Distributed measurement of supercontinuum generation along highly nonlinear optical fiber

R. Hontinfinde[1], S. Coulibaly[2], P. Megret[1], M. Taki[2] and M. Wuilpart[1]

[1]University of Mons, Mons, Department of Electromagnetism and Telecommunications
Boulevard Dolez 31, Belgium, 7000
[2]*Université de Lille, CNRS, UMR 8523 - PhLAM - Physique des Lasers Atomes et Molécules, F-59000 Lille, France*

Supercontinuum generation is the spectral broadening of an intense light arising from the interplay between several nonlinear optical effects. In this paper, a non-destructive optical time domain reflectometry set-up is proposed to measure the spatial evolution of the spectral broadening induced along an optical fiber. The method is based on the measurement of the Rayleigh backscattered signals generated by the various components of the spectral broadening. The system was experimentally tested on highly nonlinear fibers. The experimental data obtained with the proposed method were in good agreement with the optical spectra measured by an optical spectrum analyzer at the fiber output.

Introduction

Supercontinuum generation (SGC) consists in the development of a broad continuous spectrum when high power pulses propagate through a nonlinear medium [1]. During the past decade, SGC has been extensively studied in optical fibers since the light confinement in the core provides a high nonlinear efficiency [2]. It was identified that when pumping in the anomalous dispersion region and operating in the nanosecond regime, the modulation instability (MI) plays a key role in the spectral broadening [3]. The metrology of SCG has not yet been fully explored. The output spectrum can easily be measured by using an optical spectrum analyzer at the fiber end but no adequate method has been proposed to measure the spatial evolution of the spectral broadening all along the fiber. The only way up-to-now to obtain a spatially resolved measurement of the supercontinuum generation is to use the cut-back method, which leads to the destruction of the fiber. In this paper, an experimental bench based on an optical reflectometry approach is proposed for the nondestructive measurement of the spatial evolution of modulation instability and supercontinuum generation along an optical fiber. The proposed technique was applied to highly nonlinear fibers (HNLF). The experimental data were in good agreement with those obtained by using an Optical Spectrum Analyzer (OSA) at the fiber outputs. Distributed measurements of MI were already presented by the same group in [4]. However, a spatial resolution of only 30 meters was reached and only first order MI was characterized. The apparatus proposed in this letter allows obtaining a spatial resolution of 2.5 m. Moreover, second order MI and supercontinuum generation were detected. This means that for the first time, the spatial evolution of the supercontinuum spectral broadening process along an optical fiber was measured.

Experimental set up

The proposed experimental set-up is described in Figure 1. The principle relies on replacing the low power broadband source of a commercially available OTDR [5] (Optical Time Domain Reflectometer) by a high power quasi-monochromatic source. The source included in the OTDR emits optical pulses that are sent to a detector that provides at its output an electrical pulse train used for synchronizing an electrical pulse generator. The latter generates a pulse train having a repetition rate identical to that of the OTDR. The pulse duration determines the spatial resolution of the measurement [5]. The electrical signal generator is used to modulate a continuous laser source by means of an electro optic modulator of 40 dB extinction ratio. The optical pulses are then amplified by an EDFA (Erbium Doped Fiber Amplifier) to obtain the peak power level needed to generate a spectral broadening. The tunable filter 1 centered on the wavelength of the laser aims to filter out the majority of the EDFA noise. A coupler then directs the amplified pulses into the fiber under test. At the fiber input, we obtained a pulse optical signal having the same repetition rate as the signal transmitted by the OTDR and having the desired characteristics for modulation instability/supercontinuum generation (pump wavelength and peak power). When the high peak power pulses propagate in the fiber, the optical spectrum is growing all along its length. Let us consider that a new component at a wavelength λ is generated. As it propagates through the fiber, it undergoes at each point the Rayleigh backscattering phenomenon [6]. The generated backscattered signal propagates towards the fiber input and reaches the internal detector of OTDR after passing through the coupler and the tunable filter 2. The OTDR detector measures the power of the backscattered signal as a function of the pulse position. Centering the tunable filter 2 on the wavelength λ, the OTDR will display the spatial evolution of the λ component along the fiber. This reasoning can be extended to all wavelengths generated by the spectral broadening. By changing the center wavelength of the tunable filter 2, we can finally obtain the spatial evolution of the optical spectrum along the fibers.

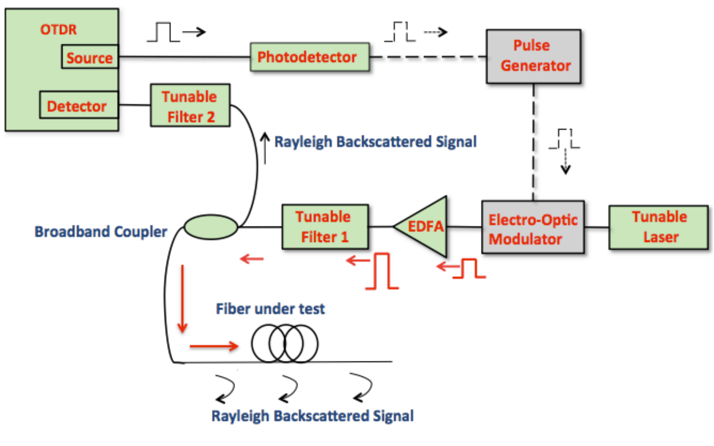

FIG. 1 Experimental set-up

Distributed measurement of modulation instability

The first experimental work aimed to perform a first distributed measurement of a spectral broadening induced by the modulation instability. Experiment has been performed along the HNLF. The pulse width was set to 10 ns, providing a 1m spatial resolution. The width of tunable filter 2 was equal to 950 pm. The parameters of the experiment are summarized in table 1 where P_0 is the pulse peak power, $\boldsymbol{\gamma}$ the nonlinear coefficient, L the fiber length, $\boldsymbol{\alpha}$ the lineic attenuation of the fiber, λ_P the pump wavelength and λ_0 is the zero dispersion wavelength(s).

