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Broad and Flat Brillouin Gain Spectrum in Optical Fiber Obtained by Modulating Driving Current of Laser Diode

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A simple method for obtaining a broad and flat Brillouin gain spectrum (BGS) is presented. By modulating the driving current of a pump laser diode with triangular waveform, a BGS with lower than 0.3 dB gain variation over >200 MHz is achieved. With this method, the bandwidth of the flattened BGS can be controlled by adjusting the amplitude and/or frequency of the current modulation.

Brillouin scattering is one of the most significant nonlinear effects in optical fibers, and has been applied to various devices and systems.[1] In some of these applications, including gain-flattened Brillouin amplifiers,[2] slow-light generators,[3] and narrow-linewidth Brillouin lasers,[4] a broad and flat Brillouin gain spectrum (BGS) can be of great benefit. Conventional methods that can be used to obtain a temporally-averaged flat BGS in an optical fiber are based on the overlapping of multiple narrow BGSs with slightly different Brillouin frequency shifts (BFSs), which include the employment of longitudinal variations in strain/temperature,[5] core diameter,[6] and/or dopant concentration.[7,8] Recently, Dragic has succeeded in obtaining a BGS with a gain variation of <0.5 dB and a bandwidth of >200 MHz by combining two acoustically anti-guiding optical fibers,[8] but the BGS in each fiber needs to be precisely controlled by optimizing the radial distribution of the doping concentration of Al, P, and Ge, which is somewhat complicated. A much simpler way to achieve a time-averaged flat BGS is required.

In this Note, we demonstrate a simple method for obtaining a broad and flat BGS. By modulating the driving current of a pump laser with triangular waveform, its output spectrum can be broadened and flattened, resulting in a broad and flat BGS. We experimentally achieve a BGS with <0.3 dB gain variation over >200 MHz, which is even flatter than Dragic's result.[8] The bandwidth of the flattened BGS can be controlled by adjusting the amplitude and/or frequency of the current modulation. The increase in gain variation is observed when the bandwidth is broader than ~200 MHz, the reason of which is also clarified.

Since the output optical frequency as well as the output optical power of a laser diode (LD) depends on the driving current, the optical frequency can be modulated by directly modulating the LD current. When high-frequency amplitude modulation is applied to the LD current, the time-averaged optical spectrum becomes broad. If we neglect the induced modulation of the output power, to obtain a flat spectrum, the LD current modulation should be performed with not sinusoidal but triangular waveform, because, ideally, the output power is uniformly distributed over the covered frequency range with the triangular modulation. Since the electrical circuit to drive the LD has an intrinsic response time (much longer than that of the LD itself), the bandwidth of the output optical spectrum depends not only on the modulation amplitude but also on the modulation frequency. The BGS measured by heterodyne detection is known to be broadened, when broadband light source is employed as a pump LD.[9]

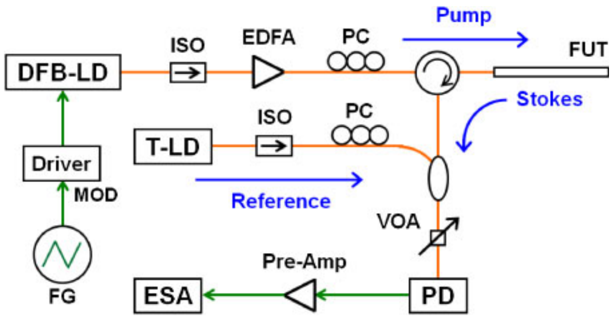
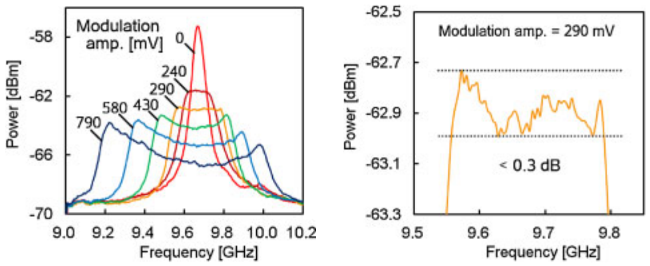


Fig. 1. (Color online) Experimental setup. DFB-LD, distributed-feedback laser diode; EDFA, erbium-doped fiber amplifier; ESA, electrical spectrum analyzer; FG, function generator; FUT, fiber under test; ISO, isolator; MOD, external modulation port; PC, polarization controller; PD, photo diode; T-LD, tunable laser diode; VOA, variable optical attenuator.

