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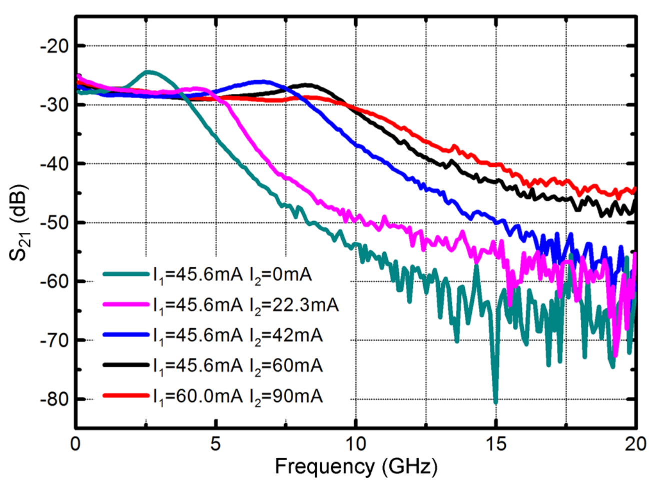

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Integrated Two-Section Discrete Mode Laser

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Abstract: The authors present the design and characterization of a novel integrated two-section discrete mode index patterned diode laser source. The two slotted regions etched into the laser ridge waveguide are formed in the same fabrication step as the ridge, thus avoiding the requirement for complex lithography and regrowth steps. The laser is encased in a temperature-controlled butterfly package, which simplifies the static and dynamic measurements. Initial static characterization of this two-section laser shows that the injection, from the master laser to the slave laser, enhances the slave's emission side-mode suppression ratio from 30 dB to over 50 dB and its relative intensity noise is reduced from about −129.3 dB/Hz to −142.6 dB/Hz. Subsequent dynamic characterization then shows that the modulation bandwidth of the laser can be improved via injection to about three times the inherent free-running bandwidth. Hence, optical injection from master section into slave section enables the improvement of various parameters, which makes this two-section device attractive as a transmitter in optical communication systems.

Index Terms: Optical injection locking, direct modulation, frequency response, relative intensity noise (RIN).

1. Introduction

Optical injection, to modify the characteristics of free-running semiconductor lasers, has been a popular field of study over the past few decades. The advantageous properties that can be derived from optical injection include the reduction of chirp [1]–[4], relative intensity noise (RIN) [5]–[7], nonlinear distortion [8], [9], and mode partition noise [10], [11]. The relaxation oscillation frequency and modulation bandwidth are two other important figures-of-merit, especially for directly modulated lasers (determines the maximum data rate achievable). In a free-running laser, the maximum modulation bandwidth is determined by the k-factor [12]. One method of increasing the laser resonance frequency and/or the modulation bandwidth is to employ the external injection-locking technique [12], which involves using two lasers in a master–slave configuration. Previous studies have illustrated that light injected from a master laser into a slave laser can result in a significant improvement of the modulation bandwidth beyond the k-factor limit [13], [14]. When injection-locking conditions are satisfied, the frequency of the slave laser is locked to that of the master laser with a constant phase offset. Two important injection-locking parameters are frequency detuning, Δf, which is the frequency difference between the master and the free-running slave laser, and injection ratio, R, which is the ratio between the injected power from the master laser and the power of the free-running slave laser. Most of the reported work on external optical injection thus far has been based on the use of multiple discrete devices including the master and slave lasers [1]–[8]. A circulator/coupler, polarization controller, and/or an isolator would be passive components required for the successful realization of this master–slave optical injection setup. Hence, such an experimental arrangement would suffer from various sources of instability such as polarization dependence and temperature variation in the injection path. Integration of the two lasers (master and slave) would alleviate the aforementioned problems, reduce the insertion losses incurred, reduce the footprint, and improve the mechanical robustness. Hence, monolithic integration offers a simplified and cost-efficient solution for the realization of external optical injection and also offers the possibility of integrating with other elements to enable the making of a highly functional photonic integrated circuit (PIC). The fabrication of monolithic PICs involves building devices into a common substrate so that all photonic couplings occur within the substrate and all functions are consolidated into a single physically unique device. This brings benefits, including significant packaging consolidation, testing simplification, reduction in fiber couplings, improved reliability, and maximum possible reduction in space and power consumption per device. Other related work, previously reported, involving monolithic integration of lasers for optical injection includes mutual injection locking of coupled cavity distributed Bragg reflector (DBR) lasers [15]. The main result demonstrated by the authors in this paper is the enhancement of the relaxation oscillation frequency to about 35 GHz. Another work involves the passive feedback distributed feedback (DFB) laser, proposed by Bornholdt *et al.*, where a passive feedback section is integrated with an active DFB section. Here, the authors report on enhancing the inherent modulation bandwidth by a factor of 3 (up to about 27 GHz) [16]. In this paper, we propose to achieve optical injection locking by fabricating a structure, which integrates the master and slave discrete mode (DM) [17] lasers on a single all-active chip. This makes the optical in, jection process simple, cost effective, and polarization independent compared with external optical injection from a separate laser. To the best of our knowledge, this is the first time such a dual-section DM laser device has been fabricated and a detailed device analysis reported on. A unique selling point of this laser is that it enables multiple applications by improving basic laser parameters such as the RIN, modulation bandwidth, side-mode suppression ratio (SMSR), and linearity. Moreover, the waveguide structure requires only a single growth stage and uses optical lithography to realize the ridge. Hence, all the aforementioned positive attributes can be realized at a relatively low cost. The paper is organized as follows: Section 2 describes the fabrication and structure of the integrated DM laser used in this paper. Section 3 focuses on the static characterization of this integrated device, which includes LI curves for both sections, optical spectra from the slave section with the master section turned off and on (without and with external injection), and also portrays the effects of injection on parameters such as RIN. In Section 4, we concentrate on the dynamic characterization of the device again under the two scenarios of operation (with and without injection). The main results illustrated in the latter section, under free-running and injection-locked conditions, are the frequency response curves of the slave section, intermodulation distortion, and direct on–off keyed modulation at 10 Gb/s.

