photonics

Review

Review of 1.55 µm Waveband Integrated External Cavity Tunable Diode Lasers

Linyu Zhang, Xuan Li, Wei Luo, Junce Shi, Kangxun Sun, Meiye Qiu, Zhaoxuan Zheng, Huiying Kong, Jinhui Zhou, Chi Zhang, Zaijin Li *, Yi Qu, Zhongliang Qiao and Lin Li

Key Laboratory of Laser Technology and Optoelectronic Functional Materials of Hainan Province, Academician Team Innovation Center of Hainan Province, Hainan International Joint Research Center for Semiconductor Lasers, College of Physics and Electronic Engineering, Hainan Normal University, Haikou 571158, China; 202213085400017@hainnu.edu.cn (L.Z.); 20213085400013@hainnu.edu.cn (X.L.); 202313085408009@hainnu.edu.cn (W.L.); 20213085400012@hainnu.edu.cn (J.S.); 202213085400009@hainnu.edu.cn (K.S.); 202213085400007@hainnu.edu.cn (M.Q.); 202213085400018@hainnu.edu.cn (Z.Z.); 202213085400006@hainnu.edu.cn (H.K.); 202313085408004@hainnu.edu.cn (J.Z.); 202313085408001@hainnu.edu.cn (C.Z.); quyi@hainnu.edu.cn (Y.Q.); qzhl060910@hainnu.edu.cn (Z.Q.); lin.li@hainnu.edu.cn (L.L.)

* Correspondence: lizaijin@hainnu.edu.cn

Abstract: The 1.55 µm waveband integrated external cavity tunable diode lasers have excellent merits such as their small volume, low cost, low power consumption, wide tuning range, narrow linewidth, large side mode suppression ratio, and high output power. These merits have attracted many applications for the lasers, such as in wavelength division multiplexing, passive optical networks, mobile backhaul, and spectral sensing technology. In this paper, firstly, the basic structure and principle of integrated external cavity tunable diode lasers are introduced, and then two main integrated structures of 1.55 µm waveband external cavity tunable diode lasers are reviewed and compared in detail, namely the hybrid integrated structure and monolithic integrated structure of 1.55 µm waveband integrated external cavity tunable diode lasers. Finally, the research progress in 1.55 µm waveband integrated external cavity tunable diode lasers in the last decade are summarised, and the advantages and disadvantages of 1.55 µm waveband integrated external cavity tunable diode lasers are analysed. The results show that, with the transformation of optical communication into more complex modulation formats, it is necessary to integrate miniature 1.55 µm waveband external cavity tunable diode lasers. Low-cost integrated 1.55 µm waveband external cavity tunable diode lasers are expected to be used in the next generation of optical transceivers in small-factor modules.

Keywords: 1.55 µm; integrated external cavity; tunable; diode laser

Citation: Zhang, L.; Li, X.; Luo, W.; Shi, J.; Sun, K.; Qiu, M.; Zheng, Z.; Kong, H.; Zhou, J.; Zhang, C.; et al. Review of 1.55 µm Waveband Integrated External Cavity Tunable Diode Lasers. *Photonics* **2023**, *10*, 1287. https://doi.org/10.3390/photonics10111287

Received: 17 October 2023
Revised: 13 November 2023
Accepted: 14 November 2023
Published: 20 November 2023

1. Introduction

With the rapid development of optical communication technology, the spectral tuning range and linewidth characteristics of semiconductor lasers have introduced higher requirements. Optimising the linewidth characteristics of the light source can improve the transmission length and transmission capacity of the optical communication system; expanding the spectral tuning characteristics of the light source can reduce the number of lasers in the optical communication network, improve the flexibility of the communication network, and contribute to the miniaturisation and integration of the communication system, thus reducing the cost [1]. Integrated external cavity tunable diode lasers extend the effective length of the resonant cavity by introducing external optical components, including Sagnac ring mirrors, micro-ring resonators (MRRs), Mach–Zehndel interferometer (MZI), and other components [2], thereby increasing the quality factor (Q) value and narrowing the laser linewidth down to the kilohertz, or even sub-kilohertz range [3,4]. In addition, the output wavelength of the laser can be changed by external optical components to achieve wavelength tuning over a wide range (tens or even hundreds of nanometers) [5]. Integrated external cavity tunable diode lasers have excellent properties such as their small volume, wide tunable range, narrow linewidth, high side mode suppression ratio (SMSR) [6,7], and ease with which they can be coupled with fibre [8]. Therefore, they are widely used in wavelength division multiplexing (WDM), gas detection, sensor applications, etc.

The 1.55 μm waveband is the standard wavelength used in optical communication, and the related lasers and integrating technologies have seen much development with the rise of optical communication [9]. In the context of the upcoming 6G era, WDM channel spacing is developing toward a narrower direction, which necessitates higher requirements on the laser characteristics. The integrated external cavity tunable diode laser brings a lower cost, low power consumption, and space savings in today's optical data transmission networks and sensor applications. Hybrid integration or monolithic integration using heterogeneous processes assembles many devices or optical functions onto a single chip, so all optical connections are on the chip without the need for external alignment and can further improve output performances.

2. Structure and Principle of Integrated External Cavity Tunable Diode Lasers

2.1. Structure of Integrated External Cavity Tunable Diode Lasers

The structure of integrated external cavity tunable diode lasers is shown in Figure 1. It is divided into two major parts, namely, the inner cavity part for active gain and the outer cavity part for passive feedback. The inner cavity generally contains the gain chip (GC), which is used to provide optical gain. The outer cavity contains the spot size converter (SSC), MRR, loop mirror (LM), Sagnac loop mirror (SLM), and other various optical components used to optimise device performance [10], where R_1 and R_2 are the reflectance on both sides of the inner cavity and R_3 is the reflectance on the right side of the outer cavity, respectively.

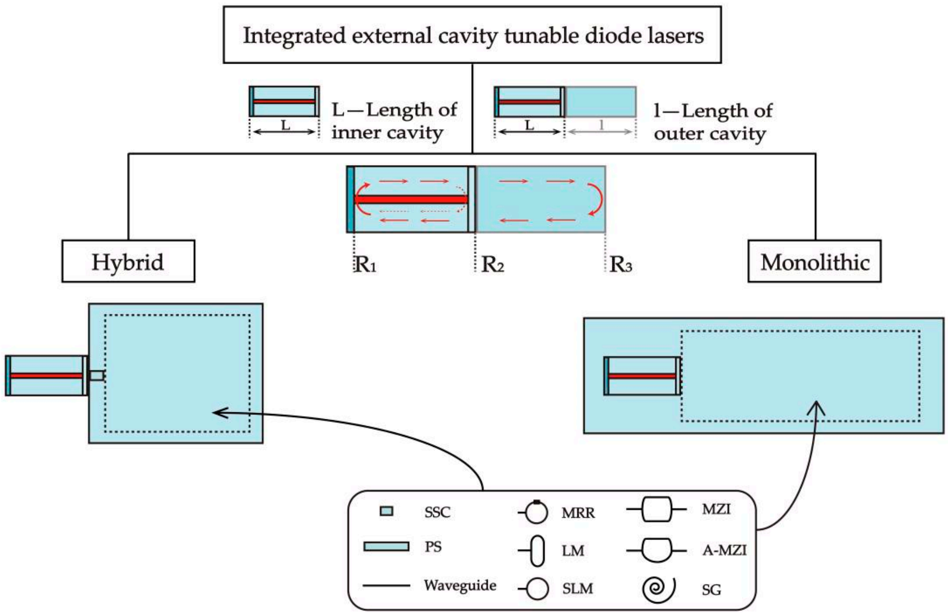

Figure 1. Basic structure of an integrated external cavity tunable diode laser. Note: gain chip (GC), spot size converter (SSC), phase shifter (PS), micro-ring resonator (MRR), loop mirror (LM), Sagnac loop mirror (SLM), Mach–Zehndel interferometer (MZI), asymmetry Mach–Zehndel interferometer (A-MZI), and spiral grating (SG).

