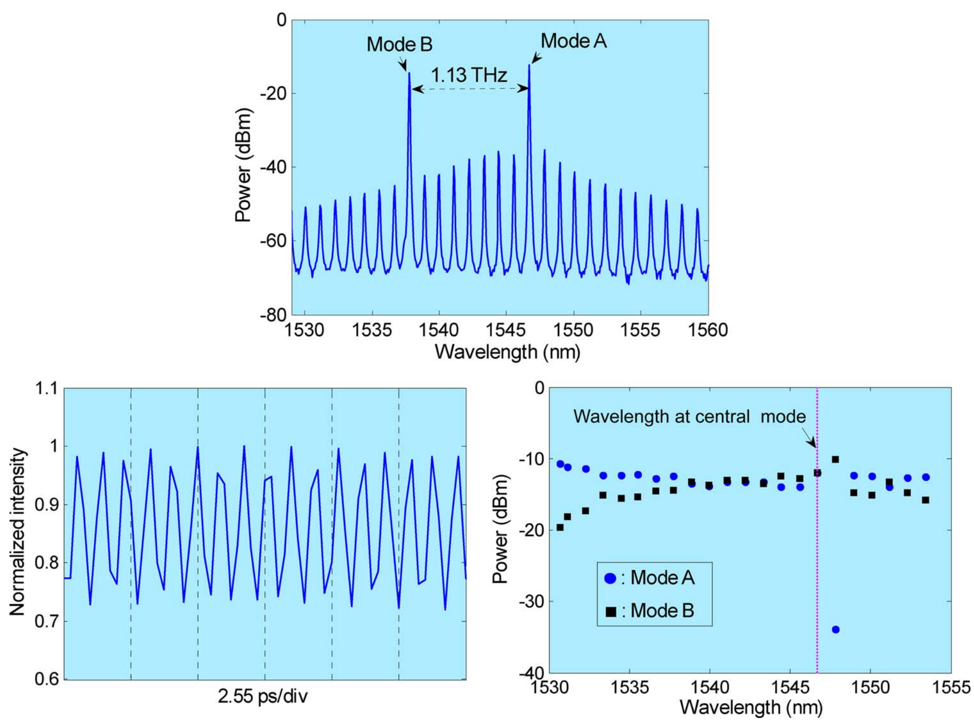
IEEE Photonics Journal
An IEEE Photonics Society Publication

Open Access

Tunable Two-Color Lasing Emission Based on Fabry-Pérot Laser Diode Combined With External Cavity Feedback

Volume 5, Number 1, February 2013

Jian Wei Wu
Bikash Nakarmi
Tran Quoc Hoai
Yong Hyub Won



DOI: 10.1109/JPHOT.2013.2241418
1943-0655/$31.00 ©2013 IEEE

IEEE photonics SOCIETY

IEEE

Tunable Two-Color Lasing Emission Based on Fabry-Pérot Laser Diode Combined With External Cavity Feedback

Jian Wei Wu,[1] Bikash Nakarmi,[2] Tran Quoc Hoai,[2] and Yong Hyub Won[1]

[1]Department of Electrical Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-714, Korea
[2]Department of Information and Communication Engineering, Korea Advanced Institute of Science and Technology, Daejeon 305-714, Korea

DOI: 10.1109/JPHOT.2013.2241418
1943-0655/$31.00 ©2013 IEEE

Manuscript received December 19, 2012; revised January 15, 2013; accepted January 15, 2013. Date of publication January 21, 2013; date of current version February 1, 2013. This work was supported by a Grant from the R&D Program (Industrial Strategic Technology Development) funded by the Ministry of Knowledge Economy (MKE), Republic of Korea. Corresponding author: J. W. Wu (e-mail: jwwu@kaist.ac.kr).

Abstract: In this paper, two-color lasing emission is experimentally demonstrated by employing a multimode Fabry-Pérot laser diode (MMFP-LD) associated with external cavity of two tunable filters and an erbium-doped fiber amplification (EDFA), whose difference frequency is quasi-continuously tunable from several hundred GHz to more than 2 THz. The obtained side-mode suppression ratio (SMSR) in the output spectrum is around ~20 dB, and the modulation depth of simulated beat signal converted by two emission modes rapidly decayed as increasing the frequency separation. In addition, optical behaviors induced by mode competition and four-wave mixing are observed and discussed, while the difference frequency was shortened to GHz regime.

Index Terms: Fabry-Pérot laser diode (FP-LD), external cavity, two-color lasing emission, mode competition and four-wave mixing.