2. Device Description

The dual-section DM device is schematically shown in Fig. 1. The laser is a ridge waveguide laser with a ridge width of 2.5 μm. The laser cavity is 700 μm long and is divided into two sections. Section 1 is 400 μm in length, while section 2 is 300 μm. For simplicity, from here on, section 1 will be referred to as the slave section, while section 2 will be called the master section. The two adjacent sections were separated by an etched trench that is 2 μm wide. Using the methods described in [18], a pattern of index perturbations was calculated to give single-mode emission at $\lambda = 1539.4$ nm at 25 °C for section 1 and $\lambda = 1540.5$ nm for section 2 when biased at about $3I_{th}$.

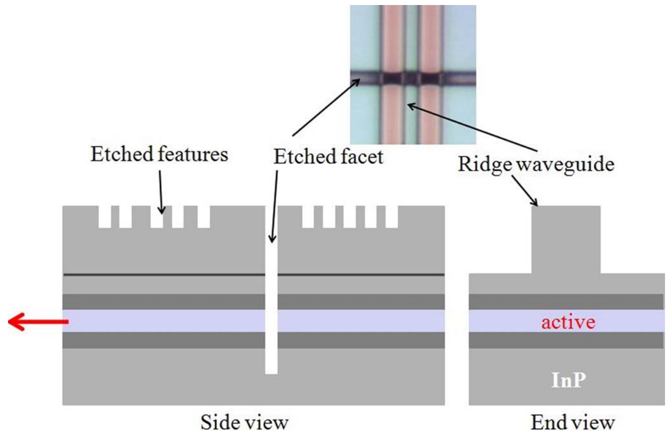

Fig. 1. Two-section injection-locking structure with a DM laser in section 1 and another DM laser in section 2. A deep ICP etch has been defined to electrically isolate the two sections.

The ridge and index perturbations were realized in the ridge upper surface using standard etch techniques used to fabricate Fabry–Pérot ridge waveguide lasers. A silicon oxide hard mask was patterned lithographically to outline both the ridge and index perturbation features. Dry etching using inductive coupled plasma using a Cl/N_2 chemistry was used to target the approximate target depths of the features, and finally, a material-selective wet etch ensured that the depths were uniform and accurate across the wafer. All surface etched features are in the upper waveguiding layers and do not extend to the Al-containing waveguide or active region.

The laser active region consists of five compressively strained (Al0.23Ga)0.3In0.7As quantum wells with a well thickness of 5 nm whose composition is chosen to give a photoluminescence wavelength centered at $\lambda = 1540$ nm. The final step in the surface processing is a deep ICP etch $(> 4\ \mu\text{m})$ to define the trench, isolating section 1 from section 2. As the etched trench acts as a back facet for section 1 and a front facet for section 2, a wet etch was next employed to reduce the surface roughness of the trench. Electrical contacting for both sections was achieved using conventional metals and SiO2 as an insulator for contact definition. Finally, the wafers were thinned by mechanical polishing, backside metals applied and the devices were cleaved to 700-μm total cavity lengths with the exterior front and back facets coated to be 30% and 95%, respectively.

3. Static Characterization

Cost-sensitive applications such as the access and enterprise markets would be better served with transmitters that operate in a predictable fashion and can be directly modulated. In addition, single longitudinal mode operation, with a high SMSR, high linearity, and low RIN properties would be highly advantageous. The first measurement of light versus current (LI) was carried out on-chip by dc probing the chip. The light was collected at the front and the back for the slave and master sections of the laser, respectively. Subsequently, in order to simplify the experimental characterization, the two-section integrated DM laser was encased in a temperature-controlled hermetically sealed seven-pin butterfly package. An RF connector attached to the slave section enabled direct modulation. It is important to note that the two sections could be biased independently since the lasers are electrically isolated by a deeply etched trench between them.

