LIMITATION IN BRILLOUIN TIME-DOMAIN ANALYSIS DUE TO RAMAN SCATTERING

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Raman scattering turns out to be very detrimental for long-range Brillouin time-domain analysis. The conditions under which this problem occurs are studied, as well as possible strategies to avoid it.

In the past few years, Brillouin sensing using either spontaneous or stimulated Brillouin scattering has proven to be an efficient tool for the measurement of physical quantities such as temperature, strain, local birefringence or core dopant concentration along a fiber[1-5]. The Brillouin effect is the non-linear process showing the lowest threshold; however an increase of the involved optical powers turns out to be necessary in order to achieve better performances in terms of spatial resolution and range.
In our pump-and-probe analyser configuration[2], an erbium-doped fiber amplifier is used to boost the pulses produced by a standard DFB laser diode at 1550 nm, giving a peak power in the range of a few Watts for pulses from 10 to 100 ns. Taking into account the very low silica absorption at this wavelength, such a high optical power results in a metric resolution over a very long range. It turns out that such ideal conditions are not practically fulfilled, as shown in *Fig. 1*. This figure shows the actual amplification of the probe signal through Brillouin interaction as a function of the position in a 25 km fiber. As it can be seen, this gain falls abruptly to zero at 10 km; after this position, varying between 10 and 20 km depending on the amount of pump power and the type of fiber, the measurement of the Brillouin frequency shift, and thus the determination of local temperature or strain, are no longer possible. Moreover the initially square pump pulses undergo strong distorsions. Neither the linear absorption nor the pump depletion due to Brillouin scattering can explain this behaviour.

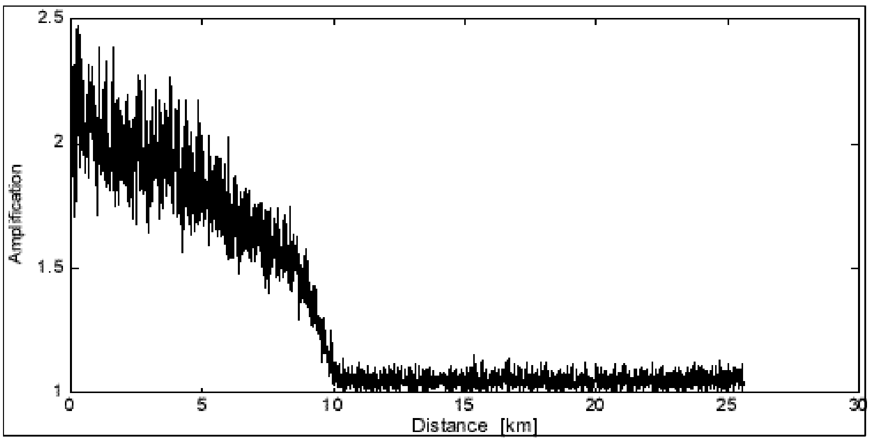

Fig. 1 *Amplification of the probe signal through Brillouin interaction as a function of distance, showing the pump depletion due to forward Raman scattering. The apparent noisy response in the initial section is due to birefringence.*

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A straightforward estimation would show that the combined effect of self-phase modulation and dispersion, though able to distort shorter pulses, is negligible for pulses equal to or longer than 10 ns, what leaves the Raman effect as unique possible cause. Raman scattering[6] has fundamental similarities with Brillouin scattering, both resulting from the interaction between light and phonons, but it shows distinct features. The most noticeable difference is the frequency shift experienced by the scattered light (13 THz for Raman, 11 GHz for Brillouin scattering), but equally important are the cross section (two orders of magnitude smaller in the Raman case) and the direction of scattered light (forward Raman scattering being possible while only backward Brillouin scattering is allowed). This last property is the key feature that makes it possible to reach the Raman threshold despite its high value : the initial – or pump – pulse and the Raman-generated pulse being copropagative they may interact over long distance, and even the entire fiber length, unlike the case of Brillouin scattering where this interaction length is limited to the pump pulse width.
It has been shown[7] that the Raman power threshold is approximated by the expression

$$P_{Ra} = \frac{16 A_{eff}}{g_R z_{eff}} \ ,$$

where g_R is the Raman gain, $z_{eff} = \frac{1}{\alpha}\left(1 - e^{-\alpha z}\right)$ the usual effective distance depending on the absorption α, and A_{eff} the effective core area. The Raman threshold is represented as the dashed curve in *Fig. 2 (left)* for typical values at 1550 nm. The solid curves on the same graph show the required power for the measurement of the Brillouin amplification :

$$P_{Br} = \frac{\log(G) A_{eff}}{g_B L_p e^{-\alpha z}} \ .$$

Here g_B is the Brillouin gain, L_p the pulse length, and G the actual needed gain. G depends on the setup and is determined by the SNR at the detection. In this example, it has been set to 1.5 to be demonstrative. This value looks high at first glance, but is not far from reality for long-range measurement, mainly owing to the phase noise of the DFB laser source.

