Experimental demonstration of distributed feedback semiconductor lasers based on reconstruction-equivalent-chirp technology

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Abstract: In this paper we report, to the best of our knowledge, the first experimental realization of distributed feedback (DFB) semiconductor lasers based on reconstruction-equivalent-chirp (REC) technology. Lasers with different lasing wavelengths are achieved simultaneously on one chip, which shows a potential for the REC technology in combination with the photonic integrated circuits (PIC) technology to be a possible method for monolithic integration, in that its fabrication is as powerful as electron beam technology and the cost and time-consuming are almost the same as standard holographic technology.

OCIS codes: (060.2330) Fiber optics communications; (140.3490) Lasers, distributed-feedback; (250.5300) Photonic integrated circuits.

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1. Introduction

Distributed feedback (DFB) semiconductor lasers are considered as reliable light sources for their dynamic single mode, compact size, integration capability, etc.[1-5]. Low cost DFB lasers with excellent performance, however, are still difficult to achieve, mainly because high-end DFB laser diodes with complex phase shifts and chirps cannot be cheaply fabricated. Up to now, electron-beam (e-beam) lithography is almost irreplaceable in DFB lasers to achieve exact phase shifts, complex chirps and different center Bragg wavelengths and simultaneously to realize both excellent lasing performance and good control of different lasing wavelengths. However, the high-cost and time-consuming nature of e-beam technology prevents it from being widely used in practical manufacture. On the other hand, although holographic exposure is extremely cheap for its simple setup, low operation cost and fast fabrication speed, it is not capable to produce complicated structure in traditional ways. Although some modifications have been made (e.g., changing the stripe width [6], using positive/negative photoresists [7], utilizing bent waveguide [8], etc.), it is still difficult to realize precise different lasing wavelengths, exact phase shifts and complex chirps. Recently proposed reconstruction-equivalent-chirp (REC) technology [9] requiring only conventional fabrication setup with sub-micrometer precision directly leads to the realization of high performance devices at very low cost, such as high-quality DFB fiber laser [10], record-long 1023-chip OCDMA en/decoder [11,12], special filters [9], optical arbitrary waveform generation [13], etc. Semiconductor laser is also numerically studied [14]. In this paper we report, to the best of our knowledge, the first experimental DFB semiconductor lasers with an equivalent quarter-wave (λ/4) phase shift. The device fabricated by conventional holographic method has a side mode suppression ratio (SMSR) of 45dB when operating in single continuous-wave (CW) mode at room temperature. The lasing is stable and the lasing wavelength varies slowly when the injection current changes. Furthermore, it is well known that multi-wavelength laser array is of great importance in wavelength-division-multiplexing (WDM) system, optical interconnection, high-speed signal processing, etc.[15]. In this experiment lasers with different lasing wavelengths are achieved simultaneously on one chip, which indicates that, combined with the photonic integrated circuits (PIC) technology, the REC technology might have a potential to make an effort for the large-scale integration and mass production to meet the ever increasing demand on optical network elements in the near future.

2. Principle and fabrication

The REC technology is demonstrated to realize various physically-realizable functions by a specially designed Sampled Bragg Grating (SBG). The principle of the REC technology can be indicated briefly in the following [10,16]: for a SBG with the index modulation of

$$\Delta n(z) = s(z)\exp\left(j\frac{2\pi z}{\Lambda} \right) + c.c \tag{1}$$

based on Fourier analysis, the SBG has multiple channels related to superimposed ghost gratings

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$$s(z)=\sum_m F_m \exp\left(j\frac{2m\pi z}{P}\right) \quad (2)$$

where Λ is the period of the grating, $s(z)$ is the sampling modulation as a periodic function, P is the sampling period and F_m is the Fourier coefficient of the m^{th} order channel of the SBG. When a sampling period increase ΔP is applied to $s(z)$ at z_0 (i.e., the SBG is sampled by $s(z-\Delta P)$ when $z>z_0$), the index modulation of the m^{th} order channel will be

$$\Delta n_m(z)=\begin{cases} F_m \exp\left(j\frac{2\pi z}{\Lambda}+j\frac{2m\pi z}{P}\right) & z\le z_0 \\ F_m \exp\left(j\frac{2\pi z}{\Lambda}+j\frac{2m\pi z}{P}-j\theta\right) & z>z_0 \end{cases} \quad (3)$$

in which the phase θ is obtained as

$$\theta = 2m\pi\frac{\Delta P}{P} \quad (4)$$

When $m\neq0$ and ΔP is changed smoothly, an equivalent chirp can be achieved. Correspondingly, when ΔP is changed discretely, an equivalent phase shift can be obtained. This is the core of the REC technology.

