Observation of spectral enhancement in a soliton fiber laser with fiber Bragg grating

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Abstract: We demonstrate that soliton generation in a fiber laser containing a fiber Bragg grating exhibits spectral enhancement near the Bragg resonance wavelength. The Bragg grating leads to a spectral hole on the soliton spectrum while the observed enhancement is always located at the long wavelength side of the Bragg resonance.

OCIS codes: (060.5530) Pulse propagation and temporal solitons; (060.3735) Fiber Bragg gratings; (190.5530) Pulse propagation and temporal solitons.

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1. Introduction

Spectral enhancement (SE) was first observed in supercontinuum (SC) generation in a fiber grating [1]. Westbrook et al. found that SC generation in a fiber containing a Bragg grating could exhibit more than 10 times of SE near the Bragg resonance wavelength, and the position of the SE could be located over a large wavelength range within the continuum with gratings of different Bragg wavelengths. The fiber Bragg grating (FBG) could even extend the SE to spectral regions beyond the generated continuum edge [2]. Such grating-related SE has shown great potential to improve the signal to noise ratio in frequency metrology applications using fiber continuum combs [3].

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To explain the physical mechanism of the SE generation in SC, various experimental, theoretical, and numerical studies have been carried out [1, 4-6]. Li et al. [4] believed that the SE around the Bragg wavelength is actually a dispersive wave. The linear Bragg reflection can be changed into nonlinear SE by increasing the coupling of SC into the grating. Westbrook et al. [5] derived a perturbative solution to the nonlinear Schrödinger equation that includes the effect of a FBG under two assumptions: one is that the bandgap of the grating is much smaller than the pulse bandwidth; the other is that the nonlinear interaction between the grating and the unperturbed waves is negligible. Applying their method to uniform and sampled gratings, they reproduced the large SE observed near the Bragg resonance when SC was generated in a FBG. Austin et al. [6] considered the SC field as a train of discrete pulses. They focused on the dynamics of the enhancement mechanism for a single pulse rather than the full SC description [1, 5]. They theoretically derived that the SE generation is due to the narrow spectral phase filtering resulted from the FBG and the nonlinear propagation in FBG. Their theoretical derivation perfectly explained a key feature of the experimentally observed SE: depletion for wavelengths below the bandgap and the SE on the long wavelength side. The role of the FBG in pulse propagation includes two parts: the phase filtering and the nonlinear propagation, either independently or interactively. To support their theory, they further considered a more general situation in which a narrowband phase feature is imposed on a pulse prior to propagating through a nonlinear medium. They verified that the nonlinear SE caused by the FBG is due to the relative phase rotation between the linear and nonlinear components, and any narrow phase feature followed by nonlinear propagation would exhibit SE effect. Präkelt et al. experimentally studied the SE dynamics based on the self-phase modulation [7] and the theoretical work for clarifying SE observed in SC experiments was recently presented by Tsoy et al. [8]

The above-mentioned works [1-6] are done in the scope of pulse propagation in FBG and for SE in SC generation, and a common assumption made is that the SC is a superposition of a series of pulse [4-6]. Bolger et al. [9] have reported tunable SE of a soliton spectrum using an acoustic long-period grating. However, the SE was superimposed onto a Raman shifted soliton at 1620 nm, not the original pulse wavelength at 1550 nm. It is well known that soliton evolution in a fiber laser is equivalent to the soliton propagation in a recurred fiber links. However, so far as we know, no experimental observation of SE in a pulse generated in a fiber laser is reported. The pulse generated in the fiber laser is a dissipative soliton [10] rather than a conventional soliton in a fiber. Apart from the balance between the cavity dispersion and the fiber nonlinearity a pulse would experience during propagation, the balance between the gain and losses determines the dissipative features of the solitons generated in the fiber laser. A question would be whether the phenomenon of SE could be observed in a dissipative soliton generated in fiber lasers containing a FBG? In this paper we present the first experimental observation of SE in a soliton fiber laser with a FBG in the cavity. We demonstrate that, similar to the SE generated in SC, soliton generation in a fiber laser containing a FBG exhibits SE near the Bragg resonance wavelength. The FBG leads to a spectral hole on the soliton spectrum while the observed enhancement is always located at the long wavelength side of the Bragg resonance in our experiments. For noise-like pulse mode locking [11], the SE is weakened and generally only spectral hole caused by the FBG can be observed.

