Self-Pulsation in Multisection Distributed Feedback Laser Diode with a Novel Dual Grating Structure

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A self-pulsating multisection distributed-feedback laser diode (DFB LD) can potentially realize all-optical clock extraction. This device generally consists of three sections, two DFB sections and one waveguide section. The most important variable in this device is detuning, which is the relative spectral position between the stop bands of two DFB sections. We fabricated a novel structure in which two gratings were located one over and one under the active layers. Each grating structure was independently defined in processing so that detuning, which is the prerequisite for self-pulsation, could be easily controlled. Observing various self-pulsating phenomena in these devices under several detuning conditions, we characterized the phenomena as dispersive Q-switching, mode beating, and self-mode-locking.

I. Introduction

To surmount the limitations of electronic regeneration devices, all-optical 3R regenerators will be an essential part of future broadband networks, [1], [2]. The key function of this type of regenerator is clock recovery, which produces a stable time clock synchronized to a high-speed optical signal. Because of the importance of this function, optical phase-locked loop and pulsating laser diodes (LDs) have been widely studied. Pulsating LDs, in which the clock can be extracted according to an injection locking property [3], [4], is attractive for its simplicity. Mode-lock LDs and self-pulsating LDs are good candidates for clock extraction. The cavity length determines the repetition rate in mode-lock LDs. In self-pulsating LDs, it can be varied by adjusting the injection current. Some papers have reported on self-pulsating phenomena in distributed feedback (DFB) LDs with saturable absorbers [5], [6]. However, their usefulness in optical communication is restricted by the limit of the repetition rate [6]. Reference [7] reported a maximum frequency of 18 GHz. In 1992, the Heinrich Hertz Institute reported the self-pulsating phenomena in multisection DFB LDs without saturable absorbers and pointed out the possibility for use in high-speed clock recovery [8], [9]. The repetition rate for their suggested structure was available up to 120 GHz [10]. They described these phenomena as dispersive Q-switching and mode beating [10]-[12]. The origin of the self-pulsation was the mutual influence between the two gain sections in the multisection DFB LD. With dispersive Q-switching, one DFB section was used as a reflector that can be achieved when the injection current is below threshold. When the lasing wavelength is located at the negative slope in the reflectivity spectrum of the

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reflector section, the lasing mode becomes unstable. The negative slope leads the lasing wavelength to a shorter wavelength. This induces an abrupt increase in the optical feedback and quickens the stimulated emission by turn. As a result of a quick gain change, carriers in the active medium are rapidly depleted. At the same time, the lasing wavelength moves to a longer wavelength. Consequently, the carrier density drops below threshold and the laser turns off. After the carrier density recovers, the above procedure can be repeated as in DFB LDs with saturable absorbers.

When the injection currents of both sections are above threshold, mode beating between the modes of each section is possible. In a multisection DFB LD, the optical signal of each section is injected into the other section and this gives rise to a phase correlation between the two modes [10], [11]. The merit of mode beating is that the repetition rate is related to the mode spacing and can be varied. To realize these self-pulsation phenomena, the critical factor is the relative position of the two stop bands. The processing parameters for determining this factor are the coupling coefficient, period of grating, and cavity length. Therefore, it is necessary to control these parameters independently in each section. In this paper, we suggest a novel multisection DFB LD structure in which the two gratings are located one over and one under the active layers and are transferred by the conventional holographic method and regrowth procedure.

II. Sample

We grew the DFB lasers used in this paper by metal organic chemical vapor deposition. The active structure is a strained compensated InGaAsP/InGaAsP multiquantum well with a 1.3Q SCH structure. To prepare the materials for selective deposition, we used reactive ion etching for structure definition and SiN_x deposition for mask fabrication. We patterned the grating structure with the conventional holographic technique [12]. This method has various merits: a flexible fabricating process, low cost, and the capability of mass production. The prepared laser consisted of three sections, two DFB sections and a phase tuning section integrated between the two DFB sections. In the longer (shorter) DFB section, the grating structure was located under (above) the active layers. This novel structure makes it possible to independently fabricate the gratings of the two DFB sections. With these two kinds of grating layers, the coupling coefficient, as well as the periodicity, can be independently determined. We changed the composition and height of the grating layers to determine the difference between the coupling coefficients of the two DFB sections. We experimentally defined the coupling coefficient for each grating structure. In this work, coupling coefficients of 80, 100, and 150 cm^{-1} were measured [13]. We measured the photoluminescence to check the difference between MQWs grown on a reference planar wafer and those on a grating structure. There was only a minor difference in the intensity and line shape, which indicated a defect-free grating structure.

