Fast Wavelength-Switching of Laser Transmitters and Amplifiers

HAIM KOBRINSKI, MEMBER, IEEE, MARIO P.VECCHI, MEMBER, IEEE, MATTHEW S. GOODMAN,
EVAN L. GOLDSTEIN, MEMBER, IEEE, THOMAS E. CHAPURAN, MEMBER, IEEE,
JANET M. COOPER, MOSHE TUR, CHUNG-EN ZAH, MEMBER, IEEE, AND
SERAFIN G. MENOCAL, JR., MEMBER, IEEE

Abstract—This paper discusses system aspects and describes experimental demonstrations of nanosecond wavelength tuning in laser diode structures. Both tunable transmitters and tunable filters are considered. The dependence of the refractive index on the carrier density in semiconductors is exploited to obtain fast wavelength tuning. Experimentally, switching times of < 15 ns have been demonstrated in a three-section DBR laser transmitter with maximum continuous tuning range of 2.2 nm. These conditions correspond to a system with 50 wavelength-addressable channels. A new scheme for simultaneous wavelength-switching and data modulation, which alleviates wavelength drifts due to thermal effects, is presented. DFB laser structures biased below the lasing threshold operate as resonant tunable amplifiers. A uniform DFB laser amplifier has been demonstrated with a 1 ns wavelength-switching time. Experiments with tunable transmitters and tunable filters that simulate their operation in packet switching systems, including both wavelength-switching and data modulation, are also described.

I. INTRODUCTION AND SYSTEM MOTIVATION

The introduction of broad-band services will require both transport and processing capacities that greatly exceed those available today. Concurrently, optical fibers are providing access to several terahertz of spectral bandwidth. This large bandwidth motivates research on new means of utilizing this resource in future telecommunication networks. Some recent examples of research efforts toward exploitation of the optical bandwidth in communication systems include the following:

- over 2 Tb · km/s bit-rate distance product and 36 Gb/s information capacity have been demonstrated in point-to-point WDM transmission over single-mode fibers [1];
- distribution of 18 wavelengths, each with 2 Gb/s data (equivalent to a total of > 200 video channels at 150 Mb/s per channel), to 16 hubs using the LAMBDANET multiwavelength network [2];
- use of high-density wavelength multiplexing for passive subscriber-loop distribution networks [3];
- subscriber-loop distribution systems, mainly for video broadcasting, with several tens of wavelength capacity and channel selection either via tunable Fabry-Perot filtering [4], [5] or coherent heterodyne receivers [6], [7];
- simultaneous optical amplification of up to 20 wavelengths to increase the capacity of optical distribution networks [8]–[10].

In these examples, the relation between a given channel and its corresponding wavelength is either fixed or dynamic (but with long tuning times; a millisecond is adequate for channel selection on a TV set). In several emerging applications—in particular, packet-switching fabric designs [11]—switching between tens of distinct wavelengths, with several nanoseconds random-switching times, is required [12].

This paper addresses the optical technology required for these packet-switching applications and other applications with similar requirements. We will briefly describe a general system architecture used for active addressing of input and output ports through fast wavelength tuning. Then, the physical features of the semiconductor laser structures which allow fast wavelength tuning are briefly summarized. In the following sections, we describe relevant experiments using a double-section distributed feedback (DFB) laser and a three-section distributed Bragg reflector (DBR) laser as tunable transmitters and a DFB amplifier as a wavelength-selective filter.

Fig. 1 illustrates a general network architecture in which wavelength tuning of either transmitters or receivers provides single-stage routing. This scheme is referred to as "broadcast and select" and can be implemented in several ways. One implementation [13], [14], implied by Fig. 1, includes tunable laser transmitters, a passive star coupler, and fixed-wavelength receivers. The star coupler broadcasts every input signal to all the output lines. An input-output connection at the physical level is accomplished by tuning the transmitter to the wavelength of the desired receiver.

In another implementation, also indicated in Fig. 1, each input is uniquely characterized by a fixed-wavelength transmitter. Multiple fixed receivers [2] or tunable receivers [11], [15], at the output, select the desired input port through selection of the appropriate wavelength addresses. A unique feature of this optical implementation is the possibility for broadcasting or selective multicast-
between the input and output at Gb/s transmission rates. Assuming a 1000 bit packet size and a tuning is performed at both the input and output or with signals from the same input. Other combinations, where the tuning is performed at the input and output or with less tuning and more fixed-wavelength hardware, have also been considered. Because of the independence of the wavelengths, architectures based on this “broadcast and select” approach can support nonblocking connectivity between the input and output at Gb/s transmission bit rates.

For application to switching systems, both the tuning control and the dynamics of the tuning are of paramount importance [11], [12]. Switch-fabric control is required either to assure contentionless communication across the system or to resolve contention when it occurs. Output port contention occurs when two input nodes try to communicate simultaneously with the same output. In order to illustrate the wavelength-switching speed issue, we use typical parameters associated with packet-switching systems. Assuming a 1000 bit packet size and a 1 Gb/s data rate, the packet transmission time is 1 μs. The implications for the tuning dynamics are: wavelength-switching times < several tens of nanoseconds and several microseconds of residency time (i.e., the time the tunable source or receiver needs to maintain a preset wavelength for transmission of the packet).

