A Fast 100-Channel Wavelength-Tunable Transmitter for Optical Packet Switching

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***Abstract*—This letter demonstrates a fast wavelength-tunable transmitter, based on a widely tunable grating-assisted co-directional coupler with sampled grating reflector laser diode for optical packet switching application. A high-speed control driver board was built to facilitate the fast wavelength channel selection and control. It supported 100 wavelength channels spaced by 0.4 nm with a side-mode suppression ratio $>$ 30 dB. Wavelength channel switching was measured to be within 100 ns.**

***Index Terms*—Optical packet switching, tunable lasers.**

I. Introduction

SEMICONDUCTOR tunable lasers have recently attracted much attention in the optical fiber communications area as they have found many practical applications in the next generation wavelength-division-multiplexing (WDM) systems. Recently, semiconductor tunable laser diodes with a wide wavelength tuning range have become commercially available. They exhibit about 40–60 nm wavelength tuning range, $>$ 30 dB sidemode suppression ratio and $>$0 dB peak output power. Typical examples are grating-assisted co-directional coupler with sampled grating reflector (GCSR) lasers [1], [2] and super structure grating distributed Bragg reflector (SSG-DBR) lasers [3]. One important feature of these lasers is that they can switch from one wavelength to another at a very fast speed, which is measured in nanoseconds. This makes them a potential candidate for building fast optical switches, which can route traffic on a packet-by-packet basis. In [4], a laser driver board for an SSG-DBR laser with 20-nm tuning range and 500-ns wavelength switching time was demonstrated. In [5], a rapid tunable transmitter based on a GCSR laser with less than 5-ns channel switching time was reported. However, they altered the currents to only two tuning sections (coupler and reflector), while applying constant current to the phase section, due to the fact that switching the current to the phase section will largely increase the channel switching time. As the phase section is primarily designed for fine-tuning of the output wavelength, their approach can hardly achieve high accuracy in wavelength tuning, though it can help to shorten the channel switching time. In this letter, we present our work of building a fast and precise 100-channel (0.4-nm spaced) wavelength-tunable transmitter based on a GCSR laser diode with a wavelength channel switching time less than 100 ns and wavelength accuracy better than $\pm$0.005 nm. All the necessary control electronics and the laser diode are integrated on one single module.

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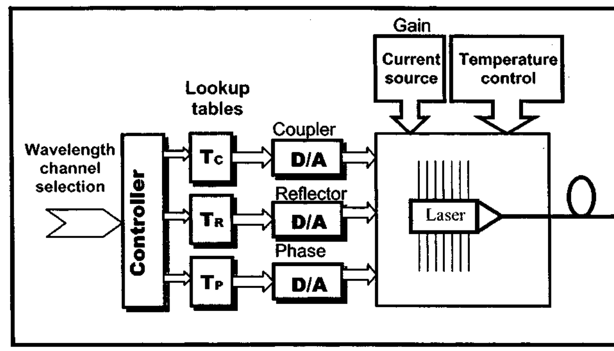

Fig. 1. Schematic diagram of the high-speed driver board for the GCSR laser.

II. Fast Wavelength-Tunable Transmitter

A GCSR laser consists of one gain section and three current tuning sections, namely *coupler, reflector,* and *phase*. A constant current, which is well above the lasing threshold, is injected through the gain section to pump the active region. Wavelength tuning is achieved by injecting current into each tuning section to vary the refractive index of the laser cavity. Based on a GCSR laser diode, we have built a fast wavelength-tunable transmitter, which offered 100 (0.4–nm spaced) accessible wavelength channels. The GCSR laser had a wavelength tuning range of 44 nm (1523.77–1567.77 nm). In order to control the four laser sections and facilitate the wavelength channel selection, we constructed a high-speed driver board with the schematic shown in Fig. 1. A temperature control circuit was implemented to stabilize the laser temperature at 25 °C, while a current source circuit was used to inject a constant current (97 mA) to the gain section of the laser. High-speed programmable logic devices (PLDs) were used as look up tables to store the digital current settings of different tuning sections in order to access all the wavelength channels. These digital current settings were converted into analog current by 10-bit high-speed digital-to-analog converters (DACs). The settling time of the DAC was 35 ns and the maximum output current was 20 mA. With 10-b resolution, step change in the current value of 0.02 mA was achieved. The driver board accepts wavelength switching instruction at the front end of the driver board and the electronics will drive the laser to switch its output wavelength.