Fig. 2 plots the LI curve for the slave section (where master section is unbiased), which, in effect, is a DM laser with a cavity length of 400 μm (black line). The LI curve is linear, and the lasing threshold current is 21 mA. The high threshold can be attributed to the increased mirror loss through the use of uncoated front and back facets of 30%, arising from the semiconductor/air interface. Overlapped on Fig. 2 is the LI curve for the master section, which consisted of a DM laser with a cavity length of 300 μm. The power was measured from the HR coated back facet, hence the low output power (red line). The LI curve is linear with a lasing threshold of 12 mA and demonstrates

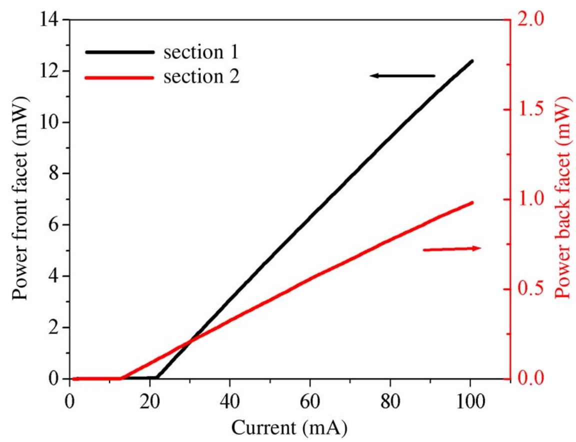

Fig. 2. Light-current curves from the individually biased slave and master lasers at a heat sink temperature of 20 °C. Threshold currents of 21 mA for the slave section and 12 mA for the master section have been extracted. The light from master section was measured out through the HR coated back facet.

that the ICP etched facet is of high quality. It should be noted that the laser operates in single-mode condition under most combinations of current applied to the master and slave lasers. This was verified by carrying out a sweep of the currents applied to both sections while observing the emission wavelength. However, certain operating points provide enhanced single-mode operation (high SMSR) in comparison with the rest. Such single-moded operating points with high SMSR ($>$ 30 dB) were obtained in the case of the slave laser over a bias current swing of 40 mA (ranging from slightly above threshold to about 60 mA), and in the case of the master laser, a 30-mA current swing ranged from 40 to 70 mA. Hence, two such operating points were chosen to perform the rest of the experimental characterization in this paper. The first of the operating points involved dc biasing only the slave section, while the second entailed biasing both slave and master sections. The latter implies that the light from the master section is used to injection lock the slave section to ensure that single-mode emission with SMSR in excess of 50 dB is achieved. The aforementioned scenarios were accomplished by initially setting the slave section bias at 45.6 mA and the master section bias at 0 mA, and subsequently keeping the slave section biased at 45.6 mA and turning on the master section and setting its bias to 50 mA. The optical spectra of the two section laser under both of the conditions are shown in Fig. 3.

As can be clearly seen in this diagram, the laser under both conditions was single moded. The red line denotes the case when only the slave section was biased, while the blue line shows the spectrum for the case where both the master and slave sections were biased. The SMSR with only the slave section turned on was about 30 dB. However, once the master was switched on to inject into the slave section, the SMSR was improved yielding an output SMSR of almost 60 dB. The figure also shows that turning on the master section resulted in the excitation of the adjacent side mode at the longer wavelength (side cavity mode of slave laser coincides in wavelength with main mode of master laser). The additional wavelength shift of about 0.2 nm can be attributed to the cavity mode shifting under injection locking. This occurs due to the change of carrier concentration in the slave cavity when subjected to external injection [19].

The final aspect of the static characterization entailed carrying out RIN measurements on the two-section DM laser. The setup diagram used for the characterization of the RIN is shown in Fig. 4. The optical output of the device under test (DUT) is passed through an isolator (ISO) and then coupled into a 50-GHz photodetector (PD) from U2T. The output of the PD, after being passed through a bias tee and amplified, is characterized with the aid of an electrical spectrum analyzer (ESA). The RIN measurements [20] were also carried out under the two previously mentioned operating scenarios, i.e., slave section on with master section off (no injection) and slave and master sections on (under external injection).

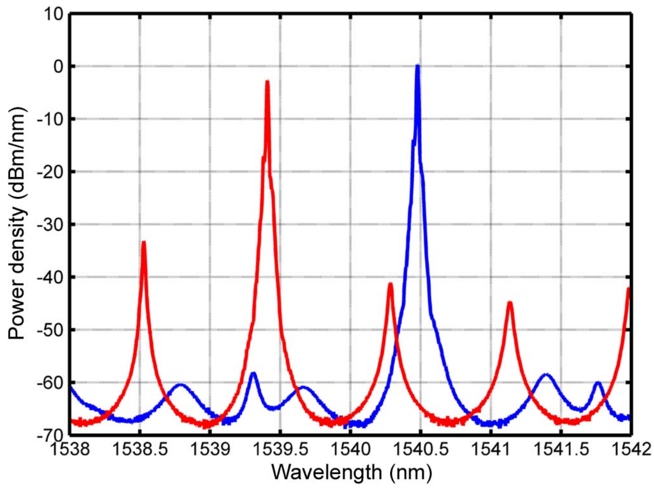

Fig. 3. CW optical spectra of the two-section monolithically integrated DM laser. The red line corresponds to the spectrum when only the slave laser is turned on while the blue line shows the spectrum for the case where both the slave and master lasers are turned on.

