been passively mode-locked, generating 15-ps pulses at repetition rates up to 15 GHz [4]. The passively mode-locked VECSEL is, moreover, particularly well-adapted to the generation of subpicosecond (sub-ps) pulses. We have previously demonstrated a laser emitting transform-limited 620-fs pulses at a repetition rate of 1.2 GHz and an average power of 100 mW [5]. In this letter, we report a short-cavity VECSEL, mode-locked at a repetition rate of >10 GHz, and generating near-transform-limited pulses of 486-fs duration. Mode-locked VECSELs naturally lend themselves to operation at high repetition rate; the low saturation fluence of the quantum-well gain medium allows multigigahertz repetition rates with no tendency to the spontaneous Q-switching that adversely affects passively mode-locked dielectric lasers [6].

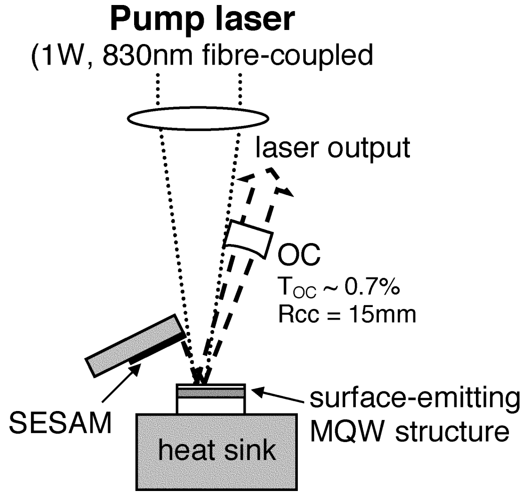

Fig. 1. Mode-locked diode-pumped VECSEL V-cavity with SESAM. OC: Output coupler mirror. T_{OC}: Output coupler mirror transmission.

The 15-mm-long laser cavity used to realize the 10-GHz repetition rate is shown in Fig. 1. The cavity has a V-shape, in which the gain structure forms an active folding mirror, and the end mirrors are the SESAM and a curved output coupler with radius of curvature (Rcc) of 15 mm and transmission of 0.7%. The short arm between the SESAM and the gain is about 2 mm long and the long arm is about 13 mm long, thus operating the cavity near its stability limit. The angle of incidence of the laser on the gain structure is about 25°, so that the SESAM structure does not occlude the pump beam. This angle shifts the wafer design wavelength of 1040 nm to about 1032 nm. The pump is a commercial 1-W 830-nm fiber-coupled multimode diode laser (SDL-2364-L2), that is focused on the gain structure in a 60-μm radius spot. In this cavity configuration, the laser spot size on the gain is about 60 μm in radius, and on the SESAM it has a waist of $\sim$13 μm. The area of the spot on the gain structure is, therefore, $\sim$20$\times$ larger than that on the SESAM, so that gain saturation remains modest for pulses that are sufficiently intense to be shaped by SESAM saturation. The laser operated in a circular TEM$_{00}$ beam.

The designs of the gain structure and the SESAM used in this laser have been described in detail previously [5]; both incorporated 27.5-pair AlAs–GaAs Bragg reflectors. The active region of the MOCVD-grown half-VCSEL structure contained six

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Manuscript received April 8, 2004; revised August 16, 2004. This work was supported by the Engineering and Physical Sciences Research Council, U.K.

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Digital Object Identifier 10.1109/LPT.2004.839464

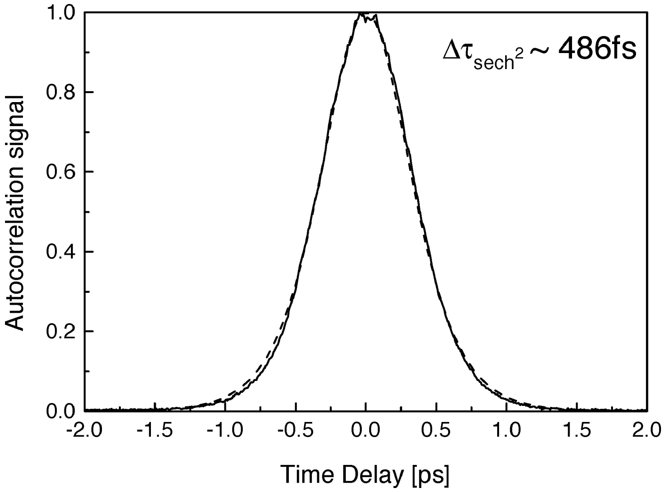

Fig. 2. Measured autocorrelation trace of the quasi-soliton pulse generated by the mode-locked VECSEL at a pump power of 706 mW, average output power of 30.3 mW. The dashed curve is a best-fit hyperbolic secant profile, pulse duration 486-fs FWHM.

