Subpeaks in the Brillouin loss spectra of distributed fiber-optic sensors

Yidun Wan, Shahraam Afshar V., Lufan Zou, Liang Chen, and Xiaoyi Bao

Department of Physics, University of Ottawa, Ottawa, Ontario K2P 0L2, Canada

Received August 10, 2004

Subpeaks in the Brillouin loss spectra of distributed fiber-optic sensors were observed for what is believed to be the first time and studied. We discovered that the Fourier spectrum of the pulsed signal and the off-resonance oscillation both contributed to subpeaks. The off-resonance oscillation at frequency $|\nu-\nu_B|$ is the oscillation in the Brillouin time domain when beat frequency ν of the two counterpropagating laser beams does not match local Brillouin frequency ν_B. This study is important in differentiating the subpeaks from actual strain–temperature peaks. © 2005 Optical Society of America

OCIS codes: 060.2370, 290.5830, 290.5900, 190.5890, 060.2310.

Pump (cw)–probe (pulsed) Brillouin-based fiber-optic sensors have been extensively studied over the past few decades because of their enhanced sensitivity for strain and temperature measurements.[1] Although a single Brillouin peak is usually observed under uniform strain–temperature conditions, multipeak spectra have also been observed[2] and associated with the cross-talk effect in nonuniformly strained fibers.[3] These multipeak Brillouin spectra contain mixed strain–temperature information. Recently another type of peak, referred to here as a subpeak, has been observed experimentally in the Brillouin spectra of even uniformly strained fibers for short pulses (duration 2–3 ns), as shown in Fig. 1(a).[4] It is important to study the origins and properties of these subpeaks to distinguish them from the peaks that resulted from the strain–temperature variations along a fiber. This is especially crucial in field tests of structural health monitoring, since misinterpretation of subpeak information may cause false warning signals. In this Letter we use stimulated Brillouin scattering transient coupled-wave equations to study the properties of the subpeaks that will help us to improve our measurement accuracy at centimeter spatial resolution and increase the system capability in structural health monitoring applications, where small stress spots can be detected by subtraction of an initial reference profile, since the subpeaks are not functions of strain–temperature and the dc level (the background of the pulsed probe).

We have found two mechanisms for the subpeaks: (1) the Fourier spectrum of the pulsed probe, (2) the periodic damping oscillation (off-resonance oscillation at frequency $|\nu-\nu_B|$) of the cw pump intensity when beat frequency ν does not match the local Brillouin frequency ν_B of the sensing fiber.

The simulation of the distributed Brillouin sensor is based on the numerical solution of the following three-wave transient model[3]:

$$\left(\frac{\partial}{\partial z}-\frac{1}{v_g}\frac{\partial}{\partial t}-\frac{1}{2}\alpha\right)E_p=\bar{Q}E_s, \tag{1a}$$

$$\left(\frac{\partial}{\partial t}-\frac{1}{v_g}\frac{\partial}{\partial t}+\frac{1}{2}\alpha\right)E_s=\bar{Q}^*E_p, \tag{1b}$$

$$\left(\frac{\partial}{\partial t}+\Gamma\right)\bar{Q}=\frac{1}{2}\Gamma_1 g_B E_p E_s^{\;*}, \tag{1c}$$

where E_p, E_s, and $\bar{Q}$ are the amplitudes of the cw pump, the pulsed probe (Stokes), and the acoustic fields, respectively; g_B (5×10^{-14} m/mW) is the gain factor; and $\Gamma=\Gamma_1+i\Gamma_2$, where $\Gamma_1=1/(2\tau)$ ($\tau=10$ ns is the phonon lifetime for silica fibers) is the damping rate and $\Gamma_2=\omega-\omega_B$ is the detuning frequency. To solve these equations we applied a numerical method introduced by Chu *et al.*[5] The boundary condition for E_s at spatial position $z=0$ is the output optical field of a Mach–Zehnder electro-optic modulator (EOM). This output field, in general, can be written as

$$E_s(t)=\sqrt{I_{\text{in}}}\{\cos\theta\exp[i\phi(t)] + \sin\theta\exp[-i\phi(t)]\}, \tag{2}$$