The device is fabricated by a conventional two-stage lower-pressure metal-organic vapor phase epitaxy (MOVPE). An InP buffer layer, a lower optical confinement layer, a multiple-quantum-well (MQW) active structure and an upper optical confinement layer are successively grown on an n-InP (100) substrate in the first epitaxial growth. The MQW structure contains five undoped 8nm-thick 0.7% compressive strain InGaAsP quantum wells. The sampled grating is then formed on the upper separate-confinement-heterostructure (SCH) layer by a conventional holographic exposure combined with conventional photolithography. Figure 1(a) is an illustration of the scanning electron microscope (SEM) morphology of the sampled grating with a quarter-wave equivalent phase shift. Figure 1(b) shows the SEM morphology of the uniform Bragg gratings in a sampling period. After the fabrication of the sampled grating, a p-InP cladding layer and a p^+-InGaAs contact layer are successively grown over the entire structure in the second epitaxial growth. Then a conventional ridge waveguide processing is performed. Ti-Au patterned p-contacts and AuGeNi n-contacts are formed on the p-side and the n-side, respectively. The total length of the device is 600μm.

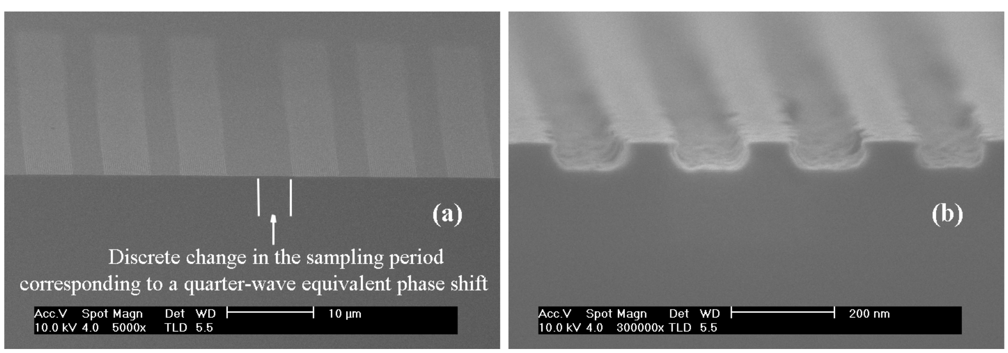

Fig. 1. Illustration of the SEM morphology of: (a) sampled grating with a quarter-wave equivalent phase shift; (b) uniform Bragg gratings in a sampling period.

3. Experiment and analysis

The laser is tested at room temperature under CW operation and the experimental results are shown in Figs. 2 to 6.

#106201 - $15.00 USD Received 12 Jan 2009; revised 12 Mar 2009; accepted 13 Mar 2009; published 18 Mar 2009

Figure 2 shows a typical spectrum of the fabricated lasers with a SMSR of about 45dB. The grating period is 243nm, leading to a center Bragg wavelength at around 1559nm. The sampling period is 19.65μm and then the 1st order Bragg wavelength is designed to be 1539.8nm. As shown in Fig. 2, the lasing wavelength is 1539.5nm at the injection current of 40mA, which fits well with the design.

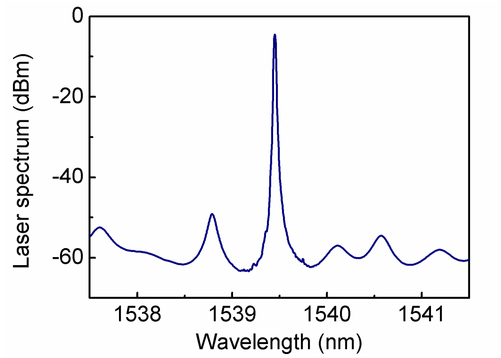

Fig. 2. Typical laser spectrum of the REC based DFB laser at the injection current of 40mA.

Figure 3(a) shows a typical light-current characteristic of the laser. The threshold current of the device is 28mA and the slope efficiency is about 0.15W/A. The typical output power is 5mW at the injection current of 60mA.