2. Laser schematic and experimental results

Figure 1 shows the fiber laser. It has a ring cavity of about 10.5 meters. Therefore the repetition rate of the fiber laser is about 19 MHz. Apart from the 7.5 m erbium-doped fiber (StockerYale: EDF-1480-T6), all other fibers are standard single-mode fiber. The averaged coefficient of the second-order dispersion is $\overline{\beta}_2 \approx -15.7$ ps^2/km at the wavelength of 1550 nm. Different from the conventional soliton fiber lasers, a uniform FBG was incorporated in the cavity. The FBG was inscribed on a 0.3 m standard single-mode fiber using the phase mask method and the FBG segment is about 1.5 cm. The laser is mode-locked with the nonlinear polarization rotation technique [12]. An in-line fiber-type polarization-dependent isolator is inserted between the wavelength division multiplexer (WDM) and the EDF. Four pieces of

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wave-plates mounted on a 7-cm-long fiber bench are used to adjust the polarization of the light. The laser is pumped by a Raman fiber laser source (BWC-FL-1480-1) of wavelength 1480 nm. We noted that the isolator between the WDM and the EDF is necessary for the self-started mode locking. As the reflection of the Bragg wavelength of the FBG is about 15 dB, without the isolator, the FBG can function as a high reflection mirror at Bragg resonance wavelength. Combined with low reflection from the other fiber end or the waveplate on the fiber bench and the strong gain of the EDF, a CW lasing centered at the Bragg wavelength was always obtained instead of the mode locking.

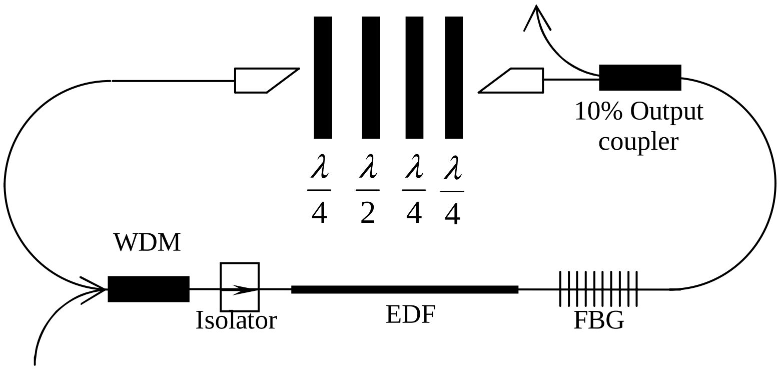

Fig. 1. Schematic of the fiber laser. λ/4: quarter-wave plate; λ/2: half-wave plate; FBG: fiber Bragg grating; EDF: erbium-doped fiber; WDM: wavelength division multiplexer.

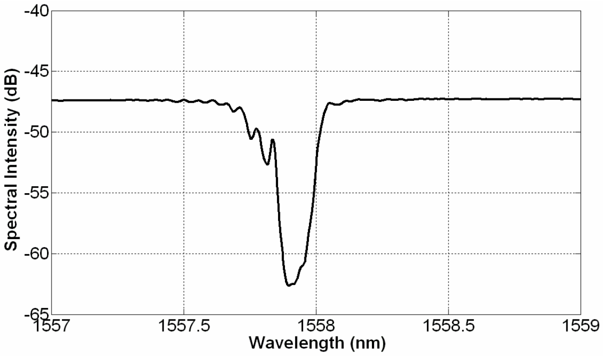

Fig. 2. Transmission spectrum of the uniform FBG.

We used the amplified spontaneous emission of the EDF with 59.1 mW pump power to directly measure the transmission spectrum of the FBG used. It is shown in Fig. 2. The Bragg wavelength is about 1557.9 nm and the 3 dB bandwidth of the spectrum is about 0.096 nm. Experimentally we found that with appropriate orientation setting of the waveplates, self-started mode locking can be achieved provided the pump power is strong enough. Similar to the case of soliton operation in fiber lasers without FBG [13], single soliton, multiple solitons, or noise-like pulse could be generated in the fiber laser. However, due to the existence of the FBG, spectral hole was always observed on the optical spectrum of the mode-locked pulse. When the central wavelength of the generated soliton is close to the Bragg wavelength of the FBG, SE could be observed on the spectrum. Figure 3(a) and Fig. 3(b) show the optical spectrum and the autocorrelation trace of a typical state observed. The state was obtained with 177.6 mW pump power and the output average power is about 2.16 mW. It is clear that there