Several technologies exist for wavelength tunability. However, the fast switching requirement implies the use of semiconductor laser devices. The main candidates are multisection single-longitudinal mode (SLM) lasers, i.e., distributed feedback (DFB) and distributed Bragg reflector (DBR) lasers. Grating structures built into the waveguides of these devices provide a gain at a single-frequency with < 100 MHz linewidths.

The oscillation wavelength in multisection SLM lasers is determined by both the grating pitch and the relative phases between the sections. Since the Bragg wavelength and the phase conditions are not controlled separately in a DFB laser, its tuning mechanism is more complicated [16] than that of the DBR laser. However, the wavelength-tuning concept in these structures is similar as summarized below. Tuning of the resonant wavelength in semiconductor materials is accomplished by controlling the refractive index of the material through its dependence on the carrier density. The Bragg wavelength in grating-based SLM structures \( \lambda_{Bragg} \) is linearly related to the material refractive index \( n \) through a resonance condition

\[
m\lambda_{Bragg} = 2nd
\]

where \( m \) is an integer and \( d \) is the grating pitch. A similar relationship holds for the resonant condition in a Fabry–Perot structure with \( d \) being the cavity length. The index of refraction decreases linearly with the carrier density \( N \) as a result of plasma oscillation of free carriers [17]

\[
\Delta n = -\Gamma C \Delta N
\]

where \( \Gamma \) is the optical-mode-confinement factor \( (\approx 0.3-0.6) \) and \( C \) is the index shift per unit-carrier density \( (\approx 10^{-20}\text{cm}^3 \text{ at } 1.55 \mu\text{m}) \). The dependence of the excess carrier density \( \Delta N \) on the injected current to the tuning region \( I \) is dominated by spontaneous recombination [18]

\[
\Delta N = (I/BeV)^{1/2}
\]

where \( B \) is the radiative recombination coefficient, \( e \) is the electron charge, and \( V \) is the volume of the layer where tuning takes place. Consequently, as the tuning current increases, the resonant wavelength shifts to lower values with a square-root dependence on the current (e.g., for \( m = 1 \))

\[
\Delta\lambda_{res} = -2d\Gamma C (I/BeV)^{1/2}.
\]

Wavelength tuning by current injection has been analyzed for both DFB and DBR structures [16], [19], [20]. Wavelength tuning with mode hopping (quasi-continuous) over 10 nm and continuously over 4 nm has been demonstrated using a three-section DBR laser [21]. The quasi-continuous tuning range is limited by the saturation of \( \Delta n \) at high current densities due to heating and nonradiative recombination. A maximum \( \Delta n/n \approx 1\% \) appears to be a practical limit, corresponding to a 15 nm tuning range. The continuous tuning range of a single lasing mode is also limited by the increase in laser threshold current, due to increasing absorption losses in the passive sections, as the injected carrier densities are increased. In multisection DFB structures, the injected current for tuning of the Bragg wavelength controls the gain as well. Since the carrier density is saturated in active sections above threshold, the tuning range is further limited. A continuous tuning range of 2.1 nm, limited by the mode spacing (stop band), has been demonstrated in a double-section DFB laser [22].

The response time for setting a given wavelength is ultimately dependent on the carrier lifetime \( \tau \). Typical recombination times for the excess carriers are in the range 0.3 ns < \( \tau < 3 \) ns. The longer times are associated with passive sections, such as the tuning regions in a three-section DBR laser, where the carrier lifetime is not decreased by the process of stimulated emission. Consequently, for high speed (> 100's Mb/s) tuning applications, as in frequency-shift-keying (FSK) transmission, DFB lasers are mostly used.

For dynamic wavelength-filtering purposes, single-mode semiconductor structures combining wavelength selectivity and optical gain are used as resonant amplifiers with electronic tunability [23]-[25]. Their tuning mecha-
anism is similar to that of the tunable laser transmitters. However, they are optimized in the transmission (rather than reflection) mode. Since these devices operate under threshold, their resonance linewidths are wider than those of the laser transmitters. Consequently, the number of channels in tunable filter systems is smaller than in tunable transmitter systems.

In this paper, we report measurements of the dynamics of wavelength switching in several SLM laser structures, first with regard to tunable transmitters, and then in a DFB amplifier, used as a tunable filter. Both switching times and wavelength stability as a function of time are considered and results are presented in the context of system requirements. System aspects such as tuning range, number of wavelength channels, channel separation, crosstalk isolation, and filter gain are also discussed. Temperature-induced variation, either of the refractive index or of the gain peak wavelength, is another possibility for wavelength tuning. However, due to the slow time response of that mechanism, we consider thermal effects only to the extent that they present a detrimental impact on current injection tuning. For example, packet transmission times longer than a few μs would require the wavelengths associated with these packets to remain constant over this length of time. However, for these microsecond residency times, wavelength drifts due to thermal effects, which are in an opposite direction to the current density effects (given a current pulse), start to take place. These effects in SLM structures are related to the temperature dependence of the index of refraction. As a result of heating (due to nonradiative recombinations in the semiconductor waveguide), the energy gap decreases and, therefore, the refractive index and the resonant wavelength increase. This issue affects the allowed channel spacing, packet lengths, and transmission bit-rates. A scheme which combines wavelength switching and data modulation to avoid these thermal-induced wavelength drifts in a three-section DBR laser is presented.

