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Ultrafast optical parametric oscillator pumped by a vertical external-cavity surface-emitting laser (VECSEL)

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Abstract: We report the first optical parametric oscillator synchronously pumped by a SESAM modelocked vertical external-cavity surface-emitting laser (VECSEL). As a nonlinear medium, we use a periodically poled MgO:PPLN crystal. The VECSEL operates at a wavelength of 982 nm and a repetition rate of 198 MHz. The pump radiation is converted to signal and idler wavelengths tunable in the ranges of 1.4-1.8 µm and 2.2-3.5 µm, respectively, simply by a change of the poling period and crystal temperature. The signal pulses have a duration between 2 ps to 4 ps and an average output power up to 100 mW.

OCIS codes: (140.5960) Semiconductor lasers; (140.7260) Vertical cavity surface emitting lasers; (140.4050) Mode-locked lasers; (190.4410) Nonlinear optics, parametric processes; (190.4970) Parametric oscillators and amplifiers.

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1. Introduction

Optically-pumped vertical external-cavity surface-emitting lasers (VECSELs) [1] are a rapidly evolving technology which exhibits a wide spectral coverage in an inexpensive and compact setup [2–5]. Their foundation on semiconductor technology has the major advantage of emission wavelength flexibility which is easily achieved by bandgap engineering. They support emission wavelengths from the ultraviolet (391 nm) [6] up to the mid-infrared (mid-IR) spectral region (5.3 μm) [7]. Such semiconductor lasers secured their position in the continuous-wave (CW) laser market [8–10], providing high power levels in fundamental transverse mode [9,11–13].

Pulsed operation of VECSELs can be obtained in the femtosecond and picosecond regime [3,4,14]. Typically, a semiconductor saturable absorber mirror (SESAM) [15] is used for pulse formation. This concept enabled impressive progress over the last years [16–20]. For example, a SESAM-modelocked VECSEL generated 5.1 W average power at 1030 nm in pulses with 682 fs duration [21]. Furthermore, operation with sub-100 fs pulse duration has been achieved for 100 mW of output power [22].

However, in contrast to the demonstrated spectral coverage of VECSELs in the CW-regime, pulsed operation has been so far limited to wavelengths up to the 2 μm-range [23] and the best performance is obtained in the spectral region between 800 and 1200 nm [3]. This limitation in emission wavelength can be remedied by nonlinear frequency down-conversion. An effective approach is the use of an optical parametric oscillator (OPO) [24–26].

Ultrafast OPOs are usually synchronously pumped at the same repetition rate as the driving laser. During the last decades, synchronously-pumped OPOs have been pumped by different ultrafast laser types, including Ti:sapphire lasers [27], Yb-fiber lasers [28,29], Nd- and Yb-based solid-state lasers [30], Tm-lasers [31], and thin-disk lasers [32].

VECSELs can serve as a cost-efficient, versatile and compact alternative pump source for OPOs. However, so far the use of semiconductor lasers to pump OPOs has been limited to the CW-regime [33]. In this work we present the first ultrafast synchronously VECSEL-pumped OPO. We use a compact 982-nm modelocked VECSEL and a periodically poled MgO:PPLN crystal with different poling periods. We evaluate pulse duration, power levels, and tuning range.

2. Experiment

2.1 Pump laser: VECSEL prototype from M squared lasers

The pump laser source is a modelocked VECSEL developed by M Squared Lasers Ltd [34]. The laser has a central emission wavelength of 982 nm [Fig. 1(a)] and operates at a fundamental repetition rate of 197.6 MHz [Fig. 1(b)].

