Distributed measurement of nonlinear interactions in WDM systems

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We describe the implementation of an optical time domain reflectometry technique to characterize the power exchanges between wavelength division multiplexed (WDM) channels in single-mode optical fibers. Thanks to this non-destructive method, we have observed the interplay between four-wave mixing and stimulated Raman scattering and how these effects are distributed along the fiber. Comparison between experiment and numerical simulations has shown that the longitudinal variations of the chromatic dispersion coefficient of the fiber critically affect this dynamics. Our measurement technique can be useful to predict the impact of the fiber nonlinearities on WDM telecommunication systems.

Introduction

With the requirement of still higher capacity, wavelength division multiplexing (WDM) in optical fiber transmission system has proven to be a very efficient technique to increase the bandwidth. By simply coupling together in a single optical fiber several source at different wavelength it is possible to multiply the bandwidth by the number of channel. With the recent progress made in the optical amplifiers required in long haul transmission system, the power of channels can be higher than in the past. Due to high confinement, the optical fiber can enhance the nonlinearities inside the core provoking interaction between the different wavelengths. Indeed, crosstalk between the channels in high power WDM systems has become a crude impairment.

We describe here the implementation of a multi-wavelengths optical time domain reflectometry (OTDR) technique to measure the power exchanges between the different channels of WDM transmission system.

Principle

If we couple OTDR-like pulses at different wavelengths, those will interact together through various nonlinear effects such as stimulated Raman scattering and four-wave mixing. Thanks to Rayleigh backscattering it is possible to follow the evolution of the power of each wavelength along the fiber.

One can show that [1]:

$$P_{NL} = \varepsilon_0 \chi_K^{(3)} E(t)E(t)E(t) + \varepsilon_0 E(t) \int_{-\infty}^{t} \chi_R^{(3)}(t-t')E(t')E(t')dt' \qquad (1)$$

$$\frac{\partial P_j(z,t)}{\partial z} = -2\gamma_j \sum_{k,l,m=1}^{N} \left[\Re\left(H_{jklm}\right)\cos(\theta) + \Im\left(H_{jklm}\right)\sin(\theta) \right] \sqrt{P_j P_k P_l P_m} - \alpha P_j \qquad (2)$$

where first terms are related to optical Kerr effect and second term are related to Raman scattering effect. $\Re$ and $\Im$ denote real and imaginary parts, P_j is the optical power of channel j, χ_R is the Raman susceptibility ,χ_K is the Kerr susceptibility, θ is the phase mismatch α is the linear attenuation γ is the nonlinear coefficient and:

$$H_{jklm} = \eta_{jkl} \frac{\varepsilon_{jjjj}}{\varepsilon_{jklm}} \tag{3}$$

$$\begin{aligned} \eta_{jjk} &= \varepsilon_0 \left(3\chi_K / 4 + \chi_R(\omega_j - \omega_k)\right) \\ \eta_{jkl} &= \varepsilon_0 \left(3\chi_K / 2 + \chi_R(\omega_k - \omega_l) + \chi_R(\omega_j - \omega_l)\right) \end{aligned} \tag{4}$$

$$\begin{aligned} \theta &= -\Delta k.z + \varphi_k + \varphi_l - \varphi_m - \varphi_j \\ \Delta k &= k_k + k_l - k_m - k_j \end{aligned} \tag{5}$$

k is the wave number φ_j is the optical phase of channel j, ε_0 is the dielectric constant of vacuum.

