High-power tunable low-noise coherent source at 1.06μm based on a surface-emitting semiconductor laser

Baptiste Chomet, Jian Zhao, Laurence Ferrieres, Mikhaël Myara, Germain Guiraud, Gregoire Beaudoin, Vincent Lecocq, Isabelle Sagnes, Nicholas Traynor, Giorgio Santarelli, et al.

High-power tunable low-noise coherent source at 1.06µm based on a surface-emitting semiconductor laser

Baptiste Chomet,[1,2] Jian Zhao,[3,6] Laurence Ferrieres,[1] Mikhael Myara,[2] Germain Guiraud,[3, 4] Grégoire Beaudoin,[5] Vincent Lecocq,[1] Isabelle Sagnes,[5] Nicholas Traynor,[4] Giorgio Santarelli,[3*] Stephane Denet,[1] and Arnaud Garnache,[2]

[1]*Innoptics, Institut d'Optique d'Aquitaine, Rue François Mitterrand, Talence, France*
[2]Institut d'Electronique et des Systèmes (IES), CNRS UMR5214, Université de Montpellier, Montpellier, France
[3]*Laboratoire Photonique, Numérique et Nanosciences (LP2N), Institut d'Optique Graduate School, CNRS, Univ. de Bordeaux, Talence, France*
[4]*Azur Light Systems, Av. de la Canteranne, Pessac, France*
[5]*C2N-CNRS - Université Paris Sud, Marcoussis, France*
[6]*Present address: MOE Key Laboratory of Fundamental Physical Quantities Measurement, School of Physics, Huazhong University of Science and Technology, 1037 Luoyu Rd., Wuhan 430074, China*
**Corresponding author:* giorgio.santarelli@institutoptique.fr

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

Exploiting III-V semiconductor technologies, vertical external-cavity surface-emitting laser (VECSEL) technology has been identified for years as a good candidate to develop lasers with high power, large coherence and broad tunability. Combined with fiber amplification technology, tunable single-frequency lasers can be flexibly boosted to a power level of several tens of watts. Here, we demonstrate a high power, single frequency and broadly tunable laser based on VECSEL technology. This device emits in the near-infrared around 1.06 µm and exhibits high output power (>100 mW) with a low-divergence diffraction-limited TEM_{00} beam. It also features a narrow free-running linewidth of < 400 kHz, with high spectral purity (SMSR >55 dB), and continuous broadband tunability greater than 250 GHz (< 15 V piezo voltage, 6 kHz cut-off frequency) with a total tunable range up to 3 THz. In addition, a compact design without any movable intracavity elements offers a robust single-frequency regime. Through fiber amplification, a tunable single-frequency laser is achieved at an output power of 50 W covering the wavelength range from 1057 nm to 1066 nm. Excess intensity noise brought on by the amplification stage is in good agreement with a theoretical model. A low relative intensity noise (RIN) value of -145 dBc/Hz is obtained at 1 MHz and we reach the shot-noise limit above 200 MHz.

OCIS codes: *(140.7260) Vertical cavity surface emitting lasers; (060.2320) Fiber optics amplifiers and oscillators; (060.3510) Lasers, fiber; (140.3070) Infrared and far-infrared lasers.*

