Highly-reflective facet-coated 16-wavelength DFB laser array with exact wavelength spacings

Gen Lv[1], Rulei Xiao*[,1], Zijiang Yang[1], Zhenxing Sun[1], Yating Zhou*[,2], Yi-Jen Chiu[3], Xiangfei Chen*[,1]

[1]*Key Laboratory of Intelligent Optical Sensing and Manipulation of the Ministry of Education & National Laboratory of Solid State Microstructures & College of Engineering and Applied Sciences & Institute of Optical Communication Engineering, Nanjing University, Nanjing 210093, Jiangsu, China*

[2]*School of Mathematics & Physics and Chemical Engineering, Changzhou Institute of Technology, Changzhou, China*

[3]*Institute of Electro-Optical Engineering and Semiconductor Technology Research Development Center, National Sun Yat-Sen University, Kaohsiung 80424, Taiwan, R.O.C.*

*xrl@nju.edu.cn, zhou-yating@163.com, chenxf@nju.edu.cn

Abstract: An HR-AR-coated sixteen-wavelength DFB laser array is experimentally demonstrated with exact wavelength spacings. The spacing accuracy is preliminary guaranteed by the reconstruction-equivalent-chirp technique. The further exact wavelength spacing is achieved by distributed phase compensation.

1. Introduction

Efficient, compact, manufacturable multi-wavelength laser sources are critical for co-packaged optical interconnects, high-performance computing, emerging artificial intelligence and machine learning systems, sensors, high-bandwidth microwave photonic systems, and coherent light direction and ranging (LiDAR) [1]. Several approaches exist to enable sixteen or more wavelengths from a compact source [2-4], but formidable challenges exist in achieving adequate power per line, stability, and wall-plug efficiency in a convenient, volume-manufacturable product. Typically, the multi-wavelength laser source for wavelength division multiplexing in telecommunications is semiconductor laser array where the Bragg gratings are defined by electron-beam lithography (EBL). Because of the point-by-point scanning of EBL, the accumulative phase errors of Bragg gratings are inevitable, which will produce the residual error of lasing wavelengths. The wavelength errors will reduce the overall yield of the laser array, which decreases exponentially when the laser count increases. To maintain the wavelength accuracy, each laser is integrated with an individual resistor heater for thermally tuning or a distributed Bragg reflector for current tuning [5]. Such tunable laser array increases the fabrication complexity and brings thermal crosstalk and extra power consumption.

To date, both facets of multi-wavelength DFB laser arrays are anti-reflective (AR) coated to avoid the random facet grating phase. The random grating phase will bring great uncertainty to lasing wavelength and longitudinal mode. However, in practical applications, the rear facet of the DFB laser is poised to be highly-reflective (HR) coated to achieve high output power and low power consumption. In addition, the HR-facet coating can also reduce the optical crosstalk from the back-scattering light in some applications, like co-packaging of laser source and detector.

We reported an HR-AR-coated sixteen-wavelength DFB laser array with exact 100-GHz-spacing ITU.T-grid wavelengths. The superior wavelength accuracy is achieved by a two-step method. First, the spacing accuracy is preliminary guaranteed by the reconstruction-equivalent-chirp technique. Here, Bragg wavelengths of ~90% of the DFB lasers are within ±0.2 nm [6]. Noted that such precision is very high because 0.1-nm error of grating period leads to ~0.6-nm error of Bragg wavelength. The further exact wavelength spacing and single-longitudinal-mode (SLM) operation is achieved by distributed phase compensation, which is realized by a two-section laser structure. By changing the ratio of the currents injected into the two sections, the refractive indexes of the two sections are slightly changed oppositely. As a result, the random facet grating phase can be compensated and the SLM operation can be guaranteed. At the same time, the lasing wavelength can be tuned to align with the wavelength grid without a large fluctuation of output power. The simple fabrication process of the laser array is similar to that of a conventional DFB laser, with no need of integrated resistor heaters or extra epitaxy growths for passive waveguides. Such laser structure with distributed phase compensation is also suitable for high-power and SLM operation.

