Invited paper

Setting an Upper-Wavelength Limit to the Supercontinuum Generated in a Photonic Crystal Fibre

Luca Tartara, Vittorio Degiorgio, Rim Cherif, and Mourad Zghal

Abstract—We report about a novel kind of supercontinuum generation in a photonic crystal fibre in which the spectral broadening occurs only on the blue side of the pump wavelength. As a consequence a limit to the extent of the supercontinuum is set and thus a way for tailoring the broadened spectrum according to a peculiar application is provided. We present a theoretical explanation along with experimental data which are supported by the results of a set of numerical simulations.

***Keywords—* nonlinear optics, photonic crystal fibres, supercontinuum generation.**

1. Introduction

Supercontinuum generation (SCG) has attracted a great deal of attention in recent years thanks to the development of photonic crystal fibres (PCFs) which have proven to be ideal media for nonlinear optical interactions [1]. In fact the tight confinement of light provided by the high refractive-index contrast makes high intensities available for long propagation lengths even at moderate power levels. Moreover, the unusual dispersion characteristics of PCFs allow for the fulfilment of the phase-matching condition for several nonlinear processes. Many phenomena contribute thus to the broadening of the input spectrum generating new spectral components which are commonly both red- and blue-shifted for hundreds of nanometers. Such a broadened spectrum can be profitably exploited in several applications with many examples coming from the field of optical communications. A multi-wavelength source covering all the telecom spectral range can be easily obtained from one single-line laser diode by broadening its spectrum. All-optical signal processing also can be performed by means of SCG: in a wavelength division multiplexed system a signal at a given carrier wavelength can be switched to a single destination or multicast to several destinations exploiting the wavelength-conversion capability offered by the filtering of the broadened spectrum of the input signal.

However, the many processes leading to SCG make it impossible to control the evolution of the spectrum in order to generate only the components to be effectively employed. As a consequence a certain amount of spectral power gets wasted falling outside the wavelength range of interest particularly when a given flatness is required. In this work we present a novel kind of SCG in a PCF in which the spectral broadening occurs only on the blue side of the pump wavelength thus setting a limit to the continuum on the long-wavelength side.

2. Theoretical Background

The physics behind SCG in a PCF by means of ultrashort pulses has been the subject of several works focusing on the regime of anomalous dispersion where solitonlike dynamics play a major role. It has indeed been shown that SCG arises from the Raman-induced fission of higher-order solitons. The driving phenomena are the perturbation suffered by the input pulse because of intra-pulse Raman scattering and the following decay into fundamental solitons. Such pulses are then progressively shifted towards longer wavelengths emitting at the same time a resonantly-coupled blue-shifted dispersive wave [2]. Both the theoretical investigations and the experimental demonstrations have considered only the propagation of the fundamental mode of a PCF for which there exists no cut-off wavelength. However, when the launch conditions at the fibre input tip enable the excitation of a higher-order mode, the propagation at wavelengths longer than the cut-off wavelength is no longer possible and therefore the spectral broadening towards the red side due to the Raman effect is prevented. Because of the resonant coupling to the spectral components generated at shorter wavelengths, also the broadening of the spectrum to the blue side is expected to be affected but it is not clear to which extent.

In fact other sources of perturbation such as higher-order linear and nonlinear dispersion have been shown to be responsible for the generation of dispersive waves at shorter wavelengths by solitonlike pulses [3]. Then the broadening of the spectrum would not be prevented and the cut-off wavelength would act as a boundary to the continuum at least on the long-wavelength side. If the input wavelength is tuned very close to the cut-off wavelength a single-sided SCG would occur with new spectral components arising only on the blue side.

We have also carried out a set of numerical simulations about the propagation in a higher-order mode of a femtosecond pulse in a PCF in order to strenghten our theoretical conclusions.

