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# High-power 760 nm VECSEL based on quantum dot gain mirror

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**Abstract**—We report high-power second-harmonic generation of 760 nm laser light from optically-pumped vertical-external-cavity surface-emitting laser based on quantum dot active medium. The laser generates  $\sim 1.2$  W in fundamental transverse mode with fixed linear polarization. The emission wavelength can be continuously tuned from 738 to 778 nm by using an intra cavity birefringent filter for fundamental radiation without readjustment of phase-matching angle of the nonlinear crystal. The result constitutes a viable alternative for applications requiring broadly tunable high brightness lasers in the 700-800 nm range.

**Index Terms**— Optical harmonic generation, semiconductor growth, surface emitting lasers, quantum dot lasers.

## I. INTRODUCTION

VERTICAL-external-cavity surface-emitting lasers (VECSELs) have attracted attention due to their capability of producing high-power high-brightness emission across vast wavelength ranges [1]. Intrinsic wavelength versatility of semiconductor gain coupled with the open resonator enables achieving fundamental and frequency converted emissions spanning from ultraviolet to mid-IR [2]. However, technological development of VECSELs has not been equally distributed across all wavelength regions, leaving certain spectral windows poorly covered with reliable approaches. An example is the 700-800 nm range, which has recently gained interest due to applications in biophotonics [3], medical [4] and spectroscopy field [5]. Furthermore, frequency doubling of this wavelength range opens new avenues to UV emission, where atomic molecular and optical physics can benefit from narrow-linewidth tunable lasers for applications in atom cooling and isotope separation [6].

The first VECSEL addressing 700-800 nm wavelength region was composed of InP quantum dot (QD)-based gain region and has delivered 52 mW of output power tunable over 716-755 nm

band [7]. As another alternative, VECSEL utilizing Raman shifting in diamond allowed to obtain 82 mW at 736-750 nm [8]. Watt-level emission was achieved by means of intracavity frequency-doubling of the 1500-1580 nm wafer-fused structures, yielding 1 W at 780 nm [9] and 1.5 W at 750 nm [10]. To date, the record VECSEL results at this wavelength region have been demonstrated with direct-emitting AlGaAs-based QW VECSELs resulting in output powers of 3.25 W and tunable over 741-773 nm [11], and 4.24 W tunable over 747-788 nm [12]. Despite these notable achievements, the state-of-the-art AlGaAs-based direct emitting structures possess a set of drawbacks, namely, low laser lifetime, and polarization peculiarities degrading the output beam at high power [11]. In this Letter, we report second-harmonic generation (SHG) based on new type of gain mirrors recently proposed for emission at 1550 nm [13]. In particular, we demonstrate  $\sim 1.2$  W of output power at the 760 nm from intracavity frequency conversion of QD-based VECSEL. The emission wavelength can be tuned from 738 to 778 nm.

## II. EXPERIMENTAL SETUP

### A. Gain mirror and cavity

The QD gain mirror structure is comprised of an InP-based active region employing InAs QDs wafer fused to a GaAs-based GaAs/AlAs DBR. Complete characterization details for fundamental operation are provided in [13] (including PL measurements). Intracavity heatspreader thermal management scheme was employed by utilizing an uncoated diamond with a thickness of 0.3 mm. Cavity configuration for the intracavity frequency doubling is shown in Fig. 1. The gain mirror was pumped by a 980 nm fiber-coupled diode. All mirrors used in the resonator had high transmission ( $>95\%$ ) at 760 nm and high reflectivity ( $>99.8\%$ ) at 1.5  $\mu\text{m}$ . A BiBO nonlinear crystal with a length of 5 mm was chosen for the type I critical phase matching and was placed at the mode waist inside the resonator.

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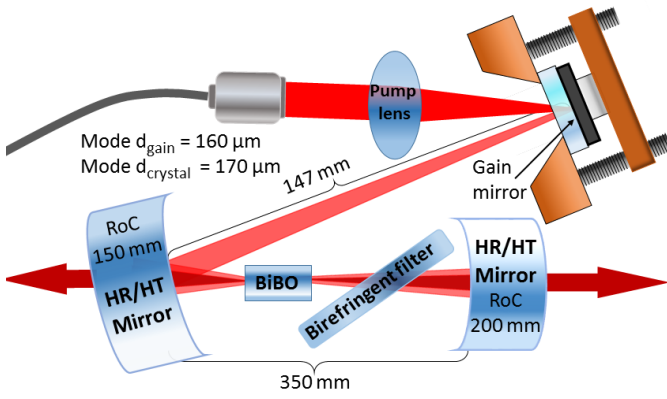


Fig. 1. Cavity schematics of the frequency-doubled QD VECSEL.