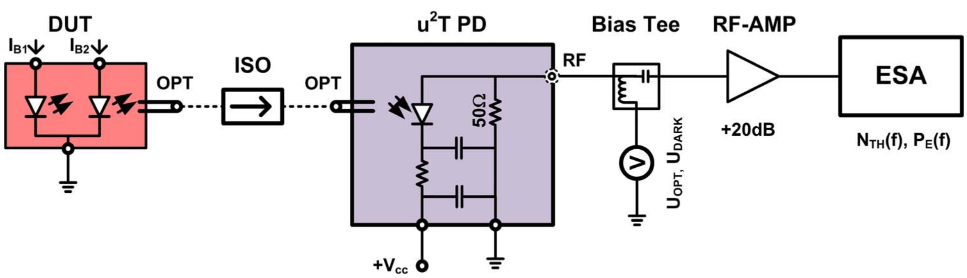

Fig. 4. Experimental setup used for RIN measurements on the two-section laser.

The achieved results are shown in Fig. 5. The averaged RIN (0.6 to 10 GHz) for the case where only the slave section was turned on was about −129.3 dB/Hz. In this case, the slave section was biased at 45.6 mA, and the master was biased at 0 mA. The averaged RIN (0.6 to 10 GHz) for the second scenario where both the master and slave sections were turned on was measured to be −142.6 dB/Hz. Here, again, the slave section bias is maintained at 45.6 mA, while the master section bias was set at 50 mA. Note that this was the same operating point chosen for the recording of the optical spectra in Fig. 3.

The reduction of the RIN under external injection is a well-studied phenomenon and is essentially due to the injected signal reducing the cavity gain and depleting the carrier density. This, in turn, decreases the spontaneous emission rate, thereby reducing the overall RIN of the laser [21], [22].

4. Dynamic Characterization

External modulation of lasers is currently the most common method to modulate a light-wave signal in optical communication systems. Although this technique provides high speed and stable data modulation, the large insertion losses and the polarization dependence of the modulator can prove to be cumbersome. The extra optical component also adds to the cost and complexity of the transmitter, rendering this technique unsuitable for cost-sensitive applications. On the other hand, direct modulation is one of the most simple and cost-efficient techniques to modulate light-wave signals, providing a low-cost small form factor transmitter. Such attributes are pertinent especially when designing cost-effective networks such as broadband optical access networks.

Nevertheless, the direct modulation technique suffers from a few major drawbacks such as the frequency fluctuation (chirp) imposed on the signal, nonlinearity of the laser frequency response, and

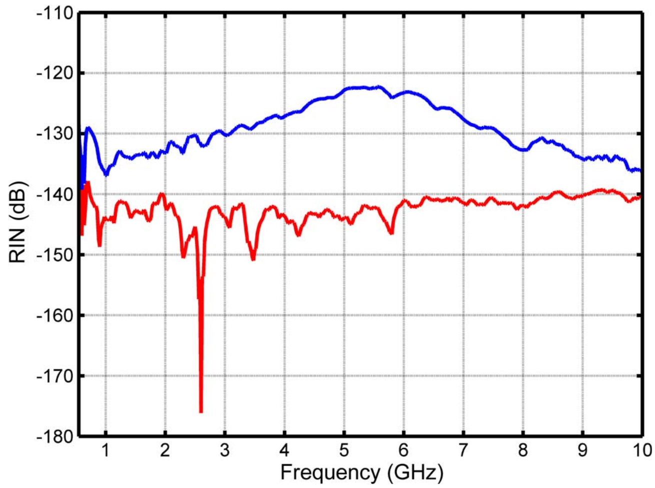

Fig. 5. RIN measurement of the two-section monolithically integrated DM laser. The blue line corresponds to the RIN when only the slave laser is turned on while the red line shows RIN for the case where both the slave and master lasers are turned on.