The model we have adopted is based on the generalized nonlinear Schrödinger equation as described in [4]. However, we have introduced a wavelength-dependent loss for keeping into account the effect of the modal cut-off. Loss is set to zero for wavelengths well below the cut-off wavelength and is very high for wavelengths far above. In the region around the cut-off wavelength the loss coefficient varies continuously from the low to the high value. Such a model allows us to clarify the contribution of the several mechanisms playing a role in the spectral evolution by running the numerical simulation excluding certain terms of the nonlinear Schrödinger equation.

The spectrum displayed in Fig. 1(a) is obtained by plugging in the simulation the whole nonlinear response made up of self-phase modulation, stimulated Raman scattering and self-steepening. The cut-off wavelength is set at 830 nm and the pump wavelength at 810 nm, while the zero-dispersion wavelength is 700 nm. The propagation length is 50 cm. Even if the modal cut-off prevents the spectrum from broadening towards longer wavelengths, a white-light radiation is clearly generated on the blue side of the pump wavelength. In such a way it is thus possible to control the extent of the supercontinuum spectrum simply by tuning the input wavelength close to the cut-off wavelength and choosing appropriate values of the input power and the fibre length fixing the short-wavelength edge.

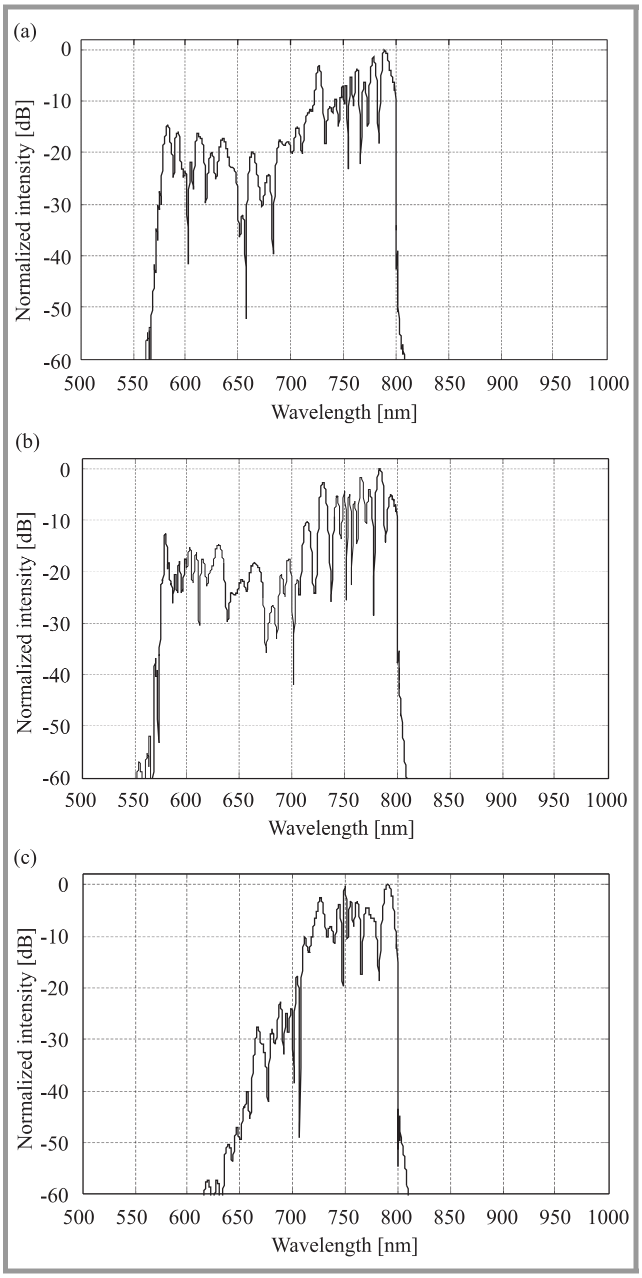

Fig. 1. Numerically computed supercontinuum spectrum: (a) by employing the whole model; (b) by excluding nonlinear perturbations; (c) by isolating the contribution of Raman scattering.

