Influence of Mode Competition on the Fast Wavelength Switching of an SG-DBR Laser

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***Abstract*—Because the sampled grating distributed Bragg reflector (SG-DBR) laser is among the most attractive sources for wavelength division multiplexing (WDM) systems, it is important and necessary to investigate its wavelength switching characteristics. This behavior will set the capability limits for reallocation in wavelength-routed optical networks. In this paper, that mode competition plays an important role in the wavelength switching dynamics of DBR-type tunable lasers is confirmed experimentally. By using a time-resolved spectrum technique, the loss-dependent mode competition behavior has been directly observed, for the first time, from measurements of wavelength switching on an SG-DBR laser.**

***Index Terms*—Dense wavelength division multiplexing (DWDM), dynamic channel reallocation, sampled grating distributed Bragg reflector (DBR) lasers, tunable semiconductor lasers, wavelength division multiplexing (WDM), wavelength switching.**

I. Introduction

The realization of widely tunable laser transmitters for use in wavelength division multiplexing (WDM) transmission and switching is seen as an ever more important goal [1], [2]. This is due to the fact they can offer several opportunities to increase the capacity, the functionality, and the flexibility of WDM networks leading to potential architecture simplification and cost-effective exploitation of networks [3]–[5]. Recent results achieved with different newly developing network architectures and techniques have further demonstrated this point [6], [7].

An important issue related to widely tunable lasers, especially in the applications mentioned here, is their wavelength switching speed as it will affect wavelength routing design and the capability limits for wavelength channel reallocation. Therefore, it has attracted more attention and related results have been reported. For a sampled grating distributed Bragg reflector (SG-DBR) laser, switching time in the range of 4–8 ns over 12 nm by driving one grating current for an SG-DBR laser has been measured [5]. For a grating-assisted codirectional coupler with rear-sampled grating reflector (GCSR) laser, switching time smaller than 14 ns over 57 nm by only driving coupler current has been obtained [8]. By using heterojunction bipolar transistor (HBT)-based arrayed laser driver technology, switching time in less than 5 ns over 45 nm for a GCSR laser has been achieved [9], [13].

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For DBR-type tunable lasers, the speed of the wavelength switching is limited by the carrier lifetime in the grating sections and mainly depends on the carrier injection in those sections. Our new experimental results on a high-speed SG-DBR laser have shown that switching delay generally decreases with increasing the amplitude of the switching signal [10]. The higher and faster the carrier injection is, the faster the wavelength switching is. However, there is a deep physical mechanism interrelated with the wavelength switching behavior of such devices. This is the carrier injection in the passive sections that also affects mode losses of the device simultaneously. When the switching signal is applied to the laser, the emitted mode power will change quickly and, hence, result in mode competition.

In this paper, the mode competition that plays an important role in the wavelength switching dynamics of DBR-type tunable lasers was investigated experimentally. By using a time-resolved spectrum (TRS) technique, the loss-dependent mode competition behavior has been directly observed, for the first time, from measurements of wavelength switching on an SG-DBR laser. Although this effect was recognized by modeling and indirect experimental results for DBR lasers a few years ago [11], the absence of a sufficiently accurate and effective measurement technique had prevented its direct observation and recognition of its significance.

Another factor is that switching should occur between *stable* operating points derived from mode boundary maps [1]. Based on the static tuning characterization of the device, desired wavelength switching routes can be designed by setting different initial points with combinations of the two grating currents. For a fixed route, four switching types are achieved by applying different amplitudes of the switching signal to the back section. Measured results of the switching delay for these switches are presented. It shows that the switching delay generally decreases with increasing the amplitude of the switching signal for the given switching types. That mode competition is an important physical mechanism for this tendency is obtained by analysing a set of accurate measured and resolved results.

II. Static Characteristics

The four-section SG-DBR laser investigated here is designed for high speed, and its structure is described in Fig. 1. It has a 50-Ω resistor matched to the back section, which allows high-speed modulation on the back section current. Measurements can be performed where the wavelength of the laser is switched by applying a 150-ps rise-time signal to this section.

