Mid-Infrared Supercontinuum Generation in Optical Fibers

Christian Rosenberg Petersen, Technical University of Denmark

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Fiber Modeling
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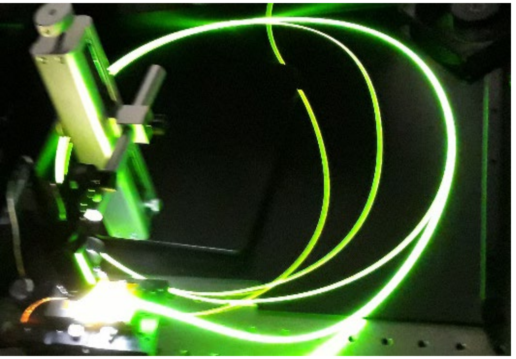
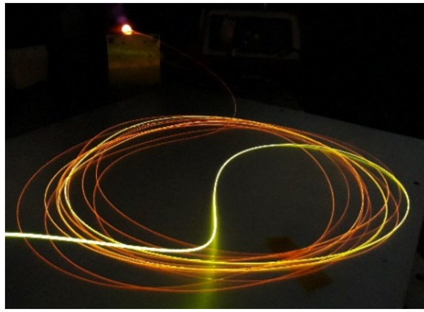
Welcomes You for the webinar on

“Mid-Infrared Supercontinuum Generation in Optical Fibers”

May *20th 2020, 10 am EDT*





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About us: A unique group of more than 900 researchers from 70+ countries from North America, South America, Europe, Asia, Africa, and Oceania.

Goals:
To benefit **OSA members** having interest in Fiber Design, Modeling, Fabrication, and Applications of fibers.
To Provide a platform to Fiber Community for connecting, Engaging and Exciting with others.
To Organize Webinars, Technical and Networking Events, and Special Journal Issues.

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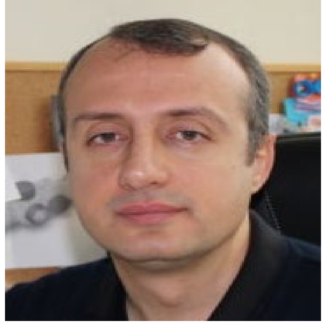
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Past Events:

1. Networking Event: Date: Tuesday, 16 Jul 2019 17:00-18:00
Location: Naupaka III, Waikoloa Beach Marriott Resort & Spa, Waikoloa Beach, Hawaii

2. Webinar 1: Everything you always wanted to know about supercontinuum modelling in optical fibers (but were afraid to ask) Date: 26th August 2019, at Swiss time 2pm/ EDT 8am
A/Prof. Alexander Heidt, University of Bern, Switzerland.

3. Webinar 2: The development of thulium and holmium fiber sources
Date: 30th September, 2019 at 1pm (UK time)/ EDT 7am
Dr. Nikita Simakov, DSTO, Australia.

4. Webinar 3: Recent development in hollow-core optical fiber
Date: 14 November, 2019, 8 am Beijing Time
A/Prof. Y Wang, Beijing University of Technology, China.

OSA Fiber Modeling and Fabrication Technical Group

Events at CLEO San Jose, CLEO Pacific-Rim, and FIO USA !!!!

Current/Future Webinars:

Webinar 1: Integration of 2-dimensional materials in fiber optics for ultra-short pulse lasers
Date: 13th March 2020, 8 pm EDT.
Prof. Kyunghwan Oh, Yonsei University, South Korea.

Webinar 2: Novel Optical Materials for optical Fibers
Date: 24th April 2020, 11 am EDT.
Prof. John Ballato, Clemson University, USA.

Webinar 3: Mid-Infrared Supercontinuum Generation in Optical Fibers
Date: 20 May 2020, 10 am EDT.
Dr. Christian Petersen, Technical University of Denmark, Fotonik.

Webinar 4: Hybrid (M-type) fibers for dispersion management
Date: 18 September, 3 pm EDT.
Dr. Svetlana Aleshkina, Fiber Optics Research Center, Russian Academy of Sciences, Russia.

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Today's Webinar

Fiber Modeling
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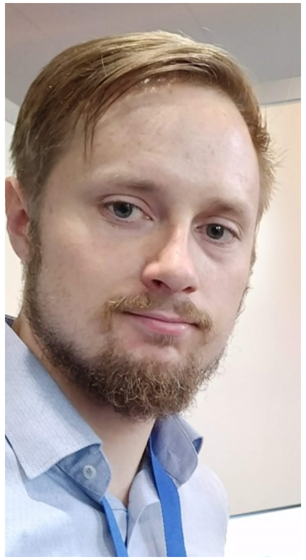
Mid-Infrared Supercontinuum Generation in Optical Fibers

Dr. Christian Petersen, Technical University of Denmark

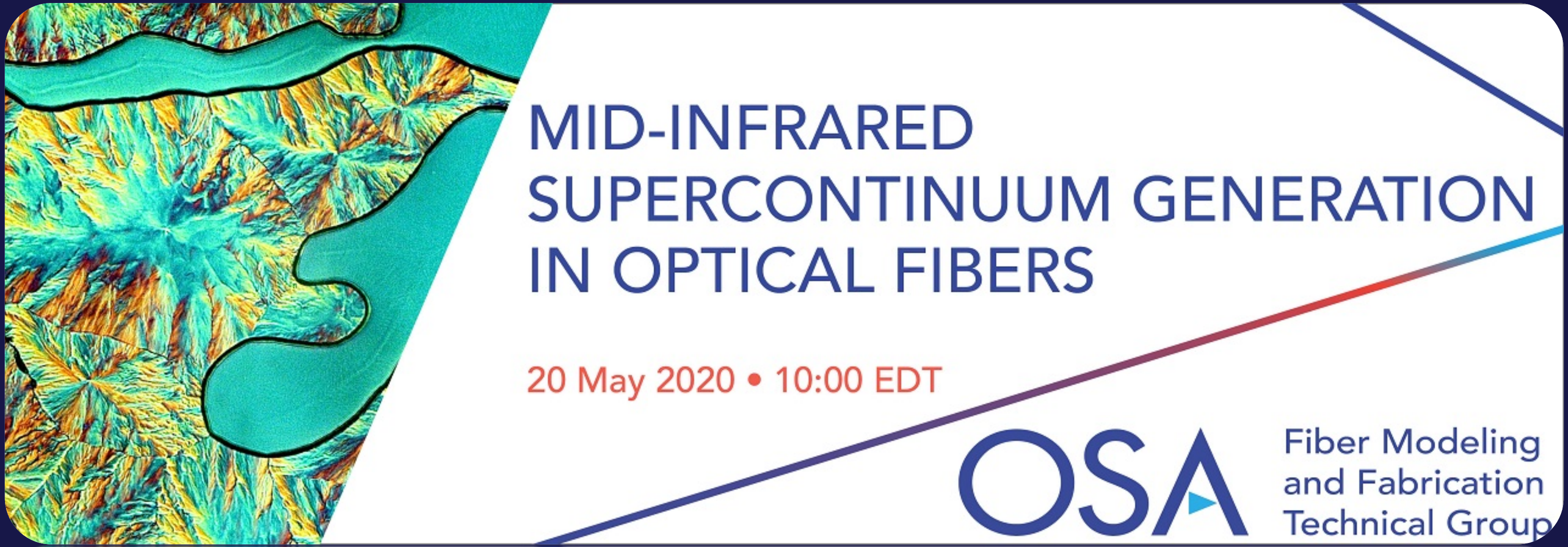


Speaker's Short Bio: Dr. Christian Rosenberg Petersen obtained his BSc. (2011), MSc. (2013), and PhD. (2016) degree from the Technical University of Denmark, Department of Photonics Engineering. During and after his PhD as a postdoc, he has been working at the department in the group of Prof. Ole Bang with a speciality in experimental mid-infrared supercontinuum generation and applications. He is also co-founder of the Danish start-up company NORBLIS, which is a university spin-out developing mid-infrared supercontinuum lasers and imaging systems.

DTU

Presenter:

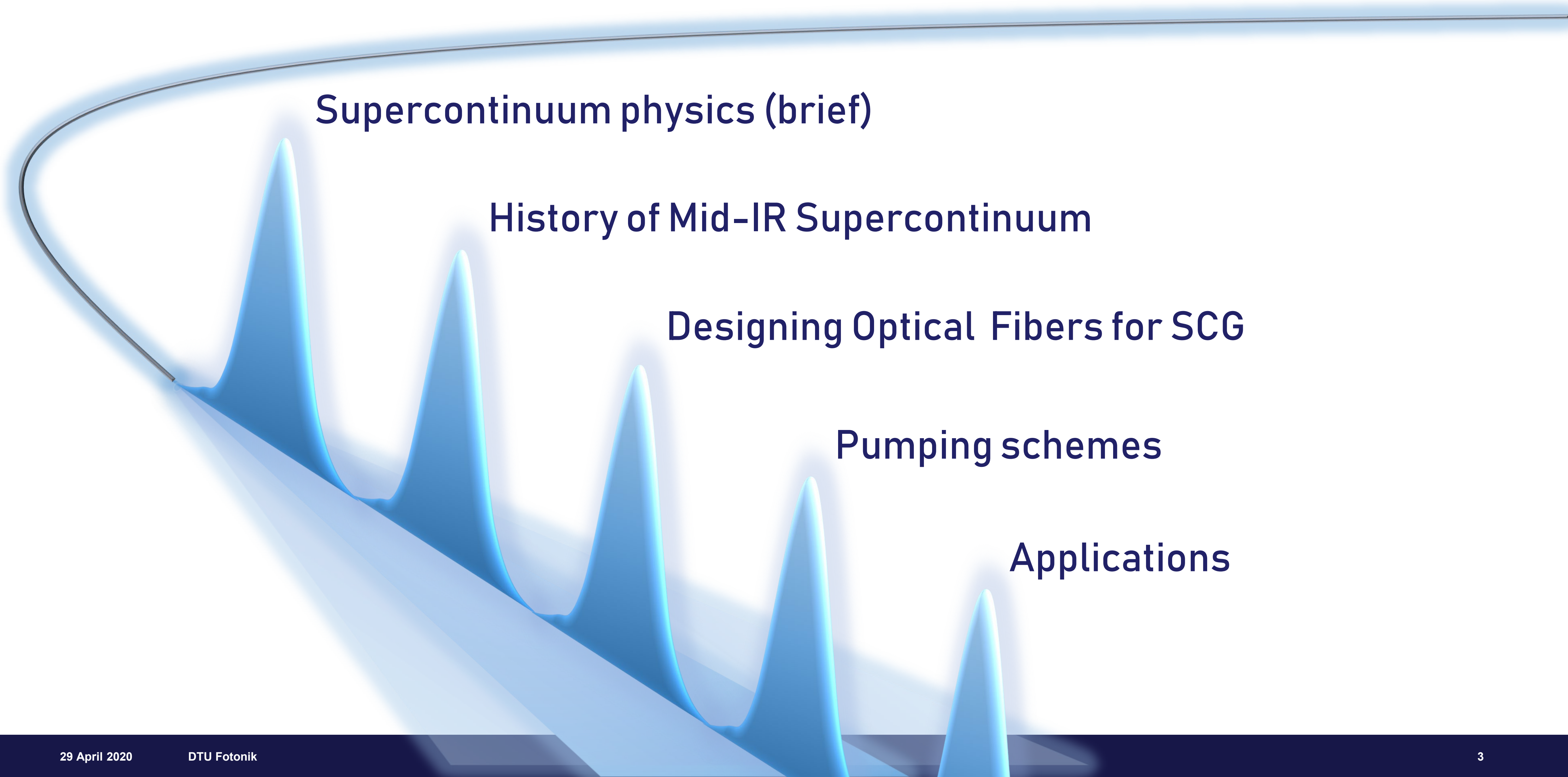
Christian Rosenberg Petersen
Technical University of Denmark



MID-INFRARED SUPERCONTINUUM GENERATION IN OPTICAL FIBERS

20 May 2020 • 10:00 EDT

OUTLINE

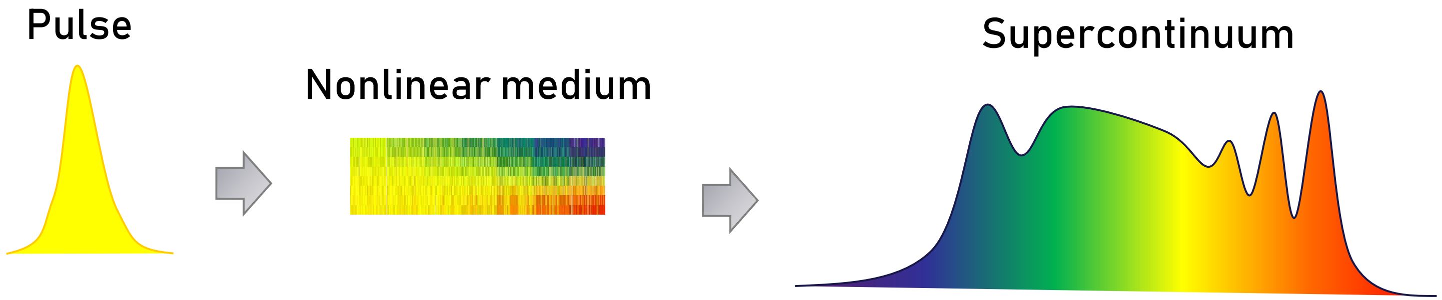


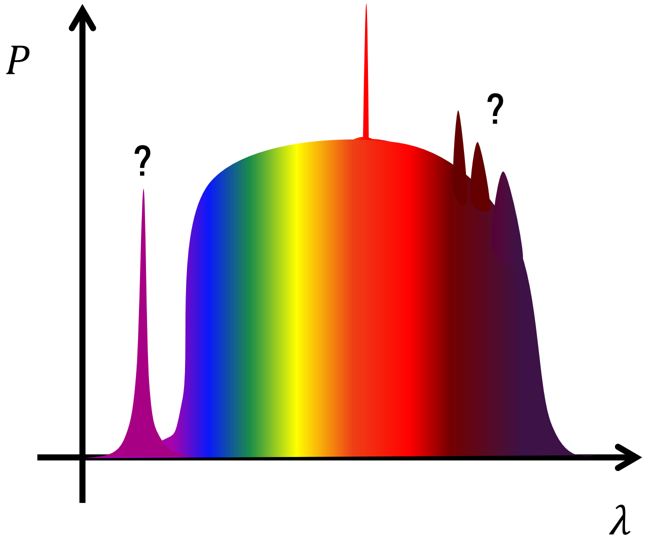
- Supercontinuum physics (brief)
- History of Mid-IR Supercontinuum
- Designing Optical Fibers for SCG
- Pumping schemes
- Applications

SUPERCONTINUUM PHYSICS

SUPERCONTINUUM

Generation of new optical frequencies covering a wide continuous spectral range through nonlinear light-matter interaction.





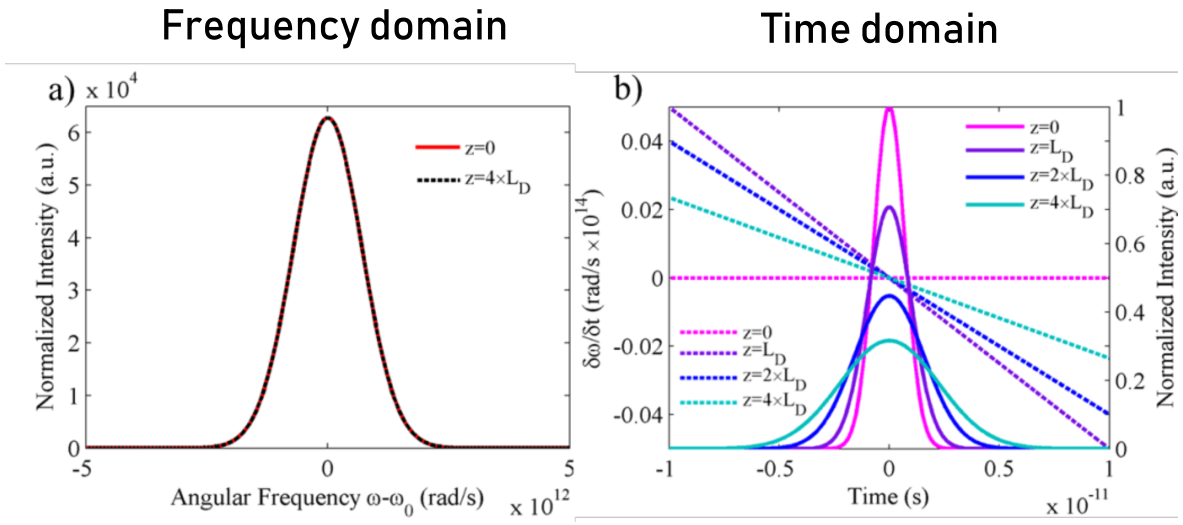
SUPERCONTINUUM PHYSICS

$$L_D = \frac{T_0^2}{|\beta_2|} \qquad L_{NL} = \frac{1}{\gamma P_0} \qquad \gamma = \frac{n_2\omega_0}{cA_{\text{eff}}}$$

DISPERSION

Group-velocity dispersion (GVD) is related to the wavelength dependent refractive index. Different frequencies travel at different speeds in a medium, and will thus introduce a frequency chirp across the pulse.

