Technical University of Denmark

Numerical demonstration of 3-12µm supercontinuum generation in large-core step-index chalcogenide fibers pumped at 4.5µm

Agger, Christian; Kubat, Irnis; Møller, Uffe Visbech; Bang, Ole; Moselund, Peter M.; Petersen, Christian; Napier, Bruce; Seddon, Angela; Sujecki, Slawomir; Benson, Trevor; Farries, Mark; Ward, Jon; Lamrini, Samir; Scholle, Karsten; Fuhrberg, Peter

Published in:
Nonlinear Optics Technical Digest

Publication date:
2013

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

Numerical demonstration of 3-12μm supercontinuum generation in large-core step-index chalcogenide fibers pumped at 4.5μm

Christian Agger, Irnis Kubat, Uffe Møller, Ole Bang
DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, 2800 Kgs. Lyngby, Denmark
oban@fotonik.dtu.dk
Peter M. Moselund, Christian Petersen
NKT Photonics A/S, Blokken 84, 3460 Birkerød, Denmark
Bruce Napier
Vivid Components Ltd., Dr.-Rörig-Damm 22, 33102 Paderborn, Germany
Angela Seddon, Slawomir Sujecki, Trevor Benson
George Green Institute for Electromagnetics Research, Faculty of Engineering, University Park, University of Nottingham, Nottingham NG7 2RD, UK
Mark Farries
Gooch & Housego (Torquay) Ltd., Broomhill Way Torquay, Devon, TQ2 7QL, UK
Jon Ward
Gooch & Housego (UK) Ltd., Dowlish Ford, Ilminster, Somerset, TA19 OPF, UK
Samir Lamrini, Karsten Scholle, Peter Fuhrberg
LISA laser products OHG, Fuhrberg & Teichmann, Max-Planck-Str.1, 37191 Katlenburg-Lindau, Germany

Abstract: We numerically demonstrate the generation of a 3-12μm mid-infrared supercontinuum in a large-core (20μm diameter) step-index fiber made from highly nonlinear chalcogenide (As_2Se_3) pumped at 4.5μm with 40ps, 1kW peak power pulses.
OCIS codes: (190.4370) Nonlinear optics, Fibers; (190.5530) Pulse propagation and temporal solitons

1. Introduction

Mid-infrared (IR) supercontinuum (SC) sources have great potential for improving spectral analysis tools, because of their spatial coherence and high power density over a broad bandwidth. A 1-4.5μm SC source was for example recently used in hyperspectral IR microscopy to demonstrate simultaneous analysis at multiple wavelengths [1]. In the food and pharmaceutical industry, analysis methods, such as Fourier Transform IR (FTIR) spectroscopy, can significantly be improved by using a broadband high-power SC source [2], and mid-IR SC sources are also ideal for stand-off ranged detection, where high power density over a broad spectral range is necessary to acquire as much information as possible about an ensemble of potentially hazardous substances from a safe distance [3]. Current state-of-the-art mid-IR SC sources cover 1-4.5μm using ZBLAN step-index fibers (SIFs) [4].

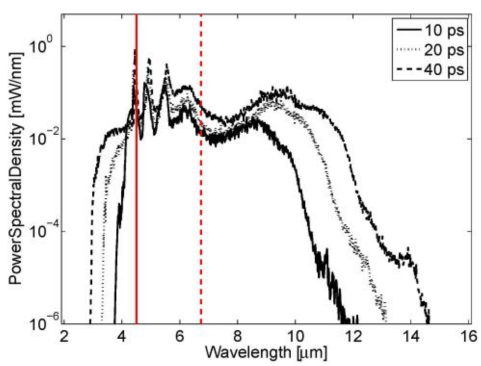

Fig. 1. Output spectrum from a 3m long chalcogenide SIF with d=20μm and NA =0.5 pumped at 4.5μm with a 10ps (solid), 20ps (dotted), and 40ps (dashed) pulse with 1kW peak power. Solid (dashed) red vertical line marks the pump and λ_{ZD} respectively.

With an aim to allow for early cancer detection with mid-IR SC sources we here consider the use of large-core (20μm diameter) chalcogenide SIFs pumped with a mode-locked Pr-doped chalcogenide fiber laser giving 40ps pulses at 4.5μm to generate a 3-12μm SC. This would cover the absorption bands of key biological compounds, such as proteins, lipids, carbohydrates, and nucleotides [5]. The use of large-core SIFs would increase the power handling capability and the robustness of the SC source. The numerically obtained SC spectra shown in Fig. 1 (see details below) demonstrate that such a 3-12μm SC source is feasible using current chalcogenide fiber technology.

2. Numerical results

We consider As_2Se_3 chalcogenide SIFs and material data summarized in [6]. Thus, the refractive index is given by the Sellmeier equation $n^2=1+\lambda^2[A_1^2/(\lambda^2-a_1^2)+A_2^2/(\lambda^2-a_2^2)+A_3^2/(\lambda^2-a_3^2)]$, where $A_1 = 2.234921$, $A_2 = 0.347441$, $A_3 = 1.308575$, $a_1=0.24164$, $a_2=19$, $a_3=2a_1$, with λ given in microns [6]. The nonlinear coefficient is $n_2=2.4\text{x}10^{-17}\text{m}^2/\text{W}$ and the total nonlinear response is $R(t) =(1-f_R)\delta(t)+f_Rh_R(t)$, where the fractional Raman contribution is $f_R=0.115$ and the delayed Raman response function is $h_R(t)=[(\tau_1^2+\tau_2^2)/(\tau_1\tau_2^2)]\exp(-t/\tau_2)\sin(t/\tau_1)$, with $\tau_1=23.1$fs and $\tau_2=195$fs. In Fig. 2 we summarize our calculated fiber dispersion and loss properties using a Numerical Aperture (NA) assumed to be frequency constant. Here the total loss is defined as a constant material loss of 1dB/m plus confinement loss. Material losses of As_2Se_3 chalcogenide much less than 1dB/m have been demonstrated by several groups [6,7].

