Optical Engineering

OpticalEngineering.SPIEDigitalLibrary.org

Wavelength stabilization of a semiconductor laser using wavelength-dependent frequency shift by stimulated Brillouin scattering

Junsu Kim
Siwoong Park
Yong-Kyu Choi
Chang-Soo Park

Junsu Kim, Siwoong Park, Yong-Kyu Choi, Chang-Soo Park, "Wavelength stabilization of a semiconductor laser using wavelength-dependent frequency shift by stimulated Brillouin scattering," *Opt. Eng.* **55**(12), 120501 (2016), doi: 10.1117/1.OE.55.12.120501.

Wavelength stabilization of a semiconductor laser using wavelength-dependent frequency shift by stimulated Brillouin scattering

Junsu Kim,[a] Siwoong Park,[b] Yong-Kyu Choi,[c] and Chang-Soo Park[a,*]
[a]Gwangju Institute of Science and Technology, School of Electrical Engineering and Computer Science, Cheomdangwagi-ro 123, Buk-gu, Gwangju 61005, Republic of Korea
[b]Electronics and Telecommunications Research Institute, 176-11 Cheomdangwagi-ro, Buk-gu, Gwangju 61012, Republic of Korea
[c]Defense Agency for Technology and Quality, Dongwon-ro 28-gil, Suseong-gu, Daegu 42037, Republic of Korea

Abstract. We propose a method of stabilizing the center wavelength of a semiconductor laser using the wavelength-dependent frequency shift of Stokes wave induced by stimulated Brillouin scattering in fiber. Due to the nonlinear behavior of fiber to a strong input power, Stokes wave is generated and its frequency varies in inversely proportional to the input wavelength over a small wavelength range of <1 nm. Therefore, we can obtain the size of the frequency change in Stokes shift due to the variation from the initial wavelength as an error signal. The wavelength can be stabilized by adjusting the current or temperature of the semiconductor laser to compensate for the error signal. In our experiment, 1-pm wavelength stability was achieved together with a long-term wavelength drift (>4 h) of 10 pm. [DOI: 10.1117/1.OE.55.12.120501]

Keywords: semiconductor lasers; high-power lasers; nonlinear optics.

Paper 161373L received Sep. 2, 2016; accepted for publication Nov. 15, 2016; published online Dec. 6, 2016.

1 Introduction

Semiconductor lasers have been recognized as good light sources because of their small size, light weight, and high output power with a narrow linewidth. However, wavelength stabilization has become an important issue in their applications, such as in dense wavelength-division multiplexing communications and high-power lasers. This wavelength variation is due to changes in the refractive index inside the active region accompanied by fluctuations in the applied current or temperature of the laser. Therefore, typical distributed feedback lasers (DFBs) have an internal thermal electric cooler (TEC) inside the package to maintain the temperature of the laser chip at a specific temperature. However, its role has limitations in the achievement of long-term stability due to the aging effect of the active region through incessant excitation (driving current and device temperature). Further stabilization methods of locking the wavelength to an absorption line of gas cells or to the transmission curve of etalon filters[1–4] has been reported. However, the possible wavelengths are predetermined by the available absorption lines of the gas composition ratio in the cells or the angle, thickness, and reflectivity of the filters. In particular, the absorption lines and peaks could be saturated or blurred when the optical power injected into the cells or the filters is too high.

We introduce a wavelength stabilization method in this paper that uses the wavelength-dependent frequency change in Stokes wave, which is induced by stimulated Brillouin scattering (SBS) in the fiber. If the wavelength is not changed, then the peak frequency of the Stokes wave is constant. Otherwise, the frequency is inversely changed depending on the variation in the center wavelength of the laser. We can compensate for wavelength variation by monitoring the amount of peak frequency shift. This method uses SBS-induced Stokes shift and, therefore, has the advantage of stabilizing arbitrary wavelengths, especially the stabilization of high-power optical signals.

