Simple and compact V-cavity semiconductor laser with 50×100 GHz wavelength tuning

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Abstract: We report simple and compact V-cavity semiconductor laser capable of full-band wavelength tuning. A half-wave coupler is used to obtain high side-mode suppression ratio (SMSR) without any grating or epitaxial regrowth. Temperature induced gain spectrum shift is employed in combination with the Vernier tuning mechanism to extend the wavelength tuning range beyond the free spectral range limit. Wavelength tuning of 50 channels at 100GHz spacing with SMSR up to 38 dB has been demonstrated. We show that with a temperature variation of 35°C, the tuning range can be extended by about 15 nm, in contrast to 0.1 nm/°C for thermo-optic tuning range in grating based lasers. At a fixed temperature, consecutive wavelength tuning of 31 channels was achieved. The response time of the channel switching under the current-tuning regime is measured to be about 20μs. The large tuning range that can cover the full C-band will enable such a simple, compact and potentially low-cost tunable laser to be used in wavelength-agile access and data center networks.

OCIS codes: (140.5960) Semiconductor lasers; (250.5300) Photonic integrated circuits.

References and links

1. V. Jayaraman, D. A. Cohen, and L. A. Coldren, "Demonstration of broadband tunability in a semiconductor laser using sampled gratings," Appl. Phys. Lett. **60**(19), 2321–2323 (1992).
2. B. Mason, G. A. Fish, S. P. DenBaars, and L. A. Coldren, "Widely tunable sampled grating DBR laser with integrated electroabsorption modulator," IEEE Photon. Technol. Lett. **11**(6), 638–640 (1999).
3. L. A. Coldren, "Monolithic tunable diode lasers," IEEE J. Sel. Top. Quantum Electron. **6**(6), 988–999 (2000).
4. J. Zhao, N. Zhou, Y. Tang, J. Zhao, L. Wang, X. Chen, X. Huang, Y. Yu, and W. Liu, "Design and fabrication of tunable laser with digital concatenated grating," Semicond. Sci. Technol. **28**(3), 035001 (2013).
5. Y. Tohmori, Y. Yoshikuni, H. Ishii, F. Kano, T. Tamamura, Y. Kondo, and M. Yamamoto, "Broad-range wavelength-tunable superstructure grating (SSG) DBR lasers," IEEE J. Quantum Electron. **29**(6), 1817–1823 (1993).
6. M. Öberg, P. J. Rigole, S. Nilsson, T. Klinga, L. Backbom, K. Streubel, J. Wallin, and T. Kjellberg, "Complete single mode wavelength coverage over 40 nm with a superstructure grating DBR laser," J. Lightwave Technol. **13**(9), 1892–1898 (1995).
7. H. Ishii, F. Kano, Y. Tohmori, Y. Kondo, T. Tamamura, and Y. Yoshikuni, "Narrow spectral linewidth under wavelength tuning in thermally tunable super-structure-grating (SSG) DBR lasers," IEEE J. Sel. Top. Quantum Electron. **1**(2), 401–407 (1995).
8. A. J. Ward, D. J. Robbins, G. Busico, E. Barton, L. Ponnampalam, J. P. Duck, N. D. Whitbread, P. J. Williams, D. C. J. Reid, A. C. Carter, and M. J. Wale, "Widely tunable DS-DBR laser with monolithically integrated SOA: design and performance," IEEE J. Sel. Top. Quantum Electron. **11**(1), 149–156 (2005).
9. J.-O. Wesström, G. Sarlet, S. Hammerfeldt, L. Lundqvist, P. Szabo, and P.-J. Rigole, "State of the art performance of widely tunable modulated grating Y-branch lasers," Opt. Fiber Commun. Conference, paper TuE2 (2004).
10. H. Ishii, K. Kasaya, H. Oohashi, Y. Shibata, H. Yasaka, and K. Okamoto, "Widely wavelength-tunable DFB laser array integrated with funnel combiner," IEEE J. Quantum Electron. **13**(5), 1089–1094 (2007).
11. J. D. Berger, Y. Zhang, J. D. Grade, H. Lee, S. Hrinya, and H. Jerman, "Widely tunable external cavity diode laser using a MEMS electrostatic rotary actuator," European Conference on Opt. Commun., Amsterdam, paper TuF3.3 (2001).
12. B. Liu, A. Shakouri, and J. E. Bowers, "Wide tunable double ring resonator coupled lasers," IEEE Photon. Technol. Lett. **14**(5), 600–602 (2002).
13. T. Segawa, S. Matsuo, T. Kakitsuka, T. Sato, Y. Kondo, and H. Suzuki, "Full C-band tuning operation of semiconductor double ring resonator coupled laser with low tuning current," IEEE Photon. Technol. Lett. **19**(17), 1322–1324 (2007).