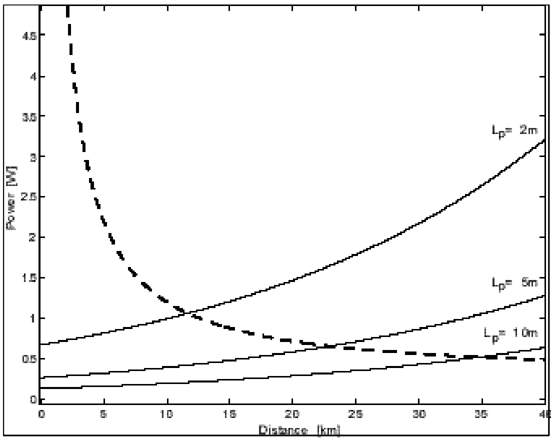

Fig. 2 Raman threshold power (dashed curve) and minimal required power for Brillouin sensing for different pulse lengths (solid curves). The parameter G (see text for explanation) is 1.5. For a fixed pulse length, the useful part of the graph lies under the dashed curve and over the solid one.

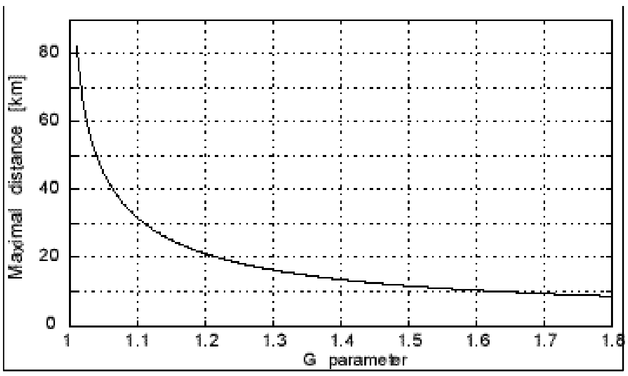

Fig. 3 Maximal measurement range as a function of the parameter G.

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The intersection of the dashed and solid curves corresponds to the maximal measurement range before pump depletion through Raman scattering takes place. The analytic expression of this distance, plotted in *Fig. 3* is

$$z_{\max} = -\frac{1}{\alpha}\log\left[\left(\frac{\alpha 16 g_B L_p}{\log(G) g_R}+1\right)^{-1}\right].$$

For a fixed resolution, the only way to increase this range is to lower the noise level so that a lower gain G is sufficient. For instance, a range of 50 km can be easily reached if the detection scheme is able to cope with a 2% (G=1.02) amplification.

So far, the pulsed nature of the pump and Raman lightwaves were not explicitly stated in the development. Actually, the expressions given above have been derived for the CW case; they are still valid, to a large extent, for pulses longer than 10 ns, as can be infered from their good agreement with the measurements, but they fail to explain the pulse distorsion resulting from Raman interaction. The additional quantity that has to be taken into account is the chromatic dispersion, which causes non-uniformities in the pulses evolution.
The propagation velocities of the pump and the Raman pulses differ from each other, owing to the large spectral distance between them (about 120 nm for a pump at 1550 nm). This difference actually ranges from 2 to 6 ns/km depending on the fiber. Since the relevant wavelengths lie in the anomalous dispersion regime, the pump pulse propagates faster than the Raman-generated wave signal. For very short pulses (L_p<5ns), this can lead to a prompt spatial separation of the pulses that quenches the Raman interaction between them. For longer pulses, such as those considered here, this walk-off is not entirely completed at the fiber end. But it results in pulse distorsions, as shown in *Fig. 4* : the leading edge of the pump pulse, being always ahead of the Raman pulse, undergoes only a negligible depletion due to spontaneous Raman scattering, while the rest of the pulse experiences the much more efficient stimulated Raman scattering made possible by the steady superposition of the two lightwaves. Consequently, the leading edge is the only part of the input pump pulse that remains unchanged if the fiber is long enough. The width of this unmodified part is related to both the difference in group velocities between the pump and Raman frequencies, and the intensity of the pump pulse, which sets the distance necessary to reach the Raman threshold. Eventually, the energy of the pump pulse is fully transfered to the Raman pulse, except in the narrow leading edge.

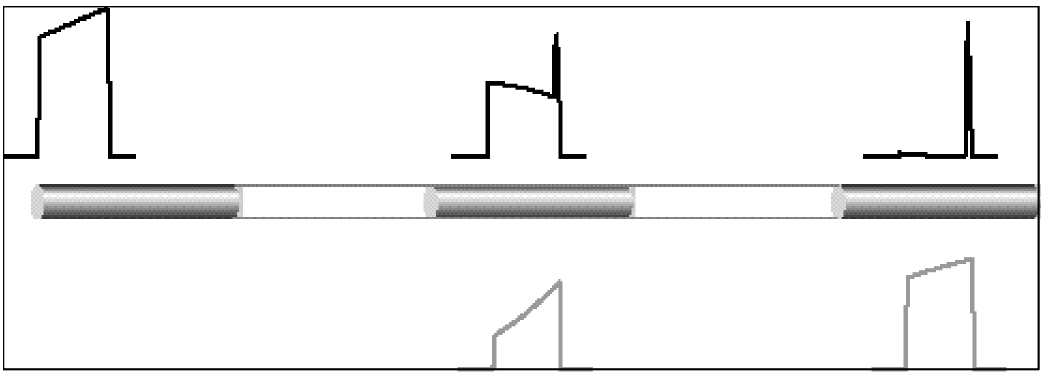

Fig. 4 Simulated evolution of pump (top) and Raman (bottom) pulses along a fiber, showing the effect of walk-off.