	P_O [W]	γ $[w.km]^{-1}$	α [dB/km]	λ_P [nm]	L [m]	λ_0 [nm]
Fiber 1	2	10.5	0.7	1565	800	1554

Table 1: Fiber parameters for the first experiments

With a systematic measurement of the power distribution made by tuning the tunable filter 2 with 1nm step, we are able to draw a map of the light generated between 1520 and 1595 nm for the fiber. From the mapping, one can be deduce where the different wavelengths are generated in the fibers.

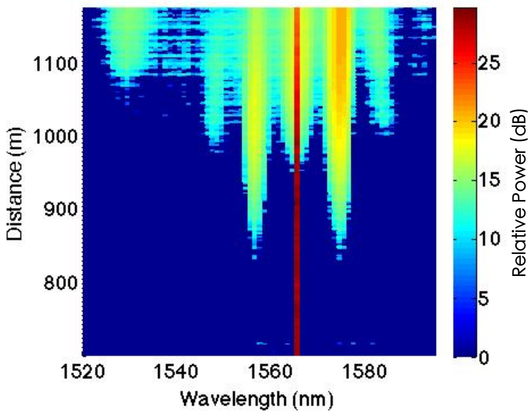

Figure 2: Map of the light generated along the fiber with P_0=2.23 w.

In figures 3 we show the output spectrum obtained with our technique by plotting the power at the end of the fiber with respect to the central wavelength of the filter 2. If we compare this result with the measurement with an optical spectrum analyzer, we find a quite good agreement.

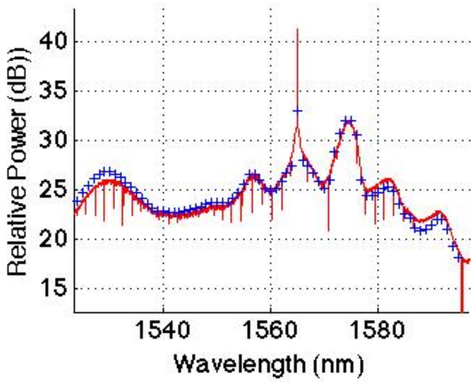

Figure 3: Optical spectra measured at the fiber output with the proposed technique (blue+) and with an optical spectrum analyzer (red)

The second experimental work consisted in the distributed measurement of supercontinuum generation. We used the same fiber and the measurement characteristics as for the previous experiment except that the peak power was increased to 6.3 W, the pump wavelength was 1561 nm, and the pulse width was set to 25 ns, providing a 2.5 m spatial resolution. The first presented result (figure 4) illustrates the measured spatial evolution of the supercontinuum spectrum along the optical fiber.

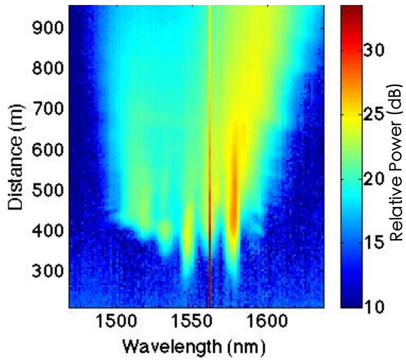

Figure 4: Evolution of the spectrum along the fiber with P_0= 6.3 w.

The figures 5 depict the output Spectrum obtained with the proposed technique and with an optical spectrum analyzer. Again, we have a quite good agreement

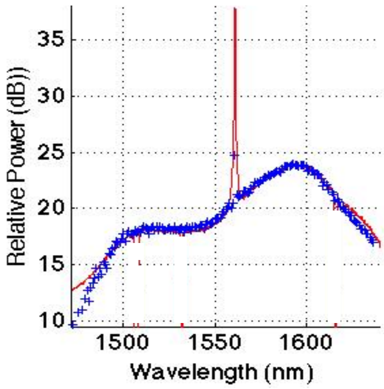

Figure 5: Spectrum measured at the fiber output with proposed technique (blue+) and with an OSA (red).

Conclusion

In conclusion, our non-destructive method for the measurement of the spectral broadening spatial was successfully tested in highly nonlinear fiber under two different input peak power conditions. The experimental results showed a good agreement with the data obtained by an OSA used at the fiber output.

Acknowledgements

The work was supported by the Interuniversity Attraction Poles program of the Belgian Science Policy (IAP 7-35).

References

[1] R.R. Alfano and S.L. Shapiro, Phys. Rev. Lett. **24**, 584 (1970).
[2] J.M. Dudley, G. Genty, and S. Coen, Rev. of Mod. Phys.**78**, 1135 (2006).
[3] A. Demircan, and U. Bandelow, Opt. Com. **244,** 181 (2005).
[4] G. Ravet et al, Proceedings of IEEE Photonics Society Summer Topicals 2010, WC1.3 (2010).
[5] D. Anderson and F. Bell, *Optical Time-Domain Reflectometry* (Tektonix, Wilsonille, 1997).
[6] M. Wuilpart, *Rayleigh Scartering in optical fibers and applications to distributed measurements* (chap 8 of *Advanced Fiber Optics Concepts and technology*, L. Thévenaz, EPFL press, Lausanne, 2011).
[7] G.P. Agrawal, Nonlinear Fiber Optics 5th Edition (Academic Press, Oxford, 2013).