A map of the static tuning characteristics of this device is shown in Fig. 2, which shows output frequency versus the front and back grating section currents. It is fan shaped with two distinct sets of steps. Each step represents a significant alignment

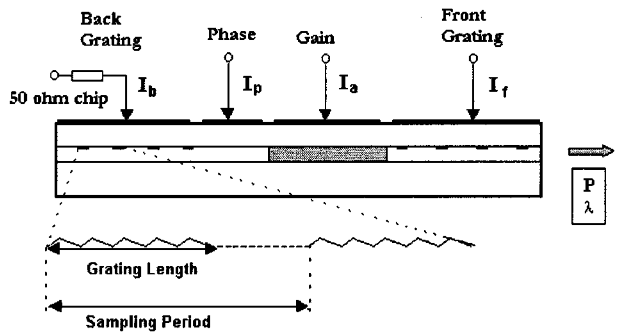

Fig. 1. Structure of the SG-DBR laser for high speed.

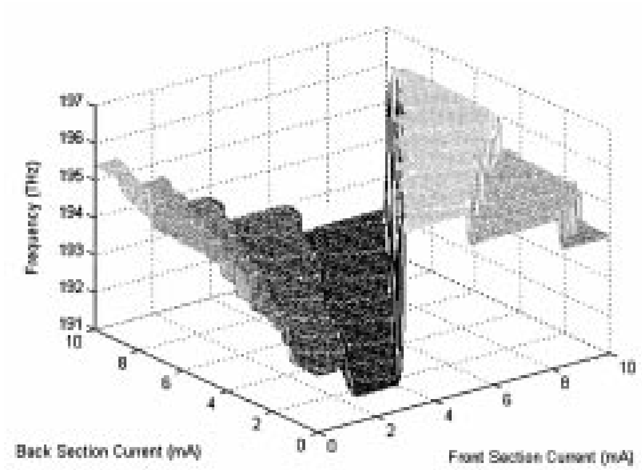

Fig. 2. Static tuning characterization for the device.

of the grating reflection peaks across the gain spectrum of the active section and so called a supermode. As shown in Fig. 2, changes in frequency can still be seen within each step region. Each smaller step is caused by shifting the comb-mode spectrum and so-called longitudinal mode. In this case, the supermode jumps and the longitudinal mode jumps are measured in the range of 4 to 8 nm (0.5 to 1.0 THz) and about 0.4 nm (50 GHz) respectively. Stable operating points are those far away from mode boundaries.

III. Dynamic Measurements

A time-resolved spectral (TRS) measurement technique based on the Fabry–Perot Interferometer (FPI) has been developed for studying the wavelength switching dynamics of lasers [10], [12]. The optical signal passes through a FPI and then to a fast detector to produce a time trace. The measurement is then obtained by combining time traces for different settings of the FPI center wavelength or frequency. The measurement system and reconstruction algorithm has been described in detail elsewhere [14]. The bandwidth of the fast detector and the sampling heads of the high-speed digital sampling oscilloscope are 20 and 25 GHz, respectively. The free spectral range (FSR) of FPI is set at 280 GHz for the following measurements. The bandwidth of the measurement system, in effect, is limited by the bandwidth of FPI, which is about 12 GHz [12].

The laser under test is mounted on a temperature-stabilized heat sink and biased by low-noise sources with an active section current of 90 mA. Desired switching routes can be designed by setting different initial bias points. For example, one switching route with the initial bias point at a front section current of 0.8 mA and a back section current of 4.3 mA is shown in Fig. 3. As can be seen from this figure, for the fixed bias point, various wavelength switching or mode switching can be achieved by applying different amplitudes ΔI_b of the square-wave switching signal to the back grating section. Here, the frequency of the switching signal is 40 MHz, which means the switching signal current stays low level for 25 ns and high level for another 25 ns. This pulse duration must be highly stable and transient occurs in 150 ps.

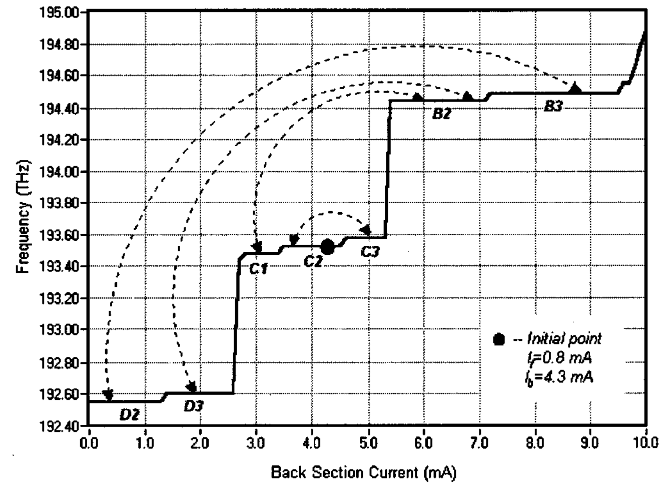

Fig. 3. Wavelength switching routing with the initial bias point at a front section current of 0.8 mA and a back section current of 4.3 mA.

