Discrete wavelength tuning characteristics of a single-frequency fiber laser with dual-wavelength external frequency-stable light injection

Motoharu Matsuura,[1] Kaoru Mori,[2] and Naoto Kishi[1]

[1]*Department of Information and Communication Engineering, University of Electro-Communications, Tokyo, 182-8585, Japan*
[2]*Currently with Hitachi, Ltd., Tokyo, 100-8280, Japan*
matsuura@ice.uec.ac.jp

Abstract: We investigate discrete wavelength tuning characteristics of a single-frequency fiber laser locked to either of two external lights. Frequency locking is achieved by the cooperatively induced spatial-hole burning (SHB) of a saturable absorber in the laser cavity. We show that lasing frequency is well locked to either of the two external lights when the lasing wavelength of the fiber laser is adjusted to the corresponding wavelength of the external light by tuning the bandpass filter in the laser cavity. The locked frequency stability of the fiber laser is as high as that of the employed external light source.

OCIS codes: (060.2330) Fiber optics communications; (0606.2380) Fiber optics sources and detectors; (140.3510) Lasers, fiber; (140.3600) Lasers, tunable.

References and links

1. International Telecommunication Union, Telecommunication Standard Sector of ITU, ITU-T G692, G694.
2. C. Gamache, M. Têtu, C. Latrasse, N. Cyr, M. A. Duguay, and B. Villeneuve, "An optical frequency scale in exact multiples of 100 GHz for standardization of multifrequency communications, " IEEE Photon. Technol. Lett. **8,** 290-292 (1996).
3. A. Bellemare, J. F. Lemieux, M. Têtu, and S. LaRochelle, "Erbium-doped ring lasers step-tunable to exact multiples of 100 GHz (ITU-GRID) using periodic filter," in Proc. European Conference on Optical Communications 1998 (ECOC 1998), 153-154 (1998).
4. T. Haber, K. Hsu, C. Miller, and Y. Bao, "Tunable erbium-doped fiber ring laser precisely locked to the 50-GHz ITU frequency grid," IEEE Photon. Technol. Lett. **12,** 1456-1458 (2000).
5. H. Y. Ryu, W.-K. Lee, H. S. Moon, S. K. Kim, H. S. Suh, and D. Lee, "Stable single-frequency fiber ring laser for 25-GHz ITU-T grids utilizing saturable absorber filter," IEEE Photon. Technol. Lett. **17,** 1824-1826 (2005).
6. H. Ryu, H. Moon, W. Lee, and H. Suh, "A discretely tunable erbium-doped fiber ring laser with 273 Ch. × 50 GHz-spacing ITU-T grids in C-& L-band regions," in Proc. Optical Fiber Communication Conference 2003 (OFC 2003), MF22 (2003).
7. J. Park, S. J. Ahn, W. J. Lee, J. Lee, H. S. Suh, and N. Park, "Widely tunable S/S+ band thulium-doped fiber laser locked to 50-GHz ITU-T grid," IEEE Photon. Technol. Lett. **16,** 404-406 (2004).
8. N. Kishi and T. Yazaki, "Frequency control of a single-frequency fiber laser by cooperatively induced spatial-hole burning," IEEE Photon. Technol. Lett. **11,** 182-184 (1999).
9. M. Matsuura and N. Kishi, "Frequency control characteristics of a single-frequency fiber laser with an external light injection," IEEE J. Sel. Topics in Quantum Electron. **7,** 55-58 (2001).
10. K. Mori, M. Matsuura, and N. Kishi, "Frequency locking of a single-frequency fiber laser with dual-wavelength external frequency-stabilized light source," in Proc. Optoelectronics and Communications Conference and International Conference on Integrated Optics and Optical Fiber Communications 2007 (OECC/IOOC 2007), 12C2-3 (2007).
11. N. Park, J. W. Dawson, and K. J. Vahala, "Frequency locking of an erbium-doped fiber ring laser to an external fiber Fabry-Perot resonator," Opt. Lett. **18,** 879-881 (1993).
12. F. L. Walls and D. W. Allan, "Measurements of frequency stability," Proc. of the IEEE, **74,** 162-168 (1986).

#88107 - $15.00 USD Received 3 Oct 2007; revised 13 Nov 2007; accepted 13 Nov 2007; published 26 Nov 2007

13. M. Ohtsu, H. Fukuda, T. Tako, and H. Tsuchida, "Estimation of the ultimate frequency stability of semiconductor lasers," Jpn. J. Appl. Phys. **22,** 1157-1166 (1983).