The phase section was an InGaAsP waveguide (λ_{PL}=1.3 μm) coupled to the DFB sections with a butt-coupling technique. We slightly tilted the interface planes to reduce the internal reflection. The internal reflection in the butt-coupling region was below 10^{-5} by low coherence reflection measurement. The efficiency of butt coupling is critical in a multisection DFB LD operation. In each DFB section, the threshold current was 15 to 40 mA and the side mode suppression ratio was above 40 dB. The electrodes were isolated by 10 μm-wide stripes, which were fabricated by reactive ion etching and wet etching. The isolation resistance measured 600 to 800 Ω by an I-V meter. Both facets were antireflection coated by multilayered dielectric coating and the reflection was below 0.5%.

DC current independently drove each section of the DFB laser and the temperature was controlled at 20 °C. The emission from the facet was coupled into a tapered fiber. The signal was split by a 3-dB coupler and measured simultaneously by an optical spectrum analyzer and an RF spectrum analyzer.

The dimensions of the investigated devices were as follows: the lengths of the two DFB sections were 400 and 200 μm and the length of the phase section was 400 μm.

III. Results and Discussion

1. Detuning Conditions

The self-pulsating phenomena in multisection DFB LDs have been actively studied at HHI since 1992. According to their results, the most important parameter was detuning, which indicated the relative position of two stop bands. Figure 1 illustrates the detuning conditions in which the self-pulsation occurred in this study: (a) and (b) dispersive Q-switching; (b) and (c) self-mode locking; (d) mode beating. Experimentally, we found stop band shifts of –0.16 nm/mA and 0.03 nm/mA for above threshold and below threshold, respectively. Although fine-tuning is possible through control of the injection currents, great care in fabricating the grating structures was necessary to achieve the desired detuning. We realized these four conditions with the conventional holographic method. HHI studies reported that conditions (a) and (b) were for dispersive self-Q-switching and (d) for mode beating. However, the self-pulsation in condition (c) has not been observed in a multisection DFB LD without a saturable absorber.

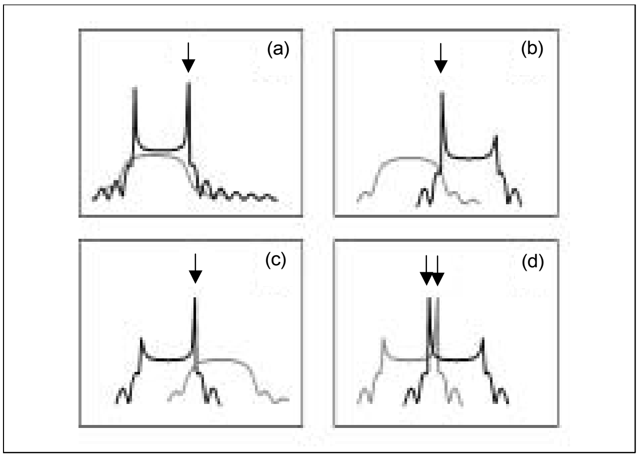

Fig. 1. Spectral correlations in the wavelength domain between the reflectance spectra of two DFB sections: The arrows indicate the modes related to self-pulsating phenomena; (a) and (b): dispersive Q-switching, (b) and (c): self-mode locking, (d) mode beating.

2. Dispersive Self-Q-Switching: Conditions (a) and (b)

Figure 2 shows a typical RF spectrum of self-pulsation for condition (a). The coupling coefficients of the two grating structures had nearly the same value, 80 cm^{-1}. In this measurement, the longer DFB section was used as the reflector. A threshold current of 15 mA was obtained for this section when the currents of the other sections were kept at 0 mA. Figure 2 shows the detailed operating conditions. For convenience, I_{long}, I_{short}, and I_{phase} represent the injection currents of the longer DFB section, the shorter DFB section, and the phase section, respectively.