2. Principle and Device Design

The lasing wavelength of a DFB laser is determined by two factors, the range of grating bandgap and the position of lasing mode in this bandgap. For a typical $\lambda/4$ phase-shifted DFB laser with both facets AR-coated, the lasing mode lies in the middle of the grating bandgap, which is the Bragg wavelength. But for an HR-coated DFB laser, the position of lasing mode depends on the facet grating phase, which is uncontrollable in the chip-cleaving process.

Therefore, to obtain an accurate lasing wavelength, both the grating bandgap and the position of lasing mode should be finely arranged.

The REC technique is used to realize the high precision spacing of the Bragg wavelength [6]. The fabrication of sampled grating requires only a common holographic exposure and micrometer-level photolithography. By REC technique, both the facility cost and fabrication time are much lower than the commonly-used EBL technique. Moreover, the grating period error can be greatly relaxed by several hundred times theoretically [7].

The position of lasing mode is finely arranged by distributed phase compensation via a two-section structure. By changing the injection current to a DFB laser, the effective refractive index will change owing to the Joule heat and free-carrier plasma effect. To maintain the overall Joule heat and total power consumption, we change the proportions of injected currents into both sections, while the total current unchanged. As a result, the effective refractive indexes of the two sections are different, and the distributed phase compensation can be realized.

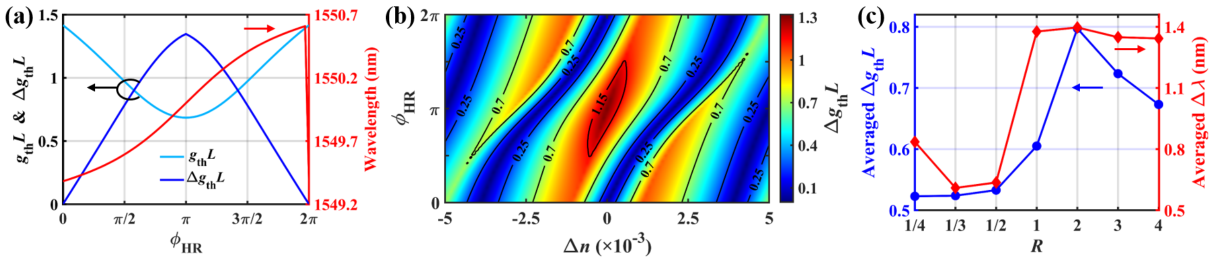

Fig. 1. (a) Calculated threshold situation when ϕ_{HR} is varied from 0 to 2π for an HR-AR coated laser; (b) calculated $\Delta g_{th}L$ when R equals to 1, Δn is varied from -0.005 to 0.005, and ϕ_{HR} is varied from 0 to 2π; (c) averaged $\Delta g_{th}L$ and $\Delta\lambda$ when R is varied from 1/4 to 4.

First, by applying coupled-mode theory combined with Fresnel equations, we calculated the threshold situation when the HR-coated facet grating phase (ϕ_{HR}) is varied from 0 to 2π for a 500-μm-long DFB laser. As shown in Fig. 1(a), all the threshold gain ($g_{th}L$), gain margin ($\Delta g_{th}L$), and lasing wavelength are varied with the ϕ_{HR}. Higher $\Delta g_{th}L$ means better SLM property, and stable SLM operation can be guaranteed when $\Delta g_{th}L$ is larger than 0.25.

Then we study an HR-AR-coated two-section DFB laser when the lengths and effective refractive indexes of the two sections are different. The sections with AR- and HR-coated facet are named as Section 1 and 2, respectively. The length ratio of Section 1 to 2 is expressed as R and the effective refractive index difference between Section 1 and 2 is expressed as Δn. The overall length is 500 μm. As shown in Fig. 1(b), the $\Delta g_{th}L$ is studied when R equals to 1, Δn is varied from -0.005 to 0.005, and ϕ_{HR} is varied from 0 to 2π. There is a region in the center of the diagram with very high $\Delta g_{th}L$. In this region, $\Delta g_{th}L$ can keep larger than 0.25 for all the ϕ_{HR} from 0 to 2π by adjusting Δn from -0.0025 to 0.0025. The lengths ratio R is also studied for optimization of the structure. To evaluate the overall laser performance, $\Delta g_{th}L$ is averaged when ϕ_{HR} is varied from 0 to 2π and Δn is varied from -0.005 to 0.005. For a certain ϕ_{HR}, the wavelength can be tuned by varying the Δn. The maximal wavelength tuning range ($\Delta\lambda$) is also averaged when ϕ_{HR} is varied from 0 to 2π. When the R is varied from 1/4 to 4, the averaged $\Delta g_{th}L$ and $\Delta\lambda$ are calculated in Fig. 3(c). An optimum R equals to 2 where both the averaged $\Delta g_{th}L$ and $\Delta\lambda$ reach the highest value.