II. WAVELENGTH-TUNABLE DFB LASER TRANSMITTERS

Variation of the injected current in a single-section DFB laser to tune the lasing wavelength is always accompanied by variations in the output intensity [13]. In order to maintain a constant output power while tuning the wavelength, DFB laser structures with two separate electrodes—front and rear—have been used [22], [26]. These two-section DFB structures result in a nonuniform excitation along the cavity, where the lasing wavelength depends on the current ratio between the two sections. To explore the high-speed wavelength tunability of two-section DFB laser structures [27], the experimental setup shown in Fig. 2 was used. A Hitachi InGaAsP buried-heterostructure DFB laser was used in which the top contact was chemically etched to provide two sections of 150 μm each with 800 Ω isolation between the two sections. The front-section facet was AR coated. The output was coupled through an isolator (30 dB isolation) into single-mode fiber. Part of the output was tapped off using a di-

rectional coupler to an optical power meter while the remaining light passed through a Fabry–Perot (F-P) interferometer with a free spectral range (FSR) of 0.5 nm and a finesse of 27. The F-P output was detected using an avalanche photodiode (APD) receiver.

In order to avoid clamping of the carriers and, consequently, to maximize the FM efficiency, methods that asymmetrically biased one section above threshold and modulated the other section around a point below threshold (acting as a phase modulator) were analyzed [28], [29]. Fig. 3 shows a plot of the emission wavelength as a function of the current ratio $I_F/I_{TOTAL}$ for the laser used in this experiment. As seen in the shaded regions of Fig. 3, multimodal instabilities are observed as the asymmetry increases. Therefore, the laser current was restricted to the range 0.4 $< I_F/I_{TOTAL} < 0.6$ corresponding to a single-mode operation. Fig. 4 shows the wavelength-tuning scheme ($I_F$ versus $I_R$) for the double-section DFB (DS-DFB) laser. We biased the device with the current in the forward and rear sections ($I_F$ and $I_R$) equal to 40 mA. Both sections were modulated as shown in the figure with a peak-to-peak signal value of 18 mA for $I_F$ and $I_R$ such that $ΔI_F = -ΔI_R$ and, therefore, a constant total current of 80 mA was maintained throughout the modulation cycle. An FM efficiency of 1–2 GHz/mA was achieved compared to 1.5–4 GHz/mA for the case of asymmetric bias and compared to a few hundred MHz/mA for an ordinary (single-section) DFB laser operated above threshold. In addition, the condition of a constant total current helped to minimize thermal effects (described below). Fig. 4 also shows schematically a constant power contour; the modulation is tangent to the curve with the bias point at the point of contact. This curve shows that, as the modulation deviates farther from the point of tangency, the output power decreases (moves to a lower constant power curve). Therefore, the necessity to remain on a line of constant total current may limit the tuning range due to constraints for minimum output power at the edges of the modulation region. However, it is easily seen that, by modulating both sections, we remain closer to the constant power curve than if only one section is modulated. Under optimum conditions, a continuous wavelength tuning range of 0.32 nm was demonstrated with switching times $<5$ ns.

Fig. 5 shows the results of an eight-wavelength switching experiment. The figure inset shows the modulation input where $I_F$ and $I_R$ were eight-step current injection patterns. The rise time between levels was $<5$ ns and the

![Fig. 2. Experimental setup for wavelength-tuning measurements using a two-section DFB laser.](image-url)
residency time at each level was 20-500 ns (200 ns shown). Switching among eight wavelengths was demonstrated over a range of 0.32 nm, as illustrated by the scanning F-P output spectrum. The output power levels decrease at the ends of the spectrum, as predicted by Fig. 4. By using the F-P as a fixed filter (no scanning) set at one of the wavelengths and observing the detected pulse, a rise time <5 ns was measured. This indicates a wavelength-switching time at least as fast as the input signal. We conducted another experiment, to demonstrate the pattern independence of the switching, in which the input was driven with several other eight-level sequences (random order). The output spectrum was unchanged, indicating a suppression of thermal effects. To support this conclusion, the same experiment was conducted with $\Delta I_F \neq -\Delta I_R$ so that the total current was not constant. In this case, the output spectrum changed significantly as the order of switching was varied. Minimal thermal effects are also indicated in Fig. 3, where there is a close agreement between the CW measurement points and those measured under modulation.

Since both electrodes of the DS-DFB laser were used for wavelength tuning, a commercial LiNbO$_3$ external modulator was inserted between the laser output and the F-P filter for data modulation, as indicated in Fig. 2. The external modulator was driven by a pseudorandom NRZ stream at rates up to 1 Gb/s [27].

III. WAVELENGTH-TUNABLE DBR LASER TRANSMITTERS

Multisection DBR lasers are somewhat more complicated to fabricate than DFB lasers but there are benefits to be obtained: the additional degree of freedom in separately controlling the device gain, the Bragg condition, and the phase matching increases the total tuning range available. In addition, the separate current controls allow us to switch wavelengths and modulate (either intensity or FSK) the data simultaneously on the same device [30], [31]. The advantages of using a single device for both fast wavelength-switching and direct data modulation are significant: the elimination of external modulators improves both the simplicity of the implementation and the available power budget.