### III. RESULTS AND DISCUSSION

#### A. Preliminary polarization investigation

Before SHG experiment additional structure characterization in terms of polarization behavior at the fundamental wavelength was performed. To fix laser polarization a 2 mm thick fused silica plate was inserted inside the cavity at the Brewster angle and was adjusted to ensure laser operation either at P- or S-polarization.

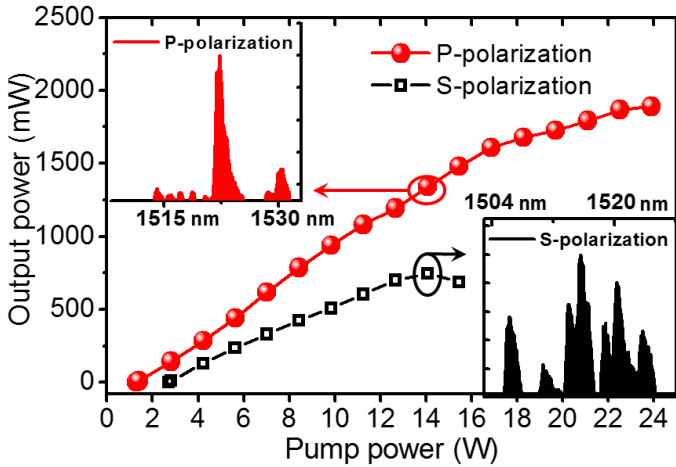


Fig. 2. Power at fundamental frequency recorded as a function of incident pump power at two orthogonal polarization orientations. Inset shows spectra of the corresponding polarization modes.

Polarization selectivity was provided by a different amount of intracavity reflection losses at fused silica interface for the different polarization orientations. Unlike to a birefringent filter, the fused silica plate did not narrow down the output spectra, although it introduced additional Fabry-Perot etalon with a very small free spectra range of 0.5 nm. Fig. 2 shows power characteristics of the VECSEL separately operating with P- and S-polarizations. As it can be observed, operations at the orthogonal polarizations exhibit different slope efficiencies, threshold values and output spectra. The higher performance obtained for P-polarization is attributed to the anisotropy of the gain mirror, which is expected for QD heterostructures [14].

Knowledge about polarization preference of the structure allowed orienting the VECSEL chip in a resonator in a way to provide maximum efficiency in the SHG setup, where fixed orientation of a birefringent filter (placed at the Brewster angle) dictated laser polarization. Usage of birefringent filter was instrumental in achieving a good SHG efficiency; the free running QD emission spectra has a FWHM of about 14 nm whereas the acceptance bandwidth of the BiBO crystal is  $\sim 7$  nm.

#### B. SHG Results

Fig. 3 shows the power characteristics for the SHG (left axis) and fundamental emission (right axis) as a function of incident pump power. The output power of SHG was combined from the two outputs and resulted in 1.23 W under 19 W of incident pump power at 14 °C of coolant temperature through the heatsink (effective temperature of the heatsink slightly increases with the pump power). Notably, QD-based active region exhibited lower temperature dependent spectral shift [15], avoiding the need to readjust the birefringent filter and the position of the nonlinear crystal under increased pump power. No measurable degradation of output power was observed during the experiments.

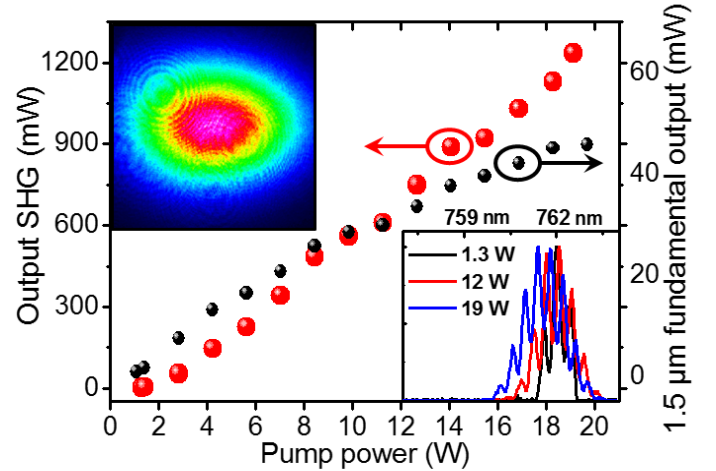


Fig. 3. Output power of SHG (left axis) and fundamental output through a HR mirror (right axis) as a function of incident pump power. Insets show beam profile recorded at 19 W of incident pump power and spectra as functions of incident pump power.

