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Picosecond pulse generation with 1.5 μm passively modelocked surface-emitting semiconductor laser

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The authors report the first demonstration of an optically pumped passively modelocked surface-emitting semiconductor laser operating in the 1.5 μm region. The modelocked laser emits pulses of 6.5 ps full width at half maximum duration with an average power of 13.5 mW at a fundamental repetition rate of 1.342 GHz. The peak power was 1.6 W.

Introduction: The vertical external cavity surface emitting laser (VECSEL) combines the spectral versatility of a semiconductor quantum well gain medium with the capacity to operate at high average power in a circular diffraction-limited beam [1]. The surface-emitting gain structure can be optically pumped by a high power diode laser, and in this way multi-watt continuous-wave (CW) operation has been reported for 0.95 μm devices [2, 3]. The external cavity allows the introduction of a nonlinear element, in particular a semiconductor saturable absorber mirror (SESAMs) with which such lasers have been passively modelocked for the first time [4]. In addition, the broad gain bandwidth of semiconductor quantum wells (QWs) is of interest for ultrashort pulse generation; recently, near transform-limited pulses of sub-500 fs duration have been reported with a VECSEL [5], with a peak power of 152 W and an average output power of 100 mW.

The modelocked VECSELs reported hitherto have operated in the 1 μm spectral region, where strained InGaAs/GaAs quantum wells and highly reflective GaAs/AlAs Bragg mirrors can be grown in the same run. Recently, 1.5 μm CW operation of InP-based VECSELs has been demonstrated [6]. In this Letter we report the first modelocked 1.5 μm surface-emitting semiconductor laser.

VECSELs are of particular interest as 1.5 μm optical pulse sources since they can be passively modelocked at multi-GHz repetition rates [2, 3] without any Q-switching instabilities [7]. This feature results from the high differential gain of $\sim 10^{-15}$–10^{-16} cm^2 and correspondingly low gain saturation fluence of the semiconductor gain medium. In the 1.5 μm spectral region, a Cr^{4+}:YAG microchip laser has been modelocked at repetition rates up to 10 GHz limited by Q-switching instabilities [8]; a passively modelocked picosecond diode-pumped Er:Yb:glass laser has been reported at a repetition rate of 10.52 GHz [9] with average output powers of 10 mW. Compared to this approach, a VECSEL has an intrinsically power-scalable design, promising significant further increases of output power. The VECSEL gain bandwidth typically extends over 5 THz, which is sufficient for sub-100 fs pulses. The limits for the pulse repetition rate yet have to be explored. An advantage of an air-filled extended VCSEL cavity of high finesse is the high pulse train stability compared to the case of an edge-emitting configuration.

Experiment: In the following, we describe the first passively modelocked OP-VECSEL at 1.5 μm. The Z-shaped laser cavity is similar to that described in [5]. A 1 W fibre-coupled diode laser emitting at 980 nm was focused to a 60 μm radius spot on the surface of a processed gain structure (described later). The end mirrors of laser cavity were the SESAM and a spherical output coupler mirror with 50 mm radius and a transmission of 0.8% at the laser wavelength. The gain structure and a highly reflecting spherical mirror with a radius of 15 mm constituted the folding mirrors. The calculated spot radius on the SESAM was ~10 μm, resulting in a mode area ratio between the gain and the SESAM of ~36, ensuring strong saturation of the SESAM without too strong saturation of the gain. Astigmatism was kept to a minimum by keeping the angle of incidence on the spherical folding mirror smaller than 6°.

The quantum well gain structure used in this laser consists of a 22 pair InP/InGaAlAs Bragg reflector (DBR), a strain-balanced InGaAsP multiple-quantum-well active region, and an InP output window [6]. The DBR and the output window form a resonant cavity with the quantum wells placed at positions with maximum field intensity. The structure was grown by MBE on an InP substrate in reverse order. The DBR side of the structure was bonded onto a silicon substrate, which in turn was indium soldered onto a brass block, and the InP substrate was etched away. There is no etalon formed in the gain sample since it has a gold mirror below the DBR, which absorbs all transmitted light. The resulting device was mounted on a Peltier-cooled copper block that was kept at a temperature of about −8°C. A dry nitrogen gas flow was applied over the sample to avoid any atmospheric water condensation. From the room temperature reflectivity spectrum of the processed sample, shown in Fig. 1 (dashed curve), it can be seen that the structure exhibits a stop band from 1465 nm to 1580 nm, which had a measured peak reflectivity of more than 99.8%, and a cavity mode at about 1505 nm. With a highly reflecting mirror in place of the SESAM, the processed gain structure operated continuously at a laser wavelength of 1514 nm, with a maximum output power of 20 mW in a single transverse mode for 1 W of incident pump power.

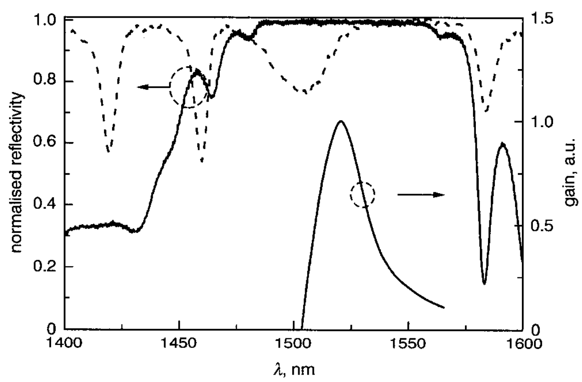

Fig. 1 *Reflectivity spectrum of gain structure and SESAM*
Position and typical shape of quantum well gain is also shown

The SESAM is an InP-based device, grown with metal-organic chemical vapour deposition (MOCVD). It contains a single 7.5 nm thin InGaAs absorber layer. The recovery time is 20 ps, the modulation depth 0.8% and the saturation fluence 14 μJ/cm^2 (all measured at 1535 nm). The reflectivity spectrum of this device is shown in Fig. 1 (solid curve).

