Sub-MHz ultrahigh-resolution optical spectrometry based on Brillouin dynamic gratings

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We propose and demonstrate an ultrahigh-resolution optical spectrometry based on Brillouin dynamic gratings (BDGs). Taking advantage of creating a long grating in an optical fiber, an ultra-narrow bandwidth optical filter is realized by operating a BDG in a long single-mode fiber (SMF), and the optical spectrometry is performed by sweeping the center wavelength of the BDG-based filter through a swept-tuned laser. The BDG-based optical spectrometry features ultrahigh resolution, large wavelength coverage, and a simple direction-detection scheme. In the experiment, a 4 fm (0.5 MHz) spectral resolution is achieved by operating a BDG in a 400 m SMF, and the wavelength coverage can be readily extended to $C + L$ bands with a commercial tunable laser.

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High-resolution optical spectroscopy [1–4] has always attracted considerable interest due to its extensive applications, including high-accuracy optical sensing [5], diagnostic and monitoring of signals in optical communication systems [6], characterizing and evaluating optical frequency comb sources [7], and characterizing narrow linewidth laser sources [8], etc. The best spectral resolution of the traditional grating-based optical spectrum analyzer (OSA) can only reach a few picometers, which is limited by the groove-line densities of the grating and the maximum optical beam diameter. The scanning Fabry–Perot interferometers can usually provide better spectral resolution than grating-based OSA but with narrower range of wavelength coverage [9]. In recent years, high-quality single-frequency semiconductor tunable lasers have become reliable and affordable, which makes swept-tuned optical spectroscopy a viable candidate for many high-end measurement applications that require ultrahigh spectral resolution. The measurement principle is to construct an ultra-narrowband optical filter with the narrow-linewidth output of the tunable laser, which sweeps across the wavelength of interest. Coherent optical spectrum analysis was first proposed based on a swept-tuned optical local oscillator and coherent detection [3], based on which the best resolution of 40 fm (5 MHz) commercial product has been available. High-resolution optical spectrometry based on stimulated Brillouin scattering (SBS) and a swept-tuned laser was also demonstrated [4], and its 80 fm (10 MHz) high spectral resolution comes from the narrowband Brillouin amplification, which, however, limits further improving the resolution.

In this Letter, we propose a novel scheme for an ultrahigh-resolution spectroscopy based on the so-called Brillouin dynamic gratings (BDGs). In the SBS process [10], a coherent acoustic wave is created when two counterpropagating waves operating with their frequency difference equal to Brillouin frequency shift, and the acoustic wave modulated the fiber refractive index forming a BDG [11]. The manipulation of a BDG with an arbitrary length at any position of a fiber can be flexibly achieved, which allows the BDGs to find applications in many fields, such as all-optical signal processing [12], sensing [13–15], microwave signal processing [16], light storage [17], and characterization of fiber birefringence [18]. Up to now, all of the publications on the BDGs used the frequency-fixed pumps to generate a BDG, whose grating pitch and reflection central wavelength are both fixed. In this work, we propose to use a swept-tuned laser to build a BDG-based tunable filter for optical spectrometry, where the grating pitch and the reflection central wavelength can be changed by sweeping the laser frequency.

It has been demonstrated that by operating in the weak grating domain, the BDG bandwidth is inversely proportional to its length [19,20], so that an ultrahigh-resolution optical spectrometry would be expected with operating a long-length BDG. Usually, the generation and probing of a BDG is operated in a polarization-maintaining fiber (PMF), since the pumps and the reflection are widely separated in the frequency-domain due to the large birefringence; thus the reflection can be readily extracted with a narrowband optical filter. However, the large birefringence nonuniformity of a PMF could lead to a broadened BDG spectrum even to a few hundreds MHz with a few tens meters fiber [14]. A remarkable narrowband of 2.4 MHz was achieved by operating a BDG in a 100 m single-mode fiber (SMF) benefiting from its small birefringence nonuniformity [21]. However, a narrower bandwidth was not available even with longer fiber length, which was attributed to the limitation induced by the birefringence-induced shift in SMF in [21]. In this work, it is revealed that, unlike a PMF, there are no fixed optical axes in an SMF; that is to say the slow and fast axes are random changing along the fiber, so the BDG bandwidth could be much narrower than the birefringence-induced shift in an SMF. In the experiment, we have realized a 4 fm (0.5 MHz) spectral resolution OSA by operating a BDG in a 400 m SMF; this is the narrowest bandwidth achieved by using the BDG to the best of our knowledge.

