# A 10 Gb/s 1.5 μm Widely Tunable Directly Modulated InGaAsP/InP DBR Laser *

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*We report 10 Gb/s data transmissions using a packaged two-section InGaAsP/InP distributed Bragg reflector (DBR) laser. The tunable DBR laser has a wavelength tuning range of 12.12 nm. The DBR laser has greater than 10.84 GHz 3-dB direct modulation bandwidth within the wavelength tuning range. The 10 Gb/s data transmissions are performed at up to a distance of 30-km.*

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In recent years, with the increasing demand for the capacity of the wireless network, the 5th generation of mobile networks (5 G) have been widely discussed and have begun to be deployed.[1–3] Fronthaul and backhaul in the 5 G network play an important role. Wavelength division multiplexed passive optical network (WDM-PON) is a promising solution for fronthaul in the 5 G network because WDM-PON has the advantages of low costs, high transmission capacity, easy maintenance and high capacity because multiple different wavelengths are transmitted at the same time. Tunable DBR lasers have many advantages such as simple tuning mechanism, compact size and low fabrication cost, which are considered to be promising low cost colorless light sources for WDM-PON systems.[4–6]

DBR lasers with InGaAlAs multiple quantum wells (MQWs) as active material and long bandgap wavelength DBR material have been reported.[7] Over 10 nm wavelength tuning range has been obtained and high quality 10 Gb/s data transmissions have been demonstrated.[8] Adoption of InGaAsP MQWs as active material simplifies the device fabrication when compared with InGaAlAs MQWs,[7] for which the butt-joint process for the DBR material has to be optimized carefully to reduce the effects of oxidization of the Al-containing material. Widely tunable directly modulated DBR lasers with InGaAsP MQWs have also been fabricated. However, only 5 Gb/s data modulations have been realized.[9]

In this Letter, we report a packaged 10 Gb/s 1.5 μm widely tunable directly modulated InGaAsP DBR laser fabricated by a butt-joint technique. The 10 Gb/s data transmissions are conducted successfully at up to 30 km in a standard single-mode fiber.

The DBR laser consists of two sections, which are a DBR section and a gain section. The active material is InGaAsP MQWs, which consist of 6 compressively strained InGaAsP wells and 7 tensilely strained InGaAsP barriers, whose photoluminescence (PL) wavelengths are 1540 nm and 1200 nm, respectively. The MQWs are sandwiched between two separate confinement heterostructure (SCH) InGaAsP layers. A bulk InGaAsP layer with 1450 nm bandgap wavelength is butt-jointed as the DBR material. After a grating was formed in the DBR section by holographic lithography, a p-type InP cladding layer and InGaAs contact layer are grown. A polyimide layer is formed under the p electrode pad to decrease the parasitic capacitance. The thickness of the polyimide layer and the size of the contact pad of the gain section are optimized to get an over 10 GHz modulation bandwidth. A 3-μm-wide ridge waveguide is formed by wet etching. The lengths of the gain and DBR sections were 300 and 150 μm, respectively. A detailed fabrication process can be found in our previous paper.[9–13]

The DBR lasers are pigtailed for further testing. A picture of the packaged device is shown in Fig. 1. Typical light-current characteristic of the packaged InGaAsP DBR laser at 10 ℃ is shown in Fig. 2. The threshold current of the device is 19 mA and the output power is 6.4 mW at 100 mA driving current when there is no current injected into the DBR section. At the same condition, the light power measured with a unpackages device is about 15 mW, indicating that the coupling coefficient between the chip and the fiber is

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about 42.7%.

**Fig. 1.** An optical image of the packaged laser.

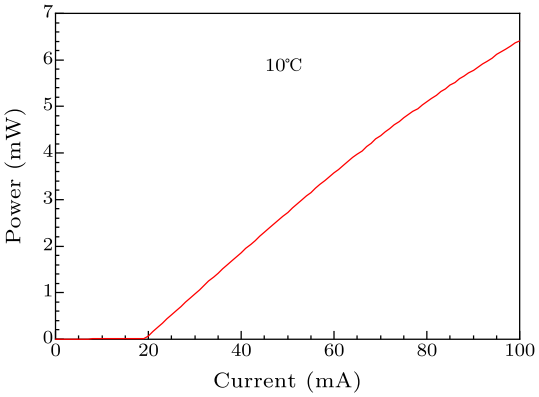


**Fig. 2.** The light-current characteristic of the packaged DBR lasers.

Figure 3 shows the emission wavelength and the corresponding side mode suppression ratio (SMSR) as a function of DBR section current. During the wavelength tuning of the laser, the current in the gain section is 80 mA. As can be seen, the lasing wavelength can be tuned from 1547.50 nm to 1535.38 nm as the DBR current increases from 0 to 100 mA, indicating a wavelength tuning range up to 12.12 nm, which is notably larger than the less than 10 nm tuning range of the DBR lasers fabricated by other techniques.[7] The large tuning range is a result of the DBR material with high refractive index. When current is injected in the DBR grating section of a DBR laser, the free carrier plasma effect and the Kramers–Kronig effect lead to a decrease of the effective refractive index of the material of the grating sections. Thus, the laser wavelength can be tuned to shorter wavelengths by current injection. For lasers having DBR material with a longer bandgap wavelength, the total amount of the variation of the effective refractive index, thus the wavelength tuning range of the DBR lasers induced by current injection is larger.[7] When the DBR current is larger than 100 mA, because the decrease of refractive index with current starts to saturate, the wavelength tuning range cannot be further increased. The thermal effect induced by current injection will even lead to a wavelength redshift.

