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Semiconductor Optical Amplifier (SOA)-Fiber Ring Laser and Its Application to Stress Sensing

Yoshitaka Takahashi[1], Shinji Sekiya[2], Tatsuro Suemune[3]
[1]*Department of Electronic Engineering, Graduate School of Engineering, Gunma University, Kiryu, Japan*
[2]*Package Material Production Division, Hitachi Cable, Ltd., Hitachi, Japan*
[3]*Personal Solutions Business Unit, NEC Corp., Kawasaki, Japan*
E-mail: *taka@el.gunma-u.ac.jp*
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Abstract

We have developed a novel optical fiber ring laser using a semiconductor optical amplifier (SOA) as the gain medium, and taking advantage of polarization anisotropy of its gain. The frequency difference of the bi-directional laser is controlled by birefringence which is introduced in the ring laser cavity. The beat frequency generated by combining two counter-propagating oscillations is proportional to the birefringence, the fiber ring laser of the present study is, therefore, applicable to the fiber sensor. The sensing signal is obtained in a frequency domain with the material which causes the retardation change by a physical phenomenon to be measured. For the application to stress sensing, the present laser was investigated with a photoelastic material.

Keywords: Fiber Laser, Fiber Sensor, Ring Laser, Semiconductor Optical Amplifier, Optical Sensor

1. Introduction

Optical fiber sensors are widely used in various uses since it has many advantages. Most of them detect an optical intensity change as a sensing signal caused by change in polarization, phase, loss, and fluorescence. In such kinds of sensors, however, fluctuation of the source intensity and/or a propagation loss will cause a measurement error. Sensors which are not influenced by the fluctuation have been required and studied, e.g. optical heterodyne, a frequency-domain sensor, and so on. For the application to a frequency-domain sensor, the authors have studied a novel optical fiber ring laser [1-3].

In general cases birefringence applied to a ring laser is reciprocal effect and no phase difference generates between two counter-propagating lights. Fiber ring lasers for frequency-domain sensors were proposed, e.g., an optical fiber gyro [4,5] using Sagnac effect and an optical current sensor [6,7] using Faraday effect. These effects are non-reciprocal effect.

But in the present study reciprocal effect, *i.e.*, birefringence was used, and making good use of the gain anisotropy of SOA the authors developed the SOA-fiber ring laser in which the phase difference occurred by introducing a birefringent medium in the ring cavity between two counter-propagating oscillations. To investigate the performance of the present laser, we introduced a photoelastic material in the ring laser cavity and confirmed the frequency difference of the counter-propagating oscillations changed by applying stress to the material proportionally.

2. Principle of Operation

The operating principle of the SOA ring laser [1] is shown in **Figure 1**. SOA is the gain medium of the laser. It has polarization anisotropy of its gain and is regarded as an amplifier only for TE-polarization, which is assumed to be in accordance with the horizontal plane. The ring cavity contains Faraday rotators R_1 and R_2 which generate +45˚ and –45˚-rotation of the state of polarization (SOP) of light propagating in the clockwise (cw) direction. The cavity also contains a medium S which has birefringence (retardation *R*) and works as a sensing element when the laser is applied to a fiber sensor.

First, consider light which propagates in the cw direction in the ring cavity. Horizontally polarized light emitted from SOA is coupled into the cavity and passes through R_1, and, as a result, SOP of the cw light rotates 45˚ (an arrow in a solid circle shown in **Figure 1**). The

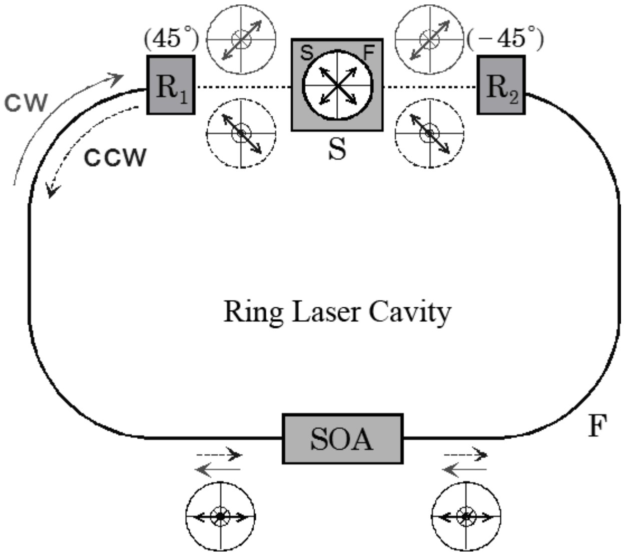

Figure 1. Schematic diagram of SOA-fiber ring laser.

