Semiconductor lasers for high-speed information technologies

(Invited Paper)

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This Review reviews semiconductor lasers with an emphasis on high-speed information technologies. Semiconductor lasers are classified based on their applications in optical communications. Different types of semiconductor lasers are discussed in terms of principle, history, advantages, and limitations.

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The concept of a laser was first proposed by Shawlow and Townes in 1958[1]. A few years later, Hall *et al.*, Nathan *et al.*, and Quist *et al.* claimed the first realization of semiconductor lasers[2–4] almost simultaneously. Semiconductor lasers are key elements in applications, such as laser printers, pumping light, optical sensors, optical storage, medical inspection, and optical communications. The rapid development of the Internet mainly benefits from the mature of high-speed semiconductor lasers. Today, semiconductor lasers are common light sources for high-speed data transmission in optical communications. They are regarded as “the laser of the future” due to their excellent properties, such as broad modulation bandwidth, compact size, power efficiency, easy integration with other devices, and long working life.

In this Review, the development of semiconductor lasers for optical communications and information technologies is reviewed. A possible category of semiconductor lasers is introduced based on their different applications in optical communication systems. Different types of semiconductor lasers are discussed in terms of working principle, development history, advantages, and limitations.

Figure 1 shows a possible category of semiconductor lasers for optical information technologies. They are classified by their applications in optical communications, including basic optical lasing source, digital and analog transmission, wavelength division multiplexing (WDM) system, and coherent fiber or space communications.

The basis of the semiconductor laser is lasing of light. The first semiconductor laser operated in pulse due to the homo-junction structures grown on GaAs substrates[5]. In 1970, the use of hetero-junctions led to the realization of the first continuous wave (CW) semiconductor laser, which was reported by Alferov *et al.* and Hayashi and Panish[6,7].

Figure 2 shows a typical static P-I curve for semiconductor lasers. The optical power is linearly proportional to the driving current when the current is beyond the threshold. For a large current condition, the laser power will be saturated. The linear working region is relatively limited, which is called the “small modulation condition”. This property makes a semiconductor laser a signal transmitter in optical communications.

Optical fiber communication was proposed in the mid-1960s by Kao and Hockham[8]. Multi-mode lasers, such as Fabry–Perot (FP) cavity lasers[9], can be used for data transmission in a multi-mode fiber. However, they suffer from high dispersion in an optical fiber, which makes it unsuitable for long haul transmission. To overcome the limitations induced by a poor and wide spectrum of FP lasers, the single mode laser is proposed. The introduction of Bragg grating increases the side mode suppression ratio and generates single longitudinal mode emission, which is the so-called distributed feedback (DFB) laser[10]. In 1973, Nakamura *et al.* reported the first GaAs DFB laser, which operated in a pulse[11]. Benefiting from a separate confinement hetero (SCH) structure, they fabricated a CW DFB laser at room temperature in 1975[12]. Figure 3 shows the schematic structures of FP and DFB lasers. Compared

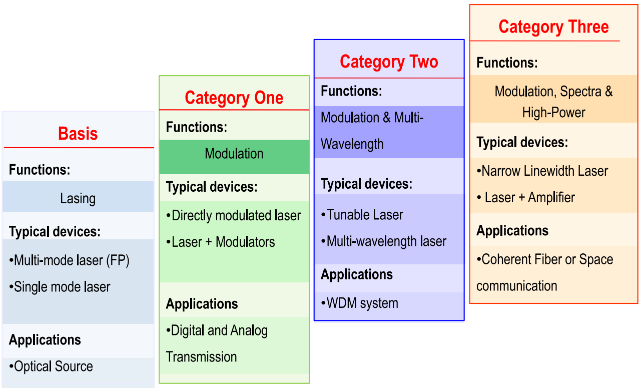


Fig. 1. Category of semiconductor lasers.