where $I_{\text{in}}=A_1^{\,2}+A_2^{\,2}/2$ is the input probe intensity into the EOM (A_1 and A_2 are the optical amplitudes in the two modulation arms of the EOM, respectively), and $\theta=\arctan(A_2/A_1)$. We assume that $\theta\in[0,\pi/4]$; $\phi(t)=\phi_0+\phi_{\max}\times f(t,t_0,\tau_p)$, where $\phi_{\max}$ is the maximum tunable phase difference induced by the applied voltage; ϕ_0 is the bias point of modulation, and $f(t,t_0,\tau_p)=\exp\{-\ln 2[2(t-t_0)/\tau_p]^m\}$ is an mth-order Gaussian pulse of width τ_p centered at t_0. In our case, $\theta\approx\pi/4$, $\phi_{\max}=\pi/4$, and $\phi_0=\pi/2+\Delta\phi/2$ with $\Delta\phi\in[0,\pi/2]$. Thus the extinction ratio of the EOM can be given by $R_x=10\log_{10}[(I_{\text{out}})_{\max}/(I_{\text{out}})_{\min}]$ $=10\log_{10}[(1+\sin\Delta\phi)/(1-\cos\Delta\phi)]$.

Figure 1(a) shows experimentally that uniform stress has no effect on the subpeak positions. Figure 1(b) shows the calculated Brillouin spectrum for 6400 $\mu\epsilon$, which matches that in Fig. 1(a) well. The change of ν_B merely results in a shift of the main Brillouin peak, so only one theoretical strain is calculated. In all simulations we use single-mode fibers with $n=1.470$ and $\nu_B=12\,795$ MHz as the reference Brillouin frequency of loose fibers at room temperature.

Considering that the spectrum of the acoustic field is similar to that of the pump field, Eq. (1c) indicates

0146-9592/05/101099-3/$15.00

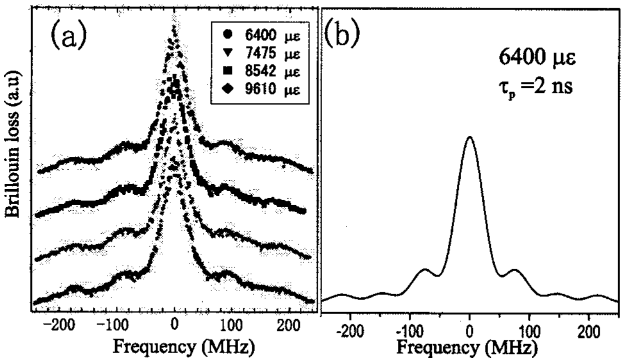

Fig. 1. (a) Experimental Brillouin spectra for a 2-ns pulse and different uniform strains. (b) Calculated Brillouin spectrum for a 2-ns pulse and 6400-$\mu\epsilon$ uniform strain. The Brillouin frequencies are translated to zero for comparison.

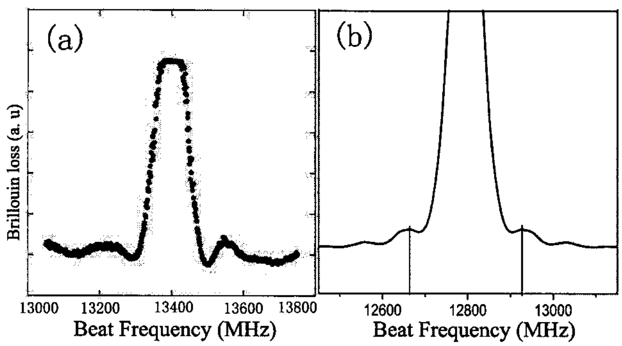

Fig. 2. (a) Experimental Brillouin spectrum at the center of a 2-m fiber for a 10-ns pulse; the flat top is due to the electrical chop off. (b) Calculated Brillouin spectrum with the same parameters as in (a).

that the Brillouin spectrum is a convolution of gain profile $g_B(\nu)$ and the Fourier spectrum of the pulsed probe, which brings subpeaks into the corresponding Brillouin spectrum. The subpeak position is independent of fiber length. Figures 2(a) and 2(b) show the experimental and calculated Brillouin spectra, respectively, at the center of a 2-m fiber for $R_x=20$ dB. The subpeaks have the same positions for Figs. 2(a) and 2(b). Furthermore, as the order of a super-Gaussian pulse decreases when its FWHM is fixed, the subpeaks move to the main peak and their heights decline. At any given time t the subpeak position does not shift except for $t_0<t<t_0+\tau_p/2$ and $t_0+2Ln/c-\tau_p/2<t<t_0+2Ln/c$. In either case, not all of the pulse is in the fiber, so the Fourier components are farther from the main Brillouin peak than those at time $t_0+\tau_p/2<t<t_0+2\,Ln/c-\tau_p/2$.