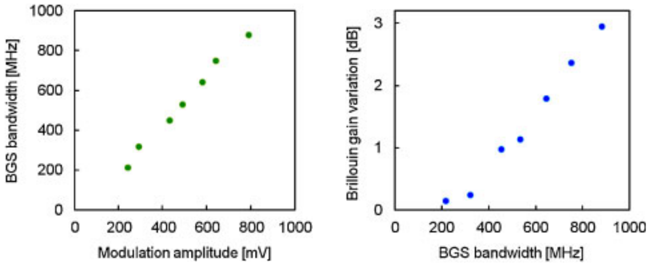
The fiber under test (FUT) employed in the experiment was a 1-km-long silica SMF with core diameter of 9 µm, core refractive index of ~1.47, numerical aperture (NA) of 0.13, propagation loss at 1.55 µm of ~0.5 dB/km, and BFS of ~10.8 GHz at 1.55 µm at room temperature. The experimental setup is depicted in Fig. 1. A distributed-feedback (DFB-) LD (DenseLight DL-CLS101B) at 1.55 µm was used as a pump light source. The driving current of the LD was modulated with triangular waveform using a function generator connected to the external modulation port of an LD driver (Thorlabs LDC-500). After being amplified to 16 dBm with an erbium-doped fiber amplifier (EDFA), the pump light was injected into the FUT. The open end of the FUT was bent to suppress the Fresnel reflection. As the frequency-modulated pump light cannot be directly used as a reference light for heterodyne detection in this experiment (for details, refer to Refs. 10 and 11), another tunable LD (T-LD; Santec TSL-210) at 1.55 µm was employed, the output of which was coupled with the Brillouin Stokes light, and then, after power adjustment with a variable optical attenuator (VOA), converted into an electrical signal with a photo diode (PD). The polarization states of the pump and the reference light beams were optimized with polarization controllers (PCs). The electrical signal was, after being preamplified, observed as a BGS with an electrical spectrum analyzer (ESA).

Figure 2(a) shows the measured BGS dependence on the peak-to-peak modulation amplitude applied to the LD current. The modulation frequency was fixed at 500 kHz. With no modulation (amplitude: 0 mV), the BGS was



(a) (b)

Fig. 2. (Color online) (a) Measured BGS dependence on modulation amplitude of LD current. (b) Magnified view when modulation amplitude was 290 mV.



(a) (b)

Fig. 3. (Color online) (a) BGS bandwidth vs modulation amplitude. (b) Brillouin gain variation vs BGS bandwidth.

observed not at ~10.8 GHz but at ~9.7 GHz, because the center frequency of the pump light was ~1.1 GHz higher than that of the reference light. By tuning the output frequency of the T-LD, the optical frequency at which the BGS is observed can be arbitrarily controlled. As the modulation amplitude was raised, the BGS bandwidth was broadened and the maximum Stokes power was decreased, which is reasonable if we consider that this broadening effect is the consequence of temporal averaging. With increasing modulation amplitude, the center frequency of the whole BGS was slightly shifted to the lower frequency, because the output frequency dependence of the LD on driving current was not completely linear. Figure 2(b) shows a magnified view of the flattened region when the modulation amplitude was 290 mV. Over the range of >200 MHz, the gain variation was lower than 0.3 dB, which is flatter than Dragic's report.[8]

The BGS bandwidth was measured as a function of modulation amplitude, as shown in Fig. 3(a). Here the BGS bandwidth was defined as the 3-dB bandwidth calculated with reference to the maximum Stokes power in the whole BGS. As the modulation amplitude was raised, the bandwidth was also almost linearly increased in this range. The Brillouin gain variation was also measured as a function of BGS bandwidth, as shown in Fig. 3(b). With increasing bandwidth, the gain variation was also increased, especially when the bandwidth was broader than ~200 MHz. The increase in gain variation according to the bandwidth broadening is due to the distortion of the flattened BGS, as shown in Fig. 2(a), which seems to originate partly from the low-pass characteristics of the electronic circuit (note that, when the modulation amplitude was 790 mV, and the modulation was switched from triangular to sinusoidal waveform, the broadened BGS scarcely changed), and partly from the output power dependence of the LD on driving current.

In conclusion, we demonstrated a simple method for obtaining a broad and flat BGS by modulating the driving current of a pump LD. The BGS with <0.3 dB gain variation over >200 MHz was experimentally achieved. We also showed that the bandwidth of the flattened BGS can be controlled by adjusting the amplitude of the current modulation. When the bandwidth was broader than ~200 MHz, gain variation was increased, probably due to the the low-pass characteristics of the LD driving circuit as well as the output power dependence of the LD on driving current. We believe that, though the broad and flat BGS obtained with this method can be applied only to a limited range of devices in which temporally-averaged spectra are exploited, it will be of great use in developing gain-flattened continuous-wave Brillouin amplifiers, etc. We also predict that the BGS can be further broadened and flattened by modulating the LD driving current with optimized arbitrary waveform.

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