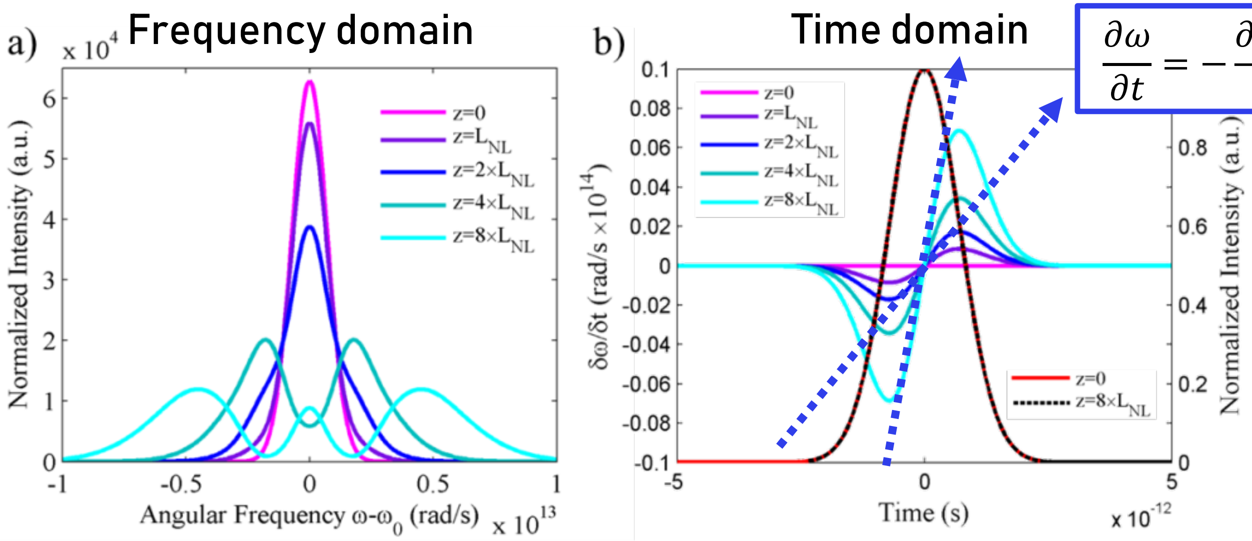
$$D = -\frac{\lambda}{c}\frac{\partial^2 n}{\partial\lambda^2} = \frac{\partial\beta_1}{\partial\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2$$



SELF-PHASE MODULATION

Self-phase modulation (SPM) is caused by the combination of an intensity dependent refractive index (Kerr effect) and a non-uniform pulse intensity profile. The effect is most pronounced in very short pulses (ps/fs) with high dΦ/dt

$$\phi = nk_0z = (n_0 + n_2|\boldsymbol{E}|^2)k_0z$$

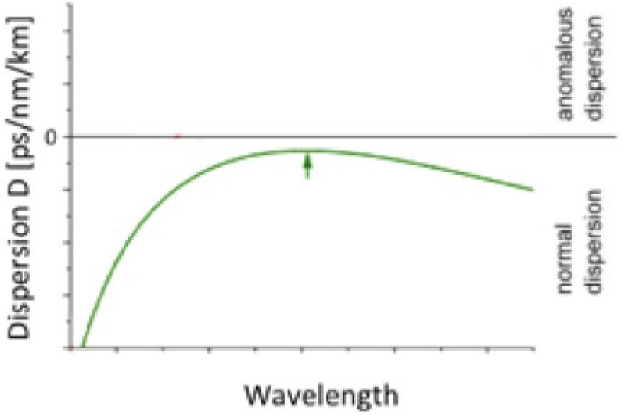


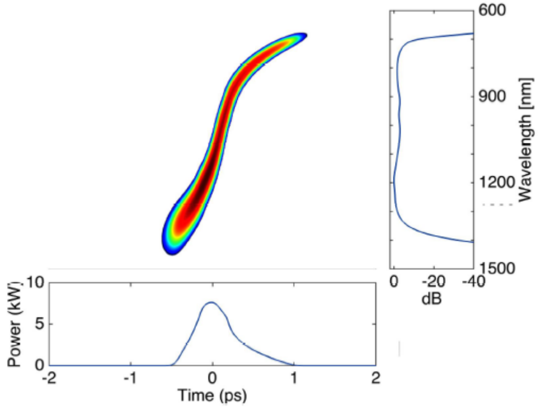
$$\boxed{\frac{\partial\omega}{\partial t} = -\frac{\partial\phi_{NL}}{\partial t}}$$

SUPERCONTINUUM PHYSICS

NORMAL DISPERSION

For $D < 0$ ($\beta > 0$) the chirp of SPM and GVD act together to stretch the pulse in both time and frequency. Such a SC is in principle fully coherent, although for high power or long fiber length the coherence may degrade.

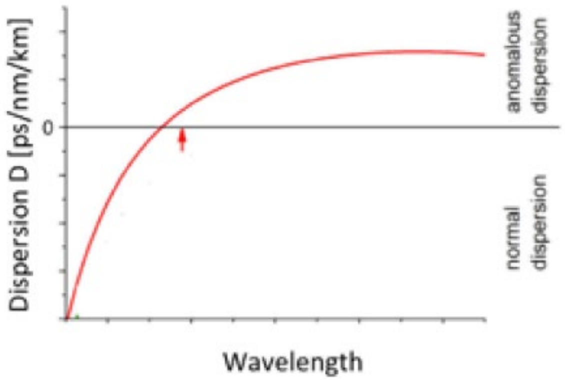


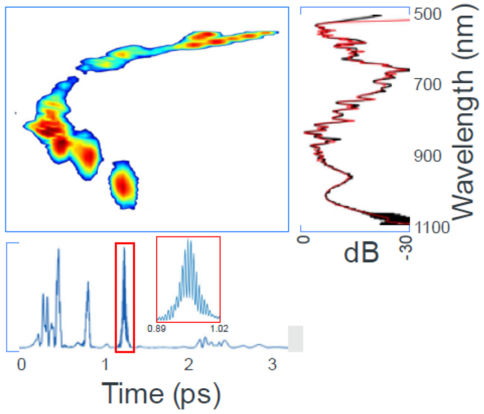


ANOMALOUS DISPERSION

For $D > 0$ ($\beta < 0$) the frequency chirp from SPM and GVD can be made to cancel out when the dispersion is anomalous.

The result is a soliton – a stable pulse that does not broaden temporally with propagation.





Alexander M. Heidt, Thomas Feurer, Proc. SPIE vol. 10591, 105910B (2018)

SUPERCONTINUUM PHYSICS

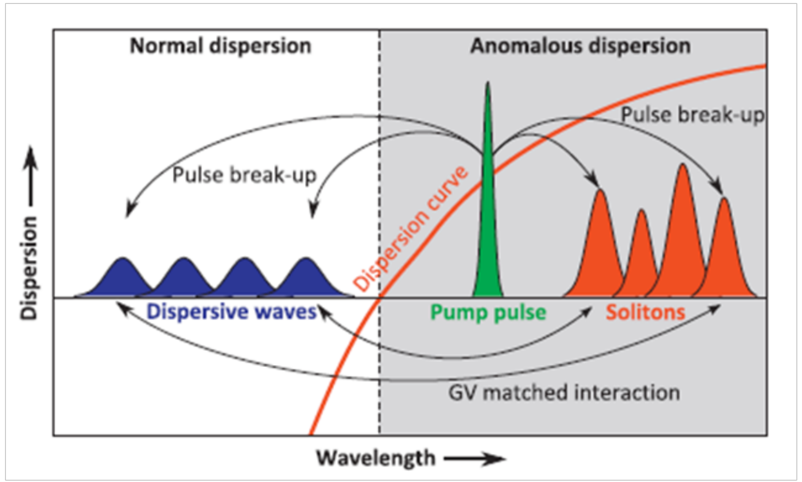
FISSION AND DISPERSIVE WAVES

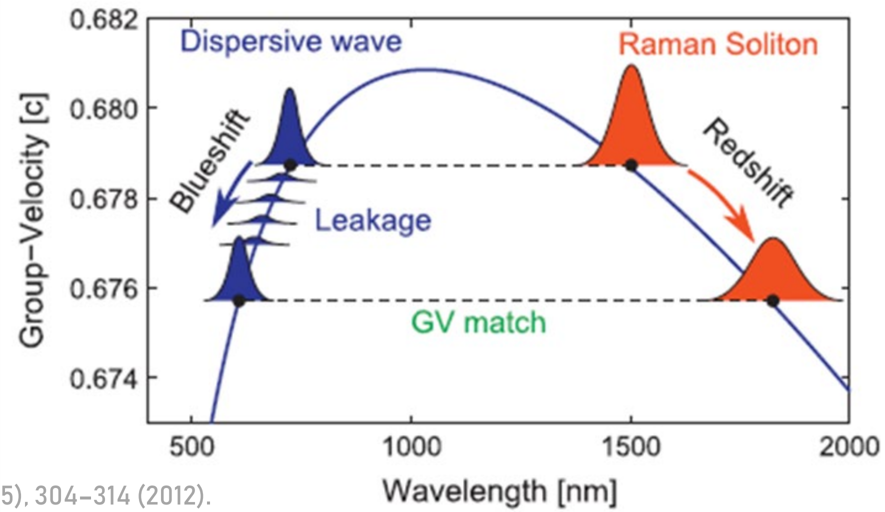
Due to higher-order dispersion, the solitons are unstable and therefore break up into N fundamental solitons (fission), generating resonant radiation in the normal dispersion region known as dispersive waves (DW).

$$N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|} \qquad L_{\text{fiss}} = \sqrt{\frac{T_0^2}{|\beta_2|\gamma P_0}}$$

SOLITON SELF-FREQUENCY SHIFTING

The generated solitons can then red-shift through intra-pulse Raman scattering, i.e. soliton self-frequency shifting (SSFS). Then, because the solitons impose a trapping potential on the DWs, it causes the DWs to blue-shift in order to match the GV of the solitons.





U. Møller et al., Opt. Fiber Technol. 18(5), 304–314 (2012).

$$\gamma = \frac{n_2\omega_0}{cA_{\text{eff}}}$$

$$L_D = \frac{T_0^2}{|\beta_2|}$$

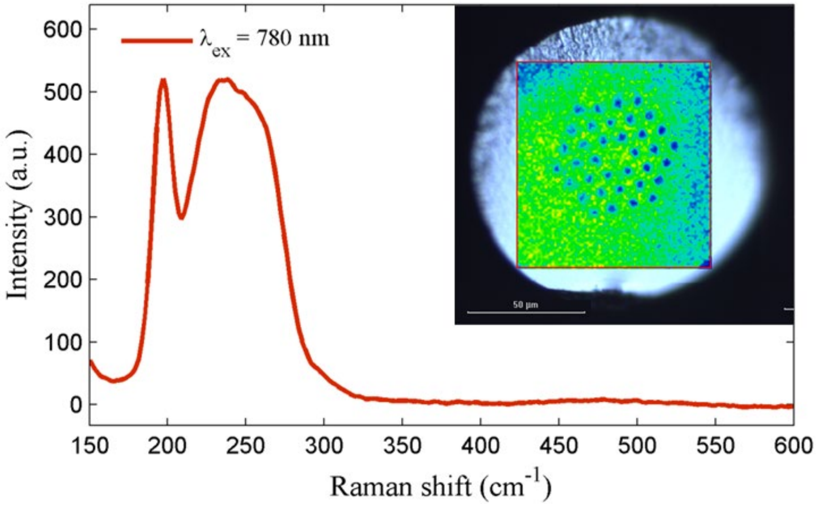
$$L_{NL} = \frac{1}{\gamma P_0}$$

SUPERCONTINUUM PHYSICS

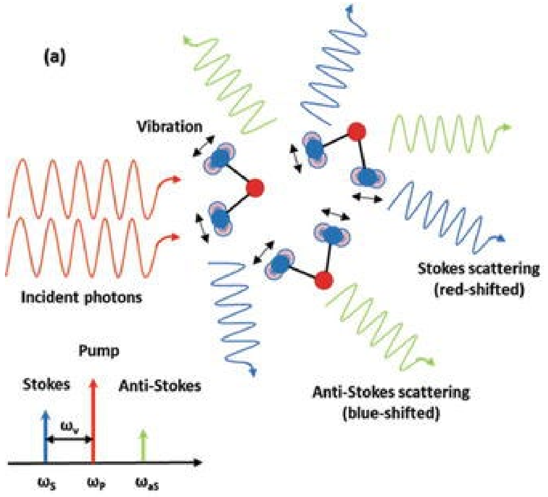
RAMAN SCATTERING

Inelastic scattering by molecules, that either excite or annihilate a quantum of vibrational energy in the form of phonons. This results in either loss of photon energy (Stokes), or increase (anti-Stokes).

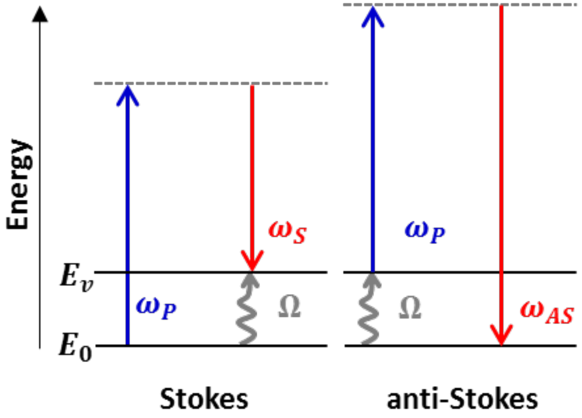
Raman response of $Ge_{10}As_{22}Se_{68}$



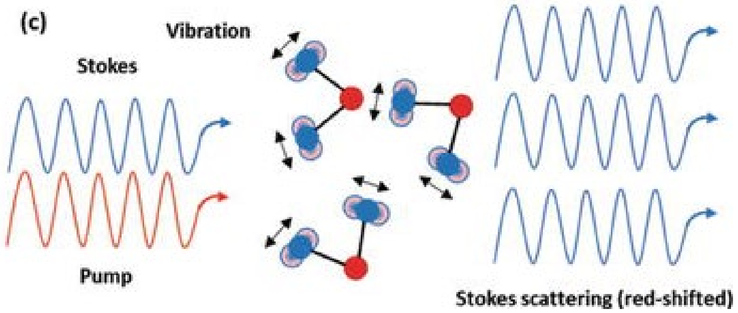
Spontaneous Raman scattering



Frequency shift



Stimulated Raman scattering



M. A. Ferrara and L. Sirleto, "Stimulated Raman Scattering in Micro- and Nanophotonics", Intechopen (2018).

SUPERCONTINUUM PHYSICS

$$L_{\mathrm{fiss}} = \sqrt{\frac{T_0^2}{|\beta_2|\gamma P_0}}$$

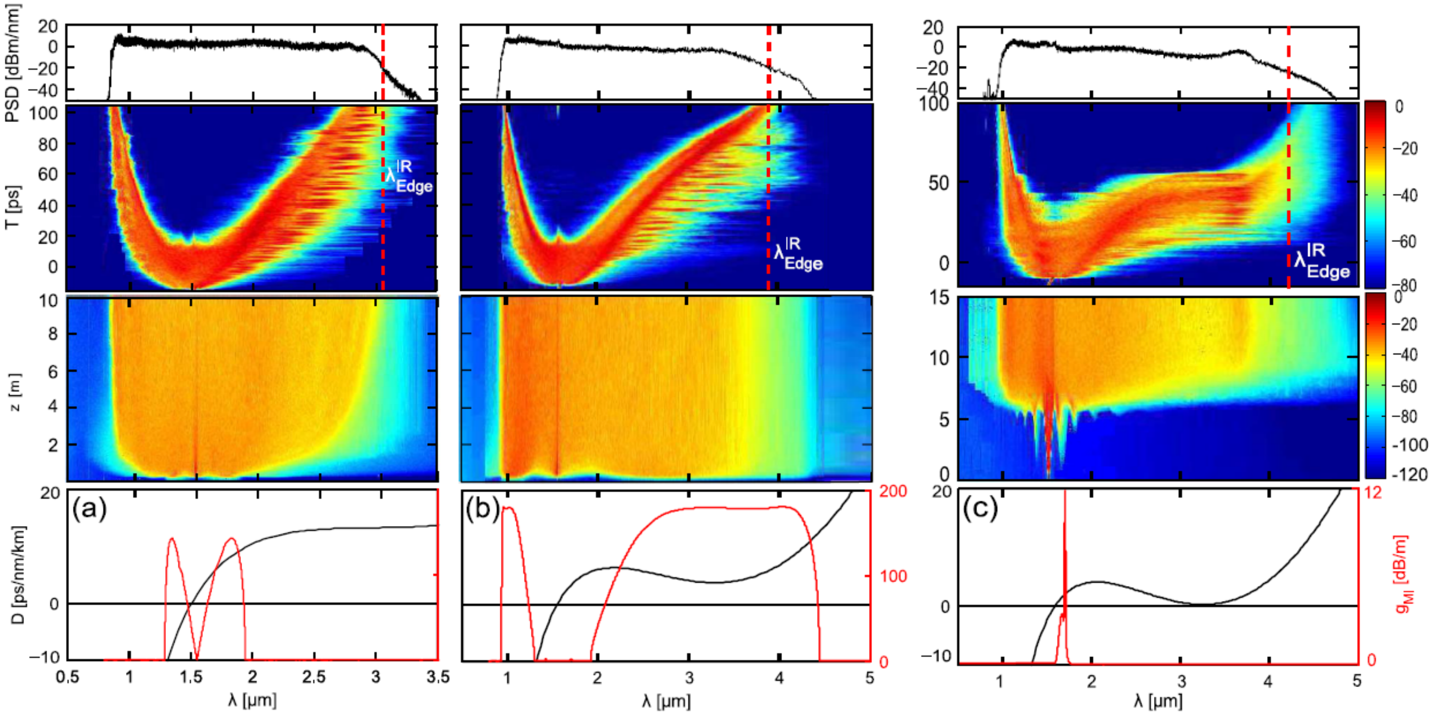
MODULATION INSTABILITY

Modulation instability (MI) is the amplification of noise in the pulse waveform that grow exponentially, resulting in the break-up of the pulse into fundamental solitons. MI is similar to fission, but requires longer pulses in the ps and ns range because the break-up mechanism is related to degenerate four-wave mixing.

$$L_{MI} \sim \frac{4}{\gamma P_0}$$

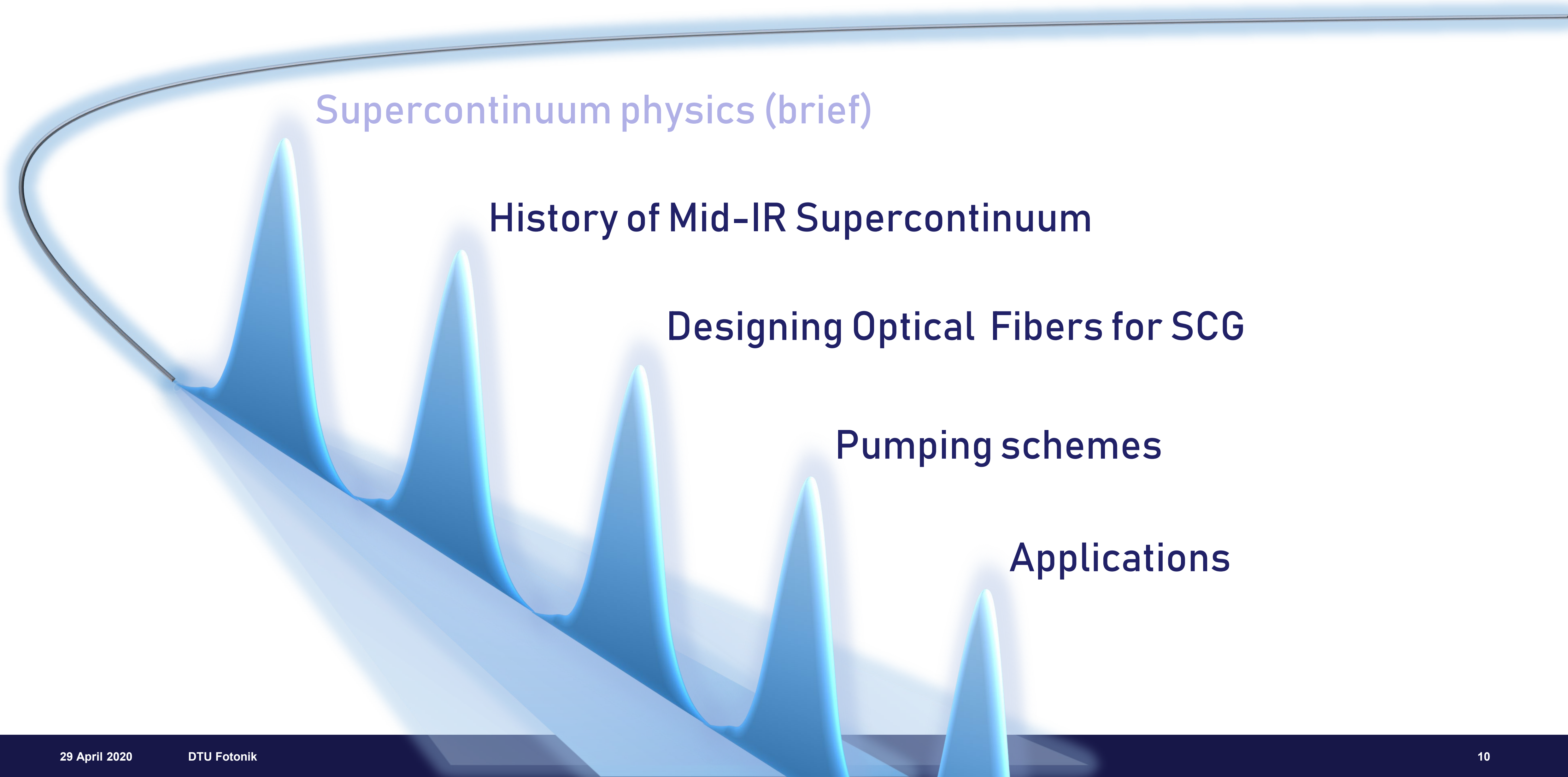
$$\Omega_{\mathrm{max}} = \pm\frac{\Omega_c}{\sqrt{2}} = \pm\left(\frac{2\gamma P_0}{|\beta_2|}\right)^{1/2}$$

$$g_{\mathrm{max}} \equiv g(\Omega_{\mathrm{max}}) = \frac{1}{2}|\beta_2|\Omega_c^2 = 2\gamma P_0.$$



