Dual-Channel Wavelength-Division Multiplexing Using a Composite Resonator Vertical-Cavity Laser

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***Abstract*—We demonstrate the use of a dual-resonator vertical-cavity laser diode as a coarse wavelength-division-multiplexing optical source. Binary data is encoded onto each of the two longitudinal modes, which can be independently modulated through current injection into each cavity. Using a single laser, we demonstrate data transmission on two independent channels.**

***Index Terms*—Composite-resonator vertical-cavity laser (CRVCL), dual-wavelength laser source, vertical-cavity surface-emitting laser (VCSEL), wavelength-division multiplexing (WDM), wavelength-division-multiplexing (WDM) laser source.**

I. Introduction

WHILE vertical-cavity surface-emitting lasers (VCSELs) are considered for a variety of applications, from laser printers to oxygen sensing, the majority of VCSELs are used for short distance data communications. The advantages of VCSELs over edge-emitting lasers in this area include lower threshold current and better coupling to optical fiber due to a circular output beam. Reducing the size and cost of a multiwavelength laser source and reducing the number of components for wavelength-division-multiplexing (WDM) applications may enable new low-cost local area networks. To replace multiple lasers with a single laser, one technique has been to pack the sources closely together so that the light emitted from all the sources can be coupled into a single multimode fiber [1]. Note that replacing several lasers with a single laser eliminates the need for an optical multiplexer, further reducing the component cost.

In this letter, we demonstrate for the first time the use of a *single* laser, the composite-resonator vertical-cavity laser (CRVCL), as a coarse WDM (CWDM) optical source. The CRVCL supports two longitudinal modes, with the wavelength separation between the modes controlled by the number of middle distributed Bragg reflector (DBR) pairs [2]. Novel laser functionality is enabled because of dual-wavelength operation [3], coupled-cavity modulation [2], Q-switching [4], picosecond pulse generation [5], bistable operation [6], and high single-mode power operation [7]. In this letter, we show that two channels of binary data can be encoded independently onto the two longitudinal modes of the CRVCL.

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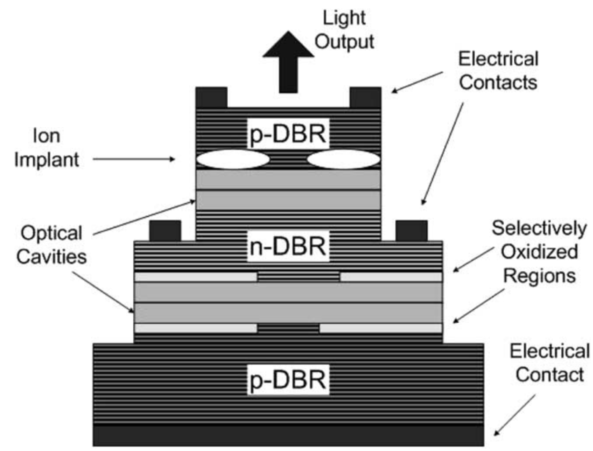

Fig. 1. Device structure for the CRVCL.

II. Results and Discussion

The CRVCL is composed of two cavities and three mirrors [4]. The two cavities in the CRVCL are optically coupled but electrically independent, allowing the two longitudinal modes to be operated independently by varying the level of current injection into each of the optical cavities. Fig. 1 shows a schematic of the CRVCL structure, which is composed of a bottom p-type DBR with 35 periods, a middle n-type DBR with 14.5 periods, and a top p-type DBR with 21 periods. Metal contacts are deposited on top of each tier of the double mesa structure as well as on the backside of the laser to allow independent electrical biasing of the top and bottom cavities. Electrical confinement in the top cavity is provided by a proton implant aperture with a 6-μm diameter. Selective wet oxidation is used to form a 10×10 μm^2 oxide aperture in the bottom cavity [8]. The different number of DBR periods in the three mirrors as well as the differences in aperture size contribute to unequal output powers at the two cavity resonances and affects the relative distribution of the longitudinal modes between the two cavities [8]. Each cavity is one wavelength long and contains five GaAs quantum wells.

The optical coupling between the two cavities, which is a function of the number of periods in the middle DBR, results in a wavelength splitting between the cavity resonances [2]. Lasing is, thus, possible at two wavelengths whose wavelength separation can be accurately designed. Fig. 2 shows spectra from a CRVCL with the implant cavity current fixed ($I_{\text{implant}} = 10$ mA) while the oxide cavity current is varied. Lasing can occur in groups of transverse modes associated with each of the two longitudinal modes. For low values of current, the laser is below threshold. As the oxide cavity current is increased, lasing

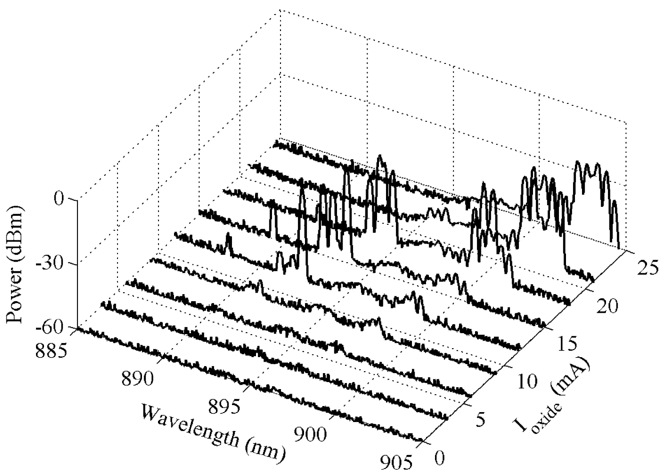

Fig. 2. CRVCL spectra for a constant implant cavity current and varying oxide cavity current.

