Wavelength Selection for Gigabits-per-Second Data Transmission Using Out-of-Band RF Modulation

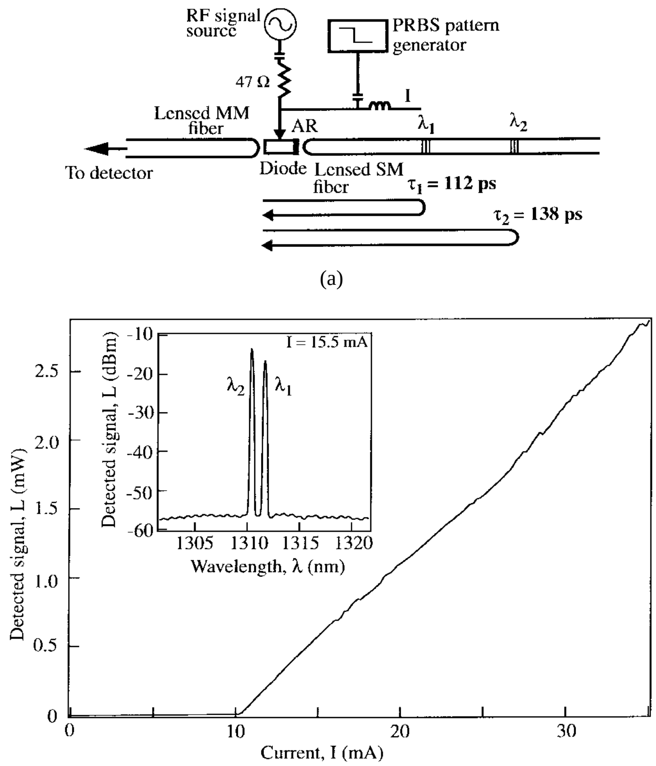
A. P. Kanjamala, *Student Member, IEEE,* and A. F. J. Levi

***Abstract*—Radio frequency modulation of a multicavity laser diode may be used to precisely select lasing optical wavelength for wavelength-division multiplexing (WDM) systems. We demonstrate gigabits-per-second in-band digital data transmission with a low bit-error ratio (BER) and out-of-band radio frequency wavelength selection with −30-dB wavelength selectivity. The same device may also be used to transmit wavelength encoded digital data.**

***Index Terms*—Digital communication, external cavity laser, fiber Bragg grating, multicavity laser, semiconductor lasers, wavelength coding, wavelength-division multiplexing, wavelength tuning.**

A TECHNIQUE to select the lasing wavelength of actively mode-locked optical pulses from a laser diode by radio frequency (RF) modulation was demonstrated in [1] using discrete Bragg gratings and in [2] and [3] using a chirped grating. The scheme of [1] shows a remarkable mode suppression ratio (MSR) of greater than −40 dB and temperature stability far superior to a conventional distributed-feedback (DFB) laser diode. In this letter, we demonstrate transmission of gigabits-per-second digital data at the RF selected optical wavelength via amplitude modulation encoding. Wavelength coding for digital data transmission is also demonstrated.

Fig. 1(a) shows the experimental arrangement used for our data transmission experiments. A 300-mm-long multiple quantum-well (QW) Fabry–Perot semiconductor laser diode [4] has a 0.1% reflecting antireflection (AR)-coated mirror on one side and a 32% reflecting cleaved mirror on the other. Optical emission at wavelength $\lambda = 1310$ nm from the AR-coated side of the diode is coupled with 40% efficiency into a lensed single-mode fiber containing two adjacent Bragg gratings (BG's). The 1-mm-long BG's have center wavelengths $\lambda_1 = 1311.7$ nm and $\lambda_2 = 1310.4$ nm, 75% reflectivity, and −3-dB optical linewidth of 0.24 nm (42.7 GHz) and 0.26 nm (46.2 GHz), respectively. The two BG's define distinct laser cavities at precise optical wavelengths. The photon cavity round-trip time in the multicavity laser (MCL) at wavelength λ_1 (λ_2) is approximately 112 ps (138 ps) with resonant RF frequency at $f_1 = 8.950$ GHz ($f_2 = 7.240$ GHz).



(b)

Fig. 1. (a) Experimental arrangement. Optical emission at $\lambda = 1300$-nm wavelength from the AR-coated side of a MQW semiconductor laser diode is coupled with 40% efficiency into a lensed single-mode fiber containing two BG's. The BG's have center wavelengths $\lambda_1 = 1311.7$ nm and $\lambda_2 = 1310.4$ nm, reflectivity of 75%, and −3-dB optical bandwidth of 0.24 and 0.26 nm, respectively. (b) Measured L–I of the MCL. The inset shows the measured optical spectrum when $I = 15.5$ mA. Lasing occurs at wavelengths λ_1 and λ_2 corresponding to the two BG's.