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14. S. Matsuo and T. Segawa, "Microring-resonator-based widely tunable lasers," IEEE J. Sel. Top. Quantum Electron. **15**(3), 545–554 (2009).
15. A. Le Liepvre, C. Janyl, A. Accard, M. Lamponi, F. Poingt, D. Make, F. Lelarge, J.-M. Fedeli, S. Messaoudene, D. Bordel, and G.-H. Duan, "Widely wavelength tunable hybrid III-V/silicon laser with 45 nm tuning range fabricated using a wafer bonding technique," IEEE 9th International Conf. on Group IV Photonics, 54–56 (2012).
16. L. Coldren, K. Furuya, B. Miller, and J. Rentschler, "Etched mirror and groove-coupled GaInAsP/InP laser devices for integrated optics," IEEE J. Quantum Electron. **18**(10), 1679–1688 (1982).
17. W. T. Tsang, "The cleaved-coupled-cavity (C3) laser," Semicond. Semimetals **22**, 257–373 (1985).
18. K. Shi, F. Smyth, D. Reid, B. Roycroft, B. Corbett, F. H. Peters, and L. P. Barry, "Characterization of a tunable three-section slotted Fabry–Perot laser for advanced modulation format optical transmission," Opt. Commun. **284**(6), 1616–1621 (2011).
19. D. Byrne, J. Engelstaedter, W. Guo, Q. Lu, B. Corbett, B. Roycroft, J. O'Callaghan, and F. H. Peters, "Discretely tunable semiconductor lasers suitable for photonic integration," IEEE J. Sel. Top. Quantum Electron. **15**(3), 482–487 (2009).
20. T. Yu, L. Zou, L. Wang, and J.-J. He, "Single-mode and wavelength tunable lasers based on deep-submicron slots fabricated by standard UV-lithography," Opt. Express **20**(15), 16291–16299 (2012).
21. J.-J. He and D. Liu, "Wavelength switchable semiconductor laser using half-wave V-coupled cavities," Opt. Express **16**(6), 3896–3911 (2008).
22. J. Jin, L. Wang, T. Yu, Y. Wang, and J.-J. He, "Widely wavelength switchable V-coupled-cavity semiconductor laser with ~40 dB side-mode suppression ratio," Opt. Lett. **36**(21), 4230–4232 (2011).
23. W.-H. Guo, Q. Lu, M. Nawrocka, A. Abdullaev, J. O'Callaghan, and J. F. Donegan, "Nine-channel wavelength tunable single mode laser array based on slots," Opt. Express **21**(8), 10215–10221 (2013).
24. J. Buus, M. C. Amann, and D. J. Blumenthal, *Tunable Laser Diodes and Related Optical Sources* (Wiley-Interscience, 2005).

