Bandwidth-adjustable dynamic grating in erbium-doped fiber by synthesis of optical coherence function

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Abstract: We present an approach for bandwidth-adjustable optical filter with the dynamic grating in erbium-doped fiber (EDF). The dynamic grating is introduced by the interference of two coherent light beams counter-propagating in the pumped EDF per the phenomenon of gain saturation. The bandwidth of the grating is determined by the length of the grating, i.e., the length of the interference region. With the technique of synthesis of optical coherence function (SOCF), we localize the interference into a range at an arbitrary position along the fiber by modulating the frequency of the two interfering light beams. The length of the range is controlled by adjusting the frequency modulation parameter. In this way, the length of the dynamic grating is controlled and its reflection bandwidth then adjusted. The experimental demonstration is given.

OCIS codes: (050.2770) Gratings; (060.2340) Fiber optics components; (060.2410) Fibers, erbium

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1. Introduction

The dynamic grating received considerable attention because of its real-time formation and its potential for applications as tunable optical filters and other functional optical devices [1-5]. When two counter-propagating coherent light beams (referred to as writing beams hereafter)

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are launched into a pumped erbium-doped fiber (EDF), they will interfere to each other and form stationary interference fringes in the EDF. The interference fringes then create a periodical gain structure per the phenomenon of gain saturation and hence produce a dynamic grating in the EDF [1-3]. A third beam launched into the fiber (referred to as reading beam hereafter) will be reflected by the dynamic grating when its wavelength is the same as the writing beams'. Simply by changing the wavelength of the writing beams, a tunable filter with the dynamic grating was realized, and its center wavelength of the reflection band can be tuned in a few milliseconds [1].

In this paper, we present a method to adjust the bandwidth of the dynamic grating in real-time. The reflection bandwidth of the grating is inversely proportional to the length of the grating. By making use of the technique of synthesis of optical coherence function (SOCF) [6], we realized the control on the length of the dynamic grating, and then demonstrated the bandwidth-adjustable filter with the dynamic grating for the first time to the best of our knowledge.

2. Principle

The reflectivity of the dynamic grating can be given as [2]

$$r = \frac{\kappa \sinh(SL)}{\{\tilde{g} - i(k_w - k_r)\}\sinh(SL) - S\cosh(SL)}, \tag{1}$$

where k_w and k_r are the wave-numbers of the writing and reading beams, $\tilde{g}$ the saturated gain factor, κ the coupling factor, L the length of the dynamic grating, and

$$S^2 = |\kappa|^2 + [\tilde{g} - i(k_w - k_r)]^2 \, . \tag{2}$$

The reflection bandwidth of the dynamic grating is obtained as [2]

$$\delta\nu = \frac{c}{2\pi n}\sqrt{\left(\frac{\pi}{L}\right)^2 + \frac{|\kappa|^2}{1 + (\tilde{g}L/\pi)^2}}, \tag{3}$$

where n is the refractive index, and c the light velocity in free space. It is obvious that the bandwidth is inversely proportional to the length of the dynamic grating since the right side of Eq. (3) can be approximated as $c/(2nL)$. Therefore, the reflection bandwidth can be adjusted by controlling the length of the dynamic grating, i.e., the length of the region of the interference between the two writing beams.

The contrast of the interference fringe as a function of the optical path difference in an interferometer, referred to as the coherence degree or the optical coherence function, is given with the Fourier transform of the spectral density of the light source. When we use a laser diode (LD) as the light source of the interferometer, the frequency of the lightwave emitted from the LD can easily be tuned by modulating directly the injection current to the LD. A frequency modulation of the laser source produces a correspondent power spectrum in the point of view of time averaging, thus a particular shape of the coherence function can be synthesized. For example, the coherence function has been synthesized into various shapes, such as delta-function-like peak, triangle, and rectangular, for applications in optical reflectometry, optical tomography, optical information processing, and fiber optic sensors [6]. A notch-shaped filter with the dynamic grating in an EDF was also demonstrated with rectangular-pulse frequency modulation [7].

