# Tunable V-cavity Semiconductor Laser and Modules

**Jian-Jun He**[1], **Xiaohai Xiong**[1], **Jianjun Meng**[1], **Sen Zhang**[1], **Xiaolu Liao**[1], **Hongli Zhu**[1], **Lin Wu**[1], **Li Zou**[2], **Lei Wang**[2], **and Guoping Li**[2]

[1]State Key Laboratory of Modern Optical Instrumentation
Centre for Integrated Optoelectronics, Department of Optical Engineering
Zhejiang University, Hangzhou 310027, China
[2]Lightip Technologies (Hangzhou) Co. Ltd.
11 Xiyuan Eighth Road, Suite D-502, Hangzhou 310030, China

(*Invited Paper*)

**Abstract**— We present the principle, design, packaging and measurement results of widely tunable V-cavity lasers. By using a novel half-wave coupler, single-mode lasing with high side-mode-suppression-ratio is achieved. Single-electrode controlled wide-band wavelength tuning with Vernier effect is realized. The full-band tuning of 50 channels with 100 GHz spacing is demonstrated by further employing temperature induced gain spectrum shift. The laser is packaged into a small-form-factor 9-pin TOSA, and the electronic driver has been developed for the wavelength tuning and direct modulation. The advantages of compactness, fabrication simplicity, and easy wavelength control offer great potential for the tunable laser to be used in low-cost access and data center networks, as well as in portable devices for spectroscopic analysis.

## 1. INTRODUCTION

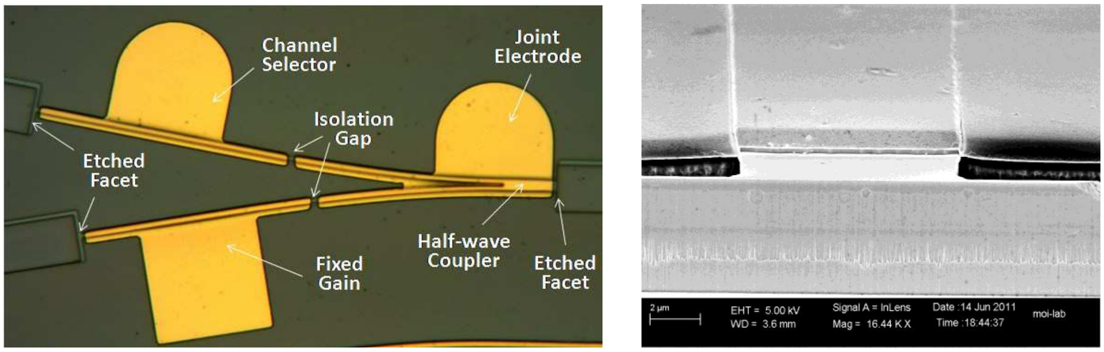
Widely wavelength tunable semiconductor lasers are important components for next-generation optical networks, and for applications in spectroscopic measurements. Over the last two decades, high performance tunable lasers have been developed based on complex structures such as sampled grating distributed Bragg reflector (SGDBR) [1], superstructure grating DBR [2], digital super mode DBR [3], modulated grating Y-branch [4], and periodically etched slots [5]. 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. With the dense wavelength division multiplexing (DWDM) technology extending towards access and data center networks, and the emerging demands of portable devices for biomedical analyses, food safety and environmental monitoring etc., the cost reduction and operational simplicity become more and more important.

To reduce the fabrication complexity, widely tunable lasers using two ring resonators as intra-cavity Vernier filters have been developed [6]. This scheme eliminates the need of the complex grating fabrication. 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 and coupling gaps which are difficult to fabricate without expensive tools such as ebeam lithography.