1. Introduction

Widely wavelength tunable semiconductor lasers are indispensable in next-generation optical networks. A variety of tunable lasers have been developed such as sampled grating distributed Bragg reflector (SGDBR) lasers [1–4], superstructure grating (SSG) DBR laser [5–7], digital supermode (DS) DBR laser [8], modulated grating Y-branch laser [9], thermally tunable distributed feedback (DFB) laser arrays [10], and MEMS based external cavity lasers [11]. For SGDBR or DSDBR lasers, for example, excellent performance has been achieved including wide tuning range covering full C- or L-band with side-mode suppression ratio (SMSR) above 40 dB. However, in addition to fabrication complexity involving non-uniform gratings and multiple epitaxial growths, multiple electrodes with complex control algorithms are usually required for wavelength tuning. As the dense wavelength division multiplexing (DWDM) technology extends towards access and reconfigurable data center networks, the cost reduction and operational simplicity become more and more important. Simple, compact and low cost tunable lasers are therefore badly needed.

To reduce the fabrication complexity, widely tunable lasers using two ring resonators as intra-cavity Vernier filters have been proposed and developed [12–15]. This scheme eliminates the need of the complex grating fabrication. The device length is also reduced from about 2 mm to 1 mm [14]. However, it still requires etch-and-regrowth for active-passive integration, and three electrodes for controlling the wavelength tuning. It also needs deeply etched ring resonators with small radius which is difficult to fabricate with low loss.

Simpler designs known as coupled-cavity lasers with an etched trench or cleaved-coupled-cavity (C^3) structure have been investigated in the 1980's [16, 17]. The advantage of the coupled cavity laser is the simple structure which does not require epitaxial regrowth. However, they have not been widely used in practice because of their poor side mode suppression ratio (SMSR). A similar design in the form of slotted Fabry-Perot laser (SFP) with multiple slots etched in an FP cavity was recently reported with good single-mode selectivity [18]. Wide wavelength tuning is also demonstrated using periodically etched slots as distributed reflectors with Vernier effect [19]. However, the etched slots of about 1μm wide limited by standard contact lithography introduce a large scattering loss which degrades the laser performance. To reduce the slot width to the deep-submicron domain requires a high resolution lithography tool such as the electron-beam lithography or a complex fabrication process [20]. To access all wavelength channels, it is necessary to control three electrodes,

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which makes the wavelength tuning still very complicated, similar to the case of SG-DBR lasers. The device length is also very long.

Recently, a more compact gratingless V-coupled-cavity tunable laser was proposed [21] and single-electrode controlled wavelength tuning of 16 and 26 consecutive channels with 100 GHz spacing was demonstrated experimentally with an excellent SMSR of about 40 dB and 37 dB, respectively [22]. It is an all-active device with no grating or ring resonators, and therefore it does not require any epitaxial regrowth. The fabrication process is similar to simple Fabry-Perot lasers and the device length is less than 0.5 mm.

For short-reach optical network applications, it is highly desirable to have tunable lasers with a tuning range of about 40 nm to cover the full C- or L- band, while having a simple and compact structure that can meet the low-cost requirements. While the V-cavity laser is the simplest and smallest tunable laser that has been reported, extending its tuning range to cover the full band is very important for many applications. In this paper, we report extended wavelength tuning range in the V-cavity laser by employing the mechanism of temperature-induced gain spectrum shift. While temperature tuning is commonly used in many types of tunable lasers, its tuning range is limited by the thermal-optic coefficient of 0.1 nm/°C and a laser array is needed to cover the full wavelength band [10, 23]. Here we show that by combining temperature-induced gain spectrum shift with current controlled co-directional wavelength tuning in V-cavity laser, the tuning range can be extended by about 15 nm with a temperature variation of only 35°C. A 50-channel tuning of 100 GHz spacing is demonstrated with side-mode suppression ratio up to 38 dB. At a fixed temperature, single-electrode-controlled consecutive wavelength tuning of 31 channels was achieved. The wavelength switching speed under the current-tuning regime is also measured.