The laser used in our work was an InGaAsP three-section flat-surface buried-heterostructure (FBH) DBR structure with an active region (254 $\mu$m long), a phase-control region (127 $\mu$m long) and a DBR region (381 $\mu$m long), and with an active region threshold current $I_{th} = 65.3$ mA at room temperature. As shown in Fig. 6, the maximum continuous-tuning range was achieved by adjusting the ratio of the injected currents to the DBR region $I_{DBR}$ and to the phase-control region $I_p$ such that $I_p = 3I_{DBR}$. A simple resistive current-divider circuit makes it possible to use one external control current $I_c$ to tune the wavelength over the whole continuous-tuning range. Fig. 6 shows the wavelength shift as a function of the control current $I_c = I_p + I_{DBR}$. The wavelength-tuning coefficient varies from $\delta\lambda/\delta I_c = -0.050$ nm/mA at low $I_c$ (longer $\lambda$'s) to $\delta\lambda/\delta I_c = -0.013$ nm/mA at high $I_c$ (shorter $\lambda$'s) in agreement with (4). The side-mode rejection-ratio is also plotted in Fig. 6 and it is >21 dB across the tuning range.
Fig. 6. Continuous wavelength tuning of the three-section DBR laser. The total tuning range shown is ±2 nm while maintaining a side-mode rejection ratio better than 21 dB. The inset on the right shows the arrangement for the simultaneous wavelength switching and data modulation. The tuning control current \( I_\text{c} \) injects carriers both into the DBR region and the phase-control region of the device. Data are superimposed by modulating either the current \( I_\text{a} \) into the active region (intensity modulation) or the tuning current \( I_\text{t} \) into the passive regions (FSK modulation).

There was no measured difference between the dc wavelength-tuning coefficients and the dynamic values.

Direct intensity data modulation was achieved through modulation of the injection current \( I_\text{a} \) in the active region, around a bias current \( I_{\text{bias}} = 80 \text{ mA} \). This modulation results in a dynamic wavelength shift and linewidth broadening of each of the channels. The resulting dynamic linewidth determines the required filter bandpass at the receiving end and, hence, the minimum channel separation. The dynamic linewidth was measured between 2.5 and 6.5 GHz depending on the modulation depth. Fig. 7 shows wavelength tuning under direct intensity modulation at 200 Mb/s for 16 different wavelengths. The maximum variation in output power was ±3 dB over the tuning range. The maximum bit-rate for this specific device using intensity modulation was ±500 Mb/s but modified fabrication processes to reduce parasitics should extend the modulation rate into the multigabit per second range.

Fig. 8 indicates the fast wavelength-switching characteristics of the device in a packet-switching simulation at 200 Mb/s. Wavelength-switching between two channels separated by \( \Delta \lambda = 2.11 \text{ nm} \) is shown on the left. The two channels are sequentially resolved using a tunable Fabry-Perot filter with a 6 GHz bandpass. Each packet contains 12 bits and has a duration of 60 ns. The first and last bits of each packet must be used as "guard bits" in order to achieve a bit-error rate BER < 10^{-9}, indicating a transient interval of ≈10 ns when switching wavelengths. Fig. 8, on the right, presents wavelength-switching for channels separated by \( \Delta \lambda = 0.15 \text{ nm} \). In this case, only one "guard" bit between packets is necessary to ensure BER < 10^{-9}, indicating a smaller transient interval of ≈5 ns. The observed transient behavior for wavelength-switching has been studied in detail and it has been correlated to the imperfect shape of the current pulse \( I_\text{a} \). For the widest wavelength-tuning range \( \Delta \lambda = 2.2 \text{ nm} \), the amplitude of \( I_\text{a} \) would have to be controlled to better than 0.5% (i.e., ±0.4 mA over an 80 mA swing), with a risetime faster than the intrinsic speed of the device, in order to maintain the entire signal spectrum within a filter with 0.05 nm bandpass. The intrinsic wavelength-switching time is limited by carrier lifetimes in the passive regions of the three-section DBR laser and the parasitic capacitance of the device. It was measured by detecting the amplitude differences during a switching-pulse transition, without wavelength filtering, to be <5 ns for this device. A wavelength-switching time of 1.8 ns was reported recently over a tuning range of 1.25 nm [32].

The maximum continuous tuning range observed for this device is 2.2 nm. From the crosstalk measurements,

\[ \Delta \lambda = 2.11 \text{ nm} \]

\[ \Delta \lambda = 0.15 \text{ nm} \]
it is determined that, in order to guarantee better than -10 dB crosstalk isolation (\(<0.5\) dB power penalty) with adequate extinction ratio, a minimum filter bandpass of 5 GHz and a channel spacing of 15 GHz (\(\approx 0.12 \text{ nm}\)) are required. Therefore, the total number of resolved wavelength channels is \(\approx 20\).

When switching between widely separated wavelengths, thermal effects have been observed to produce wavelength drifts if the switched-wavelength residency times were longer than \(\approx 1 \mu s\). In order to avoid loss of data due to these drifts for the above filter settings, packet lengths were limited to <600 ns.