1. Introduction

In recent years, there have been rapid deployments of large capacity optical transmission systems and optical measurement systems. Owing to these deployments, the demands for highly frequency-stable and narrow linewidth light source have been increasing greatly. In particular, wavelength-tunable, single-frequency fiber lasers whose frequencies are accurately defined by the ITU-T frequency grid [1, 2] are very useful for dense wavelength-division-multiplexing (DWDM) transmission systems. Although various types of such fiber lasers have already been demonstrated so far, these lasers require a periodic filter such as a Fabry-Perot interferometer (FPI) in the laser cavity to generate multiple lasing lines on the ITU-T grid [3-7]. Moreover, the frequencies of lasing lines must be adjusted precisely to the ITU-T grid by controlling the passband of FPI thermally. Therefore, in DWDM transmission systems, the requirement of precise frequency control and calibration in each light source would pose an excess cost as the number of transmitter is increased.

Previously, we proposed a simple frequency control method for a single-frequency fiber laser using a frequency-stable external light source and a saturable absorber in a laser cavity [8]. In this scheme, the lasing frequency can be tuned to the external light frequency with better frequency stability, whereas its spectral linewidth is as narrow as that of a conventional fiber laser even if a semiconductor laser diode with a broad linewidth is employed as the external light source. The detailed frequency control characteristics and frequency-stable operation as high as those of the employed external light source were previously reported [9]. In our proposed method, frequency control was achieved by tuning both the external light frequency and a tunable bandpass filter (T-BPF) in the fiber laser cavity synchronously. The T-BPF should have been roughly tuned to the external light frequency to achieve the frequency control [9]. Hence, it is more convenient to employ a frequency-stabilized multifrequency light source as the external light source. In this case, frequency tuning is simply achieved by tuning T-BPF to select one of the lines of the multifrequency light source.

This paper presents frequency locking of a single-frequency fiber laser using a frequency-stable multifrequency light source, as mentioned above [10]. By using our proposed method, it is possible to realize a narrow linewidth light source locked to an arbitrary optical frequency on the ITU-T grid if we employ a multifrequency external light source or optical frequency comb, whose frequencies are accurately defined by the ITU-T grid. In other words, this technique is very useful for realizing easily a narrow linewidth light source on the ITU-T grid without precise frequency control and calibration by itself such as a thermal [4-7] and electrical [11] control circuit. In this paper, we investigate the discrete wavelength tuning characteristics of a single-frequency fiber laser with dual-wavelength external light injection for various wavelength spacing.

2. Single-frequency fiber laser with dual-wavelength external lights injection

Figure 1 shows the configuration of a single-frequency fiber laser with dual-wavelength external light injection. The laser cavity consists of a saturable absorber, an isolator, a polarization controller (PC), T-BPF, 3-dB couplers, and erbium-doped fiber amplifier (EDFA). Lasing wavelength is roughly determined using the passband of the T-BPF, whereas precise frequency locking is achieved by cooperatively induced spatial-hole burning (SHB) in the saturable absorber [8]. In our previous study, the lasing frequency was locked to the external light by tuning the wavelengths of the lasing and external lights [8, 9]. On the other hand, in this study, the lasing frequency is locked to either of two external light frequencies by tuning only the passband of the T-BPF, which roughly determines the wavelength of the

#88107 - $15.00 USD Received 3 Oct 2007; revised 13 Nov 2007; accepted 13 Nov 2007; published 26 Nov 2007

lasing light. Because the spatial-hole burning causes an additional narrow-bandpass filtering effect, the fiber laser achieves a stable single-frequency operation at the external light wavelength when the bandpass filter is roughly tuned to the external light wavelength [8]. Note that the state of polarization of the lasing and external lights must be adjusted so that effective interference occurs in the saturable absorber. For this reason, two PCs are employed in the laser cavity as shown in Fig. 1 and at the input of the external lights.