Experimental set-up

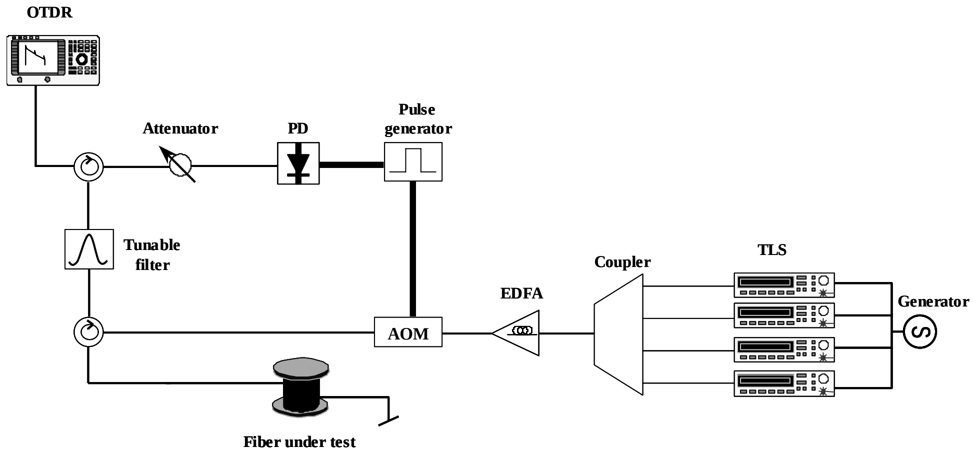

Fig 1: *Experimental set-up*

Our experimental set-up, shown on figure 1, is derived from the proposed one described in [7]. It based on a commercial OTDR whom signal is directed to a PIN photodiode through a circulator. The modulation is trigged by a pulse generator, which drives an acousto-optic modulator (AOM). This AOM modulates four external cavity tunable lasers source (TLS) that are coupled together with the use of a 6 dB coupler. So four narrow lasing lines of the ECL replace the classical OTDR spectrum. In order to have enough power so that the wavelengths interact through nonlinear effects, we need to amplify them. This is done thanks to a high power EDFA with 23 dBm output power. The nonlinear effect with the lowest threshold is stimulated Brillouin scattering (SBS). The result of SBS is the limitation of the optical power that can propagate along the fiber. This one is generally suppressed with the use of a phase modulator. As we are not interested in the study of SBS that appears in a mono-wavelength context we will prohibit it by spectral broadening of the source thanks to a slight direct modulation of the ECLs with an electrical generator. As we use a narrow linewidth lasers, we see the apparition of a coherence noise due to the interferences between components of the pulses arriving at the same time at the detector [7]. The spectral broadening of the sources also reduces that noise. The backscattered signal is directed by the circulators to the OTDR. A tunable band-pass filter is placed between the two circulators to select each wavelength at its turn.

Results

We performed measurement with our new experimental set-up on a dispersion shifted fiber (DSF)

Figure 2 shows spectra at the input and at the output of the fiber. We can see that there is already FWM inside the EDFA. Indeed, EDF have usually a smaller core than classical SMF in order to have a cut–off wavelength below 980nm, which is the common pumping wavelength for EDFA. We can see that the line at 1553 nm is more amplified that the one at 1548 nm. Indeed, it becomes comparable with the injected wavelength. This is due to a cooperative process between FWM and SRS. One can show [4] that this process critically depends on the variation of the zero–dispersion wavelength of the DSF along the all length.

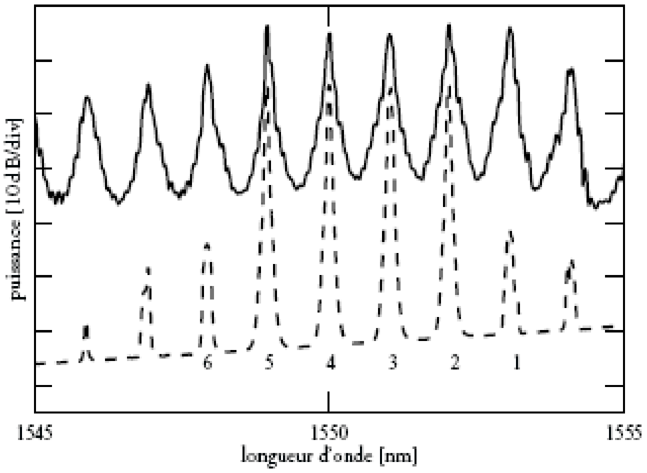

Fig.2: *Spectra of input (dashed line) and output (solid line) power. One can notice the increase of the power ratio between the channel n°1 at 1553 nm and n°2-5. Power ratio of channel n°6 also increase but less because of SRS.*

Figure 3 shows the power distribution along the fiber for the different wavelength. Thanks to our technique, we can follow the amplification of the 1553 nm wavelength due to the parametric gain.

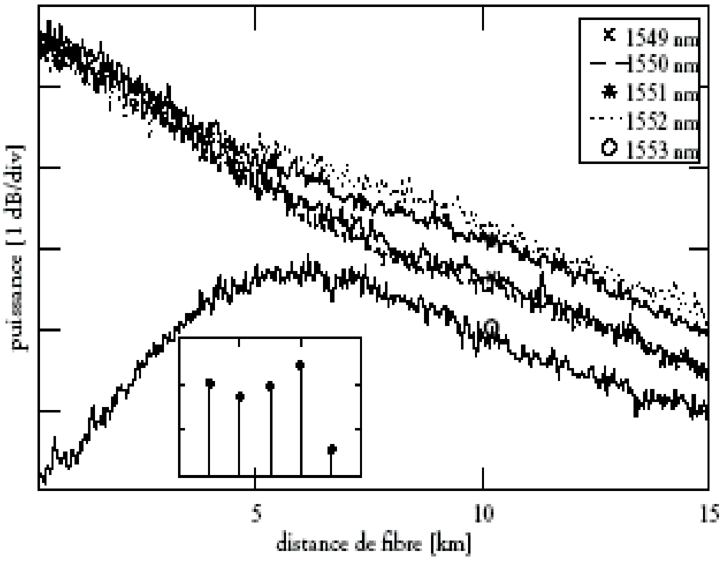

Fig 3: *Measurement of the distribution of the power between the channels*

Conclusions

We demonstrated a multi-wavelength tunable reflectometric method to predict spectral performance of WDM systems. We have emphasized the applicability of this method to the study of the various interactions between several WDM channels due to nonlinear effects. In particular SRS and FWM.

Acknowledgements

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