# Design, modelling and experiments of mid-IR SC generation in soft-glass Photonic Crystal Fibers

SUPUVIR — SUPercontinuum broadband light sources covering UV to IR applications


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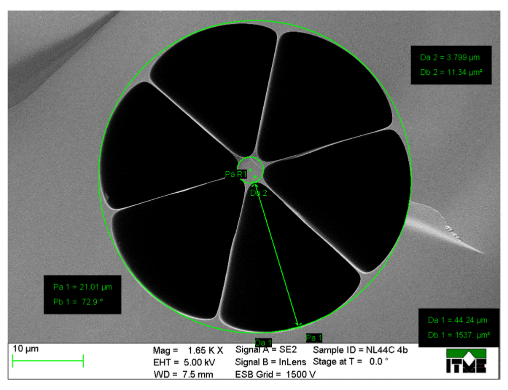
## Context

Broadband, compact, and cost-effective supercontinuum (SC) sources in the infrared (IR) are very attractive for sensing and spectroscopy applications because this wavelength range contains the ground tones of many molecules [1]. Soft glasses such as chalcogenide [1], tellurite [2], and fluoride glasses [3] have been considered as host materials for highly nonlinear fibers, giving rise to efficient SC generation in the mid-IR up to 15 µm. The main objectives are here to numerically design and experimentally demonstrate wideband and flat SC in the mid-IR band using soft-glass tapered optical fibers. Theoretical work focuses on generalizing existing models of SC to include pulse chirp, varying core diameters, OH and SH absorption bands, and accurately modelling nonlinear effects in new materials. We demonstrate SC generation in suspended-core heavy-metal-oxide soft-glass photonic crystal fibers (PCFs) using femtosecond pulses. We further designed and fabricated new polarization-maintaining chalcogenide-glass tapered PCFs.

## Heavy metal-oxide glass based photonic crystal fibers (PCFs) and experimental setup for SC generation

HE11 mode, effective refractive index and dispersion curves computed using COMSOL software

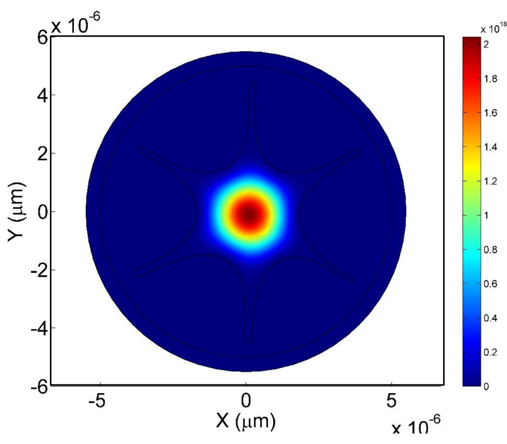


*SEM image of a suspended-core PCF*

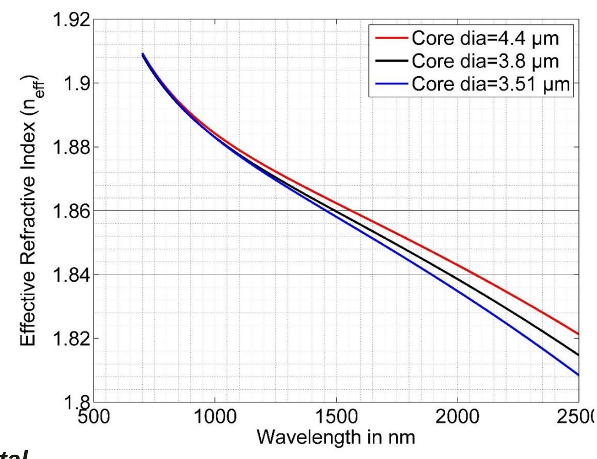
| Material | % mole | %mass |
|---|---|---|
| $SiO_2$ | 40 | 14.06 |
| $Ga_2O_3$ | 13 | 14.26 |
| $Bi_2O_3$ | 10 | 27.26 |
| PbO | 30 | 39.17 |
| CdO | 7 | 5.26 |