http://dx.doi.org/10.1364/AO.99.099999

1. INTRODUCTION

Wavelength-tunable, narrow spectral bandwidth, continuous-wave lasers are the essential workhorse of atomic, molecular and optical (AMO) related physical experiments, including atomic trapping and cooling [1] or high-resolution spectroscopy [2]. In particular, power scalable single-frequency laser sources operating at multiple wavelengths are attractive for cryogenic optical refrigeration applications [3] and for generating novel wavelengths into visible and ultraviolet spectral region by nonlinear frequency conversion [4, 5]. Initially, high-power wavelength-tunable single-frequency optical sources were provided by traveling-wave dye lasers [6]. However, a major drawback of this technology was that the dye solution needed to be frequently renewed. With the development of the Ti: Sapphire solid-state laser came both a wide tunable bandwidth and a narrow linewidth [7]. Yet an expensive cost and a complex laser configuration prohibited its use in widespread applications. Diode-pumped solid-state lasers presented both excellent beam and spectral quality at high levels of output power but suffered from the lack of compactness and discrete values of wavelength emission. Semiconductor diode laser technology enabled efficient emission in the near- to mid-infrared range in a very compact design, but at the same time exhibited poor spatial and temporal coherence. Thanks to its unique architecture, optically pumped VECSEL technology allows one to overcome the physical and technical limitations of previous technologies. This architecture exhibits a wide tunability in a single-frequency regime, with a diffraction-limited beam in a highly compact and low-cost design. These features make VECSEL technology a promising candidate for AMO experiments requiring an individual tunable laser. The typical output power of VECSELs is limited to several watts due to the thermal rollover of the semiconductor gain medium [8]. Nevertheless, up to 106 W of output power can be achieved in multimode operation by employing critical thermal management [9].

Fiber-based master-oscillator power amplifiers (MOPAs) have been shown to be suitable for single-frequency seed amplification [10-12]. In such a configuration, the power can be scaled to hundreds of watts while maintaining the excellent properties of the seed laser. Thanks to high gain and good beam quality of rare-earth doped fiber amplifiers, a kW-class tunable narrow linewidth MOPA laser source was demonstrated [13]. Linewidth broadening by phase modulation based on a white noise source is used to suppress detrimental non-linear effects like stimulated Brillouin scattering (SBS). An increase of the mode-field diameter of the gain fiber is useful to mitigate SBS. Large-mode-area double-clad microstructure fiber technology has been widely deployed to achieve high-fidelity power-amplified laser systems [14-16]. However, previously reported MOPAs have mostly been built with free-space configurations which exclude the intrinsic advantages of fiber waveguide technology, such as compactness and robustness, and reliable long-term operation. To realize an all-fibered MOPA, one must address the technical challenge of splicing a microstructure fiber to a standard fiber with low loss.

Using a fixed-wavelength external-cavity diode laser as seed, a microstructure Yb-doped all-fibered MOPA was demonstrated in Ref. [17] with an output power of 50 W and a low intensity noise performance. In this work, we inject an industry-ready packaged agile VECSEL source into the similar fiber amplifier, achieving a high-fidelity stable single-frequency laser source with a tunable range from 1057 to 1066 nm at an output power of 50 W.

2. VECSEL FABRICATION

The industry-ready packaged GaAs-based VECSEL source emitting around 1.06 µm (see Fig. 2), was fabricated and packaged into a compact module. Thanks to the high-finesse short-cavity design associated with ideal homogeneous Quantum Well (QW) gain behavior, the developed device combines low RIN (-140 dB/Hz @ 1 kHz), a narrow linewidth below 1 MHz (1 ms integration time), a side-mode suppression ratio (SMSR) greater than 50 dB and a polarization extinction ratio (PER) above 50 dB. In terms of spatial coherence, the beam is close to the diffraction limit, even at a high output power of 200 mW [18]. In addition, this intra-cavity-element-free design allows broadband tunability of the laser emission wavelength over more than 10 nm.

Depending on the application, the final product could be easily integrated into a laboratory experiment, but in most cases, the system could be transportable (e.g. wind sensing for wind prospecting, environmental science, or telemetry). Thus, particular attention was devoted to integration and robustness during the design of the module. The total target volume, including driving electronics and optical pumping system was about 5 cm^3.

The device includes a laser cavity as shown in Fig.1 formed by the gain mirror (called ½ VCSEL), an air gap (< 1 mm) and a mirror. The GaAs-based ½ VCSEL emitting at λ = 1.06 µm (and designed to be optically pumped around 800 nm), was grown on a [001] GaAs doped substrate in a low pressure (70 Torr under H_2 carrier gas) metal-organic-chemical-vapor-deposition in a D-180Veeco TurboDisc reactor using TMGa, TMAl, TMIn, and AsH_3 at 60 mTorr at a temperature of 700°C. It contains a high-reflectivity (99.95%) AlAs/GaAs distributed Bragg reflector (27 pairs) and an active layer on top, designed with 12 strain-balanced InGaAs/GaAsP Quantum Wells (QWs) and GaAs pump-absorbing barriers. The QWs are distributed among the optical standing wave antinodes to ensure a low threshold and a homogeneous gain.