Up to 5th harmonic can be identified. We observed similar results in other lasers, which we cleaved from the same wafer. A spectral line width of about 0.17 nm was not related to the RF frequency (Fig. 3). A single-mode self-pulsation is the main feature of dispersive self-Q-switching, and line broadening is natural because the main idea of dispersive self-Q-switching is the conversion from a wavelength modulation to an amplitude modulation [11], [14].

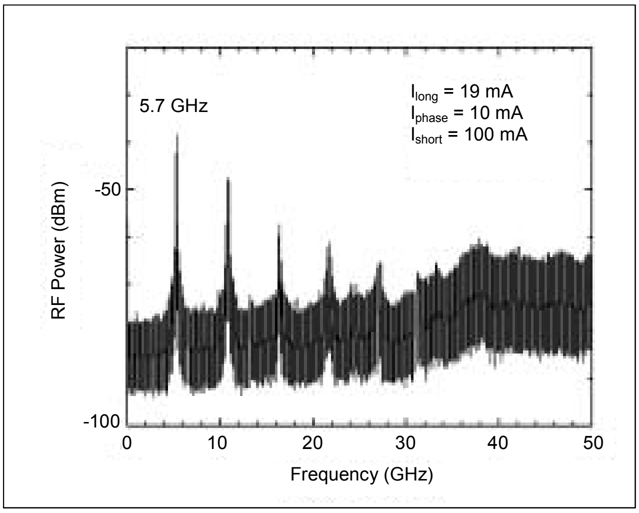

Fig. 2. This is an typical spectrum on the detuning condition of (a).

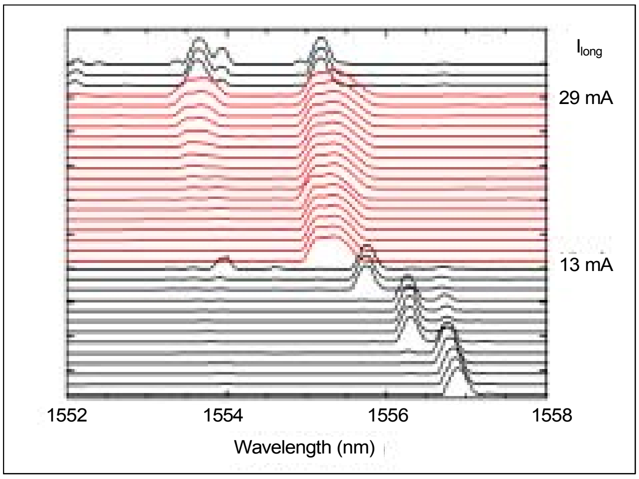

Fig. 3. Variations of optical spectra with changing the current in the reflector (0 to 32 mA, step:1 mA) The currents in the gain and the phase section were kept constant at 100 and 10 mA. The y-axis scale is 20 dBm/division.

Figure 3 shows the change of the optical spectrum with the current increase of the reflector section. The wavelength blue-shifted and hopped when the injection current increased. Other investigations often noted this kind of phenomena in the DBR LD, and [15] explained it as a change in the effective grating pitch according to the current injection. When the current reached 13 mA, the shape of the optical spectrum suddenly changed and the RF signal started to appear. We observed the RF signal only in the range of 13 to 29 mA. An optical spectrum in this range was roughly two times wider than a normal spectrum, and the RF frequency increased from 4.6 (13 mA) to 7.6 GHz (29 mA). This increase might be related to the amount of feedback. As the injection current of the reflector section increased, the negative slope became steeper. As a result, the power variation of the feedback light to the lasing section became much stronger, and the carrier depletion in the lasing section was able to recover more quickly.