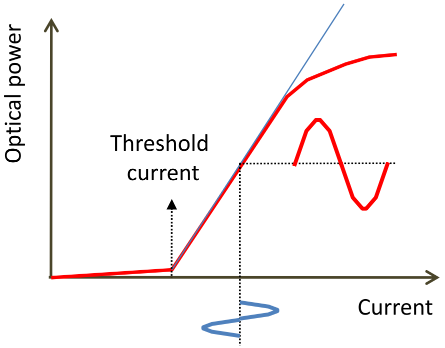
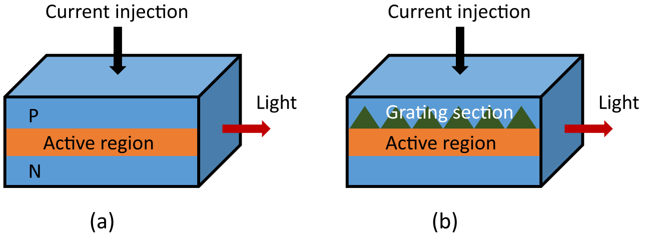


Fig. 2. Typical static *P-I* curve for semiconductor lasers.

with FP lasers, DFB lasers provide a narrow spectrum line, low chirp, and better mode selectivity. If the Bragg grating is set outside of the active region, it is called a distributed Bragg reflector (DBR) laser. In 1977, a GaAs/AlGaAs DBR laser operated at an 859.9 nm wavelength was reported by Kawanishi *et al.*[13]. One year later, they reported a long wavelength DBR laser at a wavelength of 1.243 μm. FP and single mode lasers fulfill the basic function of semiconductor lasers as an optical source.

The development of semiconductor lasers mainly spreads over three directions, i.e. high frequency response, high spectral quality, and high output power, which is illustrated in Fig. 4 as a three-dimensional (3D) coordinate. Following the basic lasing function of a semiconductor laser, the high-speed modulation of optical light is highly desired in optical fiber communications for digital and analog transmission, see the blue area in Fig. 4. Semiconductor lasers at a long wavelength attracted more attention after the prediction of low loss in silica fibers at 1.5 μm and the finding of zero dispersion at 1.3 μm[14,15]. A semiconductor laser at 1.5 μm and an optical fiber loss of 0.2 dB/km were demonstrated in 1979[16–20]. For optical transmission, a directly modulated laser (DML) is a very promising candidate. The DML can work in a single longitudinal mode under high-speed modulation and temperature or current changes[21]. The first DML at 1.5 μm was reported by Utaka *et al.* in 1981[22]. In 1984, Mazurczyk *et al.*[23] reported an optimized hetero-epitaxial ridge-overgrown (HRO) DFB laser and realized a fiber transmission of 203 km at a data rate of 420 Mb/s.



(a) (b)

Fig. 3. Schematic structures of (a) FP and (b) DFB lasers.

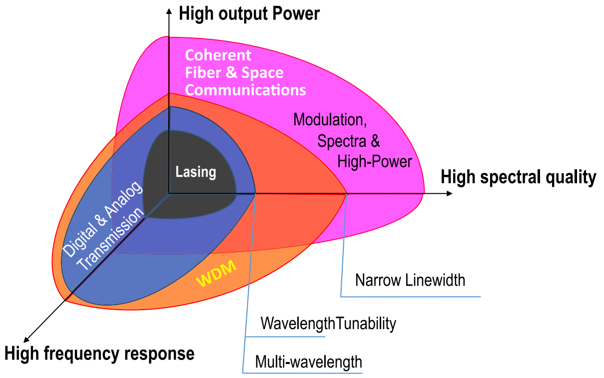
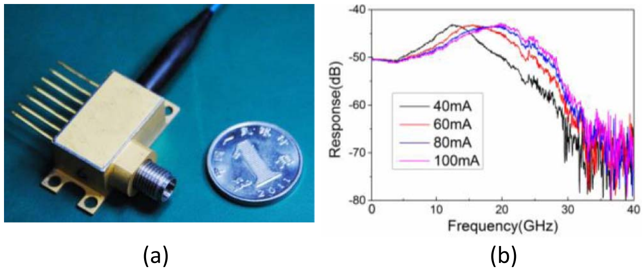


Fig. 4. 3D coordinate shows the relationship of different types of semiconductor lasers for different applications.