dielectric axes (F-axis and S-axis) of the birefringent medium S are at an angle of 45˚ to the horizontal plane. The cw light, therefore, passes through S with the polarization plane in accordance with the F-axis. The cw light turns horizontally polarized after passing through another Faraday rotator R_2, and returns to SOA with the polarization corresponding to its TE-polarization.

On the other hand, the counterclockwise (ccw) light, whose SOP's are denoted as arrows in a doted circle, is emitted from SOA and passes through S with the polarization plane in accordance with the S-axis because of the non-reciprocity of Faraday effect. It returns to SOA with the polarization corresponding to its TE-polarization in a similar way. That is, the cw and ccw lights have orthogonal polarization to each other in passing through S, while they have the same polarization in other regions and are both amplified by SOA. Thus phase difference is brought about between the cw and ccw lights by retardation in S, and causes them to oscillate in different frequencies. The frequency difference f_B is proportional to the retardation R (nm) and given by [1]

$$f_B = \frac{c}{\lambda L} R = \frac{R}{\lambda} f_{FSR} \tag{1}$$

where l nm is the lasing wavelength, c is the velocity of light, L and $f_{FSR} = c/L$ is the optical path length and the free spectral range of the ring cavity, respectively. If S is the medium which causes the retardation change by the physiccal phenomenon to be measured, the change can be detected by measuring f_B and the laser in this study can be applied to a sensor which detects the signal in a frequency domain.

3. Configuration

Figure 2 shows the configuration of the fiber ring laser. The emitted lights at 1.55 mm from both sides of SOA (Anritsu Corp.) were coupled into singlemode fibers (SMF) with singlemode ball-lens fibers (BLF), collimated with fiber-collimators (C_1, C_2) and then passed through a sensing element (S) in the space-propagating region. To reduce the lasing bandwidth 150-mm-thick glass plate E was also placed as etalon. At the ends of the two fiber-collimators Faraday rotators (R_1, R_2) 0.7 mm thick were attached. They were magnetized and generated 45˚-rotation of the polarization angle of the 1.55 mm light without an external magnet. Both the cw and ccw lights of the ring laser were output via a 10 dB-singlemode fiber directional coupler (FC_1), and in order to examine the frequency difference they were combined with each other via a 3 dB-singlemode fiber directional coupler (FC_2) and detected by an avalanche photodiode (APD). Using two fiber polarization controllers (FPC) the SOP of both cw and ccw lights were adjusted in accordance with the TE-polarization of SOA and to be linearly polarized at the end of the fiber-collimators. Two Faraday rotators (R_1, R_2) were placed complementarily as described before and thus the cw and ccw lights propagated in the orthogonal polarization to each other in passing through S. The frequency difference f_B is measured by APD with a spectrum analyser as a beat signal.

4. Experiment and Results

The lasing characteristics of SOA-fiber ring laser was investigated without briefringent medium in the resonator first and the power spectrum is shown in **Figure 3**. The laser operated in multimode in spite of introducing an etalon, then in **Figure 3** the spectrum corresponding to the signals of the free spectral range f_{FSR} and its harmonic

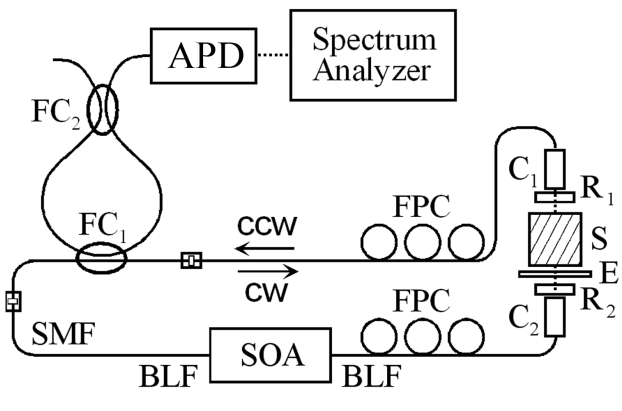

Figure 2. Configuration of SOA-fiber ring laser.

are shown. The center of the lasing wavelength was 1.562 mm. The optical path length of the ring cavity L was 16.1 m and the calculated value of $f_{FSR} = c/L$ is 18.6 MHz, which corresponds to the one shown in **Figure 3**.

