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14. ABSTRACT We have successfully demonstrated a compact high-power CW DUV source emitting at 295 nm exceeding the targeted objective. The laser is based on frequency-quadrupled optically pumped vertical external cavity surface emitting source. A highly-strained InGaAs/GaAs multi-quantum well semiconductor laser operating at 1178 nm in a single frequency is developed. By intracavity frequency doubling of the laser, multi-watt yellow laser emitting at 589 nm is generated. The single-frequency, intracavity-doubled 589-nm output is further converted to 295 nm in an					
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Report Title

Compact, High-Power, Low-Cost 295 nm DUV Laser by Harmonic Conversion of High Power VECSELs

ABSTRACT

We have successfully demonstrated a compact high-power CW DUV source emitting at 295 nm exceeding the targeted objective. The laser is based on frequency-quadrupled optically pumped vertical external cavity surface emitting source. A highly-strained InGaAs/GaAs multi-quantum well semiconductor laser operating at 1178 nm in a single-frequency is developed. By intracavity frequency doubling of the laser, multi-watt yellow laser emitting at 589 nm is generated. The single-frequency, intracavity-doubled 589-nm output is further converted to 295 nm in an external resonator using BaB₂O₄. Up to 136 mW of continuous-wave, single-frequency output at 295 nm was obtained from a frequency quadrupled optically pumped semiconductor laser.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

- Y. Kaneda, M. Fallahi, J. Hader, J. Moloney, S. Koch, B. Kunert, W. Stolz, "Continuous-wave single-frequency 295 nm laser source by a frequency-quadrupled optically pumped semiconductor laser", Optics Letters, vol. 34, p. 3511, Nov. 2009.

- M. Fallahi, C. Hessenius, Y. Kaneda, J. Hader, J. Moloney, B. Kunert, W. Stolz, S. Koch, "Novel semiconductor Lasers attractive for High-Power UV-Visible Applications," SPIE Newsroom, No. 10.1117/2.1200901.1473, Feb. 13, 2009.

Number of Papers published in peer-reviewed journals: 2.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts): 0

(d) Manuscripts

Number of Manuscripts: 0.00

Patents Submitted

Patents Awarded

Awards

Graduate Students

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Chris Hessenius	0.50
FTE Equivalent:	0.50
Total Number:	1

Names of Post Doctorates

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>	National Academy Member
Yushi Kaneda	0.20	No
Mahmoud Fallahi	0.10	No
FTE Equivalent:	0.30	
Total Number:	2	

Names of Under Graduate students supported

<u>NAME</u>	<u>PERCENT SUPPORTED</u>
Cameron Simmons	0.25
FTE Equivalent:	0.25
Total Number:	1

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	1.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:.....	1.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:.....	1.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):	1.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:	0.00

Names of Personnel receiving masters degrees

<u>NAME</u>
Total Number:

Names of personnel receiving PhDs

<u>NAME</u>
Total Number:

Names of other research staff

<u>NAME</u>	<u>PERCENT_SUPPORTED</u>
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See Attachement

Technology Transfer

Final Report on: Compact, High-Power, Low-Cost 295 nm DUV Laser by Harmonic Conversion of High Power VECSELs

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Project Description:

The InGaAs/GaAs VECSEL structure was grown using a low temperature metallorganic vapor phase epitaxial (MOVPE) process. MOVPE growth uses alternative group-V liquid sources (tertiarybutylarsine-TBA, tertiarybutylphosphine-TBP) that decompose at lower temperatures than the conventional hydride precursors. This allows for a general reduction of the growth temperature, promoting higher values of strain and, thus, reproducibly higher indium-concentrations in the active QW. In addition, GaAsP barriers with precise chemical composition are grown to balance the QW strain. The VECSEL structure consists of 10 repeats of compressive strained InGaAs quantum wells. Each quantum well is 7-nm thick and surrounded by GaAsP strain compensation layers and GaAs barriers, in which the 808-nm pump emission is absorbed. The thickness and compositions of the layers are optimized such that each quantum well is positioned at the antinodes of the cavity standing wave to provide resonant periodic gain (RPG) in the active region. A high reflectivity ($R > 99.5\%$) DBR stack made of 21-pairs of AlGaAs/AlAs is grown on the top of the active region. To avoid premature thermal rollover, a detuning between quantum well gain peak and microcavity resonance of about 30 nm is introduced which compensates the thermal detuning at higher temperatures and powers at the expense of a slight increase in threshold power. To generate coherent fundamental and yellow-orange laser, we used a folded cavity, in which the VECSEL chip and a flat mirror serve as two end mirrors and a concave spherical mirror as the folding mirror. The folding concave mirror is high-reflective coated for the fundamental laser but is highly transmissive at the yellow-orange wavelength.