2. Device structure and fabrication

Designed and fabricated in InGaAsP/InP multiple quantum well structure, the V-cavity laser (VCL) consists of two Fabry-Perot cavities with slightly different optical path lengths and a reflective 2 × 2 half-wave coupler [21], as shown in Fig. 1(a). The length of the fixed gain cavity is designed to be 466μm to match its resonant wavelengths to the ITU grid of 100 GHz spacing. The channel selector cavity is 5% longer so that the Vernier effect can be used to extend the tuning range. Three deep etched facets are used as the cavity mirrors. The half-wave coupler consists of a non-imaging multimode interference (MMI) structure with an optimal coupling coefficient to ensure high side-mode suppression ratio (SMSR). Unlike conventional directional couplers or MMI couplers, its cross-coupling coefficient has a relative phase of π with respect to self-coupling coefficient. Three electrodes are deposited on the top surface, covering over the ridge waveguides, while a common ground electrode is deposited on the back side. The fixed gain electrode and the common electrode on the coupler provide stable gain while the channel selector electrode is used for wavelength tuning. The wavelength tuning is accomplished through current injection that alters the refractive index through thermo-optic effect, thereby tuning the lasing wavelength to one of the resonant wavelengths of the fixed gain cavity by aligning it to one of the resonant wavelengths of the channel selector cavity.

The laser was fabricated on InGaAsP/InP multiple quantum wells (MQW) structure with five compressively strained 6-nm $In_{0.8}Ga_{0.2}As_{0.8}P_{0.2}$ QWs sandwiched between 10-nm $In_{0.71}Ga_{0.29}As_{0.54}P_{0.46}$ barriers, whose photoluminescence peak wavelength is about 1520 nm. The whole device uses the same MQW structure without epitaxial regrowth or bandgap engineering. Standard fabrication process for ridge waveguide Fabry-Perot lasers is used with the addition of a deep-etching step for the etched facets. The SEM sideview of the etched facet is given in Fig. 1(b), which shows the ridge waveguide with planarization and metal contact layers. The chip size is only about 500μm × 300μm.

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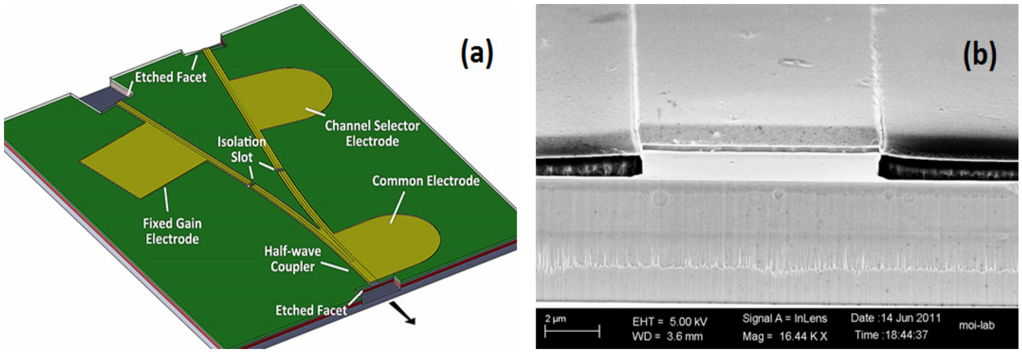

Fig. 1. (a) Schematic diagram of the VCL and (b) the SEM sideview of the deep etched facet.

3. Experimental results and discussions

The laser is mounted on an aluminum nitride (AlN) carrier with a thermal-electric cooler (TEC) for temperature control. The laser reaches the threshold when the three independent electrodes are biased at about 20 mA. When the electrodes are biased at 40~50 mA, the output power measured by collecting all the light from the coupler side using a broad area detector is about 8 mW. Figure 2 gives a typical lasing spectrum showing the single-mode operation with regularly varying side modes. The SMSR is about 38 dB in this example. By varying the current injected into the channel selector cavity and the TEC temperature, 50-channel consecutive wavelength tuning of about 100 GHz is obtained. Figure 3 shows the overlapped emission spectra of the 50 channels. The tuning conditions and SMSR characteristics are further detailed below.

