Detrimental effect of modulation instability on distributed optical fibre sensors using stimulated Brillouin scattering

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ABSTRACT

Modulation instability can limit the resolution and the range of distributed fibre sensors based on stimulated Brillouin scattering. In this paper we analyse this process and suggest adequate methods to overcome it.

Keywords: Modulation instability, stimulated Brillouin scattering, distributed measurements, optical fibre sensors

1. INTRODUCTION

Brillouin optical time-domain analysis (BOTDA) techniques are based on the stimulated flavour of Brillouin scattering to retrieve the local Brillouin spectrum along an optical fibre. They basically involve the use of two counterpropagating waves (so-called pump and probe) for which the frequency separation must be kept constant and close to the Brillouin shift (υ_B). The most straightforward method to obtain these two waves is through the modulation of the light from a single laser at υ_B[1],[2]. In the spectral domain this modulation process results in the appearance of one or more lateral bands beside the centre laser frequency, from which one sideband is used as Brillouin probe. This results in an ideal frequency stability between pump and probe waves.

The best spatial resolution and the longest range can be reached with high power pump pulses, but other nonlinear effects turn out to be no longer negligible in this case, such as Raman scattering[3] and modulation instability (MI). Taking into account that the fibres used for sensing usually present anomalous dispersion at the pump wavelength and that the peak power of the pump pulse reaches typically 200-300 mW, modulation instability turns out to be the principal limiting effect. This was recently accounted for in sensors based on spontaneous Brillouin scattering[4], as a result of the spectral self-broadening of the pump pulse. In the case of BOTDA sensors using stimulated Brillouin scattering, the effect of modulation instability is initiated entirely differently and is even more critical, since the probe wave strongly seeds the MI amplification process and this may lead to an energy transfer from pump to probe. This results in rapid pump depletion in the case of conventional SMFs.

In this paper we describe and analyse experimentally the effect of modulation instability in sensors based on stimulated Brillouin scattering and we point out adequate methods to overcome its deleterious effects.

2. MODULATION INSTABILITY

Modulation instability (MI) occurs in optical fibres as a result of the interaction between the 3rd order nonlinearity (Kerr effect) and the anomalous dispersion. This process leads to an instability of the CW or quasi-CW light which breaks-up into a periodic pulse train. Self-phase modulation (SPM) induces spectral broadening which acts as a probe in this situation and is amplified by the gain provided by the MI. As a consequence, sidebands appear in the spectrum and spread symmetrically around the initial frequency of the pulse.

The gain spectrum of MI can be calculated by solving the nonlinear Schrödinger equation and is given by[5]:

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$$G(\omega) = |\beta_2 \omega| \left(\omega_c^2 - \omega^2 \right)^{1/2} \qquad \text{with} \qquad \omega_c^2 = \frac{4\gamma P_0}{|\beta_2|} \tag{1}$$

where P_0 is the input power, β_2 is the fibre dispersion and γ is the nonlinear parameter.

The maximum gain occurs at two shifted frequencies given by:

$$\omega_{max} = \pm \frac{\omega_c}{\sqrt{2}} = \pm \left(\frac{2\gamma P_0}{|\beta_2|} \right)^{1/2} \tag{2}$$

and shows a value of $G(\omega) = 2\gamma P_0$, which is independent of the dispersion and increases linearly with the incident power. An evident effect of spontaneous MI is the creation of spectral lobes located symmetrically at $\pm\omega_{max}$ on both sides of the central frequency. In the time domain the CW or quasi-CW beam is converted into a periodic pulse train with a period is equal to $T = 2\pi / \omega_{max}$. Figure 1 shows the gain spectra calculated for several values of P_0 and Figure 2 shows a typical output pulse shape measured at the output of an 11.8 km fibre.

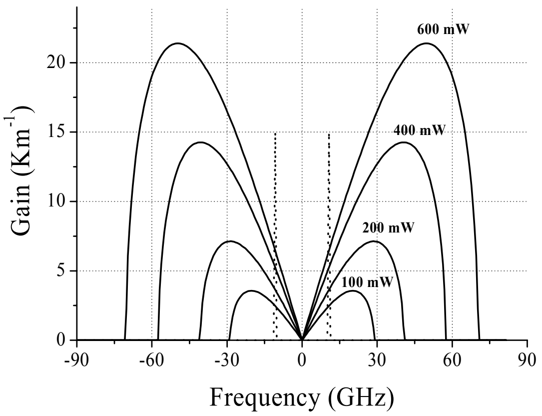

Fig. 1. Calculated gain spectra of MI for several power levels. The fibre parameters are β_2 = -21.9 ps^2 km^{-1} and γ = 1.78 W^{-1} km^{-1} at 1550 nm. Dotted lines indicate the position of modulated sidebands (at 10-11 GHz) for BOTDA sensing.