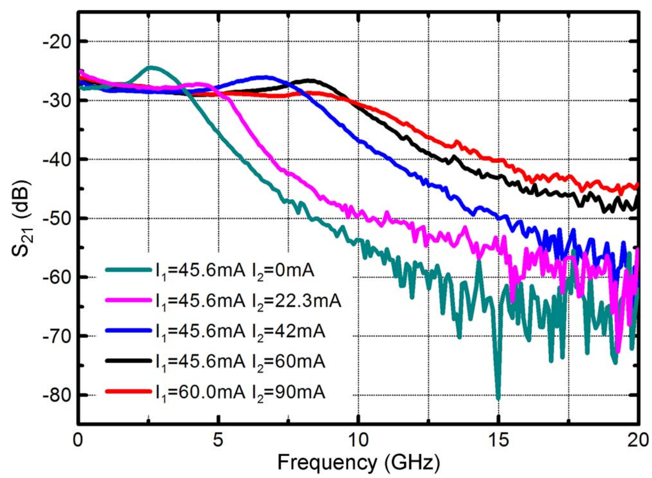

Fig. 6. Frequency response of the two-section monolithically integrated DM laser. The different colors correspond to different bias scenarios (currents on the slave and master sections of the laser).

the limited bandwidth of the lasers. However, as previously mentioned, most of these derogatory effects can be overcome by employing external injection of light into the directly modulated laser.

Fig. 6 shows the small-signal frequency response plot of the two-section laser under a few different bias configurations. The output of the 50-GHz network analyzer was used to directly modulate the slave section. The fiber-coupled output from the slave section was passed into a 90:10 coupler, and the signal from the 90% arm was detected by a 50-GHz photodiode and then directed back to port 2 of the network analyzer. The 10% monitor tap was used to ensure that the optical spectrum was always single moded (SMSR $>$ 30 dB). The green line indicates the free-running slave section at a bias of 45.6 mA (master section bias set at 0 mA). This clearly indicates that the modulation bandwidth of the slave section on its own is limited to about 3 GHz. However, by biasing the master section, thereby enabling injection into the slave section, the modulation bandwidth of the slave section is enhanced.

The purple, blue, and black lines show that, when the slave is biased at 45.6 mA and the master at 22.3, 40, and 50 mA, the modulation bandwidth can be enhanced up to about 5.5, 8.5, and 10 GHz, respectively. The red line corresponds to the case where the slave laser is biased at

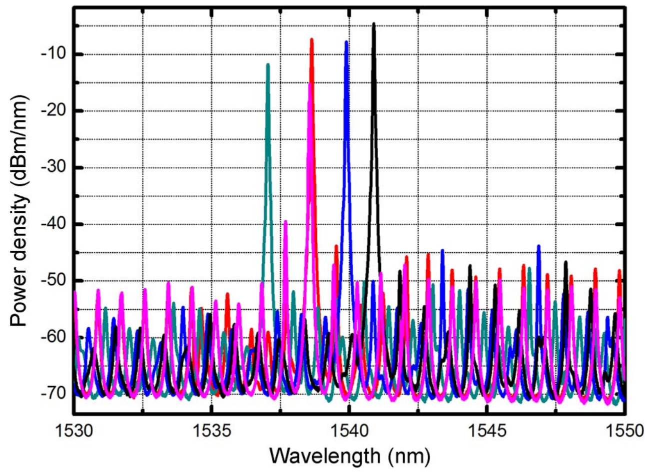

Fig. 7. Optical spectra of the two-section monolithically integrated DM laser corresponding to the bias conditions used for the frequency response plots. Free running slave section biased at 45.6 mA is denoted by the green line while the purple, blue and black relate to a slave current of 45.6 mA and a master section current of 22.3, 40 and 50 mA. The red line then relates to the case where the slave section is biased at 60 mA and the master section at 90 mA.

60 mA and the master laser bias is set at 90 mA. We can see that the bandwidth in this case is also enhanced to 10 GHz. Hence, increasing the bias in the slave section and also increasing the injection power (by increasing the master section bias current) do not enhance the bandwidth any further. This indicates that the bandwidth enhancement is limited to about 10 GHz and can mainly be attributed to the packaging. The enhancement of the relaxation oscillation frequency depends on the strength of the injected optical signal and the detuning between the optical frequencies of the injected signal and the free-running laser [23], [24].

The 10% optical coupler tap was used to monitor the optical spectrum (illustrated in Fig. 7) to ensure that it was always single moded (SMSR $>$ 30 dB). As mentioned in the static characterization section, certain operating points provide enhanced single-mode operation ($>$ 40-dB SMSR) in comparison with the rest (30-dB SMSR). The spectra corresponding to the response curves in Fig. 6 are depicted by matching colors in Fig. 7. Hence, the green line corresponds to the case of the free-running slave section, while the purple, blue, and black relate to a slave current of 45.6 mA and a master section current of 22.3, 40, and 50 mA, respectively. The red line then relates to the case where the slave section is biased at 60 mA and the master section at 90 mA.