1. Introduction

Two-color (dual-mode) lasing system as a subject of growing interest has been attracting much attention and extensive research owing to its potential applications such as terahertz generation [1]–[4], optical memory [5], [6], and switching [7]. To date, many techniques have been already proposed and demonstrated for realizing two-color lasing operation based on semiconductor laser with external cavity configuration, in which various gratings were usually adopted to select special feedback wavelength that can effectively cause the corresponding laser mode to oscillate in the active region of laser diode [8]–[12]. Of course, these presented schemes should have their distinct advantages and limitations for generating two-color laser. In various lasing system, the Fabry-Pérot laser diode (FP-LD) has, undoubtedly, attracted substantial attention and research in laser technology owing to its rich nonlinear, simple configuration, and low cost. In addition, it should be pointed out that the injection locking behavior occurred in the lasing spectrum is a basic physical mechanism for active region of FP-LD [13], [14] with the result that FP-LD-based optical functions induced by the injection locking have been proposed and demonstrated in some potential applications including format transformation [15], photonic generation of millimeter-wave and microwave signal [16], [17], wavelength conversion [18], chaos [19], and logic gate [20].

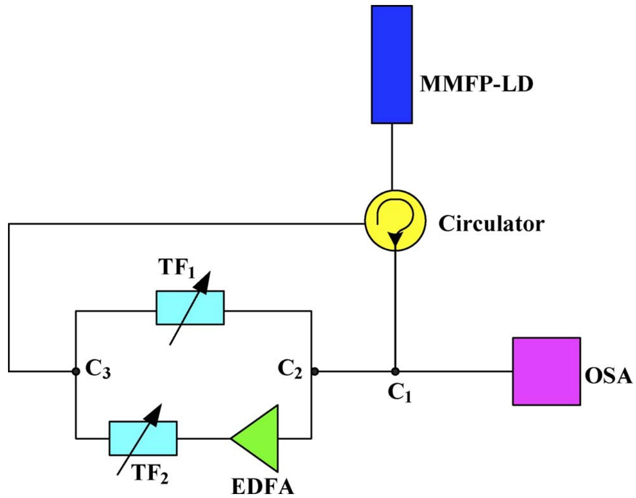


Fig. 1. Experimental setup for two-color lasing system with tunable difference frequency. (MMFP-LD: multimode Fabry-Pérot laser diode, EDFA: erbium-doped fiber amplification, TF: tunable filter, C: 50:50 fiber coupler, OSA: optical spectrum analyzer).

In reality, it is well known that the FP-LD with an external cavity feedback based optical setup is a special configuration to realize laser output [21], which was experimentally demonstrated to achieve single-mode operation with tunable emission wavelength in recent report [22]. Certainly, it is also very significant to demonstrate and discuss the two-color lasing output with various difference frequencies by using the FP-LD-based apparatus. Owing to the excitation of the referred interesting subject, in this paper, we timely present a two-color lasing system, consisting of a common multimode FP-LD (MMFP-LD) and external cavity feedback configuration incorporating two tunable filters (TFs) and an erbium-doped fiber amplification (EDFA), to generate two-color lasing emission with various difference frequencies that can be quasi-continuously tuned from several hundred GHz to THz by judiciously adjusting the filtered wavelength of TF. The side-mode suppression ratio (SMSR) for outcome two-color lasing spectrum is around 20 dB by means of proper feedback wavelength. In contrast with other demonstrated two-color laser techniques, the MMFP-LD-based architecture proposed in this paper has some prominent advantages including stable output power, wide tunable range, low power consumption, and operation flexibility, which make this laser to have strong competition ability compared to other techniques in optical applications. In addition, some optical phenomena caused by strong mode competition and four-wave mixing are further observed and discussed in this investigation, while the separation between two oscillation modes is very close. The direct results are that, despite two feedback wavelengths for laser chip, only single-mode laser emitted can be observed due to the mode competition. The power levels of other lasing modes may be little enhanced resulting from four-wave mixing induced by two feedback wavelengths with the result that the corresponding SMSR obviously decayed. Therefore, through this research, another two-color lasing system based on the MMFP-LD associated with external feedback is presented and experimentally demonstrated so that it is positive to develop a variety of applications for FP-LD-based optoelectronics device.

