LETTER

EDF Sigma laser using double-pass cascaded-chirped long-period fiber grating with birefringence compensation effect and its application for strain measurement

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Abstract In this work, we have constructed an Erbium-doped fiber sigma laser (EDFSgL) using a double-pass cascaded-chirped long-period fiber grating (C-CLPG) from the viewpoint of the sensor applications. The double-pass C-CLPG is composed of a C-CLPG and a Faraday rotator mirror (FRM) and works as a comb-like wavelength selection element as well as a sensor section in the sigma-branch of the laser cavity. Further, due to the FRM reflection scheme, the double-pass C-CLPG compensates for birefringence variation in the sigma-branch during the sensing. In the experiment, the sensor section near the C-CLPG is intentionally deformed to induce birefringence variation assuming the external disturbances; nevertheless, it is confirmed that the double-pass C-CLPG provides stable polarization states. Then, under the birefringence variation, it is demonstrated that the proposed EDFsL can achieve a stable oscillation and resultant precise measurements in contrast to the simple EDF ring laser using the single-pass C-CLPG. In addition, for the demonstration of the sensor with external force to the fiber, the oscillation wavelength of EDFsL in response to axial strain is investigated, and a linear response with sensitivity −0.32 pm/µε is obtained.

key words: optical fiber sensor, cascaded-chirped long-period fiber grating, Erbium-doped fiber, fiber laser, Faraday rotator mirror, strain measurement

Classification: Optical hardware

1. Introduction

Optical fiber grating is a kind of optical fiber element and is fabricated by periodically modulating the refractive index along the optical fiber [1]. Among them, the long-period fiber grating (LPG) is fabricated with a grating period of tens to hundreds µm [2]. The LPG couples a part of the light wave propagating as a core mode to a cladding mode propagating in the same direction at resonant wavelengths satisfying the phase matching condition. As a result, the transmittance spectrum of the LPG has a transmission loss at the resonant wavelength. Utilizing the feature of the LPG, band rejection filters in communications [2, 3, 4], gain equalizer for fiber amplifiers [5], and sensor elements [6, 7] have been widely studied. Moreover, if another LPG is additionally inscribed after the first LPG, the core and cladding modes recombine at the second LPG to form an in-fiber Mach-Zehnder interferometer, called a cascaded LPG (C-CLPG) [7, 8]. In the C-CLPG, a periodic transmittance spectrum (channeled spectrum) is obtained, and changes in physical parameters such as strain, bending, temperature, and refractive index can be detected from the shift in the channeled spectrum.

In our laboratory, we have proposed the sensor applications of C-CLPG and its further development, cascaded-chirped LPG (C-CLPG) which extends the wavelength range of the channeled spectrum by chirping in the grating period. We have reported a method based on the Fourier transform that utilizes the periodicity of the channeled spectrum, which enables highly precise measurement of strain and temperature, as well as multi-point and simultaneous measurement [8, 9, 11]. However, the method uses an incoherent broadband light source, so the output signal is a low signal-to-noise ratio; moreover, it requires the time-consuming acquisition of channeled spectrum and data processing. We have also proposed a mechanical-vibration C-CLPG sensor and an underwater-acoustic C-CLPG sensor based on an intensity modulation scheme [12, 13]. The method employs a narrowband laser source, of which wavelength is tuned to a spectral slope of one of the fringes in the channeled spectra, an operation point. Although the real-time observations of the acoustic waves can be realized from the intensity-modulated transmitted light wave, the measurand is limited to weak vibrations such as acoustic waves and sound pressure since the wavelength range of the operating point where a linear response is obtained in the channeled spectrum is very narrow.

Under these circumstances, as an alternative method to detect the channeled spectrum shift, we have constructed an Erbium-doped fiber ring laser (EDFRL) using the C-CLPG as a sensor element as well as a wavelength selection element and an erbium-doped fiber amplifier

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(EDFA) as a gain medium [14, 15]. This laser-type sensor provides a high intensity and narrow linewidth oscillation output and allows us to directly detect changes in measurements from the oscillation wavelength [16, 17, 18]. Thus, complex data processing is not required, and relatively high speed, high S/N ratio, and high accuracy measurement are expected to be realized. However, such EDFRFL configurations have the characteristics that the oscillation wavelength varies depending on the polarization state of the fiber in the cavity [19, 20]; hence, due to birefringence variation caused by disturbances in the measuring environment, the oscillation wavelength fluctuates, which is a noise source that degrades the measurement precision.

In our previous work, to compensate for the birefringence variation in the sensor section, we have proposed an EDF laser in a sigma cavity configuration (EDFol) using a double-pass C-CLPG which combines a C-CLPG and a Faraday rotator mirror (FRM). To date, we have already demonstrated that the EDFol can achieve higher precision than the conventional EDFRFL using the C-CLPG in measuring temperature [21], strain [22], and bending-based displacement [23].