As mentioned above, intensity data modulation produces a dynamic linewidth increase, or chirp, which determines the required optical filter bandpass at the receiving end and, hence, the minimum channel separation. This restriction can be alleviated by using FSK data format, modulating either the current \(I_c\) or the current into the active region \(I_A\). (The frequency chirp which was detrimental in the intensity modulation scheme was utilized here for FSK modulation in the active region.) FSK modulation and direct detection with a single Fabry–Perot (FP) filter with bandwidth \(f_{FP}\) implies a minimum channel spacing of \(\approx 6 f_{FP}\) for a power penalty <0.1 dB, provided that the laser linewidth is \(<f_{FP}/10\) [5]. The linewidth of the three-section DBR laser varies with the injected tuning current, and the laser used in the experiment had its largest linewidth of \(\approx 80 \text{ MHz}\) at high \(I_c\). Therefore the F–P filter resolution was set to \(f_{FP} \approx 1 \text{ GHz}\). Fig. 9 shows a four-level input current \(I_c\) which is composed of a two-channel tuning current and a binary FSK modulation current. The corresponding output spectrum from the three-section DBR laser is also shown in the figure. The two channels were modulated at 100 Mb/s and Fig. 9 shows the conditions corresponding to minimum channel separation: frequency deviation \(f_d = 3 f_{FP} = 3 \text{ GHz}\) and channel spacing \(f_c = 2 f_d = 6 \text{ GHz} \ (\approx 0.047 \text{ nm})\). The demodulated data of these two channels are shown in Fig. 10, where both wavelength-filtering and data demodulation were accomplished through a single F–P filter. Both the wavelength-switching of the 1 \(\mu\)s long packets and the corresponding eye diagrams are presented. The total continuous-tuning range for our device is 2.2 nm and, therefore, the maximum number of wavelength channels using the FSK conditions would be \(\approx 48\).

The maximum FSK modulation bit-rate, when modulating the passive sections of this device, is limited by carrier lifetimes in these sections to \(\approx 200\) Mb/s. FSK modulation of the active region, with the same channel separation as described above, should enable faster modulation rates as a result of stimulated emission. However, in our specific device, the FSK modulation speed of the active current \(I_c\) was limited due to parasitics to \(\approx 250\) Mb/s. The FSK response (tuning bandwidth per mA of switching current as a function of the FSK rate) in the active region was an order of magnitude smaller than in the passive sections and less uniform and, therefore, it is preferable to utilize the passive sections for FSK to alleviate thermal and pattern effects.

The transient behavior for wavelength-switching using this device with FSK modulation is similar to the ASK condition where a guard time between packets of \(\approx 15\) ns was required for the widest wavelength-tuning range of 2.2 nm.

Switching between widely separated wavelength channels requires relatively large current swings in the passive sections \((\Delta I_c \approx 80 \text{ mA} \text{ to cover } 2.2 \text{ nm})\). As a consequence, thermal effects produce wavelength drifts if the switched wavelength residency times are longer than \(\approx 1 \mu s\) [30], [31]. These thermal drifts can be understood as follows. The phase and DBR sections of this device are biased at the operating point \(I_{PE}\) and \(I_{DBR}\) and, thus, the

\[\text{Fig. 9. Two-channel FSK modulation using the tuning current } I_c. \ (a) \text{ Input current for } 0.5 \mu \text{s long packets and } 100 \text{ Mb/s data.} \ (b) \text{ Output spectrum with channel spacing } \approx 6 \text{ GHz and frequency deviation } \approx 3 \text{ GHz}.\]
injected current in the passive sections $I_C$ has two components: the wavelength-tuning current $I_C^\text{tune}$ (between 0 and $80 \text{ mA}$) and the ac-coupled FSK modulation current $I_C^{\text{FSK}}$. The FSK modulation scheme adds these two components, such that the average of the injected current $I_C$ over the packet time will be significantly different for each wavelength (Fig. 9). Hence, heating (increased current density) or cooling (decreased current density) in the passive waveguide can produce significant wavelength drifts over a packet time. Fig. 11 shows oscilloscope traces of a given packet by tuning an F-P filter, with a 3 GHz bandpass, to three slightly different wavelengths while switching is taking place between 1.5 $\mu$s long packets separated by 1.9 nm. These measurements indicate wavelength drifts due to thermal effects of the order of 0.25 GHz/mA $\cdot$ $\mu$s. Clearly, the thermally induced broadening of the packet spectrum to $>15$ GHz would significantly limit the number of allowed channels.

In order to minimize these wavelength drifts (without restricting packet lengths), the following wide-deviation FSK modulation scheme has been demonstrated. Using an RF mixer circuit, the two components were multiplied, rather than added, such that $I_C = I_C^\text{tune} \cdot I_C^{\text{FSK}}$, resulting in a combined signal, including both the data modulation and the wavelength switching currents, with zero average value and oscillating at the bit rate. This idea is illustrated in Fig. 12 where the wide-deviation FSK input current for two packets is shown, together with the corresponding optical spectrum (displayed with a 0.1 nm resolution spectrum analyzer) of the three-section DBR laser. The wide-deviation FSK was demodulated using a single F-P filter tuned to the wavelength corresponding to either the 1’s or the 0’s of the data. Fig. 13 shows an oscilloscope trace of a 2.2 $\mu$s long packet while switching between two wavelengths separated by 2.05 nm. The reduction of thermal effects using wide-deviation FSK is illustrated in this figure. For the entire packet interval, the optical spectrum remains within the passband of the 1 GHz F-P filter. This result is to be compared to the wavelength drift shown in Fig. 11 for conventional FSK modulation.
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Fig. 12. Two-channel wide-deviation FSK modulation scheme. (a) Input current for 2.2 μs long packets and 50 Mb/s data. This waveform is obtained using an RF mixer to multiply the wavelength tuning signal times the data modulation signal. Notice that the average current is constant from packet to packet, thereby reducing thermal fluctuations. (b) Output spectrum over 2.05 nm showing the four wavelengths associated with the 1’s and 0’s for each channel.

