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Passively harmonically mode-locked vertical-external-cavity surface-emitting laser emitting 1.1 ps pulses at 147 GHz repetition rate

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Coupled-cavity passive harmonic mode-locking of a quantum well based vertical-external-cavity surface-emitting laser has been demonstrated, yielding an output pulse train of 1.5 ps pulses at a repetition rate of 80 GHz and with an average power of 80 mW. Harmonic mode-locking results from coupling between the main laser cavity and a cavity formed within the substrate of the saturable absorber structure. Mode-locking on the second harmonic of the substrate cavity allows a train of 1.1 ps pulses to be generated at a repetition rate of 147 GHz with 40 mW average power.

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Mode-locked lasers with repetition rates in the 10–100 GHz range are of significant interest for applications including optical sampling,¹ arbitrary waveform generation,² and nonlinear applications such as large-mode-spacing supercontinuum generation.³ To date, high repetition rate sources have tended to be either harmonically mode-locked fiber lasers, which have reached repetition rates up to 200 GHz,⁴ or harmonically mode-locked semiconductor diode lasers, with repetition rates in the terahertz range.⁵ While both these types of source are capable of reaching high repetition rates, their performance tends to be limited in terms of both output power and pulse duration. Recent progress in solid state sources has allowed repetition rates in the 10 GHz range for femtosecond pulses⁶ and the 100 GHz range for picosecond pulses,⁷ but further progress is likely to be difficult due to both mechanical constraints and constraints placed by the laser dynamics.

Mode-locked vertical-external-cavity surface-emitting lasers (VECSELs) have been demonstrated with pulses as short as 60 fs,⁸ average powers as high as 2.1 W,^{9,10} and repetition rates up to 50 GHz.¹¹ These sources are ideally suited to high repetition rates as their active mirror architecture allows for very compact cavities and their short upper state lifetimes (of the order of 1 ns) provide strong suppression of Q-switching instabilities. Despite this, most of the demonstrations of mode-locked VECSELs have been at repetition rates in the 1–10 GHz range, limited by the difficulty of constructing short cavities with the required spot sizes on the gain sample and semiconductor saturable absorber mirror (SESAM). These mechanical limits can be overcome by integrating a quantum well based gain medium and a quantum dot based saturable absorber into a single sample. This concept, known as the mode-locked integrated external-cavity surface-emitting laser,¹² has been demonstrated but has yet to reach repetition rates beyond 10 GHz.

Harmonic mode-locking of VECSELs provides an alternative route to high repetition rates, while still allowing relatively large cavities and simple sample designs to be used. Harmonic mode-locking has already been demonstrated in

VECSELs, both in a coupled cavity configuration¹³ and as a result of gain saturation the laser,¹⁴ but the repetition rates achieved did not exceed 10 GHz. Here, we present a VECSEL emitting pulses as short as 1.1 ps at repetition rates up to 147 GHz via passive harmonic mode-locking in a coupled cavity configuration.

The layer structures of the gain sample and saturable absorber used in this work are similar to those of the structures used to demonstrate 500 fs pulses at 10 GHz in Ref. 15. In this work, however, the samples were grown by molecular beam epitaxy rather than metal-organic chemical vapor deposition as used in the previous work. The gain sample contains 6 InGaAs quantum wells in a close-to-antiresonant active region grown on top of a 27.5 repeat AlAs/GaAs distributed Bragg reflector (DBR). The SESAM consists of a single absorbing InGaAs quantum well placed 2 nm from the air interface in order to take advantage of fast surface recombination. The quantum well is grown above a DBR identical to that in the gain sample. The design reflectivities of both sample DBRs are 99.95% at the center wavelength. Both samples are grown on GaAs substrates with a thickness of approximately 0.5 mm and with unpolished back surfaces.

The laser cavity used here was a Z-cavity with a fundamental repetition rate of 984 MHz, similar to that in Ref. 8, with mode radii of 60 μm on the gain sample and 15 μm on the SESAM. The gain sample was optically pumped using an 830 nm fiber-coupled diode laser. By translating the output coupler, the laser could be made to mode-lock at certain cavity lengths, emitting pulses with a duration of 1.5 ps at a repetition rate of 80 GHz, corresponding to the 81st harmonic of the main laser cavity. The average power was 80 mW with 0.3% output coupling and with the gain sample held at a temperature of -8°C and a pump power of 1.5 W.