In this study, we confirm that the double-pass C-CLPG compensates for the birefringence variation by deforming the optical fiber near the C-CLPG which can be caused by disturbances in the measuring environment. Then, we demonstrate that the EDFol shows a stable oscillation even under the birefringence variation. Moreover, as a demonstrative experiment of sensing with deformation of optical fibers, we show the strain response of the EDFol.

2. Operation Principle

Fig. 1 shows the schematic view of the double-pass C-CLPG. In the EDFol, the double-pass C-CLPG works as a reflective wavelength selection element with comb-like spectral characteristics and a sensor section with automatically compensation for birefringence variation.

![Schematic view of double-pass C-CLPG](image)

As shown in the figure, the double-pass C-CLPG is composed of a C-CLPG and an FRM. The incident light wave initially passes through the C-CLPG once; after reflection at the FRM, it passes through the C-CLPG again. Thus, the reflectance of the double-pass C-CLPG, $R_D(\lambda)$, is given by the following equation [24].

$$R_D(\lambda) = A_{\text{loss}} \cdot T_S^2(\lambda), \quad (1)$$

where $\lambda$ is the wavelength of the light, $A_{\text{loss}}$ is the loss due to the propagation and the reflection at the FRM, and $T_S(\lambda)$ is the transmittance of the C-CLPG, so the twice passing of the C-CLPG is then denoted as $T_S^2(\lambda)$. $T_S(\lambda)$ is expressed by the following equation [24, 25].

$$T_S(\lambda) = r_c(\lambda) + r_c(\lambda) + 2\sqrt{r_c(\lambda)r_c(\lambda)}\cos \Phi, \quad (2)$$

where $r_c(\lambda)$ and $r_c(\lambda)$ are the intensity ratios of the interfering core and cladding mode to the incident light, respectively, and $\Phi$ is the relative phase difference between these modes.

Fig. 2 shows typical channeled spectra of the single-pass C-CLPG (upper black line) and the double-pass C-CLPG (lower red line) used in the experiment. As seen from the figure, periodic channeled spectra appear in the wavelength domain due to the interference between the core mode and cladding mode. As shown in Eq. (1), the channeled spectrum of the double-pass C-CLPG has higher contrast than that of the single-pass C-CLPG. The peak wavelengths of both channeled spectra appear to be closely matched; the slight mismatch is caused by the time difference between each measurement. Further, using the double-pass C-CLPG as a wavelength selection element in a laser cavity, the oscillation is obtained at the peak of the channeled spectrum. Thus, the change in the measurands is directly measured from the shift of the oscillation spectrum corresponding to that of the channeled spectrum.

![Fig. 2 Typical channeled spectra of single- and double-pass C-CLPG](image)

In the experiment, the C-CLPG was fabricated in a length of photo-sensitive fiber (Nufern, GF1AA) by irradiating a focused UV light from a KrF excimer laser (GAM laser, EX10) in a point-by-point method. The fabrication parameters of the C-CLPG are as follows, grating period ($\Lambda$): 310 ~ 315 $\mu$m, the distance between two CLPGs ($L_o$): 100 mm, CLPG length ($L_g$): 6245 $\mu$m, and the number of periods of the CLPG: 21.

To describe the birefringence compensation effect of the double-pass C-CLPG, let $E_{\text{in}} = (E_{\text{in},x}, E_{\text{in},y})$, and $E_{\text{out}} = (E_{\text{out},x}, E_{\text{out},y})$ denote the input and output light waves.
of the double-pass C-CLPG, respectively, and these relations are expressed using Jones calculus as follows [26, 27].

\[
E_{\text{out}} = [\tilde{R}] \cdot [FRM] \cdot [\tilde{R}] \cdot E_{\text{in}} , \tag{3}
\]

where \([\tilde{R}]\) is the matrix representing the change in the state of polarization (SOP) of the light wave from the input to the double-pass C-CLPG to the FRM, and \([\tilde{R}]\) is its reverse, from the FRM to the output of the double-pass C-CLPG, and they can be expressed as follows [26, 27].

\[
\begin{align*}
[\tilde{R}] &= t_{5} \cdot \alpha \cdot \begin{bmatrix} a & b \end{bmatrix}, \\
[\tilde{R}] &= t_{5} \cdot \alpha \cdot \begin{bmatrix} a & b^* \end{bmatrix}. \tag{4}
\end{align*}
\]

where \(t_{5}\) is the amplitude transmittance of the C-CLPG satisfying \(|t_{5}|^2 = T_{5}\), and \(\alpha\) is the change in complex amplitude with lead fiber propagation. Further, \(a\) and \(b\) are coefficients that depend on the birefringence of the optical fiber, satisfy \(a\alpha^* + b\alpha^* = 1\), and \((\cdot)^*\) denotes complex conjugate. Moreover, \([FRM]\) in the right term of Eq. (3) is the matrix of the FRM and is given as follows [28].