2.2. Principle of Integrated External Cavity Tunable Diode Lasers

The integrated external cavity tunable diode laser is mainly divided into two major parts, namely, the GC and external resonant cavity. The GC is a semiconductor optical amplifier (SOA) or reflective semiconductor optical amplifier (RSOA), and the external resonant cavity is a planar optical waveguide, generally with GaAs, InP, Si, and other materials as the substrate, SiO_2 and other materials as the cladding, and Si_3N_4 and other materials as the waveguide [11]. There are structures such as the MRR, SLM, phase shifter (PS), MZI, spiral grating (SG), etc., on the planar optical waveguide, and the tuning of the laser output wavelength is realised by using the thermo-optical effect and Vernier effect [12,13].

By way of integration, integrated external cavity tunable diode lasers can be mainly classified into hybrid integration and monolithic integration.

3. Hybrid Integrated External Cavity Tunable Diode Laser

3.1. Structure of 1.55 µm Waveband Hybrid Integrated External Cavity Tunable Diode Lasers

The structure of a 1.55 µm waveband hybrid integrated external cavity tunable diode laser is shown in Figure 2. It mainly refers to the design and fabrication of the laser by mounting individual prefabricated and optimised components (such as MRR, MZI, filters, etc.) on the substrate using bonding techniques (for example chip mounting, lead bonding, flip-flop bonding) and then coupling the laser into the waveguide [14–16]. For GCs and planar optical waveguides, mode matching is also achieved via SSC alignment coupling. Although the technical requirements of each single component are different, in general, the technology platform involved is relatively concentrated and the manufacturing process is compatible, and passive or active alignment technology is usually used to couple the devices [17].

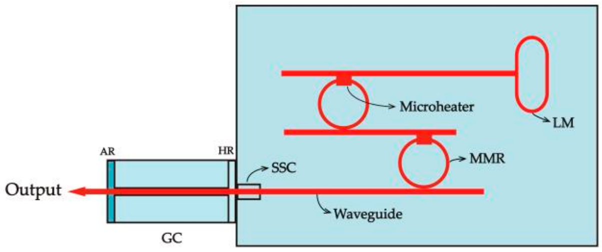

Figure 2. The structure of hybrid integrated external cavity tunable diode lasers.

3.2. Advances in 1.55 µm Waveband Hybrid Integrated External Cavity Tunable Diode Lasers

Hybrid integrated external cavity tunable diode lasers also have tunable capability, which greatly reduces the device size, resulting in a higher level of integration. The concept of integrated photonic circuits was introduced by Stewart E. Miller at Bell Labs [18] in 1969. It was not until 2004 that large-scale planar optical waveguides integrating both active and passive devices emerged. Through continuous optimisation in materials, structures and processes, the development of hybrid integrated external cavity tunable diode lasers has also matured.

3.2.1. Advances in Wavelength Tunable Width

In 2009, Tao Chu et al. [19] reported a silicon-based hybrid integrated external cavity tunable diode laser through dual MRR and SOA integration, which was the first external cavity diode laser fabricated via silicon photonics with a tuning range of about 38 nm.

In 2011, M. Lewander et al. [20] proposed a method for rapid and highly sensitive multi-species detection using a tunable modulated grating Y -branch (MG-Y) diode laser. MG-Y diode lasers employ the Vernier effect, which allows them to be reliably controlled to any wavelength within the tuning range (1529–1565 nm). Multi-species detection is achieved by quickly sequentially scanning individual absorption lines of CH_4, CO, C_2H_2, and CO_2 distributed over the tuning range of the diode laser. One-second measurements resulted in a 1σ absorbance sensitivity ranging between 5 and 8×10^{-7} when sensing only a single gas and 3×10^{-6} when detecting four gases employing fast sequential scanning over a 30 nm range.

In 2014, Youwen Fan et al. [21] reported a tunable external cavity diode laser, which used an integrated InP-Glass hybrid. The laser used Si_3N_4/SiO_2 glass as the waveguide and attained a tunable range of 46.8 nm, which is important in dense wavelength division multiplexing and phase referencing of optical beam-forming networks.

In 2015, Tomohiro Kita et al. [22] reported a hybrid integrated external cavity diode laser using two MRRs and A-MZI. The laser achieved a continuous tunability of 99.2 nm, which was sufficient to cover the C-waveband (1530–1565 nm) and L-waveband (1565–1625 nm) and could improve the utilisation efficiency of WDM systems, and coupling the silicon waveguide with SOA exhibited stable single-mode operating characteristics.

In 2018, Agnes Verdier et al. [23] reported a silicon-based ultra-wide-wavelength external cavity tunable diode laser with a tuning range of more than 95 nm using ROSA, SSC, MRR, MZI, and SLM.

In 2021, Guangju Zhang et al. [24] developed an imaging technique for reconstructing tissue structure and flow by repetitive motion using a tunable semiconductor laser as a swept-frequency light source for optical coherence tomography (OCT). A tunable semiconductor laser as a swept-frequency light source has the characteristics of good linearity, high speed, and phase stability, which can optimise the structure of the swept-frequency OCT system and also meet the needs of functional imaging. This technique is capable of accurately imaging host tissues and blood flow at different time points of cyclic motion (e.g., cardiac cycle).

In 2023, Wilson Tsong et al. [25] reported a compact photonic integrated circuit external cavity diode laser. The laser consisted of an InP gain section and a Si_3N_4 tunable mirror that can be continuously tuned at 139 nm.

3.2.2. Advances in Linewidth

In 2014, H. Debregeas et al. [26] reported a narrow linewidth tunable diode laser that used a silicon ring resonant cavity, MZI, and RSOA. The tunable range was 35 nm and the linewidth was as low as 2 kHz for applications in coherent transmission systems, optical sensing, etc.

In 2016, Youwen Fan et al. [27] reported an InP-Si_3N_4 hybrid external cavity diode laser. The laser could be tuned near the C-waveband and the tunable range was 43 nm, with the linewidth less than 300 kHz.

In 2016, J.L. Zhao et al. [28] reported a low-loss, high-Q-factor micro-ring resonant cavity using Si_3N_4/SiO_2 as the waveguide, realising a wide-wavelength tunable InP/SiN external cavity diode laser. The laser could be continuously tuned to 50 nm with a linewidth of 65 kHz and had promising applications in coherent transmission systems.

In 2021, Yilin Xu et al. [29] reported an external cavity diode laser with a tuning range of 50 nm and a linewidth of 105 kHz. The laser used 3D-printed photonic line bonding to connect an InP-based RSOA to a silicon photonic external feedback circuit, avoiding the high-precision alignment required for coupling and thus paving the way for efficient, large-scale production of external cavity diode lasers.