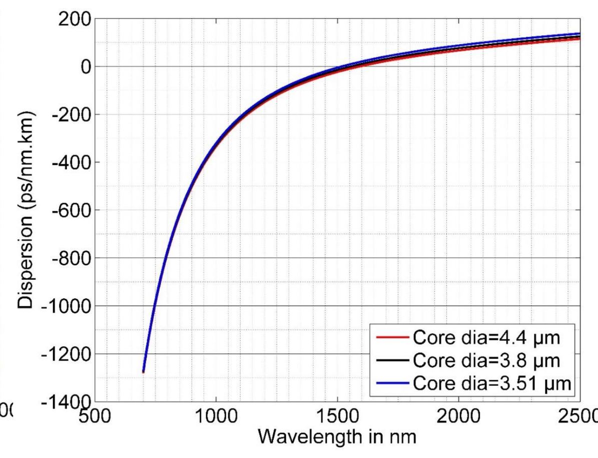
*Material composition of heavy metal-oxide PBG81 glass*

Nonlinear refractive index ⟶ $4.3 \times 10^{-19} \mathrm{m^2/W}$

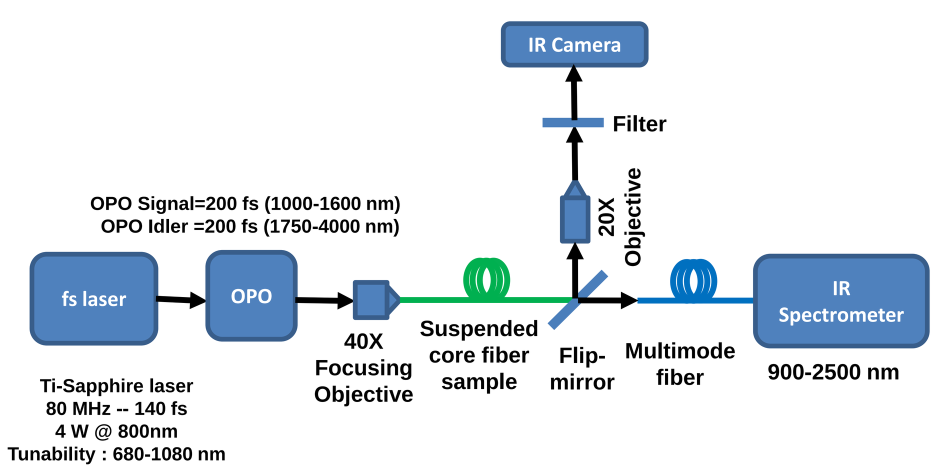



*Optical Power density of the HE11 fundamental mode at 1550 nm*



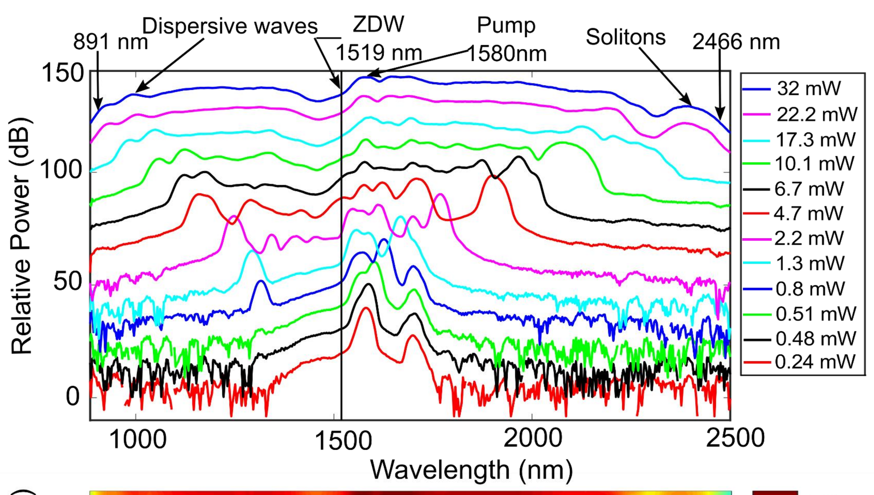



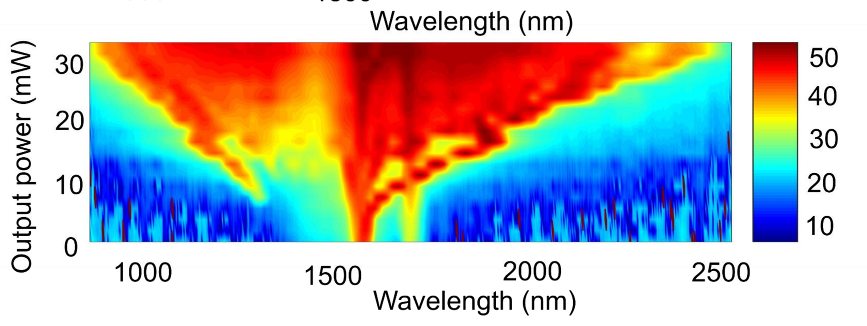

### ➢ Experimental setup




## Experimental results and comparison with improved numerical simulations

### IR SC spectrum

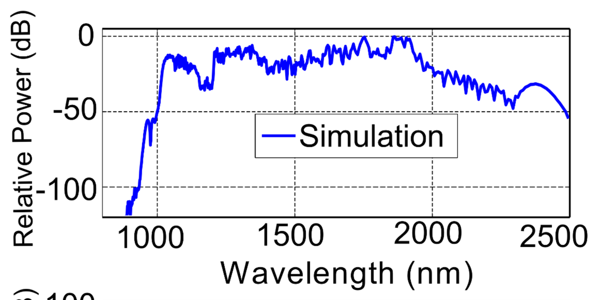