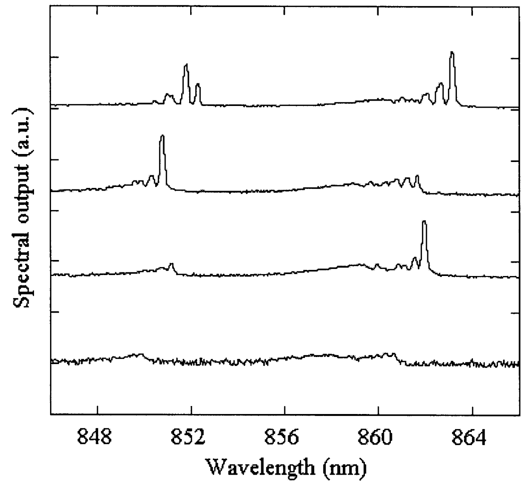

Fig. 3. CRVCL spectral output for the different logic states; $I_{\rm top}(I_{\rm bottom}) =$. (a) 0.1 (0.1 mA), (b) 5.1 (0.1 mA), (c) 0.1 (6.1 mA), (d) 5.1 (6.1 mA).

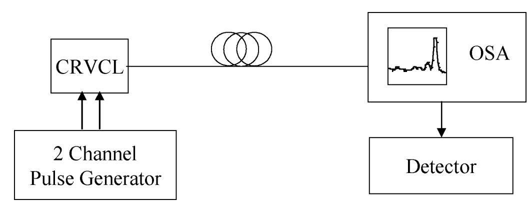

Fig. 4. Setup of CWDM interconnect experiment.

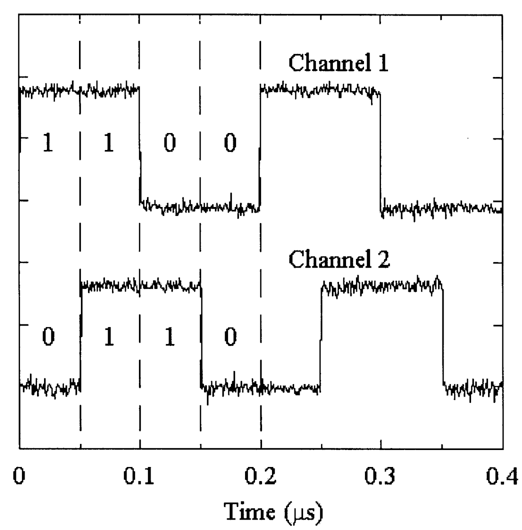

Fig. 5. Electrical inputs to Channel 1 (top) and Channel 2 (bottom) and their corresponding logic values.

occurs first at the short wavelength resonance, then at both resonances, and finally only at the long wavelength resonance. The red shift of the lasing wavelengths of resonances is due to the change of the refractive index brought about by thermal effects. Changing the implant cavity current shifts the values of the oxide cavity current where the lasing transitions occur [8]. Nevertheless, we find that lasing in one or the other longitudinal mode or both can be achieved using three bias conditions.

Independent control of the dual lasing wavelengths of the CRVCL provides the means to produce a two-channel CWDM source using a single laser which can be directly coupled to optical fiber. The four logic states in a two-channel system (01, 10, 11, and 00) are represented by lasing only at the long wavelength resonance, lasing only at the short wavelength resonance, lasing at both resonances simultaneously, and no lasing at all. As illustrated by Fig. 2, all four logic states can be achieved by applying a constant bias to one cavity and switching between four different injection current values into the other cavity. To reduce the complexity of the current source, the four logic states can also be obtained by a more practical modulation scheme in which each cavity is modulated by its own current source. Thus, two current sources, each varying between two levels, can be used to modulate a CRVCL, as verified by Fig. 3. This biasing arrangement also allows for independent data streams on each of the modulating current sources.