In 2021, Yuyao Guo et al. [30] reported a widely tunable III-V/Si_3N_4 hybrid external cavity diode laser using Si_3N_4 as the waveguide and combined with a vernier ring filter. The laser could be continuously tuned to 58.5 nm with a linewidth as low as 2.5 kHz. The excellent performance provided a potential avenue for the application of coherent lidar systems.

In 2023, Pascal Maier et al. [31] reported an ultra-narrow-linewidth tunable external cavity diode laser based on MZI and MRR using a Si_3N_4 waveguide combined with 3D-printed structures to reduce the feedback and coupling losses of the device. The laser could be continuously tuned to 90 nm with a linewidth as low as 979 Hz.

3.2.3. Advances in Linewidth and Wavelength Tunable Width

In 2017, Youwen Fan et al. [32] coupled InP and Si_3N_4 waveguides through a tapered waveguide cross section with high efficiency, combined with three ultra-high Q MRRs to design a wide-tuned ultra-narrow linewidth external cavity diode laser. The laser has a tuning range of 81 nm and a linewidth of 270 Hz.

In 2018, Hang Guan et al. [33] reported a III-V/Si hybrid external cavity diode laser. The GC is edge-coupled to the silicon chip by SSC and hybridised into the silicon chip. The whole coupling process required only passive alignment and was suitable for high-volume industrial production. The laser could be continuously tuned to 60 nm with a linewidth as low as 37 kHz.

In 2020, Albert Van Rees et al. [34] fabricated an ultra-narrow-linewidth external cavity diode laser using a Bragg structure and a ring resonator. The laser increased the continuous tuning range. It could be continuously tuned to 120 nm with the linewidth as low as 2.2 kHz.

In 2022, Paul A. Morton et al. [35] reported a hybrid external cavity diode laser using hetero structural integration of III-V materials in combination with three MRRs. The laser could be continuously tuned to 118 nm with a linewidth of less than 100 Hz. Its tuning and linewidth characteristics provided potential solutions for ultra-wide-waveband WDM transmission systems, fibre-optic sensing systems, and lidar system applications.

In 2022, Yuyao Guo et al. [36] used a tunable SLM for enhanced laser mode selection and a Si_3N_4 platform to reduce the outer cavity loss, greatly increasing the tuning range and narrowing the spectral linewidth. The laser can be continuously tuned to 172 nm with a linewidth of less than 4 kHz.

In addition, in 2021, RuiLing Zhao et al. [37] reported a dual-gain integrated external cavity diode laser. The integration of two gain channels in the same chip reduced the assembly complexity by requiring only one step of edge coupling compared to lasers using two separate GCs. The laser was continuously tunable to 44 nm with a linewidth of 6.6 kHz. Compared with unity gain, the dual-gain laser can provide higher output power and narrower linewidth, which has promising applications in optical communication, optical detection, and ranging systems.

Table 1 shows the performance parameters of hybrid integrated external cavity tunable diode lasers in the last decade. Hybrid integrated external cavity diode lasers greatly reduce the size of the device and still have good tuning range and linewidth characteristics. However, the process is more complex and the coupling efficiency still needs to be improved. In addition, because the integrated type is thermally tuned, the thermal accumulation and dissipation in the tuning process takes some time, which reduces the tuning speed of the device. The potential problems of how to further simplify the integration process, improve the coupling efficiency, and optimise the thermal accumulation and thermal dissipation still need to be solved.

Table 1. Performance parameters of 1.55 µm waveband hybrid integrated external cavity tunable diode lasers in the last decade.

Type	Tuning (nm)	Wavelength Coverage (nm)	Working Waveband	Linewidth (kHz)	SMSR (dB)	Current (mA)	Power (mW)	Year
Hybrid	38	153X~156X	C, L	-	>40	200	25	2010 [38]
Hybrid	35	154X~158X	C, L	2	>60	200	3.1	2014 [26]
Hybrid	46.8	1531~1577.8	C, L	24	>50	90	5.7	2014 [21]
Hybrid	99.2	1527.9~1627.1	S, **C**, **L**, U	-	>29	300	35	2015 [22]
Hybrid	50	1530~1580	**C**, L	65	>45	500	16	2016 [28]
Hybrid	43	154X~158X	C, L	300	>35	200	1.7	2016 [27]
Hybrid	81	1500~1581	S, **C**, L	0.29	-	-	13	2017 [32]
Hybrid	95	1540~1635	C, **L**, U	550	>35	600	20	2018 [23]

Table 1. *Cont.*

Type	Tuning (nm)	Wavelength Coverage (nm)	Working Waveband	Linewidth (kHz)	SMSR (dB)	Current (mA)	Power (mW)	Year
Hybrid	60	1515~1575	S, **C**, L	37	55	180	11	2018 [33]
Hybrid	120	1480~1600	S, **C**, L	2.2	63	300	24	2020 [34]
Hybrid	58.5	1516.5~1575	S, **C**, L	2.5	>70	500	34	2021 [30]
Hybrid	50	1515~1565	S, **C**	105	>40	100	17.8	2021 [29]
Hybrid	44	1524~1568	S, **C**, L	6.6	>67	350	23.5	2021 [37]
Hybrid	118	1480~1598	S, **C**, L	0.1	>40	500	15	2022 [35]
Hybrid	172	1487~1659	S, **C**, **L**, U	4	>40	309	26.7	2022 [36]
Hybrid	90	1480~1570	S, **C**, L	0.979	>45	100	15.8	2023 [31]
Hybrid	139	1473~1612	S, **C**, L	<5	-	350	60	2023 [25]

Note: X in the working wavelength indicates that no explicit value is given in the article. The not-bold wavebands are the involved wavebands, and the bold wavebands are the fully coverable wavebands.

4. Monolithic Integrated External Cavity Tunable Diode Laser

4.1. Structure of 1.55 µm Waveband Monolithic Integrated External Cavity Tunable Diode Lasers

The structure of a 1.55 µm waveband monolithic integrated external cavity tunable diode laser is shown in Figure 3. This mainly refers to the direct growth of III-V compound semiconductor materials on a single epitaxial wafer and the simultaneous fabrication of devices [38,39]. A single-material system, the same platform, multiple epitaxy, lithography, etching, and other processes to produce all the functional units were used to achieve the integration of each functional unit, making the process of manufacturing more difficult [40].

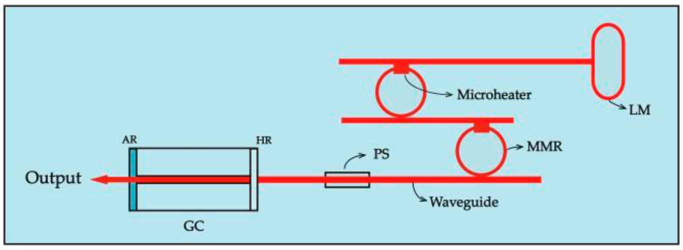

Figure 3. Monolithic integrated external cavity tunable diode laser.

