

## **Spatially-resolved measurement of supercontinuum generation along highly nonlinear optical fibers with a 14-cm spatial resolution**

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*Supercontinuum generation in optical fibers (SCG), which consists in a development of broadband spectrum when a high peak power pulse propagates through a nonlinear medium, is no more a laboratory curiosity. We report the distributed measurement of supercontinuum generation along highly nonlinear optical fibers with centimeter spatial resolution using photon-counting optical time-domain reflectometry.*

Supercontinuum generation (SCG) in optical fibers [1-3] is no more a laboratory curiosity since it has various applications in different fields such as telecommunication and spectroscopy [4-5]. Most of the SCG metrology consists in characterizing the SC spectrum at the end of the fiber, obtained with an optical spectrum analyzer (OSA). Until recently, no adequate method has been proposed to measure the spatial evolution of the spectral broadening along the fiber and the only way to obtain a spatially-resolved measurement of the supercontinuum generation was to use the cut-back method, which leads to the destruction of the fiber and for this reason, cannot be implemented in situ. To measure the evolution of the supercontinuum along an optical fiber without causing its destruction, we recently proposed an experimental setup based on optical time-domain reflectometry (OTDR), leading to a spatial resolution of 2.5 meters [6]. A distributed measurement of SC with a better spatial resolution is however necessary to characterize short fibers, for which a few centimeters resolution is required. To solve this issue, we propose in this paper an experimental setup based on photon-counting optical time-domain reflectometry (v-OTDR). To improve the spatial resolution, major changes to the existing setup presented in [6] are required. Since it is the duration of the pulses that determines the spatial resolution of the measurement [7], we propose to use pulses of 100 ps in order to obtain a centimeter spatial resolution. The extinction ratio of the pulsed signal must be excellent to avoid Rayleigh backscattering between two successive pulses. We have therefore introduced into our experimental setup an electro-optical modulator operating at 10 Gbit/s and having an extinction ratio of 40 dB. Working with pulses of 100 ps implies that the backscattered signal is not strong enough to be detected by a conventional OTDR. An OTDR equipped with a photon counting detector (v-OTDR) was therefore used. In this paper, we present the result obtained with the new experimental setup on high nonlinear optical fibers (HNLF).

The experimental setup is depicted in figure 1. As the internal source of a commercially available v-OTDR is a low power broadband source and since one needs a narrowband high power optical source for the generation of supercontinuum, the device must be adapted. For that purpose, a series of extra components has to be added. They are represented in the dotted box. The optical pulses emitted by the source included in the v-OTDR are converted in electrical pulses by the photodetector, which are used to

synchronize an electrical pulse generator. The latter generates an electrical pulse train having a repetition rate identical to that of the  $v$ -OTDR. This electrical signal is then used to modulate a continuous-wave tunable laser source by means of an electro-optic modulator of 40 dB extinction ratio. An Erbium Doped Fiber Amplifier (EDFA) amplifies the generated optical pulses in order to obtain the peak power level needed to generate SC in fibers. The tunable filter 1 centered on the tunable laser wavelength aims to filter out the majority of the EDFA noise. An optical circulator routes the amplified optical pulses into the fiber under test. At the fiber input, an optical signal pulse train having the same repetition rate as the signal emitted by the  $v$ -OTDR and having the desired characteristics for supercontinuum generation (pump wavelength and peak power) is obtained. When the high peak power optical pulses propagate in the fiber, the optical spectrum continuously broadens all along its length. Let us consider that a new SC component at a wavelength  $\lambda$  is generated. As it propagates through the fiber, it undergoes locally the Rayleigh backscattering process. The generated backscattered signal propagates towards the fiber input and reaches the detector of the  $v$ -OTDR after passing through the circulator and the tunable filter 2. The  $v$ -OTDR detector measures the power of the backscattered signal as a function of the temporally encoded pulse position. Centering the tunable filter 2 on that wavelength  $\lambda$ , the  $v$ -OTDR automatically displays the spatial evolution of the  $\lambda$  component of the SC along the fiber. This mechanism can be extended to all wavelengths generated by the SC spectral broadening. By changing the wavelength center of the tunable filter 2, we can finally obtain the spatial evolution of the SC spectrum along the fiber.

