Supercontinuum generation in a photonic crystal fibre using picosecond pulses at 1550 nm

Andersen, Peter Andreas; Peucheret, Christophe; Hilligsøe, K.; Berg, Kim Skaalum; Hansen, K. P.; Jeppesen, Palle

Published in:
Proceedings International Conference on Transparent Optical Networks/European Symposium on Photonic Crystals

Link to article, DOI:
10.1109/ICTON.2003.1264581

Publication date:
2003

Document Version
Publisher's PDF, also known as Version of record

Supercontinuum Generation in a Photonic Crystal Fibre using Picosecond Pulses at 1550 nm

Peter Andreas Andersen[1], Christophe Peucheret[1], Karen Marie Hilligsøe[2], Kim Skaalum Berg[1], Kim Per Hansen[3], Palle Jeppesen[1]

[1] *COM, Technical University of Denmark, DK-2800 Kgs Lyngby, Denmark*

Tel: +45 4525 6606, Fax: +45 4593 6581, e-mail: paa@com.dtu.dk

[2] *Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark*

[3] *Crystal Fibre A/S, Blokken 84, DK-3460 Birkerød, Denmark*

ABSTRACT

Supercontinuum (SC) generation is demonstrated in a photonic crystal fibre (PCF) at 1550 nm with pulse widths of 0.3 to 2.5 ps. Subsequent band-pass filtering of the generated SC spectrum enables the realisation of an optical clock frequency translator continuously tunable up to the L-band.

Keywords: photonic crystal fibre, nonlinearities, supercontinuum, pulse source, wavelength conversion.

1. INTRODUCTION

Photonic crystal fibres (PCF) are attractive for efficient generation of supercontinuum (SC) radiation [1-6]. This is due to their design degrees of freedom which make it possible to enhance the nonlinear effects by reduction of their effective area and tailor their dispersion in order to favour soliton generation [4] or phase-matched processes [5] in the wavelength range of interest. Until now, SC generation in PCF has been mostly demonstrated in the visible range and femtosecond regime. However, some applications of SC can also be found in the field of optical fibre telecommunications, such as the realisation of multi-wavelength short pulse sources or wavelength converters for multicasting [7]. Another interesting new application is the realisation of a tunable optical clock translator for high-speed optical time division multiplexing (OTDM) systems where a clock signal at the base rate is transmitted simultaneously with the time multiplexed data signal in order to ease the clock recovery at the receiving end, as was proposed in [8]. The optical clock signal is customarily derived from the pulse source using wavelength conversion in a non-linear optical loop mirror. Using instead a tunable clock translator based on supercontinuum would save the cost of a tunable laser. All those applications set new requirements on the SC source, which has to operate in the 1550 nm telecommunication window with pulse widths in the picosecond range, and furthermore be made compatible with fibre optics components. The realisation of a 24 channel 10 GHz pulse source based on a high non-linearity PCF has been recently reported [9]. However, the reduced core diameter necessary to achieve a high non-linear coefficient (~70 $W^{-1} \cdot km^{-1}$) required lens coupling to the PCF.

In this paper, we report on supercontinuum generation in a highly nonlinear PCF around 1550 nm using pulse widths in the 0.3 to 2.5 ps range. This result is achieved using components compatible with standard fibre optics technology, including the PCF which is spliced to a standard single mode fibre. Subsequent band-pass filtering of the generated supercontinuum enables us to demonstrate continuous optical clock translation from 1552 nm up to the L-band.

2. EXPERIMENTS

The experimental set-up is shown in Fig. 1. A pulse train is generated by a mode-locked fibre ring laser (MLFRL) with a repetition rate of 10 GHz, before being amplified by an erbium doped fibre amplifier (EDFA) delivering up to 30 dBm average power. The pulses are compressed in a non-linear pulse compressor (NLPC) made of alternating lengths of highly non-linear fibre and standard single mode fibre, before being input to 50 m

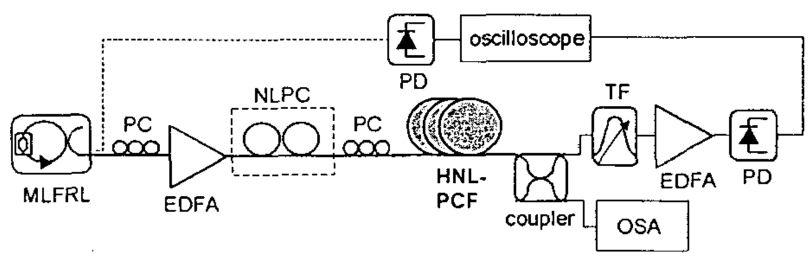

Figure 1. Experimental set-up

This work was partly supported by NKT Academy.