For an integrated external cavity tunable diode laser, a common dual MRR structure is used as an example, which is shown in Figure 3. The wavelength is λ, the speed of light in vacuum is c, the free spectral range of the MRR is FSR, and the tuning wavelength Δλ can be expressed by Equation (1) as:

$$\Delta\lambda = \frac{\lambda^2}{c}\left|\frac{FSR_1 \cdot FSR_2}{FSR_1 - FSR_2}\right| \tag{1}$$

where FSR is expressed by Equation (2) as:

$$FSR = \frac{\lambda^2 \pi r n_g}{2} \tag{2}$$

where r is expressed by Equation (3) as:

$$r = \frac{m\lambda}{2\pi n_{eff}} \tag{3}$$

where n_g is expressed by Equation (4) as:

$$n_g = n_{eff} - \lambda \cdot \frac{dn_{eff}}{d\lambda} \quad (4)$$

In Equations (3) and (4), r is the radius of the MRR, m is an integer (characterizing the resonance level), n_{eff} is the effective refractive index of the waveguide, and n_g is the group refractive index of the waveguide. In performing the wavelength tuning, the thermo-optical effect is used, that is, the physical effect of the change in the optical properties of the material with temperature. For monolithic integrated external cavity diode lasers, it mainly refers to the effective refractive index of the waveguide. By changing the magnitude of the injected current, the microheater is adjusted so that the temperature of the waveguide changes, thus changing the effective refractive index of the waveguide. From Equations (1) and (2), it is known that when the effective refractive index of the waveguide changes, the corresponding *FSR* will also change, which in turn shifts the transmission spectrum of the MRR, and the wavelength tuning is achieved by using the vernier effect. The tuning range is determined by the difference in MRR diameters, and the smaller the difference, the wider the tuning range, but the difference in transmittance between the main peak and the side peak may be small, which can lead to multimode oscillation in some cases, to the detriment of single-mode output, as shown in Figure 4 [41,42].

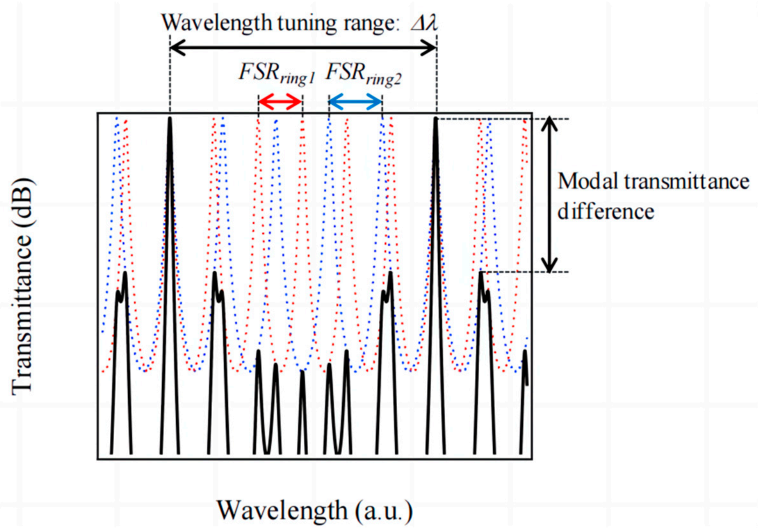

Figure 4. Wavelength tunable principle of monolithic integrated external cavity tunable diode laser. The red dashed line is transmittance of the $FSR_{ring1}$and the blue dashed line is the transmittance of the FSR_{ring2} and the black solid line is the total transmittance.

Whether hybrid integrated or monolithic integrated, the purpose is to improve the function of the device, improve the performance of the device, and reduce the size of the device, thereby significantly reducing the cost of the device and improving the stability of the device.

4.2. Advances in 1.55 µm Waveband Monolithic Integrated External Cavity Tunable Diode Lasers

In 2012, Y. Rao et al. [43] reported a novel monolithic tunable 1550 nm external cavity diode laser. The laser uses a high-contrast grating as a tunable mirror and provides current through plasmonic injection energy, thus enabling a wafer-scale, low-cost fabrication process. However, the laser was continuously tunable to only 26.3 nm.

In 2012, R M Oldenbeuving et al. [44] reported a monolithically integrated diode laser with a tunable external cavity reflector. The laser was continuously tuned to 44 nm and could completely covered the C-waveband in the communication field. The tunable laser had an overall high loss and low output power, although the cavity was shorter compared to other narrow cavity lasers.

In 2015, in order to obtain a wider tuning range and higher output power, Naoki Kobayashi et al. [45] reported a wavelength-tunable laser with a silicon photonic hybrid ring external cavity diode laser that used a passive alignment technique. The laser could be continuously tuned to 65 nm with an output power of more than 100 mW.

In 2015, Sylwester Latkowski et al. [46] reported a novel monolithically integrated tunable diode laser for application in single-line gas spectroscopy systems. It is tuned by three intracavity MZIs with an optical linewidth of 363 kHz, an output power of 3 mW, and a tuning range of 1475~1550 nm. The results show that a 0.89 GHz wide single absorption line of acetylene ($12C_2H_2$) with 6 MHz (48 fm) steps has capabilities for accurate scanning of the wavelength and applicability towards single-line gas spectroscopy.

In 2019, Stefanos Andreou et al. [47] reported a monolithic integrated InP-based tunable ring-shaped external cavity diode laser. The laser achieved wavelength tuning through a reverse bias voltage-controlled electro-optically tunable ring resonator, which could be continuously tuned to 34 nm.

In 2021, Keith A. Mckinzie et al. [48] reported a monolithic InP-based photonic integrated circuit and obtained an average power of up to 240 mW from the monolithic photonic integrated circuit with an extended C-waveband linewidth of 30~50 kHz. To further narrow the linewidth, Keith A. Mckinzie et al. narrowed the linewidth to 3 kHz with an average output power of 37.9 mW using an array of interferometric combinatorial amplifiers in an external cavity formed by feedback from silicon nitride microresonator chips. The team demonstrated a new approach to high-power, narrow-linewidth light sources that can be integrated with an on-chip single-mode waveguide platform for potential applications in nonlinear integrated photonics.

In 2022, Qi Chen et al. [49] reported an InP-based widely tuned external cavity diode laser. The V-cavity laser, modulator, SOA and passive devices were integrated on a single epi-wafer using quantum well intermixing technology, which could be continuously tuned to 52 nm.

In 2023, You-Zeng Hao et al. [50] reported a compact square/rhomboid rectangular external cavity diode laser, which consisted of a deformed square echo wall mode microcavity and a Fabry–Perot resonator. The echo wall mode microcavity was used the end face of the Fabry–Perot cavity to select the mode. The wavelength tuning of 33 nm was achieved by adjusting the injection current. In the tuning range, the laser had a linewidth of less than 4 MHz and a 3 dB modulation waveband width greater than 14 GHz.

In 2023, Gaurav Jain et al. [51] reported an InP-based tunable annular outer cavity diode laser that can be continuously tuned at 37 nm with a linewidth of less than 450 kHz.

In 2023, KuanKuan Wang et al. [52] reported an electro-optically tuned multi-channel interference external cavity diode laser. The multichannel interferometer consisted of a cascaded 1×2 multimode interferometer, eight arms of different lengths, and a multimode interferometer reflector. Cascaded multimode interferometers evenly divide the laser, and single-port multimode interferometer reflectors provide reflection at each waveguide end. The eight arms interfere with each other, forming a reflection spectrum dominated by a reflection peak on which the eight arms have the same phase. The laser mainly changes the longitudinal mode by tuning the common-phase part, and the phase part of the tuned seven arms is aligned with the reflection peak and can continuously tune 48.8 nm.

