Time biasing due to the slow-light effect in distributed fiber-optic Brillouin sensors

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The influence of the slow-light effect on the performance of distributed Brillouin sensors is studied. We show that, while in most situations it can be neglected, it may greatly affect the results obtained for certain experimental configurations. More specifically, for one of the experimental arrangements described in the literature (a strong continuous-wave pump and a weak pulsed probe) we show that this effect induces a large time biasing of the traces that depends not only on the fiber length but also on the frequency separation between pump and probe. This biasing reduces the available resolution in this experimental arrangement.

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Distributed fiber-optic sensors offer unique capabilities for the monitoring of quantities such as temperature and strain over long distances. In many applications, these sensors avoid the need for thousands of pinpoint sensors and complicated multiplexing schemes. Among these, distributed Brillouin sensors have attracted much research interest in the past years[1–7] and are now widely used for the monitoring of strain and temperature distribution within large structures in civil engineering.[2] Several techniques have been proposed for performing distributed Brillouin sensing, and the principal configurations have been summarized in Fig. 1, together with the typical parameters used in experimental setups selected from representative publications. In the Brillouin optical time-domain reflectometer (BOTDR) configuration, a pump pulse is launched into the fiber (~200 ns duration, ~150 mW of peak power), and the spontaneous Brillouin backscattered light is synchronously analyzed as a function of the time (distance along the fiber) by using heterodyne detection.[3] For each position the pump–Stokes frequency shift is determined, which is then translated into strain or temperature values.

In the Brillouin optical time-domain analysis[4] (BOTDA-1) configuration, however, the Brillouin interaction is performed in the stimulated regime, thus requiring two counterpropagating waves, a powerful pulsed pump wave (~50 ns with ~70 mW of peak power) and a weak probe wave (~100 μW). If particular phase-matching conditions are met (namely, $f_{\text{pump}} \approx f_{\text{probe}} + \nu_B$, ν_B being the Brillouin shift), an acoustic wave is generated that scatters photons from the pump to the probe wave. This leads to a local amplification of the probe wave, which yields a time-dependent variation of the detected probe signal in the pump end. An earlier version of this technique[5] (labeled BOTDA-2 in Fig. 1) uses a powerful, continuous-wave (cw) pump wave (~6 mW) and a weak pulsed probe wave (~50 ns pulse length with ~1 mW of peak power) tuned at $f_{\text{probe}} \approx f_{\text{pump}} + \nu_B$. The position-dependent Brillouin attenuation of the pump induced by the probe is recorded in terms of a variation in the cw pump power detected from the probe end. Schemes similar to BOTDA-1 and BOTDA-2 can be developed in the frequency domain.[6] The conclusions of the analysis of the time-domain configuration can be exactly translated into the frequency-domain one. Last, centimetric resolution sensors make use of the Brillouin optical correlation domain analysis (BOCDA) technique,[7] in which the short correlation length between two modulated, counterpropagating laser beams is exploited to achieve very small amplification windows whose width and position is controlled by the modulation parameters.

All these sensing schemes developed until now have estimated their resolution by using the pulse width directly (for BOTDR, BOTDA-1, and BOTDA-2) or the calculated correlation window (for BOCDA). However, in these approaches the group-velocity changes induced by the Brillouin amplification–attenuation mechanisms have been

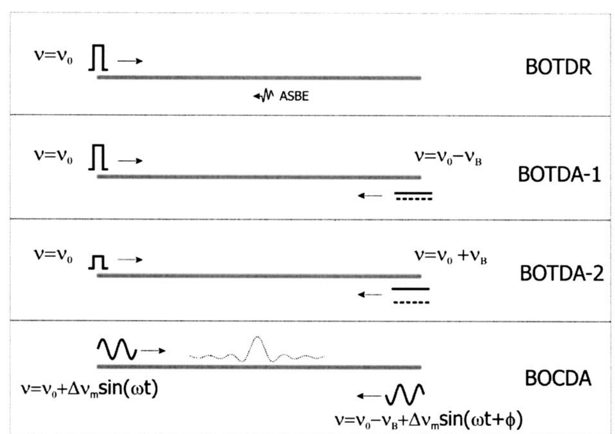

Fig. 1. Schemes for performing distributed Brillouin sensing.