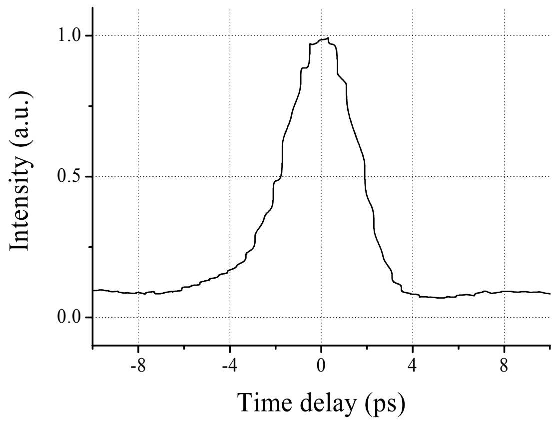

Fig. 2. Autocorrelation trace of 20-ns input pulses measured at the output of a 11.8 km long fibre, showing the breaking into a 4 ps soliton-like pulse resulting from modulation instability. The input peak power was 300 mW.

MI can be conveniently interpreted in the spectral domain as resulting from an energy transfer between the fundamental mode constituting the initial continuous wave and high-order modes. It would, however, not lead to a thermalisation of energy. Several theoretical studies have shown that after a definite propagation length the energy that spreads to different frequencies eventually returns to the initial mode. This reversible behaviour of MI is known as the Fermi-Pasta-Ulam (FPU) recurrence[6],[7].

When standard single mode fibres are used in the context of BOTDA techniques, the lateral bands (situated at $\pm\upsilon_B$ = 10–11 GHz) can strongly seed the MI process resulting in a significant pump depletion (up to 100%), which makes distributed measurements actually no longer possible. It turns out that in that case the FPU phenomenon can limit the amount of pump depletion.

3. DESCRIPTION OF THE EXPERIMENT

The experimental configuration used for our investigations on MI is schematically shown in Figure 3. The source was a distributed feedback laser operating at 1550 nm, co-integrated with an electro-absorption modulator (EAM). The modulator was driven by an RF generator in order to generate sidebands at the Brillouin frequencies. The CW light was

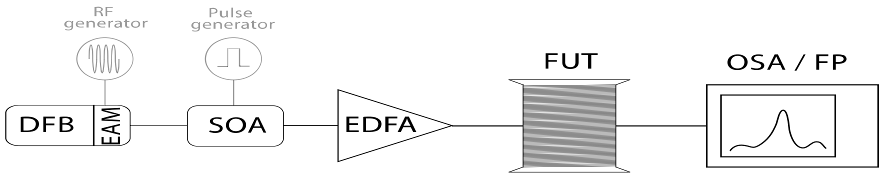

Fig. 3. Experimental configuration. DFB: laser diode; SOA: semiconductor optical amplifier; EDFA: erbium-doped amplifier; FUT: fibre under test; OSA: optical spectrum analyser; FP: Fabry-Perot analyser.

gated through a semiconductor optical amplifier (SOA) driven by a pulse generator and then amplified using an erbium-doped fibre amplifier (EDFA). A 20 ns pulse was used and the peak power was varied from 150 to 650 mW.

We investigated and compared the effects of MI on two different fibres, respectively a SMF in the anomalous dispersion region (β_2 = -21.92 ps^2/km) and a DSF fibre in the normal dispersion region (β_2 = +7.65 ps^2/km).

First the power spectrum of spontaneous MI (without the modulation of the laser) was measured on an optical spectrum analyser for both fibres as a function of the input pulse power. Then the laser was modulated and the amplification of the sidebands at the output of the fibres was measured on a Fabry-Perot analyser as a function of the input pulse power.

4. RESULTS

Figures 4 and 5 show the power spectra of spontaneous MI measured at the output of the fibres as a function of several launched peak powers.

In the case of the SMF (Fig. 4) the effect of the MI becomes stronger as the power increases. The sidebands, which appear symmetrically on both sides of central frequency, become broader and a significant amount of pump depletion is observed. In the case of the DSF (Fig. 5) the MI does not manifest itself according to theory: the power spectrum shape stays unchanged. The pump depletion observed for high powers is due to Raman scattering[3] present at 1660 nm.

To evaluate the MI effect existing in a standard SMF on the modulated laser, we measured the intensity of the sidebands at the output of an 11.8 km fibre and we normalised it by the intensity of the central pump frequency. Figure 6 shows the amplification of the right- and left-sidebands as a function of the input power. As shown, the sidebands drastically increase along with power; it turns out that for powers above 400-500 mW sidebands are even greater than the depleted pump. With such a strong depletion distributed measurements based on BOTDA techniques are definitely no longer possible.