2 Peak Frequency Detection of Stokes Shift and Wavelength Control

SBS is a well-known nonlinear process caused by the interaction between the pump wave and the Stokes wave in optical fibers.[5,6] In the case in which strong optical power (>5 mW) is excited in the optical fiber, SBS is induced as a form of nonlinear process inside the fiber and most portion of light generated by SBS is propagated backward due to the geometry confinement of the fiber. The peak frequency of the Brillouin scattering light is downshifted due to the Doppler effect associated with a grating movement at the acoustic velocity (v_a) and the amount of frequency shift (ν_B) is inversely proportional to the pump wavelength as shown below:

$$\nu_B = 2n_{\mathrm{eff}}v_a/\lambda_p, \tag{1}$$

where n_{eff} is the effective refractive index of the fiber and λ_p is the pump wavelength.[5]

When typical single-mode fiber (SMF) and a continuous wave DFB with narrow linewidth are used to induce SBS, the variation of the frequency shift with respect to the pump wavelength can be obtained from the first derivative as below:

$$\frac{\mathrm{d}\nu_B}{\mathrm{d}\lambda_p} = 2\cdot\frac{\mathrm{d}v_a}{\mathrm{d}\lambda_p}\cdot\frac{n_{\mathrm{eff}}}{\lambda_p} - 2\cdot v_a\cdot\frac{n_g}{\lambda_p^2}, \tag{2}$$

$$n_g = \left(n_{\mathrm{eff}} - \lambda_p\frac{\mathrm{d}n_{\mathrm{eff}}}{\mathrm{d}\lambda_p}\right), \tag{3}$$

where n_g is the group refractive index of the fiber. The acoustic velocity (v_a) is mainly affected by the elastic characteristics and the density of the optical fiber.[7] Therefore, the first term

*Address all correspondence to: Chang-Soo Park, E-mail: csp@gist.ac.kr

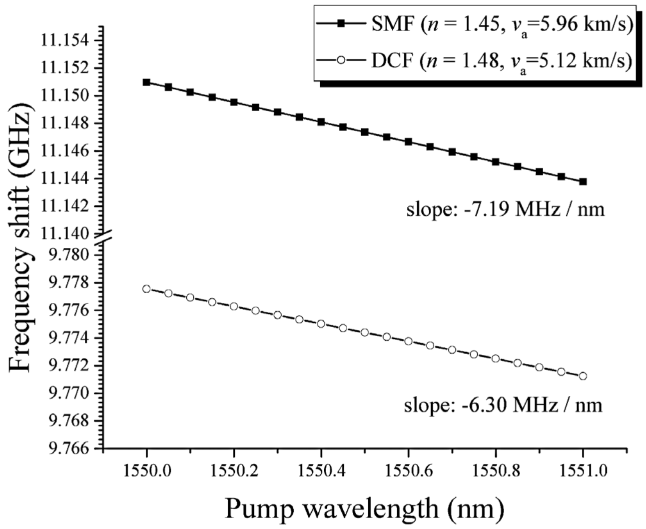

Fig. 1 Frequency shifts (ν_B) corresponding to the pump wavelength from 1550 to 1551 nm in cases of SMF (square line) and DCF (open circle line).

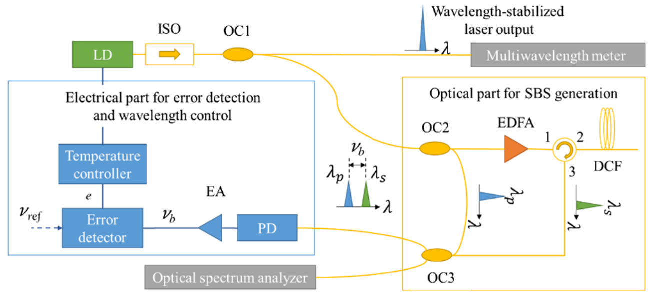

Fig. 2 Experimental setup of the proposed system. LD, laser diode; ISO, isolator; OC, optical coupler; EDFA, erbium-doped fiber amplifier; DCF, dispersion compensated fiber; PD, photodetector; and EA, electrical amplifier.

on the right-hand side of Eq. (2) can be disregarded and the equation is approximated by

$$\frac{d\nu_B}{d\lambda_p} \cong -2v_a \cdot \frac{n_g}{\lambda_p^2}. \tag{4}$$

The wavelength drift ($d\lambda_p$) of general semiconductor lasers is much less than 1 nm and the gain spectrum of SBS is some hundreds of MHz or narrower. Therefore, the variation of the frequency shift corresponding to the pump wavelength is almost constant (in the order of MHz/nm). The amount of frequency shift depends on the GeO_2 concentration in the fiber core. When dispersion compensated fiber (DCF) with a smaller diameter is used to lower the SBS threshold, the peak frequency of the Brillouin gain spectrum becomes lower than that of SMF. For both the SMF and DCF cases, the dependency of the frequency shift on the pump wavelength is shown in Fig. 1. The refractive indices and acoustic velocities used were 1.45 and 5.96 km/s and 1.48 and 5.12 km/s, respectively, from Refs. 5 and 7.

