OTDR technique for the characterization of FWM processes in optical fibers

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Thanks to a multi-wavelengths optical time domain reflectometric technique, we have experimentally demonstrated how the parametric amplification and oscillation regimes can be discriminated in degenerate four-wave mixing processes in optical fibers. With systematic measurements, we have shown how the dynamics is conditioned by the relative amount of phase-mismatch induced by the chromatic dispersion and the phase shift generated by the Kerr nonlinearity of the medium. We also show how it depends on the dispersion regime in good agreement with the theory. Numerical simulations have also been performed and demonstrated qualitative agreement with the experiments and improved their interpretation.

Introduction

Four-wave mixing (FWM) is an important consequence of the Kerr effect, *i.e.* the dependence of the refractive index on the optical intensity. It has been numerically predicted that FWM can induce parametric amplification and depletion or oscillations depending on the dispersion condition [1]. In this paper, we determine theoretically the boundary between these two regimes. An experimental method enabling the study of this phenomenon is also proposed and applied to characterizing the FWM processes in optical fibers. It is based on an optical time domain reflectometry (OTDR) technique that allows accessing the power evolution of the light along optical fibers by measuring, with respect to time, the Rayleigh backscattered power coming from optical pulses.

Theory

Let us consider four optical waves denoted from 1 to 4 with waves 1 and 2 being much more powerful than 3 and 4 so that they can be assumed constant [2]. In these conditions, the evolution of the slowly varying envelope B of the wave 3 can be described by :

$$\frac{\mathrm{d}^2 B_3}{\mathrm{d}z^2} + i\kappa\frac{\mathrm{d}B_3}{\mathrm{d}z} - 4\gamma^2 P_1 P_2 B_3 = 0 \qquad (1)$$

where P_1 and P_2 are the powers of waves 1 and 2 respectively, γ is the nonlinear coefficient of the transmission medium and

$$\kappa = \Delta k + \gamma(P_1 + P_2) \qquad (2)$$

with the wave number mismatch given by

$$\begin{aligned}\Delta k &= k_3 + k_4 - k_1 - k_2 \\ &= (n_3\omega_3 + n_4\omega_4 - n_1\omega_1 - n_2\omega_2)/c\end{aligned} \quad (3)$$

Solving equation (1) leads to two families of solution according to the condition:

$$(\kappa/2)^2 < 4\gamma^2 P_1 P_2 \quad (4)$$

If this condition is satisfied, the solution is exponential and we have thus an amplification/depletion regime. Otherwise we face an oscillatory solution.
If we consider the specific case of degenerate four-wave mixing where waves 1 and 2 being merged with $P_1= P_2 =P_0$, one finds that the condition becomes:

$$-6\gamma P_0 < \Delta k < 2\gamma P_0 \quad (5)$$

so that the kind of solution depends on the relative amount of nonlinearity and dispersion since for small wavelength difference one has

$$\Delta k = -2\pi c \frac{\Delta\lambda^2}{\lambda^2} D(\lambda_P) \quad (6)$$

where D is the chromatic dispersion coefficient. The boundary is also determined by the sign of the dispersion and so by the dispersion regime.

Experimental set-up

Our experimental set-up [3], shown on figure 1, is based on a commercial OTDR that output signal is directed to a photodetector through a circulator. The resulting electrical signal is used to drive an acousto-optic modulator (AOM) via a pulse generator. This AOM modulates two external cavity tunable lasers source (ECL) that are coupled together with the use of a 3 dB coupler. Pulses are launched into the fiber through a second circulator and are then continuously Rayleigh backscattered when they propagate down the fiber. The circulators then direct the backscattered signal to the OTDR detector. A tunable band-pass filter is placed between the two circulators in order to select one wavelength at a time. Amplification is provided using an erbium doped fiber amplifier (EDFA) with +23 dBm output power. In order to prohibit stimulated Brillouin scattering (SBS) that would limit the propagating power inside the fiber, cross-phase-modulation of the sources is provided thanks to a Raman fiber amplifier (RFA) to broaden their spectrum [6].