The cw pump and pulsed probe beams interact via an induced phonon field with the same frequency as the beat frequency of the two lasers. Thus the phonon field at any position behaves similar to the loss signal of the cw pump at the same position. That is, the spectra of the phonon field at $z=0$ also have subpeaks at the same positions as those of their counterparts in the Brillouin spectra since the cw pump is detected at $z=0$. Equation (1c) leads directly to a solution of this phonon field $\bar{Q}$ at $z=0$ (assuming the initial phonon field to be zero):

$$\bar{Q}(t)=C\int_0^t E_p(t')E_s^*(t')\exp(\Gamma t')\mathrm{d}t', \qquad (3)$$

where $C=(1/2)\Gamma_1 g_{\hat{B}}\exp(-\Gamma t)$. Since $f(t,t_0,\tau_p)=0$ when $|t-t_0|\geqslant\tau_p/2$, Eq. (2) can be approximated to yield $E_s(0,t)$ as

$$E_s(t)\approx E_{\mathrm{dc}}+E_{S_0}f(t,t_0,\tau_p), \qquad (4)$$

where E_{dc} and E_{S_0} are the field amplitudes of the dc and pulse components of the pulsed probe field. The acoustic intensity can be obtained from Eq. (3) with Eq. (4):

$$|\bar{Q}(t)|^2=C^2[|T_1|^2+2\,\mathrm{Re}(T_1T_2^{\ *})+|T_2|^2],$$

$$T_1=E_{\mathrm{dc}}^{\ *}\int_0^t E_p(t')\exp(\Gamma t')\mathrm{d}t',$$

$$T_2=E_{S_0}^{\ *}\int_0^t E_p(t')\exp(\Gamma t')f(t',t_0,\tau_p)\mathrm{d}t'. \qquad (5)$$

Although the first and third terms in Eq. (5) involve dc–pump and pulse–pump interactions, respectively, the second term represents a cross term of the two interactions. The roles of these three terms are shown in Table 1.

When $\nu\neq\nu_B$, all three terms oscillate at frequency $|\nu-\nu_B|$, hereafter called the off-resonance oscillation. These off-resonance oscillations in the time domain cause subpeaks in the Brillouin spectra as evidenced in Fig. 3. The subpeak at 12 585 MHz in the Brillouin spectrum at $t=21$ ns (in the inset of Fig. 3) evidently

Table 1. Effective Region of the Three Terms in Eq. (5)

Probe	Region	
	A $(t_0,t_0+\tau_p/2)$	B $(t_0+\tau_p/2,t_0+2Ln/c)$
With dc	Terms 1, 2, 3	Term 1
With no dc	Term 3	None

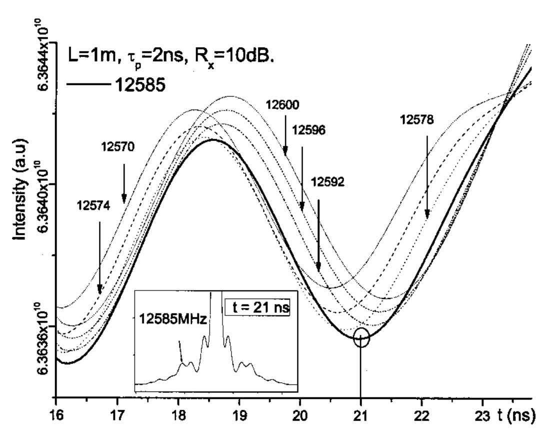

Fig. 3. Time domains of the cw pump for seven beat frequencies within the neighborhood of 12 585 MHz. Inset, Brillouin spectrum at $t=21$ ns (or $z=0.61$ m since $t_0=15$ ns for a 1-m fiber).

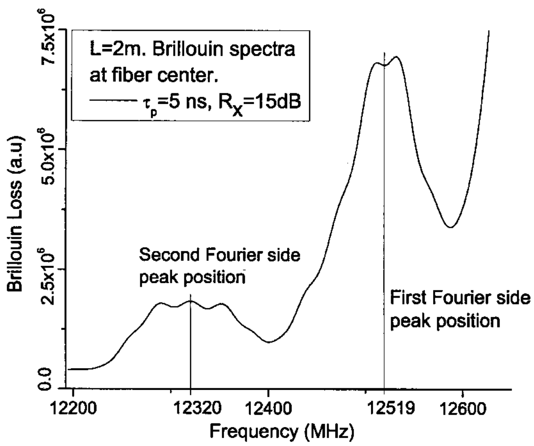

Fig. 4. Competition between the Fourier peaks and the side peaks caused by off-resonance oscillation. Positions of the first two side peaks caused by Fourier transformation are indicated.