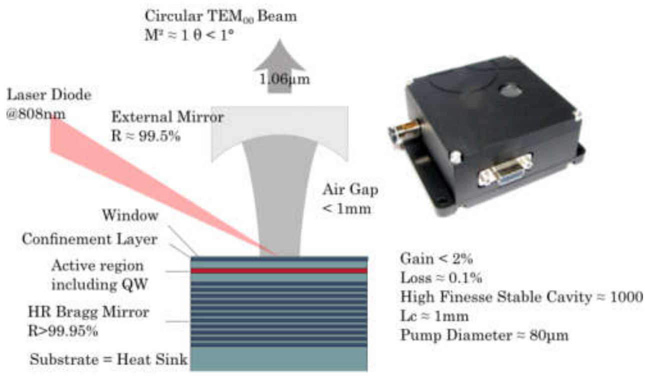

Fig. 1. VECSEL architecture, physical parameters, and packaging.

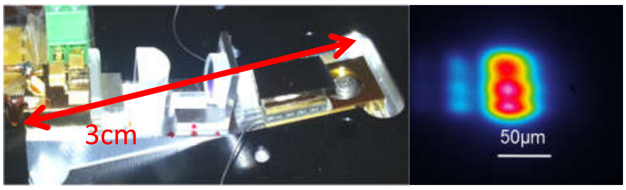

Fig. 2. (left) Close view of the laser diode and collimating lenses; (right) Focused pump spot on the chip.

The 13.5 λ/2 thick active layer is designed to be anti-resonant at the laser wavelength in order to strongly reduce both resonance effects within the laser bandwidth and perturbative thermal lens effects. This layer also has an impact on non-linear mode coupling in the quantum well gain, preventing single longitudinal-mode operation. On the top of the 13.5 λ/2-thick active layer, we grew a 30-nm-thick AlAs confinement layer, and a 15nm thick GaAs/InGaP cap layer to avoid oxydation. The mm-long laser cavity is closed by a commercial mirror, which is movable thanks to a low-voltage piezo actuator and allows the use of a low noise voltage source. The cavity design is optimized to lower the mechanical contribution to the laser's frequency noise. The chip is optically pumped with a commercial multimode laser diode delivering optical power up to 1.5 W at 808 nm and its temperature is regulated by a Peltier module. The pump beam is focused onto the gain mirror with a beam diameter of around 50 µm [see Fig. 2(right)]. Thanks to the tight integration of the pumping module [see Fig. 2(left)], the device is housed in a small enclosure measuring 74 mm × 58 mm × 32 mm.

In order to ensure high spatial coherence, VECSEL-based devices are often made with a cavity of a few centimeters—requiring the use of an intracavity filter. In our case, the combination of a broadband low gain mirror and a sub mm air gap cavity enables us to reach single frequency operation without any intra-cavity spectral filter [19]. A high spatial coherence is also obtained with this architecture. We can therefore fully take advantage of semiconductor material wavelength flexibility, reaching broadband tunability in a mode hop-free operation [20]. In a semiconductor laser, the selection of the single-longitudinal mode number within the gain bandwidth depends on the temperature of the active region, which is accessible via the heat sink thermal load or the pump-induced heat [21]. Thus, the laser emission wavelength can be coarsely tuned either with the optical pump power or the Peltier cooler. Figure 3(a) shows the emitting spectrum at different operating temperatures for a pump power of 600 mW. The central wavelength red shifts with increasing temperature at a tuning rate of 0.35 nm/K (94 GHz/K). The SMSR is more than 50 dB over the whole temperature range. For different pump powers, the wavelength tunability is shown in Fig. 3(b). The full tunable range reaches more than 10 nm. Stable mode-hop-free operation is achieved in the pump power regime of 300 - 800 mW.