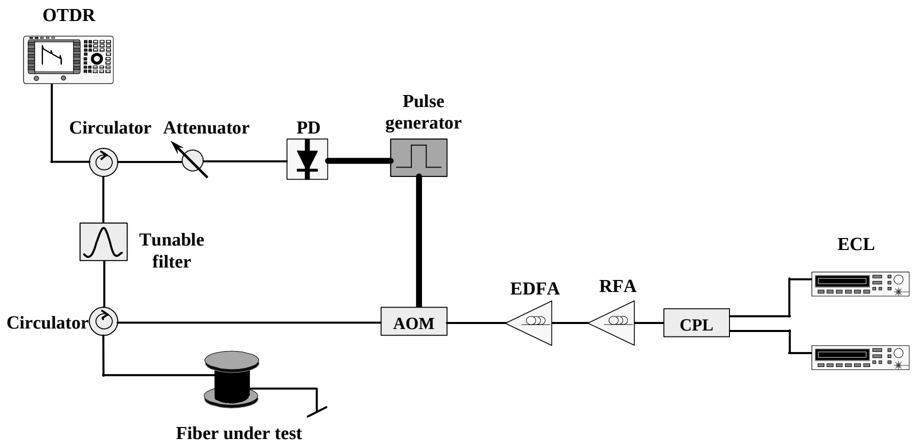

Fig 1 Experimental set-up

Results and Discussion

We performed measurements on a dispersion-shifted fiber (DSF) that has its zero-dispersion wavelength near 1550 nm. Figure 2 and 3 (a-c) shows spectra recorded at the input (solid) and at the output (dashed) of the fiber with an optical spectrum analyzer for different wavelengths spacing in the normal and the anomalous dispersion regime respectively. We can see that, beside the two lines of the ECLs denoted 1 and 2, two others denoted S and A the Stokes and anti-Stokes waves respectively are generated through FWM inside the EDFA.

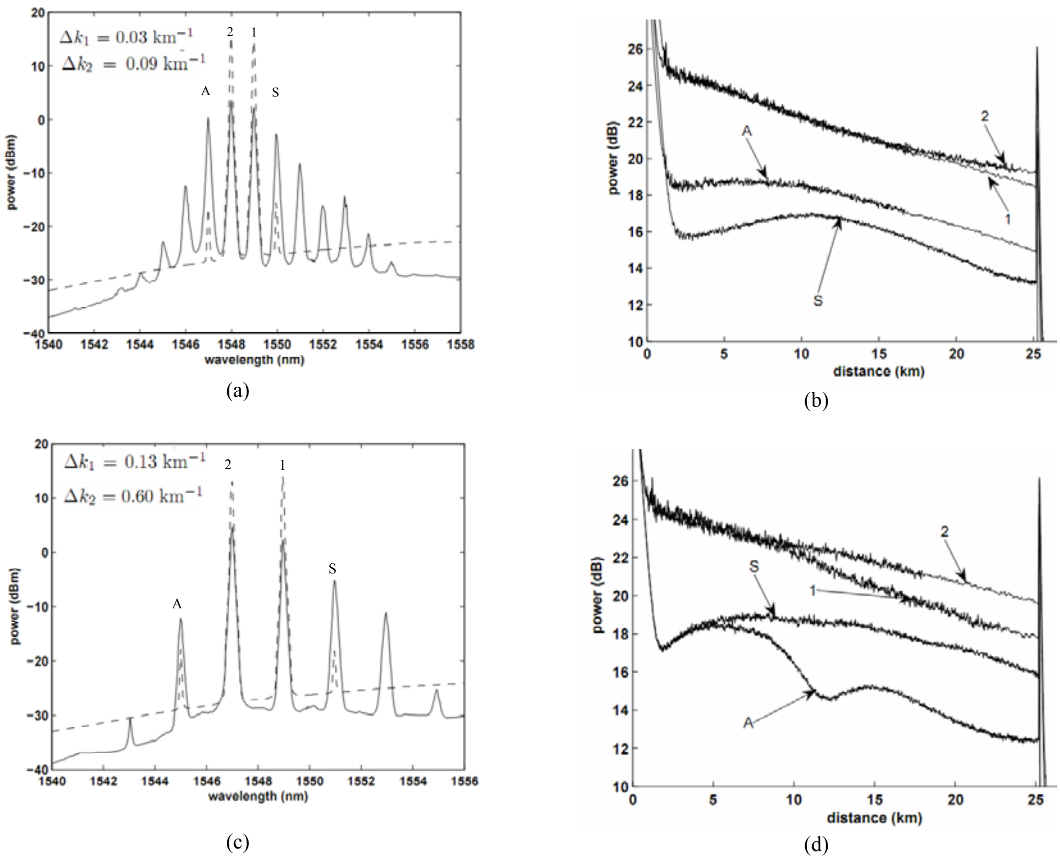

Fig 2 spectral (a-c) and spatial (b-d) distribution of the power for pumps in the normal dispersion regime for a wavelength spacing of 1 (a-b) and 2 (c-d) nm between them.

The corresponding spatial distributions of the power along the fiber are illustrated in Figure 2 and 3 (b-d).

