


## Article

# An Ultra-High-SMSR External-Cavity Diode Laser with a Wide Tunable Range around 1550 nm

Yan Wang <sup>1,2</sup>, Hao Wu <sup>1,\*</sup> , Chao Chen <sup>1</sup>, Yinli Zhou <sup>1</sup>, Yubing Wang <sup>1</sup>, Lei Liang <sup>1</sup>, Zhenhua Tian <sup>1</sup>, Li Qin <sup>1</sup> and Lijun Wang <sup>1</sup>

- <sup>1</sup> State Key Laboratory of Luminescence and Applications, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China; w\_yan05@163.com (Y.W.); chenc@ciomp.ac.cn (C.C.); 18844074562@163.com (Y.Z.); wangyubing@ciomp.ac.cn (Y.W.); liangl@ciomp.ac.cn (L.L.); tianzh2000@sina.com (Z.T.); qinl@ciomp.ac.cn (L.Q.); wanglj@ciomp.ac.cn (L.W.)
- <sup>2</sup> Center of Materials Science and Optoelectronics Engineering, University of Chinese Academy of Sciences, Beijing 100049, China
- \* Correspondence: hwu@ciomp.ac.cn

Received: 10 September 2019; Accepted: 10 October 2019; Published: 17 October 2019



**Featured Application:** External cavity diode laser emitting at around 1550 nm with an ultra-high side mode suppression ratio can be applied in the field of high-dynamic-range testing and measurement.

**Abstract:** In this paper, a widely tunable external cavity diode laser (ECDL) with an ultra-high side mode suppression ratio (SMSR) was fabricated. Three configurations were constructed to investigate the relationship between the grating features and the SMSR. When a 1200 grooves/mm grating with a first order diffraction efficiency of 91% is utilized in the external-cavity laser system, a maximum SMSR of 65 dB can be achieved. In addition, the tunable range reaches 209.9 nm. The results show that the laser performance can be improved by proper high grating groove number and first-order diffraction efficiency.

**Keywords:** external cavity diode laser (ECDL); side mode suppression ratio (SMSR); diffractive grating; tunable laser

## 1. Introduction

Based on the characteristics of broad tunability, narrow linewidth and compactness, the tunable external cavity diode laser (ECDL) has a broad application in many fields, including atomic physics, laser radar, optical communication, optical measurement, and optical sensing [1–6]. Particularly, ECDLs with high side mode suppression ratio (SMSR) emissions at around 1.5  $\mu\text{m}$  can be applied in many fields, such as high-dynamic-range testing and measurement [7,8]. Therefore, it is important to build an ECDL system with high SMSR.