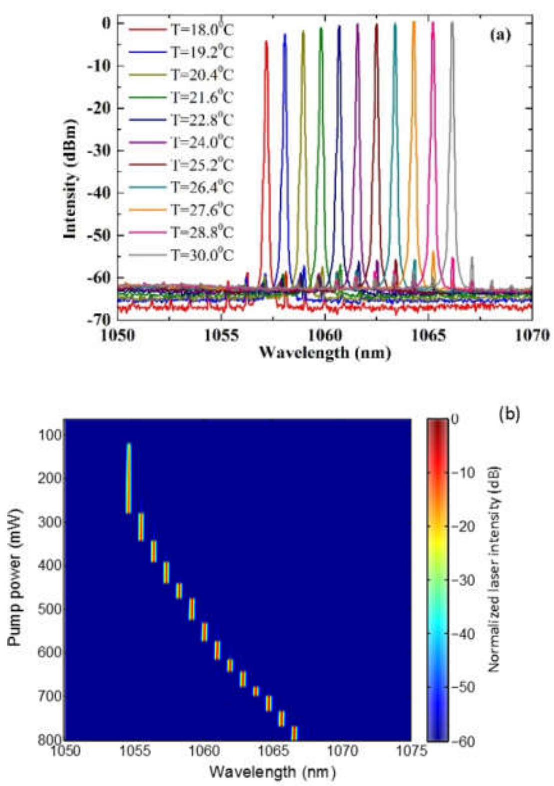

Fig. 3. Optical spectrum tunability of the VECSEL by setting different operation temperature at 600 mW of pump power (a) and the recorded emitting wavelength at various pump powers (b).

Moreover, the piezo actuator enables fine continuous tuning of the laser emission wavelength over a free spectral range, which is around 200 GHz by design. Combining those two features yields a broadband continuous tunability over tens of free spectral range. The modulation frequency of the piezo actuator is up to 10 kHz with a low supply voltage below 50 V. Finally, it is important to point out that the device design does not depend on the laser wavelength and offers the same performance in the 0.9 - 1.1 µm range.

3. VECSEL PERFORMANCE AND LIMITATIONS

The developed device operating at 1.06 µm exhibits a laser emission of about 200 mW for 1 W of pump power with a low divergence TEM_{00} beam close to the diffraction limit. The measured VECSEL optical output power versus pump power is shown in Fig. 4(a). The threshold pump power is about 200 mW. The pump power to VECSEL power efficiency is 33% at room temperature. The beam divergence angle is less than 0.4°.

This device exhibits stable spectral single-mode operation from threshold to thermal rollover with a thermal frequency drift less than a few GHz/h without any stabilization control. The measured spectra at 630 mW of pump power and at an operating temperature of 25 °C are shown in Fig. 5. The SMSR is 60 dB and reaches the quantum limit. The device features linearly-polarized light along the crystal axis of the gain mirror [110], with a measured orthogonal PER around 70 dB between the two non-degenerate states. These properties are primarily a result of gain dichroism in the quantum wells and birefringence in the crystal [19]. The RF spectrum that shows the beating between the two polarization states is shown in the inset of Fig 5. To generate this beating, we used a linear polarizer oriented at 45° with respect to the crystal axis. Then, the beam is focused on a low noise detector and the noise spectrum of the laser is measured using a RF spectrum analyzer.