The experimental setup for the operation of the BDG-based optical spectrum analyzer (BDG-OSA) is illustrated in Fig. 1. The output of a tunable laser was spilt into two arms by a 50/50 coupler providing two pump waves, i.e., pump 1 and pump 2, for generation of a BDG. The upper arm was the pump 1 connected to an Er-doped fiber amplifier (EDFA), which was used to amplify the power of the pump 1. The state of the polarization (SOP) of the pump 1 was aligned to the x pol at port 1 of the polarization beam splitter (PBS). Light transmission between the port 1 and port 2 of the PBS is in one polarization (x pol) and that between port 2 and port 3 is in the orthogonal polarization (y pol). The lower arm was modulated by a single-sideband modulator (SSBM) via a microwave generator providing pump 2 with a downshifted frequency offset from pump 1. A segment of SMF was used as the nonlinear medium for creating a BDG, and the frequency offset between the pump 1 and pump 2 was adjusted to match the Brillouin frequency shift of the SMF for the maximum efficiency of BDG generation. The SOP of the pump 2 was controlled to align it in x pol at port 2 of the PBS, minimizing the cross talk to port 3.

A fiber laser at ~1550 nm with a linewidth of less than 100 kHz was used to create a signal light to be measured (inside the dashed frame in Fig. 1). The output of the fiber laser was modulated by a phase modulator via a function generator, where the modulated light (denoted as the signal light) includes the carrier and two first-order sidebands, and their amplitudes are the same through appropriately adjusting the magnitude of the driving signal of the phase modulator. The purpose of the phase modulation is to create a multipeak spectrum with an interval of a few MHz to verify the capability of the spectral resolution of the BDG-OSA. The signal light was launched to the SMF segment, and it was combined with pump 1 through the PBS to keep their SOPs orthogonal along the SMF. The grating pitch of the BDG was changed by sweeping the frequency of the tunable laser, so that the different frequency of the signal light was reflected. The reflection traveled in the opposite direction of the signal light and then was received and recorded by a photodiode and data-acquisition card. Note that since the Brillouin frequency shift decreases with increasing the pump wavelength, when sweeping the tunable laser over a wide range, the microwave signal applied to the SSBM should be varied accordingly to maintain the maximum efficiency of generation of a BDG.

The FWHM bandwidth of a uniform weak BDG can be approximately expressed as [22]

$$\Delta v_{\mathrm{BDG}} = 0.443c/nL, \tag{1}$$

where c is the light speed in vacuum, n is the refractive-index of the fiber, and L is the length of grating. Note that the created BDG would have the same length as the fiber if the coherent lengths of the cw pump waves are larger than the fiber length. The linewidth of the tunable laser (pump waves) is a few kHz, and its coherent length can be tens of kilometers, which is much larger than the fiber lengths used in the experiment. The powers of pump 1 and pump 2 are 50 mW and 2 μW, respectively, while the power of the fiber laser is 1 mW. Figure 2 shows the measured BDG bandwidths for five different SMF segments ($L = 50$, 100, 200, 400, and 600 m) compared with the theoretical curve of a uniform weak grating in Eq. (1) (blue solid curve), where the SMF segments were circularly rolled with the diameter of 80 cm to reduce the bending-induced birefringence. Excellent agreement between experiment and theory is achieved in the case of the 50 m SMF, and the deviation from the theory becomes large as the length of the fiber increases. It is noted that the BDG spectrum width first decreases with increasing the length of the fiber then goes up, where the minimum bandwidth as low as 0.5 MHz (~4 fm) is achieved when a 400 m SMF is used.