2. Experimental Setup

Fig. 1 shows the experimental setup of the proposed two-color lasing emission, comprised of an MMFP-LD, a circulator, three 50:50 fiber couplers, two TFs and an EDFA. After the outputted optical spectrum from MMFP-LD orderly passes through the circulator and fiber coupler C_1, its property can be seen in the optical spectrum analyzer (OSA), in which only half of the total energy from circulator is captured. On the other hand, the correspondingly remained energy as an optical feedback will enter the external cavity through the coupler C_2. Within the external cavity, both TF_1 and TF_2 can be continuously tuned in a wide wavelength range to select special feedback wavelength, whereas in the

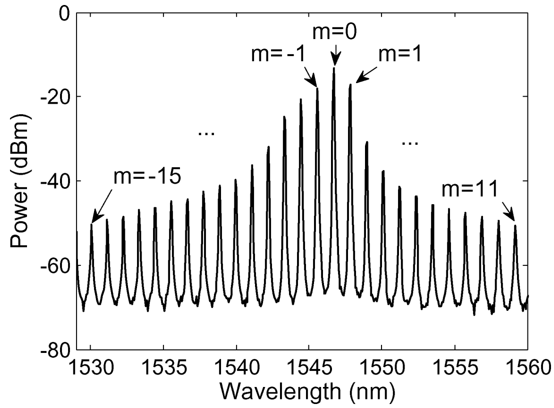


Fig. 2. Output free-running spectrum from the MMFP-LD.

experiment, the output wavelength of TF_1 is fixed at the central mode peak of free-running spectrum outputted by the MMFP-LD, and the TF_2 is continuously tuned to proper wavelength for obtaining different difference frequency between two outcome oscillation modes. In addition, it is well known that the power level of other lasing mode is lower than that of central mode with the result that the output power from the TF_2 should be firstly enhanced by the EDFA before entering the filter TF_2 so as to successfully realize two-color oscillation. Finally, two feedback wavelengths filtered by TF_1 and TF_2 are combined by the coupler C3, which are again introduced into laser chip through the circulator. As a result, the laser system will gradually locked at two lasing modes, and other lasing modes will be suppressed resulting from the injection locking behavior induced by feedback beams.

3. Experimental Results and Discussion

Fig. 2 shows the well-known spectrum from the MMFP-LD with bias current of 25 mA and operation temperature of 38.2 °C, in which the lasing mode with maximum power is defined as the central mode $(m = 0)$, and other higher order side modes can be seen in the illustrations. It is obvious that the output spectrum with only several dB SMSR has very wide bandwidth and unbalanced peak level as a result of the asymmetric gain distribution in the laser material. The mode spacing between two adjacent lasing modes is around 1.13 nm that should be the corresponding tunable step in TF_2 shown in Fig. 1. During the experiment, the output spectrum plotted in Fig. 2 can be red-shifted by increasing the operation temperature of active region, which should be located within the available gain bandwidth of EDFA, where the power level of tunable feedback wavelength can be enhanced to effectively perform the injection locking that can cause two-color oscillation.

To effectively perform the two-color lasing operation utilizing the presented system, two special wavelengths should be circulated in the external cavity. The output spectrum with changed difference frequency can be observed and measured by the OSA. In Fig. 3, four output spectra with the difference frequency of ~0.56, ~1.13, ~1.69, and ~2.11 THz are clearly plotted in order to exhibit spectral characteristic. In the experiment, to obtain effective two-color lasing emission with various difference frequencies, one feedback wavelength filtered by TF_1 is fixed at the peak wavelength (~1546.7 nm) of central mode that has a maximum power level in the free-running spectrum shown in Fig. 2 and causes an output lasing mode illustrated by mode A in Fig. 3. Another feedback wavelength is quasi-continuously tuned from 1530 nm to 1560 nm by the TF_2, in which the filtered output wavelength should be same as (or close to) peak wavelength of selected side mode shown in the free-running spectrum. This is because the pump level of EDFA is held constant so that the corresponding gain spectrum is also determined for each wavelength during the experiment. Under the condition of small signal amplification, the output power from EDFA is proportional to the corresponding input power. In addition, it is well known that the injection locking is strongly dependent on the wavelength detuning that is defined as the wavelength difference between injected wavelength and peak wavelength of adjacent side mode, and the required threshold power for injection locking is also