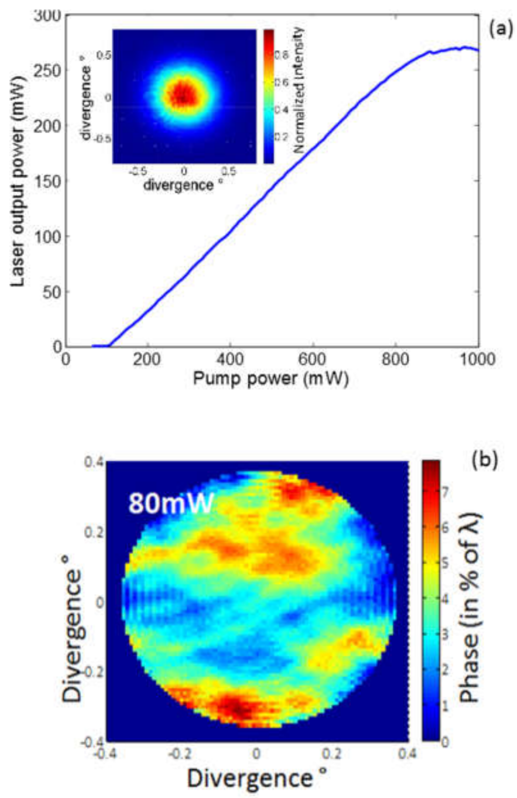

Fig. 4. (a) Optical output power of the VECSEL according to pump power and transverse beam far-field distribution (inset). (b) Far-field beam phase map at 80 mW of optical power.

The high-Q VECSEL design, which emits highly coherent radiation, should, by definition, yield low intensity and low frequency noise. Our measurements of the intensity and phase fluctuations are shown in Fig. 6. Despite the use of a multimode pump diode, the emitted power is very stable leading to relative RMS fluctuations of < 0.2% in the 1 kHz - 200 MHz frequency range. These fluctuations could be reduced using an intensity noise stabilization loop. In fact, unlike laser diodes, which exhibit white intensity noise up to a few GHz, this laser cavity acts like a low-pass filter with a cut-off frequency around 100 MHz. RIN at low frequency is pump-noise limited up to the cut-off frequency where the intensity noise spectral density reaches the shot noise level up to 200 MHz leading to an ultralow noise source in this frequency range.

We also performed direct frequency noise measurements using a homemade stable plano-concave Fabry-Perot interferometer as a frequency discriminator. The results are shown in Fig. 6. Although the fundamental limit of the linewidth given by quantum noise is at the Hz level like solid state lasers, the measured laser linewidth is about 400 kHz for 1 ms of integration time. This degradation is due to technical contributions. In fact, frequency noise is mainly dominated by frequency fluctuations generated by pump intensity noise induced by index fluctuations in the 1 kHz – 1 MHz Fourier range (see Fig. 6) [8].

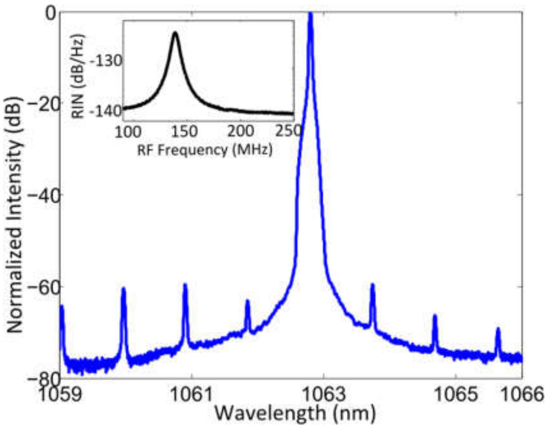

Fig. 5. Optical high-resolution spectrum at high output power and RF spectrum of the beating between the two polarization modes (inset).

In addition, the external cavity configuration is sensitive to mechanical noise, which dominates for Fourier frequencies below 1 kHz. The use of a pump noise stabilization will reduce thermal fluctuations and the improvement of the cavity mechanical stability will reduce mechanical contribution to the frequency noise.

4. FIBER POWER AMPLIFICATION

Since the emission wavelength of VECSEL is specially designed to overlap with the gain spectrum of Yb^{3+}, the laser power can be boosted by the industry-ready fiber amplifier, which has been described in Ref. [17]. The power scaling is based on a typical MOPA configuration. Here, a free-space propagating VECSEL beam provides a seed source. It is first collimated by an f = 70 mm spherical lens and then coupled into a single-mode polarization maintaining fiber (PM980). To ensure polarization stability, the polarization direction of the VECSEL is well aligned to the slow axis of the PM980 fiber. A free-space isolator is inserted following the spherical lens to avoid stray back reflections. The overall coupling efficiency is about 60%. The center wavelength of the seed source is set at 1057, 1064, and 1066 nm by adjusting the operating temperature of the VECSEL. For the preamplifier stage, the seed power is scaled up to ~1 W. For the main amplifier, the output power versus pump power at different wavelengths is shown in Fig. 7.