#### C. Tuning characteristics of SHG QD VECSEL

Tuning characteristic of the laser was obtained by means of rotating the birefringent filter (with a thickness of 0.5 mm) around the axis normal to its surface. Ten separate spectra under 13 W of incident pump power were recorded for ten azimuthal orientations of the birefringent filter and were combined in the graph shown in Fig. 4(a). Thus, SHG of the QD-based VECSEL demonstrated broad continuous tuning of 40 nm (738-778 nm), when no adjustments of nonlinear crystal or cavity mirrors had been done in order to optimize the phase-matching angle.

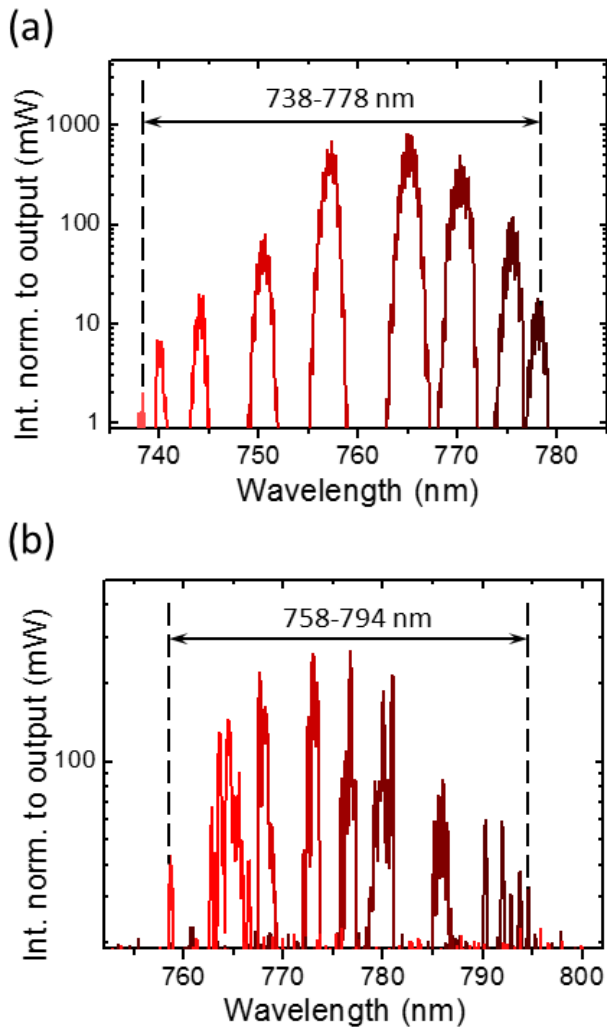


Fig. 4. Output spectra recorded at different azimuthal orientations of the birefringent filter, which were then normalized to the corresponding output power values and combined into one graph, where: (a) QD VECSEL and (b) QW VECSEL

#### D. Comparison to the SHG QW VECSEL

In comparison, we show tuning characteristics of the SHG for a QW-based VECSEL (Fig. 4(b)), with an active region structure similar to the one reported in [9] and with a DBR identical to the one used in this QD VECSEL, and with identical thermal management. The QW-based VECSEL, investigated in the same cavity, has shown inferior tuning characteristic under pump power of 13 W, both in terms of maximum output power of 290 mW, and tuning curve width, shown in Fig. 4(b). However, the QW VECSEL without the intracavity birefringent filter has yielded 2.3 W of SHG under 25 W of incident pump power at 770 nm, which may be explained by the lack of polarization losses caused by birefringent filter, present in previous measurement.

#### IV. CONCLUSION

We demonstrate 1.2 W of output power from frequency doubling of QD-based VECSEL with emission at 760 nm and

continuous wavelength tunability of 40 nm. Considerably smaller temperature-dependent spectral shift of QD gain media allowed avoiding the necessity of readjustment of the nonlinear crystal or cavity mirrors under the increased pump power. Investigation of the preferred polarization orientation of the structure allowed obtaining higher efficiency and wider tuning characteristics of the SHG with the birefringent filter inside the cavity in comparison to the tunability features achieved with a QW gain media in the same cavity. Further optimization of QD gain medium can lead to even broader wavelength tuning characteristics surpassing those of QW-based devices. The laser did not exhibit any visible degradation of output power: in this respect, SHG VECSELs are superior to direct emitting VECSELs at the same wavelength range.

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