For optical transmissions, a commercial DML has to be well packed to achieve a stable operation. In 1994, Morton *et al.*[24] reported a fully packaged 1.55 μm DFB laser module. The modulation bandwidth is around 25 GHz, which is not degraded a lot compared to that of the unpackaged chip. In 2008, the commercial DML running at 40 Gb/s has achieved a transmission of 320 km[25]. With a butterfly package, we have demonstrated a 24 GHz DFB module in 2012[26]. By optimizing the package structure and the circuit at the high frequency region, we reported a DFB laser module with a 3 dB bandwidth of 30 GHz in 2015[27]. The packaged module and its frequency response at different driving currents are shown in Figs. 5(a) and 5(b), respectively.

The first vertical cavity surface emitting laser (VCSEL) was proposed by Iga in 1977[28]. Soon after, the first device was fabricated in 1979. Figure 6 shows a typical structure of the VCSEL using a GaAs/AlAs DBR and the selective-oxidation technique[29].The threshold of the VCSEL is only 1/10 or less than that of conventional lasers. The VCSEL benefits from a lot of advantages, such as high-speed single mode operation, high relaxation oscillation frequency, easy optical coupling, extremely low threshold current, and wideband wavelength tuning. In 2015, an 850 nm VCSEL reached a data rate as high as 71 Gb/s[30].

For a high-speed DML, the *P-I* curve is not the same for different driving frequencies. Figure 7 shows dynamic *P-I* curves for different modulation frequencies[31]. As can be seen, the *P-I* curve varies a lot for dynamic modulation frequency. It is very helpful for the investigation of



(a) (b)

Fig. 5. (a) Our DFB module and (b) its frequency response at a different driving current[27].

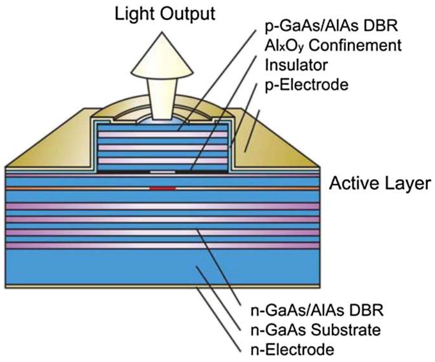


Fig. 6. Schematic structure of a typical VCSEL[29].

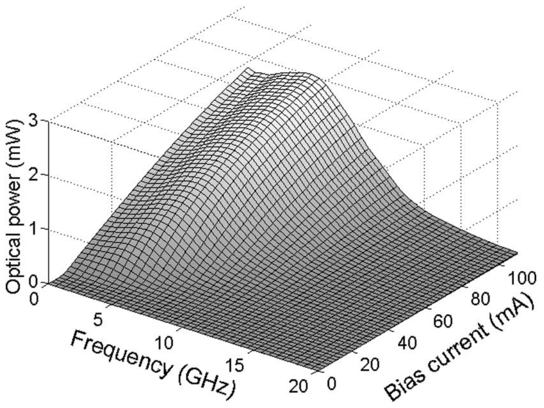


Fig. 7. Dynamic *P-I* curves for semiconductor lasers at a different modulation frequency.

high-speed lasers under small or large signal modulation conditions.

High-speed modulation of an optical signal can also be realized using the external modulation of an optical carrier using external modulators. Single mode lasers can monolithically integrate with an electro-absorption modulator (EAM) or a Mach–Zehnder modulator (MZM) to realize the simplest photonic integrated circuit (PIC). The EAM modulates an optical carrier by absorbing the signal from the laser, which is realized by changing the absorption edge of the EAM with a driving signal. In 1986, the monolithic integration of a DFB laser and an EAM was demonstrated by Kawamura[32]. The modulation bandwidth is 2.5 GHz. A DFB laser integrated with an EAM was reported in 1997[33] and 2008[34].