The output power is nearly independent of the input wavelength. At a launched pump power of 72 W @ 976 nm, the output power of ~50 W is achieved for all the wavelengths. The optical-to-optical slope efficiency is about 73%. We measure the fiber amplifier output spectrum operating at 1064 nm at 50 W output power. The signal-to-noise ratio is more than 50 dB and no sign of spectrum broadening is observed. During power amplification in the fiber amplifier, the spectral purity of the seed laser is susceptible to SBS effects.

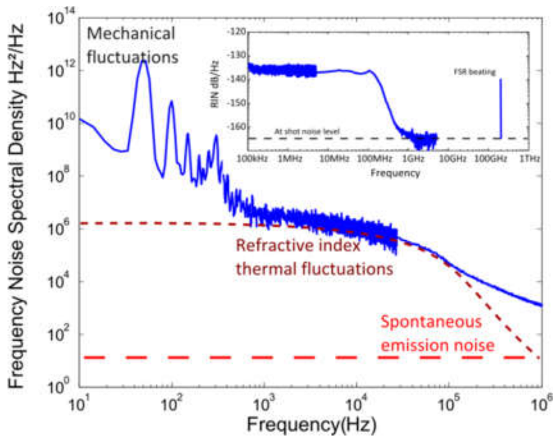

Fig. 6. Frequency noise spectral density and intensity noise spectral density (inset).

The presence of SBS can be observed from the RIN measurements, which adds a white noise floor at frequencies above 1 MHz [22]. To check the spectral fidelity after power amplification, we compare the RIN of the VECSEL with a fiber amplifier at 50 W at three different wavelengths (Fig. 8). We find that the high frequency (> 1 MHz) RIN of the fiber amplifier well reproduces that of the seed laser at each wavelength.

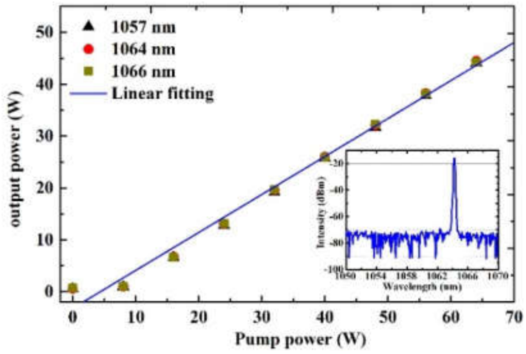

Fig. 7. Signal output power versus pump power of the fiber amplifier and a spectrum at 1064 nm and 50 W output power (inset).

These measurements rule out the occurrence of SBS. Again, the high fidelity of the fiber amplification system is validated. For the fiber amplifier operating at 1064 nm, a minimum RIN of -145 dB/Hz is achieved at frequencies higher than 1 MHz. At lower frequencies (< 10 kHz), the fiber amplifier RIN measurements are nearly identical and independent of the seed. These observations agree well with the theoretical model of noise dynamics of fiber amplifiers. Basically, the pump modulation acts as a low-pass filter and the signal modulation responds as a damped high-pass filter [23-25]. In other words, such theoretical models can be validated by the fact that the RIN of the fiber amplifier is given by the pump noise at low frequencies, and by the seed source at high frequencies.

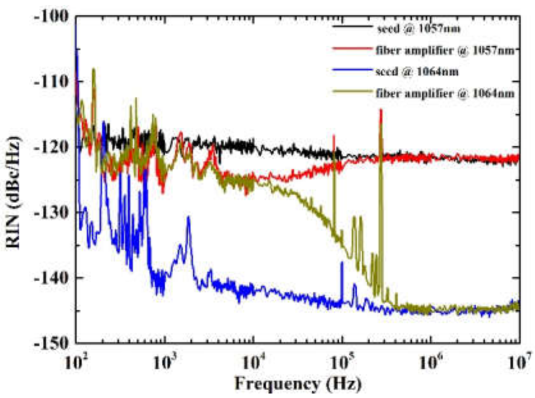

Fig. 8. Relative intensity noise measurements of the VECSEL and fiber amplifier at 50 W output power for two different wavelengths (1057 nm and 1064 nm).