I. Kubat et al., J. Opt. Soc. Am. B 30, 2743-2757 (2013)

OUTLINE



Supercontinuum physics (brief)

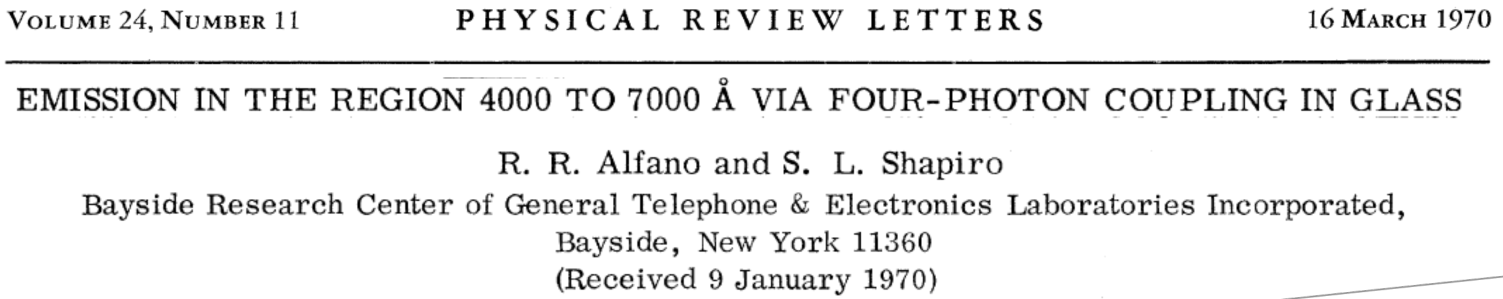
History of Mid-IR Supercontinuum

Designing Optical Fibers for SCG

Pumping schemes

Applications

HISTORY OF MID-IR SCG

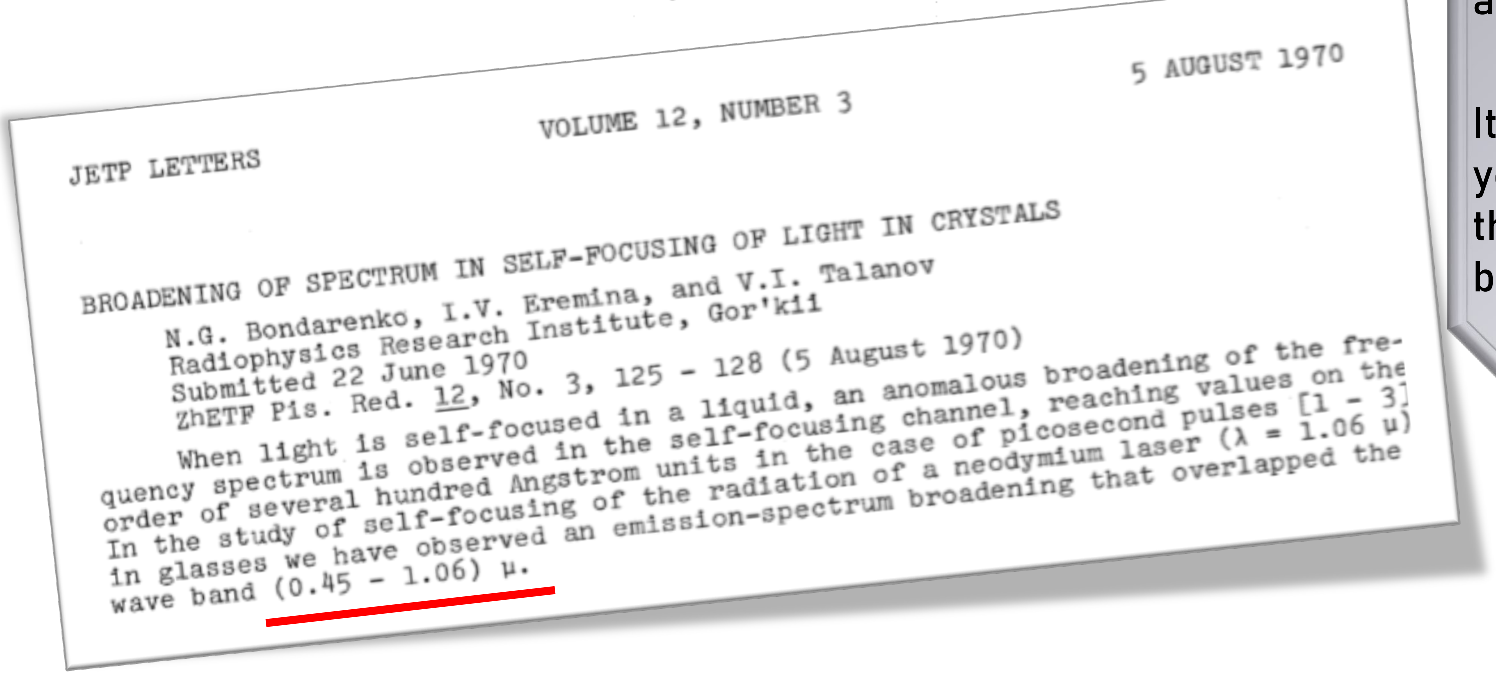


VOLUME 24, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1970

EMISSION IN THE REGION 4000 TO 7000 Å VIA FOUR-PHOTON COUPLING IN GLASS

R. R. Alfano and S. L. Shapiro
Bayside Research Center of General Telephone & Electronics Laboratories Incorporated,
Bayside, New York 11360

(Received 9 January 1970)



JETP LETTERS VOLUME 12, NUMBER 3 5 AUGUST 1970

BROADENING OF SPECTRUM IN SELF-FOCUSING OF LIGHT IN CRYSTALS

N.G. Bondarenko, I.V. Eremina, and V.I. Talanov
Radiophysics Research Institute, Gor'kii

Submitted 22 June 1970
ZhETF Pis. Red. 12, No. 3, 125 - 128 (5 August 1970)

When light is self-focused in a liquid, an anomalous broadening of the frequency spectrum is observed in the self-focusing channel, reaching values on the order of several hundred Angstrom units in the case of picosecond pulses [1 - 3]. In the study of self-focusing of the radiation of a neodymium laser (λ = 1.06 μ) in glasses we have observed an emission-spectrum broadening that overlapped the wave band (0.45 - 1.06) μ.

1970: DISCOVERY

First reported in 1970 by Alfano and Shapiro , although the term was never published until the mid-1980's, and only later received widespread acceptance.

It should be noted that later in the year a Russian group also reported the same effect, with even greater broadening.

HISTORY OF MID-IR SCG

1976: NOW IN FIBERS

First demonstration of SC in an optical fiber was achieved using a kW dye-laser produced 110-180 nm bandwidth in the visible.

New nanosecond continuum for excited-state spectroscopy

Chinlon Lin and R. H. Stolen

Bell Telephone Laboratories, Holmdel, New Jersey 07733

Applied Physics Letters, Vol. 28, No. 4, 15 February 1976

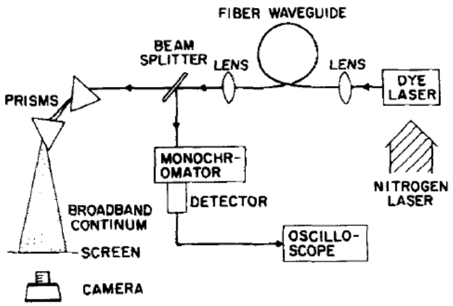


FIG. 1. Experimental arrangement for the continuum generation.

FIG. 2. (a) Continuum generated in the fiber waveguide with a broad-band Coumarin 120 dye laser as the pump.

1978: OCTAVE SPANNING

First octave spanning SC in an optical fiber, enabled by progress in low-loss silica fibers and high power Nd:YAG lasers.

WIDEBAND NEAR-I.R. CONTINUUM ($0{\cdot}7$–$2{\cdot}1$ μm) GENERATED IN LOW-LOSS OPTICAL FIBRES

ELECTRONICS LETTERS 7th December 1978 Vol. 14 No. 25

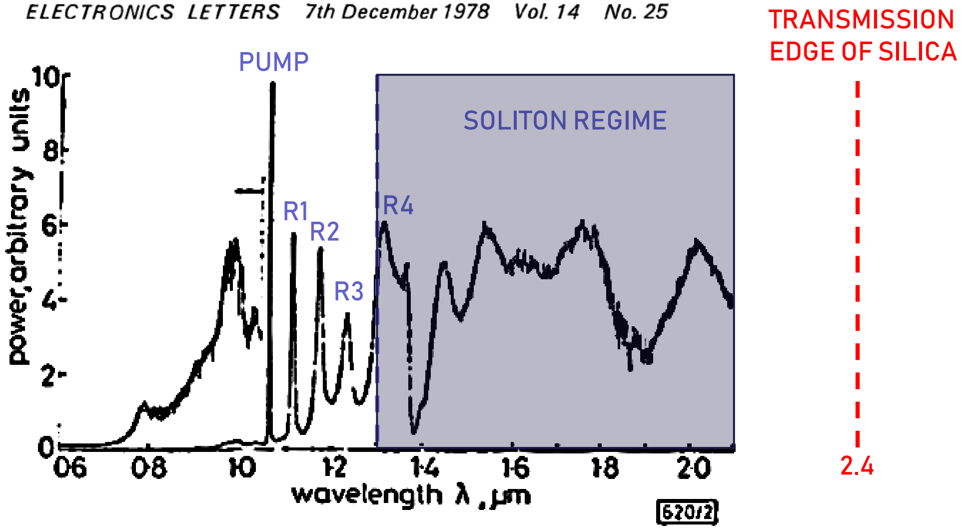
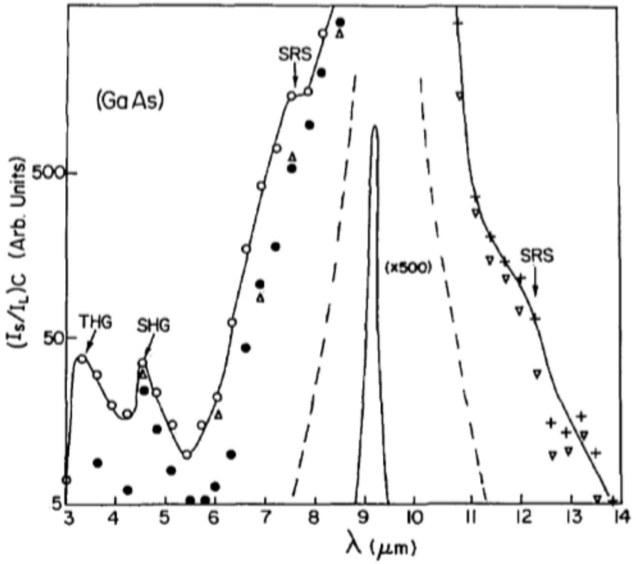


Fig. 2 Spectra of the continuum obtained in a GeO_2 doped silica-core multimode fibre

HISTORY OF MID-IR SCG

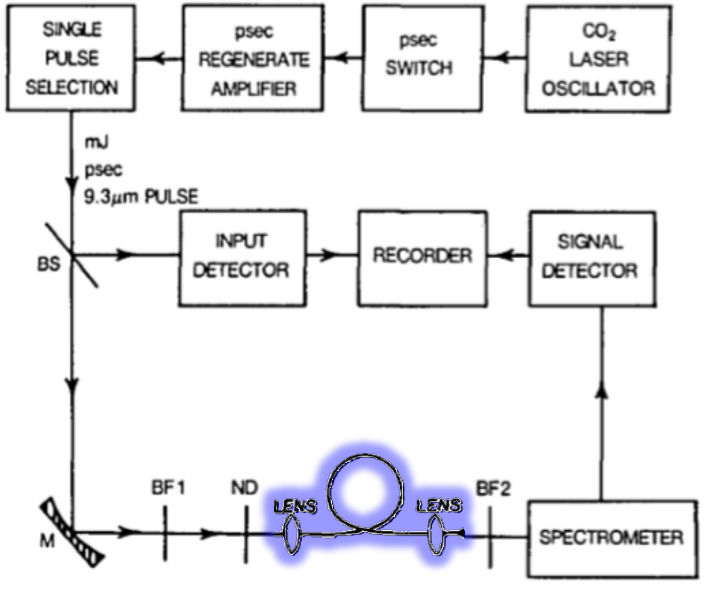
1985: MID-IR SCG

Already in 1985, SCG was demonstrated from 3-14 µm by pumping bulk GaAs with a CO_2 laser. It would take almost three decades before similar broadening was achieved in fibers.



CORKUM ET AL., OPT. LETT. 10, 624-626 (1985)

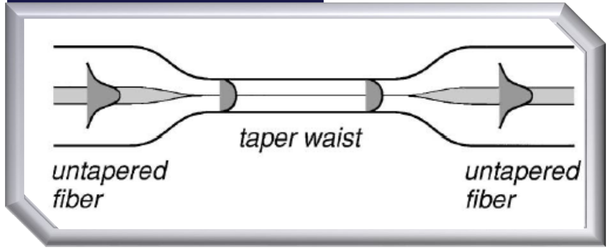
Generation of infrared supercontinuum covering 3–14 µm in dielectrics and semiconductors



MID-IR FIBERS → ?

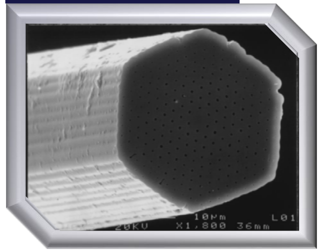
HISTORY OF MID-IR SCG

2000: TAPERS



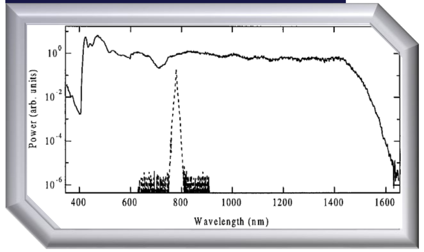
BIRKS ET AL., OPT. LETT. 25, 1415-1417 (2000)

1996: PCF



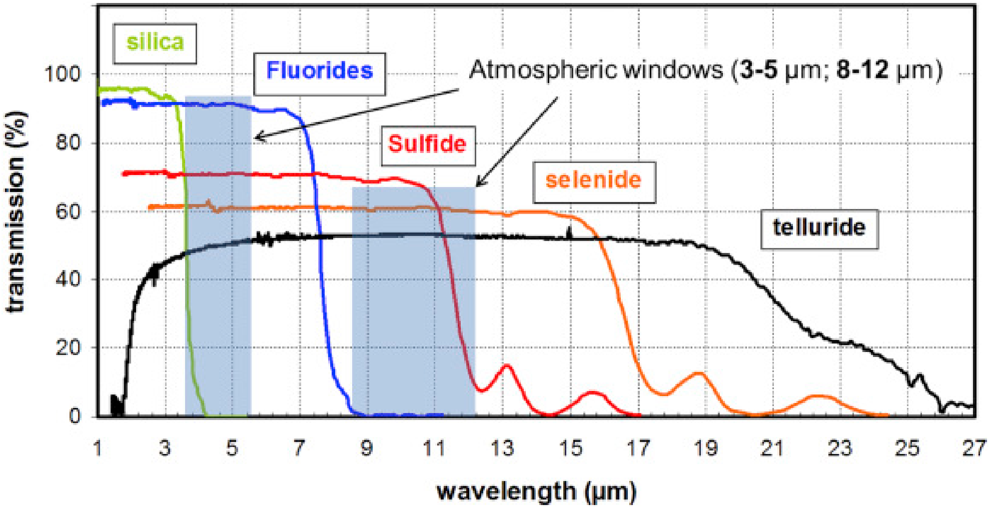
KNIGHT ET AL., OPT. LETT. 21, 1547-1549 (1996)

2000: PCF & SC



RANKA ET AL., OPT. LETT. 25, 25-27 (2000)

~~No~~ path to mid-IR

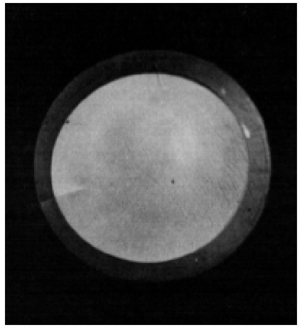


J. Lucas et al., Comptes Rendus Chimie 21 , 916-922 (2018)

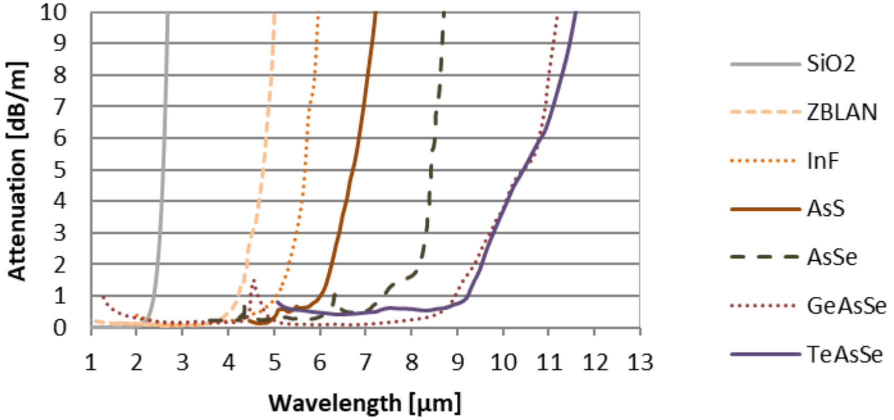
HISTORY OF MID-IR SCG

1965: CHALCOGENIDE GLASS

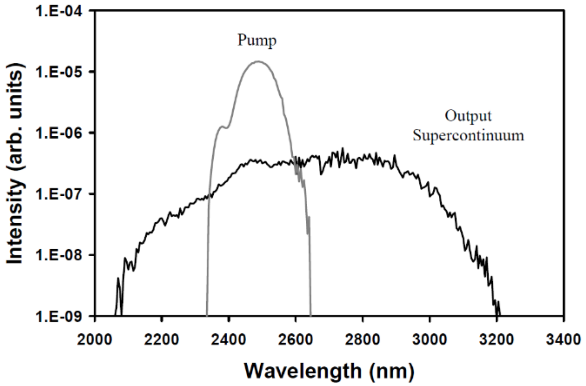
The first chalcogenide fiber made from As2S3 was a success despite having losses > 10-20 dB/m and poor mechanical stability.