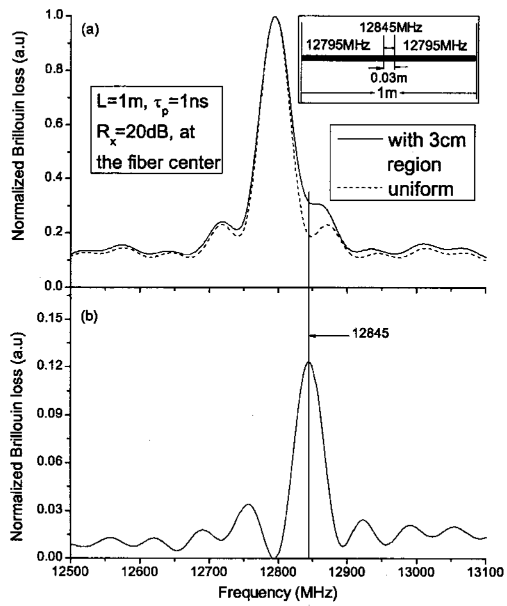

Fig. 5. (a) Brillouin spectra at the fiber center when the fiber is loose with ν_B=12 795 MHz and when it has a 3-cm strained region with ν_B=12 845 MHz. (b) Spectrum obtained by subtracting the spectrum in the loose case from that in the strained case.

is due to the maximum depletion of the cw pump for ν=12 585 MHz at 21 ns. The subpeak at ν =12 585 MHz is chosen to be far enough from ν_B to produce more than one period of oscillation in region B so that the oscillation frequency can be identified.

The subpeaks have the following features: (1) R_x and τ_p have no effect on the number and positions of the subpeaks except when the Brillouin spectra are taken too close to region A. In that case subpeak positions may be affected by τ_p because of the edge effect of the pulse. (2) The subpeak height relative to the main Brillouin peak increases with R_x and τ_p. (3) As L increases, more subpeaks appear in the Brillouin spectrum with decreased relative height.

The subpeaks from the Fourier spectrum of the probe beam and the off-resonance oscillation of the pump compete with each other especially for $\tau_p \geqslant 3$ ns when both contributions can be observed. The Brillouin spectrum at the center of a 2-m fiber with t_0=30 ns, τ_p=5 ns, and R_x=15 dB is shown in Fig. 4. The combined effect is clear: small peaks due to the off-resonance oscillations on the top of the bigger subpeaks caused by the Fourier transform of the 5-ns pulse.

In structural health monitoring it is important to distinguish the subpeaks from the strain–temperature peaks. Fortunately, for long fibers (>4 m) the subpeaks are buried in noise because the increase of the main peak height is much faster than that of the subpeaks. For short fibers, subpeaks are much more substantial. However, since subpeaks are not related to strain–temperature, we can get a reference Brillouin spectrum at a uniform stress–temperature section and subtract it from the stressed–temperatured Brillouin spectrum to remove the subpeaks. Figure 5(a) shows two normalized Brillouin spectra at the center of a 1-m fiber, τ_p=1 ns and R_x=20 dB. The dotted curve represents the loose fiber with ν_B=12 795 MHz. The solid curve is the spectrum at the center of the 3-cm uniformly strained region with ν_B=12 845 MHz. Figure 5(b) is the subtraction of the two curves in Fig. 5(a). The peak at 12 845 MHz representing the strain in the 3-cm fiber resulted from the interaction between the pulse and the cw pump. Obviously the subpeak effect has been reduced significantly through reference Brillouin spectrum subtraction.

In conclusion, subpeaks are caused not by the strain–temperature change in the fiber but by the Fourier spectrum of the pulsed probe and the off-resonance oscillation at frequency $|\nu-\nu_B|$ in the Brillouin time domain.

The authors thank the Natural Sciences and Engineering Research Council, Intelligent Sensing for Innovative Structure, and National Capital Institute of Telecommunications, Canada for their support. Y. Wan's e-mail address is lzou@uottawa.ca.

References

1. X. Bao, J. Dhliwayo, N. Heron, D. J. Webb, and D. A. Jackson, J. Low Temp. Phys. **13**, 1340 (1995).
2. X. Bao, D. J. Webb, and D. A. Jackson, Electron. Lett. **29**, 976 (1993).
3. S. Afshar V., G. A. Ferrier, X. Bao, and L. Chen, Opt. Lett. **28**, 1418 (2003).
4. A. W. Brown, "Development of a Brillouin scattering based distributed fibre optic strain sensor," Ph.D. dissertation (Department of Physics, University of New Brunswick, Fredericton, New Brunswick, Canada, 2000).
5. R. Chu, M. Kanefsky, and J. Falk, J. Appl. Phys. **71**, 4653 (1992).