In 1996, the first integration of a DFB laser and an interferometric MZM was reported by Adams *et al.*[35]. A demonstration of a data rate at 10 Gb/s over 100 km was successfully achieved. The tunability of the transmitter was improved using an integrated sampled-grating DBR (SGDBR) and an MZM, achieving 3 dB bandwidth from 13 to 18 GHz[36].

The second category of semiconductor lasers is related to the WDM system. The modulation speed of light increases four times in five years in synchronous digital hierarchy (SDH) and around 10 times in three years in the Ethernet. The bandwidth of the semiconductor laser suffers from two factors, relaxation oscillation frequency and parasitic impedance, which are mainly determined by the laser material. Since the modulation speed is hard to be improved, the WDM system is proposed to overcome this bottleneck. Different wavelengths of optical signals transmit in a single fiber, where significant improvement of transmission capacity is realized. Wavelength tunable lasers and multi-wavelength laser arrays are perfect candidates for the WDM system.

The first report of a wavelength tunable laser was realized using the DBR structure[37]. A wavelength tuning range of 100 nm was demonstrated using super-structure-grating DBR and SGDBR lasers[38,39]. For the WDM application, a multi-wavelength laser array, which has tens of single mode lasers monolithically integrated in a single chip, is highly desirable. In 1992, Pratt *et al.*[40] reported a monolithically integrated four-channel laser array. A modulation rate of 2.5 Gb/s was achieved for a wavelength spacing of 4 nm. For a laser array based on tunable lasers, Ishii *et al.* demonstrated an integrated multi-wavelength array, which can cover 97 channels of a WDM system[41]. In 2014, a 100 Gb/s transmitter was realized by using a 10 × 10 Gb/s hybrid integration DFB laser array with an array waveguide grating (AWG)[42]. A photograph of the integrated device is shown in Fig. 8.

With a butterfly package, we have demonstrated an 8 × 12.5 Gb/s DFB laser array[43], as shown in Fig. 9(a). The channel spacing is 200 GHz. The 3 dB bandwidth for every channel is 10 GHz or beyond. Moreover, clearly open eye can be observed for each channel.

In a WDM system, an integrated laser and modulator array is also preferred, since it can achieve higher data rate for each channel. In 1999, Bell Laboratories reported the first integrated wavelength selected laser source, which has 1.55 μm DFB laser array, optical amplifier, and EAM[44]. A data rate of 2.5 Gb/s for each channel was achieved. In 2014, an 8 × 50 Gb/s EA-DFB laser array, as shown in Fig. 10(a), was demonstrated by Kanazawa *et al.* for a 400 Gb/s transceiver. Figure 10(b) shows the photograph of the packaged module[45].

For an integrated DFB and MZM array, Infinera reported a 10 × 40 Gb/s transmitter with return-to-zero differential quadrature phase-shift keying (RZ-DQPSK)

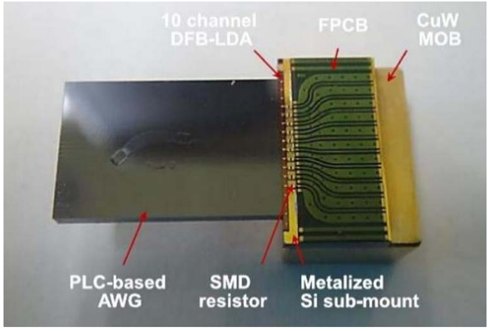


Fig. 8. Photograph of a 10 × 10 Gb/s hybrid integration module[42].