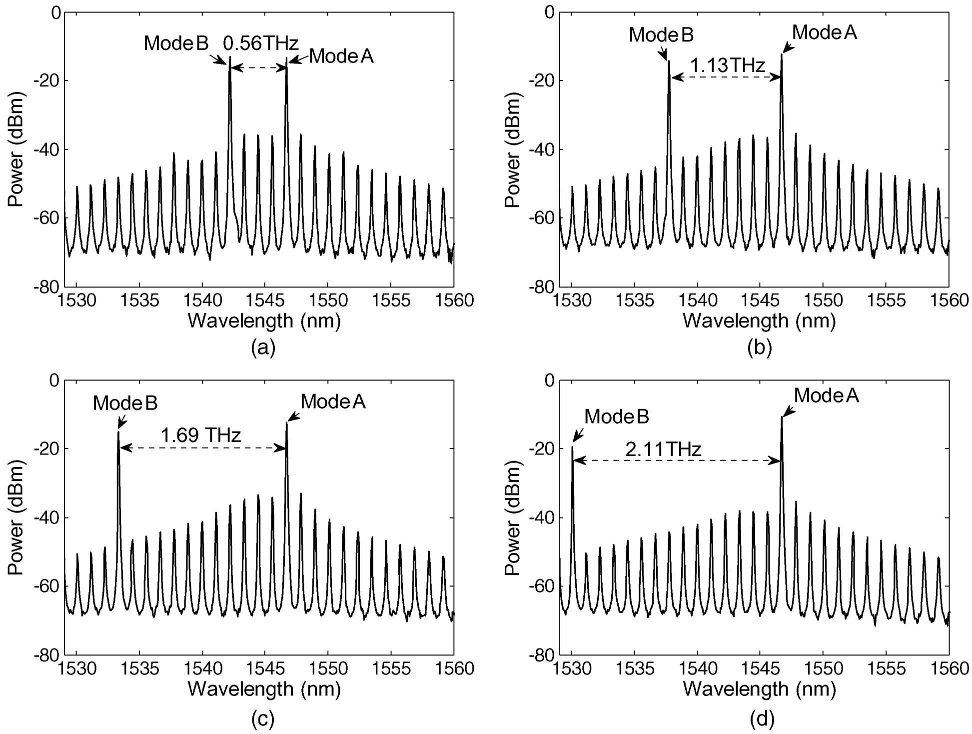


Fig. 3. Output spectrum from two-color lasing system with difference frequency, (a) 0.56 THz, (b) 1.13 THz, (c) 1.69 THz, and (d) 2.11 THz.

proportional to the wavelength detuning. Based on the experiment, we found that, in the case of single optical beam injection, a noticeable issue is that, if the referred wavelength detuning is zero or negative (injected wavelength shorter than adjacent side mode), the outcome peak wavelength at the locked mode is still fixed at the peak wavelength of selected side mode. The detailed mechanism is not presented and discussed in this paper. So, in our two-color lasing emission, the filtered wavelength by TF_1 is always fixed at the peak wavelength of central mode with the result that the peak of locked mode shown in Fig. 3 having no shift compared to the free-running spectrum. However, to simultaneously support two mode oscillations in the output spectrum, the output wavelength from TF_2 should be judiciously adjusted. As can be seen from the free-running spectrum shown in Fig. 2, the output peak level at the lasing mode gradually decayed with increasing the spacing between central mode and focused side mode. In reality, the outcome locking mode should be the combined product of injection beam and selected side mode that will produce also interference effect leading to the enhanced emission power. Hence, while the selected side mode is closed to central mode, the correspondingly filtered wavelength from TF_2 should be properly closed to the peak wavelength of adjacent lasing mode, i.e., proper wavelength detuning is required to simultaneously attain two oscillation modes, which should be same as the peak wavelength of selected side mode with opposite case due to the reduced side mode peak shown in Fig. 2. As a result, the feedback beams at filtered two wavelengths will further deplete the carriers in the active region leading to the injection locking behavior in which both mode A and mode B are simultaneously oscillated and locked, and other lasing modes are synchronously suppressed due to the reduced free carriers caused by the oscillation modes depletion. As can be seen from the output spectrum, the peak wavelengths at locked modes have no shift comparing with the free-running spectrum, and the outcome SMSR is as high as $\sim$20 dB because of the effective injection locking. In addition, the peak difference between two emission modes becomes more remarkable with extending mode spacing separation. This result should mainly be caused by the reduced feedback power from TF_2. In other words, two comparable oscillation peaks with large spacing may be achieved by enhancing the corresponding feedback power at mode B.

