Distributed measurement of parametric oscillations in WDM systems

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We describe the implementation of an optical time domain reflectometry technique to characterize the power evolution of wavelength division multiplexed (WDM) channels in single-mode optical fibers. Thanks to this non-destructive method, we have observed the parametric oscillations due to four-wave mixing and how the power exchanges are distributed along the fiber. Comparison of the agreement between experiment and numerical simulation based on both coupled mode equations and nonlinear Schrödinger equation is also provided. As the period of the oscillation partially depends on the fiber dispersion, our technique is promising for its determination along the fiber length.

Introduction

In today's optical telecommunication system with still higher demand in capacity, wavelength division multiplexing (WDM) has proven to be a very efficient technique to increase the bandwidth. By simply coupling together in a single optical fiber several sources at various wavelengths, it is possible to multiply the capacity by the number of channels. While optical amplification is making progress every day in order to meet the requirement of long haul transmission systems, the power of channels can be higher and higher. The optical fibers can exhibit high optical nonlinearities inside their core due to the high confinement that light undergoes while being guided, leading to interactions between the different wavelengths. Because of the crosstalk between the channels in those high power WDM transmission systems, this has become a limiting impairment.

In a previous paper [1], we have demonstrated the implementation of a new multi-wavelengths optical time domain reflectometric (OTDR) experimental set-up that enables the distributed measurement the nonlinear interactions between several WDM channels inside an optical fiber. The measurement of parametric amplification of a channel was provided and so were numerical simulations generated with the coupled modes model (CMM) giving account for it.

In this report, we show how to enhance the set-up so that we can highlight other physical phenomena such as the parametric oscillations generated by the interplay between the nonlinear Kerr effects and the dispersion of the fiber that were predicted in [2] by the CMM. Indeed, these two features induce the four-wave mixing of the channels that propagate along the fiber through phase-matched power exchanges requiring both good chromatic dispersion and optical power conditions.

Principle

If we couple powerful OTDR-like pulses at different wavelengths in a fiber, those will interact together through various nonlinear effects such as stimulated Raman scattering (SRS) and four-wave mixing (FWM). Thanks to Rayleigh backscattering it is possible to follow the evolution of the power at each wavelength along the fiber. One can show that the power evolution of the channels of a WDM system can be either modeled by [2]:

$$P_{NL} = \varepsilon_0 \chi_K^{(3)} E^3(t) + \varepsilon_0 E(t) \int_{-\infty}^{t} \chi_R^{(3)}(t-t') E^2(t') dt' \tag{1}$$

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

where P_{NL} is the nonlinear polarization, $\Re$ and $\Im$ denote real and imaginary parts, P_j is the optical power of channel j, $\chi_R^{(3)}$ and $\chi_K^{(3)}$ are respectively the Raman and Kerr susceptibilities, θ is the phase mismatch, α is the linear attenuation coefficient, γ is the nonlinear coefficient and:

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

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

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

where k is the wave number, φ_j is the optical phase of channel j, ε_0 is the dielectric constant in a vacuum. In equation (1) and (2), the first term is related to optical Kerr effect and its consequences such as FWM, self- and cross-phase modulation and the second term is related to SRS effects. The other way to model such kind of nonlinear interactions can be made through the generalized nonlinear Schrödinger equation (GNLSE) :

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} - \frac{\beta_3}{6} \frac{\partial^3 A}{\partial t^3} = i\gamma \left(1 + \frac{i}{\omega_0} \frac{\partial}{\partial t} \right) \left(A(z,t). \int_{-\infty}^{+\infty} R(t') \left| A(z, t-t') \right|^2 dt' \right) \tag{7}$$

$$g_R(\Delta\omega) = \frac{\omega_0}{c n_0} f_R \chi^{(3)} \, \mathrm{Im}[\tilde{h}_R(\Delta\omega)] \tag{8}$$

$$h_R(t) = \frac{\tau_1^2 + \tau_2^2}{\tau_1 \tau_2^2} \exp(-t/\tau_2) \sin(t/\tau_1) \tag{9}$$

where A(z,t) is the amplitude the slowly varying envelope of the electric field [5].

Experimental set-up and results

Our experimental set-up, shown on figure 1, was initially derived from the set-up proposed in [3,4]. It based on a commercial OTDR whom output signal is directed to a PIN photodiode through a circulator. The resulting electrical signal is used to drive an acousto-optic modulator (AOM) via a pulse generator. This AOM modulates four external cavity tunable lasers source (TLS) that are coupled together with the use of a 3 dB coupler. Consequently the narrow lasing lines of the four ECL replace the classical OTDR broadband source. 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. As an ECL is less powerful than a classical OTDR source, we need to amplify the lasers in order to have enough power to detect the backscattered signal. This amplification is provided using a high power erbium doped fiber amplifier (EDFA) with +23 dBm output power. As we use narrow linewidth lasers, we see the appearance of a coherence noise due to the interferences between components of the pulses arriving at the same time at the OTDR detector [4]. 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. This spectral broadening of the sources also reduces the coherence noise.