\[
[FRM] = \gamma \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} , \tag{5}
\]

where \(\gamma\) is the complex amplitude term with propagation losses and the reflection at the FRM. From Eqs. (3) ~ (5), \(E_{\text{out}}\) can be expressed as follows.

\[
E_{\text{out}} = \begin{bmatrix} E_{\text{out}x} \\ E_{\text{out}y} \end{bmatrix} = t_{5}^2 \cdot \gamma \cdot \alpha^2 \cdot \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \cdot E_{\text{in}}
= t_{5}^2 \cdot \gamma \cdot \alpha^2 \cdot \begin{bmatrix} E_{\text{in}x} \\ E_{\text{in}y} \end{bmatrix}. \tag{6}
\]

In this way, the output SOP is always orthogonal to the input SOP. Furthermore, the values \(a\) and \(b\) cancel out; hence, in the double-pass C-CLPG, the birefringence variation caused by the measurands or disturbances from the measuring environment is compensated at any position, which provides a stable output SOP.

3. Experimental Results and Discussions

3.1 Birefringence compensation

To confirm the birefringence compensation effect of the double-pass C-CLPG, the SOP evolution of the reflected light of the double-pass C-CLPG and the transmitted light of the single-pass C-CLPG are compared during birefringence variation, as shown in Figs. 3(a), (b). A 1550 nm narrowband laser (Koshin Kogaku, LS-601A-56S2) was used as a light source to generate different input SOPs via a fiber-squeezer-based multifunction polarization controller (MPC; General Photonics, MPC-201), and the output SOP evolutions were measured by a polarization analyzer (PA; General Photonics, PSY-201). Here, for the generated input SOPs, the MPC settings obtained with the Stokes parameters \((S_{1}, S_{2}, S_{3})\) at the PA are \((1, 0, 0)\), \((0, 1, 0)\), and \((0, 0, 1)\), respectively, are Condition 1 ~ 3. To intentionally induce birefringence variation, the optical fiber near the C-CLPG was locally deformed by using a paddle with a \(\sim 3\) cm diameter spool. The optical fiber was wound twice on the spool and the paddle angle \(\phi_{p}\) was varied \(0^\circ \sim 180^\circ\), where \(\phi_{p}\) is formed by the plane of the fiber loop and the horizontal plane. This gives a birefringence variation corresponding to the rotation of the \(\lambda/4\) plate [29, 30]. As described in Eq. (6), in the double-pass C-CLPG, the birefringence compensation effect is exerted at any position between the optical circulator and the FRM. As a typical example, for the double-pass C-CLPG, the paddle was placed between the optical circulator and the C-CLPG. For the single-pass C-CLPG being comparison, the paddle was placed just before the C-CLPG. It is noted here that the C-CLPG was not deformed.

![Fig. 3 Experimental setup for investigating the output SOP during birefringence variation in the sensor section: (a) double-pass C-CLPG and (b) C-CLPG.](image)

![Fig. 4 Emerging SOPs on the Poincaré sphere with paddle rotation: (a) paddle, (b) double-pass C-CLPG, and (c) single-pass C-CLPG.](image)
Fig. 4(a) shows the measured SOP evolution given by the rotation of the paddle. Asymmetric eight-shape trajectories appear on the Poincaré sphere depending on the input SOP, showing a change in SOP corresponding to a rotation of the $\sim \lambda/4$ plate. Figs. 4(b),(c) show the output SOPs of the double- and single-pass C-CLPG, respectively. The output SOP of the double-pass C-CLPG shows almost no change even if the sensor section is subjected to the birefringence variation; in contrast, the output SOP of the single-pass C-CLPG changes significantly with the rotation of the paddle, like Fig. 4(a). Similar results are obtained for different input SOPs, Condition 1 $\sim$ 3. It was experimentally confirmed that the double-pass C-CLPG compensates for the birefringence variation caused by the optical fiber deformation in the sensor section and provides a stable output SOP.