5. CONCLUSIONS

In this work, we have presented a high-fidelity fiber power amplification of a VECSEL-based tunable single-frequency laser source. An output power of 50 W covering the wavelength range of 1057 - 1066 nm is achieved. The laser shows high spectral purity (SMSR > 55 dB) with a narrow linewidth of less than 400 kHz. The intensity noise brought on by the fiber amplifier agrees well with the theoretical model of gain dynamics in fiber amplifiers. A RIN value of -145dB/Hz at 1 MHz was obtained. The fiber amplifier intensity noise performance validates the high fidelity of MOPA system in the absence of SBS. In the future, we plan to improve the VECSEL design with better mechanical stability and single-mode pumping to further decrease the intensity noise and linewidth. We also plan a fiber-coupled version for easier industrial integration. Further scaling of optical power in the 100 W range is under development [26].

Funding. ANRT, French RENATECH network, , SATT AxLR. Agence Nationale de la Recherche (ANR) (ANR14 LAB05 0002 01) and Conseil Regional d'Aquitaine (2014-IR60309-00003281); Post-doctoral scholarship grant from the La Fondation Franco-Chinoise pour la Science et ses Applications (FFCSA).

Acknowledgment. We thank Florian Floissat (LP2N) for both technical help and discussion.

References

1. J. Zhang, W. H. Yuan, K. Deng, A. Deng, Z. T. Xu, C. B. Qin, Z. H. Lu, and J. Luo, "A long-term frequency stabilized deep ultraviolet laser for Mg^+ ions trapping experiments," Rev. Sci. Instrum. **84**, 123109 (2013).
2. P. Cermak, B. Chomet, L. Ferrieres, S. Vasilchenko, D. Mondelain, S. Kassi, A.Campargue, S. Denet, V. Lecocq, M. Myara, L. Cerutti, and A. Garnache "CRDS with a VECSEL for broad-band high sensitivity spectroscopy in the 2.3 µm window" Rev Sci Instrum, **87**, 083109 (2016).
3. D. V. Seletskiy, S. D. Melgaard, S. Bigotta, A. Di Lieto, M. Tonelli, and M. Sheik-Bahae, "Laser cooling of solids to cryogenic temperatures," Nat. Photonics **4**, 161–164 (2010).

4. S. Ranta, M. Tavast, T. Leinonen, R. Epstein, and M. Guina, "Narrow linewidth 1118/559 nm VECSEL based on strain compensated GaInAs/ GaAs quantum-wells for laser cooling of Mg-ions," Opt. Mater. Express **2**, 1011–1019 (2012).

5. G. J. Ray, T. N. Anderson, J. A. Caton, R. P. Lucht, T. Walther, "OH sensor based on ultraviolet, continuous-wave absorption spectroscopy utilizing a frequency-quadrupled, fiber-amplified external-cavity diode laser," Opt. Lett. **26**, 1870–1872 (2001).

6. J.Walling, O. Peterson, and R. Morris, "Tunable CW alexandrite laser," IEEE J. Quantum Electron. **16**, 120–121 (1980).

7. S.-W. Chiow, S. Herrmann, H. Müller, and S. Chu, "6 W, 1 kHz linewidth, tunable continuous-wave near-infrared laser," Opt. Express **17**, 5246–5250 (2009).

8. A. Laurain, M. Myara, G. Beaudoin, I. Sagnes, and A. Garnache, "Multiwatt–power highly– coherent compact single–frequency tunable Vertical–External–Cavity–Surface–Emitting–Semiconductor–Laser," Opt. Express **18**, 14631 (2010).

9. B. Heinen, T.-L. Wang, M. Sparenberg, A. Weber, B. Kunert, J. Hader, S. W. Koch, J. V. Moloney, M. Koch, and W. Stolz, "106 W continuous-wave output power from vertical-external-cavity surface-emitting laser," Electron. Lett. **48**, 516–517 (2012).

