Influence of laser linewidth on performance of Brillouin optical time domain reflectometry*

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(Received 10 October 2012; revised manuscript received 14 December 2012)

The effects of optical sources with different laser linewidths on Brillouin optical time domain reflectometry (BOTDR) are investigated numerically and experimentally. Simulation results show that the spectral linewidth of spontaneous Brillouin scattering remains almost constant when the laser linewidth is less than 1 MHz at the same pulse width; otherwise, it increases sharply. A comparison between a fiber laser (FL) with 4-kHz linewidth at 3 dB and a distributed feedback (DFB) laser with 3-MHz linewidth is made experimentally. When a constant laser power is launched into the sensing fiber, the fitting linewidths of the beat signals (backscattered Brillouin light and local oscillator (LO)) is about 5 MHz wider for the DFB laser than for the FL and the intensity of the beat signal is about a half. Furthermore, the frequency fluctuation in the long sensing fiber is lower for the FL source, yielding about 2 MHz less than that of the DFB laser, indicating higher temperature/strain resolution. The experimental results are in good agreement with the numerical simulations.

Keywords: Brillouin optical time domain reflectometry (BOTDR), laser linewidth, distributed feedback laser, fiber laser

PACS: 42.81.Pa, 78.35.+C, 42.55.Wd, 42.55.Px **DOI:** 10.1088/1674-1056/22/7/074214

1. Introduction

A number of studies have recently focused on long-distance distributed fiber sensing technologies.[1–5] Distributed sensing based on the Brillouin scattering in optical fibers was first proposed in 1989,[1] and one of the subjects mainly investigated was Brillouin optical time domain reflectometry (BOTDR),[2,3] for the reason that it accesses one fiber-end only and offers simple implementation. The power-spectrum parameters of the backscattered spontaneous Brillouin light induced by the launched pulse into the sensing fiber, including the peakvalue and the peakvalue frequency where the intensity is maximal, are linearly related to the strain imposed on the fiber[4] and the fiber temperature.[5] Temperature and/or strain variation along the sensing fiber can be obtained according to the frequency shift and/or the intensity change.

In a BOTDR system, a narrow-linewidth highly-coherent laser (much less than the natural Brillouin linewidth, about 40 MHz) is necessary for coherent detection and long-distance sensing. Commercial distributed feedback (DFB) laser, of which the linewidth at 3 dB is generally about several MHz, may serve as the main source for the BOTDR sensing system.[6] With the development of narrow linewidth fiber laser (FL), Geng *et al.*[3] and Dong *et al.*[7] used an FL with linewidth less than 10 kHz at 3 dB as the primary laser source in the BOTDR sensing system. Other lasers, such as the Nd:YAG laser, once served as main laser in a Brillouin sensing system.[8] Because Brillouin backscattering is $\sim$ 11 GHz downshifted at 1550-nm waveband light, a coherent detection scheme is often used to reduce the detection frequency from 11 GHz down to several hundreds of MHz,[3] consequently reducing the bandwidth requirement of the detector and simplifying the data collection process. Many local oscillators (LOs) for a coherent detection scheme are available, including first-order sideband of electronic-optic modulator (EOM),[6] stimulated Brillouin scattering of a single fiber,[9] Brillouin fiber laser (BFL) of ultranarrow spectral linewidth,[3] among others. The BFL scheme is the most convenient and direct method, for the frequency shift of stimulated Brillouin scattering in the specific fiber is approximate to that of the spontaneous Brillouin scattering in the sensing fiber, and its linewidth in the oscillating cavity is much less than that of the stimulated Brillouin scattering in a single fiber.

For different linewidths of main sources and LOs, the temperature and/or strain sensing have/has been realized in diverse BOTDR configurations.[3,6–9] However, the influence of laser linewidth on the performance of BOTDR sensing system

*Project supported by the National High Technology Research and Development Program of China (Grant No. 2012AA041203), the Science and Technology Commission of Shanghai Municipality, China (Grant No. 13XD1425400), and the Pudong New Area Science and Technology Development Fund, China (Grant No. PKJ2012-D04).

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needs to be analysed. In this paper, we use two kinds of main lasers (FL and DFB laser) with different linewidths as primary sources to investigate their effects on the Brillouin power spectra, and the frequency fluctuations in the distributed sensing fiber. The results of this study will be helpful in designing the scheme of BOTDR sensing system.