Table 2 shows the performance parameters of monolithic integrated external cavity tunable diode lasers in the last decade. Monolithic integrated external cavity diode lasers further increase the integration of the device. However, the tuning range, linewidth, and other device characteristics still need to be improved. In addition, it is also necessary to solve a series of problems caused by coupling, thermal effects, and material growth, so that the device has a higher tuning range, output power, and lower linewidth characteristics.

Table 2. Performance parameters of monolithic integrated 1.55 µm external cavity tunable diode lasers in recent years.

Type	Tuning (nm)	Wavelength Coverage (nm)	Working Waveband	Linewidth (kHz)	SMSR (dB)	Current (mA)	Power (mW)	Year
Monolithic	26.3	154X~156X	C, L	-	-	20	1.5	2012 [43]
Monolithic	44	153X~157X	C, L	25	50	87	1	2012 [44]
Monolithic	65	1510~1575	S, **C**, L	<15	>45	650	160	2015 [45]
Monolithic	34	1522~1556	S, C	110	>50	200	1.8	2019 [48]
Monolithic	45	1513~1558	S, C	3	56	200	37.9	2021 [47]
Monolithic	52	1513~1565	S, **C**	-	>38	100	5.5	2022 [49]
Monolithic	33	1537.4~1570.4	C, L	<4000	>40	60	21.8	2023 [50]
Monolithic	37	1536~1573	C, L	<450	>45	-	-	2023 [51]
Monolithic	48.8	152X~157X	S, **C**, L	<320	>40	170	20	2023 [52]

Note: X in the working wavelength indicates that no explicit value is given in the article. The not-bold wavebands are the involved wavebands, and the bold wavebands are the fully coverable wavebands.

Figure 5 shows the tunable ranges of 1.55 µm waveband hybrid integrated and monolithic integrated external cavity tunable diode lasers in recent years. The tuning range of 1.55 µm waveband hybrid integrated external cavity tunable diode lasers ranges from tens to hundreds of nanometres, and with the development of technology and processes, the tuning range will exceed 150 nm. Due to a late start and slightly slower development, the tuning range of 1.55 µm waveband monolithic integrated external cavity tunable diode lasers is generally lower, but it is considered to be the ultimate solution for silicon photonic on-chip light sources and has great prospects for development. It is believed that in the near future, the tuning range of monolithic integrated external cavity tunable diode lasers can be further improved to the 100 nm level.

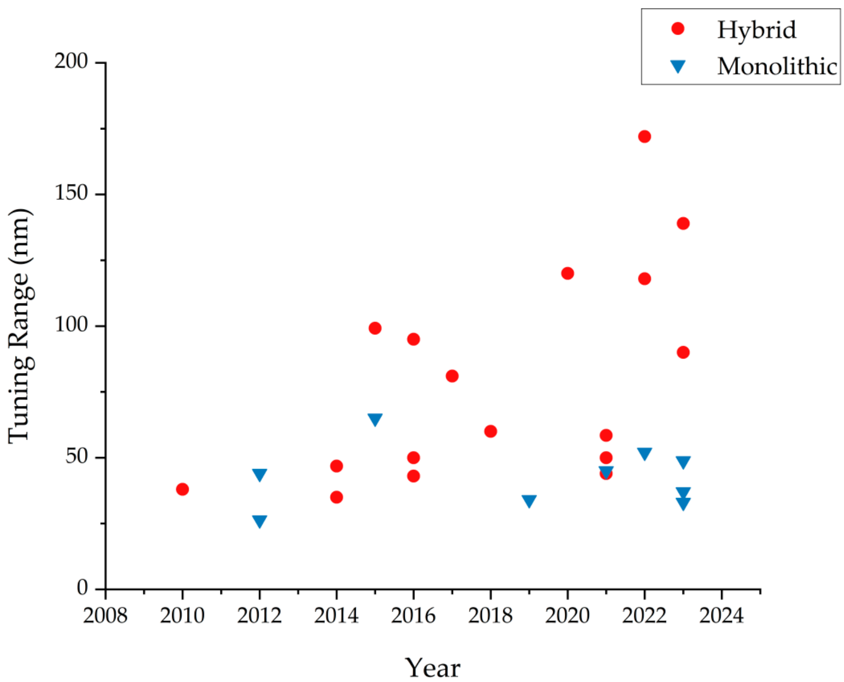

Figure 5. Comparison of the tuning range of 1.55 µm waveband hybrid integrated and monolithic integrated external cavity tunable diode lasers.

5. Conclusions

The integration of III-V materials on Si substrates achieves hybrid integration while improving the performance of individual devices due to lower losses and better lithography techniques. Monolithic integration has been achieved on InP and Si substrates. Si substrate integration has been a major research field in recent years, with the goal of reducing costs and increasing production.

Table 3 shows the comparison of the characteristics of hybrid integrated and monolithic integrated tunable external cavity diode lasers. The integrated external cavity tunable diode laser has the advantages of compact structure, small size and fast tuning speed and has a wide tuning range while realizing narrow linewidth. It is suitable for underwater optical communication, WDM, spaceborne carbon dioxide detection lidar and other fields, and has broad application prospects. However, it is still necessary to increase the coupling efficiency, reduce the reflectivity of the coupling, simplify the integration technology, and dissipate the heat accumulation so as to realise a wide-tuning-range or even ultra-wide-tuning-range, narrow-line-width, high-power, and low-cost 1.55 μm waveband tunable diode laser.

Table 3. Comparison of different structures of 1.55 μm tunable external cavity diode lasers.

Type	Maximum Tuning Range	Narrowest Linewidth	Maximum Power	Maximum SMSR	Structure	Volume	Cost
Hybrid	172 nm	100 Hz	60 mW	70 dB	Complex	Small	Lower
Monolithic	65 nm	3 kHz	160 mW	56 dB	More complex	Smaller	Low

Compared with monolithic integration, hybrid integration is more flexible in design; more functional, stable, and accurate; and suitable for mass production [53]. However, it has certain drawbacks, i.e., devices of different sizes or materials need to be aligned with submicron precision to achieve effective coupling [54]. Therefore, it also needs to be optimised in certain ways, for example, by using techniques such as photonic lead bonding. Defects are avoided as much as possible, thus improving the coupling efficiency and increasing the output power. The light of the lowest order mode, TM_{00}, mode output from the laser resonator cavity is usually taken as the ideal beam, which has a small divergence angle, high brightness effectively coupled with the fibre, and can also be focused to a smaller spot by a simple optical system, which is very beneficial for laser applications [55]. Currently, gradient-index (GRIN) fibres are promising in achieving TM_{00} beams, and GRIN fibres play an important role in optical coupling systems [56]. In the future, researchers will need to improve the beam combining technique to increase the fibre coupling efficiency and hence the output power of the laser. In the process of shaping and combining laser beams, not only do we need to focus on improving the beam quality, power, and brightness of the output beam, but we also need to pursue efficient, simple, and compact optical components to reduce the cost of the application and the size of the laser module.

