An electrical-filtered optical heterodyne technique for tuning speed measurement of DBR lasers

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A new scheme based on the electrical-filtered optical heterodyne technique is proposed for measuring the tuning speed of tunable distributed Bragg reflector (DBR) lasers. In this scheme, a 10 GHz high-pass electrical filter is used and the wavelength switching time of a tunable DBR laser for different tuning frequencies corresponding exactly to different delay lines is measured. The switching time is measured to be nearly 300 ns and can be improved by reducing the equivalent resistance-capacitance (RC) time constant of the device. The distribution of the beat signal of the DBR laser in the time domain is also obtained, and is a good match with the waveforms measured using an optical filter.

DBR laser, electrical filter, square-wave tuning, tuning speed, wavelength switching

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The tunable distributed Bragg reflector (DBR) lasers, with the advantage of fast discrete and continuous tuning speeds on both the Bragg section and the phase section [1], have many applications in frequency-hopping communications, next-generation optical switch fabrics and packet-switched wavelength-division-multiplexed systems. In such systems, the fast wavelength tuning speed of the DBR laser is needed, which is an important parameter that determines the wavelength switching speed among different channels and the minimum guard time among adjacent packets as well as the transport efficiency of the system [2]. The wavelength tuning speed is greatly dependent on the thermal effect induced by the tuning current and can be effectively reduced by a low output-impedance driver. Designing the sampled grating mirrors with reduced peak spacing to limit the tuning current, or tuning DBR lasers using pulse signals with pre-emphasis, can also improve the tuning performance of DBR lasers [3, 4].

To date, many methods for the tuning speed measure-

ment of tunable DBR lasers have been proposed. A time-resolved spectrum technique based on a scanning Fabry-Pérot interferometer was successfully used in wavelength switching measurements on SG-DBR lasers [5, 6]. In [7, 8], an optical filter was needed to filter out the lightwave in a certain channel, and the optical filter was required to have a tunable central wavelength and good stability. In [9], the authors tracked the wavelength switching behavior of a tunable laser by analyzing the low-frequency beat signal in the time-frequency domain based on a self-heterodyne method. In [10], a fixed-wavelength reference lightwave was employed for time-resolved characteristic measurements of a SG-DBR laser for optical packet switched networks.

In this paper, a new scheme is proposed to measure the tuning speed of DBR lasers using an electrical filtered optical heterodyne technique. In this method, the wavelength switching time is measured under different tuning frequencies and the distribution of the beat signal of DBR lasers in the time domain is also obtained, compared with the waveforms measured using an optical filter.

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1 Analysis and experimental setup

The experimental setup for tuning speed measurement of the tunable DBR lasers is presented in Figure 1. In this scheme, a 1.55 μm four-section DBR laser is used which includes an active section, a phase section and two shorted Bragg sections. A low-frequency square-wave signal generated by an Agilent 33250 is applied to the phase section of the DBR laser. A 150 Ω resistor is inserted between the square-wave generator and DBR laser to limit the phase section current. Under square-wave tuning with period $2\tau_0$, injecting currents into the phase section change the refractive index, and therefore, the DBR laser will lase at λ_1 and λ_2 with the duration time τ_0 , corresponding to the high and low voltage levels V_L and V_H . Here, the electric field of the lightwave from the DBR laser is written as

$$E(t) = E_0 \exp[j(\int_0^t \omega(\tau) d\tau + \varphi(t))], \quad (1)$$

where E_0 is the amplitude of the electric field, $\omega(\tau)$ is the angular frequency of the lightwave and $\varphi(t)$ describes the laser phase noise. Under tuning by the square-wave signal, the angular frequency $\omega(\tau)$ of the light beam will be ω_1 and ω_2 alternatively, corresponding to wavelengths λ_1 and λ_2 .

$$\omega(\tau) = \left[\omega_1 \text{rect}\left(\frac{\tau - \tau_0/2}{\tau_0}\right) + \omega_2 \text{rect}\left(\frac{\tau - 3\tau_0/2}{\tau_0}\right) \right] \text{comb}\left(\frac{\tau - \tau_0}{2\tau_0}\right), \quad (2)$$

where the angular frequency of the lightwave can be expressed as the convolution of the sum of two rectangle functions and a comb function. In reality, the lasing wavelength will not switch instantaneously with the injecting currents and a transient time is required. The angular frequency $\omega(\tau)$ is modified as

Figure 1 Experimental setup for tuning speed measurement of the tunable DBR-lasers using an electrical filtered optical heterodyne technique. OSA: optical spectrum analyzer, PD: photodetector, A: microwave amplifier.

$$\omega(\tau) = \omega_2 \text{rect}\left(\frac{\tau - \tau_0/2}{\tau_0}\right) - \Delta\omega \cdot \text{rect}\left(\frac{\tau - \tau_0/2}{\tau_0}\right) \cdot \left[1 - \exp\left(-\frac{\tau}{\tau_1}\right) \right], \quad (3)$$

$$\Delta\omega = \omega_2 - \omega_1. \quad (4)$$

Here the transient time constant is assumed to be τ_1 and eq. (3) only gives the angular frequency in a half period for simplicity.