The next aspect of the dynamic characterization involved evaluating the linearity of the two-section laser with the slave section in a free-running state and subsequently under injection. A two-tone test provides an indication of the level of nonlinearity introduced to the system. It is well known that the nonlinear distortions become more severe as the modulating frequency approaches the relaxation oscillation frequency due to the nonlinear coupling between the electrons and photons [25]. Hence, if the relaxation oscillation frequency is increased, the level of the third-order intermodulation distortion (IMD3) can be reduced. The slave section was directly modulated with two tones (separated by 39.06 MHz) at around 3 GHz, and the output optical signal was detected and then recorded while the slave alone was lasing (biased at 45.6 mA) and also while both the master (biased at 50 mA) and slave (biased at 45.6 mA) were biased to achieve optical injection. This reduction in nonlinearity, achieved via external injection, could be important for subcarrier multiplexed, radio-over-fiber, and/or OFDM systems [9], [26]. By performing this test for both operating conditions, the reduction in nonlinearity due to optical injection can be estimated. Fig. 8 shows that there is a decrease of 10 dB, from -15 dB to -25 dB, in IMD3 when optical injection is employed. As mentioned earlier, the RF connector on the slave section enables direct modulation. A pseudo-random bit sequence of length $2^{15} - 1$ at a bit rate of 10 Gb/s was applied to the slave section when it was biased at 45.6 mA.

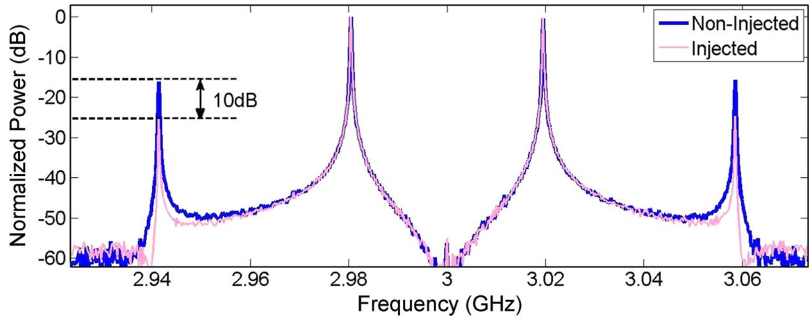

Fig. 8. Example two tone test at 3 GHz showing the IMD3 under free-running and external injection scenarios.

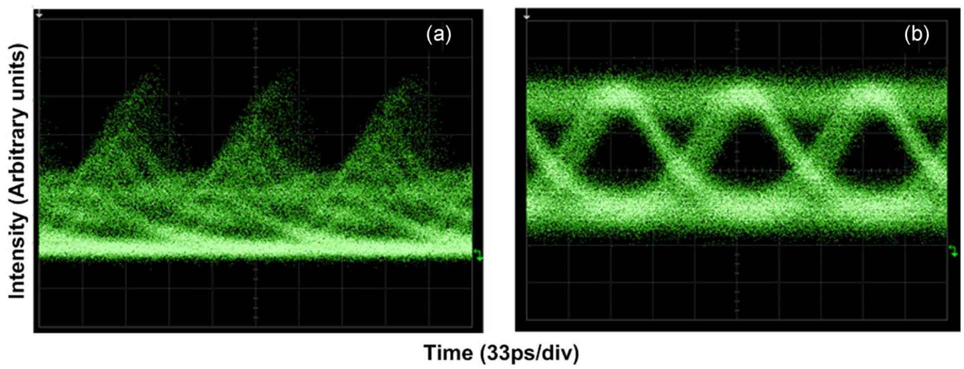

Fig. 9. Eye diagram of the two section monolithically integrated DM laser with the (a) only slave section biased at 45.6 mA (b) slave section biased at 45.6 mA and master section biased at 50 mA.

Qualitative (eye diagrams) and quantitative [bit error rate (BER) as a function of the received optical power] analyses of this two-section laser under modulation were carried out and shown in Fig. 10. The resulting eye diagram is shown in Fig. 9(a). It is completely closed essentially due to the limited bandwidth at the chosen operating point. The black line in Fig. 10 depicts the BER as a function of received power for the same scenario mentioned above. The line clearly shows an error floor at $\sim 1e^{-2}$. However, when the master section was turned on and its bias was set to 50 mA, the modulation results in a clear and open eye, as illustrated by Fig. 9(b). The related BER versus received power performance of this scenario is depicted by the blue line in Fig. 10. An additional quantitative result for the case where the slave bias was set at 45.6 mA and the master bias set at 40 mA is portrayed by the red line. The 3-dB penalty (at reference BER of $1e^{-9}$) between the red line with respect to the blue line can be attributed to the difference in the response between the two bias scenarios (as shown in Fig. 6).

As portrayed in Fig. 6, the latter two operating points were confirmed to improve the inherent modulation bandwidth, thereby improving the performance reflected by the open eye and enhanced BER performance. This enhancement demonstrates that the viability of such a device, which has to be mentioned, is at a proof-of-concept stage. We strongly feel that improved device design and superior packaging would enhance the performance of this two-section laser to yield much higher frequency of operation.