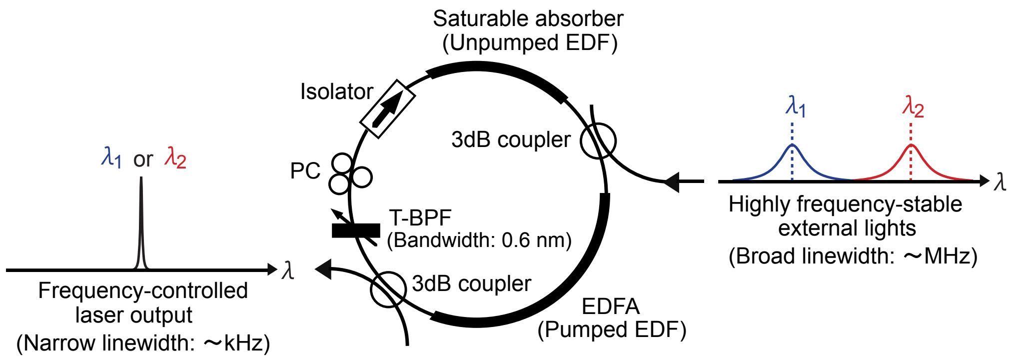

Fig. 1. Configuration of single-frequency fiber laser with external light injection.

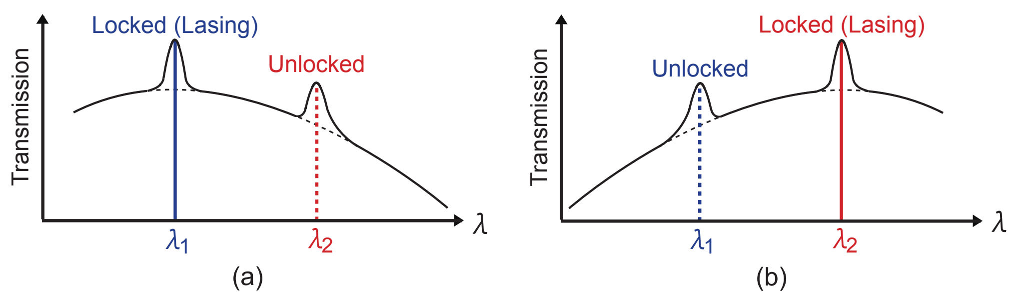

Fig. 2. Discrete frequency tuning with the T-BPF and additional filtering effect of the saturable absorber.

Figure 2 shows the principle of frequency (wavelength) locking for a dual-wavelength external light. The broad peak represents the passband of the employed T-BPF, whereas the small narrow peaks at the external light wavelengths λ_1 and λ_2 represent additional transmission due to the spatial-hole burning. When the T-BPF is roughly tuned at one of the external light wavelength λ_1, as shown in Fig. 2(a), the transmission at this wavelength is larger than that of the other external light wavelength λ_2. In this case, lasing occurs stably at λ_1. When the T-BPF is roughly tuned at λ_2, as shown in Fig. 2(b), lasing occurs stably at λ_2. In this way, lasing frequency is locked to either of the two external light frequencies. This means that discrete frequency tuning is achieved by tuning the T-BPF at one of the external light frequencies.

#88107 - $15.00 USD Received 3 Oct 2007; revised 13 Nov 2007; accepted 13 Nov 2007; published 26 Nov 2007

3. Experimental results and discussions

As frequency-stable external light sources, wavelength tunable, external-cavity DFB-LDs (ANDO AQ8201-11) are employed. The linewidth are less than 5 MHz. An erbium-doped fiber (EDF) with a gain peak wavelength of approximately 1560 nm is employed to the gain medium (EDFA) and saturable absorber in the laser cavity. The lengths of each EDF are 6 m and 1.2 m, respectively. The overall length of the laser cavity is approximately 18.2 m, corresponding to a longitudinal mode spacing of 11 MHz. In the following experiment, the bandwidth of the employed T-BPF is 0.6 nm. The lasing spectral linewidth of the fiber laser is measured by the delayed self-heterodyne method with 25 km-long fiber delay line. The measured linewidth is less than 8 kHz regardless of external light existence.

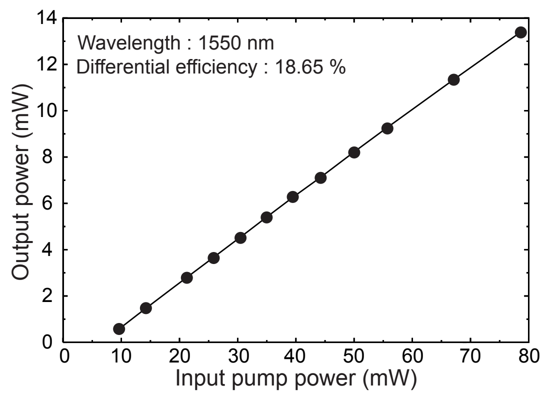

Fig. 3. Output power of the fiber laser versus input pump power at free-running operation.