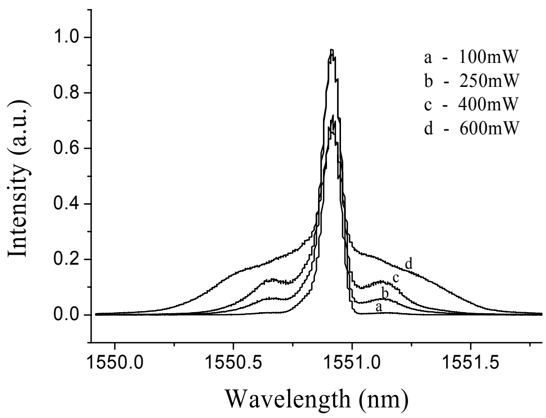

Fig. 4. Measured power spectra of spontaneous MI for a SMF in the anomalous dispersion region (β_2 <0). The input lightwave was a 20 ns pulse and the fibre was 11.8 km long.

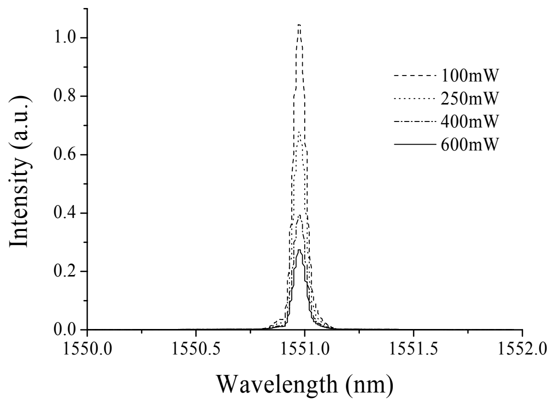

Fig. 5. Measured power spectra of spontaneous MI for a DSF in the normal dispersion region (β_2 >0). The input lightwave was a 20 ns pulse and the fibre was 3.5 km long.

There is a significant difference in the amplification of the right- and left-sidebands. This is possibly partially due to the Raman scattering which can induce some asymmetry in the spectrum. This can also be considered as the consequence of the asymmetry in the EAM characteristics. Anyway, we suppose that the pseudo-oscillation present on the right-sideband curve may be due to FPU recurrence. Several Fourier-modes (situated at multiples of the modulation frequency) appear on the spectrum and are amplified by the MI process. The energy is then distributed from pump to all the other modes, but for certain values of the input power this energy is partially fed back to the pump, recovering the depletion. This could explain why the pump does not reach a complete depletion using higher powers. Further investigations have to be done to confirm these results.

SMFs seems to be inappropriate at high powers in the context of BOTDA techniques to achieve high resolutions and range – in a similar way to techniques based on spontaneous Brillouin scattering as described in a previous work[4].

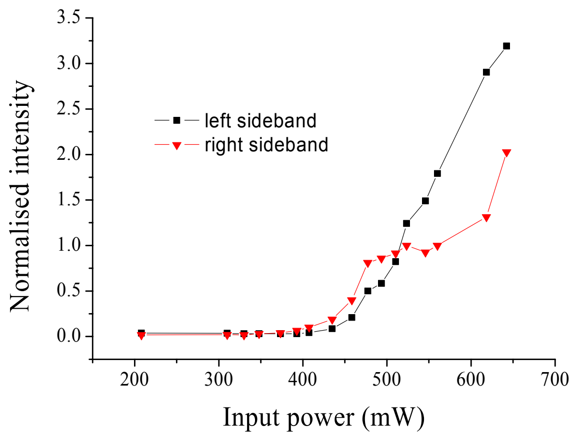

Fig. 6. Sidebands amplification due to MI in a SMF. The ratios of the sidebands intensity over the pump intensity are reported as a function of the input power.

5. CONCLUSION

In this paper we investigated the undesirable effects of modulation instability in stimulated-Brillouin-based sensors. Our aim was to understand the pump depletion occurring in BOTDA sensors in the case of high pulse power operations. It turns out that the probe wave lying within the gain spectrum of MI - generated by the pump pulse - are amplified along a fibre showing anomalous dispersion at the detriment of the pump power. Unlike sensors based on spontaneous scattering the pump spectral broadening is not the first manifestation of MI. The depletion can reach 100% for certain values of the power. At first glance MI may look more limitative in BOTDA, but actually it is not the case, since such systems require a lower pump power to observe Brillouin gain thanks to the stimulated process. We observed that the amplification of the left- and right-sidebands does not follow the same behaviour, partially as a result of Raman scattering, but more realistically to the reversibility of energy occurring in nonlinear systems (FPU recurrence).

To overcome the pump depletion due to MI, one solution consists in using single mode fibres exhibiting normal dispersion: in that case, we were not able to observe any appreciable changes in the sidebands intensity. One other solution could consist in substituting the intensity modulation by a phase modulation: ideally the presence of strong ripples due to SPM seeding the MI process would be avoided: further experiments has to be done to verify if the phase modulation is not converted into an intensity modulation due to propagation in a dispersive fibre.

Possible compensation of MI errors in distributed measurements (temperature and strain) would be possible, unless the FPU recurrence is not present. Further investigations are going to be done to study the reversibility of the energy transfer between pump and other spectral components and its impact on BOTDA-based sensors.

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