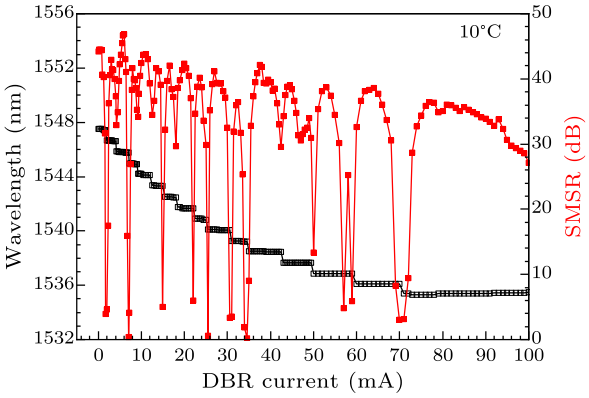


**Fig. 3.** Wavelength tuning properties of the laser at 10 °C.

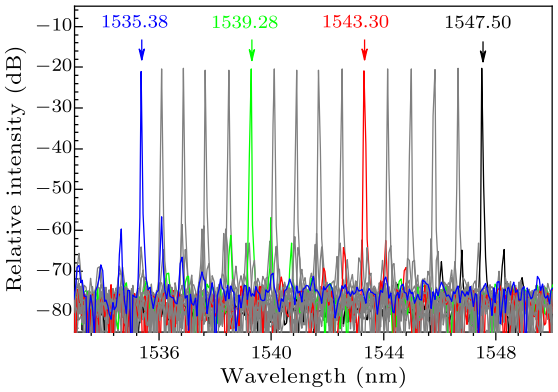


**Fig. 4.** Typical optical spectra obtained from the InGaAsP DBR lasers at 10 °C.

The SMSR is larger than 30 dB in the whole tuning range, except for the regions near the wavelength jumps. The typical optical spectra obtained from the InGaAsP laser are shown in Fig. 4, all having larger than 35 dB SMSRs. During the measurement, the resolution of the spectrum analyzer was set to be 0.01 nm.

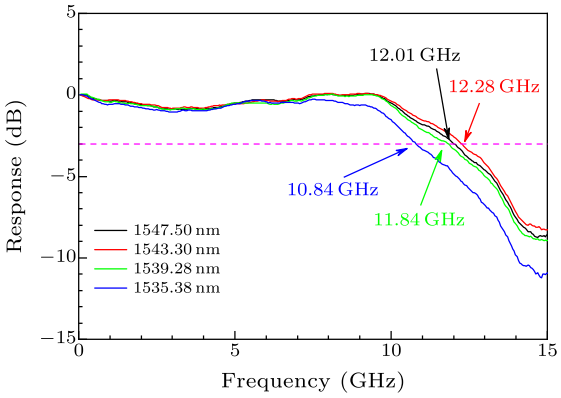


**Fig. 5.** S21 curve of the InGaAsP DBR laser at 10 °C.

A 50-GHz network analyzer is used to study the small-signal modulation properties of the device. The small signal direct modulation responses of the device at 4 different wavelengths marked in Fig. 4 are shown in Fig. 5. During the measurements, the gain current was fixed at 80 mA. The measured 3-

dB modulation bandwidths of the 4 wavelengths of 1547.50 nm, 1543.30 nm, 1539.28 nm and 1535.38 nm are 12.01 GHz, 12.28 GHz, 11.84 GHz and 10.84 GHz, respectively. The lower bandwidth at shorter wavelength can be attributed to the smaller light intensity in the laser cavity induced by free carrier absorption of light in the DBR section

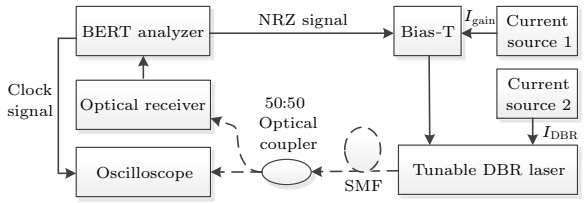


**Fig. 6.** Experimental setup used to measure the NRZ transmission characteristics of the tunable DBR laser.

Data transmission properties of the directly modulated device are characterized in standard single mode fibers. As shown in Fig. 6, the tunable DBR laser is modulated with non-return to zero (NRZ) pseudo random bit sequence (RPBS) signals. The signals having a word length of $2^{15}-1$ are generated from a bit error rate (BER) tester and are combined with DC driving current $I_{\rm gain}$ by a bias tee before being fed to the gain section of the laser.