As shown in Fig. 3, A, B, C, and D are used to denote different supermodes, and 1, 2, and 3 are used to denote different longitudinal or cavity modes. Dashed lines with arrows indicate available switching types in the experiment.

The switching delay is used here to evaluate switching speed, which can be defined as the delay between the time when the switching current applies and the time when the destination mode becomes dominant. In practice, the switching delay is taken as

$$T_{\mathrm{SD}}(F) = T_{o1} - T_{T1} - t_{d0} \tag{1}$$

and

$$T_{\mathrm{SD}}(B) = T_{o2} - T_{T2} - t_{d0} \tag{2}$$

where $T_{\mathrm{SD}}(F)$ represents the *forward switching delay* (corresponding the increase of the current) and $T_{\mathrm{SD}}(B)$ represents the *backward switching delay* (corresponding the decrease of the current). T_{T1} and T_{T2} are the times of the rising and falling edge of the switching signal, respectively. T_{o1} and T_{o2} are the instants when the power level of destination mode surpasses that of the earlier lasing mode. The term t_{d0} stands for a physically fixed path delay caused by the difference in the transmission time between the optical and electrical channel. It should be calibrated before measurements and the accuracy of the calibration should be higher than 0.1 ns.

The measured results of the wavelength switching delay based on the switching route as shown in Fig. 3 are summarized in Fig. 4. There are four sets of data in each graph, corresponding to four different types of mode switching shown in Fig. 3, i.e.,*C2* to *C3*, *C1* to *B2*, *D3* to *B2*, and *D2* to *B3*.

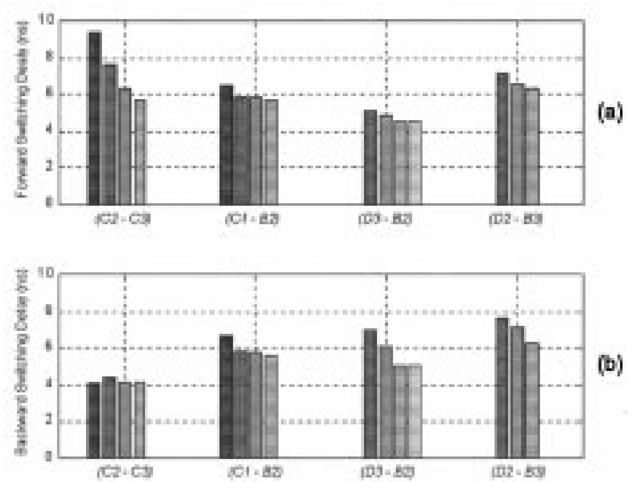

Fig. 4. Experimental results of switching delay. (a) Forward switching. (b) Backward switching (lighter bar for larger increment).

TABLE I
AMPLITUDES OF SWITCHING SIGNAL

Switching Type	Switching Signal ΔI_b (mA)			
	I	II	III	IV
C2-C3	0.8	1.0	1.3	1.6
C1-B2	2.1	2.4	2.6	2.7
D3-B2	3.4	3.8	4.8	5.1
D2-B3	6.1	6.4	6.8	

Fig. 4(a) indicates the forward switching, i.e., mode *C2* to *C3*, and Fig. 4(b) indicates the backward switching, i.e., mode *C3* to *C2*.

In each set, the gray bars decrease as the amplitude of the square-wave switching signal increases, i.e., ΔI_b. In other words, we increase the increment while remaining within the same start and destination mode. The amplitudes of the switching signal for the above switches are listed in Table I, where current values in column I correspond the cases of the darkest bar in each set shown in Fig. 4.