Low repetition frequencies are usually challenging to achieve with ultrafast VECSELs due to their relatively short gain carrier lifetime which typically leads to multi-pulsing in the cavity [35]. The pulse break-up is strongly influenced by the cavity design, the pump power, the semiconductor gain and saturable absorber characteristics. A careful selection of these parameters offers the window of operation where the laser can operate without modulation instabilities or harmonic mode-locking. The laser used in this experiment has a cavity designed without multiple passes through the gain and is passively modelocked with a SESAM [34]. It keeps a large intracavity dispersion which results in strongly chirped long pulses of a duration in the order of 60 ps. This mode of operation intends to keep the peak power low and avoid excessive nonlinear effects inside the cavity. A subsequent external compression in transmission gratings is implemented to efficiently compensate the chirp.

In Fig. 1(c), we show the autocorrelation trace of the compressed output pulses with a typical pulse duration around 3 ps full width at half maximum (FWHM) assuming a sech^2 pulse shape (intensity SHG-autocorrelator: Femtochrome FR-103). To confirm the single-pulse operation, we performed a sampling oscilloscope characterization of the laser pulse train [Fig. 1(d)]. The laser pulses are equally separated by a time delay of 5.06 ns which corresponds to the 197.6 MHz fundamental repetition rate. The ringing of the signal measured with the sample oscilloscope is an electrical artefact. The compressed VECSEL generates up to 580 mW average output power, leading to a corresponding maximum pulse energy of 2.9 nJ and a peak power of ~0.8 kW (assuming a sech^2 pulse shape). A beam quality measurement provided an M^2 factor of 1.16, close to the diffraction-limit.

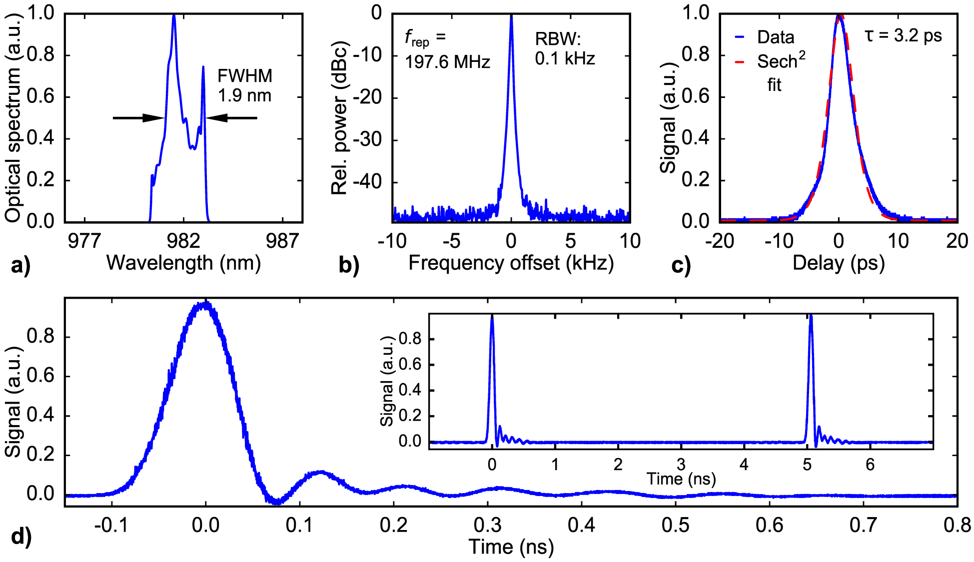

Fig. 1. Pulse characterization of the pump laser. a) Optical spectrum with a peak intensity at 981.5 nm and estimated full width at half maximum of 1.9 nm. b) RF spectrum centered at 197.6 MHz at a resolution bandwidth (RBW) of 0.1 kHz. c) Autocorrelation trace (blue) and sech^2 fit of the autocorrelation of the pulses (dashed red), corresponding to a pulse duration of 3.2 ps (FWHM). d) Sampling oscilloscope measurement with 1 ns and 8 ns (inset) span, confirming the single-pulse operation of the VECSEL. The weak ringing that follows the pulse signal trace is an artefact due to the electronics of the detection setup.