10. J. Boullet, G. Guiraud, G. Santarelli, C. Vincont, S. Salort, C. Pierre, Proc. SPIE 9730, Components and Packaging for Laser Systems II, 97300Q (2016).

11. A. Shirakawa, H. Maruyama, K. Ueda, C. B. Olausson, J. K. Lyngsø, and J. Broeng, "High-power Yb-doped photonic bandgap fiber amplifier at 1150-1200 nm," Opt. Express **17**, 447–454 (2009).

12. M. Hildebrandt, M. Frede, and D. Kracht, "Narrow-linewidth ytterbium-doped fiber amplifier system with 45 nm tuning range and 133 W of output power," Opt. Lett.**32**, 2345–2347 (2007).

13. Y. Liu, R. Su, P. Ma, X. Wang, H. Zhang, P. Zhou, and L. Si, ">1 kW all-fiberized narrow-linewidth polarization-maintained fiber amplifiers with wavelength spanning from 1065 to 1090 nm," Appl. Opt. **56**, 4213–4218 (2017).

14. C. Robin, I. Dajani, and B. Pulford, "Modal instability-suppressing, single-frequency photonic crystal fiber amplifier with 811 W output power," Opt. Lett, **39**, 666–669 (2014).

15. M. Karow, C. Basu, D. Kracht, J. Neumann, and P. Wessels, "TEM_{00} mode content of a two stage single-frequency Yb-doped PCF MOPA with 246 W of output power, " Opt. Express **20**, 5319–5324 (2012).

16. A. Liem, J. Limpert, H. Zellmer, A. Tünnermann, "100-W single-frequency master-oscillator fiber power amplifier," Opt. Lett. **28**, 1537–1539 (2003).

17. G. Guiraud, N. Traynor, and G. Santarelli, "High-power and low-intensity noise laser at 1064 nm," Opt. Lett. **41**, 4040–4043 (2016).

18. Innoptics website, www.innoptics.com

19. A. Garnache, A. Ouvrard, and D. Romanini, "Single-frequency operation of External Cavity VCSELs: non-linear multimode temporal dynamics and quantum limit," Opt. Express **15**, 9403-9417 (2007).

20. A. Ouvrard, L. Cerutti, and A. Garnache, "Broad continuous tunable range with single frequency Sb-based external-cavity VCSEL emitting in MIR", IEEE Electron. Lett., **45**, 629-631 (2009).

21. V. Lecocq, B. Chomet, L. Ferrières, M. Myara, G. Beaudoin, I. Sagnes, L. Cerutti, and A. Garnache, "Industrial integration of high coherence tunable single frequency semiconductor lasers based on VECSEL technology for scientific instrumentation in NIR and MIR", Proc. SPIE, Vertical External Cavity Surface Emitting Lasers VII, 100870A-1 (2017).

22. M. Hildebrandt, S. Büsche, P. Weßels, M. Frede, and D. Kracht, "Brillouin scattering spectra in high-power single frequency ytterbium doped fiber amplifiers," Opt. Express **16**, 15970-15979 (2008)

23. S. Novak and A. Moesle, "Analytic model for gain modulation in EDFAs," J. Lightwave Technol. **20**, 975–985 (2002).

24. H. Tünnermann, J. Neumann, D. Kracht, and P. Weßels, "Gain dynamics and refractive index changes in fiber amplifiers: a frequency domain approach", Opt. Express **20**, 13539–13550 (2012).

25. J. Zhao, G. Guiraud, F. Floissat, B. Gouhier, S. Rota-Rodrigo, N. Traynor, and G. Santarelli, "Gain dynamics of clad-pumped Yb-fiber amplifier and intensity noise control," Opt. Express **25**, 357–366 (2017).

26. J. Zhao, G. Guiraud, C. Pierre. F. Floissat, A. Casanova, A. Hreibil, W. Chaibi, N. Traynor, J. Boullet and G. Santarelli, "High-power all-fiber ultra-low noise laser," Applied Physics B, 124: 114. https://doi.org/10.1007/s00340-018-6989-7 (2018).