It is clearly seen, in Fig. 4, that the switching delay varies from 4 to 10 ns for the four switching types, either in the case of forward switching or backward switching. Sometimes, the forward-switching delay is longer than the backward-switching delay and sometimes the reverse; it depends on the relative positions of switching points in each selected mode.

From Fig. 4, we can observe that the switching delay generally decreases with increasing the amplitude of the square-wave switching signal. This feature is attributed to the mode competition behavior of the device during the switching transient. The following section uses our detailed experimental and resolved results to assist in this physical interpretation.

IV. Mode Competition Behavior

The influence of mode competition on the speed of the wavelength switching for DBR lasers was first recognized by Zhang *et al.* [11]. Unfortunately, little attention has been paid to this influence. This is because mode competition was believed to be only related to the active section. In fact, the wavelength switching caused by the carrier injection in tuning section also affects the mode losses of the device, so that the mode power changes during the wavelength switching. Moreover, the condition of single-mode lasing might be broken and mode competition will occur.

Our experimental results confirmed that the mode competition plays an important role in the wavelength switching dynamics. For the first time, the loss-dependent mode competition behavior has been directly observed from the measured results obtained by the TRS technique.

Fig. 5 presents a set of measurements under the switching between modes *D3* and *B2*. The laser initially lases at mode *D3*. When the switching event occurs, it rests at modes *C1*, *C2*, and *C3* for a short time and then switches to mode *B2*. The opposite is also true for the backward switching. This switch crosses two successive supermodes and the frequency jump is about 1.84 THz. Here, the frequency is simply represented by the FPI settings. Although switching modes might exist in the adjacent free spectral range of the FPI, the frequency of each mode can be reidentified with the aid of the time-average spectrum from an optical spectrum analyzer.

As shown in Fig. 4, four switches are present in the switching types, i.e., $D3 \Leftrightarrow B2$, but with different amplitudes of switching signal. As the amplitude of switching signal increases from 3.4 to 5.1 mA, it is obvious that there are differences in switching transient between these measurements, especially in the backward switching. The transient modes, i.e., *C1*, *C2*, and *C3*, degrade with increasing the amplitude of switching signal. Obviously, this change results in shortening durations of the switching transient, either in the forward switching or in the backward switching.

The mode competition behavior can be further seen clearly in Fig. 6, which is resolved from the original measurements shown in Fig. 5 and presented in the plots of mode power versus time during switching. As shown in Fig. 6, the mode competition during switching is rather stronger in Fig. 6(a) and it becomes weaker and weaker from Fig. 6(a) to Fig. 6(d). As the amplitude of the switching signal increases, the duration and the strength of three transient modes decrease gradually, especially for mode *C1*. This can be explained as follows. With the lower carrier injection in the back section, multimodes compete to lase during the switching transient, as the mode losses of these modes become very close. With the higher carrier injection in the back section, the mode loss of the destination mode quickly becomes the lowest one and, hence, it prevents the other transient modes from lasing.

In Fig. 6, the forward switching delay decreases from 5.1 to 4.5 ns while the backward switching delay decreases from 7.0 to 5.1 ns (see the four bars of the switch $D3 \Leftrightarrow B2$ in Fig. 4). It is possible to observe that the results of the switching delays are nearly the same for Fig. 6(c) and (d). The reason is that the mode competition during the transient has been greatly suppressed when the carrier injection exceeded the level in the case of Fig. 6(c). In addition, the power level of two switching modes is slightly lower in case Fig. 6(d). This is due to the fact that another two modes, i.e., *D2* and *B3*, tend to join the switching. Therefore, it implies that optimizing switching points for the desired switch is necessary in practice.