The autocorrelation and the optical spectrum of the laser are shown in Fig. 1. The spectral bandwidth is 0.85 nm, making the pulses 1.1 times transform limited. The optical spectrum shows modulations with spacing of 0.27 nm, although the resolution of these modulations is instrumentally limited. The rf spectrum of the laser [inset in Fig. 1(b)] showed no peaks up to the 20 GHz bandwidth limit of the instrument. The lack of peaks in the rf spectrum and the

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FIG. 1. (Color online) (a) Autocorrelation of the laser output including a sech^2 fit to the zero delay peak indicating a pulse duration of 1.5 ps. (b) Optical spectrum showing modulations with a spacing of 0.27 nm and a bandwidth 0.85 nm. Inset: rf spectrum of the laser showing no peaks up to the 20 GHz bandwidth of the instrument.

suppression of longitudinal modes that are not resonant with the coupled cavity provide excellent evidence for harmonic mode-locking. No signs of Q-switched mode locking were seen in either the autocorrelation or the rf spectrum.¹⁶

The modulations in the optical spectrum and the repetition rate of the pulses both correspond to the free spectral range of a GaAs etalon with a thickness of 550 μm . This is close to the estimated thickness of the SESAM substrate, although the thickness of the substrate was not measured directly. This implies that harmonic mode-locking results from a pulse being partially transmitted by the SESAM DBR into the SESAM substrate, scattered from the rear surface of the sample, and coupled back into the main cavity by partial transmission back through the DBR.

The pulse duration depends on the size of the mode on the SESAM, with smaller mode radii, and therefore higher fluences on the absorber, giving shorter pulses. It was not possible to reduce the pulse duration below 1.5 ps by focusing more tightly on the SESAM as the high divergence from a smaller spot affects the coupling between the cavities, causing the mode-locking to become unstable.

It may appear surprising that coupling from the main cavity to the cavity formed in the SESAM substrate can have such a dramatic effect on the laser performance. The high reflectivity of the SESAM DBR means that the coupling between the two cavities is extremely weak. In addition, the finesse of the substrate cavity is low due to the roughness of the unpolished back surface of the sample. Taken together, the high reflectivity of the DBR and the low etalon finesse mean that only $\sim 10^{-7}$ of the energy in a pulse is coupled into

the SESAM substrate and back into the main cavity. That such a small effect can affect the laser is partly due to the susceptibility of these low gain lasers to perturbation and partly due to the dynamics of these lasers, making high repetition rate operation energetically favorable. The few-nanosecond upper state lifetime means that loss of energy due to spontaneous emission is minimized at multigigahertz repetition rates. It is also possible that the short time interval between pulses means that the SESAM remains partially bleached from pulse to pulse, again encouraging high repetition rates.

Another interesting feature of this laser is that the mode-locking mechanism must be different from that in a fundamentally mode-locked VECSEL, as the typical intracavity pulse energies differ by two orders of magnitude between the two systems. The pulse fluence on the SESAM in the lasers described here is $\sim 10 \mu\text{J}/\text{cm}^2$, rather than $\sim 1 \text{ mJ}/\text{cm}^2$ in a fundamentally mode-locked VECSEL. This fluence is well below the saturation fluence of the SESAM, which is estimated to be $\sim 100 \mu\text{J}/\text{cm}^2$.¹⁵ At present, it is not clear what mechanism is responsible for the mode-locking, although we note that pulse shaping does still occur in saturable absorbers even below the saturation fluence.

The output of a coupled cavity harmonic mode-locked VECSEL depends strongly on the relative lengths of the two cavities. Stable mode-locking was only observed when the optical path length of the main cavity was set to an integer multiple of that of the substrate cavity. It was also possible to see mode-locking on the second harmonic of the substrate

FIG. 2. (Color online) (a) Autocorrelation of a 147 GHz train of 1.1 ps pulses from a VECSEL mode-locked on the second harmonic of the substrate cavity. (b) Optical spectrum of the laser showing modulations with a spacing of 0.4 nm. The 1.25 nm bandwidth indicates that the pulses are 1.2 times transform limited.

cavity by tuning the main cavity such that its length was an odd integer multiple of half the substrate cavity length.

Figure 2 shows the autocorrelation and optical spectrum of such a laser operating at a repetition rate of 147 GHz with a pulse duration of 1.1 ps. In this case, the gain sample and SESAM used were identical to those in Ref. 8, but with a single layer antireflection coating applied to both samples. The effect of the antireflection coating is not clear, although it is likely that it increases the coupling from the main cavity into the SESAM substrate by reducing the magnitude of the Fresnel reflection at the sample surface. The gain sample was held at -20°C , giving an average power of 40 mW with an output coupling of 0.7% and 1.9 W pump power. In this case, a lower resolution spectrometer was used, but modulations with spacing of 0.4 nm are clearly visible in the optical spectrum. Again, the rf spectrum showed no peaks up to the bandwidth limit of the instrument.

In conclusion, passive harmonic mode-locking has been demonstrated in a VECSEL by coupling the main laser cavity to a cavity formed within the SESAM substrate. The resulting laser emits pulses at a repetition rate set by the free spectral range of the SESAM substrate cavity. The laser output is a train of 1.5 ps pulses at a repetition rate of 80 GHz. Adjusting the main cavity length allowed a different VECSEL to be mode-locked on the second harmonic of the substrate cavity, giving 1.1 ps pulses at 147 GHz. Harmonic mode-locking is confirmed by the absence of peaks in the rf spectrum up to the bandwidth limit of the instrument and by the presence of strong modulations in the optical spectrum.

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