Compared with hybrid integration, monolithic integration can effectively solve the accuracy alignment problem arising from hybrid integration in coupling. However, due to the high density of thread dislocations generated during heterogeneous epitaxy, direct growth on the substrate will result in poor device performance and reliability of the laser, requiring the introduction of a transition layer, i.e., a buffer layer [57], or its performance can be optimised by changing the growth conditions so that it still has better performance in the case of high-density thread dislocations. Although the monolithic integrated manufacturing process is more complex and the light source performance needs to be improved, it can maximise the integration of silicon photonic processes, reduce the linewidth, and improve the integration to achieve large-scale photonic integration [58].

In summary, different structures have their own advantages and disadvantages; therefore, the right cavity type can be selected according to the actual application requirements.

Not only that, more research on different cavity types is needed, especially for monolithic integrated external cavities. In general, wider tuning range, higher tuning speed, and narrower linewidth remain the mainstream direction for future research. With the continuous development of coherent detection, optical sensing, multi-atom cooling, and dense WDM systems, 1.55 µm waveband external cavity tunable diode lasers will be used in more fields with their excellent performance.

Author Contributions: Conceptualisation, L.Z., X.L. and W.L.; methodology, J.S., K.S. and M.Q.; writing—original draft preparation, X.L. and Z.L.; writing—review and editing, Z.Z., H.K., L.L. and C.Z.; visualisation, J.Z., C.Z. and Y.Q.; supervision, Z.Q.; funding acquisition, Y.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported in part by the Hainan Provincial Natural Science Foundation of China under Grant 622RC671, Grant 120MS031; in part by Hainan Normal University College Students' Innovation and Entrepreneurship Open Fund (Banyan Tree Fund) Project under Grant RSXH20231165803X, Grant RSXH20231165811X, Grant RSYH20231165806X, Grant RSYH20231165824X, Grant RSYH20231165833X; in part by Hainan Normal University Graduate Students Innovative Scientific Research Project under Grant hsyx2022-81; and in part by the National Natural Science Foundation of China under Grant 61774024, Grant 61864002, Grant 11764012, Grant 62174046, Grant 62064004 and Grant 61964007.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank Dongxin Xu and Wenjun Yu for helping with this article.

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

References

1. Cheng, Q.; Bahadori, M.; Glick, M.; Rumley, S.; Bergman, K. Recent advances in optical technologies for data centers: A review. *Optica* **2018**, *5*, 1354–1370. [CrossRef]
2. Tang, R.; Kita, T.; Yamada, H. Narrow-spectral-linewidth silicon photonic wavelength-tunable laser with highly asymmetric Mach–Zehnder interferometer. *Opt. Lett.* **2015**, *40*, 1504–1507. [CrossRef] [PubMed]
3. Xiang, C.; Morton, P.A.; Bowers, J.E. Ultra-narrow linewidth laser based on a semiconductor gain chip and extended Si_3N_4 Bragg grating. *Opt. Lett.* **2019**, *44*, 3825–3828. [CrossRef]
4. Jin, W.; Yang, Q.F.; Chang, L.; Shen, B.; Wang, H.; Leal, M.A.; Wu, L.; Gao, M.; Feshali, A.; Paniccia, M.; et al. Hertz-linewidth diode lasers using CMOS-ready ultra-high-Q microresonators. *Nat. Photonics* **2021**, *15*, 346–353. [CrossRef]
5. Komljenovic, T.; Srinivasan, S.; Norberg, E.; Davenport, M.; Fish, G.; Bowers, J.E. Widely tunable narrow-linewidth monolithically integrated external-cavity diode lasers. *IEEE J. Sel. Top. Quantum Electron.* **2015**, *21*, 214–222. [CrossRef]
6. Sato, K.; Kobayashi, N.; Namiwaka, M.; Yamamoto, K.; Kita, T.; Yamada, H.; Yamazaki, H. High output power and narrow linewidth silicon photonic hybrid ring-filter external cavity wavelength tunable lasers. In Proceedings of the 2014 The European Conference on Optical Communication (ECOC), Cannes, France, 21–25 September 2014; IEEE: Piscataway, NJ, USA, 2014; pp. 1–3.
7. Guo, Y.; Li, X.; Xu, W.; Liu, C.; Jin, M.; Lu, L.; Xie, J.; Stroganov, A.; Chen, J.; Zhou, L. A hybrid-integrated external cavity laser with ultra-wide wavelength tuning range and high side-mode suppression. In Proceedings of the 2022 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, 6–10 March 2022; IEEE: Piscataway, NJ, USA, 2022; pp. 1–3.
8. Volet, N.; Yi, X.; Yang, Q.F.; Stanton, E.J.; Morton, P.A.; Yang, K.Y.; Vahala, K.J.; Bowers, J.E. Micro-resonator soliton generated directly with a diode laser. *Laser Photonics Rev.* **2018**, *12*, 1700307. [CrossRef]
9. Ludwig, R.; Feiste, U.; Diez, S.; Schubert, C.; Schmidt, C.; Ehrke, H.J.; Weber, H.G. Unrepeatered 160Gbit/s RZ single-channel transmission over 160km of standard fibre at 1.55 µm with hybrid MZI optical demultiplexer. *Electron. Lett.* **2000**, *36*, 1405–1406. [CrossRef]
10. Lang, X.; Jia, P.; Chen, Y.; Qin, L.; Liang, L.; Chen, C.; Wang, Y.; Shan, X.; Ning, Y.; Wang, L.; et al. Advances in narrow linewidth diode lasers. *Sci. China Inf. Sci.* **2019**, *62*, 61401. [CrossRef]
11. Luo, C.; Zhang, R.; Qiu, B.; Wang, W. Waveguide external cavity narrow linewidth diode lasers. *J. Semicond.* **2021**, *42*, 041308. [CrossRef]
12. Deki, Y.; Hatanaka, T.; Takahashi, M.; Takeuchi, T.; Watanabe, S.; Takaesu, S.; Miyazaki, T.; Horie, M.; Yamazaki, H. Wide-wavelength tunable lasers with 100 GHz FSR ring resonators. *Electron. Lett.* **2007**, *43*, 225–226. [CrossRef]
13. Li, N.; Chen, G.; Ng, D.K.T.; Lim, L.W.; Xue, J.; Ho, C.P.; Fu, Y.H.; Lee, L.Y.T. Integrated lasers on silicon at communication wavelength: A progress review. *Adv. Opt. Mater.* **2022**, *10*, 2201008. [CrossRef]