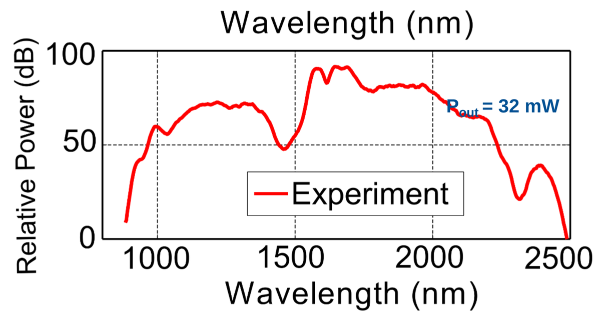




### Numerical modeling with a generalized Nonlinear Schrödinger equation

$$\underbrace{\frac{\partial A}{\partial z} + \frac{\alpha}{2}A - \sum_{k\geq 2}\frac{i^{k+1}}{k!}\beta^k\frac{\partial^k A}{\partial T^k}}_{\text{Linear dispersion}} = i\gamma\underbrace{\left(1 + i\tau_{shock}\frac{\partial}{\partial T}\right)}_{\text{Self-steepening}}\underbrace{\left(A(z,T)\int_{-\infty}^{+\infty}R(T')\,|A(z,T-T')|^2\,dT'\right)}_{\text{Nonlinear Function (Kerr + Raman)}}$$