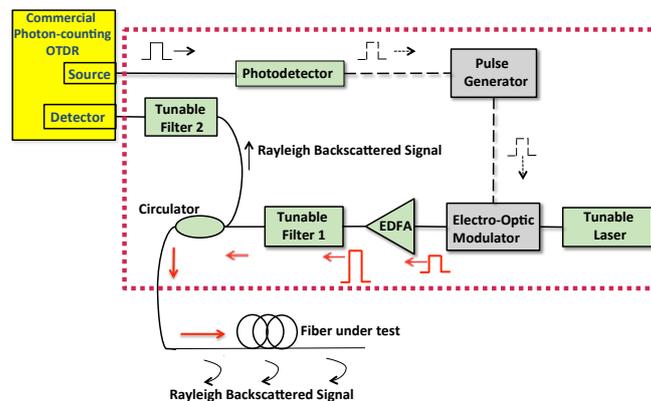


Figure. 1 Experimental method for distributed measurement of SC generation. The dotted rectangle includes the extra components required to replace the internal source of the commercial  $v$ -OTDR by an externally modulated tunable source.

We tested the proposed setup on a highly nonlinear optical fiber. The pumping was performed in the anomalous dispersion regime. The pulse width was fixed at 100 ps, the peak power  $P_0$  and the pump wavelength  $\lambda_p$  were set to 13 W and 1560 nm, respectively. The 133 m HNLF fiber was characterized by a nonlinear coefficient  $\gamma$  of  $10.5 \text{ [W.km]}^{-1}$ , an attenuation coefficient  $\alpha$  of 0.7 dB/km, and a zero dispersion wavelength  $\lambda_0$  at 1554 nm.

The spatial evolution of the backscattered power at a particular wavelength (1580 nm) is shown in the figure 2 where the blue curve is the raw measurement data and the red curve is the trace obtained after applying a spatial sliding average over 10 sampling

points, which corresponds to 14 cm (the spatial resolution of our measurement). In figure 2, we can precisely identify the position along the fiber where this wavelength component has been generated.

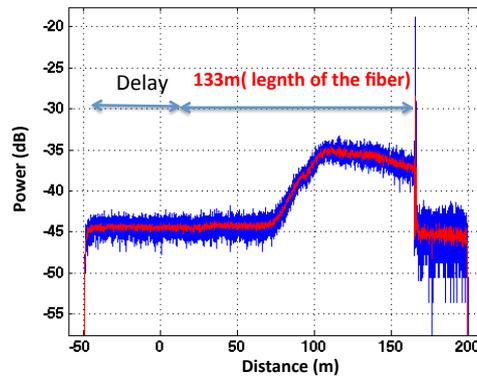


Figure 2 : Distributed measurement of the evolution of the wavelength at 1580 nm along a fiber optics

From measurements of the backscattered power spatial distribution performed by tuning the tunable filter 2, a map of the spectrum of the light generated along the optical fiber can be obtained. The result is presented in figure 3.

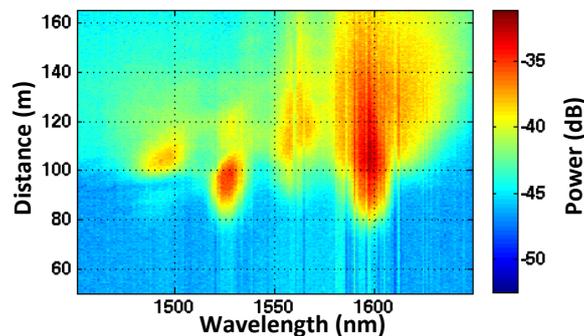


Figure. 3: Mapping of the nonlinear broadening due to the SC generation at 1560nm pump wavelength measured using 13W along the fiber.

The initial stage of the wave propagation is dominated by an approximately symmetrical spectral broadening detected from 78 m. This result agrees with the nonlinear wave propagation theory in the picosecond pulses regime, which predicts that the supercontinuum is initiated from the modulation instability. After approximately 90 m of propagation, the spectral broadening becomes highly asymmetric due to significant impact of the third-order dispersion and Raman Scattering. After 120 m and until the fiber end, the spectrum continues to broaden as a result of cascaded MI processes and Raman scattering (at longer wavelengths).

In conclusion, we proposed a non-destructive method for the distributed measurement of SCG along optical fibers with a 14 cm spatial resolution. To the best of our knowledge, it is the first time that spatially-resolved measurement of SCG is obtained

with such an accurate resolution length.

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