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Multi-wavelength generation based on Brillouin enhanced four-wave mixing in optical fibers

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Abstract: An optical comb consisting of 15 lines within 30 dB was generated with an extremely simple setup, based on the combination of amplified spontaneous Brillouin scattering and 4-wave mixing in optical fibers.
OCIS codes: (190.4370) Nonlinear optics, fibers; (290.5900) Scattering, stimulated Brillouin; (060.3735) Fiber Bragg gratings; (190.4380) Nonlinear optics, four-wave mixing.

1. Introduction

Multi-wavelength fiber lasers have attracted a great interest in the photonic community, since they have potential applications in wavelength division multiplexed transmission systems, optical metrology and wavelength conversion. Besides, such fiber lasers can be utilized in microwave photonics for RF signal processing such as harmonic micro/millimeter wave generation and their frequency up-conversion [1-2]. Many different designs have been proposed and experimentally demonstrated to produce multiple wavelength laser sources, using multiple generation of Brillouin Stokes and anti-Stokes waves [3], erbium doped fiber ring laser incorporating an optical comb filter [4] and Brillouin/Erbium fiber laser [5-7]. However, most techniques are realized based on optical cavities, which essentially make the implementation complex and leads to cavity mode noise.

In this paper, we propose a new architecture to generate an optical comb, composed of a substantial number of optical lines, equally spaced by the Brillouin frequency in optical fibers. The system makes use of two physical effects: generation of amplified spontaneous Brillouin Stokes waves in optical fibers and nonlinear line multiplication by four-wave mixing. A main advantage of this system, compared to previously reported techniques, relies on the elimination of the essential need of an optical cavity, which renders the configuration of the proposed scheme dramatically simplified. In addition, the absence of external cavity makes possible to operate the optical comb generator with a high stability since it is very robust in terms of wavelength tolerance and competition between the generated lines. Yet, it was clearly observed that a single-tone light signal travelling through an optical fiber could generate 15 new optical frequencies at the end of the fiber. So, we believe that this technique may serve as a practical basic concept for potential applications.

2. Principle

Brillouin scattering in optical fibers is usually described as light scattered by acoustic phonons. When a light signal at ν_S travels through a fiber, thermally-excited acoustic waves will act as random grating reflectors and will start to backscatter the traveling signal, consequently generating a backward propagating Brillouin Stokes wave at $-\nu_B$ below the signal frequency. The Stokes wave can then be significantly amplified by interfering with the original signal and therefore stimulating Brillouin scattering (SBS) [8]. However, it is important to point out that when the signal power increases over a critical level - commonly called Brillouin critical power - the huge amplification experienced by the Stokes wave depletes the signal and the excess of the signal power over the critical level will be entirely transferred to the Stokes wave. In the case of long uniform fiber, the estimated critical power is about 5 mW

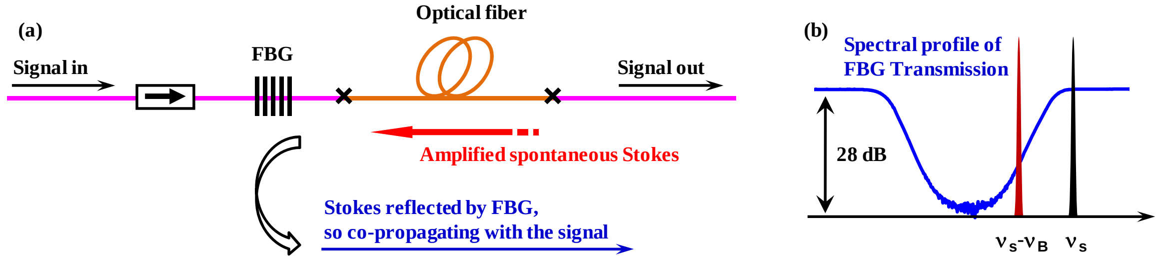

Figure.1: (a) Schematic diagram of the principle to generate multiple wavelengths, using the combination of the generation of amplified spontaneous Brillouin Stokes waves and the associated four-wave mixing in optical fibers. (b) Configuration of the signal frequency and fiber Bragg grating.