2. Theoretical analysis

Lasers are not generally of ideal single-frequency and have linewidths. If the line shape of a laser is Lorentzian in nature, it can be written as

$$E(f) = \frac{(\omega_s/2)^2}{(f-f_s)^2 + (\omega_s/2)^2}, \tag{1}$$

where $E(f)$ is the laser intensity, f_s is the central frequency of the optical source, and ω_s is the laser linewidth at 3 dB.

The laser output from the main laser is modulated to pulse sequences in order to position the temperature/strain accurately, and then launched into the long distance sensing fiber. The backward light includes Rayleigh, Brillouin and Raman scatterings. The spontaneous Brillouin scattering is very weak and is about 11-GHz down-shifted for the 1550-nm waveband. The Brillouin backscattered-light power spectrum is the superposition of many Brillouin power spectra for each frequency in the launched, pulsed light power spectrum. Actually, the Brillouin scattering is the convolution of pulse shape and the ideal Brillouin function of the sensing fiber in the time domain, or the product of pulse power spectrum, and the ideal Brillouin transfer-function in the frequency domain. For the backscattering Brillouin light, the frequency-dependent factor $H(\nu)$ is[10]

$$H(\nu) = \int_{-\infty}^{\infty} P_p(f) \frac{h(\omega/2)^2}{[\nu - (f - S_B)]^2 + (\omega/2)^2} \, \mathrm{d}f, \tag{2}$$

where h is a constant related to sensing fiber, S_B is the Brillouin frequency shift (about 11 GHz), $P_P(f)$ is the power spectrum of the launched pulse, ω is the typical full width at the half maximum (FWHM, about 40 MHz), and ν is the frequency of backward Brillouin power spectrum.

According to Eq. (2), the numerical simulations are made at various laser linewidths, where $S_B = 11$ GHz, and $P_P(f)$ is the fast Fourier transform (FFT) of 100-ns rectangular pulse. The linewidth at 3 dB of the backscattered Brillouin spectrum versus the laser linewidth is shown in Fig. 1(a). The Brillouin linewidth increases exponentially when the source linewidth is larger than 1 MHz. The Brillouin linewidth is slightly wider than the ideal Brillouin linewidth (40 MHz) if the source linewidth is less than 1 MHz. The relative peakvalue of the Brillouin scattering spectrum decreases sharply when the linewidth is over 1 MHz as shown in Fig. 1(b). When the linewidth is less than 1 MHz, the peakvalue of Brillouin scattering is almost constant. In the BOTDR sensing system, a higher peakvalue power indicates a better signal-to-noise ratio (SNR) of the Brillouin sensing signal. Figures 1(a) and 1(b) show that the variations in the linewidth of the main laser from 1 kHz to 1 MHz do not change the performance of the spontaneous Brillouin scattering spectrum and that the same spectral width and peakvalue power may be obtained, which is useful for choosing appropriate laser in BOTDR. For laser linewidth larger than 10 MHz, the linewidth of the Brillouin spectrum is much wider than the ideal Brillouin linewidth, and the peakvalue is much smaller. A corresponding decrease in SNR may also be observed.

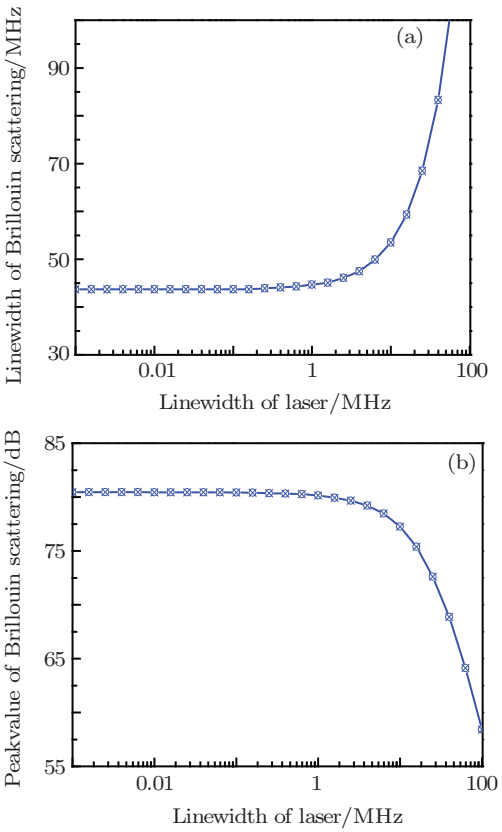


Fig. 1. (color online) Variations of (a) spontaneous Brillouin scattering spectrum width and (b) the peakvalue of the Brillouin spectrum with the linewidth of laser with a 100-ns pulse width.