Various wave plates were inserted in the laser cavity instead of a sensing element as known birefringent media to change the frequency difference f_B and the result is shown in **Figure 4**. The dashed line is calculated value with Equation (1) and the observed power spectrum at R of 387.5 nm is also shown in **Figure 4** with a quarter-wave plate of 1550 nm. The result shows that retarda tion can be determined by measuring the shift of f_B and the present fiber ring laser would be a sensor of birefringence in a frequency domain.

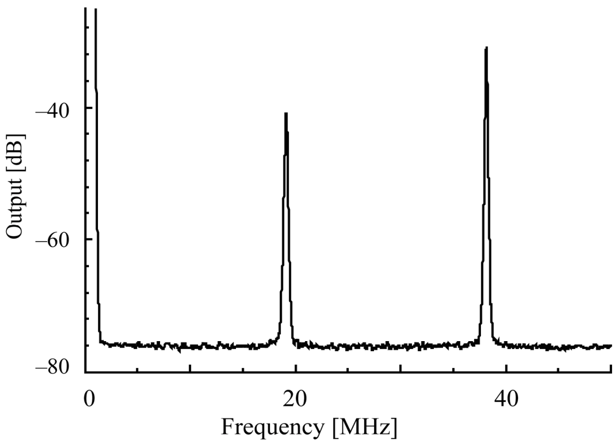

Figure 3. Power spectrum of SOA-fiber ring laser without birefringent media.

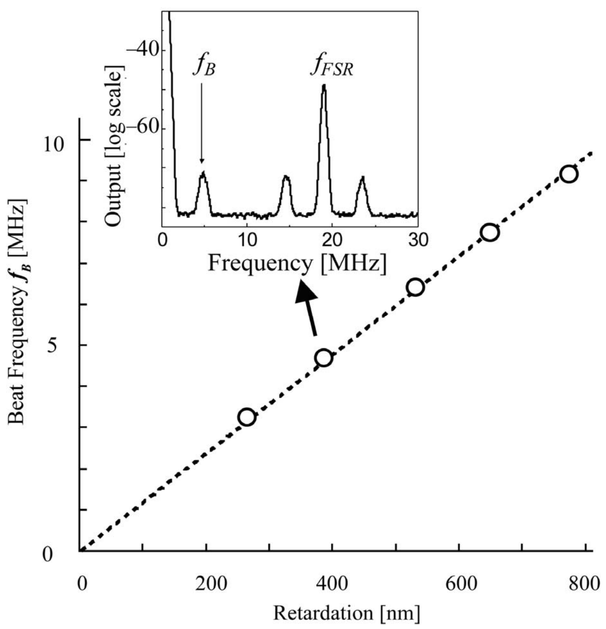

Figure 4. Change of frequency difference f_B with applied retardation. Inset power spectrum is the case of R = 387.5 nm.

In a ring laser when the phase difference between counter-propagating lights is small, oscillating frequencies of them do not differ because of lock-in phenomenon. Then if the inserted birefringence is small, f_B remains zero. Even if it is non-zero, a sign of the birefringence is uncertain. To avoid these problems a bias element is inserted in the space-propagating region in addition to a sensing element S. As the case of small birefringence, a sheet of PET film for viewgraph was inserted. **Figure 5** shows the signal of $f_{FSR} + f_B$ with and without PET film. The traces are shifted up and down to make the difference clear. The retardation was calculated as 17.2 nm from the frequency shift 0.20 MHz, which means the laser can measure such a small birefringence with a bias element.