Among the various shapes of the synthesized coherence function, the delta-function-like peak is especially significant for controlling the length of the dynamic grating. A narrow peak of coherence function means that the interference is localized into a region correspondent to the width of the peak, which means, in the case of the dynamic grating, the grating is only formed in correspondent region in the fiber [8].

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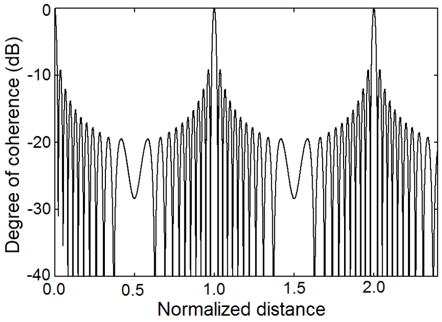

Fig.1. Coherence function synthesized by sinusoidal frequency modulation.

It has been demonstrated that the delta-function-like coherence function can be synthesized by stepwise- or sinusoidal-frequency modulation [6-8]. In this paper we adopt the sinusoidal-frequency modulation method. As given in Eq. (4), we denote the mean frequency, the modulation amplitude, and the modulation frequency as f_0, f_1, and f_2, respectively. Then the light frequency of the lightwave emitted from the LD is expressed as

$$f = f_0 + f_1 \cos(2\pi f_2 t) \tag{4}$$

By the modulation, the coherence function is synthesized into a series of periodical delta-function-like peaks as shown in Fig. 1. The period and the FWHM (full width at half maximum) width of the peaks are in inverse proportion to f_2 and f_1, respectively. We can set only one coherence-peak inside the EDF and to keep it at the middle of the fiber by selecting suitable modulation frequency f_2, which means, a dynamic grating is placed at the middle of the EDF. By changing the modulation amplitude f_1, we can control the FWHM width of the coherence peak. In this way, we can control the length of the dynamic grating, which determines the reflective bandwidth of the grating.

3. Experiment

The experiment setup is shown in Fig. 2. The total length of the EDF (Nufern DD120 high-doped EDF) is 70 cm. Two 980-nm pump LDs are used to pump the EDF. The gain of the pumped EDF is 20 dB. Two light beams I_1 and I_2 from the distributed feedback laser diode

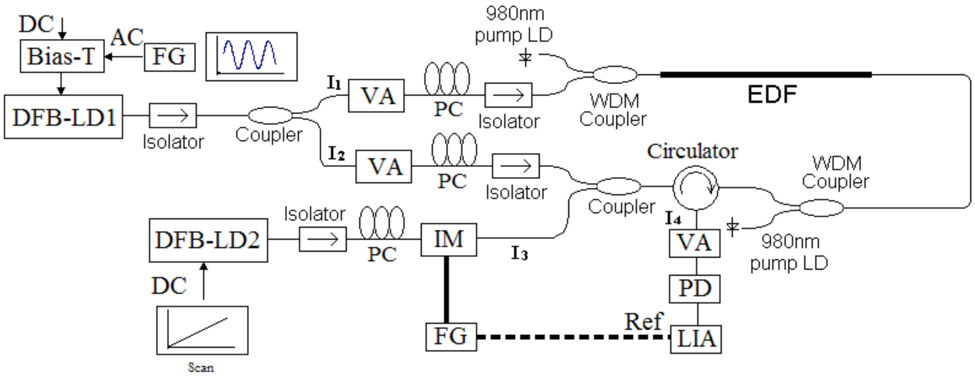

Fig. 2. Experiment setup. VA: variable attenuator; PC: polarization controller; EDF: erbium-doped fiber; IM: intensity modulator; PD: photodiode; LIA: lock-in amplifier; FG: function generator; Ref: reference signal.