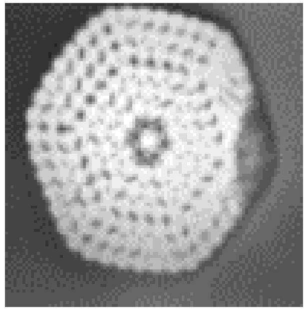


N. S. Kapany and R. J. Simms, Infrared Phys. 5, 69–80 (1965).



C. R. Petersen et al. , Infrared Physics & Technology 91, 182-185 (2018)





L. B.Shaw et al. ASSP 2005, TuC5 (2005)

2005: As2Se3 PCF

Inspired by the success of the silica PCF, researchers from Naval Research Laboratory (US) demonstrated the first SC beyond the silica transmission range.

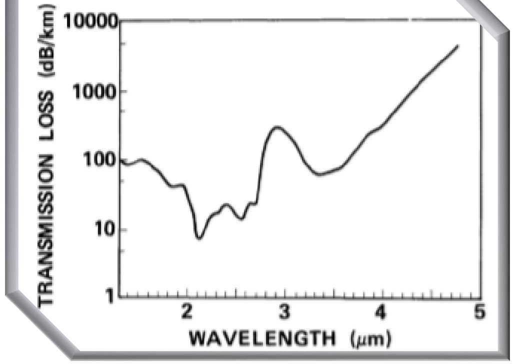
HISTORY OF MID-IR SCG

1974: ZrF4 GLASS

Heavy-metal fluoride glass was discovered around 1974, and the first fiber was made around 1980. It took many years before the loss and mechanical stability was good enough for SCG.

POULAIN ET AL., MAT. RES. BULLETIN 10, 243-246 (1975)

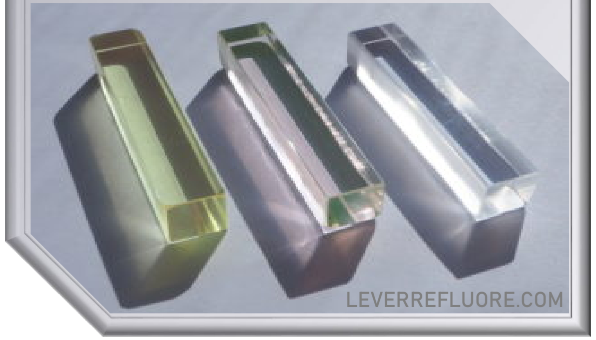
1984: LOW LOSS



MITACHI ET AL., JAP. J. APPL: PHYS. 23, 726-727 (1984)

ZBLAN GLASS

ZBLAN (ZrF_4-BaF_2-LaF_3-AlF_3-NaF) was found to be the most stable fluoride glass for optical fibers, and this was also the first fiber to be used for efficient SCG.



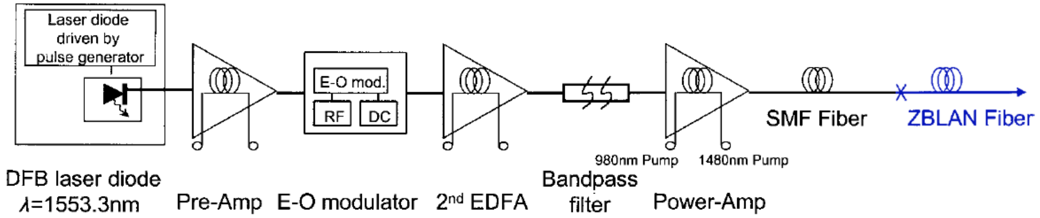
LEVERREFLUORE.COM

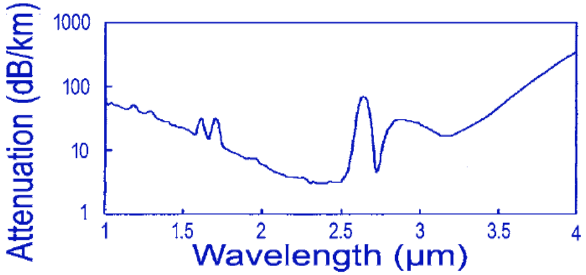
HISTORY OF MID-IR SCG

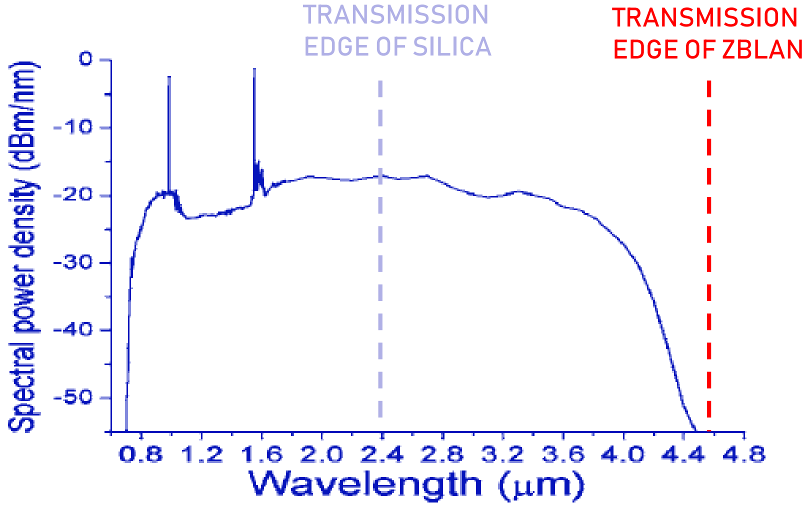
2006: ZBLAN SC

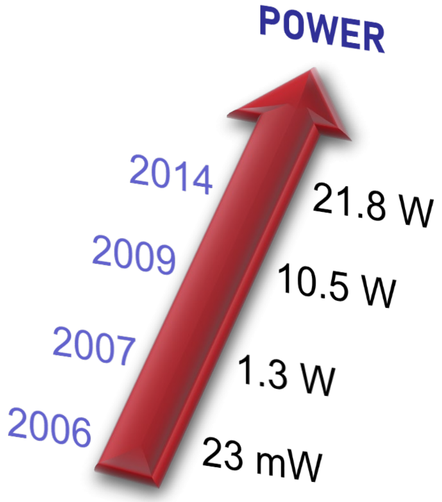
Due to the lack of practical high power mid-IR lasers, Xia et al. used a continuum pump based on silica fiber and 1.55 µm components – a concept known as cascading.

C. Xia er al., Optics Letters 31, 2553-2555 (2006)





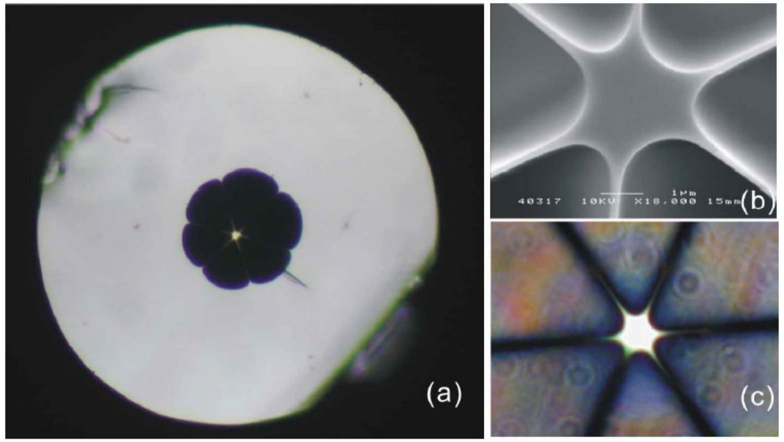


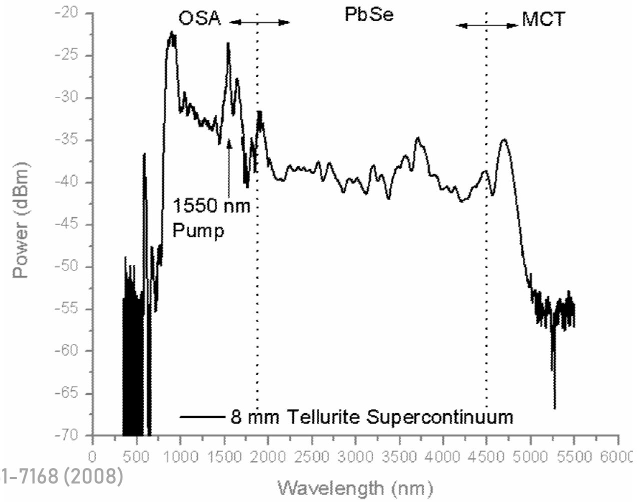


HISTORY OF MID-IR SCG

2008: TeO2

Tellurite glass was demonstrated to have potential for SCG up to 5 μm and 10-20 times higher nonlinear index, but has lower damage threshold than ZBLAN and longer ZDW.

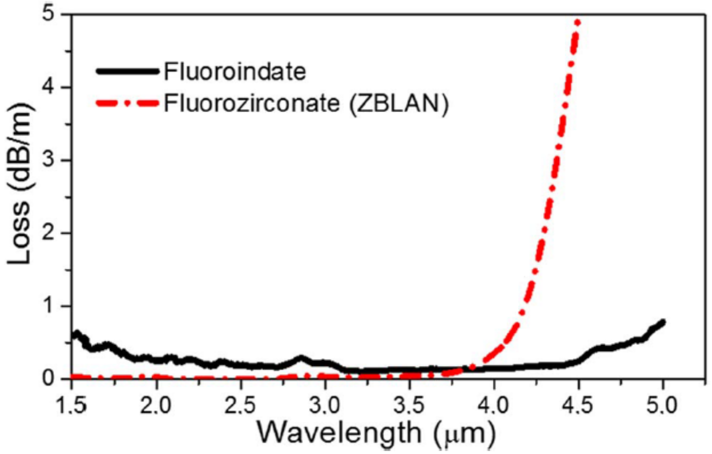


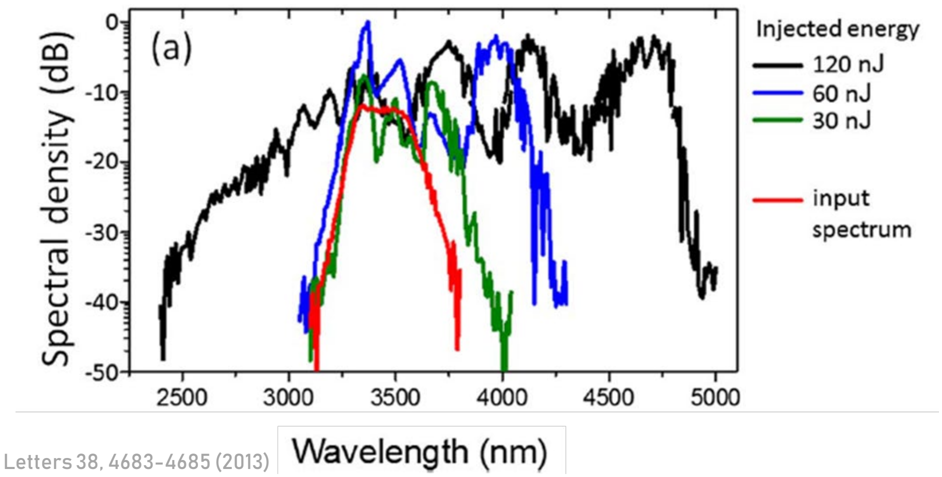


P. Domachuk er al., Optics Express 16, 7161-7168 (2008)

2013: InF3

Found to have reduced loss at longer wavelengths compared to ZBLAN, but higher loss at shorter wavelengths and thus typically lower damage threshold.





F. Théberge et al., Optics Letters 38, 4683-4685 (2013)

HISTORY OF MID-IR SCG

2012: CASCADING

The NRL group also tried cascaded pumping from silica to As2S3 fiber, but was limited by normal dispersion and losses.

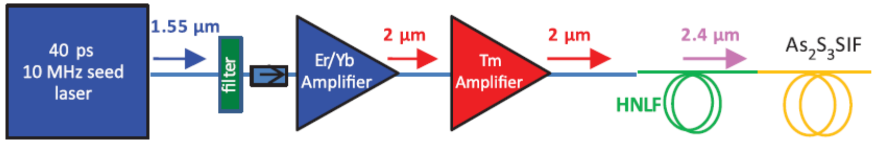
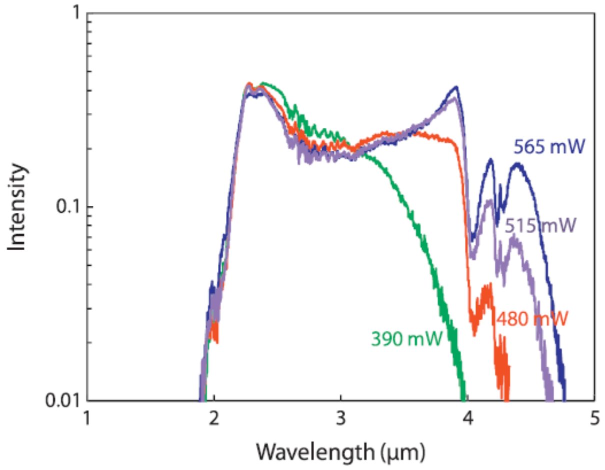


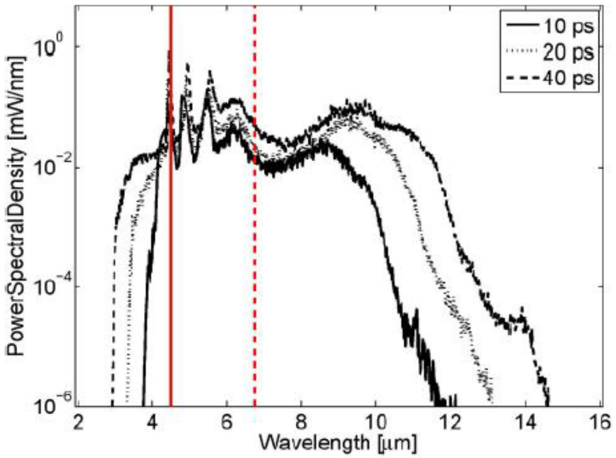
Fig. 1. Schematic of all fiber laser system. HNLF: highly nonlinear fiber, SIF: step index fiber.

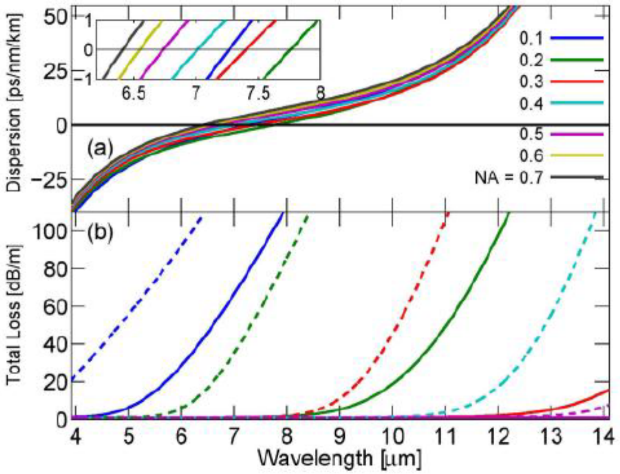
R. R. Gattass et al., Optical Fiber Technology 18, 345–348 (2012).



2013: HIGH-NA

In a numerical conference paper it was proposed by the authors, that in order to reach longer wavelengths the numerical aperture (NA) should be as high as possible to shift the ZDW towards shorter wavelengths, and to increase confinement in the core.



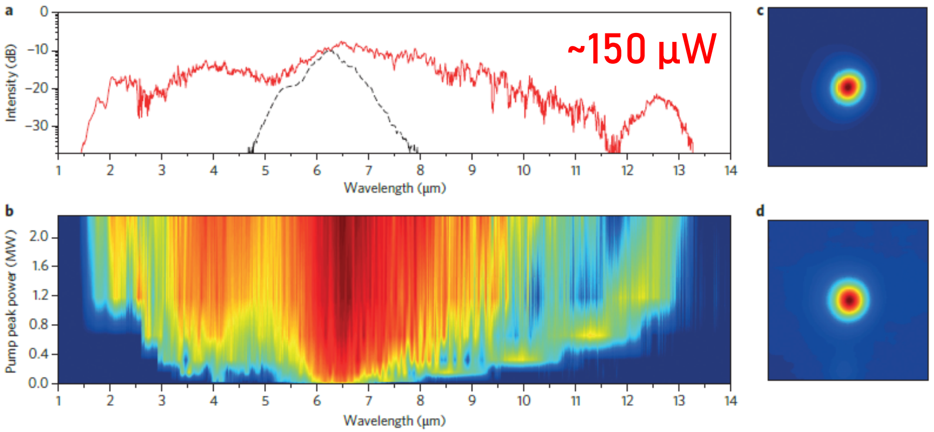


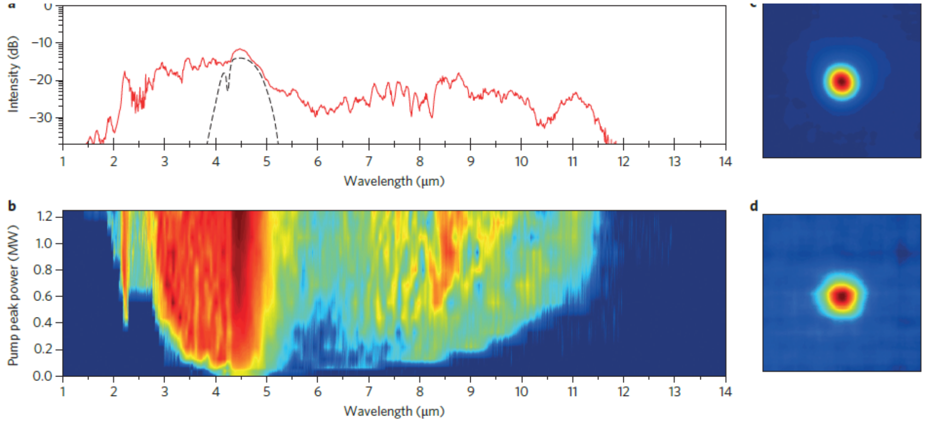
C. Agger et al., Nonlinear Optics, NW4A.09 (2013)

HISTORY OF MID-IR SCG

2014: FULL BANDWIDTH DEMONSTRATED

A year after it was demonstrated experimentally, although the laser source used was an elaborate OPA system





C. R. Petersen et al., Nature Photonics 8, 830-834 (2014)

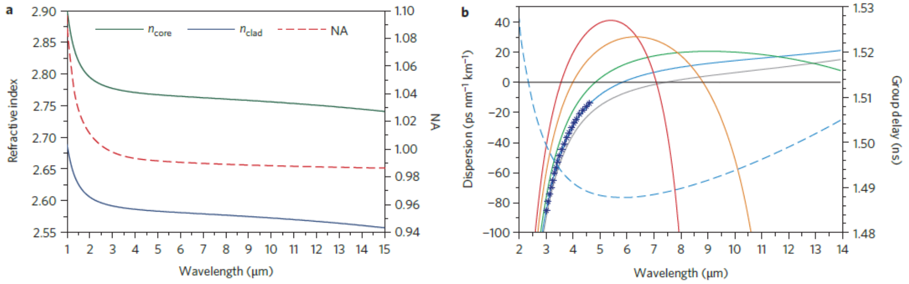


Figure 1 | Measured and calculated chalcogenide fibre parameters. a, Measured refractive indices of the fibre core and cladding glasses, and the calculated NA. **b**, Calculated dispersion profiles (solid lines) of the core material (grey) and the four dominant guided modes of the fibre, LP01 (blue), LP11 (green), LP02 (orange) and LP12 (red), together with the measured dispersion (symbols) and calculated group delay (dashed line) of LP01.