As the experiment for the application to stress sensing a fused silica substrate was used as photoelastic crystal. It is 5 × 10 × 10 mm^3 and the applied stress was monitored an attached strain gauge. It was inserted in the space-propagating region as well as a quarter-wave plate. The collimated beam passes through the 10 × 10 mm^2 square plane and the stress was applied by a vise in the direction perpendicular to the beam. The dependence of the beat frequency shift on the pressure is shown in **Figure 6**. The dotted line denotes calculated value from Brewster coefficient of fused silica at 633 nm [8] as reference. The beat frequency shift changes with the pressure proportionally and closely to the dotted line. Since dispersion of Brewster coefficient supposes to be small the present ring laser can be applied to a fiber stress sensor in a frequency domain.

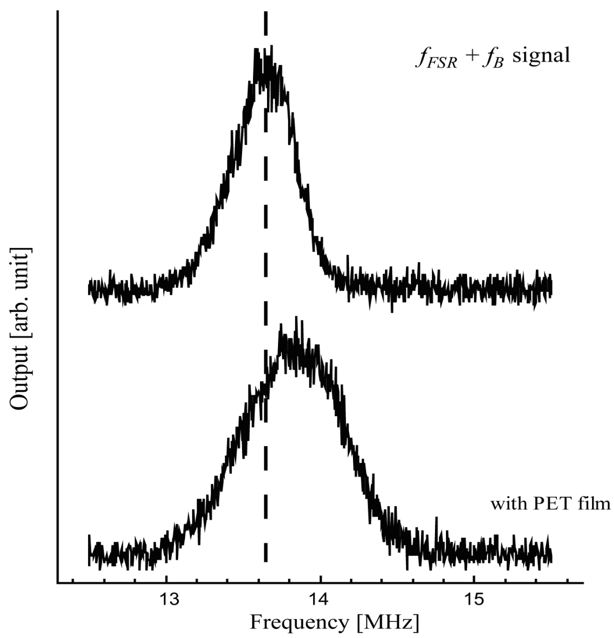

Figure 5. Power spectrum of $f_{FSR} + f_B$ signal. The upper and the lower traces show without and with PET film.

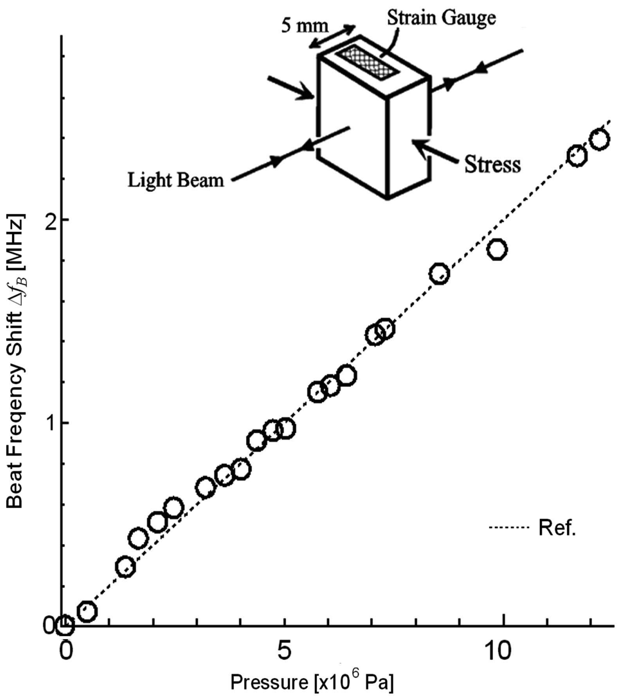

Figure 6. Beat frequency difference on applied pressure on fused silica.