The steady-state light versus current (L–I) characteristics of the MCL diode with threshold current $I_{th} = 10.5$ mA is shown in Fig. 1(b). Small discontinuities in the L–I curve are likely due to mode hopping between longitudinal external cavity modes [5]. The inset to Fig. 1(b) shows the optical spectrum of the MCL biased at constant current $I = 15.5$ mA with lasing at both BG wavelengths.

The measured small-signal RF response of the MCL shown in Fig. 2 has "out of band" peaks at f_1 and f_2, and their higher harmonics, corresponding to the photon cavity round-trip times of the two BG-defined cavities. At a bias of $I = 15.5$ mA the "baseband" −3-dB optical bandwidth is 1.2 GHz. The inset to Fig. 2 shows that this −3-dB frequency increases with

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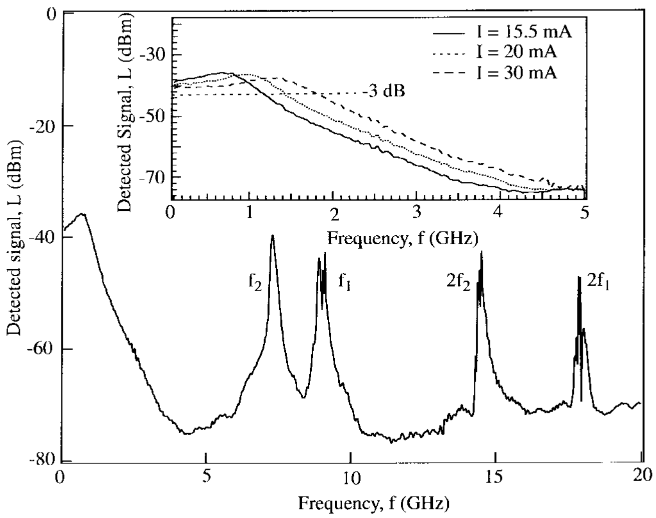

Fig. 2. Measured small-signal RF response of the MCL at a steady-state current bias of I = 15.5 mA. The baseband −3-dB optical bandwidth of the MCL at I = 15.5 mA is 1.2 GHz. The RF spectrum of the MCL shows "out of band" peaks at f_1 and f_2 and their higher harmonics corresponding to the inverse photon cavity round-trip times at wavelengths λ_1 and λ_2 respectively.

bias current. Gigabits-per-second digital data transmission is possible within this baseband.

Modulating the laser with a RF signal at f_1 (f_2) selects lasing wavelength λ_1 (λ_2). The RF power launched from the signal generator is 16 dBm and the laser is biased to a steady-state current I = 15.5 mA. Mode-locked pulses at λ_1 (λ_2) have a −3-dB optical bandwidth of 0.28 nm (0.24 nm). Digital data encoded as a small-signal amplitude modulation of 3 mA on the RF signal at f_1 (f_2) is applied to the MCL. A 1-Gb/s nonreturn-to-zero pseudorandom bit stream (NRZ PRBS) is generated by a pattern generator. The received optical signal is measured using a detector with a −3 dB optical bandwidth of 1.44 GHz. Fig. 3(a) shows the bit-error ratio (BER) versus measured eye opening relative to the clock edge. The measured phase margin at a BER of 10^{-7} is 840 ps and the optical spectrum of the transmitted signal seen in the inset to Fig. 3(a) has a MSR of −30 dB. The measured phase margin for data transmitted with no applied RF is approximately the same as when the RF signal is used to select the lasing wavelength.

Measured BER versus average received optical signal power is shown in Fig. 3(b). Light is collected using a lensed multimode fiber (MMF) and is passed through an optical attenuator before being detected. There is no measurable noise floor with a BER as low as 10^{-11} and digital data was transmitted at wavelength λ_1 (λ_2) for over 2 h with no errors. The inset to Fig. 3(b) shows the eye diagram of the received signal at λ_1. Experiments without a RF signal to select the lasing wavelength indicate that there is a −0.5-dBm power penalty when the RF signal is used to select the lasing wavelength. Thus, our preliminary results suggest that the MCL is a possible candidate for use in WDM systems which require selectable multiwavelength sources.

Wavelength-encoded data transmission is also possible using a MCL diode. In our initial experiments, the laser is biased at I = 25 mA and the coupling efficiency between the MCL and the lensed SMF with embedded BG's is adjusted so that