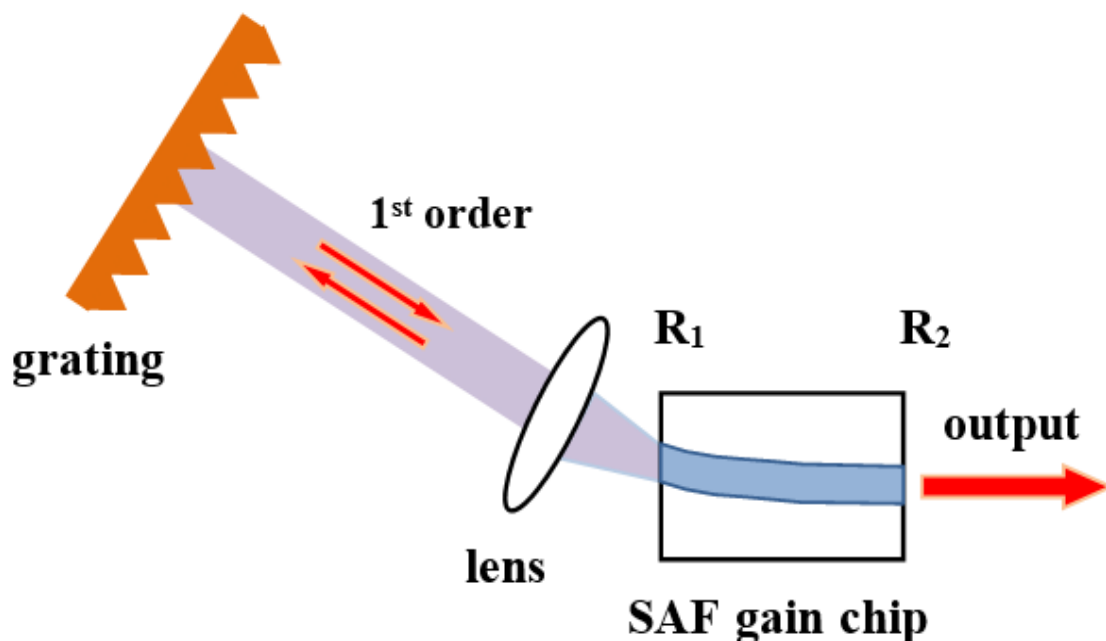
The ECDL consists of a gain chip and an optical element. Grating is the typical dispersive element and Littrow configuration is a typical grating-coupled configuration for tunable ECDL [9,10]. ECDLs with a Littrow configuration based on quantum-well or quantum-dot (QD) laser sources are now in widespread use and broadly investigated [11,12]. An external cavity laser with a tuning range of 242 nm (1320–1562 nm) based on an InGaAsP/InP multiple quantum well (MQW) laser has been demonstrated, where the SMSR is between 17 and 42 dB [13]. A tunable external cavity laser with an InGaAs-InP strained MQW has been demonstrated with a spectral range of 1494–1667 nm. The maximum SMSR is about 50 dB and the bandwidth of optical spectrum is around 0.4 nm [14]. An InAs/InP quantum-dot external cavity laser with a tunable range of 104 nm (1457–1561 nm) has been reported, and the injection current is 1 A, which is extremely high [15]. A tunable external-cavity

laser based on InAs/InP QD laser has been demonstrated, the tuning range of which is 140.4 nm (1436.6–1577 nm) [16]. A widely tunable InAs/InP QD external-cavity laser has been demonstrated, the tunable range of which reaches 190 nm under pulsed injection current, but the SMSR is only around 20 dB [17]. Although there have been some reports on the widely tunable grating-coupled external-cavity laser at 1.5  $\mu\text{m}$ , the SMSR of the ECDL is still relatively low.

In this letter, we demonstrate a Littrow external cavity laser with a high SMSR and a wide tunable range based on a commercial InP gain chip. Three Littrow configurations with 600 grooves/mm and 1200 grooves/mm gratings were constructed to investigate the influence of grating features on the performance of laser, including the SMSR and tunable range. When the 1200 grooves/mm grating with 91% first-order diffraction efficiency was utilized, the maximum side mode suppression ratio exceeded 60 dB and more than 50 dB was achieved in most of the tuning spectrum range of the ECDL. Meanwhile, a tunable range from 1425.4 nm to 1635.3 nm was achieved, encompassing the telecommunication window S (1460–1530 nm), C (1530–1565 nm) and L (1565–1625 nm), as defined by the International Telecommunication Union. And the output power was around 48.9 mW at the emitting wavelength of 1570 nm.

## 2. Experimental Setup

The configuration of the ECDL system is shown in Figure 1. To achieve the widely tunable ECDL, a commercial gain chip (Thorlabs, SAF1126H heatsink assembly, Newton, NJ, USA) was chosen, one facet of which was with ultra-low reflectivity ( $R_1 < 0.01\%$ ). And the reflectivity of another facet was about 10% ( $R_2$ ). The gain chip was accurately cooled by the thermoelectric cooler (TEC) and the measuring temperature was 20  $^{\circ}\text{C}$ . According to the simulation by ZEMAX, an aspherical lens (NA = 0.6) with focal length of 2.97 mm (Thorlabs, 355660-C, Newton, NJ, USA) was chosen to collimated the output beam from rear facet ( $R_1$ ). The collimated beam was diffracted on the surface of a diffractive grating mounted in Littrow configuration and the first order diffractive beam from the grating was fed back into the gain chip.