Reference [14] attributed the frequency variability in self-pulsating DFB LDs to the relation between the amount of the injection current to the gain section and the recovery time. We also confirmed the frequency increase with an increased current in the lasing section. We observed this kind of behavior in other LDs, which had somewhat different lengths and coupling coefficients; however, the repetition rate did not go beyond 10 GHz. In principle, the speed of the carrier depletion and the recovery determines the repetition rate in dispersive Q-switching. As this procedure is similar to relaxation oscillation, it can be characterized by the 3 dB modulation bandwidth. To realize high-speed performance above 10 GHz with the dispersive Q-switching mode, the structure of the LDs must precisely control the material and structure parameters.

We also investigated the influence of the phase section current. When we applied 100 mA (19 mA) to the lasing (reflector) section, we changed the current of the phase section from 0 to 60 mA. In that case, the self-pulsation was up to 30 mA and the RF frequency decreased from 6.8 (0 mA) to 4.1 GHz (30 mA). There was no RF spectrum over 30 mA. The peak wavelength became shorter in this range and started to shift to long wavelengths above 30 mA. When we increased the injection current of the phase section, the refractive index decreased and the peak wavelength shifted to a shorter wavelength. This might decrease the variation of the feedback and the repetition rate naturally decreased. If the peak wavelength reached the flat region of the reflection spectrum, the RF spectrum disappeared. It was reported [11], [16] that the self-pulsation turned on and off periodically when the current of the phase section increased. However, we did not find any periodicity. Furthermore, the window was much wider than the reported result (>5 mA). These facts might suggest that the change of the refractive index was too small. However, the reason is still being investigated.

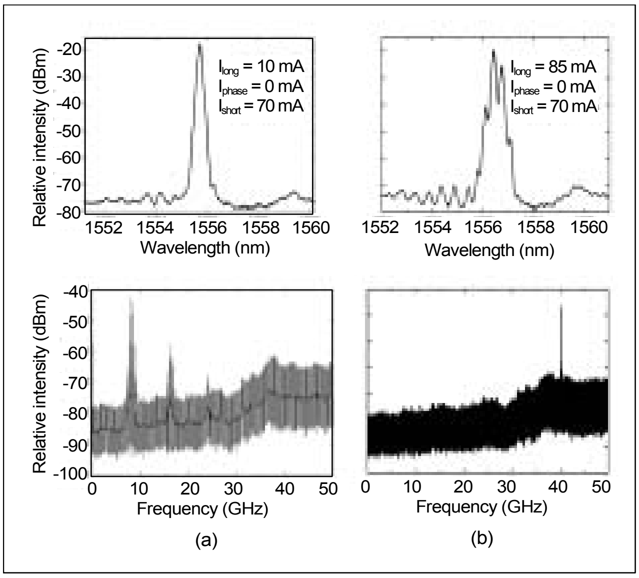

Fig. 4. The transition of spectrum according to the injection current (the detuning condition) in one device : (a) optical spectrum and RF spectrum when the current of the longer DFB section was below threshold (detuning condition (b) of Fig. 1), (b) optical spectrum and RF spectrum when the current of the longer DFB section was above threshold (detuning condition (d) of Fig. 1).

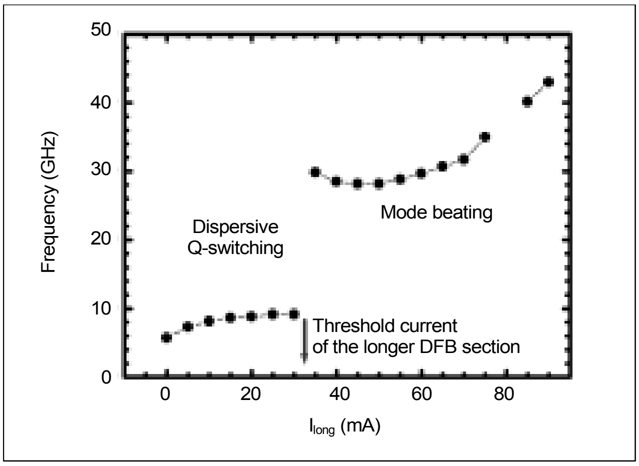

Fig. 5. Self-pulsating frequency versus the injection current of the longer DFB section (I_{short}=70mA, I_{phase}=0mA).