The schematic of the laser cavity is shown in Figure 1. It contains a 10-mm long LiB_3O_5 (LBO) crystal, cut at $\theta=90^\circ$, $\phi=3.5^\circ$, for phase-matching at room temperature. The end mirror is flat, and is highly reflective from 300 to 1250 nm, reflecting both fundamental and second harmonic. The LBO crystal used in the experiment has AR coatings on both ends for the fundamental and the second harmonic, but there seems to be a sizeable amount of residual reflectivity as we observed an etalon effect as we tune the angle and temperature of LBO crystal. When the angle of the LBO crystal is tuned, we observed satellite orange beams around the principal beam. We expect that the performance of the 589-nm source can be improved with a crystal with better AR coatings. The lengths of two legs are 110 mm and 50 mm, giving mode sizes about 180 μm radius at the OPSP device and 60 μm radius at the LBO. The rotation angle of the quartz birefringence filter is adjusted while monitoring the fundamental wavelength with an optical spectrum analyzer so that the fundamental wavelength is 1178 nm. By rotating the quartz birefringent plate, the OPSP device used in the experiment was capable of operation between 1160 and 1190 nm. Because of the optics used for the locking of the resonator, we performed the wavelength

conversion experiment only at the fundamental wavelength of 1178 nm, but we believe similar performance can be achieved in the 1160-1190 nm wavelength range, corresponding to the second harmonic wavelength of 580 and 595 nm and fourth harmonic wavelength of 290 to 298 nm. At the second harmonic of 589 nm, up to 2 W was observed without an etalon in the resonator. In the fourth harmonic generation experiment, we inserted a solid etalon in the resonator to ensure single frequency operation for extended periods of time. Using 18W of pump power from a fiber-coupled diode laser bar at 808 nm, 1.2 W of fundamental power at 589 nm was available in a single frequency for the wavelength conversion experiment. We chose a BBO crystal for 295 nm generation.

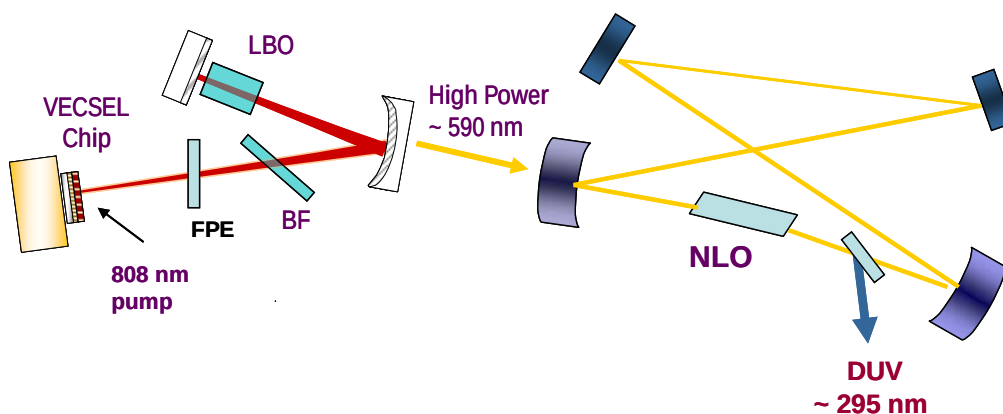


Figure 1: Schematic of the proposed approach for 295 nm generation

Although we did not insert an etalon inside the resonator, the output remained in the single-frequency most of the time. The longitudinal mode is shown in Fig. 2. Because of small walk off angle (2.2 mrad) within the LBO, we disregarded the ellipticity of the output beam and use spherical singlets to mode-match to the external resonator.