The modulated light signals after fiber transmission are divided into two parts by an optical coupler. One part of the signals is converted into electrical signals, which are used to calculate BERs. The other part is fed into a sampling oscilloscope for eye diagram measurements. The BER tester also provides the oscilloscope a clock signal for synchronization. Under 10 Gb/s direct modulation, BERs are measured at different wavelengths and different transmission distances.

Figure 7 shows the 10-Gb/s eye diagrams measured from the tunable DBR laser in the cases of back-to-back (BTB), 10-km, 20-km and 30-km transmissions when the wavelengths are tuned at (a) 1547.50 nm, (b) 1543.30 nm, (c) 1539.28 nm, and (d) 1535.38 nm, respectively. The gain current and the peak-to-peak modulation voltage are set to be 80 mA and 1.2 V, respectively. As can be seen, the eyes are clearly opened for all the test conditions. The measured BERs as a function of received optical power at four different wavelengths and different transmission distances are shown in Fig. 8. For the 1543.30, 1539.28 and 1535.38 nm emissions to obtain $10^{-9}$ BERs the power penalties after 30 km transmissions are smaller than 2 dB when compared with the BtB conditions. For the 1547.5 nm wavelength, the corresponding power penalty is about 4 dB. As can be seen from Figs. 8(a) and 8(c), for some conditions the needed optical power is lower for longer transmission distance than that for shorter distance. This can be attributed to the different chirp parameters of the DBR laser under different working conditions.[14]

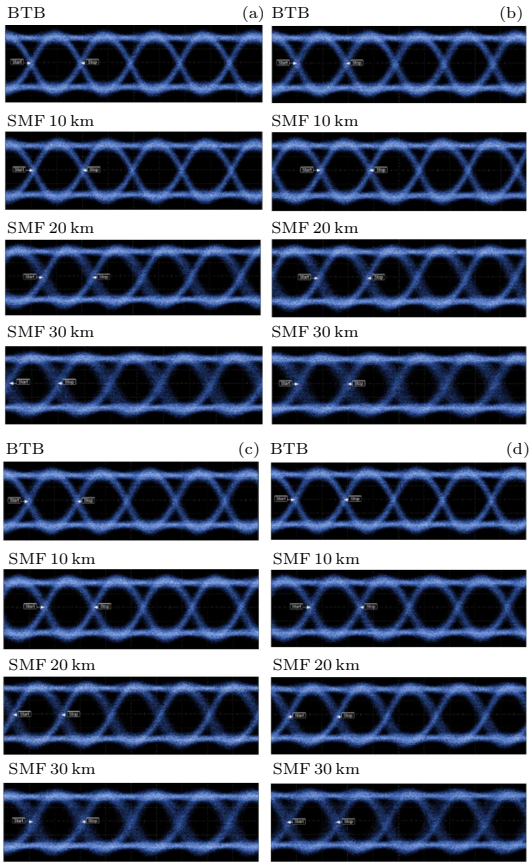


**Fig. 7.** The 10 Gb/s eye diagram for BTB, 10 km, 20 km and 30 km transmission when the tuned wavelength is (a) 1547.50 nm, (b) 1543.30 nm, (c) 1539.28 nm, and (d) 1535.38 nm.

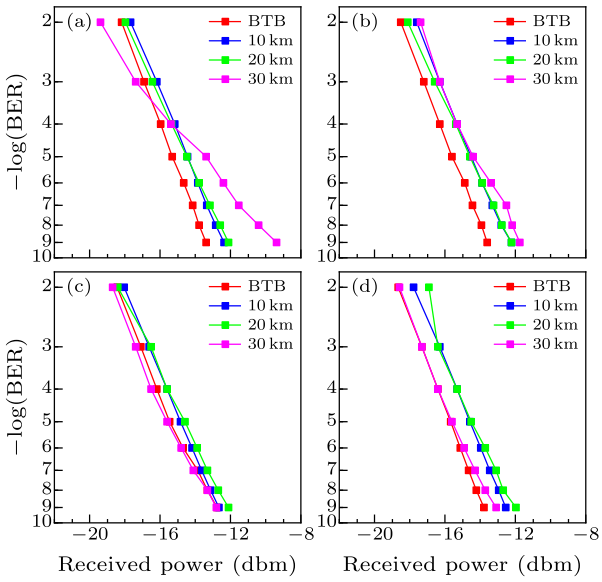


**Fig. 8.** BER performance of tunable DBR laser for BTB, 10 km, 20 km and 30 km transmission when the tuned wavelength is (a) 1547.50 nm, (b) 1543.30 nm, (c) 1539.28 nm, and (d) 1535.38 nm.

In summary, a two-section InGaAsP/InP DBR laser with a wavelength tuning range of 12.12 nm is fabricated. Transmission of 10 Gb/s over 30 km is

achieved. The presented data show that the direct modulated of DBR laser is a promising colorless light source for 5 G fronthaul WDM-PON systems.

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