0-7803-7816-4/03/$17.00 ©2003 IEEE

of a highly nonlinear PCF with zero dispersion at 1552 nm [10]. The nonlinear coefficient of the PCF was measured to be 18 $W^{-1}\cdot km^{-1}$ and its birefringence is estimated to 1.1×10^{-4}. The PCF is spliced to standard single-mode fibre pigtails. Due to the fibre birefringence, a polarisation controller (PC) is used before the PCF. Part of the signal is tapped with a coupler at the PCF output in order to check the width of the generated supercontinuum with an optical spectrum analyser (OSA). The remaining fraction of the light at the PCF output is filtered using a tunable optical band-pass filter (TF) before being amplified, detected by a photodiode (PD) with 50 GHz bandwidth and displayed on a high speed sampling oscilloscope.

First, pulse durations smaller than 0.5 ps were used to generate a supercontinuum with a pump wavelength of 1550.5 nm. The influence of the fibre birefringence is illustrated in Fig. 2 (a) and (b) where two SC spectra with fairly different features are shown, depending on the state of polarisation of the light at the PCF input. In the first case (Fig. 2 (a)), the SC extends over 60 nm (-20 dB bandwidth), whereas for the orthogonal state of polarisation (Fig. 2 (b)), a larger SC bandwidth of 75 nm is obtained, at the expense of a deeper notch in the spectrum around 1585 nm. Such bandwidths cover the C and L bands used for optical communication. It was checked whether the generated supercontinuum could be sliced using the tunable band-pass filter placed after the PCF. Fig. 2 (c) and (d) show the clock signal obtained from the supercontinuum at a wavelength of 1578.4 nm and 1574.1 nm respectively, and corresponding to the spectra of Fig. 2 (a) and (b) respectively. The top trace in those figures show the original clock signal at 1550.5 nm, whereas the bottom trace corresponds to the converted clock signal. A clear converted signal appears whenever the clock at the PCF input is launched parallel to one of the principal polarisation axes of the fibre. This enabled us to ensure that the spectra of Fig. 2 (a) and (b) correspond to pump light launched parallel to the principal axes. It should be noted that the pulse duration is slightly different in the cases of Fig. 2 (a)(c) and (b)(d), with full-width half-maximum of the autocorrelation trace equal to 0.5 and 0.4 ps respectively. We have therefore demonstrated that, with such pulse durations, we are able to translate our original clock signal up to the L-band. The maximum wavelength for which clock translation was observed in our experiments was limited by the band-pass filter tunability and not by the extent of the supercontinuum.

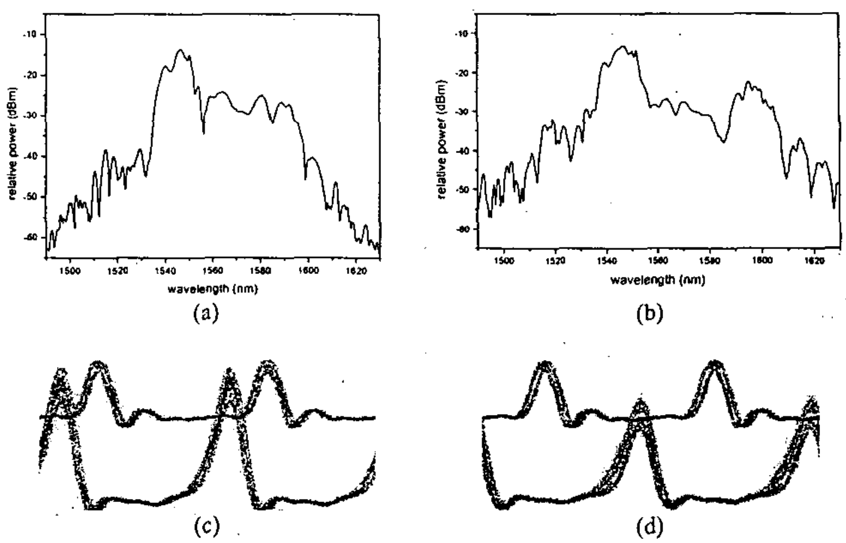

Figure 2. Supercontinuum spectra and converted clock signals when the pump signal is launched parallel to the PCF principal polarisation axes. In (c) and (d) the top trace corresponds to the original clock at 1550.5 nm, whereas the bottom trace shows the converted clock signal at 1578.4 and 1574.1 nm respectively. (a) and (c) are obtained with the pump aligned to one of the fibre principal polarisation axes, whereas (b) and (d) are obtained when the pump is aligned to the orthogonal principal polarisation axis.