5. Conclusion

Integrating two DM lasers that can be injection locked has been shown to be a versatile, low-cost, and low-complexity technique that could be employed in a variety of low-cost applications. The absence of regrowth or high-tolerance steps such as buried grating formation offers the possibility of

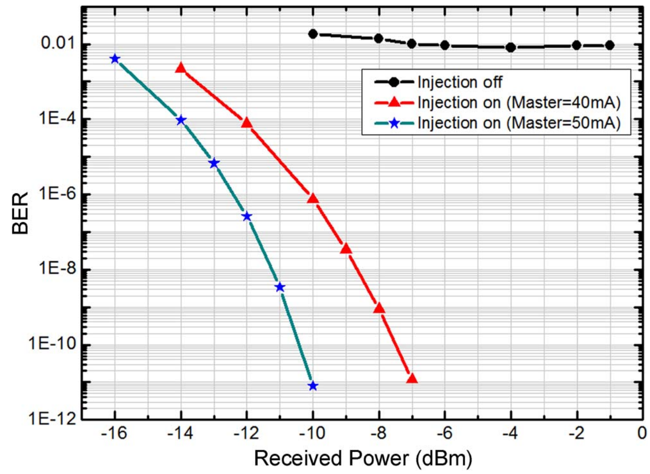

Fig. 10. BER versus received optical power for three different bias scenarios. Black line shows the case where the slave section is free running at a bias of 45.6 mA. The red and the blue lines show the cases where the slave section is biased at 45.6 mA and the master section is set at 40 and 50 mA, respectively.

obtaining high-performance single-mode sources with the high yields and low-cost fabrication that will be required by the consumer optical communications market. This paper has shown that the integrated two-section laser, when implemented in an injection regime, improves the static and dynamic characteristics of the transmitter. Experimental verification has shown that the injection improves the SMSR from about 30 dB to $>$50 dB, reduces the RIN from approximately $-$129.3 dB/Hz to $-$142.6 dB/Hz while it enhances the modulation bandwidth from 3 GHz to 10 GHz, and also reduces the nonlinearity by about 10 dB. We strongly feel that, if the laser packaging were to be improved, the bandwidth enhancement can be enhanced well above the current 10-GHz limit that we report in this paper. This is part of the ongoing developmental work together with improved device design.

Acknowledgment

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References

[1] C. Lin and F. Mengel, "Reduction of frequency chirping and dynamic linewidth in high-speed directly modulated semiconductor lasers by injection locking," *Electron. Lett.*, vol. 20, no. 25, pp. 1073–1075, Dec. 1984.
[2] N. Olsson, H. Temkin, R. Logan, L. Johnson, G. Dolan, J. van der Ziel, and J. Campbell, "Chirp-free transmission over 82.5 km of single mode fibers at 2 Gbit/s with injection locked DFB semiconductor lasers," *J. Lightw. Technol.*, vol. 3, no. 1, pp. 63–67, Feb. 1985.
[3] P. Anandarajah, C. Guignard, A. Clarke, D. Reid, M. Rensing, L. Barry, G. Edvell, and J. Harvey, "Optimized pulse source employing an externally injected gain-switched laser diode in conjunction with a nonlinearly chirped grating," *IEEE J. Sel. Topics Quantum Electron.*, vol. 12, no. 2, pp. 255–264, Mar./Apr. 2006.
[4] S. Mohrdiek, H. Burkhard, and H. Walter, "Chirp reduction of directly modulated semiconductor lasers at 10 Gb/s by strong CW light injection," *J. Lightw. Technol.*, vol. 12, no. 3, pp. 418–424, Mar. 1994.
[5] T. Simpson, J. Liu, and A. Gavrielides, "Bandwidth enhancement and broadband noise reduction in injection-locked semiconductor lasers," *IEEE Photon. Technol. Lett.*, vol. 7, no. 7, pp. 709–711, Jul. 1995.
[6] R. Zhou, S. Latkowski, J. O'Carroll, R. Phelan, L. P. Barry, and P. Anandarajah, "40 nm wavelength tunable gain-switched optical comb source," *Opt. Exp.*, vol. 19, no. 26, pp. B415–B420, Dec. 2011.
[7] L. Chrostowski, C.-H. Chang, and C. Chang-Hasnain, "Reduction of relative intensity noise and improvement of spur-free dynamic range of an injection locked VCSEL," in *Proc. 16th Annu. Meet. IEEE LEOS*, Oct. 2003, vol. 2, pp. 706–707.
[8] X. Meng, T. Chau, D. Tong, and M. Wu, "Suppression of second harmonic distortion in directly modulated distributed feedback lasers by external light injection," *Electron. Lett.*, vol. 34, no. 21, pp. 2040–2041, Oct. 1998.

[9] C. Browning, K. Shi, S. Latkowski, P. M. Anandarajah, F. Smyth, B. Cardiff, R. Phelan, and L. P. Barry, "Performance improvement of 10 Gb/s direct modulation OFDM by optical injection using monolithically integrated discrete mode lasers," *Opt. Exp.*, vol. 19, no. 26, pp. B289–B294, Dec. 2011.