We have found out the current settings of all three tuning sections to access 100 wavelength channels (1528.17–1567.77 nm) with a spacing of 0.4 nm. This was done by changing the three

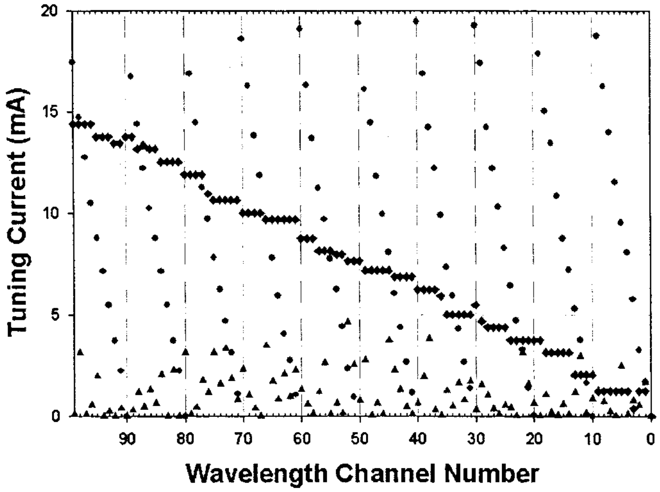

Fig. 2. Tuning currents to (♦) coupler section; (●) reflector section; (▲) phase section; for all 100- wavelength channels.

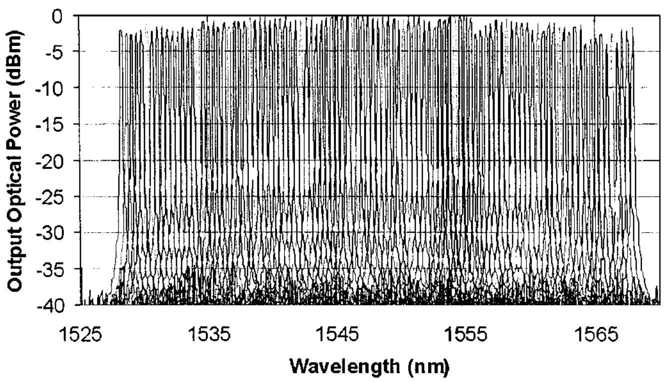

Fig. 3. Superimposed optical spectra of 100 wavelength channels with 0.4-nm spacing (resolution bandwidth: 0.2 nm)

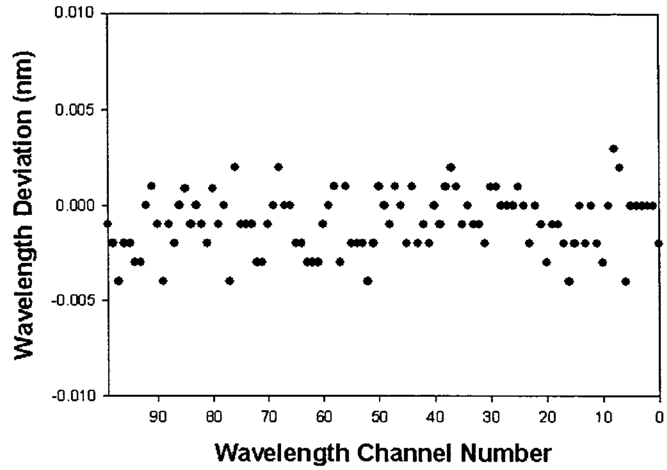

Fig. 4. Measured wavelength deviation of all output channels.

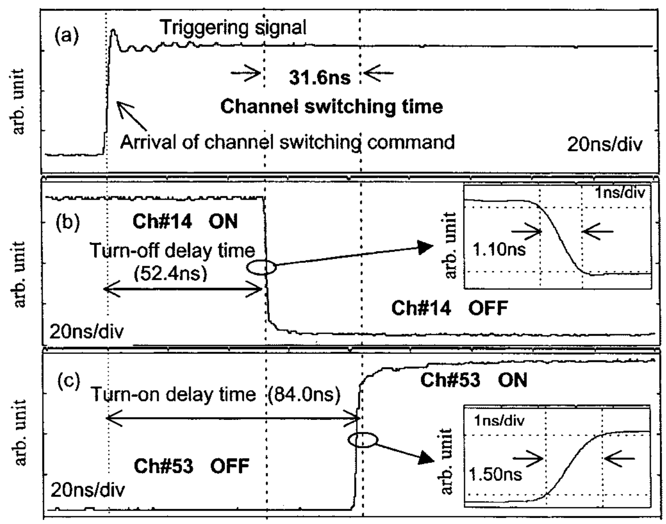

Fig. 5. Output waveforms for switching from Channel 14 to Channel 53: (a) triggering signal and (b) at output port for Channel 14 (Ch#14 is turned off); Inset: Magnified view for falling edge, (c) at output port for Channel 53 (Ch#53 is turned on); Inset: Magnified view for rising edge.

tuning currents in steps of 0.02 mA and the operating points, where the output side-mode suppression ratio (SMSR) and the output optical power are at least 30 dB and -5 dBm, respectively, are chosen. The respective set of tuning currents for each accessible wavelength channel is shown in Fig. 2. It is shown that the reflector current curve repeats in every 4-nm interval, which corresponds to the spacing of the reflection peaks from the sampled grating in the laser's reflector section. The relations of respective tuning currents and the output wavelength are quite predictable, thus, facilitates the calibration process. The obtained digital values of the tuning currents have been electrically programmed to the lookup table devices. As suggested by the laser's manufacturer, instead of zero-resetting the currents for a certain period of time [4] to avoid a hysteresis effect, the GCSR laser intrinsically possesses a hysteresis-free wavelength tuning property, and those corresponding current values can be found by scanning the currents from high and low values to the ones being tested. Fine optimization can be done by slightly adjusting the currents for the reflector and phase sections. The wavelength calibration process can be automated as described in [6]. Fig. 3, which shows the output spectra of all 100 wavelength channels. The output optical power and SMSR for all channels were at least -5 dBm and 30 dB, respectively. Higher output optical power could be achieved by applying a higher current (maximum 150 mA) to the gain section of the laser. Fig. 4 shows that the deviation of the measured output wavelength values from the original wavelength assignment is about ± 0.005 nm. We have not yet noticed any significant wavelength drift over a period of several months.