3. Mode Beating: Condition (d)

We observed self-pulsation in detuning condition (d). The optical spectrum was clearly of a multimode type and the RF frequency was over 25 GHz. In addition, when the current of one section decreased below threshold, a new RF signal appeared. The reason was that the detuning condition changed from (d) to (b). Typical examples are shown in Fig. 4. The coupling coefficients were 150 cm^{-1} (the longer DFB section) and 100 cm-1 (the shorter one).

Spectra (a) were obtained when the currents were 10, 0, and 70 mA in order and for (b) 85, 0, and 70 mA. Figure 5 shows the current dependence of the self-pulsation frequency. In this measurement, we varied the current of the longer DFB section from 0 to 85 mA. Two regions were clearly differentiated. In the low current region (0 to 30 mA) corresponding to detuning condition (b), the frequency increased from 5 to 10 GHz. This behavior can be understood according to the above description. Above a threshold current of 33 mA, the frequency decreased from 30 GHz to 28 GHz with an increasing current up to 45 mA and then increased up to 43 GHz. The repetition rate was correlated to the mode spacing. It was closely related to the relative position of the stop bands of the two grating sections. The minimum separation between the two modes was achieved when two uncoupled DFB LDs had the same lasing mode. Reference [10] provided a detailed explanation. We concluded from these facts that the mode beating was the origin of pulsation in detuning condition (d). The merit of mode beating is that a high repetition rate is possible and it is easily tunable. However, the coupling efficiency between sections was critical. Our simulation results (Time Domain Model) showed that stable pulsation was possible only when the coupling efficiency was larger than 80%. We cleaved the devices with different cavity lengths and measured the reflection. The waveguide loss was about 30dBm/cm, the internal reflection was below 10^{-5}, and the coupling efficiency was over 90%. Reference [17] pointed out that mutual feedback was strongly related to the modulation index. Our maximum value was only about 25%; however, the cause was unclear.

We observed self-pulsation as described above in other samples with different dimensions and coupling coefficients. There was no significant difference between the samples with different coupling coefficients. The most important factor was the detuning between the two DFB sections.

4. Self-Mode Locking: Conditions (b) and (c)

In detuning condition (c) (Fig. 1), self-pulsation occurred in a wide range of 2.5 to 40 GHz. However, the range was small in one device. As several kinds of mechanism were possible at a low frequency range, we only introduce the results at a high frequency. Figure 6 illustrates the typical spectrum. The injection current was 15 mA for the longer DFB, 20 mA for the phase, and 103 mA for the shorter DFB section. The threshold current of the longer DFB section was 19 mA. The RF frequency range was 28 to 30 GHz when the current of the reflector (the shorter DFB) was below the threshold current and 38 to 40 GHz when it was over the threshold (Fig. 7). As dispersive Q-switching and mode beating are impossible below threshold [10], [11], [13], there should be another mechanism that produces this pulsation. Reference [18] theoretically suggested self-mode locking in an external cavity LD. Feedback is the critical variable in achieving self-mode locking, because the amount of feedback determines whether pulsation is possible. Furthermore, the repetition rate can be controlled by adjusting the amount of feedback. Recently, [19] settled this point with a structure integrating a DFB and an amplifying section. That study also reported that the injection current of the amplifying section was closely related to the repetition rate. The slope of reflectivity in a reflector section can be used for this purpose because the relative position of the lasing mode in the slope is adjustable with the injection current. We believe that this is the origin of self-pulsation at a positive slope. However, there are other important factors, such as the coupling efficiency at butt coupling and the reflectivity of the reflector. Those factors may be the origin of the wide frequency range (15 to 35 GHz) we observed. This suggests that uniformity is a knotty subject for the practical use of self-mode locking. The origin of the observed self-pulsation above threshold was not clear because the mode beating was possible.

We also observed a high frequency (35 to 40 GHz) self-pulsation in detuning condition (b). The coupling coefficient of each DFB section was 80 cm^{-1}. When I_{long}=111, I_{phase}=5, and I_{short}=10 mA, the RF frequency was 35 GHz. Dispersive Q-switching and mode beating do not describe this observation because the optical spectrum was clearly of the multimode type; the spacing of the optical spectrum was correlated to the RF frequency, and the current of one section was below threshold. Self-mode locking may be the origin of that.