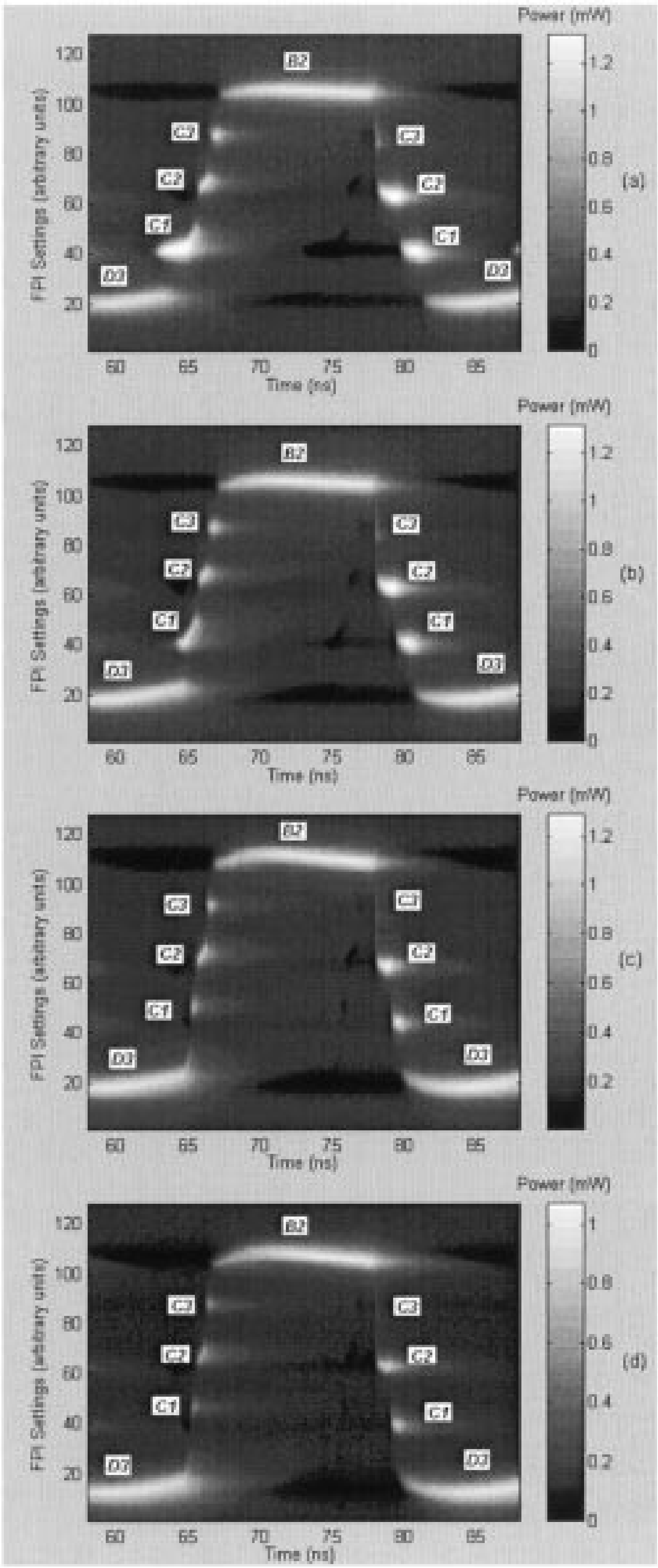

Fig. 5. Measurements obtained by the TRS technique for different amplitudes of the switching signal within the switching type $-D3 \Leftrightarrow B2$: (a) 3.4 mA, (b) 3.8 mA, (c) 4.8 mA, and (d) 5.1 mA. The presence of the C modes decreases with ΔI_b.