14. Bian, Y.; Ramachandran, K.; Peng, B.; Hedrick, B.; Mills, S.; Donegan, K.; Esopi, M.; Hirokawa, T.; Jacob, A.; Karra, V.; et al. Integrated laser attach technology on a monolithic silicon photonics platform. In Proceedings of the 2021 IEEE 71st Electronic Components and Technology Conference (ECTC), Vancouver, BC, Canada, 13 November 2020; IEEE: Piscataway, NJ, USA, 2021; pp. 237–244.
15. Luo, X.; Cao, Y.; Song, J.; Hu, X.; Cheng, Y.; Li, C.; Liu, C.; Liow, T.; Yu, M.; Wang, H.; et al. High-throughput multiple dies-to-wafer bonding technology and III/V-on-Si hybrid lasers for heterogeneous integration of optoelectronic integrated circuits. *Front. Mater.* **2015**, *2*, 28. [CrossRef]
16. Valicourt, G.D.; Chang, C.M.; Eggleston, M.S.; Melikyan, A.; Zhu, C.; Lee, J.; Simsarian, J.E.; Chandrasekhar, S.; Sinsky, J.H.; Kim, K.W.; et al. Photonic integrated circuit based on hybrid III–V/silicon integration. *J. Light. Technol.* **2018**, *36*, 265–273. [CrossRef]
17. Kato, K.; Tohmori, Y. PLC hybrid integration technology and its application to photonic components. *IEEE J. Sel. Top. Quantum Electron.* **2000**, *6*, 4–13. [CrossRef]
18. Miller, S.E. Integrated optics: An introduction. *Bell Syst. Tech. J.* **1969**, *48*, 2059–2069. [CrossRef]
19. Chu, T.; Fujioka, N.; Ishizaka, M. Compact, lower-power-consumption wavelength tunable laser fabricated with silicon photonic wire waveguide micro-ring resonators. *Opt. Express* **2009**, *17*, 14063–14068. [CrossRef]
20. Lewander, M.; Fried, A.; Weibring, P.; Richter, D.; Spuler, S.; Rippe , L. Fast and sensitive time-multiplexed gas sensing of multiple lines using a miniature telecom diode laser between 1529 nm and 1565 nm. *Appl. Phys. B* **2011**, *104*, 715–723. [CrossRef]
21. Fan, Y.; Oldenbeuving, R.M.; Klein, E.J.; Lee, C.J.; Song, H.; Khan, M.R.H.; Offerhaus, H.L.; Slot, P.J.M.; Boller, K.J. A hybrid semiconductor-glass waveguide laser. In Proceedings of the Laser Sources and Applications II. *SPIE* **2014**, *9135*, 231–236.
22. Kita, T.; Tang, R.; Yamada, H. Compact silicon photonic wavelength-tunable laser diode with ultra-wide wavelength tuning range. *Appl. Phys. Lett.* **2015**, *106*, 111104. [CrossRef]
23. Verdier, A.; Valicourt, G.D.; Brenot, R.; Debregeas, H.; Dong, P.; Earnshaw, M.; Carrère, H.; Chen, Y.K. Ultra wide band wavelength-tunable hybrid external-cavity lasers. *J. Light. Technol.* **2017**, *36*, 37–43. [CrossRef]
24. Zhang, G.; Wei, W. 4-D Imaging of Beating Tissues Using Optical Coherence Tomography. *IEEE Photonics J.* **2021**, *13*, 3900211. [CrossRef]
25. W. TsongI. van den VlekkertS. MusaN.F. RaimondA.S. NoorH. MarcelM. ArjanJ.K. EdwinG. Dimitri139 nm tuning range, high speed wavelength modulation, and high output power up to 60 mW from a single gain, two-ring vernier external cavity laser. In Proceedings of the Integrated Optics: Devices, Materials, and Technologies XXVII; San Francisco, CA, USA, 30 January–2 February 2023, SPIE: Bellingham, WA, USA, 2023; Volume 12424, pp. 86–90.
26. Debregeas, H.; Ferrari, C.; Cappuzzo, M.A.; Klemens, F.; Keller, R.; Pardo, F.; Bolle, C.; Xie, C.; Earnshaw, M.P. 2kHz linewidth C-band tunable laser by hybrid integration of reflective SOA and SiO_2 PLC external cavity. In Proceedings of the 2014 International Diode Laser Conference, Palma de Mallorca, Spain, 7–10 September 2014; IEEE: Piscataway, NJ, USA, 2014; pp. 50–51.
27. Fan, Y.; Epping, J.P.; Oldenbeuving, R.M.; Roeloffzen, C.G.H.; Hoekman, M.; Dekker, R.; Heideman, R.G.; Slot, P.J.M.; Boller, K.J. Optically Integrated InP–Si_3N_4 Hybrid Laser. *IEEE Photonics J.* **2016**, *8*, 1505111. [CrossRef]
28. Zhao, J.L.; Oldenbeuving, R.M.; Epping, J.P.; Hoekman, M.; Heideman, R.G.; Dekker, R.; Fan, Y.; Boller, K.J.; Ji, R.Q.; Fu, S.M.; et al. Narrow-linewidth widely tunable hybrid external cavity laser using Si_3N_4/SiO_2 microring resonators. In Proceedings of the 2016 IEEE 13th International Conference on Group IV Photonics (GFP), Shanghai, China, 24–26 August 2016; IEEE: Piscataway, NJ, USA, 2016; pp. 24–25.
29. Xu, Y.; Maier, P.; Blaicher, M.; Dietrich, P.I.; Palomo, P.M.; Hartmann, W.; Bao, Y.; Peng, H.; Billah, M.R.; Singer, S.; et al. Hybrid external-cavity lasers (ECL) using photonic wire bonds as coupling elements. *Sci. Rep.* **2021**, *11*, 16426. [CrossRef]
30. Guo, Y.; Zhao, R.; Zhou, G.; Lu, L.; Stroganov, A.; Nisar, M.S.; Chen, J.; Zhou, L. Thermally tuned high-performance III-V/Si_3N_4 external cavity laser. *IEEE Photonics J.* **2021**, *13*, 1500813. [CrossRef]
31. Maier, P.; Chen, Y.; Xu, Y.; Bao, Y.; Blaicher, M.; Geskus, D.; Dekker, R.; Liu, J.; Dietrich, P.I.; Peng, H.; et al. Sub-kHz-linewidth external-cavity laser (ECL) with Si_3N_4 resonator used as a tunable pump for a Kerr frequency comb. *J. Light. Technol.* **2023**, *41*, 3479–3490. [CrossRef]
32. Fan, Y.; Oldenbeuving, R.M.; Roeloffzen, C.G.H.; Hoekman, M.; Geskus, D.; Heideman, R.G.; Boller, K.J. 290 Hz intrinsic linewidth from an integrated optical chip-based widely tunable InP-Si_3N_4 hybrid laser. In Proceedings of the 2017 Conference on Lasers and Electro-Optics (CLEO), Munich, Germany, 25–29 June 2017; IEEE: Piscataway, NJ, USA, 2017; pp. 1–2.
33. Guan, H.; Novack, A.; Galfsky, T.; Ma, Y.; Fathololoumi, S.; Horth, A.; Huynh, T.N.; Roman, J.; Shi, R.; Caverley, M.; et al. Widely-tunable, narrow-linewidth III-V/silicon hybrid external-cavity laser for coherent communication. *Opt. Express* **2018**, *26*, 7920–7933. [CrossRef] [PubMed]
34. Rees, A.V.; Fan, Y.; Geskus, D.; Klein, E.J.; Oldenbeuving, R.M.; Slot, P.J.M.; Boller, K.J. Ring resonator enhanced mode-hop-free wavelength tuning of an integrated extended-cavity laser. *Opt. Express* **2020**, *28*, 5669–5683. [CrossRef]
35. Morton, P.A.; Xiang, C.; Khurgin, J.B.; Morton, C.D.; Tran, M.; Peters, J.; Guo, J.; Morton, M.J.; Bowers, J.E. Integrated coherent tunable laser (ICTL) with ultra-wideband wavelength tuning and sub-100 Hz Lorentzian linewidth. *J. Light. Technol.* **2022**, *40*, 1802–1809. [CrossRef]
36. Guo, Y.; Li, X.; Jin, M.; Lu, L.; Xie, J.; Chen, J.; Zhou, L. Hybrid integrated external cavity laser with a 172-nm tuning range. *APL Photonics* **2022**, *7*, 066101. [CrossRef]
37. Zhao, R.; Guo, Y.; Lu, L.; Nisar, M.S.; Chen, J.; Zhou, L. Hybrid dual-gain tunable integrated InP-Si_3N_4 external cavity laser. *Opt. Express* **2021**, *29*, 10958–10966. [CrossRef]