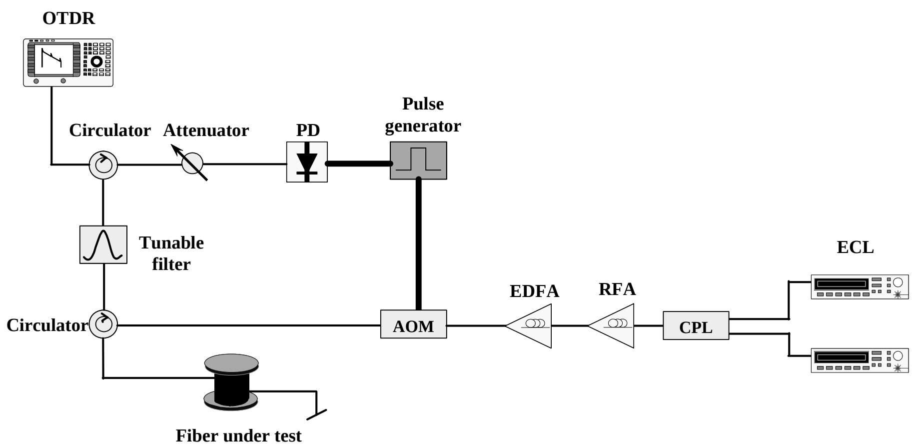

Fig 1 Experimental set-up

We performed measurements with our experimental set-up on a dispersion-shifted fiber (DSF) that has its zero-dispersion wavelength near 1550 nm. Figure 2 shows spectra recorded at the input and at the output of the fiber with an optical spectrum analyzer. We can see that, beside the two lines of the TLS, two others are generated through FWM inside the EDFA. The newly generated wavelengths are nearly equally spaced 1 nm apart. On figure 2, we denote n°1–6, the six channels around 1550 nm from highest to lowest wavelength, n°2–5 being the four wavelengths et the input of the fiber. After propagation inside the fiber, there has been a power exchange between wavelength n°2–5 and n°1 and 6 that were generated from the EDFA ASE noise through FWM.

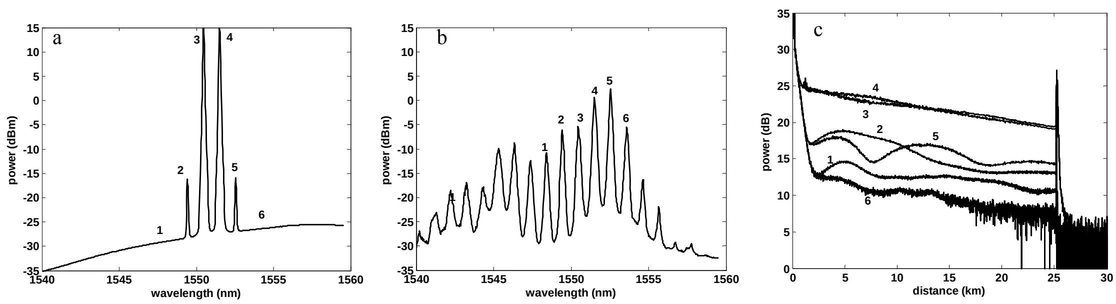

Fig 2 (a) Input spectrum, (b) output spectrum, (c) distribution of the power of channels 1-6

Thanks to our modified OTDR, we could measure the power distribution along the fiber for the different wavelengths. Results are presented on figure 2.
Numerical simulations based on both equations (2) and (7) were performed. Results are presented on figure 4. Comparing to the experiment, one can notice that qualitative behaviors could be reproduced. However, the simulations exhibit some disagreement with our measurement. This can be explained by the fact that we did not take the zero-dispersion wavelength variation along the fiber into account [7].

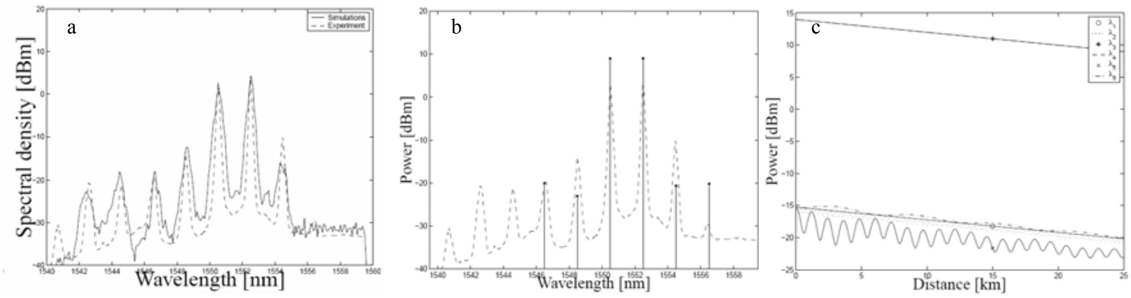

Fig 3 (a) Spectrum produced by simulation of GNLSE, (b) spectrum produced by simulation of the CMM, (c) distribution of the power produced by simulation of the CMM

Conclusions

We have demonstrated a new kind of reflectometry technique for WDM systems characterization. It is based on a multi-wavelength tunable OTDR. This method can be useful to characterize nonlinear effects in WDM systems. We have emphasized the applicability of this method to the study of the interactions between several channels leading to parametric oscillations due to FWM.

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