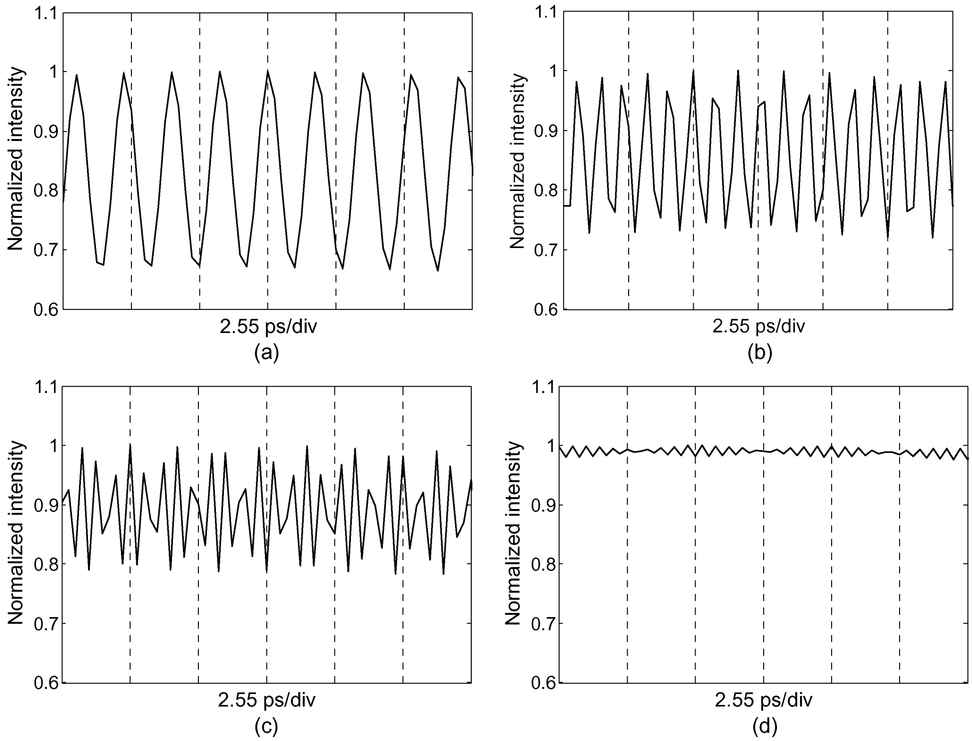


Fig. 4. Autocorrelation trace in time domain with various difference frequency in the corresponding spectrum, (a) 0.56 THz, (b) 1.13 THz, (c) 1.69 THz and (d) 2.11 THz.

Based on the characteristic of output spectrum captured by the OSA equipment, it is well known that beat signal in the time domain can be observed owing to the mode beating between two emission lasing modes, whose autocorrelation trace is shown in Fig. 4 by means of simulation, in which beating signal in time domain is firstly achieved by utilizing inverse fast Fourier transform (IFFT) to the generated two-color lasing spectrum and is then again converted into the temporal autocorrelation trace based on the autocorrelation function. Compared to Fig. 3, the repetition frequency of beat signal generated is the corresponding difference frequency between two locked lasing modes. From Fig. 4(a), one can see that the modulation depth in the beat signal is about 35% with the repetition frequency of $\sim$0.56 THz that is same as the mode separation illustrated in Fig. 3(a). However, while increasing the difference frequency of output emission modes, the outcome modulation depth in Fig. 4(b) and (c) obviously decayed resulting from the decreased interaction and enhanced peak difference between two lasing modes, which is, respectively, reduced to about 25%, and 15% in the case of $\sim$1.13-THz and $\sim$1.69-THz difference frequencies. Another noticeable phenomenon should be pointed out that, when the mode spacing is increased to $\sim$2.11 THz, the modulation depth in the converted autocorrelation trace tends to zero. This implies that the mutual interaction between two emission modes is very weak, and peak power difference between two emission modes shown in Fig. 3(d) is further increased.

In addition, some noticeable issues are that both nonlinear four-wave mixing and mode competition are enhanced as the difference frequency between two feedback wavelengths is further shortened to GHz regime so that interesting phenomena are easily observed in Figs. 5 and 6. As can be seen from Fig. 5, the output lasing spectrum has noticeable phenomenon, while the difference frequency is decreased to $\sim$0.28 and $\sim$0.43 THz. Besides the two main peaks (mode A and mode B), two small peaks on the two sides of the main peaks are almost equally spaced, i.e., two small peaks at $m = -4$ (-3) and 2 (6) in the case of $\sim$0.28 ($\sim$0.43) THz difference frequency, which are the direct result of four-wave mixing process induced by mode A and mode B. However, while the feedback wavelength filtered by TF_2 effectively causes the laser emission (mode B) at $m = 1$, i.e., the