In addition, the variation of the frequency shift of the three types of optical fiber was experimentally measured in Ref. 8. In the case of SMF, the above theoretical result is considered virtually the same as the experimental result in Ref. 8. Moreover, we can easily extract the variation of the frequency shift because the SBS gain bandwidth is ~50 MHz, which is relatively small compared to that of the Stokes shift (9 to 11 GHz). Therefore, the wavelength change of the semiconductor laser can be monitored by measuring the extent to which the Stokes shift deviates from the initial value. That is, by adjusting the injected direct current or temperature of the semiconductor laser in such a way to always match the amount of shift in the initial value, we can stabilize the center wavelength of the laser.

3 Experimental Setup and Results

An experimental setup was arranged to investigate the feasibility of wavelength stabilization using SBS nonlinear characteristics, as shown in Fig. 2. An InGaAsP-based semiconductor laser with the internal TEC was selected as a pump source with DC-biased at 60 mA (threshold current: 25 mA). The output power and the wavelength of the semiconductor laser (λ_p) were ~7.35 dBm and 1550.457 nm, respectively. The wavelength of the laser was controlled using an external temperature controller with a 0.5-pm wavelength tuning resolution.

The output was optically isolated to block the reflection back to the laser and divided into two through OC2: One to an erbium-doped fiber amplifier (EDFA) with 16-dB optical gain and the other to OC3 as a reference for beating. The output of the EDFA was passed through the optical circulator (insertion loss: 1.5 dB/port) to the DCF for the SBS process. We used DCF instead of SMF to lower the threshold level for the nonlinear process because it has a smaller core diameter. The DCF was angled-connected to remove the Fresnel reflection from the far end. The length of DCF used was 10 km, and a pump power of 10.51 dBm was injected into the DCF. The scattered wave in the backward direction (its peak wavelength was λ_s) entered back into port 2 and finally appeared at port 3. This signal was combined with the reference through OC3 and the beat signal was generated by using a photodetector. The higher frequency components in the beat signal were removed by the bandwidth of the electrical amplifier. Then, the lower frequency of the beat signal ($\nu_B = \nu_p - \nu_s$) was counted by using a frequency detector and compared with the initial frequency value of Stokes shift (ν_{ref}) corresponding to the initial pump wavelength of the semiconductor laser. Finally, the error frequency ($e = \nu_B - \nu_{ref}$) was used to change the temperature of the laser in such a way to maintain the current wavelength at the initial wavelength value.

The optical spectra of the pump and backscattered lights and their beat frequency were measured with an Ando AQ-6315A optical spectrum analyzer with 0.01-nm resolution and an Agilent E4448A electrical spectrum analyzer, respectively. The wavelength difference appeared to be ~0.08 nm and the corresponding electrical beat frequency was 9.49 GHz around 1550.5 nm, as shown in Figs. 3 and 4. Moreover, we confirmed that the beat frequency decreased as the wavelength of the semiconductor laser increased. The variation of the beat frequency was ~ -7.64 MHz/nm from 1550.15 to 1551.04 nm for the DCF used and was plotted in Fig. 5. To investigate the impact of pump power and polarization on the stability, we changed the pump power and polarization before the DCF but did not observe any fluctuation except for an output power variation of ~0.1 dB. Because we used a