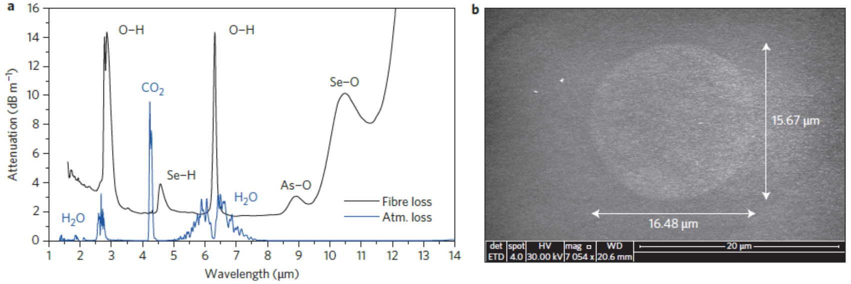


Figure 2 | Measured fibre and atmospheric losses and fibre geometry. a, Loss measurements performed using a Fourier transform infrared spectrometer, where the fibre measurement was performed using an intermediate fabrication step fibre with a core diameter of ~288 µm and the atmospheric loss was measured in a 250 mm compartment. **b**, Scanning electron microscope image of the fibre core. Vertical and horizontal scale bars for the core are 15.67 µm and 16.48 µm, respectively.

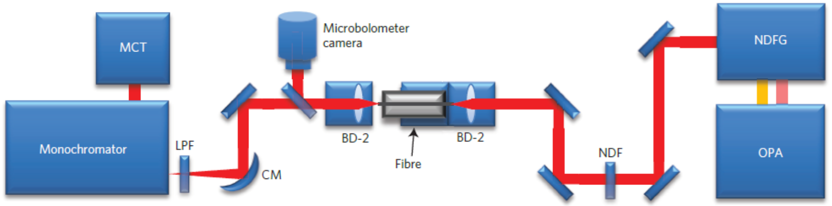


Figure 3 | Experimental set-up for generating and measuring MIR SC. A noncollinear difference frequency generation (NDFG) unit pumped by an optical parametric amplifier (OPA) was used to produce the MIR pump. The output was free-space-coupled into the fibre and subsequently collimated by aspheric lenses. A concave mirror was placed before the monochromator to prevent beam clipping and compensate for chromatic aberrations. Proper coupling to the core was verified by near-field imaging using a micro-bolometer camera. BD-2, black-diamond-2 aspheric lenses; NDF, neutral density filter; CM, concave mirror; LPF, long-pass filter.

HISTORY OF MID-IR SCG

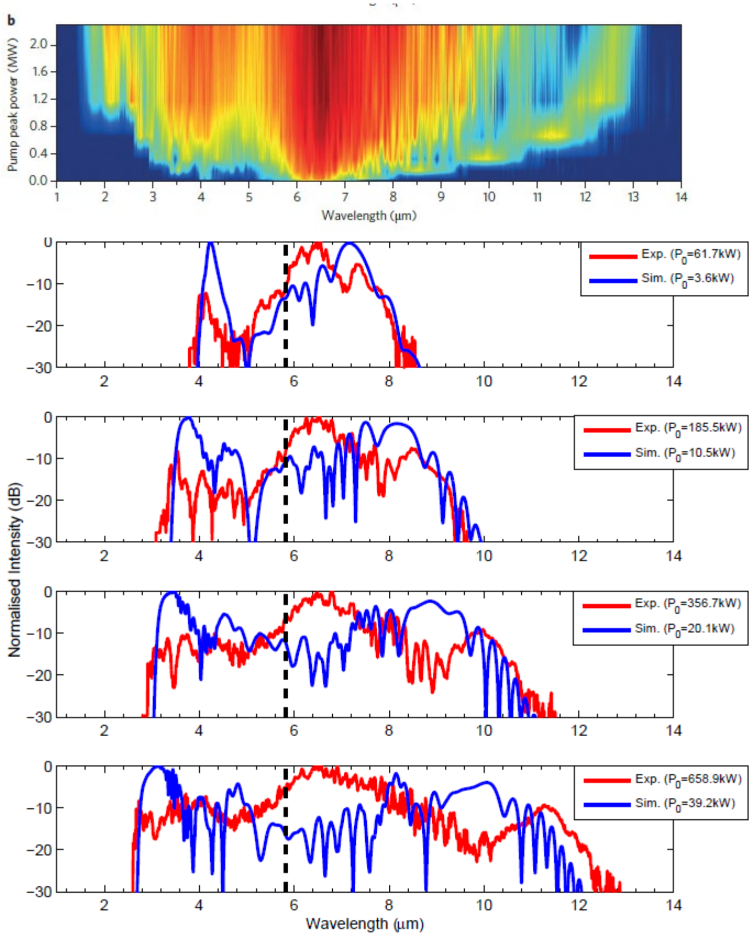


Figure B | Comparison between experimental and simulated SCG for the 6.3μm pump case for varying input peak power, together with the ZDW of the fibre (black dashed). The simulations were able to reproduce some of the same features present in the experimental spectra at low input power by reducing the simulated input peak power by a factor of ~17.5. The high factor may be due to the fact that in our experiment a large part of the light is present around the pump wavelength, where the simulations predict that almost all of the light will be shifted away. This may be caused by the excitation of HOMs, which tend to cause little broadening and thus increase the signal around the pump.

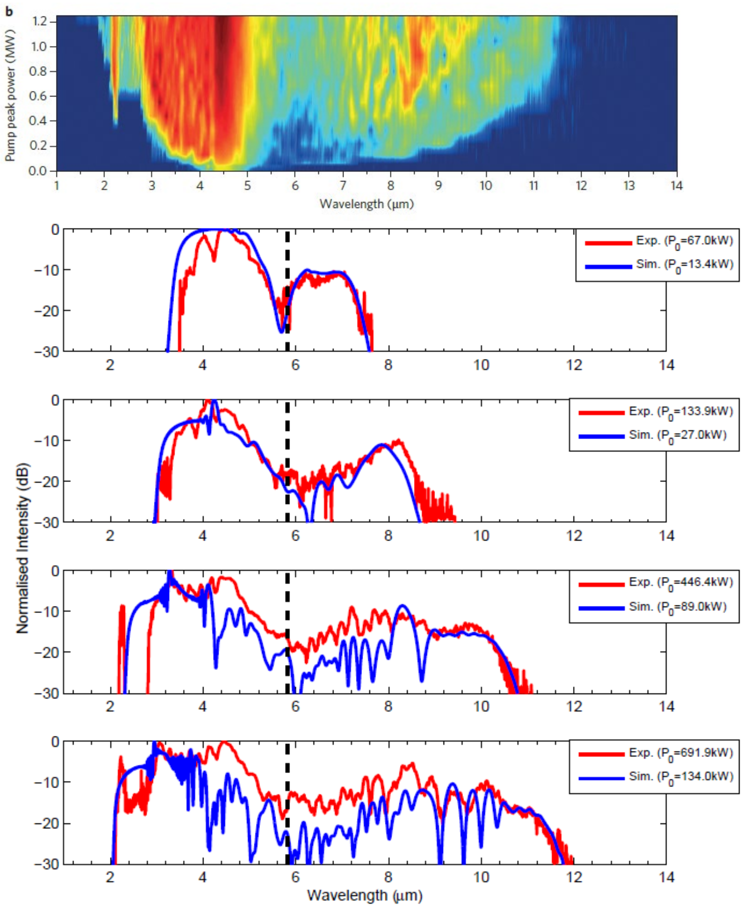
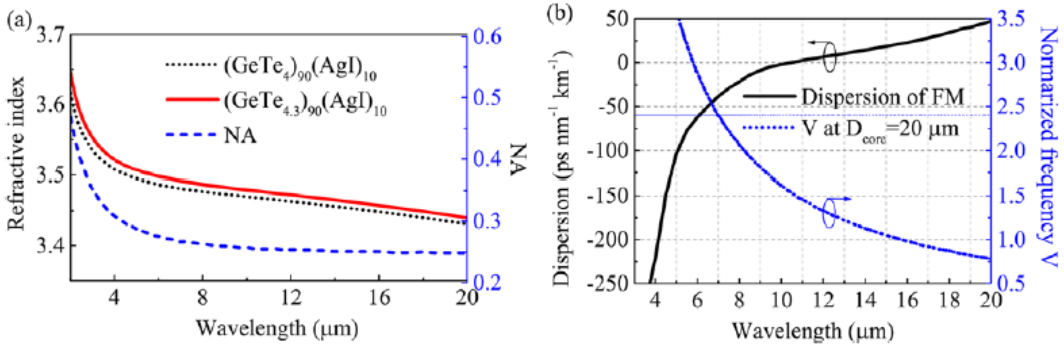


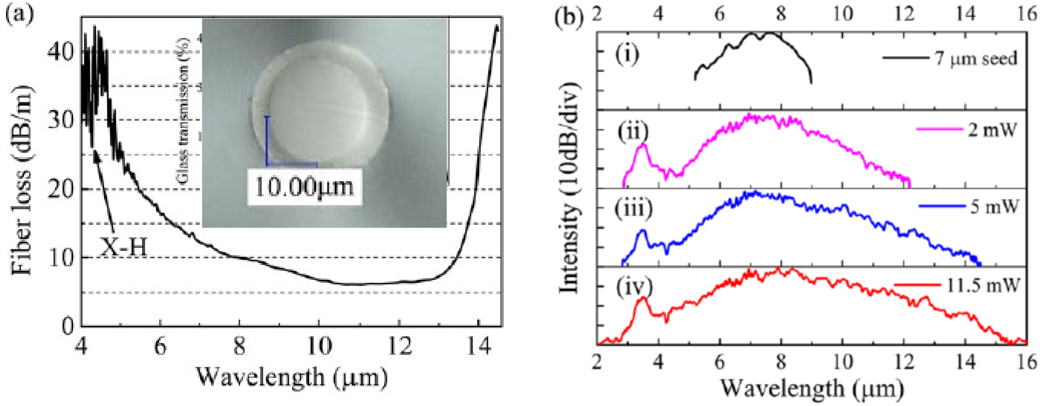
Figure A | Comparison between experimental (red solid) and simulated (blue solid) SCG in the 4.5μm pump case for varying input peak power, together with the ZDW of the fibre (black dashed). The simulations were able to reproduce many of the same features present in the experimental spectra by reducing the simulated input peak power by a factor of ~5, which then accounts for measurement uncertainty, loss of power to the orthogonal polarisation and HOMs. However, the short-wavelength SPM edge was consistently shorter than what was observed experimentally, which may be due to a much higher loss of the test fibre at 2.9μm compared to the large-core fibre used for loss measurements.

HISTORY OF MID-IR SCG

2017: CHALCO-HALIDE

Introducing halide elements improves the long-wavelength transmission, but sacrifices the short edge.

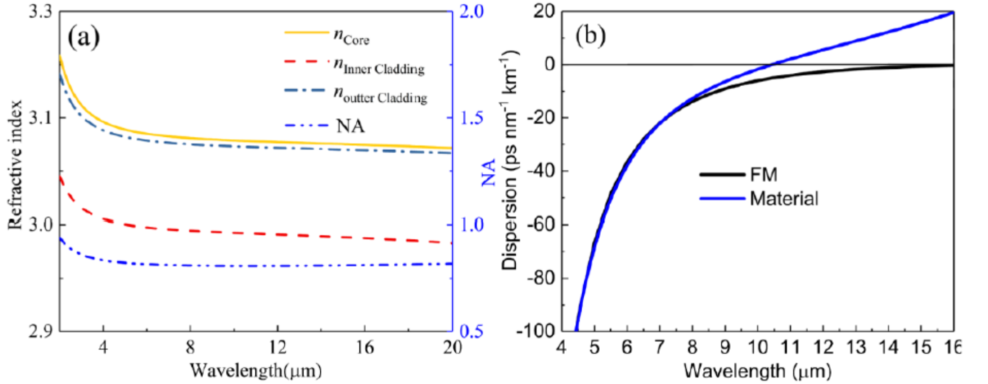


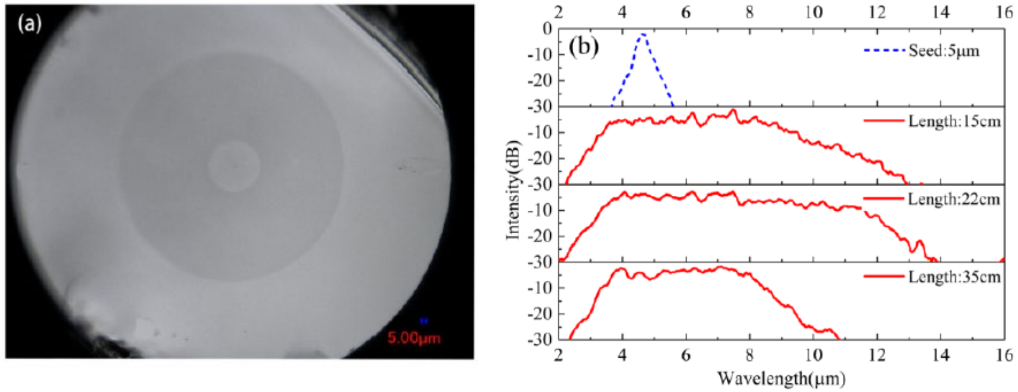


Z. Zhano et al., Laser Photonics Rev. 11, No. 2, 1700005 (2017)

2019: ALL-NORMAL

ANDi profile achieved through double-clad design. In general DCF are interesting due to the many combinations of chalcogenide glasses.



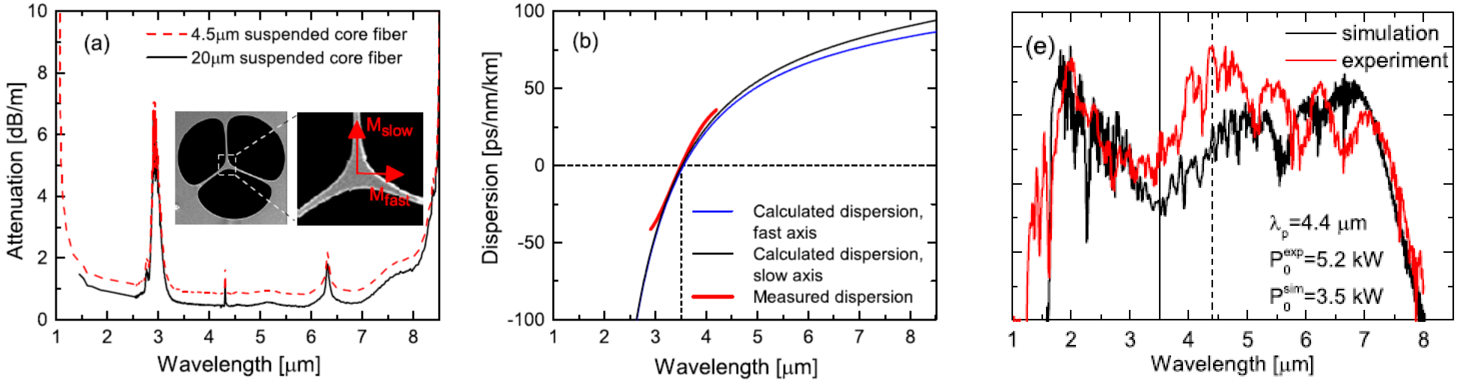


K. Jiao et al., Optics Express 27, 2036-2043 (2019)

HISTORY OF MID-IR SCG

2015: MULTI-MILLIWATT

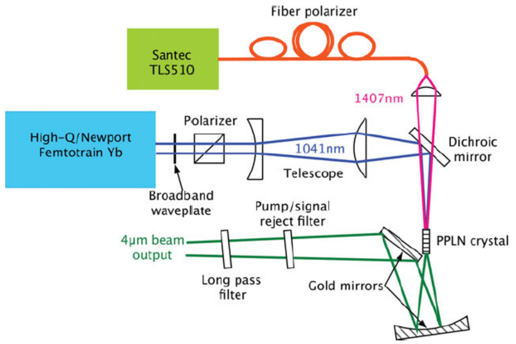
Using a tunable OPA based on a MHz femtosecond laser the average output power could be increased. Combining this with a As-Se suspended-core, to reduce the ZDW to 3.5 µm.



~15 mW

U. Møller et al., Optics Express 23, 3282-3291 (2015)

Tunable MHz OPA to increase average power



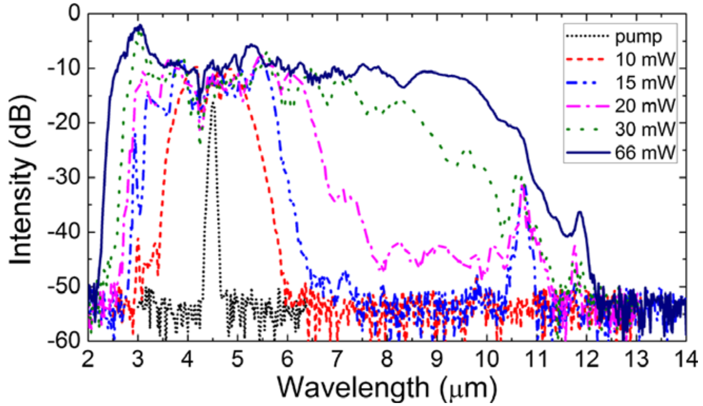
Y. Yu et al., Laser Photonics Rev. 8, No. 5, 792–798 (2014)

2016: HIGH NA SIF

Ge-Sb-Se core and a Ge-Se cladding with numerical aperture (NA) of 1.1.