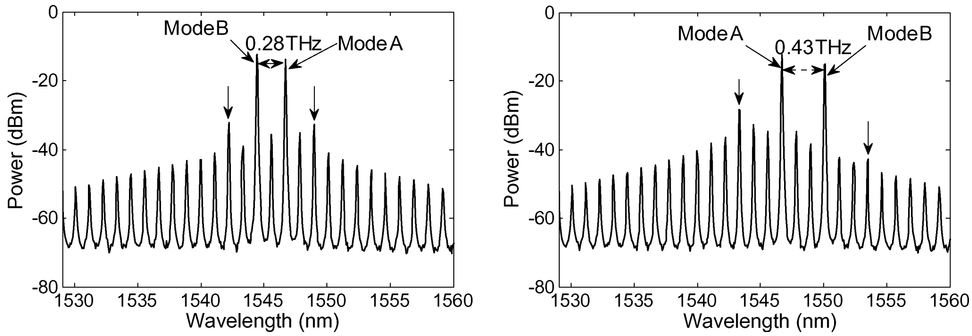


Fig. 5. Output spectrum of FP-LD with dual-wavelength feedback in the case of difference frequency of 0.28 and 0.43 THz.

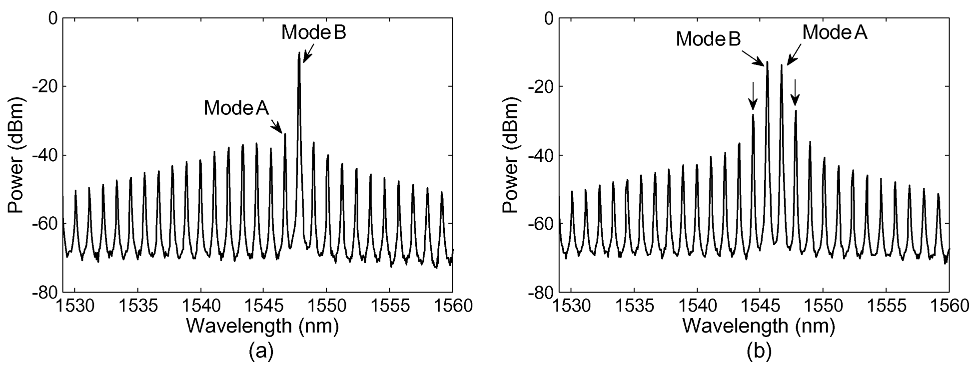


Fig. 6. Output spectrum with difference frequency of about 0.14 THz for two output modes.

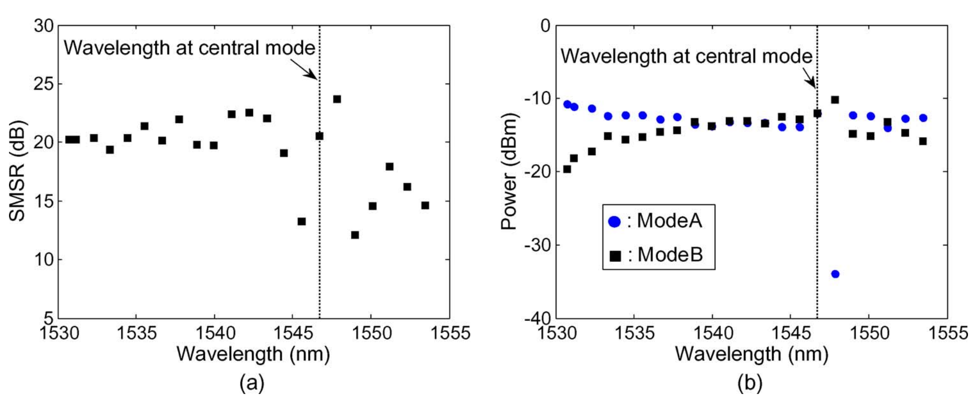


Fig. 7. Output spectrum properties including (a) SMSR, and (b) Peak levels of mode A and mode B against the changed wavelength at mode B.

corresponding difference frequency is about 0.14 THz, the central mode (mode A) at $m = 0$ is highly suppressed as a result of strong mode competition between mode A and B with the result that only single-mode output is observed. On the contrary, when the mode B is oscillated at $m = -1$, mode A cannot be suppressed. Two obvious small peaks are still observed at $m = -2$ and 1 due to the enhanced four-wave mixing effect that also results in the decreased SMSR.

The outcome SMSR and peak levels at mode A and mode B are, respectively, illustrated with respective to the changed wavelength at mode B in Fig. 7(a) and (b), in which another issue should be noted that, when feedback wavelength from the TF_2 is longer than the wavelength of central mode, the SMSR in the obtained two-color lasing spectrum shown in Fig. 7(a) is generally decreased compared to other opposite cases. The reason should be mainly attributed to asymmetrical gain spectrum and material characteristic of laser diode. Here, the shown SMSR in Fig. 7(a) is the average parameter of SMSR at mode A and mode B.