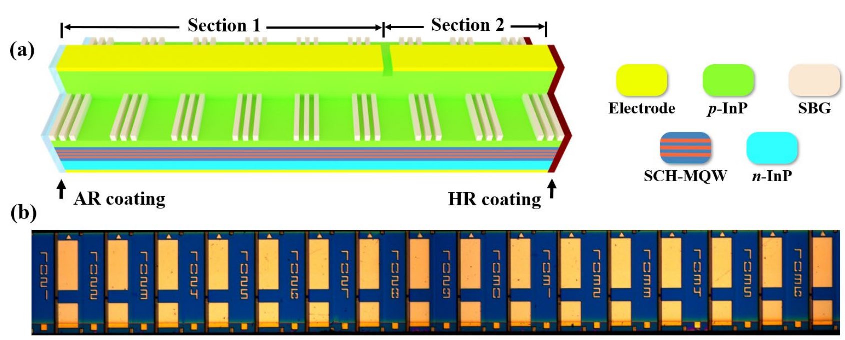

Fig. 2. (a) Schematic of the proposed two-section HR-AR coated DFB laser. (b) Microscopic top view of a fabricated sixteen-channel laser array. (SBG: sampled Bragg grating, SCH-MQW: separate-confinement heterostructure multi-quantum well)

3. Device Fabrication and Characteristics

The device structure is depicted in Fig. 2(a), which is typical a ridge-waveguide laser structure with sampled Bragg grating. The electrical isolation between the two sections is based on etching shallow groove on the ridge waveguide. The facets are coated with AR and HR layers. The microscopic top view of the laser array is shown in Fig. 2(b).

In our measurement, the laser chip was mounted on a sub-mount, the temperature of which was controlled at 25℃ by a thermoelectric cooler. The optical spectra were measured by coupling the light into a tapered fiber. The currents injected into Section 1 and 2 are denoted as I_1 and I_2, respectively. First, we measured the power-current-voltage curve of a single DFB laser when the injection current densities of both sections were kept same. The threshold current is 18.1 mA and the slop efficiency keeps high even if the total current reaches 150 mA. Then we measured the lasing spectra when the current injection ratio was changed. The total current was fixed at 120 mA to avoid extra Joule heat and power consumption. From Fig. 3(b) and (c), the wavelength can be tuned within a certain range of ~1 nm, which agrees with our theoretical prediction.