In the experiment, the output lightwave is coupled into a 10 dB coupler after being amplified by an Er-doped fiber amplifier (EDFA). One part of the lightwave from the 10% port is used for optical measurement by an optical spectrum analyzer (Advantest Q8384); the other part is launched into an asymmetric Mach-Zehnder interferometer with a delay fiber length corresponding to the delay time τ_0 for the optical heterodyne. Thus, the lightwaves with wavelengths λ_1 and λ_2 will arrive at the photodetector (HP 11982A) simultaneously. The total electric field of the lightwaves can be expressed as

$$E_{\text{total}} = E(t) + E(t + \tau_0). \quad (5)$$

Because of the matching of the delay fiber length and the half-period τ_0 of the square-wave signal, there is strict correspondence between rise time and fall time in the two channels of the M-Z interferometer which is shown in Figure 2, and the optical current i_{PD} generated in the photodetector is written as

$$i_{PD} \propto 2E_0^2 \cos \left[\Delta\omega t + 2\Delta\omega\tau_1 \exp\left(-\frac{t}{\tau_1}\right) - 2\Delta\omega\tau_1 + \varphi(t + \tau_0) - \varphi(t) \right]. \quad (6)$$

During the periods, except for the wavelength switching time, the output signals can beat to generate a microwave signal whose frequency is $\Delta\omega$ corresponding to the wavelength difference between λ_1 and λ_2 at the photodetector, and the noise, whose frequency is less than $\Delta\omega$, also exists with the duration of the switching time between λ_1 and λ_2 . After being amplified by an electrical amplifier, the beat signal, whose frequency equals $\Delta\omega$, can pass through, and the noise is filtered out by an electrical filter and the time-varying envelope of the beat signal can be detected by a microwave detector for waveform measurement by an oscilloscope (Rigol DS1204B). Thus, the intensity of the beat signal is not

Figure 2 Schematic representation of the Mach-Zehnder interferometer outputs, τ_0 : the delay time corresponding to the fiber delay, τ_1 : switching time.

continuous in the time-domain whose period is half that of the square-wave tuning signal and the intervals indicate the wavelength tuning of the DBR laser. Based on the electrical-filtered optical heterodyne technique, the process of wavelength switching has been transferred to the varying intensity detected by the oscilloscope.

2 Results and discussion

In the experiment, a tunable DBR laser fabricated in our laboratory was biased at 50.0 mA in its active section at a constant temperature 25°C, and the output power is 536 μ W measured at the pig-tail fiber. The voltage levels V_H and V_L which were applied on its phase section were fixed at 894 mV and 800 mV. Figure 3 shows the measured optical spectrum of the tunable DBR laser under square-wave tuning, the working wavelengths are 1534.440 nm and 1534.536 nm, corresponding to voltages V_H and V_L , with a 0.096 nm wavelength difference. A 10 GHz high-pass electrical filter was used to filter out the noise generated in the transient time with the high-pass filter transmission shown in Figure 4(c). Figure 4(a) and (b) show the power spectra

Figure 3 Measured optical spectrum of the tunable DBR laser under square-wave tuning.

Figure 4 Measured power spectra of the tunable DBR laser under square-wave tuning (a) without electrical filter and (b) with a 10 GHz high-pass filter; (c) measured transmission of a 10 GHz high-pass filter.

of the beat signal without and with the electrical filter, which were measured by an electrical spectrum analyzer (Advantest R3182). The noise whose frequency is less than 10 GHz was suppressed by nearly 20 dB and the beat signal can pass through the filter without any suppression.