Fig. 13. Reduction of thermal effects using wide-deviation FSK. The F-P filter, with 1 GHz resolution, is tuned to the 1’s of a channel switched between two wavelengths separated by 2.05 nm as shown in Fig. 12. Notice that the entire 2.2 μs long packet remains within the F-P filter bandwidth, indicating the successful reduction of wavelength drifts due to thermal effects.

The minimum spacing between channels (i.e., the distance between 1’s of one λ and 1’s of the next λ) for wide-deviation FSK is

\[ f_s = 3 f_{fp} \approx 3 \text{ GHz} \approx 0.023 \text{ nm}, \]

i.e., about half the value required by a conventional FSK. The usable tuning range is less than the total tuning range because the 0’s of the data, for each wavelength, are not detected. Notice that for wide-deviation FSK modulation we choose the bias current to be in the center of the range, for instance, \( I_{bias} = 40 \text{ mA} \) from Fig. 6. Because of the nonlinear wavelength versus current characteristics, the wavelength at the bias point is not at the center of the continuous tuning range. As a consequence, more than half of the tuning range can be used. Therefore, using wide-deviation FSK, the number of available channels could be as large as \( \approx 1.28 \text{ nm}/0.023 \text{ nm} = 56 \).

IV. WAVELENGTH-SELECTIVE OPTICAL AMPLIFIERS

Multiwavelength optical network proposals increasingly require tunable receivers that can rapidly select among many narrowly spaced wavelength-multiplexed channels. Tunable wavelength selection can be obtained by exploiting the resonant amplification in DFB structures biased below threshold. Measurements on these devices have shown continuing improvement in dc selectivity, gain, and tuning range [23], [24], [33]. A multisection phase-shift controllable DFB filter has been used to separate eight channels over a 0.6 nm tuning range [34]. More recently, a 0.95 nm tuning range with a constant 24.5 dB optical gain has been demonstrated in a similar device, corresponding to an 18 wavelength-channel selection [35]. The dynamical properties under both fast wavelength-switching and high bit-rate data streams have also been investigated [36]. We discuss in this paper experimental results for the fast-tuning properties of distributed-feedback optical amplifiers (DFB-OA), including BER measurements at >1 Gb/s for packets switched between two wavelengths to simulate the high-speed transient conditions of a packet-switching system [37].

The experimental arrangement is shown in Fig. 14. The DFB-OA used in this experiment was a commercially available 1.5 μm BH device with a first-order grating, one cleaved facet, and one AR-coated facet. The resonant wavelength of the DFB-OA was adjusted either by controlling the temperature (slow tuning) or by varying the injected current (fast tuning). Two DFB laser transmitters (TX A and TX B), directly modulated and combined in a 2 × 2 directional coupler, provided the incident-light signal through an optical isolator. The polarization of the light incident on the AR-coated facet was manually matched to the TE mode of the DFB-OA. This polarization-matching requirement may be alleviated, for example, by using polarization maintaining systems—not a stringent limitation due to the small dimensions of the intended systems. A lock-in detection system was used for
the dc characterization. The fast wavelength-switching and the BER measurements were made using three separate pattern generators, all synchronized by a common clock signal. Generators A and B provided data modulation for their respective transmitters and generator C provided a synchronized square-wave signal for the electronic tuning of the DFB-OA wavelength.

The dc characteristics of the DFB-OA device are summarized in Fig. 15. The dc wavelength-tuning coefficient, the change in resonant wavelength relative to the change in the amplifier-bias current, is \( \Delta \lambda / \Delta I = -0.17 \text{ nm/mA} \), with a wavelength-selectivity (full-width half-maximum) bandwidth of 0.1-0.2 nm, in agreement with previous dc tuning results for similar devices [23]. It is important to notice that the sign of the tuning coefficient \( \Delta \lambda / \Delta I \) is negative, indicating that carrier-density effects dominate temperature effects even for dc measurements. The net gain was measured by comparing the DFB-OA input and output signal power, using a lock-in amplifier to remove spontaneous emission components that would otherwise generate inflated gain estimates. Coupling losses of \( 3.8 \pm 0.5 \text{ dB} \) are included in the measured net gain. Measurements were made at input power levels below \(-32 \text{ dBm}\) to avoid gain-saturation effects. A maximum net gain of \( 
abla g \) dB is obtained for a DFB-OA current \( I_g = I_0 \) and, as expected, it is reduced for smaller \( I_g \) values. Higher gains were observed when the amplifier was biased significantly above threshold in the injection-locking regime; however, considerable pattern distortion occurred in this regime, so it was not used in the system experiments described below. The amplifier's tuning range of \( 0.4 \text{ nm} \) was modest compared to the tuning ranges of the phase-controllable DFB devices mentioned above; it was limited primarily by the rapid gain changes that accompany the carrier-density-dependent index change. High-speed measurements of wavelength-selective amplification were made by superimposing a tuning current from pattern generator C on the DFB-OA bias current of \( I_g = 0.96 I_0 \). This square-wave current had an amplitude \( \Delta I_g = 1.2 \text{ mA peak-to-peak} \), corresponding to two resonant wavelengths separated by \( \Delta \lambda = 0.23 \text{ nm} \).