Results: For modelocking, we replaced the mirror with the SESAM and obtained an average output power of 13.5 mW for 1 W incident pump power. The laser output beam was characterised with an autocorrelator for pulse width measurements, a fast photodiode connected to a radio frequency (RF) spectrum analyser, and an optical spectrum analyser. The RF spectrum showed a clean peak at the fundamental 1.342 GHz repetition rate of the cavity, characteristic of stable modelocking. The peak went down to the noise level at −70 dBm and had a width of less than 30 kHz at the noise level. The corresponding autocorrelation is shown in Fig. 2 (solid curve) with a fitted hyperbolic secant pulse profile (dashed curve), corresponding to a full width at half maximum (FWHM) pulse duration of 6.5 ps.

The inset of Fig. 2 shows the optical spectrum, exhibiting a bandwidth of 0.5 nm FWHM at a centre wavelength of 1518.4 nm. The spectrum is with peaks separated by ~35 GHz corresponding to the small satellite pulse at ~30 ps from the main pulse.

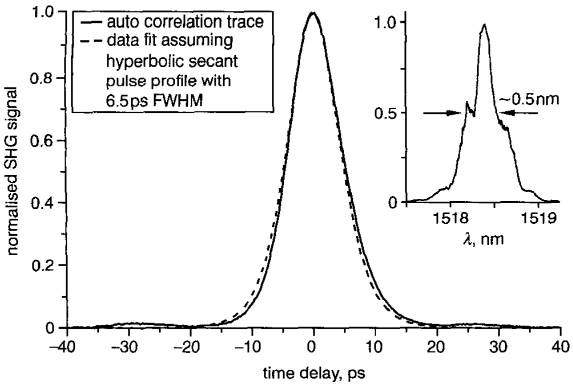

Fig. 2 *Autocorrelation trace of modelocked pulses*

Small satellite pulse can be observed at about 30 ps from main pulse. Slight asymmetry in measured trace is due to imperfect alignment of autocorrelator
Inset: Measured optical spectrum of modelocked laser output

The time-bandwidth product of the obtained pulses is ~0.42, which is ~1.3 times the Fourier limit for sech^2-shaped pulses. Future work will involve designs of gain structures in which dispersive and nonlinear phase shifts will cancel to give transform-limited pulses [5].

Conclusion: In summary, we have shown that passive modelocking of diode-pumped VECSELs, first demonstrated in the 1 μm region, can be transferred to other wavelength ranges using different semiconductor materials. We have reported here the first passively modelocked diode-pumped surface-emitting semiconductor laser at 1.5 μm. The all-semiconductor device generated 6.5 ps pulses with 13.5 mW average power at a fundamental repetition rate of 1.342 GHz. In the future, the pulse duration can be reduced by at least one order of magnitude, since the technique that was used to generate sub-500 fs pulses from a 1 μm OP-VECSEL can be implemented in the 1.5 μm laser. Improving the slope efficiency to realise a higher output power will be a major task, involving the reduction of losses in the SESAM structure and of the thermal resistance of the gain device. More compact cavity designs will allow operation at multi-gigahertz repetition rates. We believe that the concept of passively modelocked diode-pumped VECSELs will lead to compact, efficient high power pulsed lasers in various interesting wavelength regions, and that they may find applications such as photonic switching and optical clocking.

Acknowledgments: The authors would like to thank the Systems group of the Optical Research Centre at the University of Southampton and in particular J. Teh for supplying the necessary equipment and useful discussions. The authors from Southampton gratefully acknowledge the financial support of the Engineering and Physical Sciences Research Council. The work at ETH Zürich was supported by a research grant from ETH and the Swiss Commission for Technology and Innovation (KTI/CTI).

31 March 2003
Electronics Letters Online No: 20030576
DOI: 10.1049/el:20030576

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Frequency selective absorption using lumped element frequency selective surfaces

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A three-layer frequency selective surface (FSS) filter is presented that over a narrow frequency band simultaneously attenuates the microwave signal transmitted through and reflected from the filter. This is achieved using a lumped element resistive FSS in between a conventional FSS and a lumped element capacitive FSS. The device is simulated and its functionality is experimentally confirmed using a waveguide setup. More than 30 dB attenuation is observed in both the reflected and transmitted power.

Introduction: Band-stop frequency selective surfaces (FSS) are filters designed to block, by reflection, the transmission of a microwave signal through them. Such reflection may be unwanted when trying to improve, by frequency selective shielding, the spectrum efficiency of indoor wireless communication networks as they can lead to undesirable multpath effects. Hence, the use of an absorbing frequency selective surface is proposed. The use of FSS in designing a broadband Jaumann absorber has already been explained by Munk [1]. This absorber consists of multilayer resistive sheets backed by a conductive screen [2]. The latter blocks the transmission of all the frequencies. The thickness of the absorber can be reduced by using capacitive sheets [3]. Such an absorber can become frequency selective by replacing the conductive screen with an FSS. This was demonstrated in [4] using a combination of FSS and thin film ITO.

Presented in this Letter is an alternative approach, support by simulation results, that has the potential of realising a large-scale smart absorber. A combination of lumped-element resistive and capacitive FSS [5] backed by a conventional FSS is proposed to achieve, simultaneously, frequency selective reflection and transmission. Using transmission line theory, as described in [1], this novel FSS structure is designed and subsequently experimentally assessed in a waveguide. The experimental results show simultaneous 30 dB attenuation in the reflected and transmitted power at around 2.24 GHz.