It is well known that the frequency difference between the first-order sidebands and the carrier equal to the driving signal frequency for the phase modulated light. So a signal light with multipeak spectrum with an interval of a few MHz is created by using phase modulation to verify the capability of the spectral resolution of the BDG-OSA. The wavelength of the tunable laser is tuned in the vicinity of the signal light whose spectrum is to be measured. Figure 3 shows the measured spectra of the signal light

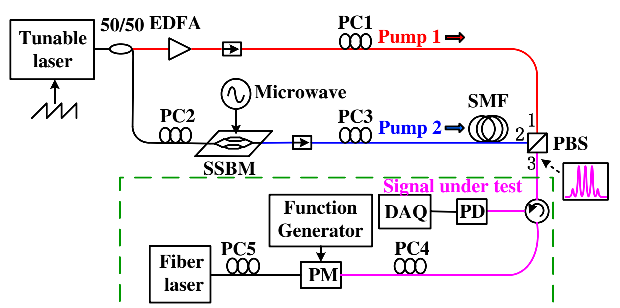

Fig. 1. Experimental setup. SSBM, single-sideband modulator; PM, phase modulation; PBS, polarization beam splitter; PD, photodiode; DAQ, data-acquisition card. Dashed frame: a multipeak spectrum with an interval of a few MHz is created to verify the capability of the spectral resolution of the BDG-OSA.

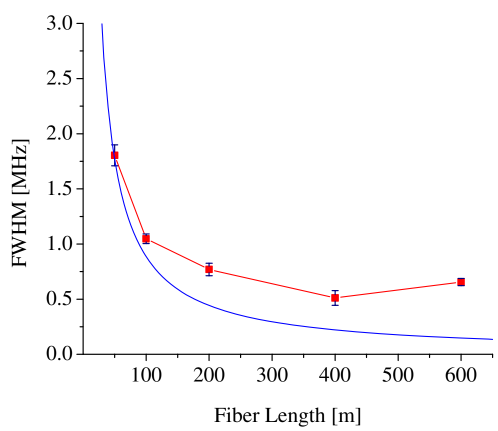

Fig. 2. Red dots show the measured FWHM bandwidth of BDG versus to the fiber length; blue curve shows the theory of a uniform weak grating.

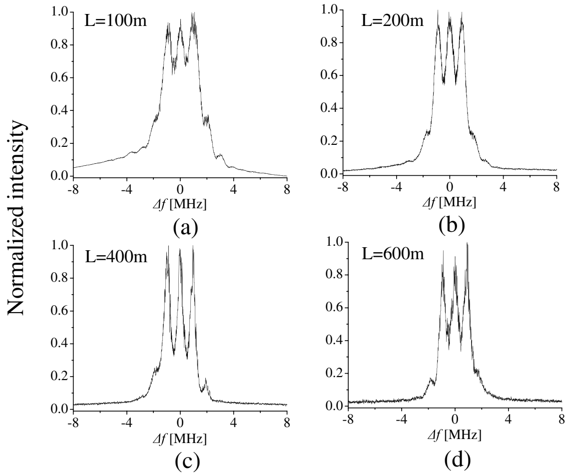

Fig. 3. Measured spectra with SMF segments of (a) 100 m, (b) 200 m, (c) 400 m, and (d) 600 m. The frequency interval of the multipeak spectrum is 1 MHz.

by using a 1 MHz driving signal with different SMF segments of 100, 200, 400, and 600 m. As can be seen, the different sidebands are separated and can be distinguished clearly, especially in the case of 400 m since that the bandwidth of the BDG (0.5 MHz) achieved in the 400 m SMF is the narrowest, which proves that the resolution of the spectrometry based on BDG can reach to sub-MHz.

For PMFs or SMF loops with small diameters [23], there are fixed optical axes including fast axis and slow axis, so the shifted direction of the BDG spectrum from the pumps depends on which axis is used to generate or probe a BDG. However, it is different for a loose SMF since its birefringence is not constant along the fiber but changes randomly, both in magnitude and direction. As a result, the nonuniform broadening of a BDG spectrum in an SMF should be toward both directions, and the extent to which depends on the accumulation of the birefringence along the fiber. Figure 4 shows a typical BDG spectrum in a 400 m SMF segment and a Gaussian fitting curve, where the discrepancies between the two curves (inside the dashed elliptical circle) are attributed to randomly changing birefringence from different sections of the SMF. A Brillouin pump-probe scheme was used to characterize the distributed birefringence of the SMF

