High peak power, sub-ps green emission in a passively mode locked W-cavity VECSEL

JASON T. MEYER,1,* MICHAL L. LUKOWSKI,1 CHRIS HESSENIUS,1 EWAN M. WRIGHT,1 AND MAHMOUD FALLahi1

College of Optical Sciences, The University of Arizona, Tucson, AZ 85721, USA
*jtmeyer@email.arizona.edu

Abstract: We report on the experimental results of a passively mode-locked vertical external cavity surface emitting laser (VECSEL), implemented in a W-cavity configuration, using a lithium triborate (LBO) crystal for intra-cavity second harmonic generation (SHG) at 528 nm. The W-cavity configuration allows separation of the crystal from the semiconductor saturable absorber mirror (SESAM), enabling independent control over the Gaussian beam sizes at the crystal, chip, and SESAM. This optimized cavity demonstrated a second harmonic pulse width of \( \sim 760 \) fs at a frequency of 465 MHz and 230 mW average output power, resulting in a peak pulse power of 580 W.

© 2020 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

1. Introduction

There has been immense growth in VECSEL technology since its first demonstration by Kuznetsov et al.[1], primarily because of the inherent flexibility of the readily configurable external cavity [2,3]. Advanced VECSEL chip designs have been shown to generate high-power continuous-wave (CW) beams in excess of 100 W [4], while access to the high circulating power has been utilized for nonlinear optical conversion, such as efficient second harmonic generation [5] or difference frequency generation in the mid-infrared spectral region [6]. The inclusion of a SESAM results in a passively mode locked VECSEL and has achieved ultra-short pulse widths [7], high average power or peak power [8,9], and multi-GHz operation [10]. Pulsed lasers in the green spectral region are of particular interest for applications such as the micro-machining of glass and quartz [11], standoff lasers for explosives materials detection [12], and as a trigger for single-photon sources [13].

In the past several years, the combination of passively mode locked VECSELS with nonlinear optics for second harmonic generation has been demonstrated with the generation of blue and UV pulses in the picosecond regime [14,15]. Despite this progress, both lasers were limited in achievable average output power, generating 6 mW at 489 nm and 0.5 mW at 325 nm. While the results of [14] were obtained using the ideal InGaAs multi-quantum well chip structure, they were limited in passively mode locked second harmonic generation primarily as a result of a non-optimal V-cavity geometry that resulted in the nonlinear optical crystal being placed in front of the SESAM for intra-cavity frequency doubling. In this configuration, the SESAM absorbs a portion of the second harmonic, since the distributed Bragg reflector on the SESAM is not designed for reflection at this wavelength. Furthermore, the placement of the crystal in the same arm as the SESAM restricts the Gaussian beam size at the crystal to approximately the same dimensions as that on the SESAM. However, depending on cavity geometry, the ideal beam size for efficient second harmonic generation will be very different from the ideal beam size on the SESAM required for stable mode locking. We believe that this drastically limited the capability of both of these lasers.

In this paper, we present the results of an optimized passively mode locked VECSEL in a W-cavity configuration. This cavity provides greater flexibility over the ideal Gaussian beam spot sizes at the nonlinear optical crystal, chip, and SESAM. Control can be exerted over maintaining...
the ideal saturation parameter for mode locking simultaneously with efficient second harmonic generation. The crystal is placed in a cavity arm that includes a high-reflectivity (HR) flat mirror that enables a double-pass through the crystal for greater conversion to the second harmonic. This beam is then extracted from the cavity through an output coupler.

2. Experimental setup

The VECSEL chip was grown using a metal oxide chemical vapor deposition (MOCVD) process in a bottom-emitter design. It consists of a strain-compensated InGaAs/GaAs/GaAsP multi-quantum-well (MQW) semiconductor heterostructure with a corresponding DBR designed for emission at \(\sim 1070\) nm. The active region consists of 12 compressively strained InGaAs quantum wells that are sandwiched between GaAs/GaAsP barriers. Each quantum well is placed at the location of an antinode of the standing wave of the electric field in the chip microcavity to achieve resonant periodic gain [16]. The DBR stack consists of 25 pairs of alternating AlGaAs/AlAs layers that achieves a reflectivity of \(\sim 99.9\%\) around the fundamental wavelength.