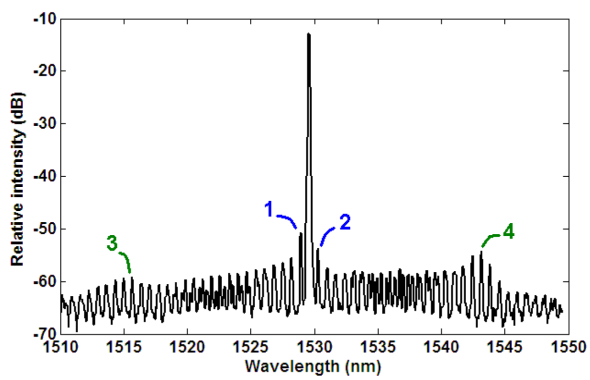

Fig. 2. Measured single mode spectrum with a SMSR of 38 dB.

For the wavelength tuning experiment, we set the current on the fixed gain electrode and the common electrode to 34 mA and 53 mA, respectively. Because all of the three sections under different electrodes comprise the same MQW structure without epitaxial regrowth or bandgap engineering, when the current on the tuning electrode increases, the output power first increases but then saturates due to thermal effect that increases the non-radiative recombination. The variation of the carrier density is insignificant because of the gain clamping effect. The refractive index increases due to the dominance by thermal-optic effect, and the material gain spectrum shifts to longer wavelength at the same time. As a result, when the temperature is set at 20°C and the current on the channel selector electrode in the long cavity increases from 37 mA to 129 mA, the laser wavelength increases and 31 consecutive channels can be obtained, although the free spectral range (FSR) determined by the Vernier tuning mechanism is only 20 channels for 5% cavity length difference. The extra tuning range of 11 channels (~8 nm) can be attributed to the temperature induced gain spectrum shift,

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which moves in the same direction as the wavelength tuning. Since the temperature coefficient of the gain spectrum shift is about 0.5 nm/K [24], the estimated average junction temperature variation due to the current tuning is about 16°C.

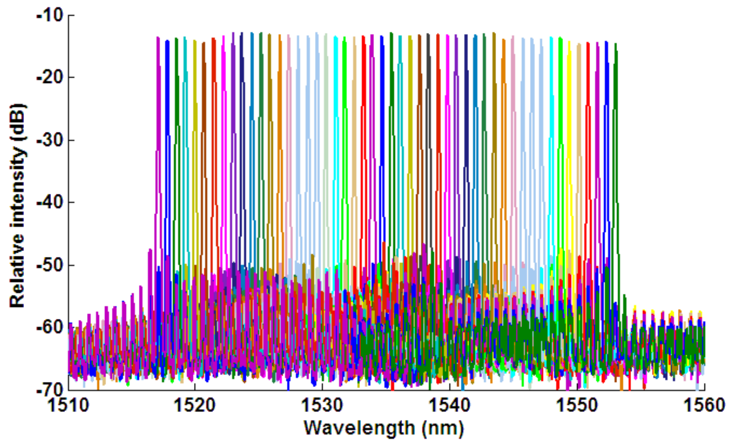

Fig. 3. Overlapped 50-channel laser spectra.

Note that in the above experiment the channel selector electrode in the longer cavity is used to tune the wavelength towards longer wavelength when the gain spectrum shifts in the same direction as the current and temperature increase. This co-directional tuning is necessary for extending the tuning range. If the tuning electrode is in the shorter cavity, the wavelength tuning by the Vernier mechanism would shift the wavelength towards shorter wavelength, in opposite direction as the gain spectrum shift, resulting in a reduced tuning range.

To further extend the tuning range, we changed the TEC temperature in four steps at 10°C, 20°C, 37°C and 45°C, and obtained consecutive wavelength tuning of 6 channels, 31channels, 7channels, and 6 channels, respectively, for a total of 50 channels. With a temperature variation of 35°C, the tuning range is therefore extended by 19 channels (or about 15 nm). The current on the channel selector electrode was tuned from 16 mA to 148 mA. Figure 4 shows the wavelength of the lasing mode as a function of the tuning current on the channel selector electrode. In the low temperature (10°C) and low tuning current end, the extension of tuning range by 6 channels matches approximately the gain spectrum shift of 5 nm due to the temperature change of 10°C. However, at the high temperature (37~45°C) and high tuning current end, the tuning range extension of 13 channels (~10 nm) over 25°C TEC temperature change is less than calculated by the assumed linear shift of 0.5 nm/°C, and further increase of the TEC temperature does not improve much the tuning range but degrades the laser performance in terms of both output power and SMSR. This can be attributed to the degradation of quantum efficiency and gain spectrum of the MQW at high temperature.