(will get back to this one later)

~17 mW

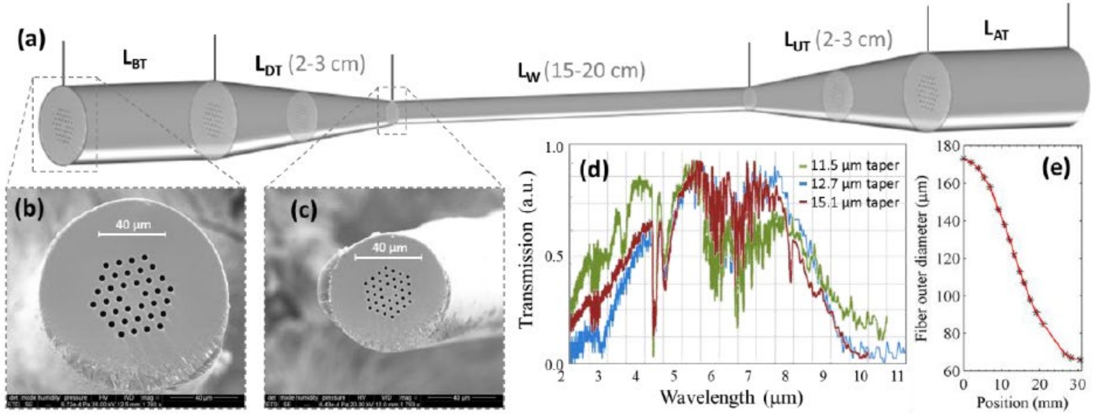


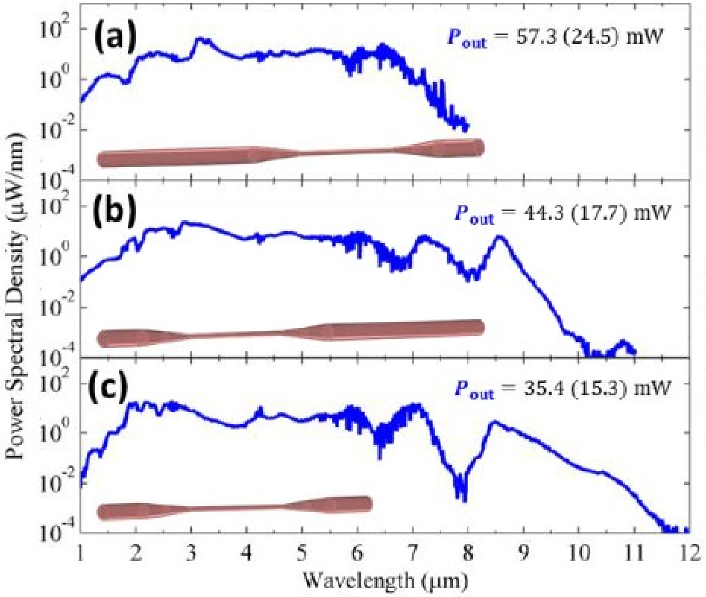
B. Zhang et al., J. Am. Ceram. Soc., 1–4 (2016)

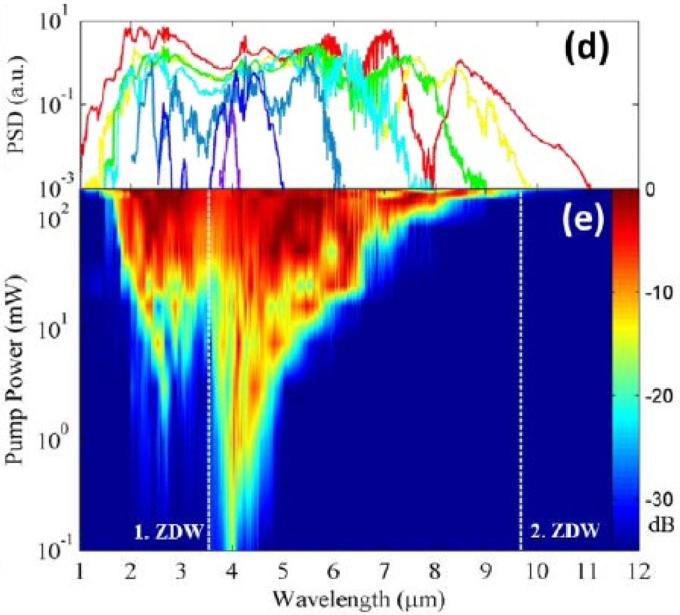
HISTORY OF MID-IR SCG

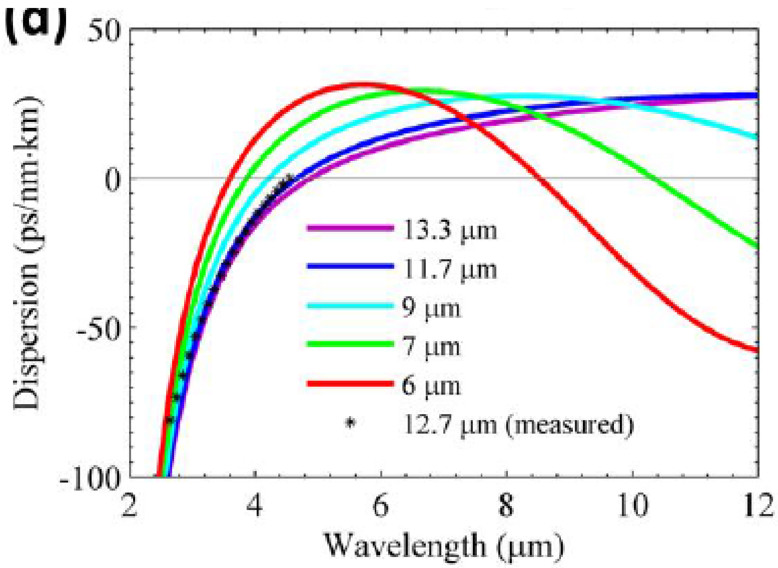
2017: TAPERS

To improve powerhandling and scaling of average power, one idea is to taper larger mode-area fibers to combine power handling at the input with higher intensity and short ZDW in the taper waist.



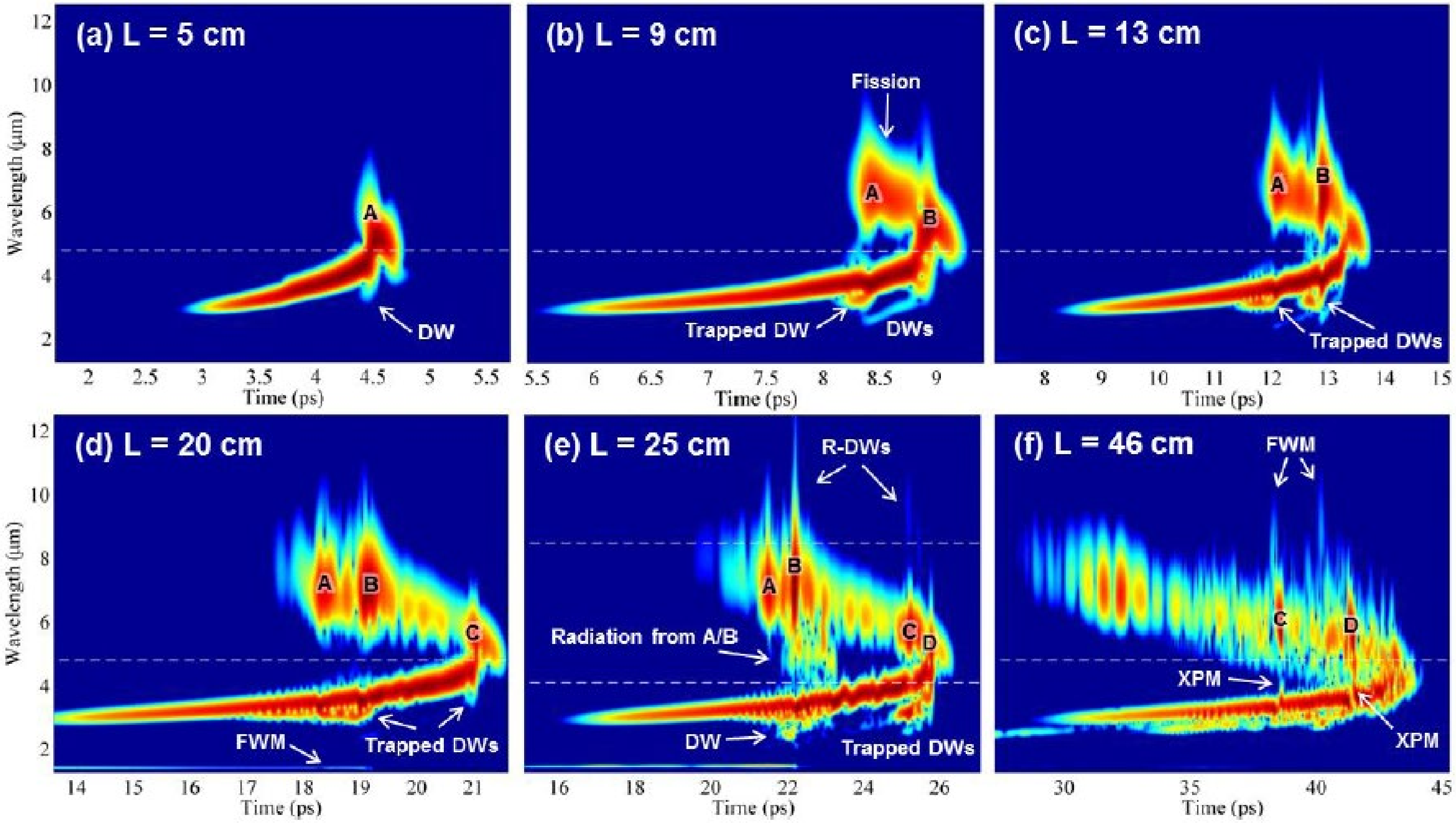






C. R. Petersen et al., Optics Express 25, 15336-15347 (2017)

HISTORY OF MID-IR SCG

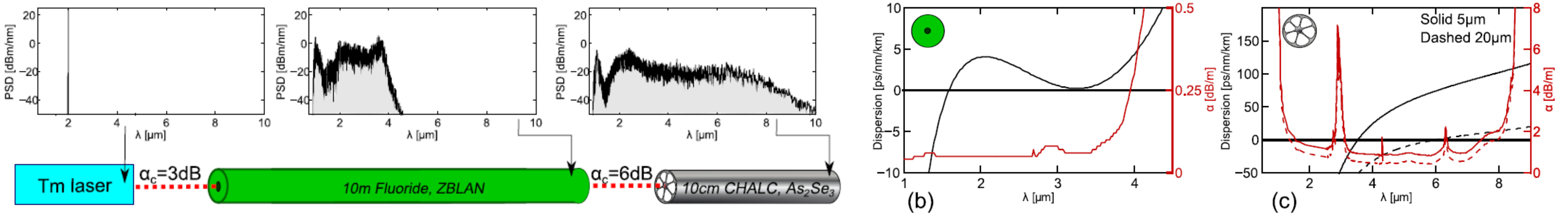


C. R. Petersen et al., Optics Express 25, 15336-15347 (2017)

HISTORY OF MID-IR SCG

2014

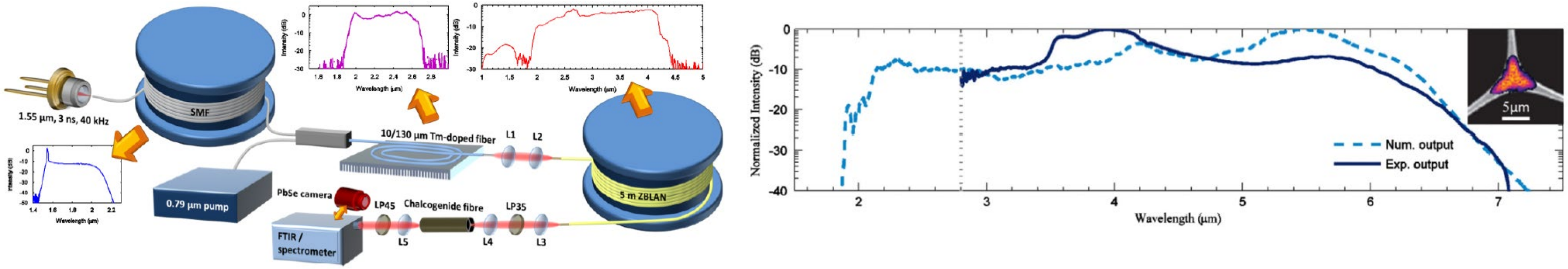
Numerical proof-of-principle of cascaded SCG in concatenated ZBLAN-As2Se3



I. Kubat et al., Optics Express 22, 3961-3967 (2014).

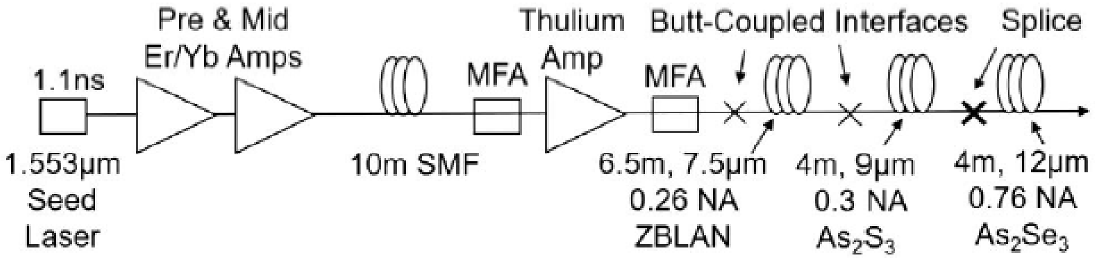
2016

Experimental realization of cascading.



C. R. Petersen et al., Optics Express 24, 749-758 (2016)

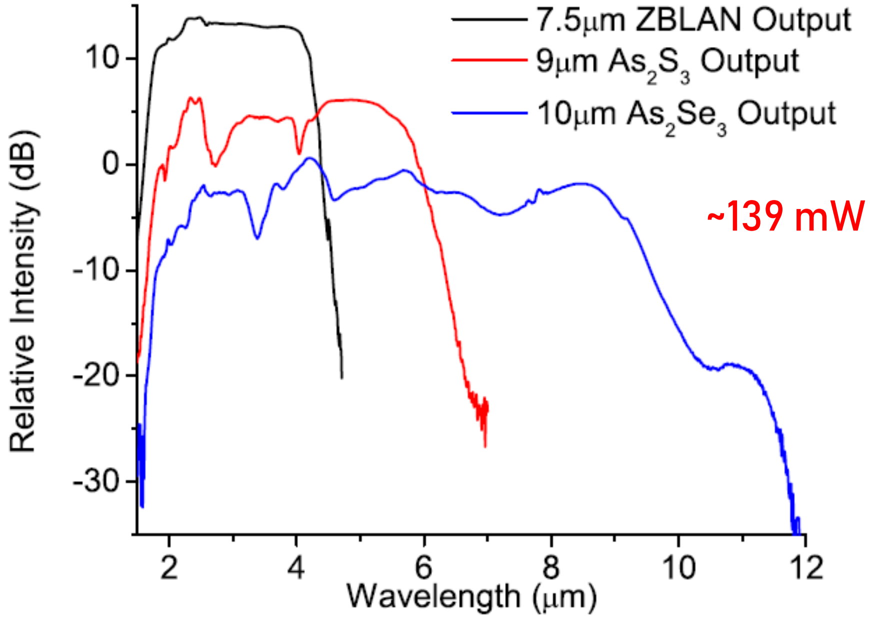
HISTORY OF MID-IR SCG



2018

The concept of cascading was finally demonstrated to reach up to 12 µm with greater power scalability and stability.

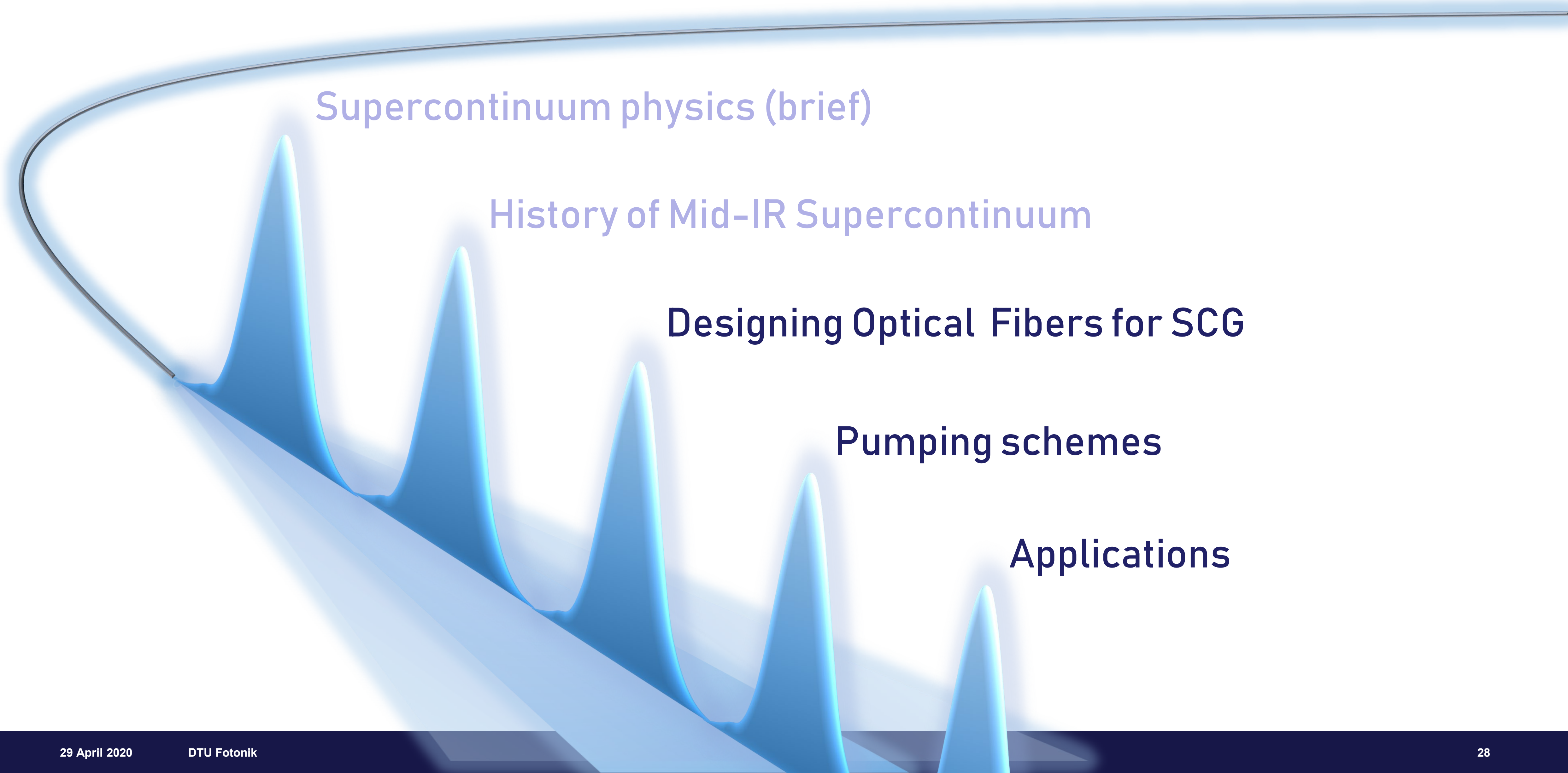
Remarkably this was done using only commercial fibers.