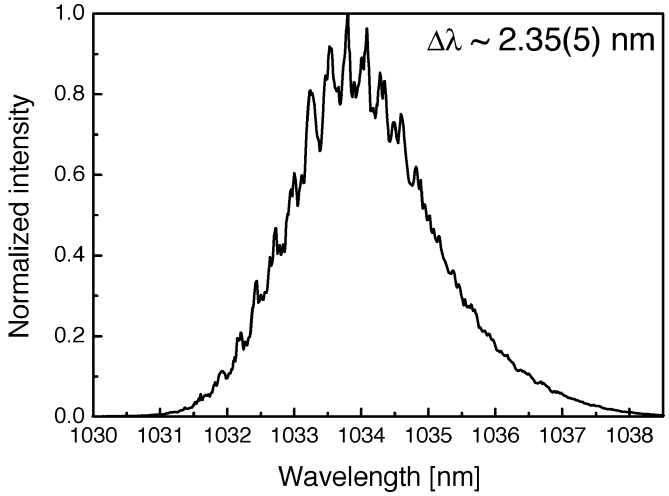

Fig. 3. Measured optical spectrum of the quasi-soliton pulse of Fig. 2. The spectrum has an FWHM of 2.35(5) nm. The modulation on the spectrum is caused by scattering from the back surface of the substrate under the gain structure.

strain-balanced InGaAs–GaAs quantum wells, designed for an operating wavelength of 1030 nm. The absorbing element of the SESAM was a single InGaAs–GaAs quantum well, with band edge at 1025 nm. The saturation fluence on the exciton peak was estimated to be $\sim 100\ \mu\mathrm{J}\cdot\mathrm{cm}^{-2}$. The well was positioned 2 nm below the air surface of the structure, so that rapid carrier recombination at the surface ensured a short absorption recovery time. An SESAM structure of identical design, grown in a different reactor, exhibited a measured absorption recovery time of 21 ps [5]. The calculated wavelength dependence of the group dispersion delay (GDD) of the SESAM and the gain structure have been reported in [5]. Both devices are designed to operate over the range 1030–1050 nm; the GDD of the gain structure varies (nonlinearly) from 900 fs^2 to 0 over this range; the SESAM from -10 to -50 fs^2.

The laser exhibited stable self-starting mode-locking at a wavelength that could be tuned from ~1030 to 1040 nm by varying the incident pump power on the wafer. At either end of the tuning range ~1.5-ps pulses were formed. Within this range, the pulse duration passed through a minimum at 706-mW incident pump power, at an operating wavelength of 1034 nm. This wavelength range lies just to the low energy edge of the SESAM exciton resonance; thus, the laser operated in a regime where the ac Stark effect contributes a fast nonlinearity to the SESAM response [7]. The intensity autocorrelation of the mode-locked pulse is shown in Fig. 2; it exhibits a pedestal-free profile (solid line); the fit represents a hyperbolic secant pulse of full-width at half-maximum (FWHM) duration 486 fs (dashed line). The average output power was 30.3 mW. The radio-frequency spectrum of the laser exhibited a stable peak at 10.014 GHz, with a linewidth of >500 kHz at the -85-dB noise floor, attributed to cavity instabilities. The optical spectrum, shown in Fig. 3, had an FWHM bandwidth of 2.35(5) nm and is slightly modulated with a period of ~0.25 nm corresponding to the etalons between the Bragg reflector and the bottom of the substrate in each unprocessed wafer. The time-bandwidth product of the pulse is 0.32(1).

The near-transform-limited nature of the hyperbolic secant pulse deserves comment in view of the phase shifts associated with saturation effects in semiconductor lasers. We have, therefore, estimated the size of the dominant phase shifts. The accumulated round-trip GDD is $\sim +400$ fs^2, corresponding to a phase shift of $\sim +3.6$ mrad for a pulse of bandwidth 2.4 nm. Within the gain structure, gain saturation gives rise to a phase shift of $+(2\text{–}3)$ mrad per round-trip [9]; the phase shifts produced by the Kerr effect and two-photon absorption (TPA) are negligible by comparison. In the SESAM, the phase shift associated with absorption saturation is estimated to be $-(4\text{–}5)$ mrad [9]; moreover, the tightly focused mode induces significant Kerr and TPA phase shifts, of order $-(0.2\text{–}0.5)$ and $-(0.1\text{–}0.2)$ mrad, respectively [10]. The overall phase shift per round-trip induced by saturation, TPA and the Kerr effect is, therefore, estimated to be $\sim -(1\text{–}4)$ mrad. The size range brackets the calculated GDD phase shift, and the sign is opposite. Numerical analysis has shown [8] that the net effect of gain and absorption saturation can be qualitatively similar to that of a negative Kerr medium, allowing quasi-soliton pulses to circulate in the presence of positive GDD.

