Measurement of the distributed Raman Gain spectrum in single-mode optical fibers

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We describe the implementation of a wavelength tunable optical time domain reflectometry technique to characterize C-band Raman fiber amplifiers. Thanks to this non-destructive method we have characterized the distributed Raman on-off gain spectrum along the length of various types of single-mode optical fibers pumped by unpolarized light source. This measurement technique also allows to determine the ratio between the gain coefficient and the effective area. This method can be useful to predict performances of distributed Raman amplification used in order to upgrade transmission capacity on installed fibers in a WDM framework.

Introduction

Stimulated Raman scattering (SRS) based optical amplification is one of the key elements for future broad bandwidth high capacity wavelength division multiplexed (WDM) optical fiber transmission links [1]. This amplification technique provides various advantages such as implementation simplicity, the transmission fiber being the amplifying medium, flexibility since amplification can occur at any wavelength, and potential broad bandwidth and gain flattening by combining different pump wavelength [2]. A major drawback is the cost of the needed high power pumps. This emphasizes the need of prediction technique to optimize a distributed Raman amplifier (DRA). In a recent study [3], the distributed gain along various types of fiber was measured with an OTDR but no information about the spectral shape of the gain was provided. A method for distributed measurement of the gain spectrum based on a pulsed pump method is proposed in [4], but requires access to both fiber ends. We propose a new experimental set-up based on a tunable OTDR to characterize the distributed Raman gain spectrum of optical fibers.

Principle

If we couple a pump with OTDR-like pulses, those will be amplified by SRS if their wavelength lies within the bandwidth of the Raman gain spectrum corresponding to the pump. As SRS is bi-directional, Rayleigh backscattered fraction of the power of the pulses is also amplified. Following [5], the evolution of the OTDR pulse power P_s^+ for co-propagation with the pump P_p will be given by :

$$\frac{\partial P_s^+}{\partial z} = -\alpha(\lambda_s)P_s^+ + \frac{C_R}{K}P_pP_s^+ \tag{1}$$

and the backscattered power evolution follows:

$$\frac{\partial P_s^-}{\partial z} = \alpha(\lambda_s)P_s^- - \frac{C_R}{K}P_pP_s^- \tag{2}$$

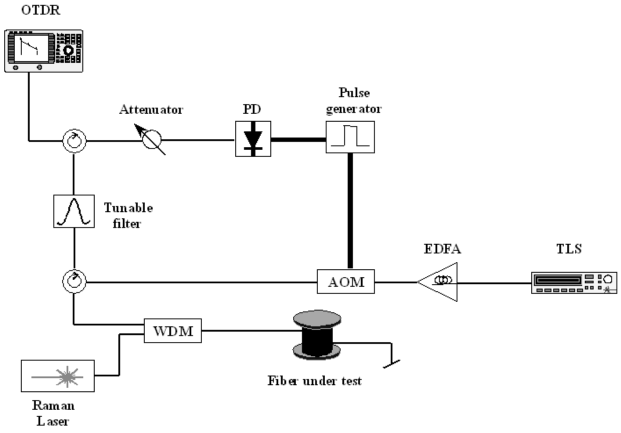

Figure 1: *Tunable OTDR set-up for the measurement of distributed Raman Gain Spectrum.*

where α is the attenuation coefficient of the fiber, $C_R = g_R/A_{eff}$ is the ratio between the gain coefficient and the effective area also called Raman efficiency coefficient. K is the depolarization factor which varies between 1 and 2 for a degree of polarization of the pump between 100 and 0%. The pump power is given by :

$$\frac{\partial P_p}{\partial z} = -\alpha(\lambda_p)P_p - \frac{C_R}{K}P_p\left(P_s^+ + P_s^-\right) \tag{3}$$

If we make the common assumption that the pump depletion is negligible compared to the fiber losses and thus neglect the second term in equation (3), we can solve equations (1)-(3) analytically: The backscattered power will be given by [6]:

$$P_s^-(z) = P_{s0}^+ B e^{-2\alpha(\lambda_s)z} G^2(\lambda_s, z) \tag{4}$$

where P_{s0}^+ is the initial peak pulse power, B is the Rayleigh backscattering coefficient and

$$G(\lambda_s, z) = exp\left\{\frac{C_R(\lambda_s)}{K}P_0\frac{1-exp\left(-\alpha_p z\right)}{\alpha_p}\right\} \tag{5}$$

is the gain undergone by a signal propagating with the pump in the fiber compared to a propagation without pump (on-off gain). OTDR traces are obtained by the following equation [6]:

$$T(z) = 5log\left[P_s(z)\right] \tag{6}$$

and we can deduce the gain calculating the difference between two OTDR measurements with and without pump. Knowing the injected pump power P_0, we can deduce the efficiency coefficient C_R by a suitable least square fit with equation (5).