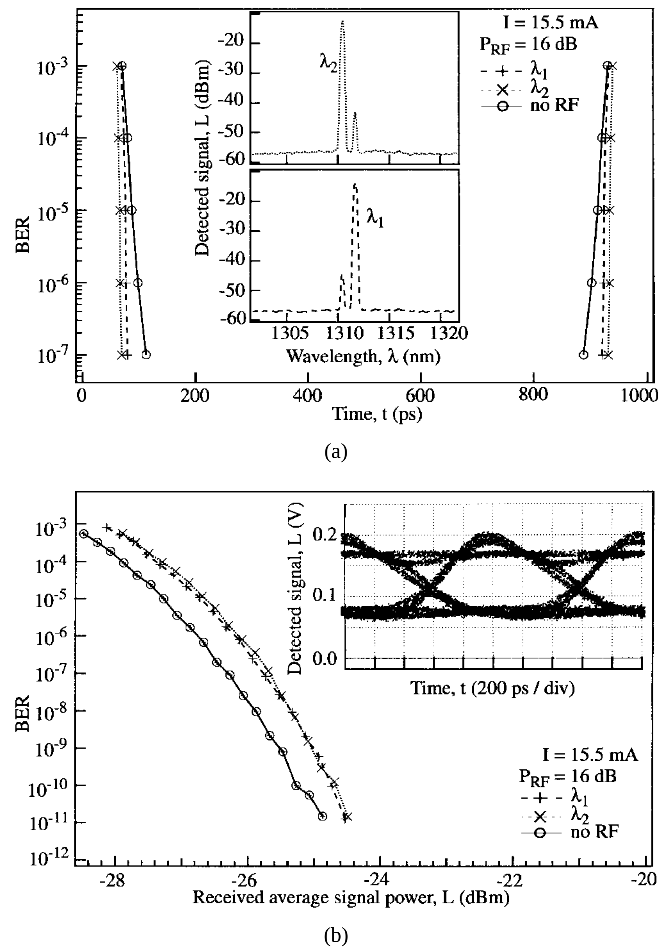

Fig. 3. (a) Measured BER versus eye opening relative to clock edge. A $2^7 - 1$ NRZ PRBS is transmitted at 1 Gb/s. A 16-dBm RF signal launched by the signal generator at f_1 = 8.95 GHz (f_2 = 7.24 GHz) is used to select λ_1 (λ_2). The phase margin at a BER of 10^{-7} is 840 ps. The inset shows the time averaged optical spectrum of the MCL when transmitting digital data at λ_1 (λ_2). (b) Measured BER versus average received optical signal power at λ_1 (λ_2). Inset is eye diagram of received signal for a 1-Gb/s $2^7 - 1$ NRZ PRBS transmitted at wavelength λ_1.

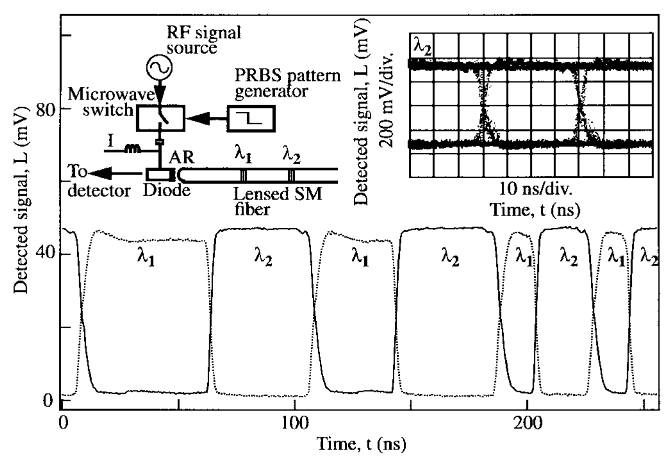

Fig. 4. Measured waveform of wavelength-encoded $2^7 - 1$ NRZ PRBS transmitted at wavelengths λ_1 and λ_2. The transmitted 25-Mb/s signal has a BER of less than 10^{-9}. Inset shows a schematic diagram of the experimental arrangement and the eye diagram of the received signal at wavelength λ_2. Biased at current I = 25 mA, the laser has emission at wavelength λ_1. The 23-dBm RF signal at frequency f_2 incident on the laser is turned on and off using a microwave switch. A logical high-data input turns the microwave switch on and the RF signal selects lasing wavelength λ_2.

the device lases at wavelength λ_1 [5]. A schematic of the experimental arrangement is shown as an inset to Fig. 4. A 23-dBm RF signal at frequency f_2 selects λ_2 as the lasing wavelength. In our first experiments, the RF signal applied to the laser is turned on and off using a microwave switch. Logical high-data input turns the switch on and is encoded as emission at wavelength λ_2. Logical low-data input turns the switch off and is encoded as emission at wavelength λ_1. Wavelength-encoded NRZ PRBS is transmitted at 25 Mb/s with a BER of less than 10^{-9}. Fig. 4 shows a measured time-trace of the transmitted signal at wavelengths λ_1 and λ_2. The eye diagram of the transmitted signal at λ_2 is shown as an inset to Fig. 4. At present the microwave switch limits the wavelength switching rate to less than 100 Mb/s. However, experiments on the transient response of wavelength switching in MCL's [1], [6] indicate that gigabits-per-second data rates are possible in such MCL devices.

In conclusion, we have demonstrated 1-Gb/s digital data transmission at precisely defined optical wavelengths selected using an RF signal applied to a MCL diode. Our results suggest that the MCL is a possible candidate for use in WDM systems which require selectable multiwavelength sources. Preliminary experiments also indicate the multicavity laser diode may be used to transmit wavelength encoded digital data.

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