2.2 Optical parametric oscillator setup

Two different periodically-poled magnesium-doped lithium niobate (MgO:PPLN) crystals were used in the experiment. Their parameters are summarized in Table 1. Crystal #1 is a commercially available crystal from Covesion Ltd. with multiple poling periods and dimensions of 10 mm x 10 mm x 0.5 mm. Four poling periods were used in our OPO configuration: 27.91 µm, 28.28 µm, 28.67 µm and 29.08 µm. Input and output facets have an anti-reflection (AR) coating optimized for 1064 nm and 1.4-1.8 µm wavelengths. Crystal #2 was custom made by the company Raicol Crystals. It has a single poling period of 29.15 µm and a length of 5 mm. Both facets are AR-coated for 980 nm and 1520 nm wavelengths. The transmission of the pump through the crystals has been characterized using a CW diode (3S PHOTONICS 1999CHP) emitting at 976 nm. We measured a transmission of 96.3% for crystal #1 and 98.9% for crystal #2 at 100 mW of pump power. We operated both crystals at elevated temperatures between 50°C and 150°C in a crystal oven for temperature tuning.

Table 1. Crystals parameters

	Length [mm]	Poling periods [µm]	AR coating (from the datasheets)	Transmission at 976 nm
Crystal #1	10	27.91, 28.28, 28.67, 29.08	1064 nm (R<1.5%); 1400-1800 nm (R<1%); 2600-4800 nm (R~6%-3%)	96.3%
Crystal #2	5	29.15	980 nm & 1520 nm	98.9%

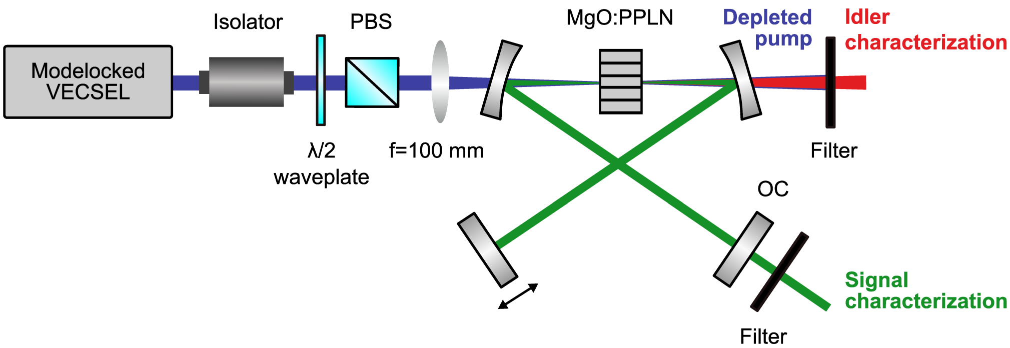

Fig. 2. Experimental setup of the VECSEL-pumped OPO.

The experimental setup of the VECSEL–pumped OPO is shown schematically in Fig. 2. The resonator is a standing-wave cavity, designed for the signal wave. The three highly reflective (HR) mirrors and the output coupler (OC) are broadband coated to cover a signal wavelength range from 1.40 µm to 1.75 µm. The two curved HR mirrors have a radius-of-curvature of 150 mm and are separated by approximately 170 mm. From simulations, it results in a waist with a radius of 75 µm for the signal beam in the crystal (software: RP Resonator). The curved mirrors have an AR coating for the pump wavelength on the backside and a high transmission at 980 nm on the front side in order to minimize the losses before the crystal and to eliminate the residual pump rapidly after the parametric conversion. An important part of the idler radiation exits the cavity through the curved mirror, where the idler spectral characterization is performed after a long pass filter with a cutoff wavelength of 1000 nm, used to remove residual pump and nonlinear frequency mixing signals. The idler output power cannot be directly measured due to the wavelength dependent absorption of the fused silica substrate of the curved mirror in the 2-3.5 µm range. In the following we state the idler power computed from the signal output power times the ratio of the signal wavelength to the idler wavelength. A flat HR mirror is used as one end mirror of the cavity, while the other cavity end is formed by an OC with 1.5% transmission at the signal wavelength. The signal output power is measured after a long pass filter with a cutoff wavelength of 1000 nm. We corrected the output power for the losses in this filter (20%). The cavity length is ~750 mm, corresponding to a total round trip length for the pulses of ~1500 mm that matches the pump laser repetition rate. We did not use active stabilization of the cavity length, but adjusted the HR-end-mirror position manually with a standard mechanical translation stage.