Fig. 2 Longitudinal mode of 589 nm

In the fourth harmonic generation experiment, we inserted a solid etalon in the resonator to ensure single frequency operation for extended periods of time. Using 18W of pump power from a fiber-coupled diode laser bar at 808 nm, 1.2 W of fundamental power at 589 nm was available in a single frequency for the wavelength conversion experiment.

For the harmonic generation of this wavelength range, several nonlinear crystals can be considered. We considered 4 different materials; β -BaB₂O₄ (BBO), LBO, CsLiB₆O₁₀ (CLBO), and CsB₃O₅ (CBO). We compared 2 particular aspects; 1) tuning capability, and 2) conversion efficiency. Although in frequency conversion in the resonator the scattering and absorption losses are more important than the optical nonlinearity, we assume that the optical losses of these crystals are the same in this comparison. Some properties of the 4 different crystals are summarized in Table 1. As can be seen from Table 1, BBO features the smallest tuning angle needed to tune across 290-298 nm range, and second highest normalized conversion efficiency next to CBO. LBO possesses desirable properties including small walk off angle (less than 1°) as well as availability of a high quality crystal. As a result we chose a BBO crystal for 295 nm generation.

	Δ (deg.)	d_{eff} (pm/V)	ρ (mrad)	Relative normalized efficiency
BBO	2.67	1.86	82.5	1
LBO	8.25	0.38	14.6	0.247
CLBO	2.99	0.69	37	0.442
CBO	8.22	1.15	20	1.84

Table 1: Comparison of nonlinear crystals. CLBO assumed to be at 150C, others are at room temperature.

The resonator mode has a waist in the center of BBO crystal that is 58 x 37 μm in radius in tangential and sagittal orientation, respectively. The resonator was locked to the input 589 nm using the polarization locking technique. The input-output characteristic of the external resonant doubler is the same as previously reported. The resonator was locked to the input 589 nm using the polarization locking technique. The input-output characteristic of the external resonant doubler is shown in Figure 3. With the input power of 1180mW, a maximum output power at 295 nm of 136 mW is observed. Considering the 22% reflection at the output facet of the Brewster-cut BBO crystal, the generated UV light is more than 170 mW. The conversion efficiency does not show any saturation effect up to the maximum input power, which seems to indicate higher powers may be obtained with higher input powers.

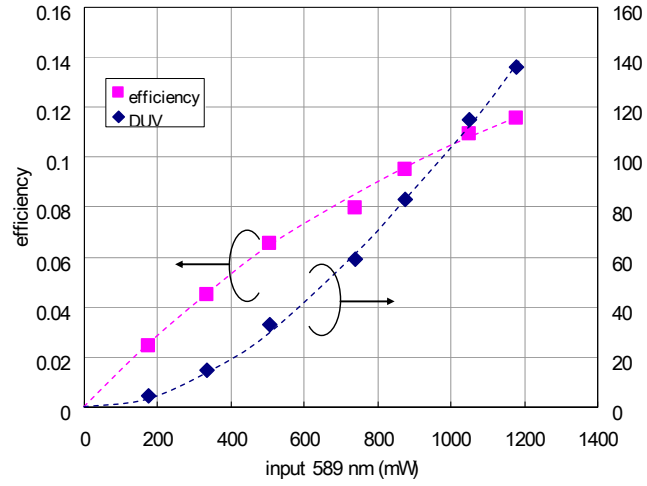


Fig. 3. Output characteristic and efficiency of the external resonator
Solid curves show the simulation results.

In summary, we have demonstrated continuous-wave, 295-nm single frequency output power up to 136 mW, by the fourth harmonic of an OPSL operating at 1178-nm. 589 nm was generated by intracavity SHG, and 295 nm was generated using BBO crystal inside an external resonator.