Simpler designs known as coupled-cavity lasers with an etched trench or cleaved-coupled-cavity ($C^3$) structure were investigated in the 1980's [7, 8]. However, they have not been widely used in practice because of their poor side mode suppression ratio (SMSR). Recently, a compact grating less V-coupled-cavity tunable laser was proposed [9] and single-electrode controlled wavelength tuning of 16 and 26 channels with 100 GHz spacing was demonstrated experimentally with an excellent SMSR of about 40 dB and 37 dB, respectively [10]. By combining temperature-induced gain spectrum shift with current controlled Vernier tuning mechanism, the tuning range was extended to 50 channels with a temperature variation of only 35°C [11]. It is an all-active device with no grating or ring resonators, and therefore does not require any epitaxial regrowth. The fabrication process is similar to simple Fabry-Perot lasers and the device size is only about $0.5 \times 0.3\,\mathrm{mm}^2$.

## 2. DESIGN AND OPERATION PRINCIPLE

Figure 1 shows the top view of a V-cavity laser. It comprises a fixed gain cavity and a channel selector cavity with different optical path lengths, which form V-shaped branches with a reflective $2 \times 2$ half-wave coupler. The half-wave coupler, in which the cross-coupling coefficient has a $\pi$ phase relative to the bar-coupling coefficient, is important for achieving high SMSR. A conventional directional coupler or self-imaging multimode interference coupler, in which the cross-coupling coefficient has a relative phase of $\pi/2$ (quarter-wave) with respect to the bar-coupling coefficient, would produce no mode selectivity for the laser. In order to accurately control the coupler length for achieving optimal coupling coefficient, deeply etched facets are used to form the cavity mirrors. The length of the fixed gain cavity is designed so that its resonance frequency interval matches 100 GHz ITU grids. The length of the channel selector cavity is slightly longer so that the Vernier effect can be employed to realize wide tuning range. The whole device comprises the same quantum well structure without epitaxial regrowth or bandgap engineering.



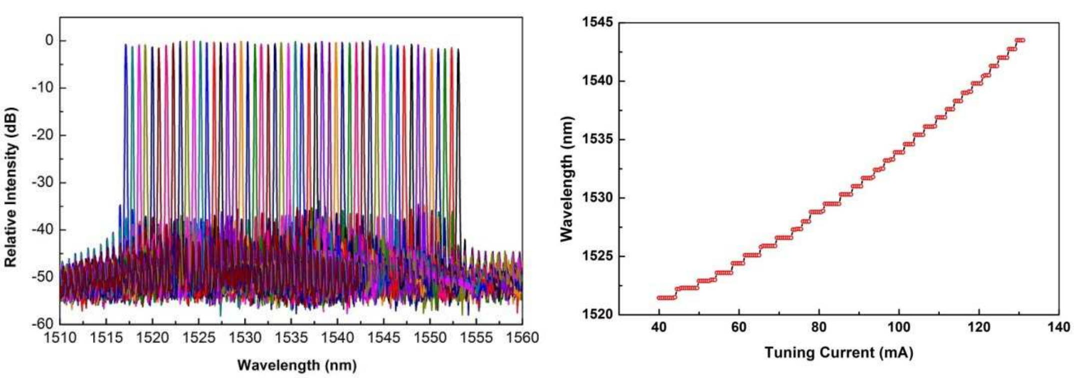

(a) (b)

Figure 1: (a) Top view of an InGaAsP/InP based V-cavity laser with a chip size of 500 µm × 300 µm; (b) Deeply etched facet.

The principle of the wavelength tuning is based on the Vernier mechanism. Each of the two cavities has a series of resonant modes with slightly different frequency interval. The main lasing mode occurs at a common resonant frequency which can be switched to an adjacent mode of the fixed cavity by slightly shifting the resonant frequency comb of the channel selector cavity. Only a single electrode is required for the wavelength switching. Although the Vernier effect is also used in other widely tunable lasers such as SGDBR lasers, they typically have frequency interval larger than 600 GHz due to the limitation of the device length required for accommodating many sampling periods of the grating. For common dense wavelength division multiplexing applications with 50 GHz or 100 GHz channel spacing as defined by ITU, a multi-electrode control is necessary for accessing all operating channels. This complexity is removed with the V-cavity laser.