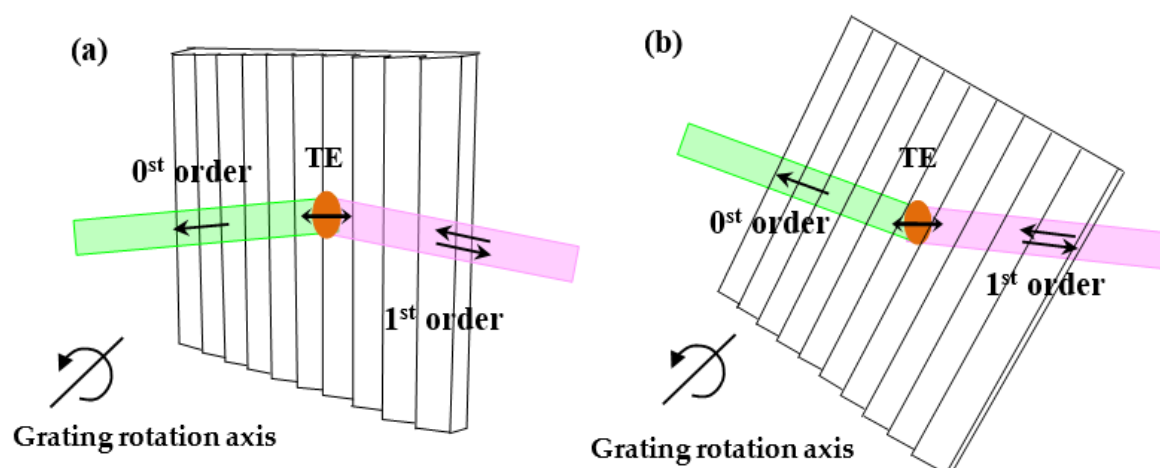
**Figure 1.** The configuration of the Littrow external-cavity diode laser (ECDL) system.

To learn the influence of grating features, including diffraction efficiency and ruling density, on the SMSR and the tunable range, two gratings with different ruling densities were used in the external cavity system, and the parameters of different configurations are listed in Table 1. Configuration A had

the same grating as configuration B, and the grating parameter was 600 lines/mm (Thorlabs, GR13-0616, Newton, NJ, USA). The grating diffraction efficiency of configuration A was about 90%. However, the grating diffraction efficiency of configuration B was changed by rotating the grating along the axis of incident beam to ensure that configuration A and B had the same experimental condition. For configuration B, the polarized direction of the incident beam was non-orthogonal to the direction of grating groove, as shown in Figure 2b, and the diffraction efficiency in the first order at the blazed wavelength of 1550 nm was about 17%. The diffractive grating II (Thorlabs, GR13-1208, Newton, NJ, USA) in configuration C was 1200 lines/mm. And the diffraction efficiency was about 91% for the first order at the blazed wavelength of 1550 nm, which was almost the same as configuration A. For configuration A and C, the polarization direction of the incident beam was perpendicular to the direction of grating groove, as shown in Figure 2a.