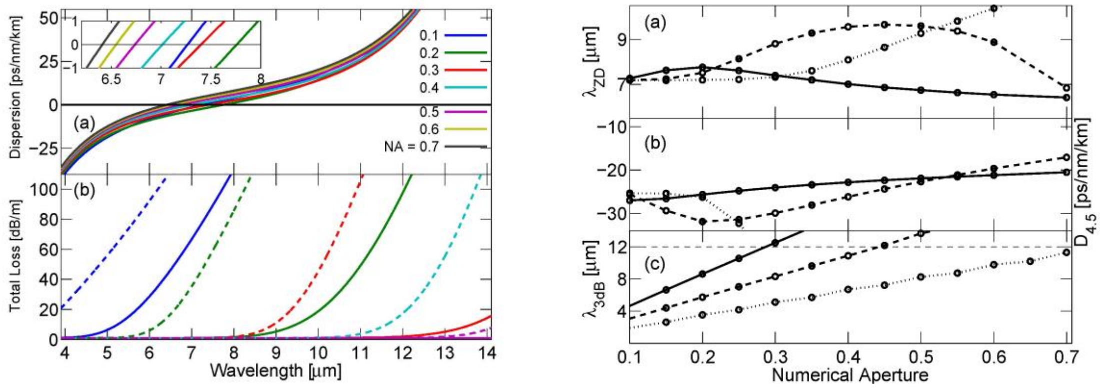

Fig. 2. Left: dispersion (a) and total loss (b) versus wavelength for a d=20μm (solid curves) and d=10μm chalcogenide SIF for different values of NA. Right: Zero-dispersion wavelength λ_{ZD} (a), dispersion at 4.5μm $D_{4.5}$ (b), and 3dB/m total loss edge λ_{3dB} (c) of a d=20μm (solid), d=10μm (dashed), and d=5μm (dotted) chalcogenide SIF versus NA.

Figure 2 shows that if we want to use a 20μm (10μm) core diameter and generate an SC extending to 12μm then we need an NA of at least 0.3 (0.45) in order to overcome confinement loss. We also see that a 5μm core gives too high a loss. Looking at the dispersion we see that our 4.5μm pump will always be in the normal dispersion regime. We therefore need to bring the zero-dispersion wavelength (λ_{ZD}) as close as possible to the pump to minimize the number of Raman Stokes orders necessary to transfer light across the λ_{ZD} into the anomalous dispersion regime and generate solitons that can further extend the SC to 12μm. For NA>0.3 the 10μm core fiber has too long a λ_{ZD} to be of use, except for very high NA above 0.7. Thus, focussing on the 20μm core diameter fiber, we see that λ_{ZD} and the absolute value of the dispersion at the pump both decrease with NA. At a reasonable NA value of 0.5, achievable with today's chalcogenide fiber technology, λ_{ZD}=6.74μm. We have modeled SC generation in 3m of such a fiber using the generalized nonlinear Schrödinger equation as detailed in [8]. For a fixed feasible peak power of 1kW the results shown in Fig. 1 clearly demonstrate that a 3-12μm SC can be generated with a pulse length of 40ps or longer.

This work is part of the integrated project MINERVA (www.minerva-project.eu) supported through the EC Seventh Framework Programme (FP7).

3. References

[1] S. Dupont, C. Petersen, J. Thøgersen, C. Agger, O. Bang, S.R. Keiding, "IR microscopy utilizing intense supercontinuum light source", Opt. Express. **20**, 4887–4892 (2012).
[2] S. Wartewig, R.H.H. Neubert, "Pharmaceutical applications of Mid-IR and Raman spectroscopy", Adv. Drug Delivery Rev. **57**, 1144-1170 (2005).
[3] M. Kumar, M. N. Islam, J. Fred L. Terry, M. J. Freeman, A. Chan, M. Neelakander, T. Manzur, "Standoff detection of solid targets with diffuse reflection spectroscopy using a high-power mid-infrared supercontinuum source", Appl. Opt. **51**, 2794–2807 (2012).
[4] P.M. Moselund, C. Petersen, S. Dupont, C. Agger, O. Bang, S.R. Keiding, "Supercontinuum – broad as a lamp bright as a laser, now in the mid-infrared", Proc SPIE **8381**, 83811A (2012).
[5] Chapter 11 of "Biomedical Applications of Synchrotron Infrared Microspectroscopy: A Practical Approach", Ed. David Moss, Publisher: RSC Analytical Spectroscopy Monographs (2011).
[6] B. Ung, M. Skorobogatiy, "Chalcogenide microporous fibers for linear and nonlinear applications in the mid-infrared", Opt. Express **18,** 8647-8659 (2010).
[7] H. Rowe, J. Shephard, D. Furniss, C.A. Miller, S. Savage, T.M. Benson, D.P. Hand, A.B. Seddon., "The application of the mid-infrared spectral region in medical surgery: chalcogenide glass optical fibre for 10.6 mu m laser transmission", Proc. SPIE **6852**, 685208 (2008).
[8] C. Agger, C. Petersen, S. Dupont, H. Steffensen, J.K. Lyngsø, C.L. Thomsen, S.R. Keiding, O. Bang, "Supercontinuum generation in ZBLAN fibers – detailed comparison between measurement and simulation", J. Opt. Soc. Am. B **29**, 635-645 (2012).