We have examined a two-channel CWDM interconnect using a single CRVCL as the dual-wavelength source. The experimental setup is shown in Fig. 4. A dual-output Agilent 8110A pulse generator is used to modulate the coupled cavities. A timing diagram of the two data channels is shown in Fig. 5. The two data channels allow for the four possible logic levels to be applied: 10, 11, 01, 00. The output of the CRVCL is coupled into a 62.5-μm diameter multimode fiber (5 m in length) and sent to an Agilent 86141B optical spectrum analyzer operated in filter mode with a resolution bandwidth of 5 nm. The 5-nm bandwidth is necessary to account for wavelength shifts between the different bias conditions (Fig. 2). Additionally, the bias levels need to be set such that the received power of the two ON-states for each channel are the same whether the device is lasing at one or both cavity resonances. The output of the filter is measured by a Broadband Communications Products 310B Si avalanche photodiodes detector. The detector response is captured by an oscilloscope and is plotted as a function of time in Fig. 6. Fig. 6(a) and (b) shows the detector response for Channel 1 (pattern 1100) and Channel 2 (pattern 0110), respectively.

While both channels transmit the correct data, there is significant overshoot apparent in Fig. 6, particularly when the two cavities are lasing simultaneously. This could be due to electrical or optical coupling between the cavities. If the two modes are correlated due to mode competition in the same gain regions,

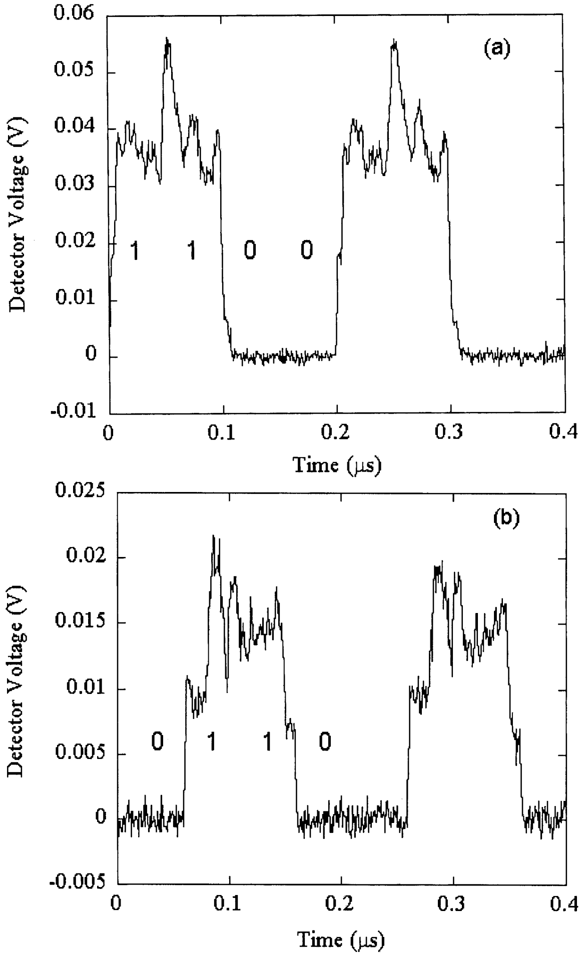

Fig. 6. Logical output from (a) Channel 1 (pattern 1100) and (b) Channel 2 (pattern 0110).

some amount of crosstalk would be expected. The relative intensity noise (RIN) at the bias conditions is measured as well. The RIN peak is observed at 2.6 GHz when biased for the long wavelength resonance and at 1.5 GHz when biased at the short wavelength resonance. When both wavelengths are lasing, the RIN peak is at 2.2 GHz, though the signal is greatly reduced. This reduction in noise may be due to the correlated nature of the two lasing modes and is under investigation.

The aggregate modulation speed is 20 Mb/s. Though small signal modulation speeds of over 20 GHz [9] have been reported for conventional VCSELs, the structure of the CRVCL devices studied here has not been optimized for high-speed operation. DC probes are used to contact the two topside concentric electrical contact rings, while the third contact, through which a forward bias to the lower cavity is applied, is broad area (see Fig. 1). The maximum applied modulation frequency for this configuration is limited to the tens of megahertz. Coplanar bond pads would allow for the use of high-speed probes, eliminating bandwidth limitations of the dc probes presently used. We have positioned a high-speed ground-signal probe across the opposite corners of the concentric contact rings. The rise time for the upper cavity when large signal modulated at a rate of 1.25 GHz is 0.161 ns, suggesting an upper frequency limit of almost 3 GHz, in agreement with the observed RIN peak at 2.6 GHz. An estimate for the lower cavity cannot be done in a similar manner since both contacts are not on the top side of the wafer.

III. Conclusion

We demonstrate two-channel modulation from a single laser, eliminating the need for an optical multiplexer if used as a CWDM optical source. Independent modulation of the two optical cavities in a CRVCL faithfully transmitted a two-channel bitstream with an aggregate data rate of 20 Mb/s. The measured bandwidth is presently hampered due to the device design since the absence of high-speed contacts limits the measurement. However, risetime estimates and RIN measurements suggest modulation frequencies above 1 GHz are possible. The number of channels could potentially be increased by incorporating additional longitudinal cavities and contacts into the epitaxial structure. Therefore, the multiple lasing wavelengths represent new CRVCL functionality that offer potential advantages for low-cost WDM applications.

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