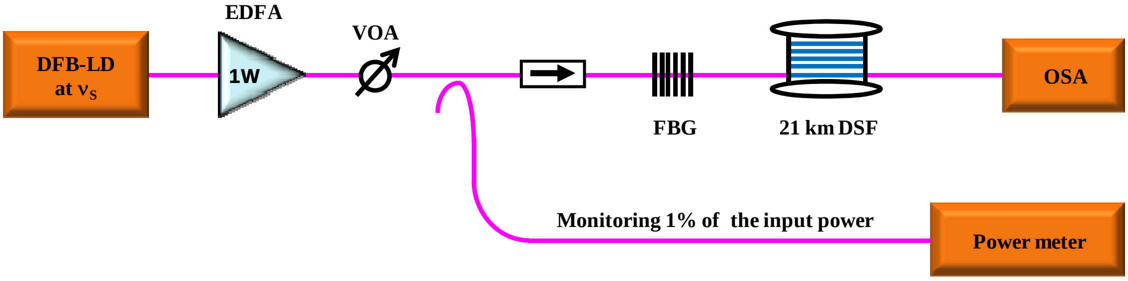

Figure.2: Experimental setup for the generation of multi-wavelength laser, based on Brillouin enhanced four-wave mixing in optical fibers. EDFA; erbium doped fiber amplifier, VOA; variable optical attenuator, FBG; fiber Bragg grating, DSF; dispersion shifted fiber.

at 1550 nm [9]. It means that the generated Stokes wave can be also depleted when its power is strongly boosted beyond the critical level, so as to generate a second order Stokes wave at ν_S-2ν_B. This process will be sustained until the excess energy of the signal is contributed to the generation of higher order Stokes waves. On the other hand, an anti-Stokes wave can be also observed at ν_S+ν_B, due to the presence of the thermally activated acoustic wave. However, unlike the Stokes process, the stimulation of Brillouin scattering will attenuate the anti-Stokes wave instead of amplifying it, which will remain at a very low power level.

Figure 1(a) depicts the schematic diagram of the principle for the multiple line generation. The basic idea of this scheme relies on the presence of a fiber Bragg grating (FBG) with a ultra-narrowband and high reflectivity, 28 dB at the peak reflection. As shown in Figure 1(b), the signal enters into the fiber with no significant loss, since the signal is spectrally placed out of the FBG reflection window. However, the generated Stokes wave backward propagating with respect to the signal is reflected by the FBG, hence co-propagating with the signal wave. The mutual interaction between the two waves efficiently initiates the four-wave mixing (FWM) process to generate idler waves at two different frequencies, ν_S+ν_B and ν_S-2ν_B. As a result, the combined physical processes result in the generation of multiple Brillouin Stokes and anti-Stokes waves sustained by the four-wave mixing products.

3. Experiments and Results

A standard distributed-feedback laser diode operating at a wavelength of 1551 nm was used as a seed light source. The laser power was strongly boosted using an erbium doped fiber amplifier (EDFA) with a 30 dBm saturation power, and the output power was continuously controlled by a variable optical attenuator before entering a 21 km dispersion shifted fiber (DSF), so that dispersion is kept low to favor the phase matching in 4-wave mixing. 1 % of the output power from the EDFA was monitored using an optical power meter. The measured Brillouin characteristics of the DSF show a Brillouin shift at 10.71 GHz with FWHM gain spectral width of 27 MHz. The signal spectrum after propagation through the fiber was then measured and recorded using an optical spectrum analyzer with 0.01 nm resolution for different signal powers (1 mW, 50 mW and 280 mW), as shown in Figure 3. Figure 3(a) shows that at low signal powers below the Brillouin critical power, no significant Stokes waves were generated in this system, so that the output spectrum is identical to the spectrum of the incident signal. However, for higher signal powers it was clearly observed that a number of new wavelengths with a spectral spacing determined by the Brillouin shift were present at the end of the fiber, as shown in Figure 3(b) and 3(c). We also observed a linear dependence of the number of comb lines within 30 dB power difference on the logarithmic signal power. In our experiment, an optical comb consisting of 15 lines over a spectral range of 150 GHz was achieved at our maximum signal power of 280 mW. However, it must be pointed out that the maximal number of optical comb lines can be further increased, simply by increasing the input power of the signal.