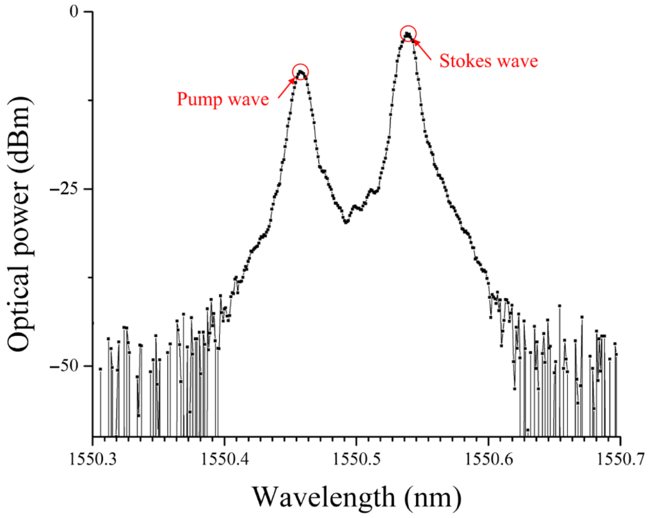

Fig. 3 Optical spectra of the pump and Stokes waves.

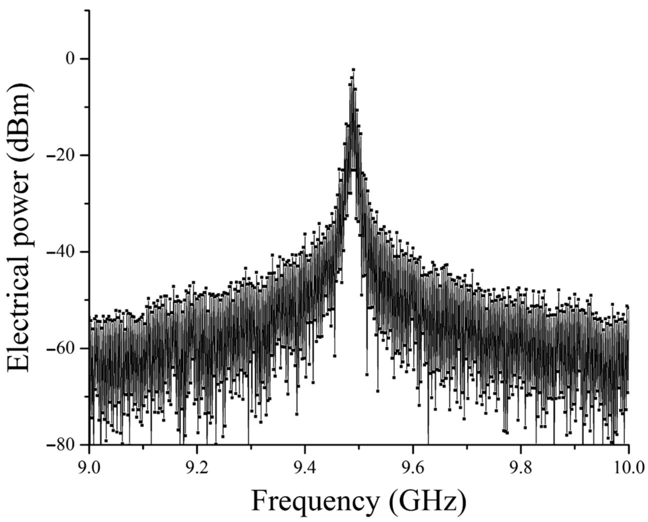

Fig. 4 Beat frequency (ν_B) between the pump wave and the Stokes wave.

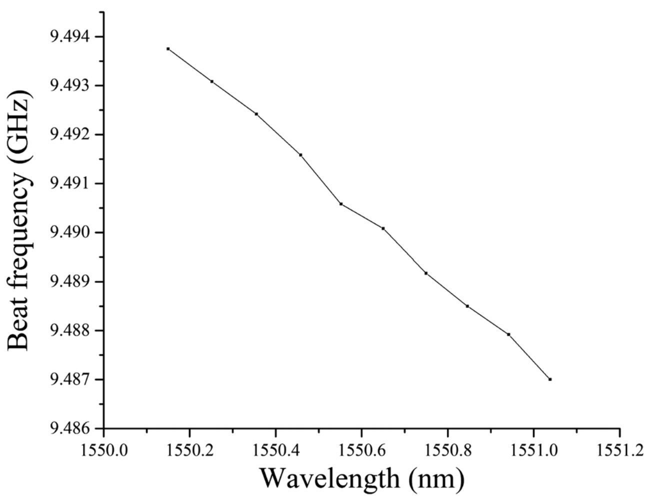

Fig. 5 Electrical beat frequency corresponding to the pump wavelength.

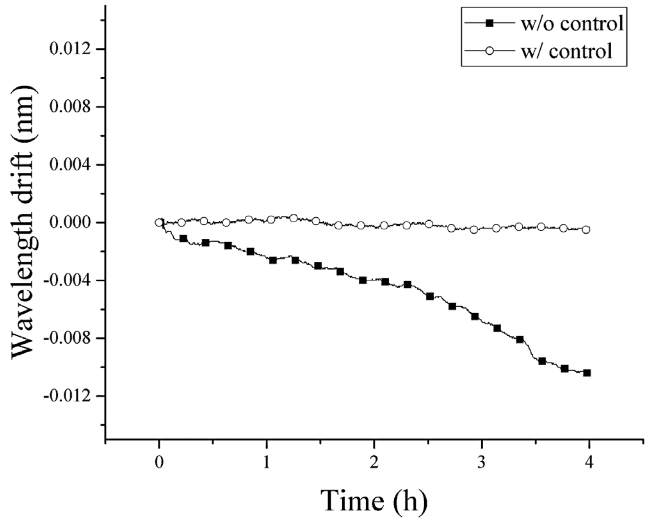

Fig. 6 Wavelength stability of the semiconductor laser when the proposed method is applied (open circle line) or not applied (square line).

pump source with a linewidth of ~1 MHz, which was considerably smaller than ~50 MHz (gain bandwidth), the spectral width of the beat signal was almost determined by that of the backscattered light, and the peak frequency was not changed, not limiting the accuracy.