~139 mW

R. A. Martinez et al., Optics Letters 43, 296-299 (2018)

OUTLINE

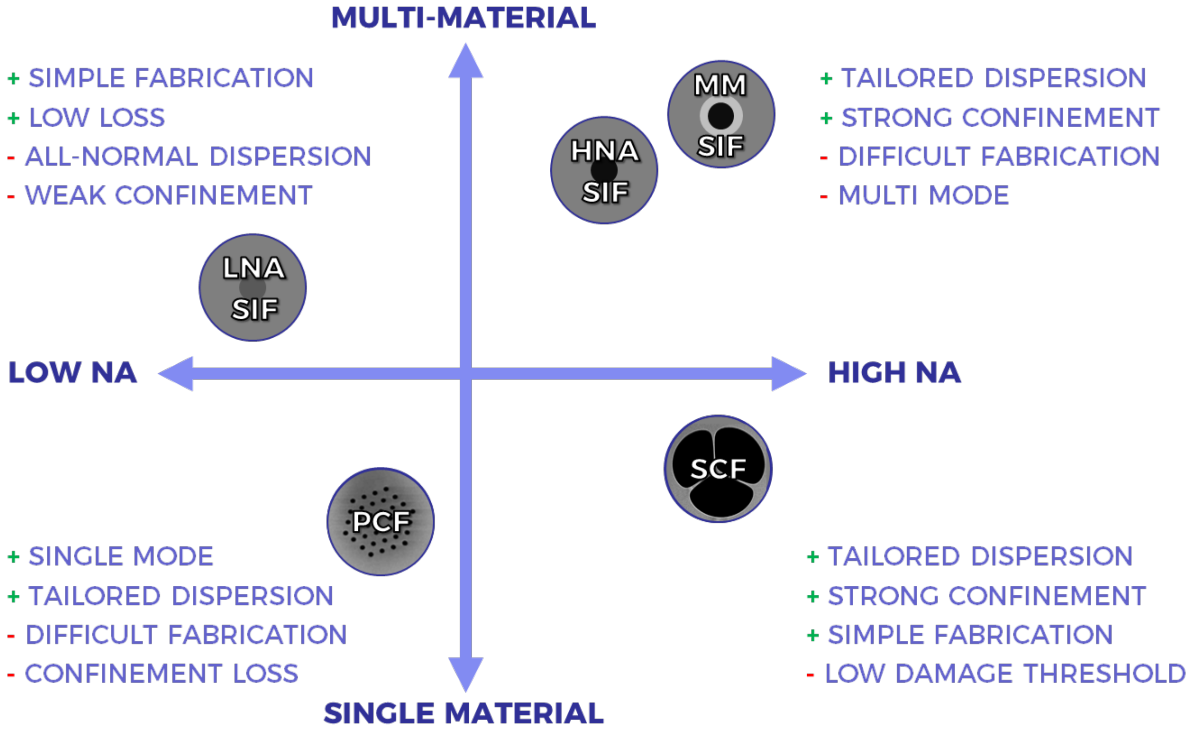


- Supercontinuum physics (brief)
- History of Mid-IR Supercontinuum
- Designing Optical Fibers for SCG
- Pumping schemes
- Applications

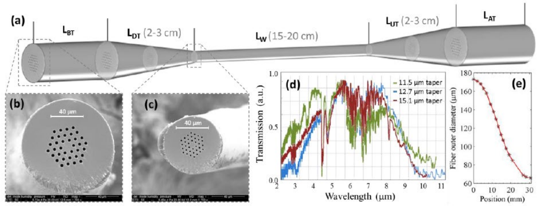
DESIGNING OPTICAL FIBERS FOR SCG

PARAMETER SPACE

In general most optical fibers used for SCG can be divided into five main groups, depending on the NA and single vs. Multi-material design.

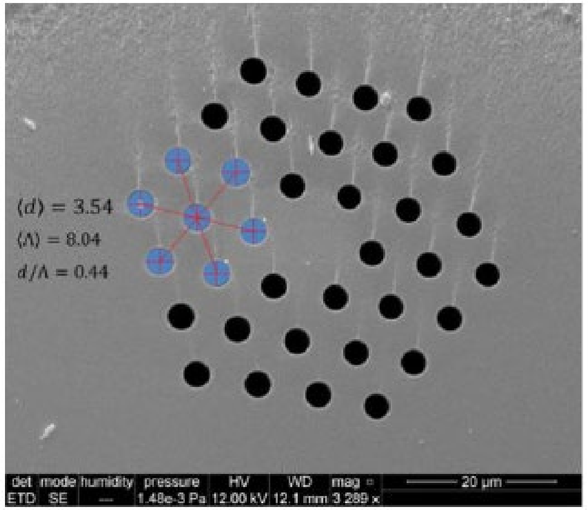


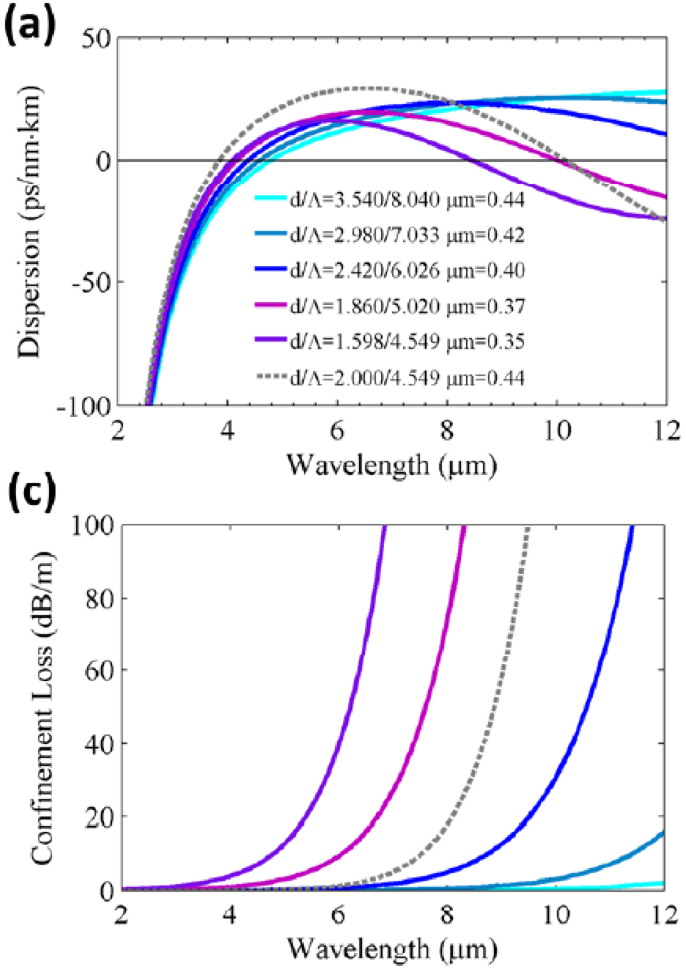
DESIGNING OPTICAL FIBERS FOR SCG



CONFINEMENT LOSS

Single-index fibers, like PCFs, exhibit confinement losses (CL) at longer wavelengths. This depends on core diameter, hole size, pitch, and number of rings. In this case, the holes shrunk during tapering, resulting in increased CL.





C. R. Petersen et al., Optics Express 25, 15336-15347 (2017)

DESIGNING OPTICAL FIBERS FOR SCG

NUMERICAL APERTURE

Numerical aperture (NA) is given by the index contrast between core and cladding. High NA means high degree of confinement, and thus have a large impact on the nonlinearity and dispersion of a fiber.

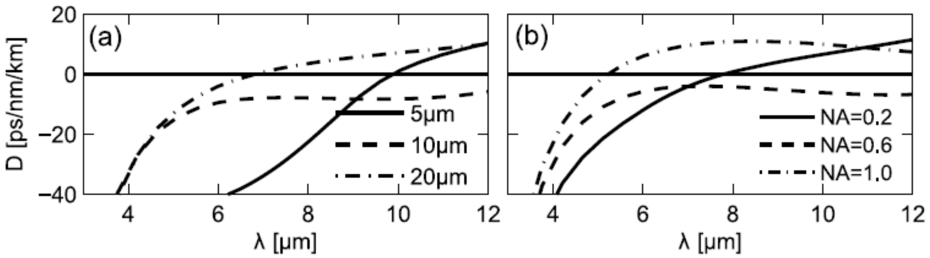
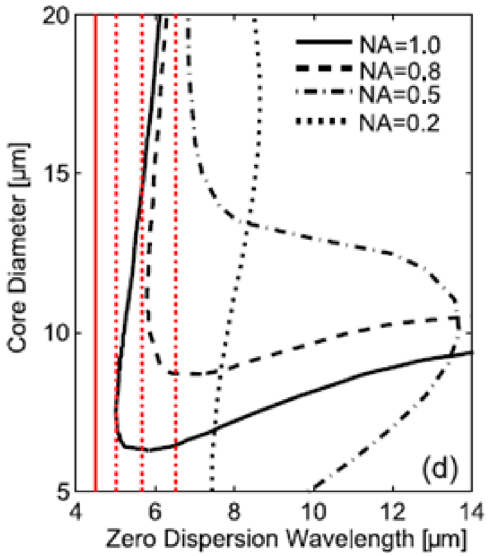
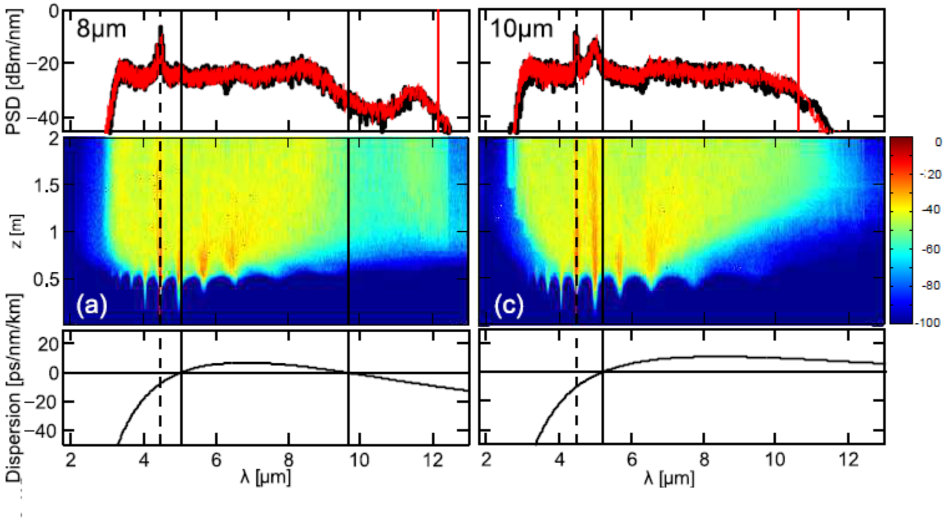


Fig. 2. (a) Dispersion for a SIF with NA=0.5 and core diameter of 5, 10, and 20μm. (b) Dispersion for a SIF with core diameter 10μm and NA of 0.2, 0.6 and 1.0.



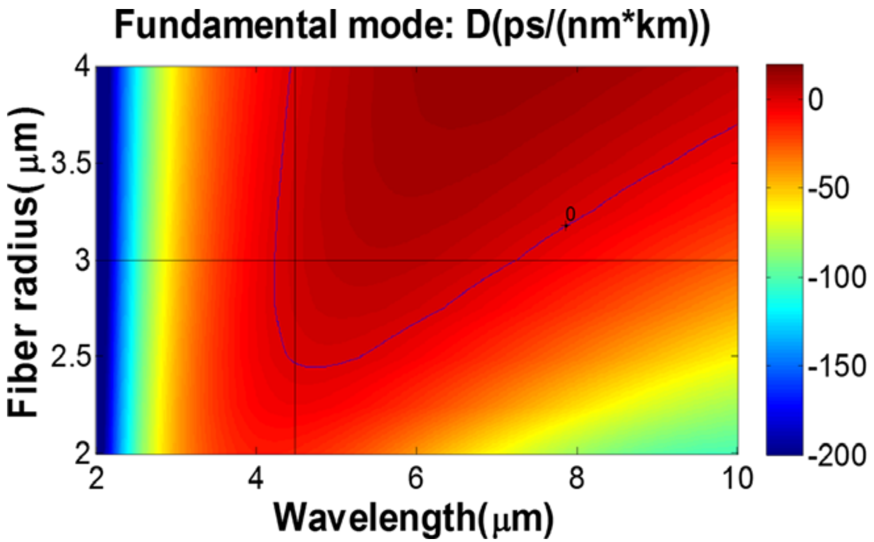


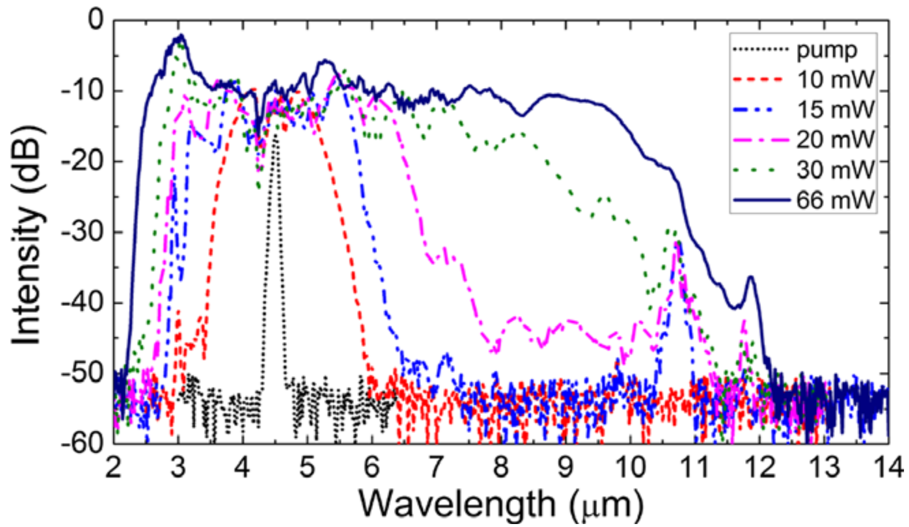
I. Kubat et al., Optics Express 22, 19170-19182 (2014)

DESIGNING OPTICAL FIBERS FOR SCG

COMING BACK

Coming back to this result, part of the success comes from the introduction of the 2nd ZDW, which is also visible in the experimental spectrum at ~ 10.7 µm.



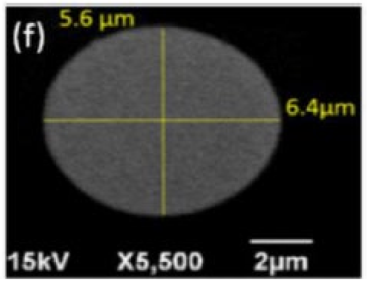


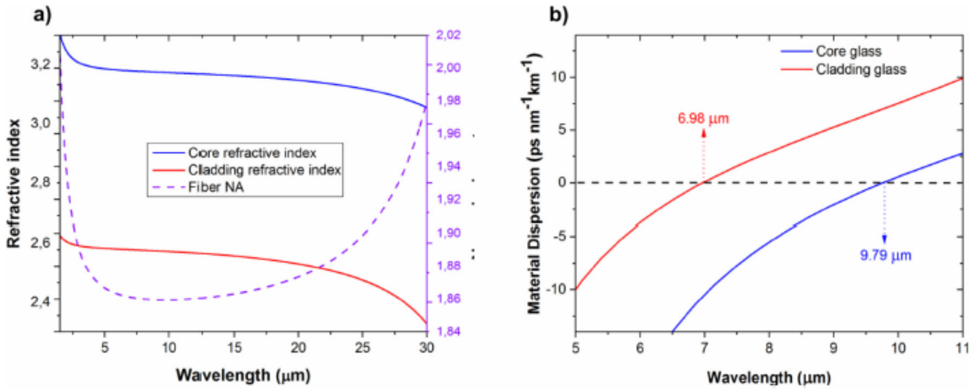
B. Zhang et al., J. Am. Ceram. Soc., 1–4 (2016)

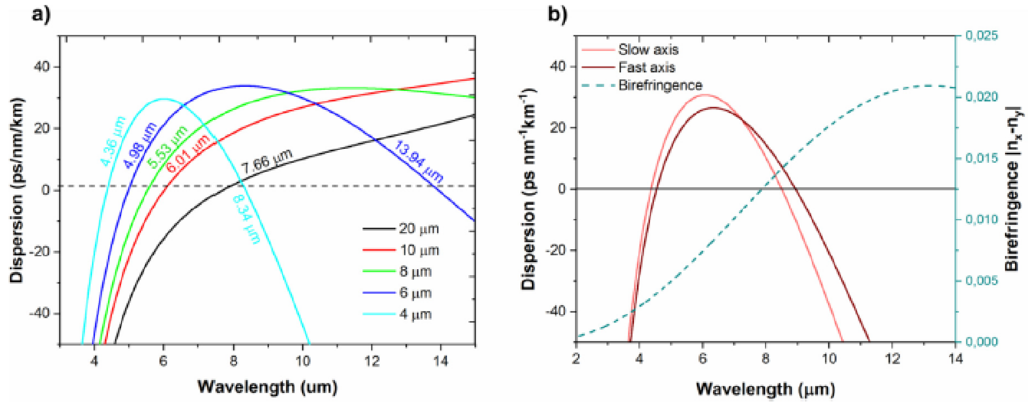
DESIGNING OPTICAL FIBERS FOR SCG

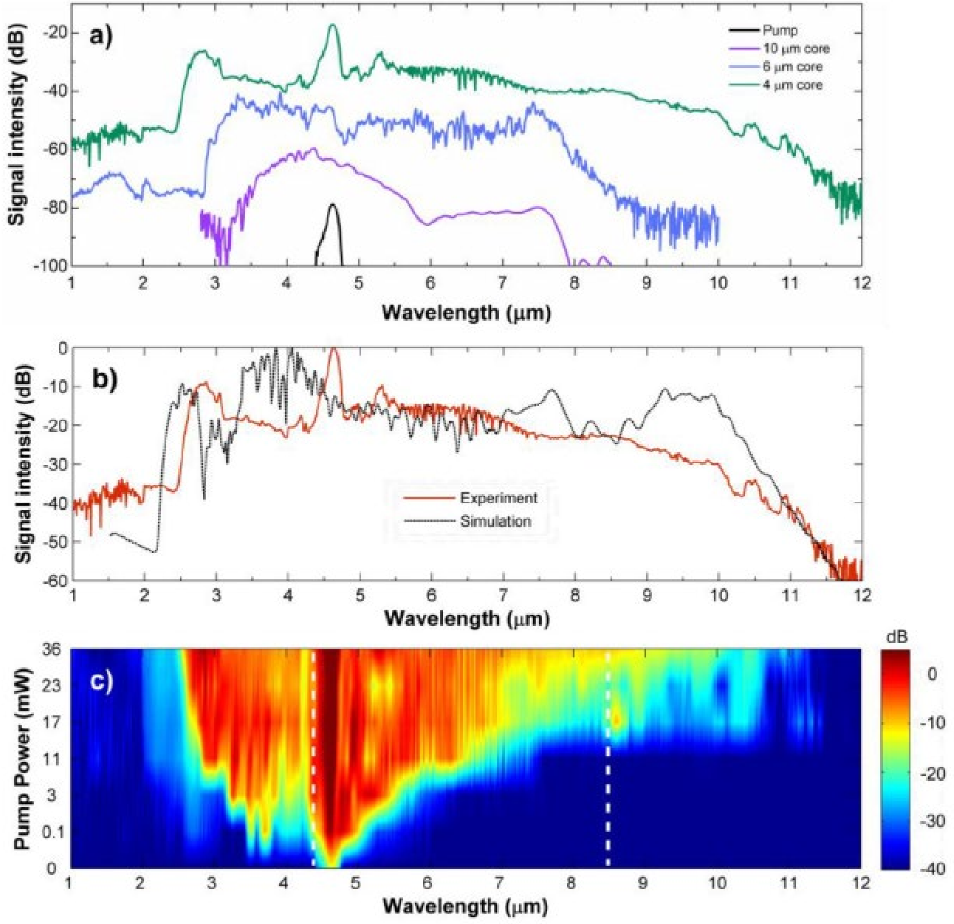
ULTRA HIGH NA

Using a core and cladding made from $Ge_{16}As_{24}Se_{15.5}Te_{44.5}$ (at.%) and $Ge_{10}As_{23.4}Se_{66.6}$ (at.%), respectively, an NA of ~1.88 was achieved from 2.5-15 µm.