**Table 1.** List of the parameters for configuration A, B, and C.

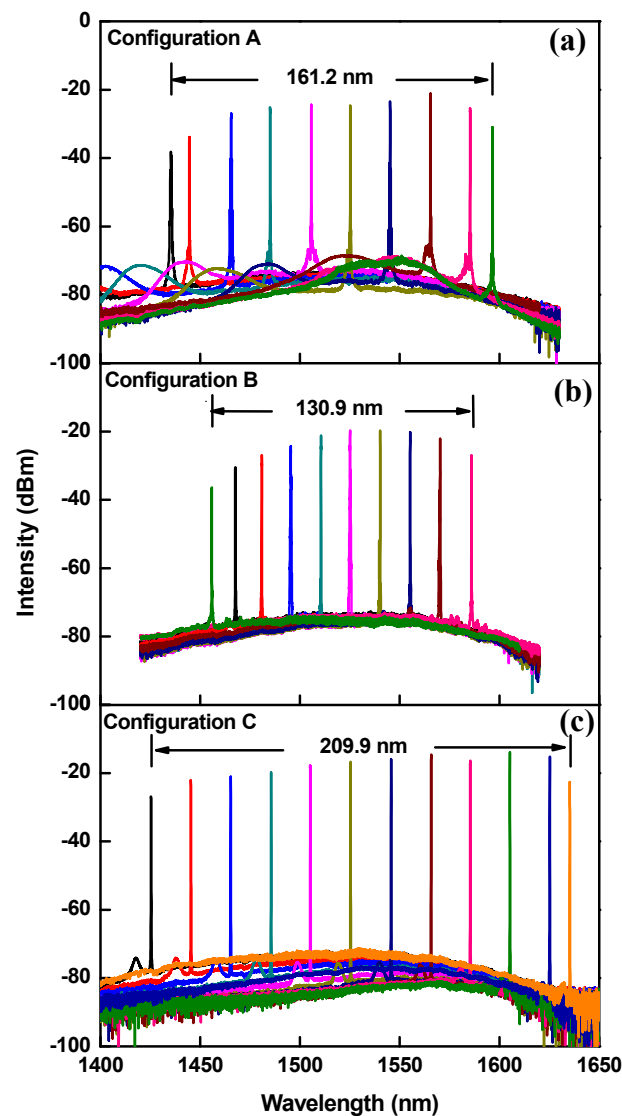
Grating	Configuration	Ruling Density (Grooves/mm)	Diffraction Efficiency in the First Order (%)
Grating I	A	600 lines/mm	90
	B		17
Grating II	C	1200 lines/mm	91



**Figure 2.** (a) Configuration A and C: the polarization direction of the incident beam was perpendicular to the direction of grating groove. (b) Configuration B: the polarization direction of the incident beam was non-orthogonal to the direction of grating groove.

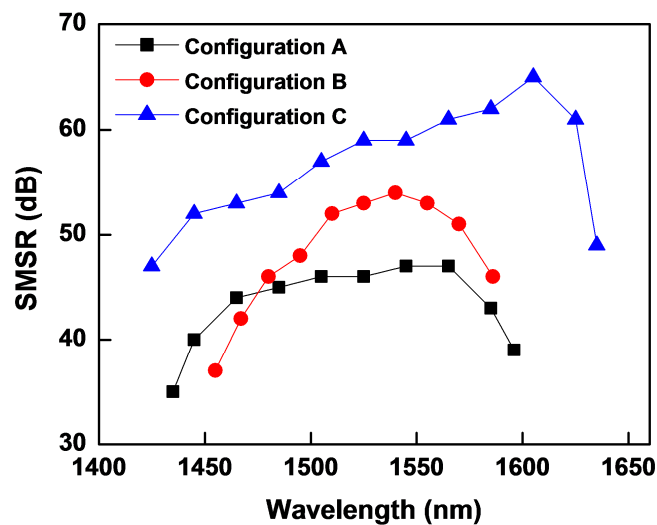
### 3. Results and Discussion

The optical spectra of the ECDL system with different configurations were measured by an optical spectrum analyzer (OSA, YOKOGAWA, AQ6370D, Tokyo, Japanese), the resolution of which was 0.02 nm. The resonance wavelengths were obtained by rotating the grating along the vertical direction. Figure 3 shows the measured spectra of different configurations with an injection current of 300 mA. For configuration A, the tunable range was 161.2 nm from 1435.3 nm to 1596.5 nm, as shown in Figure 3a. The SMSR achieved 47 dB. For configuration B, the SMSR achieved 54 dB, as shown in Figure 3b. The tunable range was 130.9 nm from 1455.4 nm to 1586.3 nm. Compared with configuration A, the tunable range was reduced, but the SMSR was improved. In Figure 3c, the ruling density of grating was increased and a highest SMSR of 65 dB was realized for configuration C. And the tunable range was significantly increased. The tunable range achieved 209.9 nm from 1425.4 nm to 1635.3 nm.