Supercontinuum was also successfully generated using a pulse width of 2.5 ps as shown in Fig. 3. Here, the pump clock signal was tuned to 1547.7 nm. Figure 3 shows the build-up of supercontinuum when the pump average power is increased from 17.4 to 22.2 dBm. A peak at 1585 nm can be seen to shift towards lower frequencies when the pump power is increased. In addition, the peak appears at a wavelength approximately phase matched to the principal peak in the spectrum. This phase matching across the zero dispersion wavelength is seen in the soliton fission process, when a femtosecond pulse is used to generate a supercontinuum [4]. Furthermore, the side lobes around the pump wavelength indicate a contribution from degenerate four wave mixing, a process that has been clearly observed in a regime of longer picosecond pulses [2]. Therefore, physical processes associated with SC generation with femtosecond pulses as well as processes associated with SC generation with picosecond pulses appear in the regime presented here (0.3-2.5 ps), but the respective contribution of the different physical processes need to be better elucidated. Numerical simulations offer a flexible tool in order to identify the physical origin of the SC features and to optimise the generated spectra and some work has been initiated in this direction.

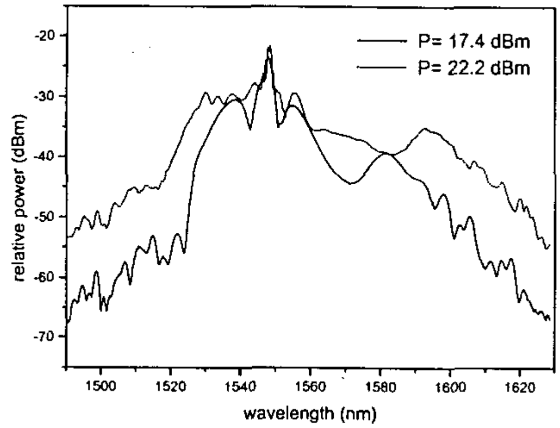

Figure 3. Supercontinuum spectra obtained with 2.5 ps FWHM pulses at 1547.7 nm and average input power of 17.4 (solid line) and 22.2 dBm (dashes).

3. NUMERICAL MODEL

The supercontinuum generation was modelled using the propagation equation (1), including the effects of the dispersion profile of the fibre, Kerr non-linearity and stimulated Raman scattering [11].

$$\frac{dA(z,t)}{dz} = \hat{D}A(z,t) + i\gamma\left(1 + \frac{i}{\omega_0}\frac{\partial}{\partial t}\right) \times \left(A(z,t)\int_{-\infty}^{t} dt' R(t') \left|A(z,t-t')\right|^2\right) \tag{1}$$

$A(z,t)$ is the slowly varying envelope of the electric field corresponding to a single polarization, γ is the PCF nonlinear coefficient and $R(t)$ is the Raman response function. The dispersion profile of the fibre was experimentally measured and included through the propagation constant $\beta(\omega)$. The action of $\hat{D}$ was evaluated in the frequency domain as $\hat{D}\tilde{A}(z,\omega) = i(\beta(\omega) - \omega / v)\tilde{A}(z,\omega)$, where v is the group velocity of the pulse.

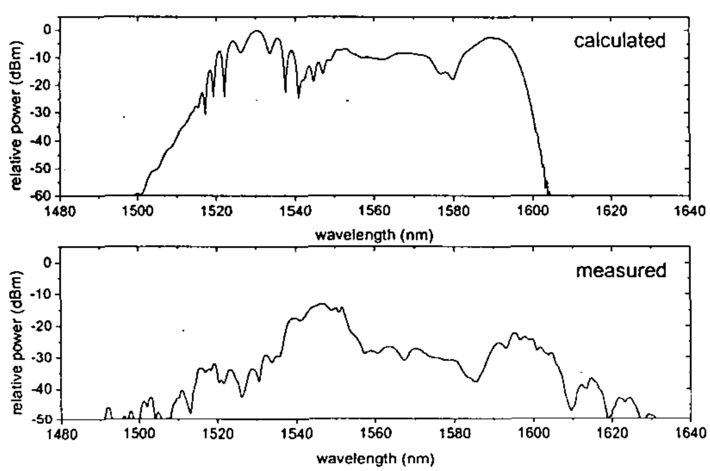

Figure 4. Comparison of calculated (top) and measured (bottom) supercontinuum spectra for the experimental conditions of Fig. 2 (b).