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is about 10dB SE superimposed on the soliton spectrum. The pulse width of the soliton is about 340.2 fs if a Sech^2 pulse profile is assumed. To highlight the SE relationship with the FBG, we have shown in Fig. 3(c) the zoom-in regime around the Bragg wavelength. Compared with Fig. 2, the short wavelength side of the FBG spectrum was inherited. The spectral modulation of Fig. 3(c) is caused by the multiple soliton operation [13]. The FWHM of the SE is about 0.07 nm, which corresponds to the spectral width of a ~100 ps pulse. Due to the limited scan range of the autocorrelator used (50 ps) and the weak strength of this broad dispersive wave, such background is not easy to be distinguished in the autocorrelation trace. Anyway, Fig. 3(b) showed a very weak and broad background.

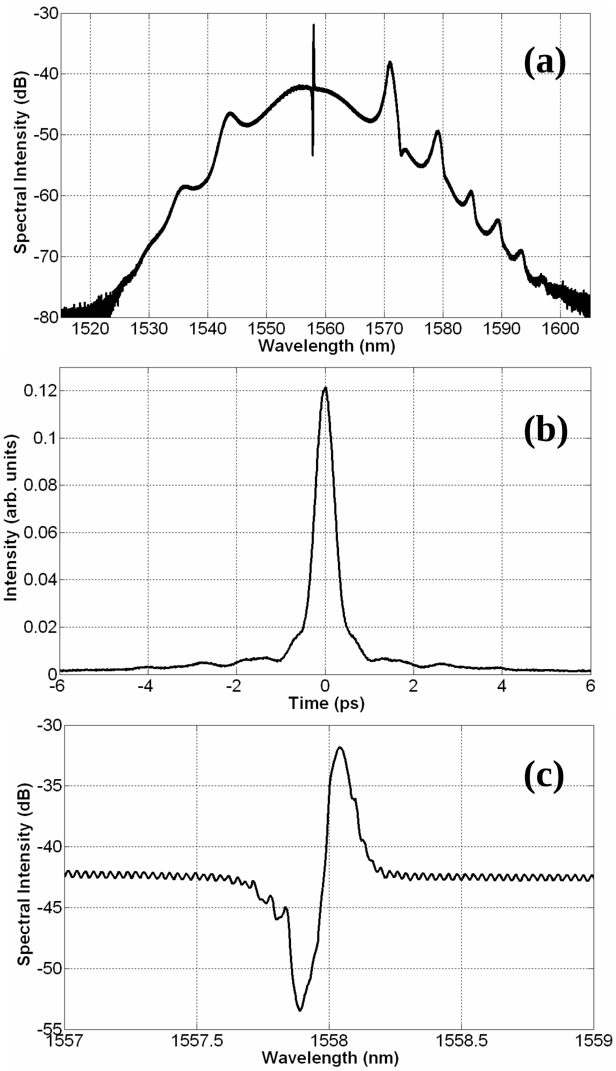

Fig. 3. A typical soliton operation state with 10dB spectral enhancement. (a) Optical spectrum; (b) Autocorrelation trace; (c) Zoom-in spectrum around the Bragg resonance.

Experimentally we tried to study the SE variation with the continuous shift of the central wavelength of the generated soliton. However, as the tuning of the central wavelength of the generated soliton is through rotating one of the waveplates, and such modulation simultaneously changes the linear phase delay bias in the cavity [13], which will at the same time considerably change the soliton parameters such as pulse width, peak power and so on. No quantitative relation could be obtained.

The SE exists once the mode-locked pulse is generated in the fiber laser. Experimentally we can still observe SE when the central wavelength of the soliton was shifted away from the Bragg wavelength. Figure 4 showed examples when the soliton was shifted to either the short wavelength side or the long wavelength side. The SE and the spectral hole still existed on the soliton spectrum. However, the SE is much weaker compared with that shown in Fig. 3(a).