**Figure 3.** Optical spectra of the output beam for the ECDLs with (a) configuration A, (b) configuration B, and (c) configuration C. The injection current was 300 mA.

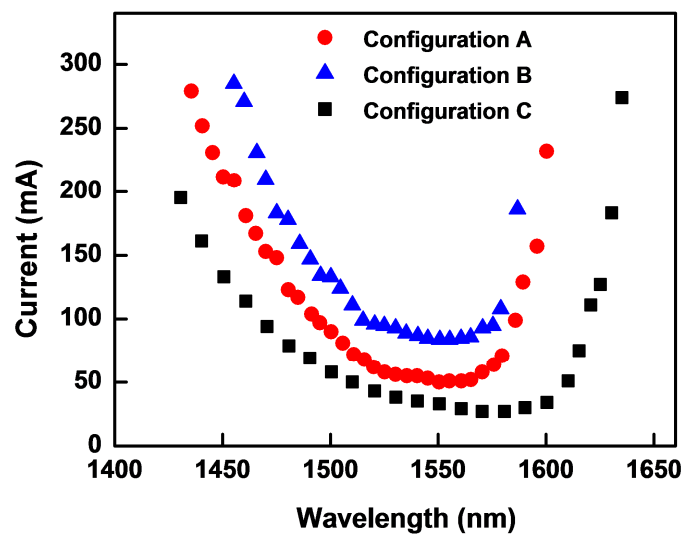
As can be seen in the above experimental results, the grating parameters have a great effect on the characteristics of the external-cavity laser. The SMSRs for three configurations are investigated in Figure 4. Compared with configuration A, the SMSR of configuration B was improved. And the SMSR of configuration C was the maximum. For the configuration A, there were gradual mounts in the optical spectra, as seen in Figure 3a, which greatly reduced the SMSR. For configuration B, the SMSR was improved by thoroughly eliminating the gradual mount, which may be due to the polarization mismatch between the polarization direction of the incident light and the direction of grating groove. For configuration C, the SMSR was significantly improved by increasing the grating groove density and the tunable range was also improved.



**Figure 4.** The side mode suppression ratio (SMSR) versus tuning wavelength for configuration A, B, and C, respectively.