Figure 4 presents a comparison of the calculated and experimental spectra obtained for a pump wavelength of 1550.5 nm, a pump power of 22 dBm and a pulse width equal to ~0.3 ps (corresponding to Fig. 2 (b)). A number of spectral features such as the two peaks at 1545 and 1595 nm, the plateau in-between and the notch around 1585 nm are reproduced in the numerical results, although a wavelength offset can be noticed when compared to the measurement.

Possible explanations for this discrepancy are: (i) the wavelength dependence of the effective area and (ii) the loss coefficient are not taken into account; (iii) the fibre birefringence and difference in GVD for the two principal polarisation axes are not modelled. Nevertheless, our model enables to accurately predict the main features of the generated supercontinuum. It is therefore expected that a more accurate description of the experimental conditions should allow for a closer match between the SC spectra obtained experimentally and by numerical simulation.

4. CONCLUSION

We have demonstrated supercontinuum generation over the entire C and L band by pumping a highly non-linear photonic crystal fibre with zero dispersion at 1552 nm with picosecond pulses at a repetition frequency of 10 GHz. Spectral slicing was achieved using an optical tunable bandpass filter, enabling to demonstrate the realisation of an optical clock wavelength translator from ~1550 nm up to the L-band. It should be emphasised that the highly non-linear PCF used in those experiments was spliced to standard single mode fibre pigtails, making our clock wavelength translator entirely compatible with fibre optics technology. Numerical simulations have been initiated in order to identify the mechanisms involved in the generation of supercontinua in the picosecond regime. Optimisation of the dispersion profile of the PCF should allow for a better control of the physical processes involved in order to optimise the generated SC spectrum, especially with respect to its wavelength uniformity.

REFERENCES

[1] J. K. Ranka *et al.*: Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm, *Opt. Lett., vol. 25, pp. 25-27, Jan. 2000.*

[2] S. Coen *et al.*: Supercontinuum generation by stimulated Raman scattering and parametric four-wave mixing in photonic crystal fibers, *J. Opt. Soc. Am. B, vol. 19, pp. 753-764, Apr. 2002.*

[3] W. J. Wadsworth *et al.*: Supercontinuum generation in photonic crystal fibers and optical fiber tapers: a novel light source, *J. Opt. Soc. Am. B, vol. 19, pp. 2148-2155, Sep. 2002.*

[4] A. V. Husakou and J. Herrmann: Supercontinuum generation, four-wave mixing, and fission of higher-order solitons in photonic-crystal fibers, *J. Opt. Soc. Am. B, vol. 19, pp. 2171-2182, Sep. 2002.*

[5] L. I. Nikolov *et al.*: Designing the dispersion for optimum supercontinuum bandwidth using picosecond pulses, *Proc. OFC 2003, Atlanta, U.S.A., Mar. 2003, paper MF16.*

[6] M. Lehtonen *et al.*: Supercontinuum generation in a highly birefringent microstructured fiber, *Appl. Phys. Lett., vol. 82, pp. 2197-2199, Mar. 2003.*

[7] S. Watanabe and F. Futami: All optical wavelength conversion using ultra-fast nonlinearities in optical fibre, *IEICE Trans. Electron., vol. E85-C, pp. 889-895, Apr. 2002.*

[8] T. Yamamoto *et al.*: 640-Gbit/s optical TDM transmission over 92 km through a dispersion-managed fiber consisting of single-mode fiber and "reverse dispersion fiber", *IEEE Photon. Technol. Lett., vol. 12, pp. 353-355, Mar. 2000.*

[9] Z. Yusoff *et al.*: 24 channels × 10GHz spectrally sliced pulse source based on spectral broadening in a highly nonlinear holey fiber, *Proc. OFC 2003, Atlanta, U.S.A, Mar. 2003, paper FH3.*

[10] K. P. Hansen *et al.*: Highly nonlinear photonic crystal fiber with zero dispersion at 1.55 μm, *in Proc. OFC 2002, Anaheim, U.S.A., Mar. 2002, post-deadline paper FA9.*

[11] G. P. Agrawal: Nonlinear fiber optics, 3rd edition, Academic Press, 2001.