For different modulated pulse widths, the linewidth of the backward Brillouin spectrum decreases to an ideal value (40 MHz) if the pulse width is adequately wide as shown in Fig. 2(a). When the pulse width is 10 ns, the Brillouin linewidth is over 100 MHz. The Brillouin peakvalue increases with pulse width as shown in Fig. 2(b). So when the pulse width is near to the acoustic life (about 10 ns), in other words, the spatial resolution is about 1 m, the Brillouin power spectrum becomes wide and the intensity becomes small. For the shorter pulse width, i.e., higher spatial resolution, the linewidth of Brillouin scattering is wider, and fitting of the Brillouin spectrum is less accurate.

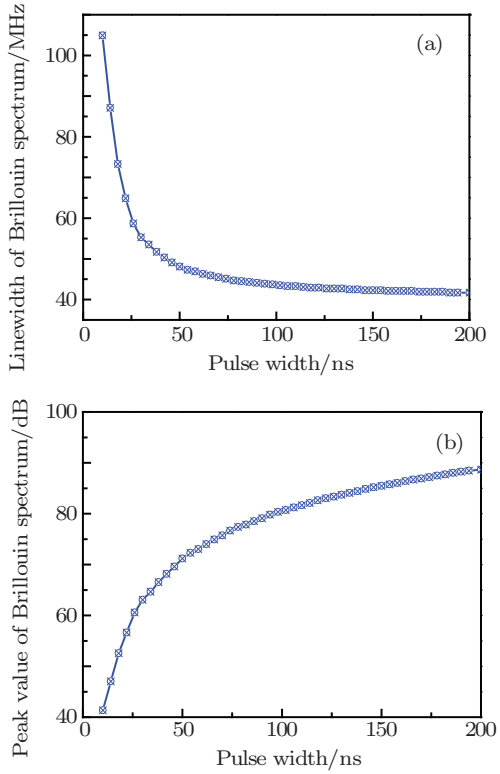


Fig. 2. (color online) Variations of (a) spontaneous Brillouin scattering spectrum width and (b) the peakvalue of the Brillouin spectrum with the modulated pulse width of laser with a linewidth of 1 kHz.

3. Experimental setup

To verify the theoretical analysis above, an experimental BOTDR fiber sensing system was built as shown in Fig. 3. Two main laser components, an FL with 4 kHz at 3 dB[11,12] and a DFB laser (FITEL, WAIT-TECH Technology CO., Ltd.) with 3 MHz at 3 dB, were applied to the BOTDR system. The outputs of both lasers were 28 mW. Figure 4 shows the linewidths of the FL and the DFB laser determined by the homodyne spectrum method. Half of the main laser output is used to pump the LO, which was composed of a compact BFL.[13] The detailed illustration of the BFL, including its configuration and output spectrum, was shown in Ref. [14]. The other half of the main source was for the sensing branch, which was amplitude modulated by an acousto-optic modulator (AOM, Model MT160-IIR10-FIO, AA Inc.) to generate pulse sequences with a repetition rate of 4 kHz and pulse width of 100 ns. The modulated pulse was appropriately amplified (avoiding stimulated Brillouin scattering) by an erbium doped fiber amplifier (EDFA), and then launched into the long sensing fiber to generate the backscattered spontaneous Brillouin signal. The sensing fiber was 10-km SMF-28. The backscattered spontaneous Brillouin signal, which carried local information about temperature or/and strain along the whole sensing fiber, could be detected by the coherent heterodyne detection. The beat signal between the spontaneous Brillouin signal and LO was injected into a double balanced photodetector (DB-PD, New Focus 1617-AC, Newport) through a 1:1 coupler, and then amplified by a microwave amplifier (MWA, ALPHALAS BBA-100-VG, bandwidth from 0.01 GHz to 2 GHz). All the data were collected by a high-speed data-acquisition card (DAQ, Gage, Model CS82G, 3GS/s sample rate). Data acquisition was synchronized with the signal generator for the AOM.