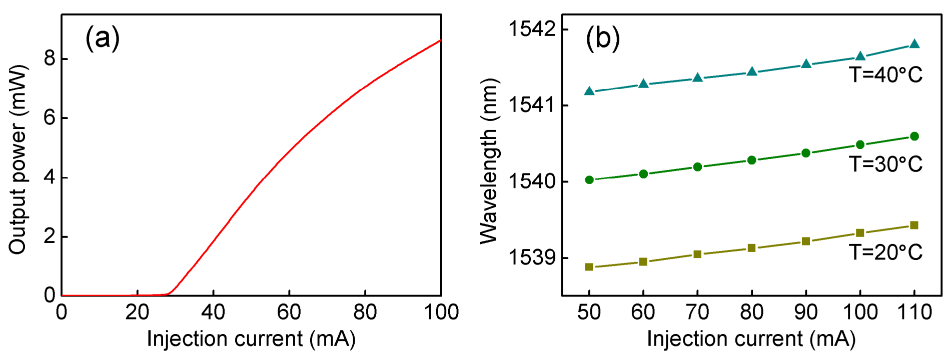

Fig. 3. (a). Light-current characteristic of the REC based DFB laser; (b) lasing wavelengths at different injection currents (above threshold) and temperatures.

Figure 3(b) shows the lasing wavelengths of the device under different injection currents and temperatures. It can be seen that the lasing wavelength will have a red-shift of ~8pm/mA with the increase of the injection current, which is much better than the conventional DFB lasers without equivalent phase shifts fabricated in our experiments (~30pm/mA). The wavelength shift with the injection current is mainly caused by the injection current induced refractive index change and can also be caused by the instability of the lasing mode (not the mode jumping). When the laser is operating below threshold, the carrier density increases as the injection current increases, and the effective refractive index decreases, leading the lasing wavelength to a blue-shift; when operating above threshold, the pn junction is heating continuously by the increasing injection current and the effective refractive index increases as the temperature goes up, leading to a red-shift [17]. Although a thermoelectric cooler (TEC) is used and the spatial hole-burning effect may increase the carrier density slightly, heating cannot be fully compensated, which still results in a small red-shift.

Because of the spatial hole-burning effect in quarter-wave shifted DFB lasers, the stable single longitude mode will eventually be destroyed as the injection current increases. Such phenomena have been predicted and studied theoretically by Whiteaway et al. [18].

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Figure 4 shows the laser spectra at different injection currents. Figure 4(a) is at the injection current of 27mA (below the threshold). It can be seen clearly that the lasing wavelength locates accurately in the center of the 1st order channel, which obviously indicates that a quarter-wave phase-shift occurs in the lasing mode. The lasing begins at the injection current of 28mA. At the injection currents of 60mA, 70mA and 80mA, the lasing wavelengths are 1539.7nm, 1539.8nm and 1540.0nm, with the SMSRs of 43dB, 42dB and 36dB, respectively. Side modes eventually occur when the injection current continues to increase. As shown in Fig. 4(b), two main modes are at 1540.3nm and 1539.5nm at the injection current of 100 mA. The wavelength shift rate of the main mode is 15pm/mA without a TEC, which is also better than conventional DFB lasers we fabricated.

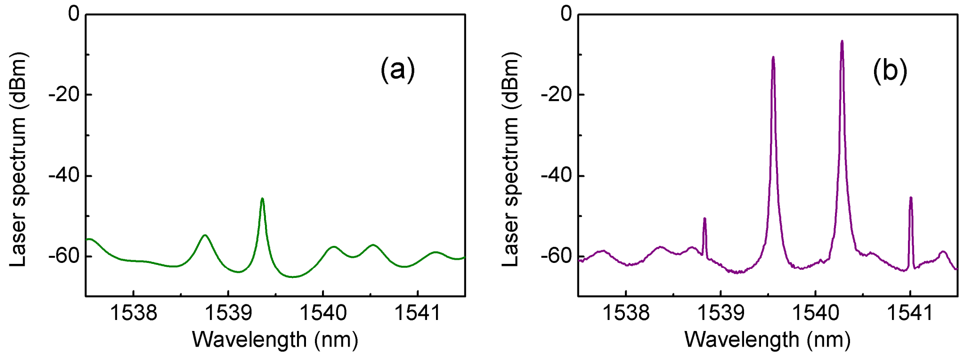

Fig. 4. Typical laser spectra at the injection currents of 27mA (a) and 100mA (b).