Figure 5 shows the square-wave signals applied to the phase section of the DBR laser observed by the oscilloscope. The periods are 100.1300 μ s, 4.8294 μ s and 1.1521 μ s, corresponding to the fiber delay length 10.231 km, 493.5 m and 117.7 m which were exactly measured by a vector network analyzer (Agilent 8722ET). Figure 6 gives the measured waveforms of the beat signal with different-period square-wave signals applied to the phase section of the DBR laser which was observed in Figure 5. The periods of the beat signal were just half the square-wave periods. From Figure 6, one can see that the rise time and fall time are asymmetric which is caused by the asymmetry of the switching response time. This is because of the asymmetry of the optical frequency tuning deviation versus the tuning current [1]. It is also limited by the different RC constants of the tuned phase section of the DBR laser in the charging and discharging process. The measured tunable DBR laser took about 300 ns for the wavelength and optical power of the DBR laser to become steady in each tuning period. With the fiber delay becoming shorter and tuning frequency increasing, the switching time can be measured more precisely. From Figure 5, it can be seen that the rise time of the

Figure 5 Square-wave signal applied to the phase section of the DBR laser with different periods. (a) 100.1300 μ s; (b) 4.8294 μ s; (c) 1.1521 μ s.

Figure 6 The measured waveforms of the beat signal with different-period square-wave signal applied to the phase section of DBR laser. (a) 100.1300 μs ; (b) 4.8294 μs ; (c) 1.1521 μs .

square-wave signal applied to the phase section of the DBR laser is about 5 ns; however, the wavelength switching time of the DBR laser is much longer. That is because the wavelength switching time is mostly determined by the heat capacities and thermal resistances of the laser chip, the submount, the heatsink and the thermal contacts [11–13]. On the other hand, the output-impedance of the driver to the phase section strongly affects the wavelength switching time, and the use of a low output-impedance driver to the phase section may reduce the equivalent resistance-capacitance (RC) time constant effectively [2]. With higher current injections into the phase section of the DBR laser, a faster switching time can be achieved at the cost of the greater influence of thermal effects [11]. Using pre-emphasis at the beginning of the square-wave signal is also a significant way of improving the tuning speed [3].

To confirm the accuracy of the method proposed in Figure 1, another scheme using an optical filter proposed in [8] was carried out for the same tunable DBR laser under the same tuning period, with the experimental setup shown in Figure 7. In this method, a fiber Bragg grating (JDSU TB9) was used as an optical filter with a full width at half maximum (FWHM) 30 GHz bandwidth. The filter was adjusted to allow only the lightwave with wavelength λ_1 corresponding to the low voltage level V_L to pass through it while the

lightwave with wavelength λ_2 was filtered out. Therefore, the lightwave after the filter will be square-wave tuned. As shown in Figure 8, the waveforms measured by the oscilloscope with the method proposed in Figure 7 can be a good match with the former method.

Comparing the electrical-filtered optical heterodyne technique with other methods [5–10], the optical heterodyne technique has the advantages that the choice of the electrical filter is much more arbitrary and the stability of the electrical filter is superior. A tunable optical filter is not necessary and the problems of the instability of the optical filters can be avoided. The limit of the free spectral range of the Fabry-Pérot interferometer would not be encountered. Us-

Figure 7 Experimental setup for tuning speed measurement of the tunable DBR lasers using an optical filter. FBG: fiber Bragg grating, PD: photodetector.

Figure 8 Measured waveforms in the experimental setup in Figure 7, with different square-wave periods. (a) 100.1300 μs ; (b) 4.8294 μs ; (c) 1.1521 μs .

ing the asymmetric Mach-Zehnder interferometer can make the two-wavelength lightwaves arrive at the photodetector simultaneously and another external tunable laser as local oscillator is not required for synchronous detection, which would introduce extra disturbance [14].

3 Conclusions

We have proposed a new scheme for tuning speed measurement of the tunable DBR lasers using an electrical filtered optical heterodyne technique. Based on the new scheme, the process of the wavelength switching has been transferred to the varying intensity detected by the oscilloscope. In the measurement, a 10 GHz high-pass filter is used to filter out the noise of the beat signal whose frequency is less than 10 GHz. The wavelength switching time is measured at about 300 ns under different tuning periods corresponding exactly to different delay lines. The wavelength tuning speed can be improved by reducing the heat capacities and thermal resistances of the laser chip, the submount, the heatsink and the thermal contacts. The use of a low output-impedance driver to the phase section may also effectively reduce the equivalent resistance-capacitance (RC) time constant. In this method, a tunable optical filter or a reference lightwave as a local oscillator is not needed and the problem of the instability of the optical filter can be avoided. The choice of the electrical filter is more arbitrary and superior in terms of stability. The distribution of the beat signal of DBR lasers in the time domain is also obtained and is a useful method with a good match to that using an optical filter.

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