Fiber parameters:
$d_c$= 3.51 µm
L = 180 cm



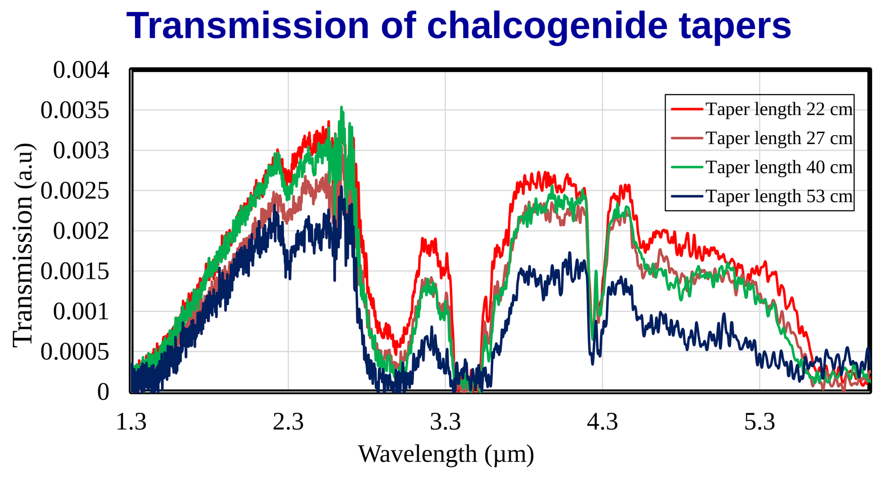




| Numerical parameters | |
|---|---|
| Pulse duration | 220 fs |
| Peak power | 25 kW |
| Loss factor | 5 dB/m |
| Fiber length | 10 cm |
| Nonlinear coefficient | 200 $W^{-1}km^{-1}$ |
| Pulse chirp | Linear chirp (parabolic phase) |
| $f_R$ | 0.05 |

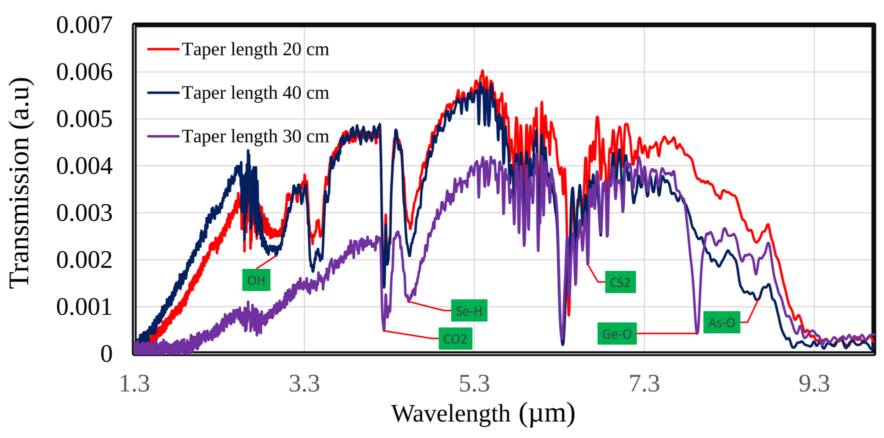
- We demonstrated wideband SC generation from 891 nm up to 2466 nm by pumping single mode heavy metal oxide glass fibers with femtosecond pulses at 1580 nm.
- Numerical simulations show that the supercontinuum is generated through self-phase modulation, Raman-induced soliton self-frequency shift, and dispersive wave generation.

## Expected results and progress towards objectives:

### Transmission of chalcogenide tapers



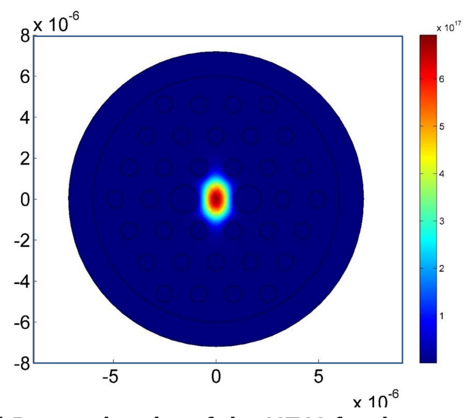

*Transmission spectrum of $As_{38}Se_{62}$ PM PCF tapers with 1.7 µm core diameter*



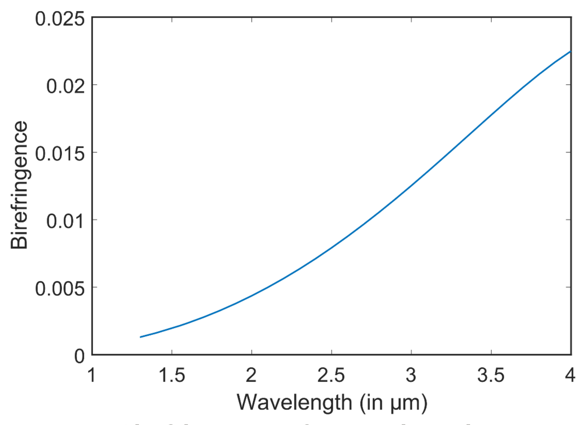

*Transmission spectrum of $Ge_{10}As_{22}Se_{68}$ PCF tapers with 5 µm core diameter*