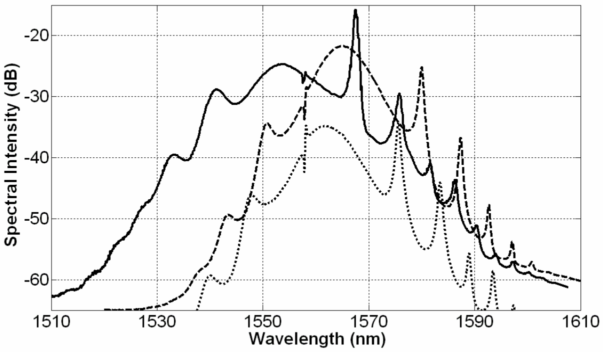

Fig. 4. Optical spectrum of soliton operation with the central wavelength of the soliton largely shifted away from the Bragg wavelength.

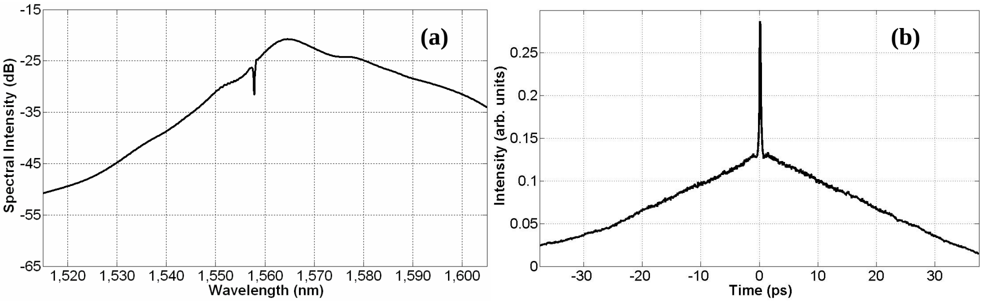

Fig. 5. Noise-like pulse. (a) Optical spectrum; (b) Autocorrelation trace.

We also studied the influence of the FBG on the noise-like pulse. As shown in Fig. 5(a), the spectral hole induced by the FBG could be observed when the soliton fiber laser is operated in the noise-like pulse mode locking state. However, the SE is very weak compared to the case of soliton mode locking. Physically it is easy to understand such performance: the noise-like pulse consists of many evolving ultrashort pulses bound together as indicated by Fig. 5(b), therefore, the phase of the individual ultrashort pulses or intra-structure of the noise-like pulse is changing when it goes through the FBG; secondly, the central wavelength of the individual ultrashort pulses or intra-structure of the noise-like pulse randomly varies, which may be far away from the Bragg resonance wavelength. As the measured optical spectrum is actually an averaged one (the scan time of the OSA is ~ ms, while the repetition rate of the fiber laser is ~ MHz), the SE caused by the phase shaping of the FBG [6] would be further weakened.

We note that in our experiments no matter the central wavelength of the soliton / noise-like-pulse was coincided or shifted away from the Bragg wavelength, the SE always appeared at the long wavelength side.

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3. Discussion

The generation of SE needs two conditions: a spectral signal (generally provided by an ultrashort pulse) and a filter. As the fiber laser itself can generate an ultrashort pulse, the inserting the FBG in the laser cavity results in a simple SE source that can be used for possible applications [3]. The fiber laser with an inserted FBG is also a suitable test-bed for the study of SE phenomenon as we can change the features of the FBG to study the influence of the FBG to the SE generation. The cavity structure also strengthens the interaction between the FBG and the spectral signal as the pulse cycles in the laser cavity, which is not possible for pulse propagation in fibers. Although the inserted FBG changed the laser dynamics, because of the short length of the FBG compared with the cavity length and the narrow bandwidth of the FBG compared with the soliton spectrum, we did not observe significant changes for the fiber laser performance compared with the fiber laser without the FBG.

4. Conclusion

In conclusion, we have reported the first experimental observation of SE based on soliton operation in a fiber laser. The inclusion of a FBG in the cavity would not affect the soliton dynamics of the fiber laser as the soliton and noise-like pulse mode-locking could still be self-started like that of the laser without the FBG. However due to the existence of the FBG, spectral hole is imposed on the optical spectrum of the solitons or the noise-like pulses. SE is observed on the optical spectrum of the solitons. And the SE is stronger when the soliton central wavelength is closer to the Bragg wavelength of the FBG. As the FBG bandwidth is far smaller than the soliton bandwidth of around 8nm, the hypothesis in Ref. [5, 6] can be fully satisfied. Therefore, the theoretical analysis and conclusion in Ref. [5, 6] could be applied here but now it is indeed based on dissipative solitons but not on SC generation. That is, the SE is caused by the phase filtering resulted from the FBG and the interaction between the dissipative soliton and linear dispersive waves during propagation.

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