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DFB-LD1 are used to write the dynamic grating and their power are both set to –10 dBm by adjusting two variable attenuators (VAs). Two polarization controllers (PCs) are used to align the writing beams at the same polarization directions in order to obtain a maximum interference pattern in the EDF. We use I_3 from DFB-LD2 as the reading beam to read the grating and its power is –20 dBm. I_3 is chopped by using an intensity modulator (IM) for the purpose of synchronous detection. The polarization direction of I_3 need not be the same as those of I_1 and I_2. The PC before the IM is used only for aligning the polarization direction of I_3 with the polarization axis of the IM. In experiment, we found that the chopping frequency has to be fast enough to avoid the gain modulation, which is a phenomenon caused by the chopping of I_3 here. The gain modulation results in a spurious signal in the frequency of the synchronous detection. If the chopping is much faster than the sub-millisecond response time of the EDF gain dynamics [9], the gain modulation induced spurious signal will disappear. Here we set the chopping frequency at 10 MHz. The optical frequency of I_3 is scanned by changing the injection current and the I_4, which is the reflection of I_3 at the dynamic grating, is monitored by using the lock-in amplifier (LIA) after the photodiode (PD).

We made sinusoidal frequency modulation for the writing beams as shown in Eq. (4). The dynamic grating is localized at the middle of the fiber by selecting suitable modulation frequency f_2 to control the position of the coherence peak. In our experiment, we measured the optical path difference between the two writing beams with optical method, then after careful calculations, we decided the modulation frequency f_2 to be 28.37MHz to put the first-order coherence peak at the middle of the EDF. This frequency is also fast enough to avoid the gain modulation.

The length of the dynamic grating is inversely proportional to the modulation amplitude f_1. We can change the f_1 simply by adjusting the amplitude of AC injection current to DFB-LD1, i.e., by adjusting the peak-to-peak voltage V_{pp} supplied by the function generator (FG) in the experiment. In our system, the FWHM of the coherence peak, i.e., the grating length L_{FWHM}, is pre-measured and is found to have a relationship with V_{pp} as

$$L_{FWHM}\,[\mathrm{m}] = 30 / V_{pp}\,[\mathrm{mV}] \tag{5}$$

when the modulation amplitude f_1 is ten times greater than the modulation speed f_2. In our experiment, V_{pp} has been chosen as 40 mV and 100 mV, which correspond to grating length of 75 cm and 30 cm, respectively.

Figure 3 shows the reflectivity of the dynamic grating when no modulation for the DFB-LD1 is performed. The raw data are fitted with a Gaussian function. We can see that a 10% reflectivity at the Bragg frequency is obtained, and the –3-dB bandwidth of the reflection spectrum is 175 MHz. The noise exhibiting in Fig. 3 includes following four components: 1) amplified Rayleigh backscattering (RBS), 2) double-path amplified reflection of I_3, i.e., amplified I_3 reflected at the splicing point and then amplified again (RG^2I_3), 3) beating of amplified I_1 with RG^2I_3 (B_{13}), and 4) beating of amplified I_1 with amplified spontaneous emission (B_{1A}). The noise of B_{13} not only contributes to the noise floor but also influences the

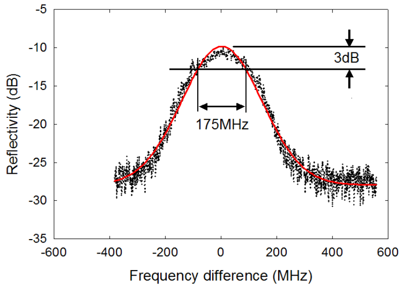

Fig. 3. Reflectivity from the dynamic grating without modulation on writing beams.

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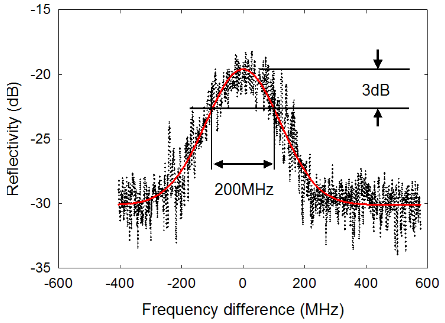


Fig. 4. Reflectivity from the dynamic grating localized by using the technique of SOCF. The length of the dynamic grating L_{FWHM} = 75 cm.