38. Chen, S.; Li, W.; Wu, J.; Jiang, Q.; Tang, M.; Shutts, S.; Elliott, S.N.; Sobiesierski, A.; Seeds, A.J.; Ross, L.; et al. Electrically pumped continuous-wave III–V quantum dot lasers on silicon. *Nat. Photonics* **2016**, *10*, 307–311. [CrossRef]
39. Hu, Y.; Liang, D.; Mukherjee, K.; Li, Y.; Zhang, C.; Kurczveil, G.; Huang, X.; Beausoleil, R.G. III/V-on-Si MQW lasers by using a novel photonic integration method of regrowth on a bonding template. *Light Sci. Appl.* **2019**, *8*, 93. [CrossRef] [PubMed]
40. Fuchs, E.R.H.; Bruce, E.J.; Ram, R.J.; Kirchain, R.E. Process-based cost modeling of photonics manufacture: The cost competitiveness of monolithic integration of a 1550-nm DFB laser and an electroabsorptive modulator on an InP platform. *J. Light. Technol.* **2006**, *24*, 3175–3186. [CrossRef]
41. Suzuki, K.; Kita, T.; Yamada, H. Wavelength tunable laser diodes with Si-wire waveguide ring resonator wavelength filters/Silicon Photonics VI. *SPIE* **2011**, *7943*, 361–367.
42. Kita, T.; Tang, R.; Yamada, H. Narrow spectral linewidth silicon photonic wavelength tunable laser diode for digital coherent communication system. *IEEE J. Sel. Top. Quantum Electron.* **2016**, *22*, 23–34. [CrossRef]
43. Rao, Y.; Chase, C.; Huang, M.C.Y.; Khaleghi, S.; Chitgarha, M.R.; Ziyadi, M.; Worland, D.P.; Willner, A.E.; Chang-Hasnain, C.J. Continuous tunable 1550-nm high contrast grating VCSEL. In Proceedings of the CLEO: Science and Innovations. Optica Publishing Group, San Jose, CA, USA; 2012; pp. 6–11.
44. Oldenbeuving, R.M.; Klein, E.J.; Offerhaus, H.L.; Lee, C.J.; Song, H.; Boller, K.J. 25 kHz narrow spectral bandwidth of a wavelength tunable diode laser with a short waveguide-based external cavity. *Laser Phys. Lett.* **2012**, *10*, 015804. [CrossRef]
45. Kobayashi, N.; Sato, K.; Namiwaka, M.; Yamamoto, K.; Watanabe, S.; Kita, T.; Yamada, H.; Yamazaki, H. Silicon photonic hybrid ring-filter external cavity wavelength tunable lasers. *J. Light. Technol.* **2015**, *33*, 1241–1246. [CrossRef]
46. Latkowski, S.; Hänsel, A.; Bhattacharya, N.; Bhattacharya, N.; de Vries, T.; Augustin, L.; Williams, K.; Smit, M.; Bente, E. Novel widely tunable monolithically integrated laser source. *IEEE Photonics J.* **2015**, *7*, 1503709.
47. Andreou, S.; Williams, K.A.; Bente, E.A.J.M. Electro-optic tuning of a monolithically integrated widely tuneable InP laser with free-running and stabilized operation. *J. Light. Technol.* **2019**, *38*, 1887–1894. [CrossRef]
48. McKinzie, K.A.; Wang, C.; Noman, A.A.; Mathine, D.L.; Han, K.; Leaird, D.E.; Hoefler, G.E.; Lal, V.; Kish, F.; Qi, M.; et al. InP high power monolithically integrated widely tunable laser and SOA array for hybrid integration. *Opt. Express* **2021**, *29*, 3490–3502. [CrossRef]
49. Chen, Q.; Wang, Z.; Zhao, J.; Meng, J.; Song, G.; He, J.J. Tunable V-Cavity Laser Monolithically Integrated With Traveling Wave Mach-Zehnder Modulator. *IEEE Photonics Technol. Lett.* **2022**, *34*, 1046–1049. [CrossRef]
50. Hao, Y.-Z.; Sheng, M.-W.; Zhang, Z.-N.; Li, J.-C.; Xiao, J.-L.; Yang, Y.-D.; Huang, Y.-Z. High-Speed Directly Modulated Widely Tunable Hybrid Square/Rhombus-Rectangular Coupled Cavity Lasers. *J. Light. Technol.* **2023**, *41*, 5668–5674. [CrossRef]
51. Jain, G.; Andreou, S.; McGuinness, C.; Gutierrez-Pascual, M.D.; Troncoso-Costas, M.; Venkatasubramani, L.N.; Barry, L.P.; Augustin, L.; Smyth, F.; Duggan, S. Widely tunable C-band laser and module with nanosecond tuning and narrow linewidth. *Proc. SPIE* **2023**, *12424*, 124241M-1–1424241M-7.
52. Wang, K.; Chen, Q.; Jiang, C.; Chen, Z.; Tan, S.; Lu, M.; Lu, Q.; Guo, W. Narrow linewidth electro-optically tuned multi-channel interference widely tunable semiconductor laser. *Opt. Express* **2023**, *31*, 4497–4506. [CrossRef]
53. Kim, J.H.; Aghaeimeibodi, S.; Carolan, J.; Englund, D.; Waks, E. Hybrid integration methods for on-chip quantum photonics. *Optica* **2020**, *7*, 291–308. [CrossRef]
54. Thomson, D.; Zilkie, A.; Bowers, J.E.; Komljenovic, T.; Reed, G.T.; Vivien, L.; Morini, D.M.; Cassan, E.; Virot, L.; Fédéli, J.M.; et al. Roadmap on silicon photonics. *J. Opt.* **2016**, *18*, 073003. [CrossRef]
55. Fang, Q.; Shi, Y.; Gao, H. A review of new techniques for improving the beam quality of semiconductor lasers. *Opt. Technol.* **2003**, *1*, 107–109+112.
56. Liu, M.; Zhang, F.; Xu, C.; Ma, Z.; Zhong, S.; Duan, J. Coupling efficiency of laser diode to GRIN fiber by aspherical lens. *Opt. Fiber Technol.* **2022**, *73*, 103069. [CrossRef]
57. Wang, Z.; Tian, B.; Pantouvaki, M.; Guo, W.; Absil, P.; Campenhout, J.V.; Merckling, C.; Thourhout, D.V. Room-temperature InP distributed feedback laser array directly grown on silicon. *Nat. Photonics* **2015**, *9*, 837–842. [CrossRef]
58. Yan, Z.; Han, Y.; Lin, L.; Xue, Y.; Ma, C.; Ng, W.K.; Wong, K.S.; Lau, K.M. A monolithic InP/SOI platform for integrated photonics. *Light Sci. Appl.* **2021**, *10*, 200. [CrossRef]