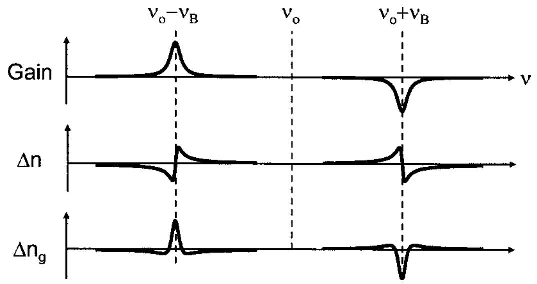

Fig. 2. Principle of group-velocity changes induced by the Brillouin interaction in optical fibers.

fully neglected. Recent theory and experiments[8] have shown, however, that these group-velocity changes can be extremely large in certain situations and can cause significant signal delay or advancement even when modest amplifications are achieved. In this Letter we systematically analyze all the signal delay–advancement effects that can take place in any of the reported Brillouin distributed sensor configurations, and we quantify those that can affect the sensor performance.

We start by considering the interaction of a cw wave at f_{cw} with a pulsed signal tuned at $f_s = f_{\mathrm{cw}} - \nu_B$. For the following theory, we make two assumptions: (1) The linear loss α is identical for the pump and signal, and (2) the cw experiences a negligible amplification or depletion as a result of the interaction with the pulse signal. Let the pulse amplitude be A_s, and the cw amplitude be A_{cw}. The well-known basic relation for the amplitudes in the Brillouin interaction reads as

$$\frac{\mathrm{d}A_s}{\mathrm{d}z} = \frac{g_B}{2A_{\mathrm{eff}}} \frac{|A_{\mathrm{cw}}|^2}{1 + 2j\left(\dfrac{\nu - \nu_B}{\Delta\nu_B}\right)} A_s - \frac{\alpha}{2} A_s, \tag{1}$$

where g_B is the Brillouin gain coefficient, A_{eff} the mode effective area, ν the light frequency, $\nu - \nu_B$ the frequency offset from the peak gain frequency ν_B, $\Delta\nu_B$ the gain bandwidth, and α the linear attenuation coefficient. Since we assume that the interaction has no effect on the cw wave, its intensity is just modified by the linear loss. Thus, for a counterpropagating wave with intensity I_o at the far end (input intensity),

$$I_{\mathrm{cw}}(z) = |A_{\mathrm{cw}}(z)|^2 = I_o \exp[-\alpha(L - z)], \tag{2}$$

where L is the total fiber length. Substituting Eq. (2) into Eq. (1) yields a differential equation with a straightforward solution of the form

$$A_s(z) = A_s(0)\exp[G(z)/2 - j\Phi(z)]\exp[-(\alpha/2)z], \tag{3}$$

so that $G(z)$ represents the well-known gain factor in intensity, $I_s(z) = I_s(0)e^{G(z)}e^{-\alpha z}$, and $\Phi(z)$ is the additional phase summed up at position z due to the Brillouin interaction. These two quantities read as

$$G(z,\nu) = g_B \frac{1}{1 + \left(\dfrac{\nu - \nu_B}{\Delta\nu_B/2}\right)^2} I_0 e^{-\alpha L} \frac{e^{\alpha z} - 1}{\alpha}, \tag{4}$$

$$\Phi(z,\nu) = \frac{1}{2} g_B \frac{\dfrac{\nu - \nu_B}{\Delta\nu_B/2}}{1 + \left(\dfrac{\nu - \nu_B}{\Delta\nu_B/2}\right)^2} I_o e^{-\alpha L} \frac{e^{\alpha z} - 1}{\alpha}. \tag{5}$$