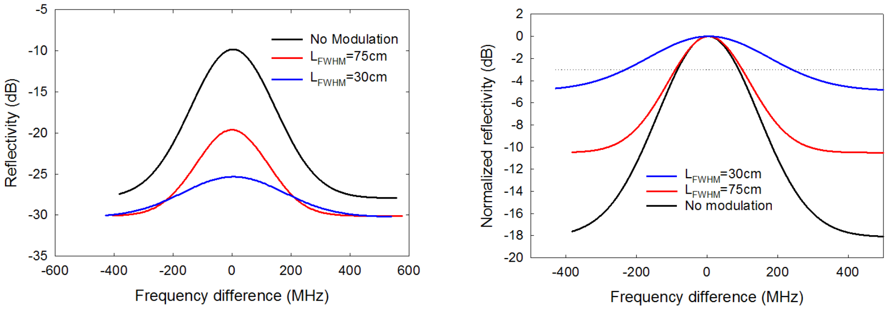
peak while other three noises only contribute to the noise floor, which is around –30-dB reflectivity in this experimental system.

When the optical frequency of the DFB-LD1 is modulated and the V_{pp} is set to be 40 mV, which corresponds to L_{FWHM} of 75 cm, the –3-dB bandwidth of the reflection spectrum is broadened from 175 MHz to 200 MHz, as shown in Fig. 4.

In Fig. 5, the fitted reflection spectra of three different dynamic gratings are compared, where Fig. 5(b) shows the normalized reflection spectra for comparison between their bandwidths. From Fig. (5), we can see obviously that the bandwidth becomes wider and the reflectivity gets lower as the length of the dynamic grating decreases.

The bandwidth broadening can be seen clearly in Fig. 5(b). When the V_{pp} is set to be 40 mV (L_{FWHM} = 75 cm) and 100 mV (L_{FWHM} = 30 cm), the –3-dB bandwidth of the reflection spectrum is broadened from 175 MHz to 200 MHz and 475 MHz, respectively. This result is in good agreement with the theory that the bandwidth is in inverse proportion to the length of the dynamic grating. We also tried a peak-to-peak voltage V_{pp} larger than 100 mV ($L_{FWHM} <$ 30 cm) in the experiment. In this case, the reflectivity is lower than the noise floor, which prevents us from detecting any significant reflection signal.

Figure 5(a) shows that the bandwidth broadening is accompanied by significant decrease of the reflectivity. This is an intrinsic limitation of the system because a shortened dynamic grating for a broadened bandwidth will give a lower reflectivity. This problem can be improved by adjusting the intensity of the pump light from the 980-nm LDs, that is, to increase the pump level when the length of the dynamic grating is shortened, then the decreased reflectivity can get compensated.



(a)

(b)

Fig. 5. (a) Fitted reflection spectra of three different dynamic gratings, (b) normalized graphs of (a).

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4. Conclusion

With sinusoidal-modulation on the optical frequency of the writing beams, we localized the dynamic grating in EDF in a region corresponding to the position of the coherence peak where the interference of the writing beams takes place. By adjusting the modulation amplitude of the frequency modulation to control the width of the coherence peak, the reflection bandwidth of the dynamic grating is adjusted. Our experiment results show that the reflection bandwidth becomes wider when we use greater frequency modulation amplitude, which corresponds to shorter grating length. In this way, the manipulation on the dynamic grating in EDF with the technique of SOCF provides an approach to realize a bandwidth-adjustable optical filter. Together with the tuning on the center frequency of the reflection band by changing the wavelength of the writing beams, and the adjustment of the reflectivity by controlling the intensity of the writing beams, we can synthesize arbitrary reflection characteristics with the dynamic grating – arbitrary center frequency, arbitrary reflectivity and arbitrary bandwidth. This kind of variable filter can provide us with great potential for applications in the fields of optical communications and optical sensing.

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