We put the DCF module into the chamber and increased the temperature from 25°C to 40°C to investigate the influence of the DCF on the stability under different environmental conditions (here, temperature fluctuation). A variation of 11.6 MHz was observed for temperature fluctuations greater than $\Delta T = 15°\mathrm{C}$ corresponding to 0.77 MHz/°C. We measured the frequency variation of Stokes shift with the stabilized light source locked to the HCN gas cell (stability of <0.8 pm) inside the chamber kept at 25°C to investigate the influence of the DCF used on the wavelength stability. The variation was measured to be within ±100 kHz and could be ignored compared to the wavelength variation of the semiconductor laser.

The final output of the semiconductor laser was measured by using an Agilent 86122A multiwavelength meter with 0.1-pm resolution to measure the long-term wavelength drift, and the wavelength stability was drawn in Fig. 6. In the case of using only TEC, the stability was increased to 10.0 pm (square line). Meanwhile, the proposed method showed a stability of 1.0 pm (open circle line), showing a mean value of ~ -0.13 pm.

4 Conclusion

We proposed a wavelength stabilization method using the Stokes shift induced by the SBS process in fiber. In general, the amount of Stokes shift depended on the wavelength of the semiconductor laser. Comparing the current Stokes shift with the reference Stokes shift corresponding to the peak wavelength of the laser to be stabilized allowed us to obtain information on the wavelength variation, which can be used as an error signal. The stability of the proposed method was confirmed to be 1.0 pm, better than that (10.0 pm) of the TEC case, using the experimental results. This technique is more suitable for the wavelength stabilization of high-power lasers that can easily induce nonlinear behavior in fiber.

Acknowledgments

This material is based upon work supported by the Ministry of Trade, Industry and Energy, Korea, under Industrial Technology Innovation Program No. 10049151, "Development of Subnanometer Interferometer System" and the "Gwangju Institute of Science and Technology (GIST) Research Institute" Project through a grant provided by GIST in 2016.

References

1. Y. Sakai, S. Sudo, and T. Ikegami, "Frequency stabilization of laser diodes using 1.51–1.55 μm absorption lines of $^{12}C_2H_2$ and $^{13}C_2H_2$," *J. Quantum Electron.* **28**(1), 75–81 (1992).
2. K. Numata et al., "Frequency stabilization of distributed-feedback laser diodes at 1572 nm for lidar measurements of atmospheric carbon dioxide," *Appl. Opt.* **50**, 1047–1056 (2011).
3. P. K. J. Park and Y. C. Chung, "Analysis of frequency offset in the frequency stabilization of semiconductor laser based on frequency dithering technique," *Opt. Express* **15**, 14213–14218 (2007).
4. H. Qi, Y. Yu, and W. Chen, "Modeling and measurement of locking stability for a fiber Fabry–Perot tunable filter based on the dithering technique," *Opt. Appl.* **43**, 343–352 (2013).
5. G. P. Agrawal, "Stimulated Brillouin scattering," in *Nonlinear Fiber Optics*, 3rd ed., pp. 355–388, Academic Press, California (2001).
6. A. Kobyakov, M. Sauer, and D. Chowdhury, "Stimulated Brillouin scattering in optical fibers," *Adv. Opt. Photonics* **2**, 1–59 (2010).
7. A. Yeniay, J.-M. Delavaux, and J. Toulouse, "Spontaneous and stimulated Brillouin scattering gain spectra in optical fibers," *J. Lightwave Technol.* **20**, 1425–1432 (2002).
8. C. S. Park, C. G. Lee, and C. S. Park, "Photonic frequency upconversion by SBS-based frequency tripling," *J. Lightwave Technol.* **25**, 1711–1718 (2007).