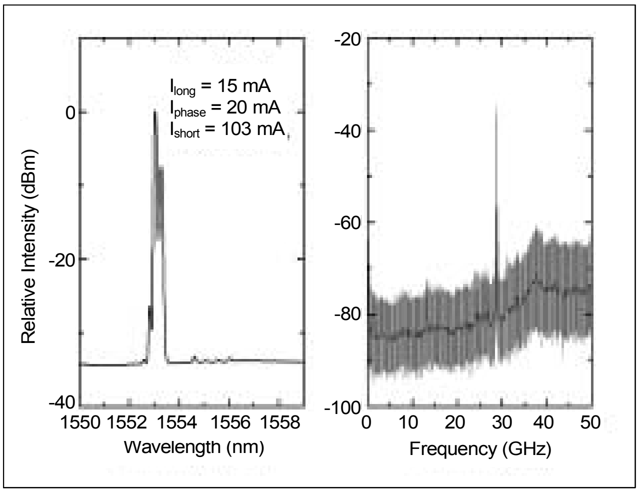

Fig. 6. The optical spectrum and the RF spectrum (I_{long}=15 mA, I_{phase}=20 mA, I_{short}=103 mA).

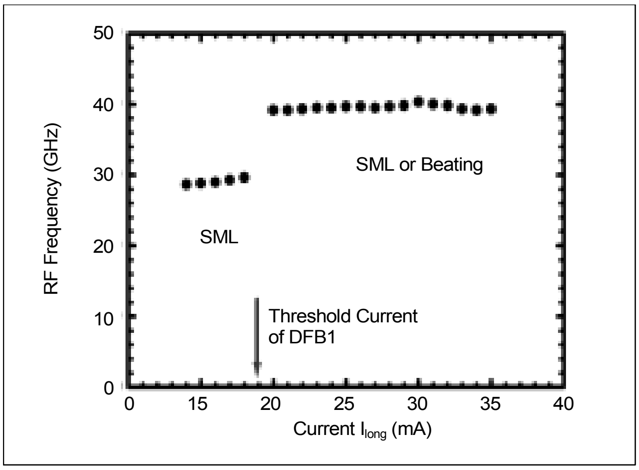

Fig. 7. RF frequency versus the current of the longer DFB section (I_{phase}=20 mA, I_{short}=103 mA).

IV. Conclusion

We fabricated multisection DFB LDs with a novel detuned grating structure. This asymmetric grating structure has the following merits:

(1) The detuning can be easily controlled.
(2) Each grating structure has its own grating layer.
(3) It can be realized by conventional holographic

lithography.

We also adopted a PBH structure to obtain a low threshold and high coupling efficiency. The observed self-pulsations in the fabricated LDs were classified into three types: dispersive Q-switching, mode beating, and self-mode locking. As the repetition rate of dispersive Q-switching is restricted (less than about 10 GHz) and self-mode locking has a problem in controlling the repetition rate, we conclude that at this point, mode beating is more practical because it has a range of 25 to 50 GHz and can control the repetition rate.

References

[1] O. Kamatani, S. Kawanishi, and M. Saruwatari, "Prescaled 6.3GHz Clock Recovery from 50Gbit/s TDM Optical Signal with 50GHz PLL Using Four-Wave Mixing in a Traveling-Wave Laser Diode Optical amplifier," *Electron. Lett*., vol. 30, no. 10, May 1994, pp. 807-809.

[2] A.D. Ellis, K. Smith, and D.M. Patric, "All Optical Clock Recovery at Bit Rates up to 40Gbit.s," *Electron. Lett*., vol. 29, no. 15, July 1993, pp. 1323-1324.

[3] C.G. Lim, S. Iezekiel, and C.M. Snowden, "Nonlinear Dynamics of Optically Injected Self-Pulsating Laser Diodes," *IEEE J. Quantum Electron*., vol. 37, no. 5, May 2001, pp. 699-705.