To investigate the effect of adjusting GDD, and the influence of the ac Stark effect, we studied the variation of pulse properties as a function of pump power. Increasing pump power raises the temperature of the active region, shifts the pulses to longer wavelength and smaller values of +ve cavity GDD, tunes the laser through the SESAM exciton resonance where the ac Stark effect operates, and varies pulse energy, duration, and peak intensity, modifying the intensity-dependent phase shifts. Fig. 4 shows the pump power dependence of (a) the intracavity peak power and average output power, (b) the pulse duration, (c) the optical bandwidth, (d) the time-bandwidth product, and (e) the center wavelength of the spectrum. The center wavelength of the mode-locked laser tunes monotonically by ~20 nm/W. For increasing pump power, the pulse duration shortens from ~2 ps to <500 fs. Further increase in pump power initially has little effect on the pulse duration, however, for pump power

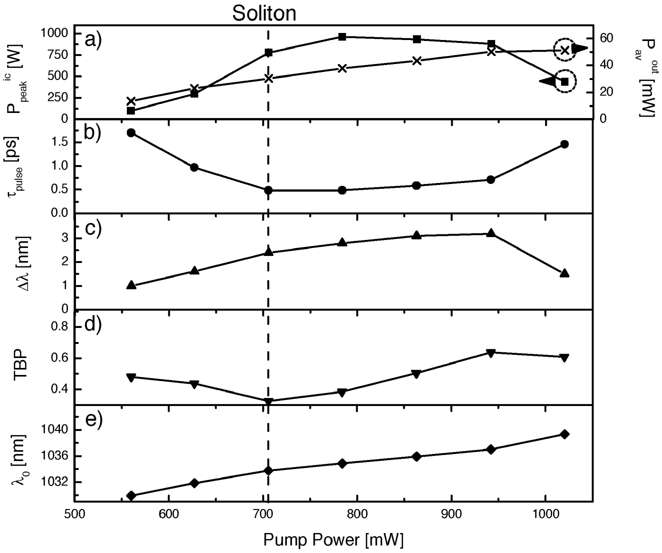

Fig. 4. Incident pump power dependence of (a) intracavity peak power (left, squares) and average output power (right, crosses); (b) pulse duration; (c) spectral bandwidth; (d) time-bandwidth product; and (e) center wavelength. The repetition rate was 10.104 GHz and the temperature of the gain structure was 283 K.

$>\sim$950 mW, the pulses revert abruptly to the picosecond regime. The time-bandwidth product has a shallow minimum around the point at which the pulses are transform-limited; at the longest wavelength it appears to decrease again.

The long pulses seen at low pump power are formed in a regime in which the intracavity peak power is low, the phase shifts due to saturation are low, and the net cavity GDD at the operating wavelength is <1000 fs^2. The contribution from the ac Stark effect to the pulse formation is likely to be small at this wavelength. Increasing the pump power tunes the center wavelength of the optical spectrum into the ac Stark regime; stronger pulse shaping with fast recovery produces a shorter pulse with a broader spectrum. The corresponding increase in intracavity peak power generates larger phase shifts due to saturation, however, these are balanced by the +ve GDD. Both pulse duration and time-bandwidth-product take minimum values for incident pump power of 706 mW. Tuning to yet longer wavelength reduces the cavity GDD, so that quasi-soliton formation can only support longer pulses. Fig. 4(a) shows that for increased pump power, the average power increases monotonically, while the intracavity peak power decreases slightly as a result of the slight increase of the pulse duration. In addition, the modulation depth associated with the ac Stark effect decreases with increasing wavelength, until it ceases to contribute, and the SESAM operates as a slow saturable absorber with a small modulation depth. At the longest wavelengths studied, the pulses revert to $\sim$1.5-ps duration, the phase shifts due to saturation and GDD become very small, and the pulse experiences less chirp, as can be noted in Fig. 4(d), where the time-bandwidth product decreases for a pump power of >1 W.

In conclusion, we have developed a diode-pumped VECSEL, passively mode-locked by an SESAM, that was operated for the first time at a repetition rate of >10 GHz without showing any evidence of Q-switching instabilities. The laser emitted near-transform-limited quasi-soliton pulses of duration 486 fs. A study of the variation of pulse characteristics with pump power confirmed that the ac Stark effect plays an important role in the generation of sub-ps pulses. Future work will involve scaling these lasers to higher repetition rates and higher average power.

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