It is very important to measure the possible lasing at the center Bragg wavelength of the 0th order channel [14]. The gain of the 1st order mode is higher than that of the center Bragg mode because the material gain curve peak is at around 1537nm, which is very near of the 1st order channel but far from the 0th order channel. Furthermore, generally the quarter-wave phase shift will result in the lowest threshold, so the lasing at the center Bragg mode is difficult to occur. Figure 5(a) shows the lasing spectrum measured at the injection current of 70mA in a wide wavelength range. The center Bragg mode at about 1559nm is suppressed significantly by more than 50 dB compared to the 1st order mode. The lasing at the center Bragg mode occurs when the injection current is increased to 140mA, as Fig. 5(b) shows. In fact, such 0th order lasing mode can be completely diminished by decreasing the sampling period. Decrease of the sampling period results in an increase of the wavelength difference between the 1st order mode and the center Bragg mode.

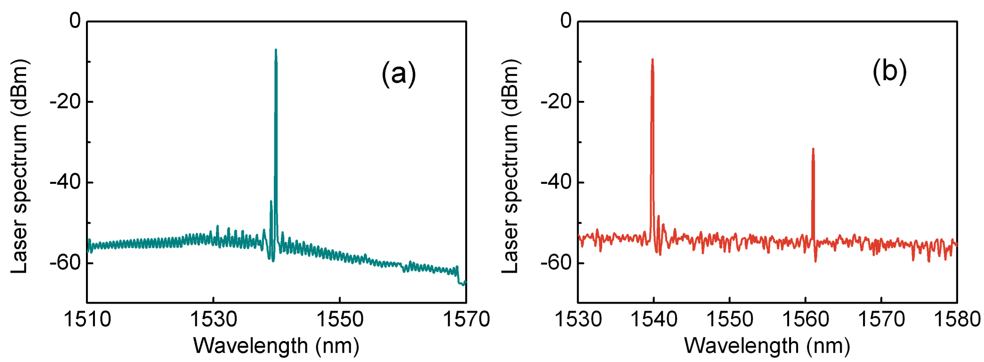

Fig. 5. Typical laser spectra of the REC based DFB laser in a wide wavelength range at the injection currents of 70mA (a) and 140mA (b).

In the fabrication of multi-wavelength laser array, two most important factors are the lasing performance and the wavelength control. On the one hand, the REC technology itself

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provides the laser with a quarter-wave phase shift to ensure a high performance. On the other hand, the REC technology inherits the characteristics of the sampling structures that, with the same grating period, the resonant channel can be varied simply by adjusting the sampling period and the duty cycle. For example, with a decreased sampling period, the 1st order Bragg wavelength decreases in terms of the Fourier theory. Therefore, in REC based lasers, some lasing performances and the lasing wavelengths can be controlled precisely and easily.

In this experiment, lasers with a different lasing wavelength are achieved on the same chip. In a different area of this chip, the sampling period is changed to 9.2 μm, leading to another 1st order Bragg wavelength at about 1518nm. As shown in Fig. 6, the lasing wavelength is 1517.4nm at the injection current of 20mA (around threshold), which also matches well with the design. Different lasing wavelengths controlled by careful adjustment of the sampling period make the REC technology possible to benefit the design and fabrication of the DFB lasers for PICs [15].

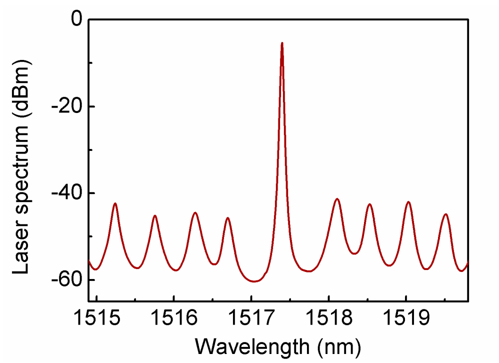

Fig. 6. REC based DFB semiconductor laser with a different wavelength in a different part of the same chip at the injection current of 20mA.

4. Conclusion

To our knowledge, this paper reports the first DFB semiconductor laser based on the REC technology, in which quarter-wave shifted DFB lasers are realized by conventional holographic process. REC based DFB lasers can have good performances such as stable single mode operation ability, a SMSR of 45dB under CW operation and room temperature, a steady lasing wavelength shift of 15pm/mA as the injection current changes, etc. Meanwhile, it is also demonstrated that, by a low-cost and high-speed manufacturing method, complex structures and different lasing wavelengths can be arbitrarily controlled and easily achieved simultaneously on one chip. All the aforementioned aspects may provide REC technology with the possibility to combine with PIC technology and contribute to industrial mass production of high-end DFB lasers and multi-wavelength laser arrays.

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