The *Fig. 5* presents a demonstrative measurement of this walk-off effect. At the end of a 25 km fiber, the 100 ns pump pulse at 1550 nm has been fully depleted and its energy transfered to the 1670 nm Raman pulse, except the leading 5 ns that remains unchanged.

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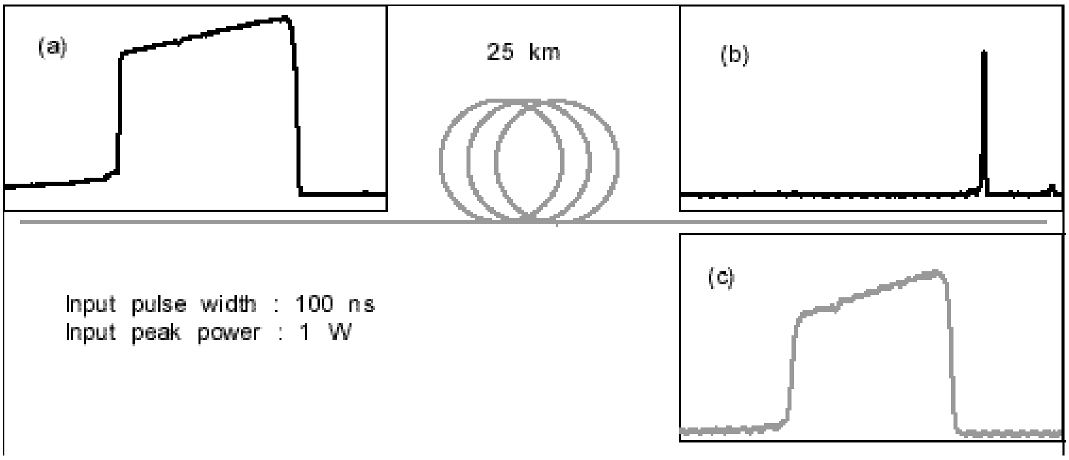

Fig. 5 Measured time-domain waveforms of (a) the input pump pulse at 1550 nm, (b) the corresponding output pulse at the same wavelength after propagation along a 25 km fiber, and (c) the pulse generated by Raman scattering at 1670 nm. The vertical scales are arbitrary.

One may think that advantage could be taken of this walk-off effect : all in all, it preserves short pulses from the depletion due to forward Raman scattering. From this point of view, fibers with high dispersion at the operation wavelength, like standard telecom fibers at 1550 nm, are more favourable than dispersion-shifted or other low-dispersion fibers
Unfortunately, in most cases, pulses short enough to avoid Raman scattering through walk-off effect turn out to be of no use in Brillouin sensing for reasons related to the physics of Brillouin scattering (spectral broadening). The only solution is then to limit the optical pump (see figure 2). As a rough estimate, this must be kept under 0.5 W for a 40 km measurement range. Consequently, the resulting Brillouin amplification G can be low, what requires a properly designed detection stage and an efficient reflection suppression to avoid any interference.

References

[1] T. Kurashima, T. Horigushi, M. Tateda, *"Distributed temperature sensing using stimulated Brillouin scattering in optical fibers"*, Opt. Lett., vol. **15**, pp 1038-1040, 1990.
[2] M. Niklès, L. Thévenaz, P. Robert, *"Simple distributed fiber sensor based on Brillouin gain spectrum analysis"*, Opt. Lett., vol. **21**, pp 758-760, 1996.
[3] M.Niklès, L.Thévenaz, P. Salina, Ph. Robert, *"Local analysis of stimulated Brillouin interaction in installed fiber optics cables"*, OFMC '96, NIST Special Publication 905, pp.111-114.
[4] L. Thévenaz *et al., "Evaluation of local birefringence along fibres using Brillouin analysis"*, OFMC'97, pp. 82-85.
[5] X. Bao *et al.*, *"Experimental and theoretical studies on a distributed temperature sensor based on Brillouin scattering"*, J. Lightwave Technol., vol. **13**, pp 1340-1348, 1995.
[6] G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed., Academic Press, 1995.
[7] R. G. Smith, *"Optical power handling capacity of low loss optical fiber fibers as determined by stimulated Raman and Brillouin scattering"*, Appl. Opt., vol. **11**, pp 2489-2494, 1972.

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