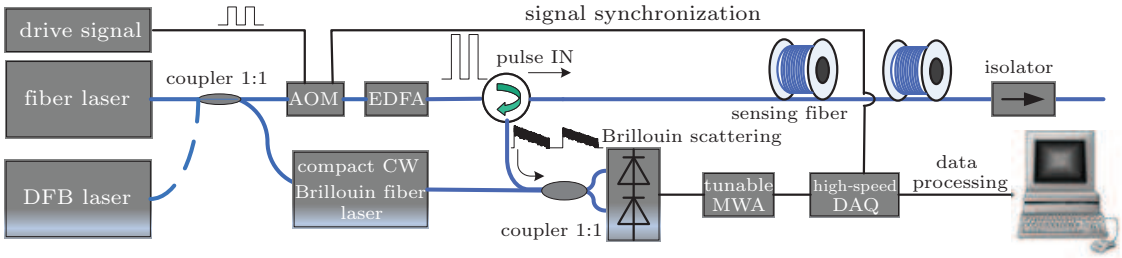


Fig. 3. (color online) Experimental setup of the BOTDR sensing system.

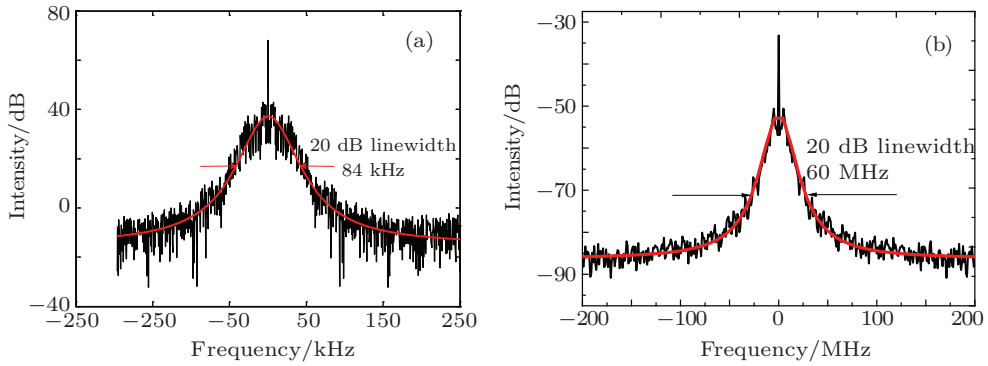


Fig. 4. (color online) Measurements of laser linewidths for (a) fiber laser and (b) DFB laser.

Acquisition and analysis of the sensing signal were real-time processed by a customized LabVIEW program. During data processing, FFT of the time domain signal in the range of a single spatial resolution was performed. The signal was then fitted to a Lorentzian curve. The peakvalue of the Lorentz fitting was regarded as the intensity, and the central frequency where the intensity was maximal, was considered to be the peakvalue frequency.

4. Results and discussion

To compare the influences of different laser linewidths on the performance of BOTDR sensing system, the FFT of the beat signal of spontaneous Brillouin scattering and LO is made in a single space resolution, and then fitted by a Lorentzian function. Figures 5 and 6 show the fitting linewidths and intensities at different sensing points respectively. The fitting linewidth is wider for DFB laser (average value is about 46 MHz) than for the FL (average value is about 41 MHz) at the same BFL LO, especially when the sensing distance is remote and the SNR is small. The deviation observed mainly comes from the difference between the spontaneous Brillouin spectra; because the linewidth of BFL is only of the order of kilohertz for the FL and DFB main laser, and the linewidth difference between the Brillouin spectra is about several MHz. The linewidth difference between BFL LO spectra is about only 1/1000 compared with that between Brillouin spectra and can be ignored. The experimental results are consistent with the numerical simulations.

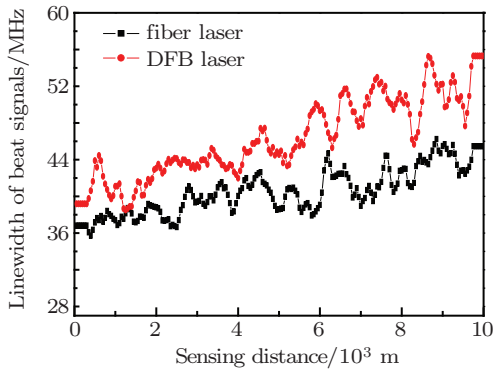


Fig. 5. (color online) Linewidth fitting for the beat signal of Brillouin scattering/LO along the sensing fiber.