With increase of the spacing between mode A and mode B, their peak levels shown in Fig. 7(b) has slight fluctuation except a special wavelength that only makes mode B oscillate, and mode A is highly suppressed owing to the very strong mode competition with the result that the single-mode operation shown in Fig. 6(a) is generated. In addition, as the filtered wavelength from TF_2 is drifted to the range of 1530–1535 nm, their peak difference is very obvious as a result of the reduced feedback power at mode B shown in Fig. 1. Namely, the output peak at mode B remarkably decayed, and the mode A that can obtain enhanced stimulation emission has an increased output peak. Based on above discussion, we can conclude that, in order to achieve two-color lasing emission with effective SMSR and peak power, it is advantageous to select a proper short feedback wavelength at mode B comparing to the central mode wavelength.

4. Conclusion

A two-color lasing system based on the MMFP-LD with external cavity feedback consisting of two filters and an EDFA has been experimentally demonstrated and discussed, in which the achieved two-color operation with tunable difference frequency from several hundred GHz to more than 2 THz. The effective SMSR in the output spectrum is about 20 dB. While wavelength detuning between two feedback wavelengths is very close, both mode competition and four-wave mixing effects produce obvious influence on the output spectrum with the result that the two-color operation disappeared or the outcome SMSR of two-color lasing output remarkably decayed. By means of simulation, the generated beat signal with high repetition frequency has been observed, whose modulation depth is strongly dependent on the mode separation and mutual interaction. Hence, in order to realize effectively two-color lasing operation, judicious feedback wavelengths should be selected. Through the research in this paper, it is obvious that the potential application of FP-LD-based laser system is further extended.

Acknowledgment

The authors would like to thank all interested persons at MKE and at the Korea Evaluation Institute of Industrial Technology (KEIT).

References

[1] C. S. Friedrich, C. Brenner, S. Hoffmann, A. Schmitz, I. C. Mayorga, A. Kleher, G. Erbert, and M. R. Hofmann, "New two-color laser concepts for THz generation," *IEEE J. Sel. Topics Quantum Electron.*, vol. 14, no. 2, pp. 270–276, Mar./Apr. 2008.

[2] M. Tang, H. Minamide, Y. Y. Wang, T. Notake, S. Ohno, and H. Ito, "Tunable terahertz-wave generation from DAST crystal pumped by a monolithic dual-wavelength fiber laser," *Opt. Exp.*, vol. 19, no. 2, pp. 779–786, Jan. 2011.

[3] H. Maestre, A. J. Torregrosa, J. A. Pereda, C. R. Fernandez-Pousa, and J. Capmany, "Dual-wavelength Cr^{3+} : $LiCaAlF_6$ solid-state laser with tunable THz frequency difference," *IEEE J. Quantum Electron.*, vol. 46, no. 11, pp. 1681–1685, Nov. 2010.

[4] A. Klehr, J. Fricke, A. Knauer, G. Erbert, M. Walther, R. Wilk, M. Mikulics, and M. Koch, "High-power monolithic two-mode DFB laser diodes for the generation of THz radiation," *IEEE J. Sel. Topics Quantum Electron.*, vol. 14, no. 2, pp. 289–294, Mar./Apr. 2008.

[5] S. Osbome, K. Buckley, A. Amann, and S. O'Brien, "All-optical memory based on the injection locking bistability of a two-color laser diode," *Opt. Exp.*, vol. 17, no. 8, pp. 6293–6300, Apr. 2009.

[6] P. Heinricht, B. Wetzel, S. O'Brien, A. Amann, and S. Osborne, "Bistability in an injection locked two color laser with dual injection," *Appl. Phys. Lett.*, vol. 99, no. 1, pp. 011104-1–011104-3, Jul. 2011.

[7] S. Osborne, P. Heinricht, N. Brandonisio, A. Amann, and S. O'Brien, "Wavelength switching dynamics of two-colour semiconductor lasers with optical injection and feedback," *Semicond. Sci. Technol.*, vol. 27, no. 9, pp. 094001-1–094001-6, Sep. 2012.

[8] A. Biebersdorf, C. Lingk, M. De Giorgi, J. Feldmann, J. Sacher, M. Arzberger, C. Ulbrich, G. Böhm, M. C. Amann, and G. Abstreiter, "Tunable single and dual mode operation of an external cavity quantum-dot injection laser," *J. Phys. D, Appl. Phys.*, vol. 36, no. 16, pp. 1928–1930, Aug. 2003.