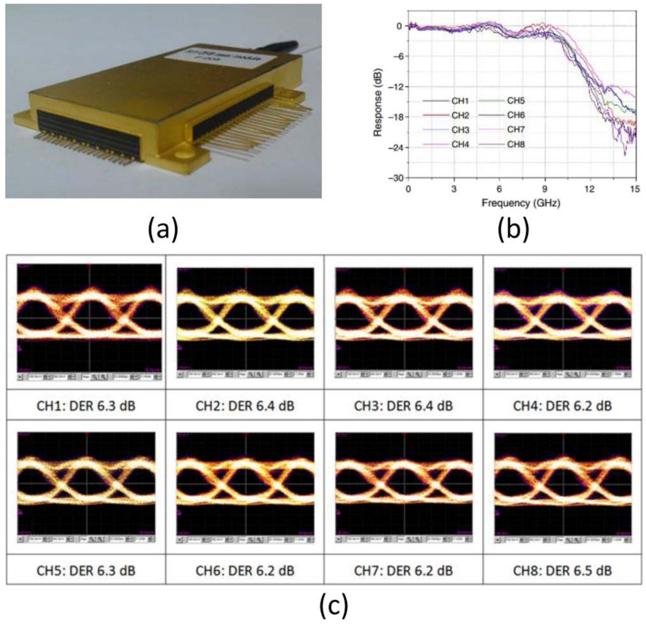


Fig. 9. Photograph of (a) a packaged 8 × 12.5 Gb/s transmitter module, (b) the small signal responses for each channel, and (c) the measured eye diagram for each channel[43].

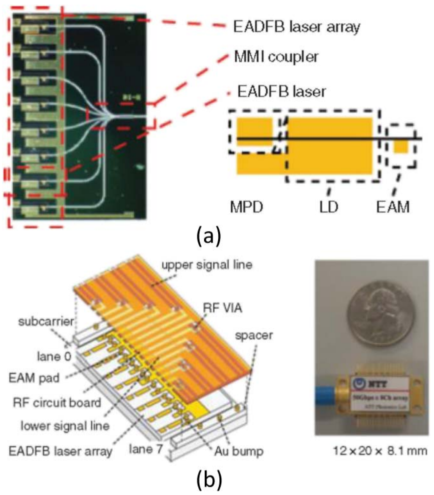


Fig. 10. Photographs of (a) the EADFB laser array and the structure of EADFB laser and (b) the 8 × 50 Gb/s module and the schematic structure of the interconnection module and photograph of Ref. [45].

modulation[46]. Saito *et al.* realized a tunable DFB laser array integrated with MZMs for a 44.6 Gb/s DQPSK transmitter in 2002[47], as shown in Fig. 11.

Narrow linewidth high power lasers are highly required in coherent optical communications. Coherent optical fiber communications were proposed in the 1980s. It benefits from the high sensitivity of the coherent receiver, which is capable of improving the unrepeated transmission distance[48]. However, coherent optical communications have cooled down since 1990, due to the high performance of the WDM system. In 2005, digital carrier-phase estimation in a coherent receiver makes a comeback in coherent optical communication because it enables us to use many spectrally efficient modulation formats. For a coherent optical fiber or space transmission, high power and narrow linewidth lasers are preferred, which are classified as the third category of semiconductor lasers. In this category, high power performance, as well as fine optical spectrum manipulating of the semiconductor lasers, is emphasized.

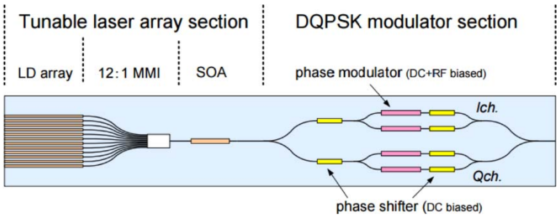


Fig. 11. Schematic diagram of the TLA-MZMs[47].

The linewidth of semiconductor lasers is mainly determined by two factors. One is caused by spontaneous emission coupled to the lasing mode[49], which contributes to the white frequency noise. The other one is called $1/f$ frequency noise, which is induced by the current and temperature noise or mechanical vibrations. Spontaneous emission determines the intrinsic linewidth. The full width at half-maximum (FWHM) linewidth is related to both factors.

Narrow linewidth semiconductor lasers have been reported based on FP, DFB, DBR, and external cavity lasers[50,51]. Actually, the linewidth of the semiconductor laser can be reduced by optimizing the laser length, as well as the optical confinement factor and coupling coefficient. Moreover, the linewidth of the laser can also be narrowed by simply increasing the driving current. In this way, the modulation bandwidth, as well as the output power, can be enhanced at the same time[52]. In 1992, the first high-speed and narrow linewidth semiconductor laser was reported by Blez *et al.* in a GaInAs/AlGaInAs platform[53].