The numerical tool we have developed allows then to identify which kind of perturbation turns out to be mainly responsible for the generation of the blue-shifted continuum. Figure 1(b) shows the spectrum obtained when the nonlinear perturbations are neglected, that is to say, when the terms accounting for the stimulated Raman scattering and the self-steepening effects are not included in the nonlinear Schrödinger equation. The contribution of the higher-order linear dispersion is instead working. The values of the excitation and of the fibre parameters are kept constant. The result is highly similar to the one reported in Fig. 1(b) suggesting that the main reason for the growth of dispersive waves leading to SCG is the effect of the differential dispersion. As a proof of that one can consider the spectrum displayed in Fig. 1(c), which is the result provided by the numerical tool when the only active perturbation is the one coming from the Raman effect. In such a case the broadening to the blue side has a much smaller extent as the impossibility for the Raman solitons to propagate hinders the resonant coupling to the shorter-wavelength dispersive waves.

3. Experimental Set-up

The photonic crystal fibre used in our experiments is shown in Fig. 2. The air-silica microstructure is made up of holes with a 2.5-μm average diameter which are arranged in a hexagonal pattern with a 2.7-μm pitch. The linear dimension of the solid core is about 2.2 μm.

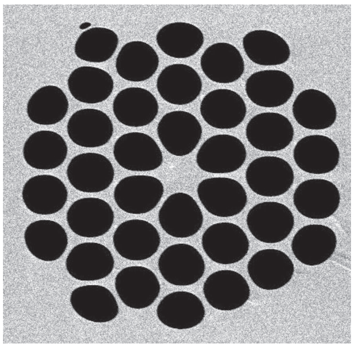

Fig. 2. Image of the cross section of the fibre taken by a scanning electron microscope.

We have performed a numerical investigation about the modal properties of the fibre. The spatial patterns of the fundamental mode and of the first two higher-order modes are depicted in Fig. 3. We will refer to them as mode 0, mode 1 and mode 2. The zero dispersion wavelengths are 840 nm, 660 nm and 600 nm, respectively. The cut-off wavelength of mode 1 is around 1300 nm and the cut-off wavelength of mode 2 is 830 nm.

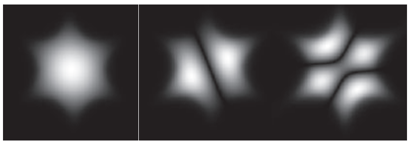

Fig. 3. Spatial patterns for mode 0 (left), mode 1 (centre), and mode 2 (right).

The light source is a cw-mode locked Ti:Sapphire laser delivering a train of femtosecond pulses at the repetition rate of 80 MHz. The wavelength can be tuned from 700 nm to 900 nm. In order to avoid harmful backreflections from the input tip of the fibre we employ a Faraday isolator which broadens the pulsewidth up to 190 fs.

The laser beam is coupled into a PCF span of 50-cm length by means of an aspheric lens having a numerical aperture of 0.65. The fibre is mounted on a three-axes translation stage allowing the positioning of the fibre with a resolution of 20 nm. Thanks to this kind of set-up we can exploit an offset pumping technique moving the input tip of the fibre in the focal plane. We are thus able to obtain a selective excitation of different fibre modes at the expense of the coupling efficiency: the higher the order of the mode, the lower the coupled power.

At the output end of the fibre the light is collected by a 100 x objective with a numerical aperture of 0.95. The spectral properties of the output radiation are monitored by an optical spectrum analyzer having a resolution of 0.1 nm.

4. Experimental Results

For input wavelengths above 810 nm only mode 0 can be excited regardless of the positioning of the fibre in the focal plane. By increasing the input power, we can record a progressive broadening of the output spectrum occurring in quite a symmetrical fashion as no limitations to the propagation occur. We will not discuss this case any longer as it represents the usual situation described in many other works. A further insight is nevertheless reported in [5].

When the pump wavelength is tuned below 810 nm we are able to excite several modes. By a proper positioning of the fibre in the focal plane the excitation turns out to be highly selective so that at the output of the fibre we can easily detect either mode 0 or mode 1, or mode 2.