[10] K. Iwashita and K. Nakagawa, "Suppression of mode partition noise by laser diode light injection," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-30, no. 10, pp. 1657–1662, Oct. 1982.

[11] P. Anandarajah, L. Barry, and A. Kaszubowska, "Performance issues associated with WDM optical systems using self-seeded gain switched pulse sources due to mode partition noise effects," *IEEE Photon. Technol. Lett.*, vol. 14, no. 8, pp. 1202–1204, Aug. 2002.

[12] R. Olshansky, P. Hill, V. Lanzisera, and W. Powazinik, "Frequency response of 1.3 μm InGaAsP high speed semiconductor lasers," *IEEE J. Quantum Electron.*, vol. QE-23, no. 9, pp. 1410–1418, Sep. 1987.

[13] L. Chrostowski, X. Zhao, C. J. Chang-Hasnain, R. Shau, M. Ortsiefer, and M.-C. Amann, "50-GHz optically injection-locked 1.55 μm VCSELs," *IEEE Photon. Technol. Lett.*, vol. 18, no. 2, pp. 367–369, Jan. 2006.

[14] L. Barry, P. Anandarajah, and A. Kaszubowska, "Optical pulse generation at frequencies up to 20 GHz using external-injection seeding of a gain-switched commercial Fabry–Perot laser," *IEEE Photon. Technol. Lett.*, vol. 13, no. 9, pp. 1014–1016, Sep. 2001.

[15] A. Tauke-Pedretti, G. Vawter, E. Skogen, G. Peake, M. Overberg, C. Alford, W. Chow, Z. Yang, D. Torres, and F. Cajas, "Mutual injection locking of monolithically integrated coupled-cavity DBR lasers," *IEEE Photon. Technol. Lett.*, vol. 23, no. 13, pp. 908–910, Jul. 2011.

[16] C. Bornholdt, U. Troppenz, J. Kreissl, W. Rehbein, B. Sartorius, M. Schell, and I. Woods, "40 gbit/s directly modulated passive feedback DFB laser for transmission over 320 km single mode fibre," in *Proc. 34th ECOC*, Sep. 2008, pp. 1–2.

[17] C. Herbert, D. Jones, A. Kaszubowska-Anandarajah, B. Kelly, M. Rensing, J. O'Carroll, R. Phelan, P. Anandarajah, P. Perry, L. Barry, and J. O'Gorman, "Discrete mode lasers for communication applications," *IET Optoelectron.*, vol. 3, no. 1, pp. 1–17, Feb. 2009.

[18] J. Patchell, D. Jones, B. Kelly, and J. O'Gorman, "Specifying the wavelength and temperature tuning range of a Fabry–Perot laser containing refractive index perturbations," in *Proc. SPIE*, 2005, vol. 5825, p. 113.

[19] H.-K. Sung, E. Lau, and M. Wu, "Optical properties and modulation characteristics of ultra-strong injection-locked distributed feedback lasers," *IEEE J. Sel. Topics Quantum Electron.*, vol. 13, no. 5, pp. 1215–1221, Sep./Oct. 2007.

[20] Eagleyard-Photonics, *Relative Intensity Noise of Distributed Feedback Lasers*. [Online]. Available: http://www.eagleyard.com/fileadmin/downloads/app_notes/App_Note_RIN_1-5.pdf

[21] X. Jin and S. L. Chuang, "Relative intensity noise characteristics of injection-locked semiconductor lasers," *Appl. Phys. Lett.*, vol. 77, no. 9, pp. 1250–1252, Aug. 2000.

[22] E. Peral, W. K. Marshall, D. Provenzano, and A. Yariv, "Effect of many weak side modes on relative intensity noise of distributed feedback semiconductor lasers," *Appl. Phys. Lett.*, vol. 72, no. 8, pp. 888–890, Feb. 1998.

[23] T. Simpson and F. Doft, "Double-locked laser diode for microwave photonics applications," *IEEE Photon. Technol. Lett.*, vol. 11, no. 11, pp. 1476–1478, Nov. 1999.

[24] A. Kaszubowska, L. Barry, and P. Anandarajah, "Multiple RF carrier distribution in a hybrid radio/fiber system employing a self-pulsating laser diode transmitter," *IEEE Photon. Technol. Lett.*, vol. 14, no. 11, pp. 1599–1601, Nov. 2002.

[25] K. Y. Lau and A. Yariv, "Intermodulation distortion in a directly modulated semiconductor injection laser," *Appl. Phys. Lett.*, vol. 45, no. 10, pp. 1034–1036, Nov. 1984.

[26] C. Browning, K. Shi, S. Latkowski, P. Anandarajah, F. Smyth, B. Cardiff, and L. Barry, "Increased bit rate direct modulation AMO-OFDM transmission by optical injection using monolithically integrated lasers," *IEEE Photon. Technol. Lett.*, vol. 24, no. 11, pp. 879–881, Jun. 2012.