The switching signal had a fundamental frequency of 50 MHz and a risetime of 0.2 ns. An incident optical signal from TX A, modulated at 1 Gb/s, was temperature-tuned to match one of the two wavelengths. The amplified optical signal was detected by the fast APD receiver (RF bandwidth > 2 GHz), and a risetime \( \tau_{\text{sw}} = 1 \text{ ns} \) was observed for the wavelength selection by the DFB-OA, Fig. 16(b), a value consistent with typical carrier lifetimes in InGaAsP/InP structures. The dynamic wavelength-tuning coefficient measured under these conditions was \( \Delta \lambda / \Delta I_g = -0.19 \text{ nm/mA} \), which agrees with the measured static tuning coefficient within the limitations imposed by experimental error.

The wavelength selectivity of the DFB-OA was investigated by using the two transmitters, TX A and TX B, each independently modulated with NRZ (\( 2^{15} - 1 \)) pseudorandom words at 1 Gb/s, and then measuring the BER as a function of wavelength separation. First, the optical

![Fig. 14. Schematic diagram of the experimental arrangement to measure the DFB optical amplifier static and dynamic characteristics. The three pattern generators and the BER test set are synchronized by a common master clock, not shown in the figure.](image)

![Fig. 15. Static characterization of the DFB optical amplifier as a function of bias current \( I_0 \). The wavelength for peak gain \( \lambda_p \) and the wavelength-selection bandwidth are shown on the left vertical axes. The net peak gain, including coupling in and out of the DFB-OA, is shown on the right vertical axis. The threshold current for this device is \( I_{\text{th}} = 15.0 \text{ mA} \).](image)

![Fig. 16. Oscilloscope traces showing the fast wavelength-tuning properties of the DFB optical amplifier. The upper trace is the DFB-OA tuning current showing a risetime of 0.2 ns. The lower trace is the detected light showing a wavelength-selection risetime of 1 ns superimposed on the 1 Gb/s NRZ pseudorandom data stream.](image)
powers of the two transmitters were adjusted such that the output (amplified) powers were approximately equal, -26 dBm, when the DFB-OA was tuned to each individual transmitter separated by $\Delta \lambda = 0.23$ nm. The tuning current levels were $I_1 = 1.01I_{th}$ when tuned to signal TX A, and $I_2 = 0.92I_{th}$ when tuned to interference TX B. The incident optical power of the interfering channel TX $B$ was approximately 6 dB larger than for the signal channel TX A. This difference was balanced by the variation of the DFB-OA gain with the two current levels. Then, the DFB-OA current was held constant at $I_1 = 1.01I_{th}$ and the signal from TX A was temperature-stabilized to match the wavelength of the DFB-OA. The interference channel from TX $B$ was temperature-tuned in order to vary the wavelength separation $\Delta \lambda$ and the consequent crosstalk while measuring the BER performance of the amplified optical signal from TX A. The results of these BER measurements as a function of the channel separation and crosstalk are shown in Fig. 17. These results indicated a minimum channel separation of $\Delta \lambda = 0.2$ nm for BER $< 10^{-9}$ at 1 Gb/s. It should be noted that these crosstalk results are valid only at a received optical power of -26 dBm.

Measurements of the APD receiver sensitivity, with and without the DFB-OA, determined that the noise introduced by the optical amplification under the larger gain values results in a rather large power penalty of up to 8 dB. Thus, the value of this uniform DFB amplifier resides in its ability to serve as a fast, electronically tunable wavelength filter; it does not provide any useful enhancement of the receiver sensitivity.

An experiment was performed to simulate the transient conditions of a packet-switching system using the DFB-OA for fast wavelength-selection of high bit-rate wavelength-multiplexed signals. The three pattern generators (see Fig. 14) were controlled by the same master clock at 1.2 Gb/s and their 24 bit long patterns were selected as follows: generator A, a stream of twelve 0101... bits, followed by twelve 0’s; generator B, a stream of twelve 0’s, followed by twelve 0011... bits; and generator C, a stream of twelve 1’s, followed by twelve 0’s (corresponding, effectively, to a 100 MHz switching rate). The waveforms are shown in Fig. 18. The wavelength of the DFB-OA, biased at $I_0 = 0.95I_{th}$, was switched between $\lambda_1$ and $\lambda_2$, separated by $\Delta \lambda = 0.23$ nm. A BER $< 10^{-9}$ was measured for the total detected pattern of packets at $\lambda_1$ and $\lambda_2$ of Fig. 18(a). Next, the BER was measured for one signal channel while another channel at the other wavelength was directly overlapping it in time. First, the pattern from TX $B$ at $\lambda_2$ was made to interfere by shifting it to the time-slot corresponding to the packet from TX $A$ at $\lambda_1$. The BER measurements at $\lambda_1$ yielded BER $< 10^{-9}$ for the packets shown in Fig. 18(b). Finally, the patterns of generators A and B were readjusted such that TX $A$ at $\lambda_1$ interfered with the packet from TX $B$ at $\lambda_2$ as shown in Fig. 18(c), and again a BER $< 10^{-9}$ was measured for the selected signal at $\lambda_2$. These measurements of BER under bursty transmission at a 1.2 Gb/s data rate indicate that no bits are lost during the fast transitions from one wavelength to another.