Figure 3 shows the output power of the fiber laser versus the input pump power at free-running operation (without external light injection). The lasing wavelength is set to 1550 nm by tuning the T-BPF. The measured differential efficiency is approximately 18.85 % regardless of external light existence. As the output power is increased, the fiber laser at a free-running operation tends to cause frequent mode hopping, which degrades frequency locking performance. Thus, in the following experiment, the output power of the fiber laser is set to 1.162 mW to realize a better frequency locking operation.

To investigate the frequency locking performance of our proposed method, we measure the frequency stability of the lasers with changing injected external light powers and their wavelength spacing. In all the experiments, the frequency stabilities of the lasers are quantitatively estimated using Allan variance [12, 13]. For example, the Allan variance of the fiber laser at a free-running operation is on the order of more than several hundreds of MHz^2, whereas that of the employed highly frequency-stable external light is approximately 10 MHz^2.

Figure 4 shows the frequency stabilities of the fiber laser locked to either of the external lights with changing injected power of the unlocked light into the laser cavity. In the case of the wavelength spacing of 0.8 nm and 0.2 nm, as shown in Fig. 4(a) and (b), no marked change in the frequency stability is observed even when the unlocked light power is changed. On the other hand, it can be clearly observed that the frequency stability strongly depends on the locked light power. In the case of 0.1-nm wavelength spacing, as shown in Fig. 4(c), high-frequency stabilities are not obtained for all the injected powers of the locked and unlocked lights. In particular, higher unlocked light powers give rise to lower frequency stabilities, because a higher unlocked light power strongly interferes with the frequency locking to the locked light as the wavelength spacing becomes narrower. In addition, we believe that this behavior is also due to a much broader bandwidth (0.6 nm) of the employed T-BPF than the

#88107 - $15.00 USD Received 3 Oct 2007; revised 13 Nov 2007; accepted 13 Nov 2007; published 26 Nov 2007

wavelength spacing between the external lights. Further improvement of the frequency stability will be possible by introducing T-BPF with a narrower bandwidth.

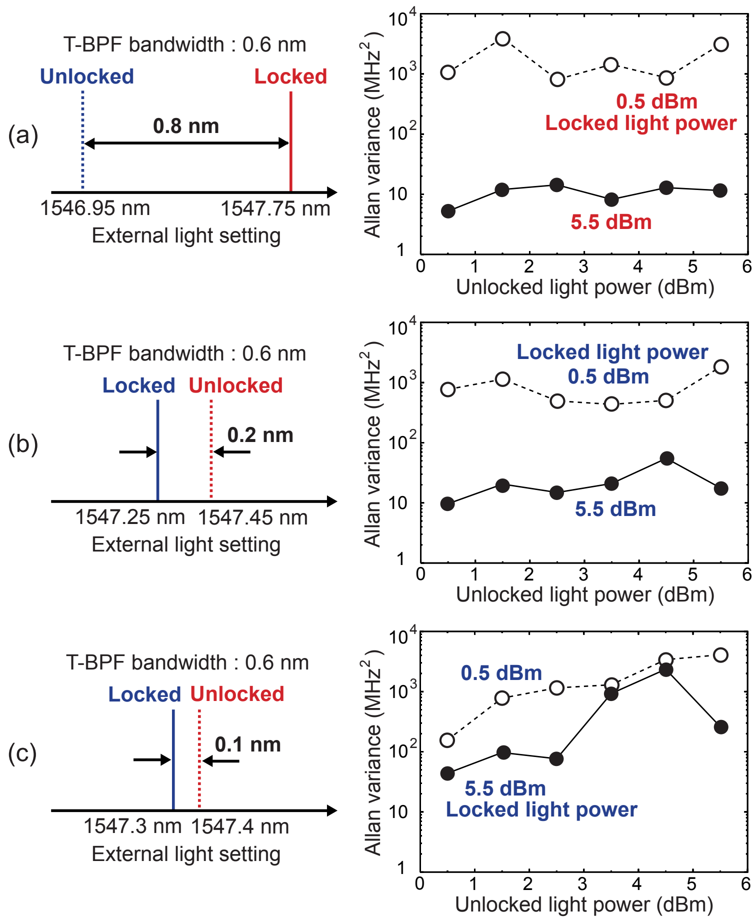

Fig. 4. Allan variances with changing unlocked light power. Wavelength spacing of (a) 0.8 nm, (b) 0.2 nm, and (c) 0.1 nm.