The microfabrication of the VECSEL chips includes electron-beam evaporation of Ti/Au and indium onto the epitaxial side (DBR) of a cleaved piece of wafer and a piece of CVD diamond, which acts as a very efficient heat sink. The chip and diamond are solder bonded together and then the GaAs substrate and etch stop layers are removed through a chemical wet etch process, exposing the active region of the chip. The chip assembly is then clamped to a water-cooled copper block for heat dissipation.

The processed chip is placed in a designed W-cavity configuration, as shown in Fig. 1. This cavity was simulated using the ABCD matrix method to have a beam diameter of \(\sim 100\) \(\mu\)m at M1 and M3, and a beam diameter of \(\sim 440\) \(\mu\)m at the chip. An 808 nm pump diode is fiber coupled and focused to a beam diameter of \(\sim 500\) \(\mu\)m at the chip surface. The SESAM used in this experiment has a relaxation time of 15 ps, modulation depth of 4\%, and nonsaturable loss of 1\%. The 7.5 cm radius of curvature (RoC) mirror (M1) in front of the SESAM has a reflectivity coating of \(\sim 99\%\) at \(\sim 1064\) nm and serves as the output coupler for the fundamental. The second 7.5 cm RoC mirror (M2) in front of the broadband flat is HR coated for \(\sim 1064\) nm and AR coated for \(\sim 532\) nm. This mirror serves as the output coupler for our second harmonic. The broadband flat mirror (M3), HR coated for 400-1200 nm, is placed at the opposite end of the cavity from the SESAM.

![Fig. 1. Schematic of the W-cavity configuration.](image-url)
The distances between the components in the cavity were selected such that the cavity geometry results in a beam diameter of approximately 100 µm at both the SESAM and broadband flat mirror. The chip acts as a fold mirror in this cavity and was positioned along the beam path between M1 and M2 such that the ratio between the spot area on the chip versus the SESAM resulted in a saturation parameter of ∼14. This parameter is in the typical range required for stable mode locking [17,18]. The fold angle off of the chip was specifically chosen to be 30° to enhance the gain [19].

The nonlinear optical crystal used in this cavity was an angle-cut 5x4x4 mm (LxWxH) lithium triborate (LBO) crystal with both facets AR coated at 1064 nm and 532 nm. It was placed in the cavity in front of M3, enabling a double-pass for second harmonic generation. When the crystal was placed in the cavity, the position of M3 was adjusted appropriately to account for the change in optical path length to maintain the designed Gaussian beam geometry.

This cavity was simulated using the operator method [17] for the evolution of the intracavity field to verify stable pulse formation for both the fundamental and second harmonic wavelengths. An additional operator was included to incorporate the nonlinear coupling between the fundamental and second-harmonic fields in the crystal, and also the effects of group delay dispersion and group velocity mismatch caused by the crystal. The simulations start with noise that approximates spontaneous emission and demonstrates stable pulse formation after a few thousand round trips in the cavity. An example simulation for the stabilized output is shown in Fig. 2 for both the fundamental (red line) and second-harmonic (green line) pulse intensity profiles. Similar results were obtained when a weak starting pulse was used as the initial condition.

![Simulated pulse intensity profiles](image)

**Fig. 2.** Pulse simulations for the fundamental and second harmonic. The FWHM is approximately 1.2 ps and 2.6 ps for the fundamental and second harmonic, respectively.

### 3. Experimental results

The W-cavity was initially constructed and tested without the LBO crystal in order to characterize lasing performance of the fundamental. With M1 acting as an output coupler for our fundamental, we coupled this beam into our APE pulseCheck 150 autocorrelator in non-collinear mode. We measured a sech² pulse shape with a FWHM of ∼700 fs (Fig. 3).

The fundamental wavelength was measured on an optical spectrum analyzer and demonstrates emission at ∼1057 nm with a cavity repetition rate of ∼465 MHz (Fig. 4). This frequency is in good agreement with the calculated frequency of 462 MHz that was expected from a total cavity
length of 32.5 cm. Moreover, the absence of any secondary peaks between the primary peaks in the RF spectrum is a further indicator of a stable mode lock. The separation between maximum peak intensity and the noise floor in the RF spectrum was roughly 30 dBm. We measured 180 mW average output power exiting the cavity from M1, which has a ~1% transmission at the fundamental wavelength. This results in a peak power of ~490 W.