The usual treatment of these equations in the literature has basically concentrated on the exponential intensity increase of the signal wave, but the effect of the additional phase shift $\Phi(z,\upsilon)$ induced in the signal wave has been largely omitted. This additional phase shift can be regarded as a change in the propagation constant; hence $\Phi(z,\upsilon) = \Delta\beta(z,\upsilon)z$, which can be translated into an equivalent refractive index change $\Delta n = (c/2\pi\nu)\Delta\beta$. A brief inspection of $\Delta\beta$ shows that it has a strong frequency dependence (hence Δn), as we try to show schematically in Fig. 2. If we consider a pulse propagating at the probe wavelength, its velocity will be related to the group velocity; hence the derivative of the propagation constant with frequency $V_g = (\mathrm{d}\beta \mathrm{d}\omega)^{-1}$. Thus a sudden change in the propagation constant with frequency produces a strong change in the group velocity, which in turn introduces an additional delay of the signal (pulse) at the fiber output. The group-velocity change can be written as

$$\Delta V_g^{-1} = \frac{\Delta N_g(z,\nu)}{c} = \frac{1}{2\pi} \frac{\mathrm{d}\Delta\beta(z,\nu)}{\mathrm{d}\nu}$$

$$= \frac{1}{2} g_B I_o e^{-\alpha L} \frac{e^{\alpha z} - 1}{\alpha z} \frac{2}{2\pi\Delta\nu_B} \frac{1 - 3\left(\dfrac{\nu - \nu_B}{\Delta\nu_B/2}\right)^2}{\left[1 + \left(\dfrac{\nu - \nu_B}{\Delta\nu_B/2}\right)^2\right]^2}, \tag{6}$$

and the extra time delay can be evaluated as $\Delta t = \Delta N_g(z/c)$, where ΔN_g represents the group index change. If the frequency difference between the pump and the probe exactly matches the Brillouin shift ($\nu - \nu_B = 0$), the resultant optical time delay is given by $\Delta t = G(L,\nu_B)/2\pi\Delta\nu_B = g_B I_o L_{\mathrm{eff}}/(2\pi\Delta\nu_B)$, where the effective fiber length L_{eff} adopts its usual definition.[9]

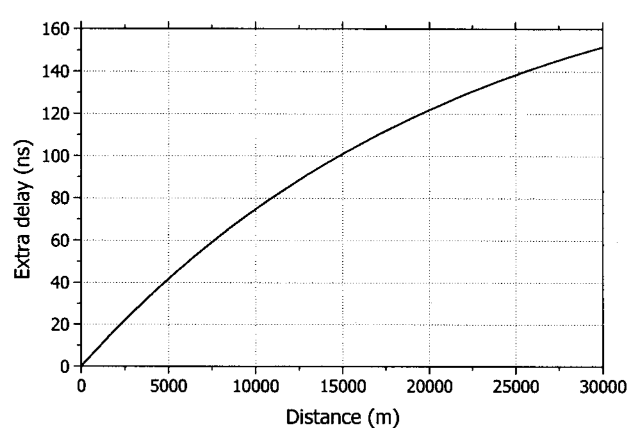

Fig. 3. Probe pulse delay as a function of distance for the BOTDA-2 configuration; the pump power is 6 mW.

We can thus say that the delay varies logarithmically with the net gain (loss) experienced by the probe. A fast evaluation of these quantities in conventional single-mode fibers ($\Delta\nu_B \approx 35$ MHz) leads to a surprisingly simple rule of thumb: 1 ns delay is introduced per decibel gain introduced in the probe. The same calculations can be performed in the case of Brillouin loss (this is when for the signal frequency $f_s = f_{cw} + \nu_B$) and the results hold basically the same except for the sign of the delay, which is reversed. This can be viewed as a certain advancement of the pulse with respect to its conventional propagation.