By comprehensively considering the driving current, optical coupling, the cavity of the laser, and the package parameters, we reported a narrow linewidth and high-speed DFB laser with linewidth of 130 kHz and a 3 dB bandwidth of 30 GHz[27]. Figure 12(a) shows the lineshape of the delayed self-heterodyne signal, as well as the fitted Lorentz profile. The experiment setup used for linewidth measurement is shown in Fig. 12(b).

Although the linewidth of the semiconductor laser can be as narrow as tens of kilohertz, it still suffers from a wavelength stability problem due to the variation of cavity length under temperature change and mechanical vibration. We also made efforts to stabilize the wavelength of narrow linewidth laser. The narrow linewidth is realized by optical feedback. Figure 13(a) shows the configuration of the wavelength-stabilized narrow linewidth laser. The output of a DFB laser is split by a 10 dB optical coupler. The end face of the 10% part is coated with total reflection film to reduce the linewidth using external feedback. The wavelength of the DFB laser is stabilized

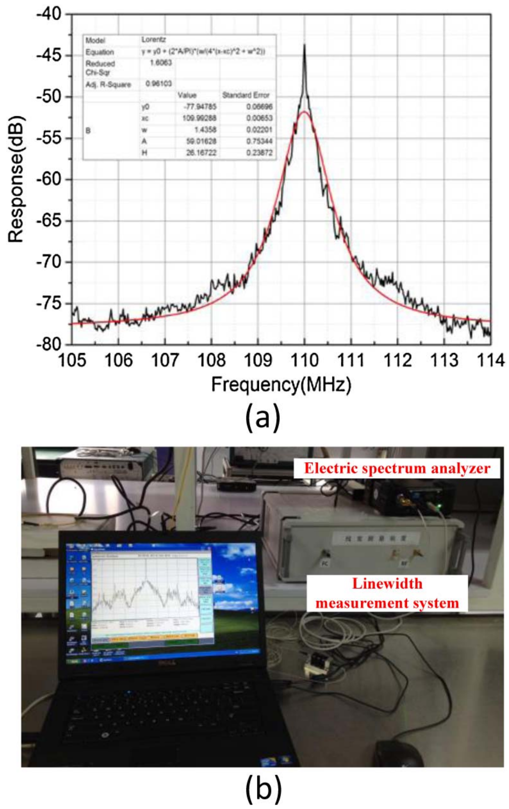


Fig. 12. (a) Lineshape of the delayed self-heterodyne signal at 70 mA[27], and (b) the linewidth measurement setup.

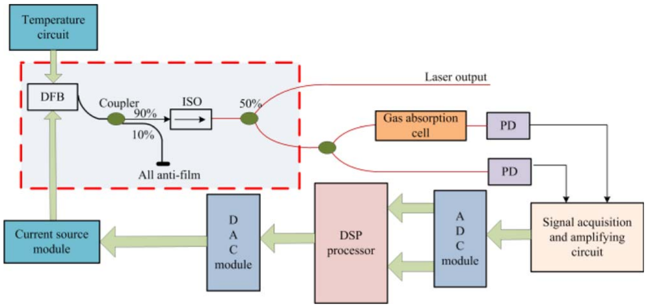


Fig. 13. Configuration of a wavelength-stabilized narrow linewidth semiconductor laser[54].

at the slope of the absorption line of $H_{13}C_{14}N$ using the sideband frequency stabilization method. With the help of a digital signal processor (DSP), a stable single mode operation of the laser with a linewidth of less than 100 kHz was obtained. The frequency shift is within 15 MHz in 24 h of measurement[54].

In conclusion, this Review presents a review of semiconductor lasers for optical communications. Depending on their applications, they are classified into different categories. Their working principle, development history, and future directions have been discussed. With the increase of data traffic in future optical networks, PIC devices will attract more and more attention due to their excellent performance, compact size, and low cost. Exciting progress on photonic devices will be continued.

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