## 3. EXPERIMENTAL RESULTS

The fabrication process is similar to that of a Fabry-Perot laser with the addition of a deep etching step for the etched facets. Fig. 2 shows the overlapped spectra of 50 channels tuning in an InGaAsP/InP multiple-quantum well (MQW) V-cavity laser, obtained by varying the current injected into the channel selector cavity in combination with TEC temperature variation from 10°C to 45°C which extends the tuning range by shifting the MQW gain spectrum. The SMSR ranges




(a) (b)

Figure 2: (a) Overlapped 50-channel laser spectra with 100 GHz spacing from an InGaAsP/InP MQW V-cavity laser; (b) Single-electrode controlled tuning curve when the TEC temperature is fixd at 20°C.

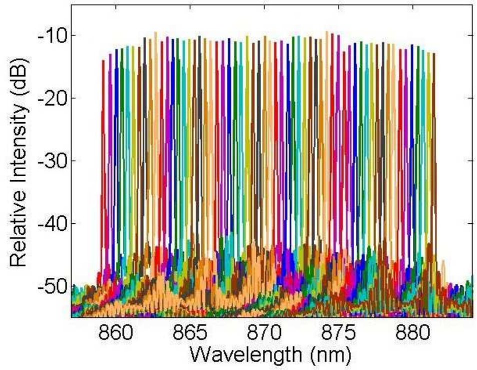



Figure 3: Overlapped 60-channel laser spectra with 150 GHz spacing from a GaAs/AlGaAs MQW V-cavity laser.

from 35 dB to 38 dB for most of the channels. The laser reaches the threshold when the three 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. The wavelength tuning range of ∼ 40 nm can potentially cover the full C- or L-band. Fig. 2(b) shows the wavelength tuning curve of the single-electrode controlled tuning of 31 channels when the TEC temperature is fixed at 20°C.

The grating less tunable V-cavity laser is even more advantageous for GaAs/AlGaAs based material system operating in the 850 nm window because it can overcome the two difficulties faced by grating based tunable lasers: the much smaller grating period (∼ 120 nm versus 240 nm) that requires e-beam lithography and the oxidation of AlGaAs during the grating fabrication. Fig. 3 shows the measured spectra of a GaAs/AlGaAs MQWV-cavity laser, which cover 60 channels with ∼ 150 GHz spacing. This wavelength band is within the transparent optical window of human tissue, and is therefore useful for wearable health monitoring devices.

## 4. PACKAGED MODULES

The V-cavity laser has been packaged into a small-form-factor 9-pin transmitter optical subassembly (TOSA). It contains a tunable laser diode chip-on-carrier, a monitoring photodiode, a TEC, a thermistor, an optical isolator, and optical lenses. The size of the housing box is only 7.4 mm × 5.8 mm × 5.3 mm, which is a small fraction of a conventional butterfly package, as shown in Fig. 4(a). An electronic driver has been developed for the wavelength tuning and direct modulation, as shown in Fig. 4(b). High speed modulation up to 5 Gbps has been achieved. The wavelength tuning can be controlled by computer software. Fig. 4(c) shows a compact module with an USB interface for computer control.