We now analyze the effect of this extra delay–advancement on the performance of the distributed Brillouin sensors. In the BOTDR configuration, a noise photon is generated with equal probability over the whole pulse length, which subsequently suffers Brillouin amplification along the pulse interaction length. With the previously supplied data (peak power $P_o = 150$ mW, pulse length $\tau_P = 200$ ns) and the usual fiber parameters ($g_B = 2.3 \times 10^{-11}$ m/W, mode field diameter $A_{\mathrm{eff}} = 80\ \mu\mathrm{m}^2$, $\Delta\nu_B = 35$ MHz) the maximum delay that can be introduced in a single noise photon is 3.6 ns, which is small in comparison with the resolution and corresponds to a position inaccuracy of about 0.72 m. A complete evaluation of the noise-induced loss (depletion) of the pump pulse would require a numerical resolution of the Brillouin equations taking into account the spontaneous noise,[10] but we can consider that this advancement is negligible by noting that in their usual application (long-range sensing) this scheme requires a nearly negligible pump depletion and thus no visible advancement of the pump pulse.

In the BOTDA-1 configuration the maximum overall delay that the pump pulse introduces on the probe wave is 0.4 ns (a maximum of 0.4 dB gain). The theoretical attenuation of the probe wave on the pump pulse is, however, more limiting. In the worst case (completely homogeneous fiber) and with the previous data, this attenuation can amount to as much as 2.2 dB in 30 km of fiber, and hence a 2.2 ns advancement of the pump pulse (or a 0.22 m position shift). This is still negligible in comparison with the pulse length, but it can have a certain effect in short-range high-resolution systems with higher values of pump depletion. An even worse case appears when we consider the consequences of the slow-light effect for the performance of the BOTDA-2 configuration. Although the attenuation effect of the probe pulse on the cw pump is less than 0.05 dB (hence there is no visible pump wave advancement), the probe pulse is amplified greatly at the expense of the pump wave. Again, a worst-case estimation leads to a 130 ns probe pulse delay, i.e., more than twice the reported resolution (see Fig. 3). Of course, all these estimations have been done in the worst case (ideally homogeneous fiber and $\nu - \nu_B = 0$), assuming no spontaneous Brillouin scattering and no pump depletion. A more realistic approach would require accounting for these last effects, which would very probably limit the amount of pulse advancement to a few tens of nanoseconds. Still, this simple evaluation suffices to raise awareness of the problem, and the worst case must be considered to set the system accuracy.

Even though the time biasing of the Brillouin trace is already an inconvenience, it should be possible to correct it in a relatively easy way. A more delicate question arises when we consider the effect of this time biasing on the resolution of the sensor. When instead of $\nu - \nu_B = 0$ we have $\nu - \nu_B = \Delta\nu_B/2$, the delay–advancement is halved; i.e., the time encoding of the fiber length varies as a function of the analyzed frequency. This means that the resolution is no longer given by the pulse length only, but by the sum of the pulse length with half of the maximum time delay–advancement of the probe–pump pulse for each fiber position. A frequency-dependent correction of the horizontal axis of the trace is thus necessary to maintain the resolution of the measurement, where additional difficulties may arise, since a perfect correction should require the unknown local Brillouin gain profile. Cumulative errors arising in a multipass feedback algorithm may severely impair the accuracy.

In the BOCDA configuration with the usual parameters, the maximum observable amplification–attenuation in the probe–pump wave is of the order of 10^{-4} dB, implying a negligible delay of 0.1 ps.

In conclusion, we have demonstrated that the slow-light effect can have a strong consequence in certain configurations of Brillouin sensors, especially in those having a strong, cw pump (BOTDA-2). In these systems the slow-light effect introduces not only a time biasing of the trace but also a strong impairment in the available resolution because this time biasing is strongly dependent on the pump–probe frequency difference. A frequency-dependent correction of the time axis should be sufficient to overcome this resolution impairment.

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