III. Wavelength Switching Characteristics

We have measured the wavelength switching performance of this fast wavelength-tunable transmitter. The channel switching time is defined as the time interval between the original channel turned off and the new channel turned on. The tunable transmitter was driven to periodically switch between two selected wavelength channels. Two 1×40 arrayed waveguide gratings (AWGs) (50-GHz spaced) of different transmission bands (1530–1546 nm and 1546–1562 nm) were used to filter out the selected wavelength channels at the respective output ports. Fig. 5 shows the measured output waveforms when the transmitter was driven to switch from Channel 14 to Channel 53, which were spaced 15.6- nm apart. A triggering signal

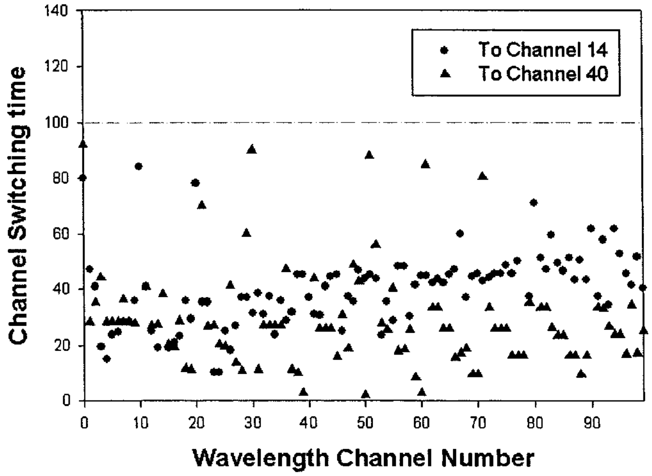

Fig. 6. Measured wavelength switching time when all other channels are switched to (●) Channel 14 and(▲) Channel 40.

[Fig. 5(a)] was applied to the front end of the transmitter to trigger the channel switching. The laser responded after a certain delay time, which was due to the propagation and processing time for the electronics (PLDs and DACs). Channel 14 was turned off after a delay time of 52.4 ns [Fig. 5(b)], while Channel 53 was turned on after a delay time of 84.0 ns [Fig. 5(c)]. Thus, the channel switching time was measured to be 31.6 ns. The falling edge of Channel 14 spanned 1.10 ns (Fig. 5(b) inset), while the rising edge of Channel 53 spanned 1.50 ns (Fig. 5(c) inset). In some cases, the output wavelength was observed to exhibit over-tuned behavior in which one or multiple time glitches were observed on the rising edge of the channel. The time period ($<$ 10 ns) of such over tuned behavior was regarded as wavelength instability just after tuning and was also counted toward the channel switching time. Fig. 6 shows the measured channel switching time when other channels were switched to Channel 14 and Channel 40. It is shown that the channel switching times were, in general, below 100 ns. The variation in values was found to depend on the relative changes in the tuning currents, that is, longer channel switching time was expected for greater step change in one of the tuning currents. This is limited by the switching response of the DAC and can be improved by using DACs with better response time. During the period that a channel is being switched, the tuning currents are swept through the values corresponding to intermediate channels, but their power levels are about 25 dB down from that of the destined wavelength. To suppress such unwanted power, it is not desirable to switch off the laser's gain section during this interchannel switching period due to the possible large power transient when the laser is switched on again. For high data rate application, say 10 Gb/s, such laser has to be externally modulated due to its limited modulation bandwidth ($\sim$3–4 GHz). Thus, the unwanted power can be well-suppressed by switching the voltage bias of the external modulator to the lowest transmission state during that channel switching period.

IV. Application—Optical Packet Router

With the nanosecond wavelength switching characteristics of the above transmitter, it is suitable to perform fast switching or routing of high-speed optical packets. Our transmitter can be employed to realize a multiterabit optical packet switch fabric [7]. The switching is achieved using the well-known wavelength routing properties AWGs. Our transmitter, followed by an external modulator, is connected to each input port of an $N \times N$ AWG. By switching the output wavelength channel from the transmitter, the data is wavelength routed to one and only one output port. Thus, a strictly nonblocking $N \times N$ crossbar switch fabric is realized. A 1-Tb/s optical packet switch fabric with an 80×80 AWG [8] and at 12.5-Gb/s data rate per port has been experimentally demonstrated [7].

V. Conclusion

In summary, we have demonstrated a fast and precise 100-channel wavelength-tunable transmitter, which is suitable for optical packet switching. The wavelength switching performance has been characterized and its application in an optical packet router has been discussed.

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