V. CONCLUSION

System requirements for packet switching and other applications based on multil wavelength interconnection addressing indicate the need for 32–128 individually selectable channels with Gb/s transmission rates [11]. Random access times between these channels are required to be less than $\approx 10\%$ of a packet time, implying access times typically less than $\approx 50$ ns. In addition, residency times of up to several microseconds, during which the wavelength must be stable, are required. We have considered semiconductor-based structures for wavelength-selectable transmitters and filters meeting the above time requirements. Furthermore, these tunable laser transmitters and
tunable filters have been studied under conditions simulating packet transmissions.

Tunable transmitters based on three-section DFB lasers and double-section DFB lasers have been used in system experiments demonstrating rapid tuning. With DFB lasers, which are capable of continuous tuning ranges of several nanometers, the number of accessible channels has been demonstrated to be >20 with ASK modulation and >50 with FSK modulation. Switching with <15 ns access time has been demonstrated using both DFB and DBR devices, meeting the switching time requirements stated above. The tuning ranges (and, therefore, the number of accessible channels) of research DBR devices, therefore, meet the minimum levels required. DFB structures, however, appear to be more limited in tuning range despite ongoing work on this issue at several laboratories. Our experiments, together with other studies [38], indicate that although the three-section DBR devices can be directly FSK modulated, they are inherently limited to modulation rates of only a few hundred Mb/s—far slower than the FSK rates achievable with directly modulated DFB lasers. External modulation of DBR lasers may combine adequate tuning ranges, switching speeds, and data rates for the applications considered in this paper. An additional limitation for dynamic wavelength-switching applications arises from wavelength drifts due to thermal effects for packets with residency times longer than 0.5 μs. In order to meet the system goals that require residency times of several microseconds, either the transmission bit-rate (for a given packet size) has to increase or the number of accessible channels must be limited. An alternative solution uses the novel scheme presented in this paper: combining data modulation and wavelength-switching to alleviate these thermal effects.

Wavelength-selective filters based on DFB optical amplifiers have been shown to be capable of selecting Gb/s data packets with nanosecond switching times and with BER < 10^-9 satisfying the timing requirements. However, currently available tuning ranges imply <20 wavelength channels. Additional studies of the noise characteristics of the DFB-OA’s and their effect on the overall power budget are also needed.

Research on improved laser diode structures and materials for high-speed switching applications, in addition to integrated devices, represents an essential ingredient for the future application of multiwavelength networks.

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REFERENCES


Haim Kobrinski (M’84), for a photograph and biography, see this issue, p. 1003.

Mario P. Vecchi (S’69–M’69–SM’81–F’89), for a photograph and biography, see this issue, p. 1003.

Matthew S. Goodman, for a photograph and biography, see this issue, p. 1003.

Evan L. Goldstein (S’84–M’89) was born in Seattle, WA, on October 20, 1932. He received the B.A. degree from Antioch College, Yellow Springs, OH, in 1957, and the M.A. and Ph.D. degrees from Columbia University, New York, NY, in 1977 and 1981, respectively, all in philosophy. He then received the B.S., M.S., and Ph.D. degrees in electrical engineering from Columbia University in 1985, 1986, and 1989, respectively.

In 1986, he joined the Optical Networks Research Division of Bellcore, Morristown, NJ, moving to a similar group at Bellcore’s Red Bank, NJ, facility in 1989. His recent research has concerned the tuning properties of distributed-feedback laser amplifiers and the noise properties of semiconductor lasers and resonant amplifiers coupled to guided-wave optical systems.

Dr. Goldstein is a member of the Optical Society of America and the American Physical Society.

Janet M. Cooper, photograph and biography not available at the time of publication.

Moshe Tur, photograph and biography not available at the time of publication.
Chung-En Zah (M'85) was born in Taiwan, Republic of China, in 1955. He received the B.S. and M.S. degrees from the National Taiwan University, Taiwan, Republic of China, in 1977 and 1979, respectively, and the M.S. and Ph.D. degrees from the California Institute of Technology, Pasadena, in 1982 and 1986, respectively, all in electrical engineering. His thesis research was in the area of millimeter-wave integrated circuits.

In 1985, he joined Bell Communications Research, Navesink Research Center, Red Bank, NJ. He is currently involved in optoelectronic devices research for optical fiber communication systems, including semiconductor lasers and optical amplifiers.

Dr. Zah is a member of the Optical Society of America.

Serafin G. Menocal, Jr. (M'40-LM'77) was born in Havana, Cuba, on August 8, 1952. He received the B.S. degree in physics, with high honors, from Georgia Institute of Technology, Atlanta, in 1974.

From 1975 to 1980, he served as a Line Officer on board an operational nuclear submarine. Subsequently, he joined Bell Laboratories, where he worked on semiconductor laser research in the Lightwave Devices Laboratory. In 1984, the startup of a new research organization led him to Bell Communications Research (Belcore), Red Bank, NJ, where he constructed and operates an advanced laser characterization laboratory. He has done graduate work at Stevens Institute of Technology and is close to completing the M.B.A. degree at Rutgers University, New Brunswick, NJ.

Mr. Menocal is a member of Tau Beta Pi, Sigma Pi Sigma, Phi Eta Sigma, and Phi Kappa Phi. He is also a member of the American Physical Society.