To verify the catalyzing role of FWM between the Stokes and signal waves in this technique, we slightly shifted the input signal frequency by 15 GHz above the original frequency while keeping the signal power at 280 mW. In this frequency configuration, the generated amplified spontaneous Stokes wave is no longer reflected by the FBG, thereby no more seeding the FWM interaction. Figure 3(d) shows the signal spectrum after propagating through the fiber. It proves that the combined effect of SBS *and* FWM is essential for the generation of multiple spectral lines in this system.

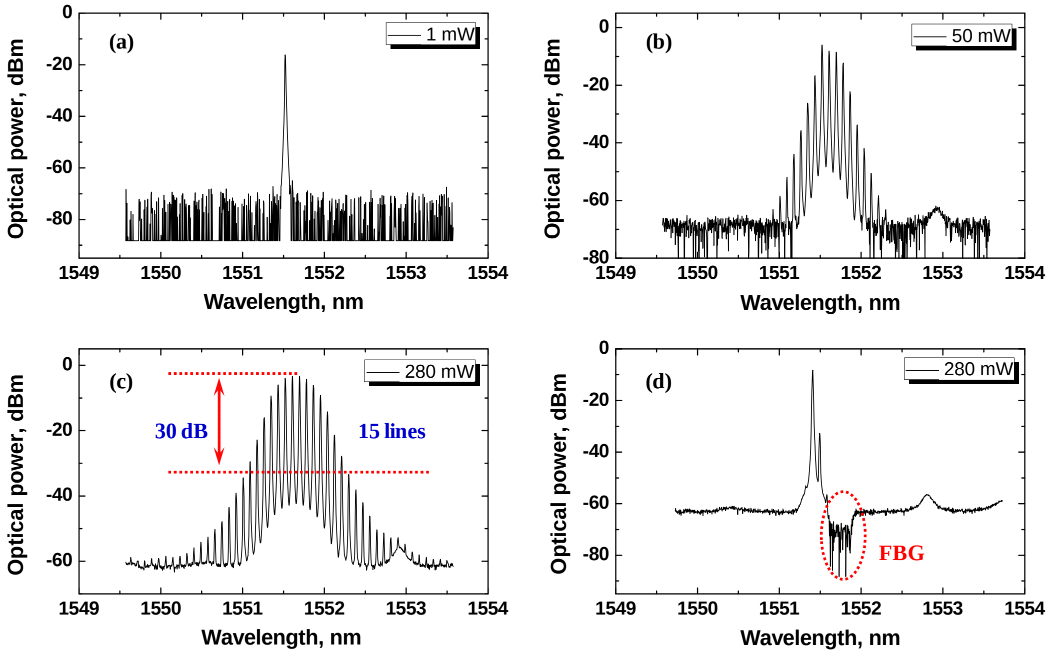

Figure.3: (a), (b) and (c) show the spectra of the output signal after propagating through the 21 km DSF for different signal powers at 1, 50 and 280 mW, clearly showing the generation of a substantial number of wavelengths at a 280 mW signal power. (d) The output signal spectrum in the absence of the FWM interaction between the original signal and the Brillouin Stokes.

4. Conclusions

We have proposed and experimentally demonstrated an extremely simple and intrinsically stable setup for the generation of multiple equally-spaced spectral lines (comb), based on the combination of Brillouin scattering and four-wave mixing in fibers. From a practical point of view, this technique may be implemented as a robust solution for real applications such as microwave or millimeter wave generation.

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