5. Discussion

In **Figure 6** there are fluctuations and the accuracy is degraded, which must be the problem in developing a practical sensor. These might be caused by errors of a sensing element and instability of the laser oscillation.

a) Errors of a sensing element

The applied stress might cause nonuniform strain in the crystal. And it was difficult to attach a strain gauge on the fused silica and the adhesion might be imperfect, which causes errors of the measured pressure.

b) Instability of the laser oscillation

The polarization of the propagating light is not constant because singlemode fibers were incorporated into the ring laser cavity, and it is probable to cause the instability. In addition the difference between the designed wavelength (1.55 mm) and the lasing wavelength, which centered at 1.562 mm, will affect the oscillation. It causes errors of both the polarization and the phase difference. The former reduces the SOA gain and the latter induces errors of the retardation. Assuming circular birefringence of a Faraday rotator and linear birefringence of a sensing element has no dispersion, the rotation angle and the retardation changes in proportion to the ratio of the wavelengths. With this assumption the retardation error was calculated and the result is plotted in **Figure 7**. From **Figure 7** the difference of the wavelength does not seem to affect the oscillation significantly.

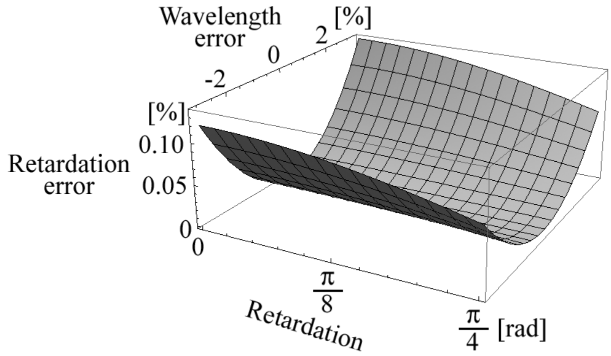

Figure 7. Retardation errors dependence on wavelength deviation.

6. Conclusions

The SOA-fiber ring laser has been developed and as the application to stress sensing by introducing a photoelastic material in the cavity the beat frequency changed as applying pressure proportionally. In the present laser phase difference is generated by birefringence which is reciprocal effect in the ring cavity. Since birefringence is induced by many phenomena such as electromagnetic field, pressure, and temperature, etc., sensors utilizing the present fiber ring lasers are expecting to detect such physical quantity in a frequency domain.

As described in the previous section, because of using singlemode fiber the polarization of the propagating light might vary and should be stabilized. Using polarization-maintaining fiber instead of singlemode fiber the authors have studied the stabilization of the fiber ring laser. The improvement would make the practical fiber sensor.

7. References

[1] Y. Takahashi, S. Sekiya and N. Iwai, "Semiconductor Optical Amplifier(SOA)-Fiber Ring Laser for Sensor Application," *Optical Review*, Vol. 10, No. 4, 2003, pp. 315-317. doi:10.1007/s10043-003-0315-1

[2] Y. Takahashi, H. Kuroda and T. Suemune, "Semiconductor Optical Amplifier-Fiber Laser and Its Application for Temperature Sensing," *The Review of Laser Engineering*, Vol. 33, No. 5, 2005, pp. 329-332.

[3] T. Suemune and Y. Takahashi, "SOA-fiber ring laser and its application to electric field sensing in frequency domain," *Optics and Lasers in Engineering*, Vol. 45, No. 7, 2007, pp. 789-794. doi:10.1016/j.optlaseng.2006.12.002

[4] R. K. Kadiwar and I. P. Giles, "Optical Fibre Brillouin Ring Laser Gyroscope," *Electronics Letters*, Vol. 25, No. 25, 1989, pp. 1729-1731. doi:10.1049/el:19891157

[5] S. K. Kim, H. K. Kim and B. Y. Kim, "Er^{3+}-Doped Fiber Ring Laser for Gyroscope Applications," *Optical Letters*, Vol. 19, No. 22, 1994, pp. 1810-1812.

doi:10.1364/OL.19.001810

[6] A. Kung, P.-A. Nicati and P. A. Robert, "Reciprocal and Quasi-Reciprocal Brillouin Fiber-Optic Current Sensors," *IEEE Photonics Technology Letters*, Vol. 8, No. 12, 1996, pp. 1680-1682. doi:10.1109/68.544717

[7] Y. Takahashi and T. Yoshino, "Fiber Ring Laser with Flint Glass Fiber and Its Sensor Applications," *Journal of Lightwave Technology*, Vol. 17, No. 4, 1999, pp. 591-597. doi:10.1109/50.754788

[8] D. E. Gray, "American Institute of Physics Handbook," 3rd Edition, McGraw-Hill, New York, 1972, pp. 233-236.