An isolator is placed at the output of the pump laser to prevent disturbance of the VECSEL by back reflections from the OPO. A half-wave plate and a polarizing beam splitter (PBS) are used as polarization selective elements and for a continuous adjustment of the pump power. The pump beam is focused into the crystal with a lens of 100 mm focal length resulting in a waist with a radius of 60 µm in air, which optimizes the matching of the pump and signal spot size in the crystal according to the simulations.

2.3 Results

When operated with crystal #1, the typical cavity configuration for the maximum OPO output power generates a signal at wavelength between 1410 nm and 1550 nm. Using the poling period of 28.28 µm, a maximum signal output power of 60 mW (48 mW measured with the power meter at the OC after the filter) is reached at 1413 nm for a pump power of 540 mW. The signal power conversion efficiency is 11%.

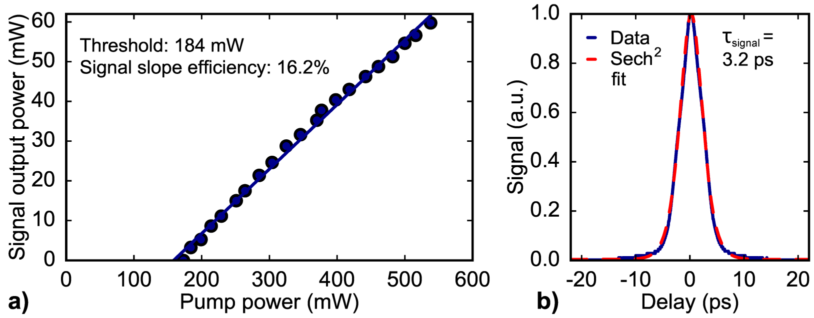

Fig. 3. a) OPO signal output power as a function of the pump power and b) signal autocorrelation trace (blue) and sech^2 fit of the autocorrelation of the pulses (dashed red), corresponding to a pulse duration of 3.2 ps (FWHM) for a cavity configuration with the 10 mm-long crystal #1, period of 28.28 µm, crystal temperature of 120°C and signal wavelength of 1413 nm.

The corresponding computed idler power is 26 mW at 3214 nm. Figure 3 presents the signal output power as a function of the pump power. The OPO has a threshold at a pump power of 184 mW and operates with a signal slope efficiency of 16.2%. The signal emission wavelength is tuned by changing the temperature of the oven from 50°C to 150°C and using the four different poling periods of the crystal. Thereby it is possible to generate a signal wavelength covering a bandwidth of 420 nm from 1360 nm to 1780 nm with a corresponding idler wavelength varying from 2190 nm to 3530 nm.

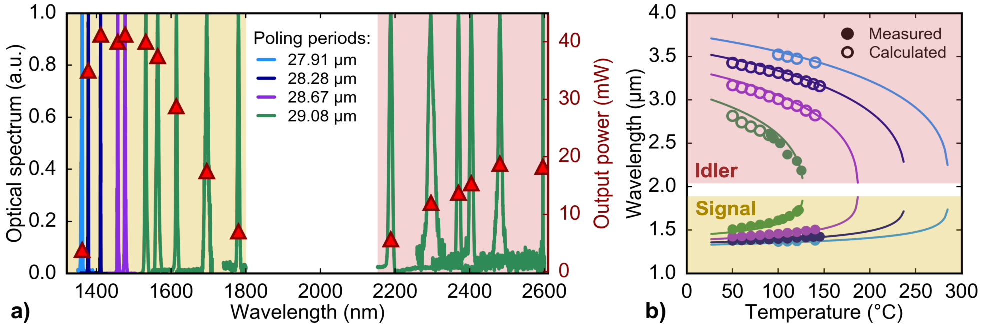

Fig. 4. Characterization of signal and idler wavelengths with crystal #1 for the four different poling periods 27.91 µm (light blue), 28.28 µm (dark blue), 28.67 µm (violet), 29.08 µm (green). a) Signal and idler optical spectrum normalized (left axis) and the output power for a pump power of 450 mW (red triangles, right axis). b) Measured (filled dots) and computed (empty dots) signal and idler wavelengths as functions of the crystal temperature and the theoretical expected values (solid lines).