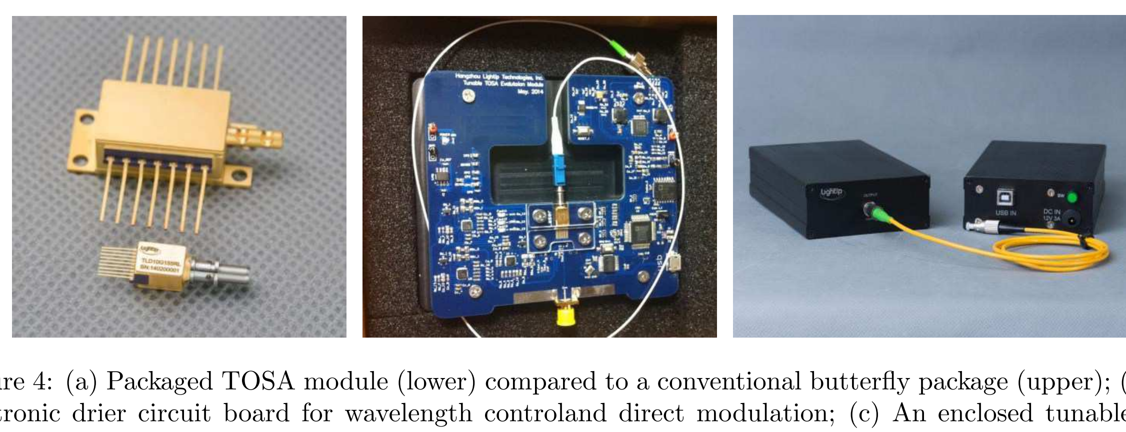


Figure 4: (a) Packaged TOSA module (lower) compared to a conventional butterfly package (upper); (b) An electronic drier circuit board for wavelength controland direct modulation; (c) An enclosed tunable laser module with an USB interface for computer control.

## 5. CONCLUSION

We have developed a simple and compact V-cavity tunable semiconductor laser which is capable of full-band wavelength tuning. By combining the current tuning on just one electrode and the TEC temperature control, $> 5000$ GHz frequency tuning is achieved in both InGaAsP/InP and GaAs/AlGaAs material systems. The laser structure does not involve any grating or epitaxial regrowth, and has a size of only $500\,\mu\text{m} \times 300\,\mu\text{m}$. Compact modules and electronic drivers have been developed for the wavelength tuning and direct modulation. The advantages of compactness, fabrication simplicity and easy wavelength control offer great potential for the tunable laser to be used in low-cost access and data center networks, and for portable medical and environmental monitoring devices.

## ACKNOWLEDGMENT

This work was supported by the National High-Tech R&D Program of China (grant No. 2013AA01 4401).

## REFERENCES

1. Coldren, L. A., "Monolithic tunable diode lasers," *IEEE J. Sel. Topics in Quantum Electron.*, Vol. 6, 988, 2000.
2. Tohmori, Y., Y. Yoshikuni, and H. Ishii, "Broad-range wavelength-tunable superstructure grating (SSG) DBR lasers," *IEEE J. Quantum Electron.*, Vol. 29, 1817–1823, 1993.
3. Ward, A. J., 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. Select. Topics Quantum Electron.*, Vol. 11, 149–156, 2005.
4. Wesström, J.-O., 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. Conf.*, paper TuE2, 2004.
5. Byrne, D., J. Engelstaedter, W. Guo, Q. Lu, B. Corbett, B. Roycroft, J. O'Callaghan, F. H. Peters, and J. Donegan, "Discretely tunable semiconductor lasers suitable for photonic integration," *IEEE J. Sel. Topics Quantum Electron.*, Vol. 15, 482–487, 2009.
6. Segawa, T., 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.*, Vol. 19, 1322–1324, 2007.
7. Coldren, L., K. Furuya, B. Miller, and J. Rentschler, "Etched mirror and groove-coupled GaInAsP/InP laser devices for integrated optics," *IEEE J. Quantum Electron.*, Vol. 18, 1679–1688, 1982.
8. Tsang, W. T., "The cleaved-coupled-cavity (C3) laser," *Semicond. Semimetals*, Vol. 22, 257, 1985.
9. He, J.-J. and D. Liu, "Wavelength switchable semiconductor laser using half-wave V-coupled cavities," *Opt. Express*, Vol. 16, 3896–3911, 2008.
10. Jin, J., L. Wang, Y. Wang, T. Yu, and J.-J. He, "Widely wavelength switchable V-coupled-cavity semiconductor laser with $\sim 40$ dB side-mode suppression ratio," *Opt. Lett.*, Vol. 36, 4230–4232, 2011.
11. Zhang, S., J. Meng, S. Guo, L. Wang, and J.-J. He, "Simple and compact V-cavity semiconductor laser with $50 \times 100$ GHz wavelength tuning," *Opt. Express*, Vol. 21, 13564, 2013.