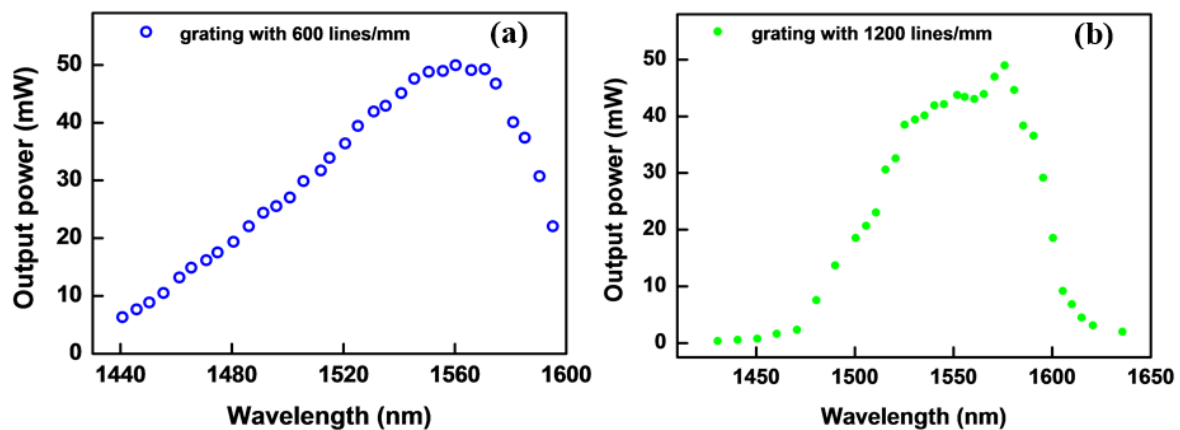
The grating groove density has a great influence on the laser performance. For the external-cavity laser, the diffraction angle is related to the grating equation:  $2d\sin\theta_L = m\lambda$ , where the  $d$  is the grating period, the  $\theta_L$  is the diffraction angle. According to the equation, grating diffractive angle is related to the number of grating grooves. The higher the number of grating grooves, the larger the diffraction angle. Due to  $d\theta/d\lambda = 1/(2d\cos\theta)$ , a large grating diffraction angle is helpful to improve grating resolution. Meanwhile, a larger diffractive angle produced a larger spot size on the grating, which means more groove periods are effective to provide optical feedback with the function of wavelength selection. And the noise is better suppressed with a large diffractive angle. Compared with configuration A and B, the grating used in configuration C had a higher groove number and a larger diffraction angle according to the grating equation. For the configuration A, B, and C, when the wavelength of output beam was 1550 nm, the diffraction angle was  $27.7^\circ$ ,  $27.7^\circ$ , and  $68.4^\circ$ , respectively. Therefore, configuration C, with a better ability to suppress the noise, can achieve the higher SMSR. However, the grating groove density should not be too large to avoid the diffraction angle being too close to  $90^\circ$ . In the configurations, a better SMSR was achieved in the long-wavelength region of the spectrum, which is also due to the grating diffractive angle of long output wavelength being relatively large. In the longer output wavelength region, it arrives at the edge of material gain, which will lead to a drop in the SMSR.

The threshold current as a function of wavelength of external-cavity laser was investigated. Figure 5 compares the threshold currents of different external-cavity configurations. It can be observed that the variation trend of threshold current was consistent. The threshold current decreased significantly at an intermediate tuning range due to the high material gain and increased when the output wavelength was changed toward the long or short wavelength. With the same diffraction grating, the higher first diffraction efficiency means stronger feedback intensity, which may effectively reduce the mirror loss and then decrease the threshold current. Compared with configuration B, configuration A showed a lower threshold current due to the higher first diffraction efficiency. The minimum threshold currents of configuration A and B were 50 mA and 84 mA, respectively. The minimum threshold current of configuration C was 37 mA, which was the lowest in the three configurations. It can be observed that higher grating resolution can significantly decrease the threshold current.



**Figure 5.** Threshold current of the external cavity diode laser at different wavelengths with configuration A, B, and C.

Figure 6 shows the output power of the ECDLs, which was changed with the wavelength and measured by a power meter (Thorlabs, S146C, Newton, NJ, USA). The injection current was 300 mA and the measuring temperature was 20 °C. The output power of configuration B was significantly decreased due to the low first diffraction efficiency, which was reported in our previous article [18]. Thus it is not given here. For configuration A with the grating of 600 lines/mm, the maximum output power was 49.9 mW. For configuration C with the grating of 1200 lines/mm, the maximum output power was 48.9 mW. As can be observed in the figures, the number of grating lines had little influence on the output power of the ECDL with a similar first diffraction efficiency.



**Figure 6.** The output power of the ECDL was measured with the change in wavelength for the (a) configuration A and (b) configuration C. The injection current was 300 mA.

#### 4. Conclusions

In this paper, three configurations with different grating parameters, including diffraction efficiency and groove density, were investigated. It was demonstrated that the external-cavity laser performance can be improved by increasing the groove density of grating in the Littrow configuration. For configuration A, the SMSR was relatively low. The SMSR was improved significantly in configuration B, which may be due to the polarization mismatch between the polarization direction of the incident light and the grating. When the grating groove density was increased appropriately, as shown in configuration C, the laser performance including SMSR can be further improved.