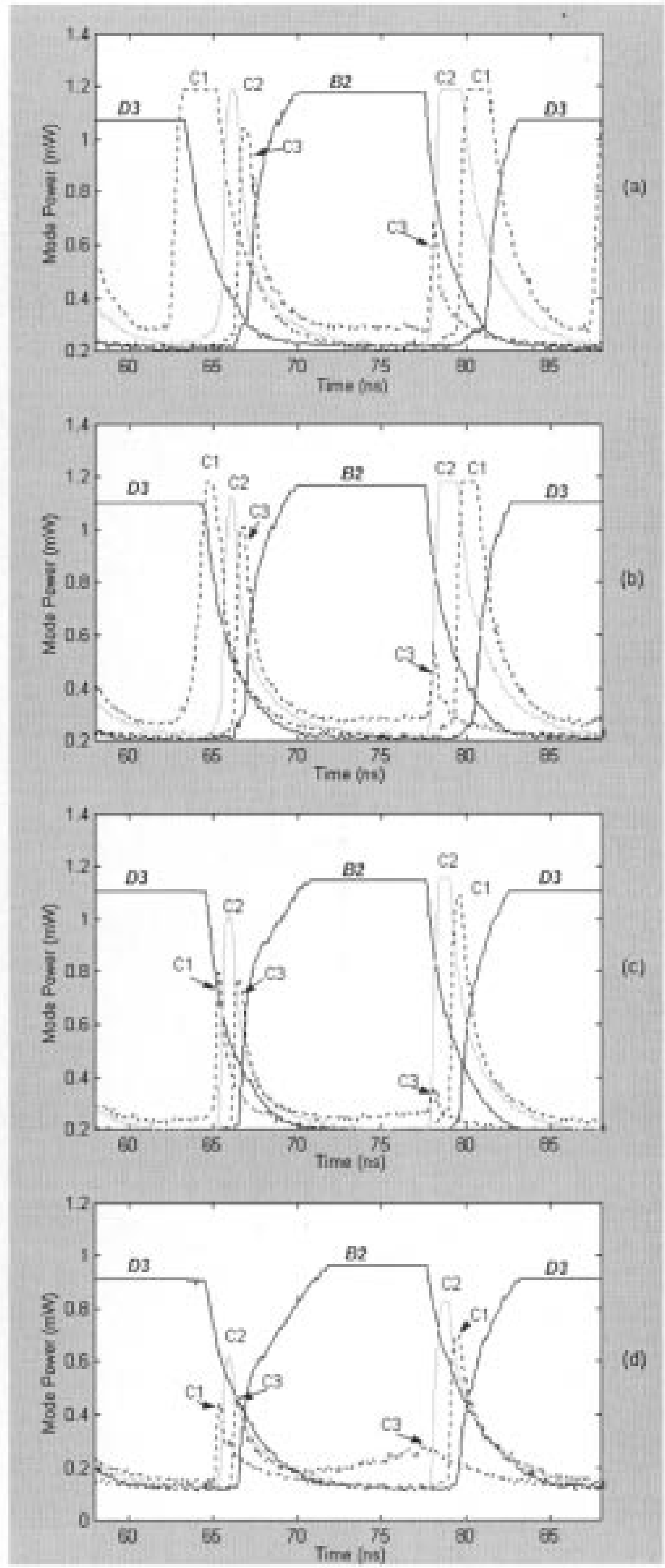

Fig. 6. Resolved results showing dependence of transient mode duration and switching speed on switching signal for the four cases shown in Fig. 5: (a) 3.4 mA, (b) 3.8 mA, (c) 4.8 mA, and (d) 5.1 mA.

In Fig. 6, it is also possible to observe the rising and falling time of mode *B2* increase with switching signal. This is related to the laser feature itself. The output power level of the SG-DBR laser varies not only in the whole tuning region, but also in each mode area. As the switching signal increases, the switching point falling in the area of mode *B2* moves toward the edge closest to mode *B3* (see Fig. 3). This results in the changes of the emitted power of mode *B2* and, hence, its rise and fall times. In view of these facts, therefore, it is advisable to combine other important criteria, such as the switching time or the turn-on and the turn-off timse with the switching delay, to evaluate the overall switching speed of the device for the system application [8].

The influence of *thermal effects* is not applicable here. This is because the injected current in the measurements discussed here is smaller than 10 mA, and the thermal effect is a relative slow response (a few microseconds) compared to the event of the wavelength switching (40 MHz). It should be noted that the power ratios of the main modes and the side modes shown in Fig. 6 are smaller than their real value. This is due to the fact that the leakage effect of the FPI raises or reduces the real power level of transmitted light at each wavelength. It is expected to improve the resolved algorithm to reduce this error as far as possible in order to acquire the true dynamic side-mode suppression ratio.

In addition, hysteresis effects in the laser might be another factor that will affect the switching dynamics as well. Hysteresis manifests itself in the laser by having memory of the last injected current [4]. Although some experimental results (not shown in this paper) indicate possible influence of light hysisteresis effects in the laser tested, it is still needed to further investigate to obtain explicit analysis. The reason is that the injected current state in dynamic switching is rather complicated.

V. Conclusion

The wavelength switching dynamics of the SG-DBR laser have been investigated experimentally. For the first time, the mode competition behavior under switching has been directly observed from the measured results obtained by the TRS technique.

Our experimental and further resolved results confirmed that the mode competition plays an important role in the wavelength switching dynamics of SG-DBR-type tunable lasers. This behavior will not only affect the switching speed but also might cause cross-talk during channel switching. For this reason, optimizations of the dynamic behavior of such devices for the switching applications are necessary in practice.

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