With the performance of the fundamental fully characterized, an LBO crystal was inserted into the cavity approximately 1-2 mm in front of M3. The cavity length was carefully adjusted along with the alignment and position of the crystal to obtain stable mode locking of the second harmonic. Stable mode locking for the second harmonic was determined by switching the optics kit in our pulseCheck to change its detection range from the fundamental to the second harmonic. Measurements were simultaneously performed to determine the RF spectrum of the cavity along with the optical spectrum of the second harmonic.

The measured pulse was fit with a sech² pulse shape that estimates a FWHM pulse duration of ~760 fs (Fig. 5). The pulse broadened slightly, which is expected because of the group delay dispersion and group velocity mismatch caused by the double pass through the 5 mm LBO
crystal. The optical spectrum (Fig. 6) shows second harmonic operation at a wavelength of $\sim 528$ nm while the RF spectrum for the second harmonic again demonstrates stable mode locking operation by the absence of any secondary peaks between the primary peaks, with a noise floor approximately 30 dBm below maximum intensity.

![Fig. 5. Experimentally measured second harmonic pulse compared against a sech² pulse fit demonstrating a FWHM of $\sim 760$ fs.](image)

![Fig. 6. Optical spectrum (left) and RF spectrum (right) of the mode locked second harmonic pulse.](image)

With nearly all of the generated second harmonic extracted from the cavity through M2, an average output power of $\sim 230$ mW at a wavelength of $\sim 528$ nm was measured. When combined with a pulse width of $\sim 760$ fs and a frequency of 465 MHz, this results in a second harmonic peak pulse power of 580 W. This is a significant improvement over previous work.

Stable mode locking for the second harmonic was achieved with the crystal positioned $\sim 2$-3 mm in front of M3. This position is still within the Rayleigh range with respect to the beam waist at M3, which results in a larger beam diameter in the crystal. The high circulating fundamental peak pulse power within the cavity allowed observation of the onset of strong saturation effects when the crystal was translated too closely to the mirror, leading to loss of mode locking due to competition between the strong peak pulse power of the fundamental and second harmonic generation, as alluded to in Refs. [14,15]. This is likely caused by the significantly increased
intensity at the crystal as the beam diameter is reduced. Careful alignment and positioning of the crystal enabled operation within the weak saturation regime and obtaining stable mode locking.

A potential optimization to increase the green peak pulse power would be to reduce the beam diameter at the crystal. The W-cavity is symmetric, which results in a similar spot size at both the SESAM and LBO crystal. The designed beam diameter of ∼100 µm at the SESAM and end mirror is still not perfect for second harmonic generation. For a double-pass through a 5 mm long LBO crystal, the ideal beam diameter is approximately ∼40 µm. This might result in operation within the strong saturation regime and would have to be compensated by reducing the LBO crystal length to maintain stable mode locking. Furthermore, there is also an additional 2% loss in the cavity caused by M1 that is necessary for the characterization of the fundamental but unnecessary during second harmonic generation. This results in pulse broadening and a reduction in laser efficiency. Replacing M1 with an HR mirror of equivalent curvature should result in greater circulating power of the fundamental and greater conversion to the second harmonic as long as operation within the weak saturation regime is maintained.

4. Conclusion
We successfully designed, simulated, and experimentally demonstrated the performance of a W-cavity configuration for second harmonic generation in a passively mode locked VECSEL. This improved cavity geometry places the nonlinear optical crystal in a separate cavity arm opposite to the SESAM and allows for a double-pass through the crystal and complete second harmonic extraction from the cavity through an output coupler. This resulted a high average output power for the second harmonic of ∼230 mW at ∼528 nm and a pulse width of around ∼760 fs. At a cavity repetition rate of 465 MHz, this results in a green peak pulse power of 580 W. These results can provide a path toward intra-cavity harmonic generation of ultra-short, high peak power pulses at targeted wavelengths.

Funding
National Science Foundation (NSF) Directorate for Engineering (1709918).

Disclosures
The authors declare no conflicts of interest.

References