The improvement of SMSR is attributed to the larger diffractive angle with a high grating groove. Larger diffractive angle means a larger spot size, which can cover more grating lines and improve the grating resolution. In this way, the noise can be suppressed better and a higher SMSR obtained. At the same time, the tunable range is also increased. When a grating with 1200 lines/mm and a first-order of 91% was used, the SMSR of the ECDL reached up to 65 dB, and more than 50 dB was achieved in most of the tuning spectrum range of the ECDL. The tunable range reached 209.9 nm. The threshold current was 37 mA and the output power was 48.9 mW. We have achieved the highest SMSR, compared with the five references [13–17], which are listed in Table 2.

**Table 2.** Basic properties of the five references [13–17] and the three configurations.

(External Cavity Diode Laser) ECDL System	Maximum (Side Mode Suppression Ratio) SMSR (dB)	Tunable Range (nm)	Maximum Power (mW)
ECDL based on InGaAsP/InP MQW laser [13]	42	242	45
ECDL based on InGaAs/InP strained multi-quantum-well laser [14]	50	173	81
ECDL based on InAs/InP quantum-dot laser [15]	-	104	34
ECDL based on InAs/InP QD laser [16]	-	140.4	6
ECDL based on InAs/InP QD laser [17]	20	190 (pulsed current)	-
This work	Configuration A	161.2	49.9
	Configuration B	130.9	5.5
	Configuration C	209.9	48.9

**Author Contributions:** Y.W. (Yan Wang) and H.W. conceptualized the work. L.L., Z.T., and C.C. prepared the experiment platform and equipment. Y.W. (Yan Wang), H.W., and Y.Z. performed the characterization of the external cavity diode laser. Y.W. (Yan Wang), H.W., Y.W. (Yubing Wang), L.Q., and L.W. analyzed and prepared the data. Y.W. (Yan Wang) and H.W. wrote the article; all authors reviewed data and manuscript.

**Funding:** This research was funded by National Key Research and Development Program of China with Project No. 2018YFB2201103 and Science and Technology Key Project of Jilin Province with Project No. 20170204013GX.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Phillips, W.D. Laser cooling and trapping of neutral atoms. *Rev. Mod. Phys.* **1998**, *70*, 721–741. [\[CrossRef\]](#)
2. Bashkansky, M.; Lucke, R.L.; Funk, E.; Richard, L.J.; Reintjes, J. Two-dimensional synthetic aperture imaging in the optical domain. *Opt. Lett.* **2002**, *27*, 1983–1985. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Ma, Y.; Yang, Q.; Tang, Y.; Chen, S.; Shieh, W. 1-Tb/s single-channel coherent optical OFDM transmission over 600-km SSMF fiber with subwavelength bandwidth access. *Opt. Express* **2009**, *17*, 9421–9427. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Zhang, D.; Zhao, J.; Yang, Q.; Liu, W.; Fu, Y.; Li, C.; Luo, M.; Hu, S.; Hu, Q.; Wang, L. Compact MEMS external cavity tunable laser with ultra-narrow linewidth for coherent detection. *Opt. Express* **2012**, *20*, 19670–19682. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Bagnoli, P.E.; Beverini, N.; Falciai, R.; Maccioni, E.; Morganti, M.; Sorrentino, F.; Stefani, F.; Trono, C. Development of an erbium-doped fibre laser as a deep-sea hydrophone. *J. Opt. A Pure Appl. Opt.* **2006**, *8*, S535–S539. [\[CrossRef\]](#)
6. Lu, Y.; Zhu, T.; Chen, L.; Bao, X. Distributed Vibration Sensor Based on Coherent Detection of Phase-OTDR. *J. Lightwave Technol.* **2010**, *28*, 3243–3249.
7. Kitching, J.; Boyd, R.; Yariv, A.; Shevy, Y. Amplitude noise reduction in semiconductor lasers with weak, dispersive optical feedback. *Opt. Lett.* **1994**, *19*, 1331–1333. [\[CrossRef\]](#)
8. Doringshoff, K.; Ernsting, I.; Rinkleff, R.; Schiller, S.; Wicht, A. Low-noise, tunable diode laser for ultra-high-resolution spectroscopy. *Opt. Lett.* **2007**, *32*, 2876–2878. [\[CrossRef\]](#)
9. Chi, M.; Jensen, O.B.; Holm, J.; Pedersen, C.; Andersen, P.E.; Erbert, G.; Sumpf, B.; Petersen, M. Tunable high-power narrow-linewidth semiconductor laser based on an external-cavity tapered amplifier. *Opt. Express* **2005**, *13*, 10589–10596. [\[CrossRef\]](#)