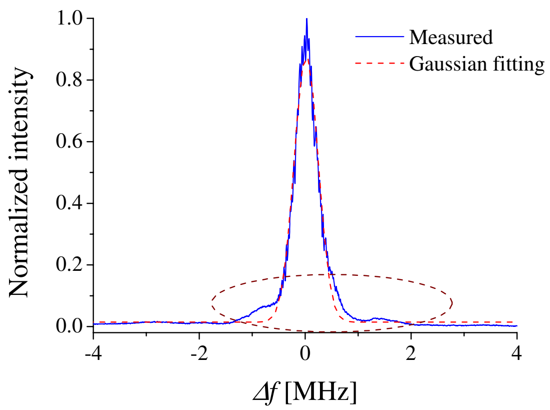

Fig. 4. Typical reflection spectrum of a BDG in a 400 m SMF segment.

segments (400 and 600 m) used in [24]. Figure 5 shows the Brillouin signals for both maximum and minimum SOP matching between the pump and probe waves, and the results show that the typical beat length of the SMF segment is in the range of 10–50 m, whose birefringence-induced shift in BDG spectrum is 4–20 MHz [11]. Note that the BDG bandwidth of 0.5 MHz achieved with a 400 m SMF is much smaller than the birefringence-induced shifts of an SMF.

The intensity variation of the Brillouin signal in Fig. 5 indicates the polarization change induced by accumulation of the birefringence along the fiber. From the comparison of the two figures in Fig. 5, it is observed the signal in the first 300 m section is relatively flat and varies considerably in the 300–400 m section in Fig. 5(a), while most sections exhibit considerable variation in Fig. 5(b). This indicates that accumulation of the birefringence for the 600 m SMF is larger than that of 400 m SMF, which can qualitatively explain the BDG bandwidth increase for a 600 m SMF. It is also expected that a narrower BDG bandwidth would be achieved with a longer SMF with even smaller birefringence.

In conclusion, we have demonstrated a novel scheme of OSA based on operating a BDG in the SMF, which features ultrahigh resolution, large wavelength coverage, and a simple direction-detection scheme. A multipeak optical spectrum with 1 MHz frequency interval was clearly distinguished, indicating the capability of the spectral resolution of the BDG-OSA. It is also revealed that because the birefringence is not constant along the SMF

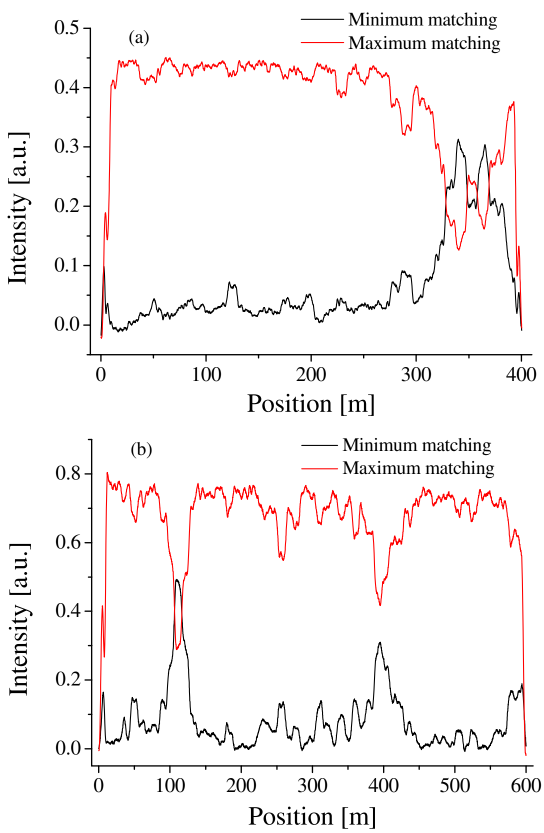

Fig. 5. Measured Brillouin signals for maximum and minimum SOP matching between the pump and probe waves in (a) 400 m SMF and (b) 600 m SMF.

but changes randomly both in magnitude and direction, the broadening of the BDG bandwidth would be much narrower than the birefringence-induced shifts of an SMF. Since the nonuniform broadening of a BDG spectrum in an SMF depends on the accumulation of the birefringence, a narrower BDG bandwidth and subsequently a higher spectral resolution would be expected by using a longer SMF with even smaller birefringence. In addition, the reflectivity of the BDG can be flexibly adjusted by changing the pump power to accommodate the power of the signal light and subsequently can extend the OSA dynamic range.

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