Figure 4(a) presents a selection of optical spectra of signal and idler waves measured with an optical spectrum analyzer (Anritsu MS9710B for the signal and A.P.E waveScan USB IR, which is limited to 2.6 µm, for the idler) and their corresponding output power (measured for the signal and computed for the idler) for a pump power of 450 mW with an optimization of the cavity length at every step. The limitation in the tunability of the generated signal is attributed mainly to the bandwidth of the HR coatings of the cavity mirrors which are limited to 1400-1750 nm. Figure 4(b) displays the signal and idler wavelengths as a function of the crystal temperature for the four different poling periods, illustrating the good fit between the measured and computed data. The signal pulse characterization was performed with the same autocorrelator as in section 2.1, measuring pulse durations of 2-4 ps FWHM [see Fig. 3(b)], determined by the duration of the input pulses.

Crystal #2 provided higher output powers with a maximum signal output power of 100 mW (80 mW measured with the power meter) at a pump power of 450 mW. In this configuration, the crystal is stabilized at a temperature of 85°C. The generated signal wavelength is 1630 nm with a computed idler power of 66 mW at a wavelength of 2467 nm. This corresponds to a signal power conversion efficiency of 22%, which is two times higher compared to crystal #1.

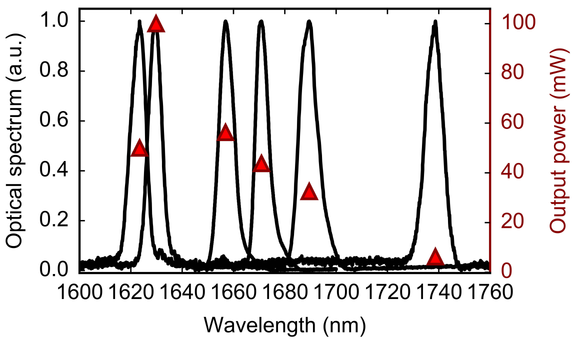

Fig. 5. Characterization of operation with crystal #2. Signal optical spectra normalized (left axis) and output power for a pump power of 450 mW (red triangles, right axis).

A change of the crystal temperature from 80°C to 120°C tuned the signal from 1623 nm to 1739 nm, i.e. over a bandwidth of 116 nm (see Fig. 5). The higher output power is surprising given that the crystal length is only 5 mm, i.e. half of the first crystal. An important effect that can reduce the conversion efficiency of longer crystals is the pump spectral acceptance bandwidth, which scales inversely proportional to the crystal length. However, the acceptance bandwidth of crystal #1 is stated above the 1.9 nm bandwidth of the pump VECSEL, suggesting only minor contribution to the conversion efficiency. We attribute the increase in efficiency with crystal #2 to the better quality of the AR coating for both the pump and signal wavelengths, minimizing the losses of the cavity.

3. Conclusion

We have demonstrated an OPO pumped by a picosecond VECSEL emitting at wavelength of 982 nm. We obtained signal and idler wavelengths tunable in the ranges of 1.4-1.8 µm and 2.2-3.5 µm, respectively, by changing the crystal temperature and poling periods. A maximum signal output power of 100 mW was generated from 450 mW of pump with a corresponding idler output power of 66 mW and a signal power conversion efficiency of 22%. This encouraging result paves the way for more compact and low-cost tunable ultrafast sources emitting in the IR and mid-IR spectral regions.

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