The frequency stabilities of the fiber laser can also be described as a function of the locked light power, as shown in Fig. 5. In the case of a 1.5 dBm unlocked power as shown in Fig. 5(a), higher locked powers result in higher frequency stabilities. On the other hand, as shown in Fig. 5(b), when a high unlocked power of 4.5 dBm is injected with a wavelength spacing of 0.1 nm, high-frequency stability can not be obtained even if the locked power is increased. Therefore, in the narrow wavelength spacing, the unlocked light power as well as the locked light must be optimized to obtain higher frequency stability. In addition, the bandwidth of the T-BPF is also an important parameter for the frequency locking with high-frequency stability, as mentioned above. It is readily understood from Fig. 2, that the selection of one of the transmission peaks at λ_1 and λ_2 becomes more difficult for a broader bandwidth of the T-BPF.

Figure 6 shows the frequency stability of the fiber laser when the lasing wavelength is shifted from 1546.94 nm to 1547.26 nm by tuning the T-BPF. The dotted horizontal line shows the Allan variance of the employed external lights. The wavelengths of the external lights are 1547.0 nm and 1547.2 nm (with a wavelength spacing of 0.2 nm), respectively. These injected powers are set to 5.5 dBm. As shown in Fig. 6, the lasing wavelength is well locked to either of the external light with good frequency stability comparable with that of the

#88107 - $15.00 USD Received 3 Oct 2007; revised 13 Nov 2007; accepted 13 Nov 2007; published 26 Nov 2007

external light, when the lasing wavelength of the fiber laser is tuned to the corresponding wavelength of the external lights. This indicates that frequency locking is well achieved by tuning the lasing wavelength to either of the two external lights. Thus, discrete wavelength tuning is easily achieved by tuning the T-BPF.

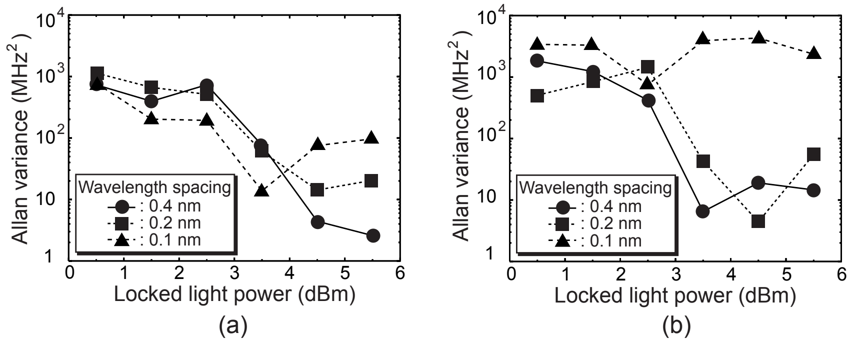

Fig. 5. Allan variances with changing locked light power for various wavelength spacing. The unlocked light powers are set to (a) 1.5 dBm and (b) 4.5 dBm, respectively.

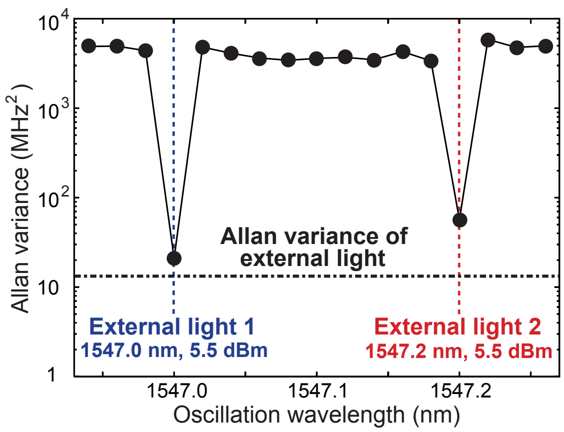

Fig. 6. Allan variances versus oscillation wavelength by tuning the T-BPF in the laser cavity. The wavelengths of two injected external lights are set to 1547 nm and 1547.2 nm (with a wavelength spacing of 0.2 nm and each injected power of 5.5 dBm), respectively.

4. Conclusion

We demonstrated frequency locking with dual-wavelength external light injection and investigate its frequency control characteristics. In a wavelength spacing of more than 0.2 nm of the external light wavelength, the lasing frequency of the fiber laser was successfully locked to either of the external light frequency with high-frequency stability. If we employ an optical frequency comb or multiple external light sources on the ITU-T grid, the proposed fiber laser will achieve a wavelength tunable and narrow linewidth operation corresponding to the ITU-T grid. Such a light source will be useful for future DWDM transmission systems.

#88107 - $15.00 USD Received 3 Oct 2007; revised 13 Nov 2007; accepted 13 Nov 2007; published 26 Nov 2007