The intensity of the beat of the Brillouin scattering and LO is larger for the FL as shown in Fig. 6, because that the spontaneous Brillouin scattering in the sensing fiber has a larger peakvalue, and so does the LO. In principle, a larger peakvalue indicates a better SNR of the beat frequency signal. In the BOTDR sensing system, the temperature and strain measurement accuracy are both proportional to the frequency resolution $\delta\nu$: $\delta T/T = \delta\nu/C_{\mathrm{T}}$, $\delta\varepsilon/\varepsilon = \delta\nu/C_{\varepsilon}$, and the frequency resolution is related to the SNR of Brillouin scattering[15]

$$\frac{\delta\nu}{\Delta\nu} \propto \frac{1}{\sqrt{2}(\mathrm{SNR})^{1/4}},$$

where δT is the temperature resolution and $\delta\varepsilon$ the strain resolution, $C_{\mathrm{T}} = 1.1\mathrm{MHz/K}$, $C_{\varepsilon} = 0.05\ \mathrm{MHz}/\mu\varepsilon$, $\delta\nu$ is the frequency resolution, and $\Delta\nu$ the natural linewidth of Brillouin scattering in the fiber (about 40 MHz). In the same systematic condition, higher amplitude indicates better SNR, correspondingly better strain and/or temperature resolution. In the data processing, all the discrete data are processed by the FFT in a single space resolution, and then fitted to Lorentzian function, whose linewidth is set to be around 40 MHz. Narrower linewidth of the Brillouin signal will have a higher accuracy in the data processing. Final frequency fluctuation along the sensing fiber is shown in Fig. 7. Compared with the DFB laser of 3 MHz linewidth, the FL has a better frequency resolution. The frequency fluctuation observed in the FL is about 2 MHz less than that observed in the DFB laser.

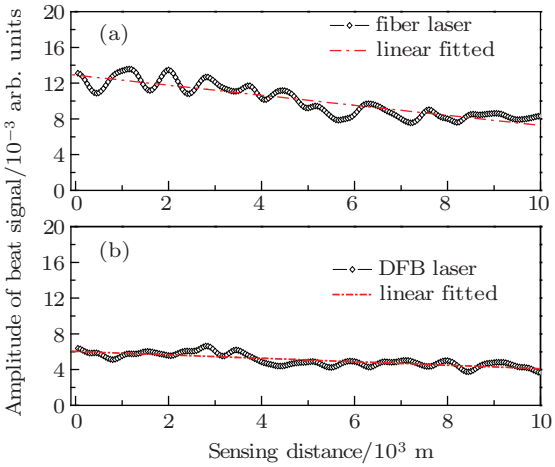


Fig. 6. (color online) Peakvalues of (a) the beat of Brillouin scattering and (b) LO along the sensing fiber.

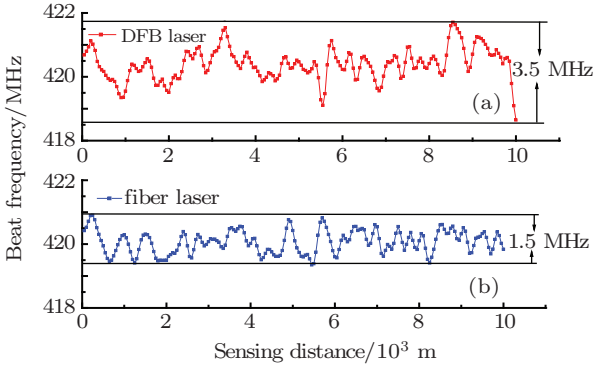


Fig. 7. (color online) Frequency fluctuations along the sensing fiber for (a) DFB laser and (b) fiber laser.

5. Conclusions

The influence of the laser linewidth on BOTDR sensing system is numerically analysed and experimentally studied.

The results show that when the linewidth of main laser is less than 1 MHz, the amplitude distribution is larger than when it is over 1 MHz, and the linewidth of the Brillouin signal is narrower. In the frequency region less than 1 MHz, the linewidth and intensity of spontaneous Brillouin signal almost stay constant. The experimental results show that the frequency fluctuation tends to flatten for fiber laser, and correspondingly the frequency resolution is better for the narrow linewidth source, which is accordant with the numerical simulation. The analysis and results are helpful for choosing the main laser and designing the scheme of BOTDR sensing system.

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