[9] I. Park, C. Sydlo, I. Fischer, W. Elsäßer, and H. L. Hartnagel, "Generation and spectroscopic application of tunable continuous-wave terahertz radiation using a dual-mode semiconductor laser," *Meas. Sci. Technol.*, vol. 19, no. 6, pp. 065305-1–065305-9, Jun. 2008.
[10] N. Kim, J. Shin, E. Sim, C. W. Lee, D. S. Yee, M. Y. Jeon, Y. D. Jang, and K. H. Park, "Monolithic dual-mode distributed feedback semiconductor laser for tunable continuous-wave terahertz generation," *Opt. Exp.*, vol. 17, no. 16, pp. 13 851–13 859, Jul. 2009.
[11] S. C. Feng, O. Xu, S. H. Lu, T. G. Ning, and S. S. Jian, "Switchable single-longitudinal-mode dual-wavelength erbium-doped fiber ring laser based on one polarization-maintaining fiber Bragg grating incorporating saturable absorber and feedback fiber loop," *Opt. Commun.*, vol. 282, no. 11, pp. 2165–2168, Jun. 2009.
[12] Z. J. Jiao, J. R. Liu, Z. G. Lu, X. P. Zhang, P. J. Poole, P. J. Barrios, D. Poitras, and J. Caballero, "Tunable terahertz beat signal generation from an InAs/InP quantum-dot mode-locked laser combined with external-cavity," *IEEE Photon. Technol. Lett.*, vol. 24, no. 6, pp. 518–520, Mar. 2012.
[13] N. H. Zhu, W. Li, J. M. Wen, W. Han, W. Chen, and L. Xie, "Enhanced modulation bandwidth of a Fabry-Pérot semiconductor laser subject to light injection from another Fabry-Pérot laser," *IEEE J. Quantum Electron.*, vol. 44, no. 6, pp. 528–535, Jun. 2008.
[14] M. Pochet, N. A. Naderi, N. Terry, V. Kovanis, and L. F. Lester, "Dynamic behavior of an injection-locked quantum-dash Fabry-Pérot laser at zero-detuning," *Opt. Exp.*, vol. 17, no. 23, pp. 20 623–20 630, Oct. 2009.
[15] Y. C. Chang, Y. H. Lin, J. H. Chen, and G. R. Lin, "All-optical NRZ-to-PRZ format transformer with an injection-locked Fabry-Pérot laser diode at unlasing condition," *Opt. Exp.*, vol. 12, no. 19, pp. 4449–4456, Sep. 2004.
[16] M. Pochet, T. Locke, and N. G. Usechak, "Generation and modulation of a millimeter-wave subcarrier on an optical frequency generated via optical injection," *IEEE Photon. J.*, vol. 4, no. 5, pp. 1881–1891, Oct. 2012.
[17] S. L. Pan and J. P. Yao, "Wideband band frequency-tunable microwave generation using an optoelectronic oscillator incorporating a Fabry-Pérot laser diode with external optical injection," *Opt. Lett.*, vol. 35, no. 11, pp. 1911–1913, Jun. 2010.
[18] J. M. Kang, H. C. Kwon, S. H. Lee, and S. K. Han, "A single to multi-wavelength converter using Fabry-Pérot laser diode with linear optical amplifier and its applications to the wavelength division multiplexing-passive optical network system," *Opt. Commun.*, vol. 254, no. 4–6, pp. 223–235, Oct. 2005.
[19] M. J. Zhang, T. G. Liu, P. Li, A. B. Wang, J. Z. Zhang, and Y. C. Wang, "Generation of broadband chaotic laser using dual-wavelength optically injected Fabry-Pérot laser diode with optical feedback," *IEEE Photon. Technol. Lett.*, vol. 23, no. 24, pp. 1872–1874, Dec. 2011.
[20] B. Nakarmi, M. Rakib-Uddin, and Y. H. Won, "Realization of all-optical multi-logic functions and a digital adder with input beam power management for multi-input injection locking in a single-mode Fabry-Pérot laser diode," *Opt. Exp.*, vol. 19, no. 15, pp. 14 121–14 129, Jul. 2011.
[21] H. K. Hisham, G. A. Mahdiraji, A. F. Abas, M. A. Mahdi, and F. R. Mahamd Adikan, "Characterization of turn-on time delay in a fiber grating Fabry-Pérot lasers," *IEEE Photon. J.*, vol. 4, no. 5, pp. 1662–1678, Oct. 2012.
[22] H. Wu, N. H. Zhu, J. W. Man, and H. Q. Yuan, "Continuously wavelength-tunable laser source using a self-injected Fabry-Pérot laser diode," *IEEE Photon. Technol. Lett.*, vol. 23, no. 6, pp. 332–334, Mar. 2011.