[4] G-H. Duan and G. Pham, "Injection-Locking Properties of Self-Pulsation in Semiconductor Lasers," *IEE Proc. Optoelectron*. vol. 144, no. 4, Aug. 1997, pp. 228-234.

[5] Masayasu Ueno and Roy Lang, "Conditions for Self-Sustained Pulsation and Bistability in Semiconductor Lasers," *J. Appl. Phys*., vol. 58, no. 4, Aug. 1985, pp. 1689-1692.

[6] Peter P. Vasil'ev, Ian H. White, and John Gowar, "Fast Phenomena in Semiconductor Lasers," *Rep. Prog. Phys*., vol. 63, Oct. 2000, pp. 1997-2042.

[7] Peter P. Vasil'ev, "Picosecond Injection Laser: A New Technique for Ultrafast Q-Switching," *IEEE J. Quantum Electron*., vol. 24, no. 12, Dec. 1988, pp. 2386-2391.

[8] M. Möhrle, U. Feiste, J. Hörer, R. Molt, and B. Satorius, "Gigahertz Self-pulsation in 1.5μm Wavelength Multisection DFB Lasers," *IEEE Photon. Technol. Lett*., vol. 4, no. 9, Sept. 1992, pp. 976-978.

[9] U. Feiste, D.J. As, and A. Ehrhardt, "18GHz All-Optical Frequency Locking and Clock Recovery Using a Self-Pulsating Two-Section DFB-Laser," *IEEE Photon. Technol. Lett*., vol. 6, no. 1, Jan. 1994, pp. 106-108.

[10] Martin Möhrle et al., "Detuned Grating Multisection-RW-DFB Lasers for High-Speed Optical Signal Processing," *IEEE J. Select. Topics Quantum Electron*., vol. 7, no. 2, Mar/Apr. 2001, pp. 217-223.

[11] Bernd Satorius et al., "Dispersive Self-Q-Switching in Self-Pulsating DFB Lasers," *IEEE J. Quantum Electron*., vol. 33, no. 2, Feb. 1997, pp. 211-218.

[12] Sang-Wan Ryu and Jeha Kim, "An Asymmetric Sampled Grating Laser and Its Application to Multi-Wavelength Laser Array," *ETRI J*., vol. 24, no. 5, Oct. 2002, pp. 341-348.

[13] Leonard J.P. Ketelsen, Isako Hoshino, and David A. Ackeman, "Experimental and Theoretical Evaluation of the CW Suppression of TE Side Modes in Conventional 1.55μm InP-InGaAsP Distributed Feedback Lasers," *IEEE J. Quantum Electron*., vol. 27, no. 4, Apr. 1991, pp. 965-975.

[14] M. Radziunas et al., "Modeling self-pulsating DFB lasers with an integrated phase tuning section," *IEEE J. Quantum Electron*., Vol. 36, No. 9, Sept. 2000, pp. 1026-1034.

[15] Mitsuo Fukuda, *Optical Semiconductor Devices*, John Wiley & Sons, Inc., New York, 1999.

[16] M. Möhrle, B. Satorius, R. Steingrüber, and P. Wolfram, "Electrically Switchable Self-Pulsations in Integratabe Multisection DFB-Lasers," *IEEE Photon. Technol. Lett*., vol. 8, no. 1, Jan. 1996, pp. 28-30.

[17] Xinhong Wang et al., "Optical Generation of Microwave/Millimeter-Wave Signals Using Two-Section Gain-Coupled DFB Lasers," *IEEE Photon. Technol. Lett*., vol. 11, no. 10, Oct. 1999, pp. 1292-1294.

[18] Alexei A. Tager and Klaus Petermann, "High-frequency Oscillations and Self-Mode Locking in Short External-Cavity Laser Diodes," *IEEE J. Quantum Electron*., vol. 30, no. 7, July 1994, pp. 1553-1561.

[19] O. Brox, S. Bauer, J. Kreissl, M. Möhrle, and B. Satorius, " DFB –Lasers with Amplified Optical Feedback for Tunable High-Frequency Generation," *Optical Amplifiers and their Applications*, OAA 2002 Vancouver, Canada, paper OWC2.

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