The power for pumps was 30 mW and the nonlinear coefficient 2 km^{-1}W^{-1} so that $2\gamma P_0$=0.132 km^{-1} and $-6\gamma P_0$=-0.4 km^{-1}. By comparing with the values of the wave numbers mismatch provided inset, one can see that condition (5) is well corroborated by the experimental datas. For 1 nm spacing both in normal and anomalous dispersion, Δk is well below the boundary and thus A and S undergo amplification. For higher spacing giving absolute wave number mismatches higher than the boundary, A and S are in the oscillation regime.

Numerical integration of the nonlinear Schrodinger equation that rules nonlinear propagation has been performed with the split-step Fourier method [2] and show good agreement with the experiment [5].

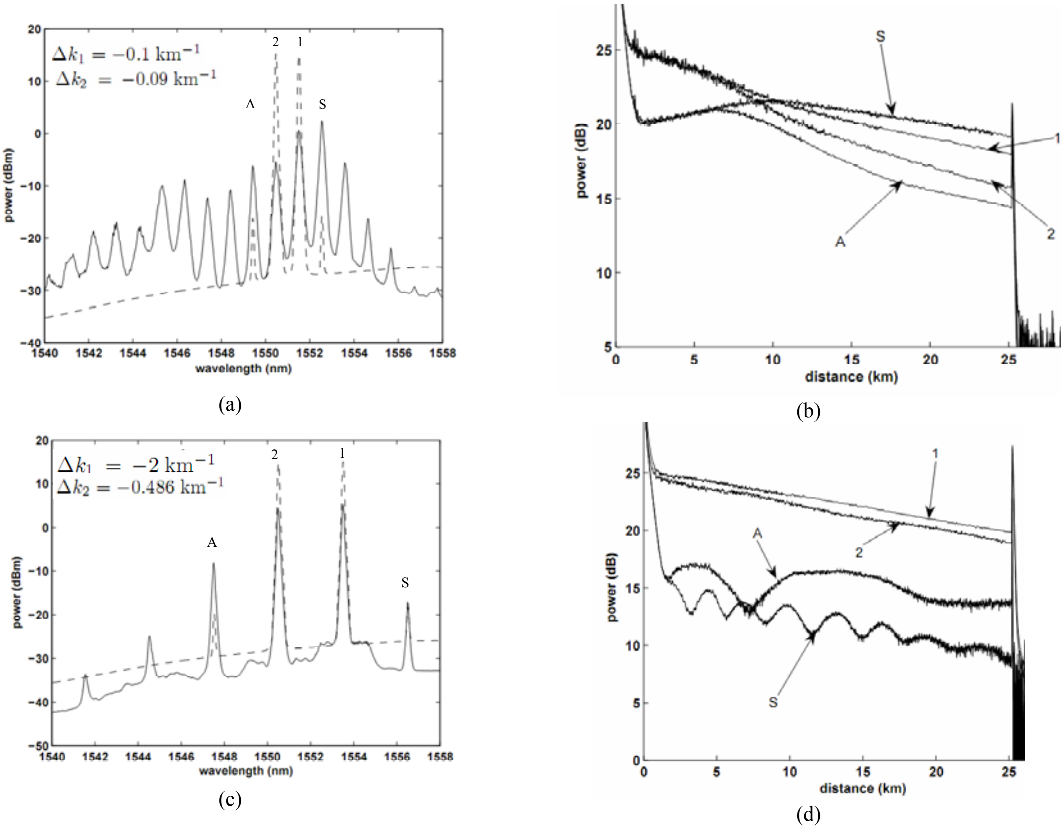

Fig 3 spectral (a-c) and spatial (b-d) distribution of the power for pumps in the anomalous dispersion regime for a wavelength spacing of 1 (a-b) and 3 (c-d) nm between them.

Conclusions

We have demonstrated a new kind of reflectometry technique for the characterization of FWM phenomena in optical fibers. It is based on a multi-wavelength tunable OTDR. Measurements confirm that the nature of the FWM process being either amplifying or oscillating depends on the amount of dispersion and on the dispersion regime.

Acknowledgements

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References

[1] F. Vanholsbeeck et al., "Dynamics of stimulated Raman scattering and four-wave mixing process in WDM systems", in Proceedings of the Optical Amplifiers and their Applications Conference, 2001, OTuE18.

[2] G. P. Agrawal, Non-linear fiber optics 3rd ed., Academic Press, 2001.

[3] M. Wuilpart et al., "Distributed measurement of Raman gain spectrum in concatenation of optical fibres with OTDR", IEE Electronics Letters Vol. 39, 2003, pp88-89.

[4] G. Ravet et al., "Suppression of Stimulated Brillouin scattering with a Raman Fiber Amplifier", in Proceedings of the IEEE/LEOS Benelux Chapter Conference, 2004, pp. 199-202.

[5] G. Ravet ,"Linear and non linear effects in Raman fiber amplifiers and lasers", Ph. D. Thesis, Faculté Polytechnique de Mons, 2007.