10. Loh, H.; Lin, Y.J.; Teper, I.; Cetina, M.; Simon, J.; Thompson, J.K.; Vuletić, V. Influence of grating parameters on the linewidths of external-cavity diode lasers. *Appl. Opt.* **2006**, *45*, 9191–9197. [[CrossRef](#)] [[PubMed](#)]
11. Saliba, S.D.; Scholten, R.E. Linewidths below 100 kHz with external cavity diode lasers. *Appl. Opt.* **2009**, *48*, 6961–6966. [[CrossRef](#)]
12. Shin, D.K.; Henson, B.M.; Khakimov, R.I.; Ross, J.A.; Dedman, C.J.; Hodgman, S.S.; Baldwin, K.G.; Truscott, A.G. Widely tunable, narrow linewidth external-cavity gain chip laser for spectroscopy between 1.0–1.1  $\mu\text{m}$ . *Opt. Express* **2016**, *24*, 27403–27414. [[CrossRef](#)] [[PubMed](#)]
13. Bagley, M.; Wyatt, R.; Elton, D.J.; Wicks, H.J.; Spurdens, P.C.; Seltzer, C.P.; Cooper, D.M.; Devlin, W.J. 242 nm continuous tuning from a GRIN-SC-MQW-BH InGaAsP laser in an extended cavity. *Electron. Lett.* **1990**, *26*, 267–269. [[CrossRef](#)]
14. Fedorova, K.A.; Cataluna, M.A.; Kudryashov, I.; Khalfin, V.; Rafailov, E.U. Broadly Tunable InGaAsP–InP Strained Multiquantum-Well External Cavity Diode Laser. *IEEE Photonic Technol. Lett.* **2010**, *22*, 1205–1207. [[CrossRef](#)]
15. Gao, F.; Luo, S.; Ji, H.M.; Yang, X.G.; Yang, T. Enhanced performance of tunable external-cavity 1.5  $\mu\text{m}$  InAs/InP quantum dot lasers using facet coating. *Appl. Opt.* **2015**, *54*, 472–476. [[CrossRef](#)]
16. Gao, F.; Luo, S.; Ji, H.M.; Yang, X.Z.; Liang, P.; Yang, T.S. Broadband tunable InAs/InP quantum dot external-cavity laser emitting around 1.55  $\mu\text{m}$ . *Opt. Express* **2015**, *23*, 18493–18500. [[CrossRef](#)]
17. Yuan, H.H.; Gao, F.; Yang, T. Ultra-broadband tunable single- and double-mode InAs/InP quantum dot external-cavity laser emitting around 1.65  $\mu\text{m}$ . *Opt. Lett.* **2018**, *43*, 3025–3028. [[CrossRef](#)] [[PubMed](#)]
18. Wang, Y.; Wu, H.; Zhang, X.; Liu, J.G.; Chen, C.; Wang, Y.B.; Zhou, Y.L.; Liang, L.; Zhang, J.; Qin, L.; et al. 1550 nm external cavity diode laser with enhanced SMSR based on polarization mismatch by grating rotation. *Appl. Opt.* **2019**, *58*, 5213–5218. [[CrossRef](#)] [[PubMed](#)]



© 2019 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).