Mode 1 can be easily excited and the coupling efficiency is not severely degraded in comparison to the fundamental mode. Soliton dynamics play a fundamental role as the propagation occurs in the anomalous dispersion regime. Therefore the spectral evolution leading to SCG is characterized by the appearance of new components on both sides of the input wavelength. However, it is important to notice that the generation of red-shifted spectral components stops at wavelengths shorter than 1300 nm with a progressive decaying intensity above 1100 nm. The explanation for such a behavior is the influence of the cut-off wavelength making the propagation at wavelengths longer than 1300 nm impossible.

The excitation of mode 2 is instead rather difficult. The focal spot of the pump beam has in fact to be carefully positioned on the input cross section of the fibre far away from the point yielding the highest coupling efficiency. Such a strong offset severely affects the available power inside the fibre, which results very low in comparison to mode 0 and even mode 1. The maximum average power we can record at the output of the fibre span is indeed below 20 mW even if the exact value could be slightly higher because of the limited collection efficiency provided by the objective. Nevertheless the spectrum broadens down to the blue region as in the previous cases. However, no spectral components on the long wavelength side are generated. An example of such a kind of supercontinuum spectrum is shown in Fig. 4. Even when the pump wavelength is tuned down to 705 nm, the spectrum broadening is exclusively towards shorter wavelengths except for an isolated peak arising near 800 nm with a very weak intensity.

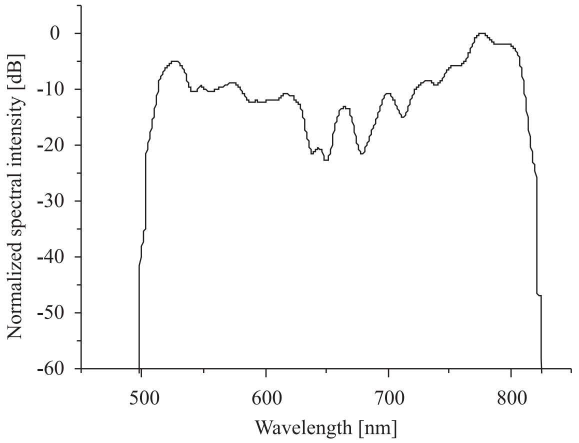

Fig. 4. Supercontinuum spectrum obtained for mode 2 when the pump wavelength is 785 nm and the output power is 5 mW.

This spectrum shown in Fig. 4 is a clear demonstration of the possibility of controlling and limiting the extent of the supercontinuum by exploiting the cut-off wavelength of a higher-order mode.

5. Conclusions

We have studied both numerically and experimentally the role played by the cut-off wavelength in the dynamics of supercontinuum generation in a photonic crystal fibre. It has been shown that its effect does not hinder the spectrum from broadening towards shorter wavelengths. On the contrary it can be exploited to tailor the extent of the supercontinuum setting a limit on the long-wavelength edge.

References

[1] J. M. Dudley, G. Genty, and S. Coen, "Supercontinuum generation in photonic crystal fibers", *Rev. Mod. Phys.*, vol. 78, no. 4, pp. 1135–1184, 2006.

[2] L. Tartara, I. Cristiani, and V. Degiorgio, "Blue light and infrared continuum generation by soliton fission in a microstructured fiber", *Appl. Phys. B*, vol. 77, no. 2–3, pp. 307–311, 2003.

[3] Y. Kodama and A. Hasegawa, "Nonlinear pulse propagation in a monomode dielectric waveguide", *IEEE J. Quant. Electron.*, vol. 23, no. 5, pp. 510–524, 1987.

[4] I. Cristiani, R. Tediosi, L. Tartara, and V. Degiorgio, "Dispersive wave generation by solitons in microstructured optical fibers", *Opt. Expr.*, vol. 12, no. 1, pp. 124–135, 2004.

[5] R. Cherif, M. Zghal, L. Tartara, and V. Degiorgio, "Supercontinuum generation by higher-order mode excitation in a photonic crystal fiber", *Opt. Expr.*, vol. 16, no. 3, pp. 2147–2152, 2008.

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