3.2 Wavelength stability

Next, the oscillations of the EDFoL and the EDFRL while causing birefringence variation in the optical fiber of the sensor section are investigated. Figs. 5(a),(b) show the EDFoL and the EDFRL configurations, respectively. The common components of the cavity are a commercial EDFA (Mitsubishi Cable, FA155D-168FS), an optical coupler with a 90:10 splitting ratio, and a manual three-paddle polarization controller. These components are connected by a single-mode fiber (SMF). Here, the isolators built in the EDFA ensure unidirectional operation. Further, the EDFA was backward-pumped by a built-in laser diode with a constant drive current of 100 mA. In the EDFRL, the C-CLPG is placed in the ring loop of the cavity. On the other hand, in the EDFoL, the double-pass C-CLPG is placed in the sigma-branch connected to the ring loop by an optical circulator. Thus, the ring loop can be protected for stable operation by distancing from the sensor section; besides, flexible sensor arrangements can be applied. Here, these wavelength selection elements are inserted between the EDFA and the optical coupler to improve the S/N ratio [31]. Further, a variable optical attenuator (VOA; Anritsu, MN9611B) with an additional loss setting of 3 dB was inserted just after the C-CLPG in the EDFRL cavity to adjust the intra-cavity loss to oscillate at a similar wavelength as the EDFoL [15].

Figs. 6(a),(b) show typical oscillation spectra of the EDFoL and the EDFRL with different paddle angles $\phi_p$, respectively. Here, the paddle was inserted between the optical coupler and the C-CLPG in the EDFoL, while between the EDFA and the C-CLPG in the EDFRL. These oscillation spectra were measured by an optical spectrum analyzer (Anritsu, MS9740A) with a resolution of 0.03 nm. As shown in the figures, in the EDFoL, the variation of the oscillation wavelength is relatively small due to the birefringence compensation effect of the
double-pass C-CLPG. On the other hand, in the EDFRL, the oscillation wavelength varies significantly with paddle rotation, and not only single-peak oscillations but also split-peak oscillations are observed.

Fig. 7 shows the oscillation wavelengths of the EDFsL (circle symbols) and the EDFRL (triangle symbols) measured with $\phi_1$ changing $0^\circ$ ~ $180^\circ$ in $10^\circ$ steps. The variation ranges of the oscillation wavelengths for the EDFsL and the EDFRL are 1567.56 ~ 1567.63 nm (0.07 nm) and 1567.44 ~ 1567.80 nm (0.36 nm), respectively. Further, the mean value and standard deviation of these oscillation wavelengths are obtained to be 1567.60 nm ± 0.02 nm for the EDFsL and 1567.61 nm ± 0.10 nm for the EDFRL. Therefore, due to the birefringence compensation effect of the double-pass C-CLPG based on the FRM reflection, the EDFsL shows stable oscillation and enables precise measurements.

3.3 Strain measurement
As a demonstrative experiment for measuring physical quantities with deformation of optical fibers, the strain response of the EDFsL is investigated. In the experiment, both ends of the C-CLPG, including the lead fiber, were glued onto a fixed stage and a movable stage (SIGMAKOKI, TAMM60-15C). Here, the initial distance between the two stages $L_0$ was set to 25 cm, and the outward displacement $\Delta L$ of the movable stage was varied from 0 to 500 $\mu$m in 50 $\mu$m steps to apply axial strain ($\varepsilon = \Delta L/L_0$) to C-CLPG.

![Fig. 8](image)

Fig. 8 Strain dependence of EDFsL: (a) oscillation spectra, and (b) oscillation wavelengths.

Fig. 8(a) shows typical oscillation spectra with applied strain. As can be seen from the figure, the oscillation spectra shift toward the longer wavelength side with applied strain, but the shape of the spectrum remains almost unchanged. Fig. 8(b) shows the wavelengths as a function of strain. The oscillation wavelength shifts according to the strain dependence of the peak wavelength of the C-CLPG channeled spectrum, obtaining a strain sensitivity of 0.32 pm /$\mu$m in the range 1567.72 ~ 1568.40 nm (0.68 nm). Further, the $R^2$ value was 0.993, confirming that the oscillation wavelength shows a linear response to the applied strain. According to the strain sensitivity and the standard deviation of the oscillation wavelength under birefringence variation described in section 3.2, the error range of strain detection is estimated to be ± 63 $\mu$m for the EDFsL and ± 313 $\mu$m for the EDFRL.

4. Conclusion
In this study, we have demonstrated stable oscillation of the EDFsL using the double-pass C-CLPG and its sensor operation under birefringence variation assuming a disturbance in the measuring environment. In the experiment, the optical fiber in the sensor section is intentionally deformed to cause birefringence variation, and then it is confirmed that the SOP variations appearing in the single-pass C-CLPG are effectively compensated in the double-pass C-CLPG. Moreover, it is also confirmed the EDFsL shows stable oscillation even under birefringence variation due to the birefringence compensation, which enables highly precise measurement. Furthermore, as a detection of physical quantity with deformation of the optical fiber, measurement of axial strain applied to C-CLPG was demonstrated and confirmed its effectiveness.

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References


