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 increasing demand of capacity in optical telecommunication system, 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. With the recent progress made in optical amplification in order to meet the requirement of long haul transmission systems, the power of channels can be higher than in the past. Due to high confinement, the optical fiber can enhance nonlinearities inside the fiber core leading to interactions between the different wavelengths. The crosstalk between the channels in high power WDM transmission systems has become a limiting impairment. We describe here the implementation of a multi-wavelengths optical time domain reflectometry (OTDR) technique to measure the power exchanges due to nonlinearities between the channels of WDM systems.

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 modeled by [1]:

$$P_{NL} = \varepsilon_0 k^{(3)}E^3(t) + \varepsilon_0 E(t) \int_{-\infty}^t \chi^{(3)}_R(t-t')E^2(t')dt'$$

(1)

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

(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, $\theta$ is the phase mismatch, $\alpha$ is the linear attenuation coefficient, $\gamma$ is the nonlinear coefficient and:

$$H_{jklm} = \eta_{jkl} \frac{\varepsilon_{ijij}}{\varepsilon_{jklm}}$$

$$\eta_{jkl} = \varepsilon_0 \left( 3 \chi_K^{(3)} / 4 + \chi_r^{(3)} (\omega_j - \omega_k) \right)$$

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

$$\theta = -\Delta k \cdot z + \phi_k + \phi_l - \phi_m - \phi_j$$

$$\Delta k = k_k + k_l - k_m - k_j$$

where $k$ is the wave number, $\phi_j$ is the optical phase of channel $j$, $\varepsilon_0$ 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; the second term is related to SRS effects. Our experimental set-up described below allows comparing this theoretical model with the experience.

**Experimental set-up**

![Multi-wavelength OTDR set-up for nonlinear interaction measurement in WDM systems](image)

Our experimental set-up, shown on figure 1, is derived from the set-up proposed in references [2,3]. 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 6 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, a direct modulation of the sources is applied to broaden their spectrum. This spectral broadening of the sources also reduces the coherence noise.

**Results**

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 four lines of the TLS, several 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 more powerful wavelengths from highest to lowest, n°2–5 being the four wavelengths of the TLS. After propagation inside the fiber, there has been a power exchange between wavelength n°2–5 and n°1 and 6 that were amplified through FWM. We can see that the line n°1 at 1553 nm is more amplified that the symmetric one n°6 at 1548 nm. Wavelength n°1 becomes nearly as powerful as the wavelength n°2–5. This is due to the interaction through SRS who amplifies longer wavelengths and depletes lower ones. One can show by numerical simulations [5] that this process critically depends on the variation of the zero-dispersion wavelength of the DSF along its length.

Thanks to our modified OTDR we could measure the power distribution along the fiber for the different wavelengths. Our technique allows us to follow the amplification of the wavelength n°1 due to the nonlinear interactions. Results are presented on figure 3. We can see that the interaction occurs during the first ~6 km. After this distance the attenuation becomes predominant. Wavelength n°6 was under the detection threshold of the OTDR.

Numerical simulations based on equation (2) 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 [6]. The comparison between simulations performed for slightly different values of the second order dispersion $\beta_2$ at 1550 nm is shown on fig. 4 (a) and (b). Results are pretty different what highlights the importance of that parameter for simulation purpose. Measurements of the zero-dispersion wavelength performed on different lengths of the fiber under test gave a difference up to 2 nm. This means that taking into account the variation of $\beta_2$ is relevant in our case.

Figure 4: Numerical simulations for different values of $\beta_2$. Insets show the output power of the various channels.

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 various interactions between several channels due to nonlinear effects, in particular SRS and FWM.

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References