### Numerical simulations in the tapered and untapered ($As_{38}Se_{62}$) PM PCF

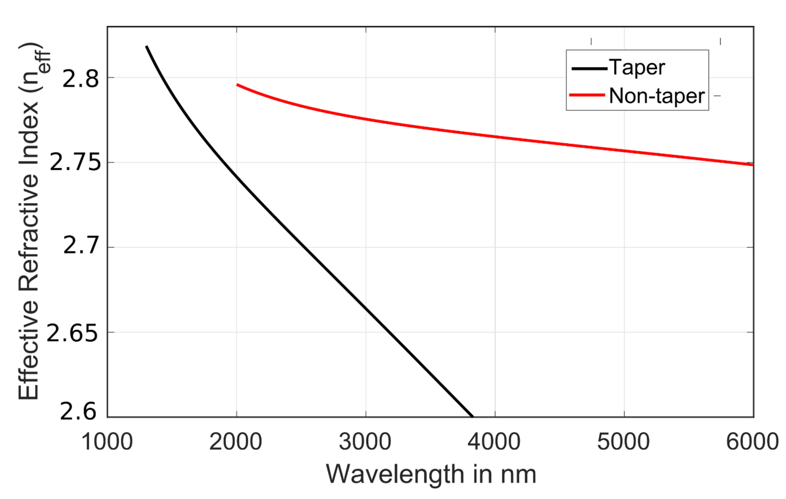
HE11 mode, effective refractive index and dispersion curves computed using COMSOL software

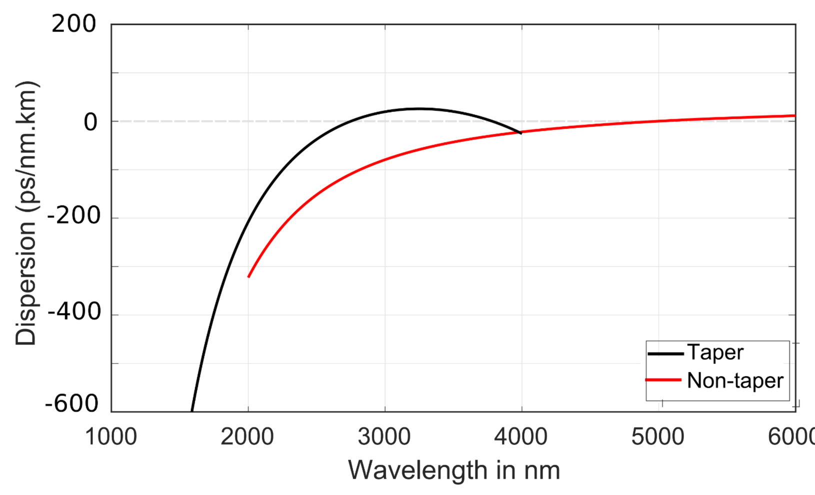


*Optical Power density of the HE11 fundamental mode at 2000 nm in the taper section*




*Birefringence of tapered section*




Nonlinear refractive index of $As_{38}Se_{62}$ glass ⟶ $1.08 \times 10^{-17} \mathrm{m^2/W}$

Nonlinear refractive index of $Ge_{10}As_{22}Se_{68}$ glass ⟶ $1.35 \times 10^{-17} \mathrm{m^2/W}$

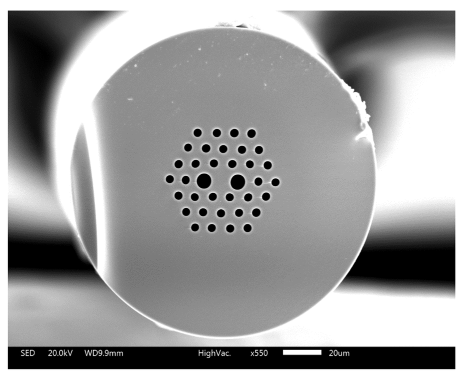
- ➢ These tapered fibers will be tested with MHz OPA laser system (tunable from 3.7-4.6 µm) in DTU Fotonik for SC generation beyond 6 µm.
- ➢ Numerical simulations based on the generalized nonlinear Schrödinger equation will also be performed to compare it with experimental results.