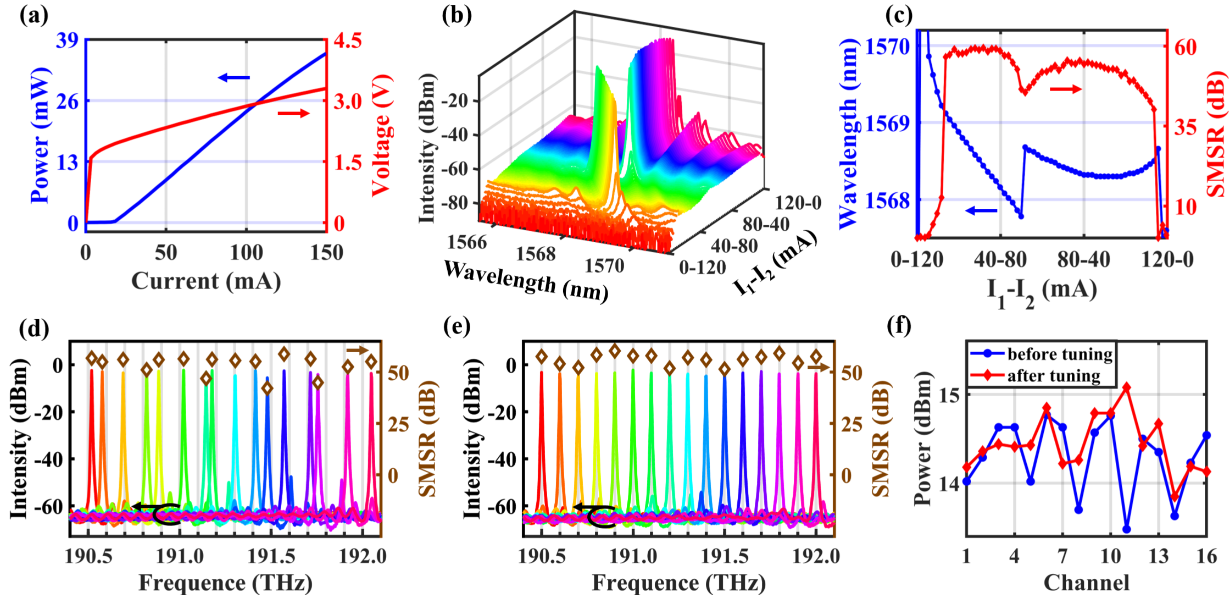

Fig. 3. (a) Measured P-I-V curve of the two-section DFB laser. (b) Superimposed spectra, (c) wavelengths and SMSRs of a DFB laser when the injection current proportion was varied. Superimposed spectra of the sixteen-wavelength laser array (d) before and (e) after the tuning of current injection proportion. (f) Output power of all channels before and after the tuning of current injection proportion.

Then the sixteen-wavelength laser array was measured. First, each laser was treated as one-section DFB laser with same injection current densities into both sections and total injection current was 120 mA. The superimposed measured spectra are shown in Fig. 3(d). Due to the random grating phase, the lasing wavelengths of the sixteen channels are misaligned with the corresponding grid. By changing the injection current proportions of the I_1-I_2 of the sixteen lasers to 75-45, 89-31, 93-27, 35-85, 39-81, 66-54, 49-71, 100-20, 77-43, 69-51, 51-69, 82-38, 73-47, 44-76, 66-54, 48-72 mA, all the lasing wavelengths are exactly in the wavelength grids, as shown in Fig. 3(e). Moreover, all the SMSRs are above 50 dB. As shown in Fig. 3(f), the output power keeps with a fluctuation of less than 1.2 dB, which is nearly the same with that before changing the injection proportions.

4. Acknowledgement

This work was supported in part by the National Natural Science Foundation of China under Grant 62004094 and Grant 61975075, in part by the Nature Science Foundation of Jiangsu Province of China under Grant BK20200334

5. References

[1] https://www.darpa.mil/work-with-us/for-small-businesses/HR001121S0007-07
[2] T. J. Kippenberg, R. Holzwarth, and S. A. Diddams, Microresonator-based optical frequency combs. Science 332,555-559 (2011)
[3] D. J. Moss, R. Morandotti, A. L. Gaeta, and M. Lipson, New CMOS-compatible platforms based on silicon nitride and Hydex for nonlinear optics. Nat. Photonics 7, 597-607 (2013)
[4] A. Liu, S. Srinivasan, J. Norman, A. C. Gossard, and J. E. Bowers, Quantum dot lasers for silicon photonics. Photon. Res., 3 (2015)
[5] S. H. Oh, J. U. Shin, Y. J. Park, S. H. Park, K. S. Kim, S. B. Kim, H. K. Sung, Y. S. Baek, and K. R. Oh, "Wavelength-tuning of hybrid integrated multiwavelength lasers using a heater," IEEE Photonics Technol. Lett. 20, 422–424 (2008).
[6] Y. Shi, S. Li, X. Chen, L. Li, J. Li, T. Zhang, J. Zheng, Y. Zhang, S. Tang, L. Hou, J. H. Marsh, and B. Qiu, "High channel count and high precision channel spacing multi-wavelength laser array for future PICs," Sci. Rep. 4, 1–6 (2014).
[7] Y. Shi, S. Li, L. Li, R. Guo, T. Zhang, L. Rui, W. Li, L. Lu, T. Song, Y. Zhou, J. Li, and X. Chen, "Study of the multiwavelength DFB semiconductor laser array based on the reconstruction-equivalent-chirp technique," J. Light. Technol. 31, 3243–3250 (2013).