It is worthwhile to point out that the temperature induced wavelength tuning is 0.1 nm/°C for grating based tunable lasers due to refractive index variation. For a temperature variation of 35°C, the wavelength tuning range is only about 3.5 nm [23]. The temperature-induced tuning range extension in the V-cavity laser is 5-times more sensitive by using the mechanism of the gain spectrum shift. Since the TEC is always required to stabilize the wavelength for lasers used in DWDM systems, the tuning range extension by TEC temperature does not increase any packaging complexity or size. The compactness of the V-cavity laser also allows the use of a small TEC with low power consumption.

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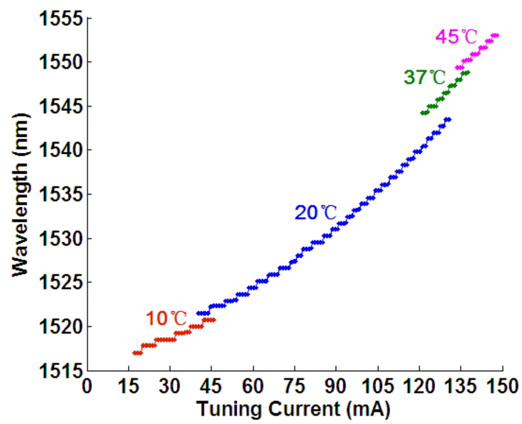

Fig. 4. Measured tuning curve at 4 different TEC temperatures.

Although the temperature change during the full range tuning can change the optical path length of the cavities and consequently the channel spacing, the spacing change corresponding to ± 20°C temperature variation is calculated to be ± 0.13% (i.e. ± 0.13 GHz for 100 GHz spacing), which is negligible. While the wavelength spacing is defined by the cavity length of the fixed gain cavity, the wavelength of the lasing mode can be fine-tuned and stabilized by the TEC temperature or the bias current of the common electrode on the coupler, which adjusts the phases of the two cavities simultaneously. Unlike the case of DBR or SGDBR tunable lasers where a phase-section is needed to tune the FP cavity mode to or within the reflectivity peaks of the DBRs, the phases of the two FP cavities in the V-cavity laser are inherently matched for the lasing mode when the channel selector cavity is optimally tuned to a wavelength channel. Therefore, no additional phase tuning section is necessary. The mode-hopping occurs in a controlled manner, which corresponds to the desired channel switching through the Vernier mechanism. For direct modulation, if the fixed gain electrode is used for injecting the modulation current, undesirable dynamic mode-hopping can occur due to associated phase variation in the fixed gain cavity alone. However, by using appropriately designed common electrode on the coupler for the direct modulation, the phase changes in the two cavities can be synchronized so that the mode-hopping is avoided. The experimental results of the direct modulation will be reported elsewhere.

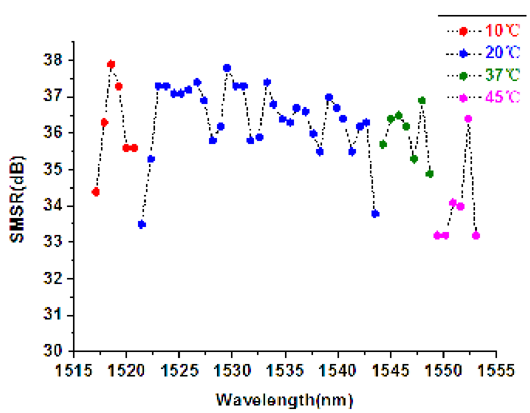

Fig. 5. SMSRs of the 50 channels.