## Planned secondment

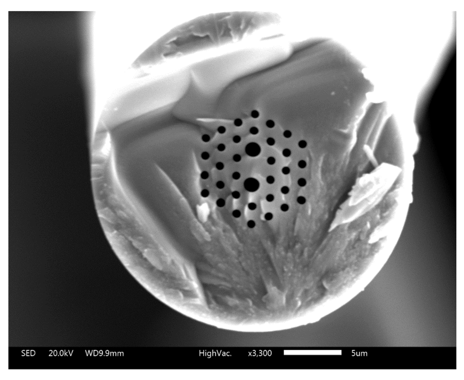
Secondment in Selenoptics and University of Rennes 1 from June 1st to June 21st, 2018 with M. Meneghetti (ESR10), L. Brilland, and J. Troles.

- ➢ Chalcogenide glass synthesis
- ➢ Drawing of gradient index (GRIN) chalcogenide Canes
- ➢ Drawing of AsSe polarization-maintaining (PM) PCF
- ➢ Fabrication of PM and GeAsSe PCF tapers

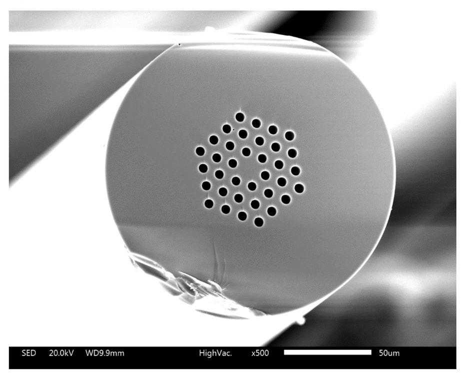
### SEM images



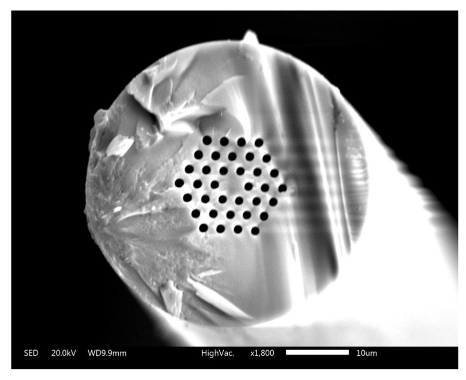
$As_{38}Se_{62}$ PM PCF (Normal section)



$As_{38}Se_{62}$ PM PCF (Tapered section)



$Ge_{10}As_{22}Se_{68}$ PCF (Normal section)



$Ge_{10}As_{22}Se_{68}$ PCF (Tapered section)

## Status of Publications

**A. N. Ghosh**, M. Klimczak, R. Buczynski, J. M. Dudley, and T. Sylvestre, "Supercontinuum generation in heavy-metal oxide glass based suspended-core photonic crystal fibers," J. Opt. Soc. Am. B 35, 2311-2316 (2018).

**A. N. Ghosh**, M. Klimczak, R. Buczyński, J. M. Dudley, T. Sylvestre, "Supercontinuum generation in a suspended core heavy metal oxide glass photonic crystal fiber," SPIE Photonics Europe 2018, Strasbourg, France, 26 April 2018. (Proc. SPIE 10681, 9 May 2018) **INVITED PAPER**.

**A. N. Ghosh**, M. Klimczak, R. Buczynski, J. Dudley, T. Sylvestre, "Supercontinuum Generation in Suspended-Core Heavy-Metal Oxide Glass Photonic Crystal Fibers," OSA Advanced Photonic Congress, Paper SoTh3H.2, Zurich, 2-5 July 2018. (oral presentation and **Best Student Paper Award**).


[1] C. R. Petersen *et al.*, Nat. Phot. **8**, 830 (2014)
[2] F. Désévédavy et al., Springer Series Mat. Sci. 254 (2017)
[3] C. Xia *et al.*, Opt. Lett. **31**(17), 2553 (2006)
[4] C. Caillaud *et al.*, Opt. Express **24**, 7977 (2016)
[5] Q. Coulombier *et al.*, Opt. Express **18**, 9107 (2010)



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