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 a external cavity tunable laser source (TLS). So the classical OTDR wide spectrum is replaced by the narrow one of the ECL, what allows us to resolve spectrally the Raman gain. As classical TLS has lower power than the OTDR source, it is therefore necessary to amplify the signal, what is done with an EDFA. Thanks to a second circulator the signal is launched in the fiber under test through a multiplexer which combines it with a CW pump signal at 1455nm. This pump power is provided by a cascaded Raman laser which is unpolarized, so that there is no polarization dependant gain. As the peak of the Raman gain is frequency downshifted from the pump wavelength of 13.2 THz, its wavelength will be around 1555nm in the C-band. The backscattered signal is directed by the circulators to the OTDR. A tunable band-pass filter, whose central wavelength is synchronized with the TLS, is placed between the two circulators to filter spontaneous Raman backscattering due to the presence of the pump.
As we use a narrow linewidth laser, 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]. To reduce that noise, we tune the wavelength of the laser in a 1nm interval around the measurement wavelength what provides an averaging of the interference fringes but reduces the spectral resolution.

Results

Figure 2 shows typical traces obtained with the Raman-OTDR (ROTDR) for various pump power in a 10 km standard step index single mode fiber. Probe wavelength is at 1555nm near the gain peak. We can see on figure 3 the comparison between the on-off gain spectrum obtained at the end of the fiber with the distributed measurement and the one obtained by a classical technique with an optical spectrum analyser for 200mW pump power.

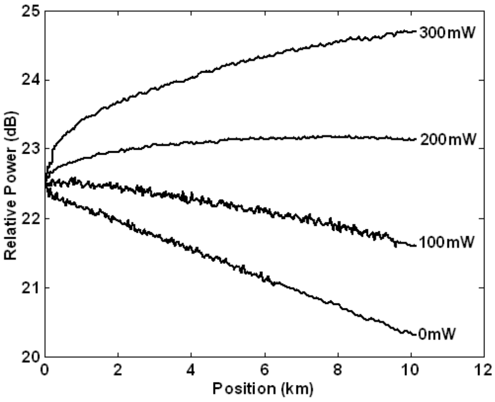

Figure 2: *Spatial distribution of the signal amplified by SRS along a standard single mode fiber for various pump power.*

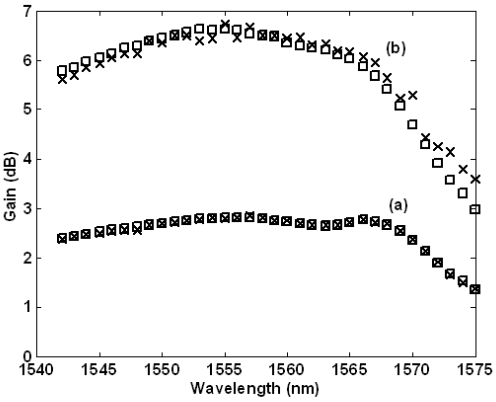

Figure 3: *Comparison between Raman gain spectra measured by OTDR (×) and classical technique (□) for (a) SMF and (b) DCF.*

The spectral Raman efficiency coefficient C_R for standard single mode fiber (SMF) and dispersion compensating fiber (DCF) calculated from ROTDR traces is represented on figure 4. For SMF, assuming an effective area of $80\mu m^2$ and a peak value of $g_R = 6.8\,10^{-14} m/W$ for 1455nm pumping gives a value of $C_R = 0.86(km.W)^{-1}$. With our technique and multiplying by 2 to take the depolarization into account, we obtain $C_R = 0.76(km.W)^{-1}$. Value of DCF is much higher since they are more Ge-doped and have a smaller effective area.

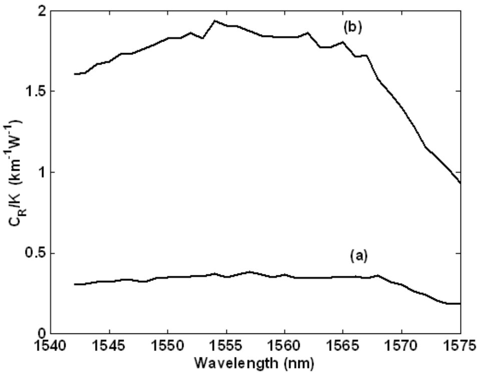

Figure 4: *Raman efficiency spectra for (a) SMF and (b) DCF with a depolarized pump.*

Conclusions

We demonstrated a wavelength tunable reflectometric method to predict spectral performance of distributed Raman amplifiers. This method can easily be adapted for WDM systems or multi-pump DRA. It can also be extended to fiber links composed of a concatenation of different types of fiber. This method also allows to calculate the Raman Gain efficiency spectrum.

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