The SMSR of the laser is plotted in Fig. 5 for the 50 channels. For wavelength channels in the middle of the tuning range at each temperature, the SMSR is determined by the highest adjacent mode (i.e. mode 1 or 2 in Fig. 2). It mostly ranges from 35.5 dB to 38 dB. The

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variation is mainly due to inaccurate manual current setting in our experiment with respect to optimal values. For edge channels at each temperature, the SMSR is determined by the highest mode at approximately one FSR away from the main mode (i.e. mode 3 or 4 in Fig. 2). It ranges from 33~35 dB. It can be envisaged that by smoothly tuning the TEC temperature in synchronization with the tuning current on the channel selector cavity, a continuous staircase tuning curve and improved SMSR can be achieved with elimination of the edge channels at each temperature.

The speed of the wavelength tuning between two channels accessed by using two different TEC temperatures depends on the thermal load of the laser package and is inherently slow. This is not a problem for many "set-and-forget" applications such as colorless ONUs in WDM access networks. For applications in reconfigurable optical networks, we investigated the channel switching speed of the tunable V-cavity laser under the current-tuning regime for which 31 channels are available for temperature fixed at 20°C. The speed measurement is done by applying a square-wave driving voltage of 1 kHz frequency and 50% duty cycle to the channel selector electrode, switching the wavelength between two adjacent channels. The laser output is fed into an edge filter to achieve the wavelength-intensity conversion, and the resulting waveform is observed on a real time oscilloscope. Figure 6 shows the rise and fall edges of the switching waveform between two wavelength channels. The rise time is about 18μs and the fall time is about 22μs. This confirms that the switching mechanism is dominated by the thermal effect. The fall time is 4μs longer than the rise time due to faster heating than cooling. The switching response time of the V-cavity laser is much faster than other thermally tuned semiconductor lasers (~1 ms) [7], mainly benefiting from its small thermal load due to compact structure.

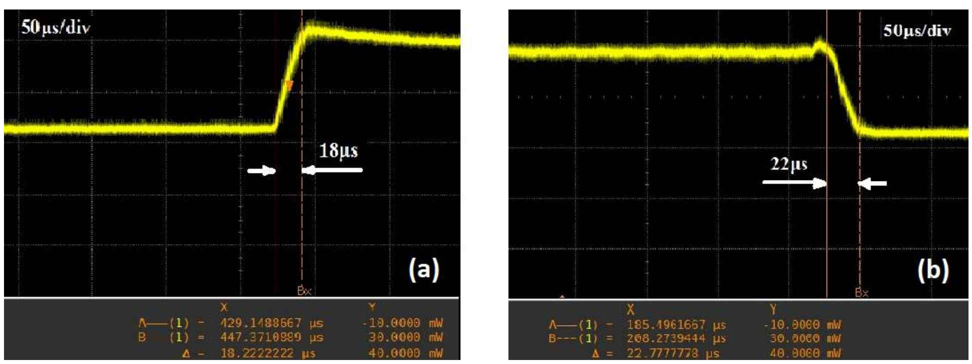

Fig. 6. Rise (a) and fall (b) edges of switching waveform between two wavelength channels.

4. Conclusions

We have successfully demonstrated a simple and compact V-cavity tunable semiconductor laser with 50-channel wavelength tuning of 100 GHz spacing. By combining the current tuning on just one electrode and the TEC temperature control, ~40 nm of wavelength tuning range can be achieved, which can potentially cover the full C- or L-band. The SMSR is mostly above 35 dB and can be as high as 38 dB. At a fixed temperature, single-electrode controlled consecutive wavelength tuning of 31 channels was achieved. The wavelength switching speed under the current-tuning regime is measured to be ~20μs. The laser structure does not involve any grating or epitaxial regrowth, and has a size of only 500μm × 300μm. The advantages of compactness, fabrication simplicity and easy wavelength control offer great potential for the tunable laser to be used in low-cost access networks such as TWDM-PONs.

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