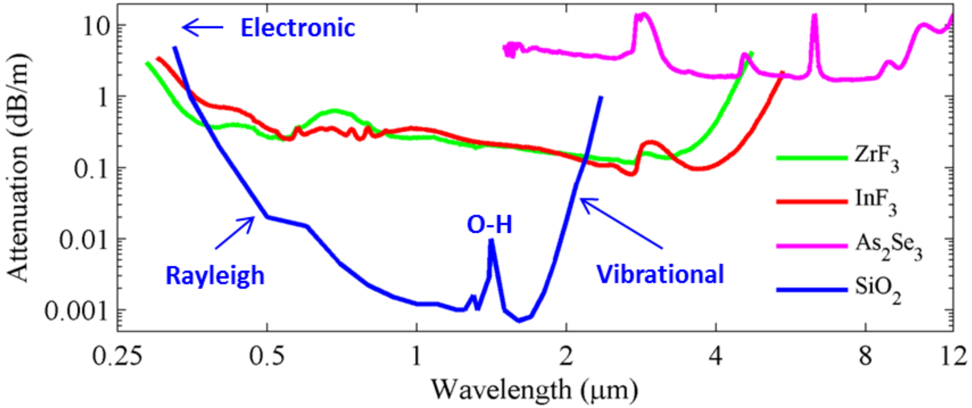


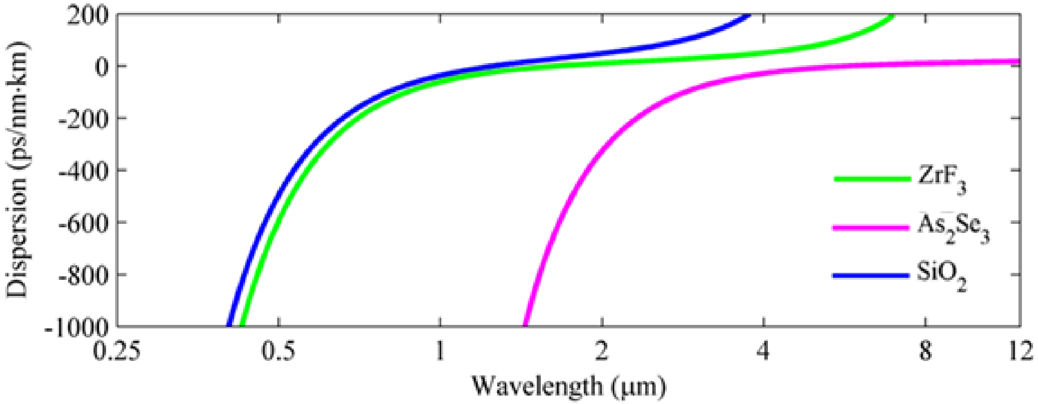
D. Jayasuriya et al., Optical Materials Express 9, 2617-2629 (2019)

DESIGNING OPTICAL FIBERS FOR SCG

CASCADING

The fiber materials, core diameters, and lengths must be carefully chosen to optimize the efficiency of the cascade. For this task numerical modelling is very handy.



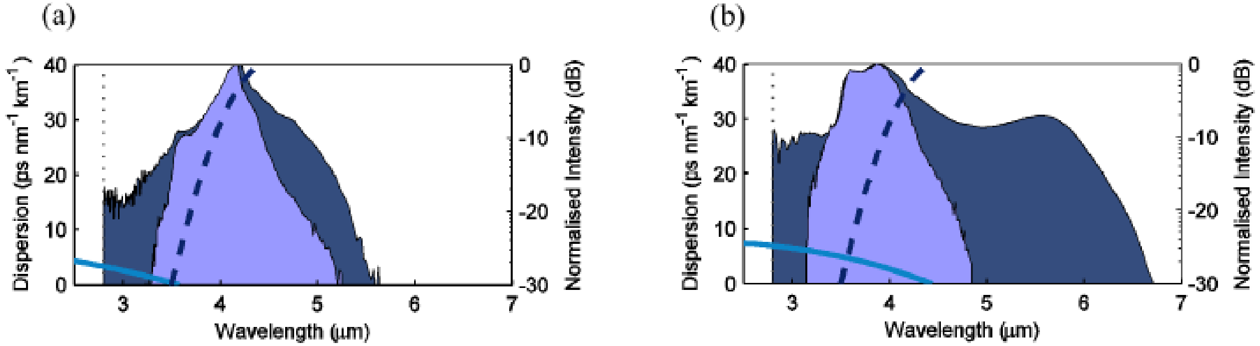


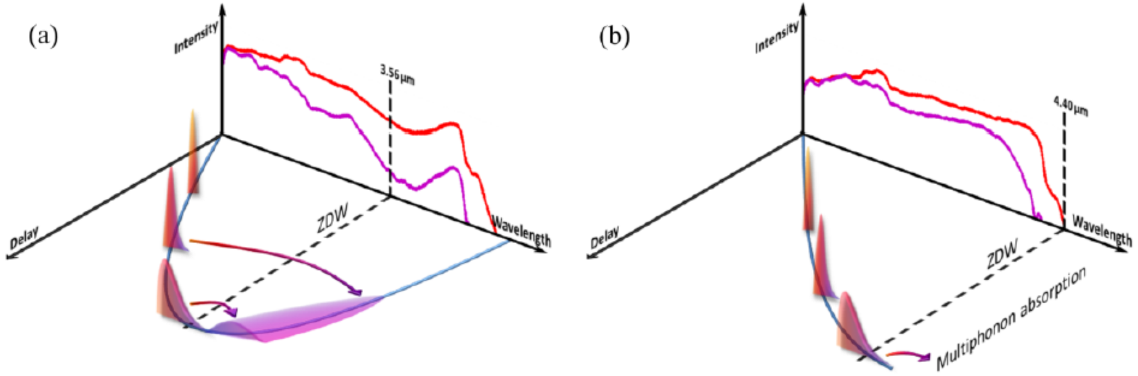
DESIGNING OPTICAL FIBERS FOR SCG

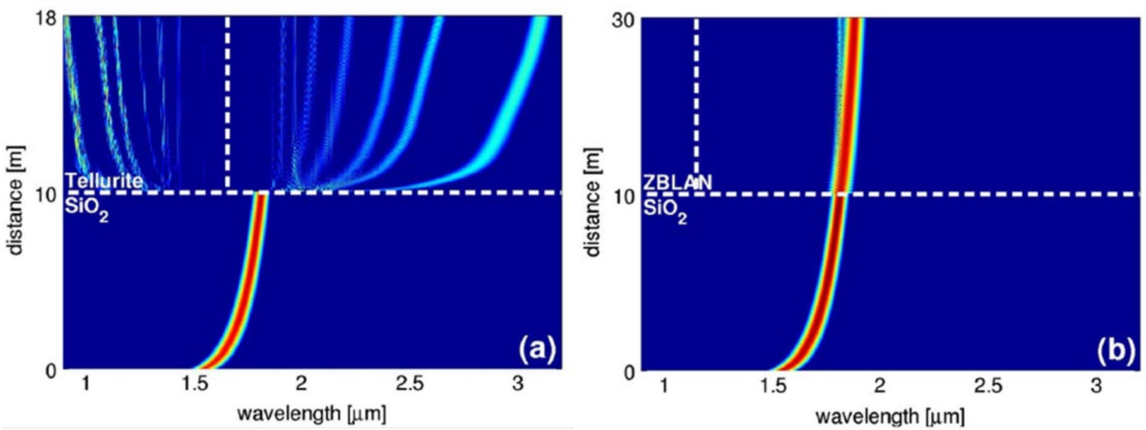
SOLITON COUPLING

Solitons are the main driving force behind cascaded SC, so one must make sure to design the cascade to allow solitons to couple between fibers. If the difference between two fibers is large, solitons may fission or disperse.

C. R. Petersen et al., Optics Express 24, 749-758 (2016)





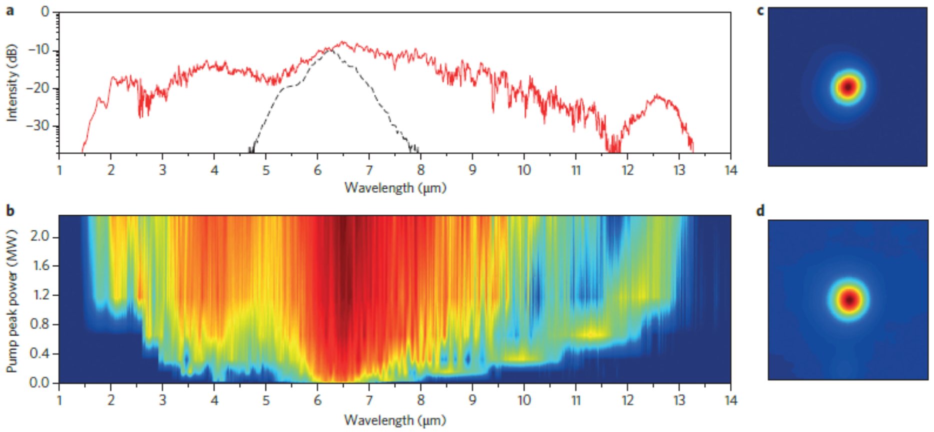


C. Agger et al., Optics Letters 36, 2596-2598 (2011)

OUTLINE

- History of Mid-IR Supercontinuum
- Physics of SCG
- Designing Optical Fibers for SCG
- Pumping schemes
- Applications

PUMPING SCHEMES



Direct pumping: **PULSE** → **FIBER**

In-amplifier generation: **PULSE** → **AMPLIFIER**

Cascaded generation: **PULSE** → **FIBER 1** → **FIBER 2** → ● ● ●

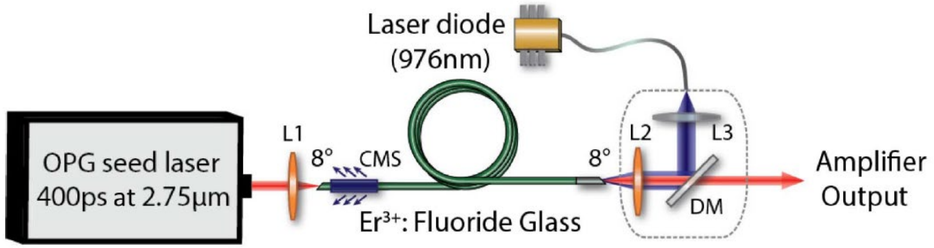
Combination (in-amp. + casc.): **PULSE** → **AMPLIFIER / FIBER** → **AMPLIFIER / FIBER** → ● ● ●

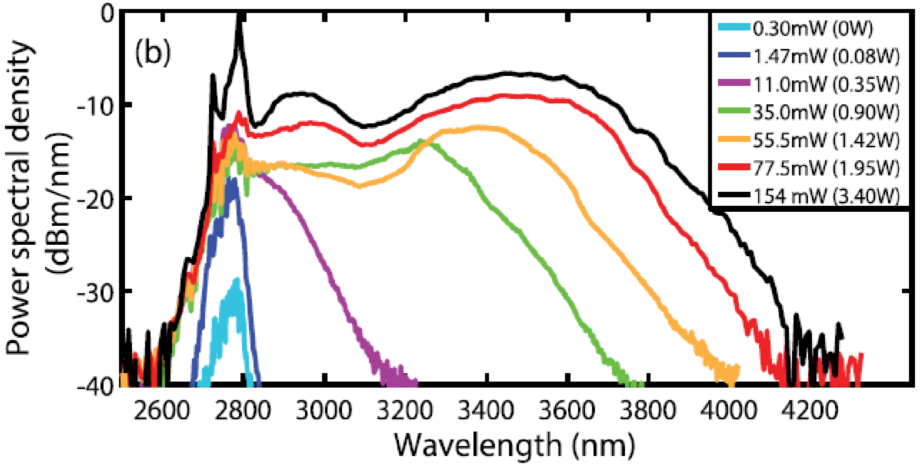
PUMPING SCHEMES

IN-AMPLIFIER SCG

In-amplifier generation

PULSE → **AMPLIFIER**





J.-C. Gauthier et al., Optics Letters 40, 5247-5250 (2015)

PRO

- Simple source design

CON

- Amplification is limited by nonlinear dynamics

PUMPING SCHEMES

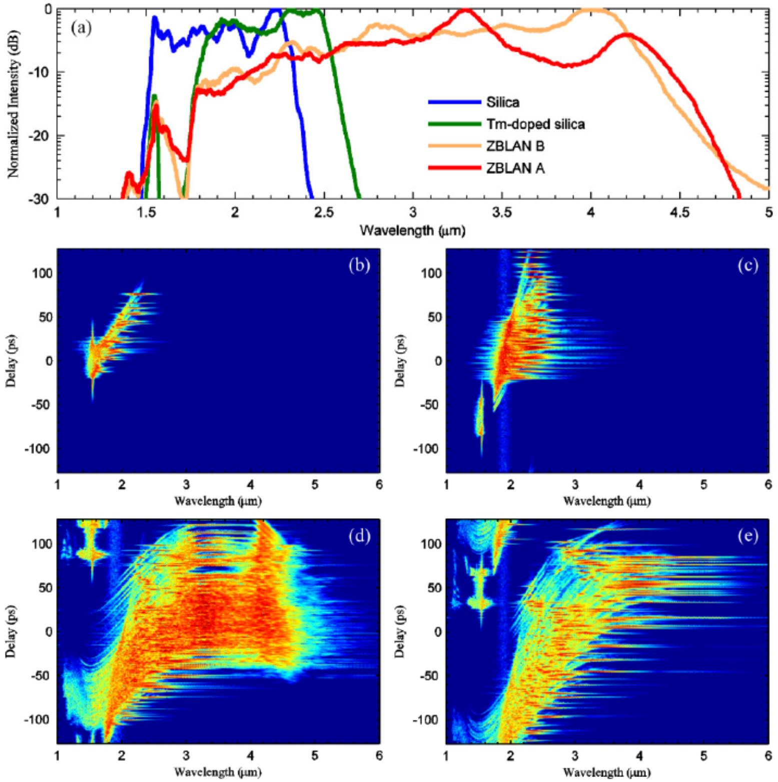
CASCADING

Cascaded generation

PULSE

FIBER 1

FIBER 2



Petersen et al.

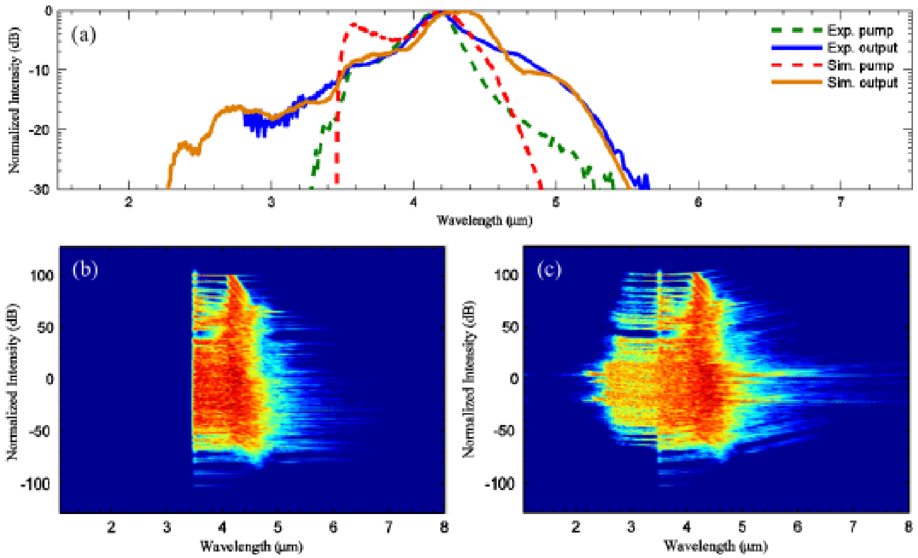
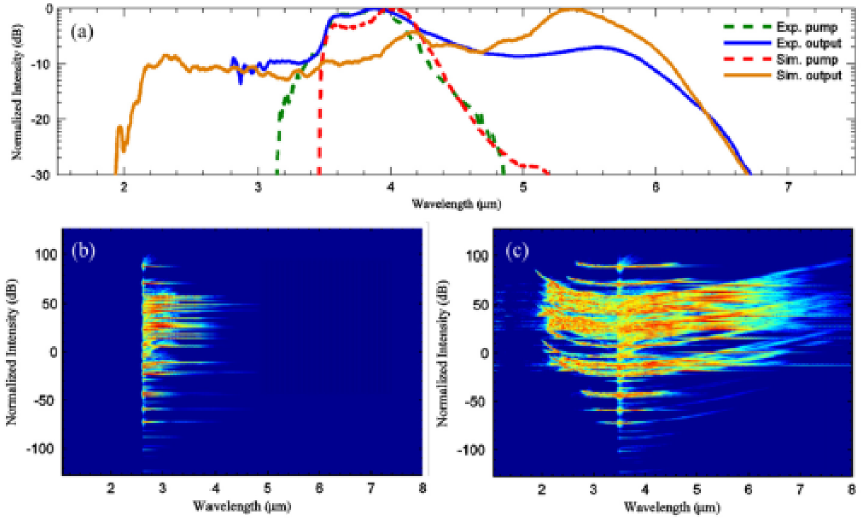


Fig. 6. (a) Comparison between the experimental and simulated pump/output spectra for the ZBLAN A pump case. (b,c) Corresponding normalized simulation spectrograms for the filtered ZBLAN A pump, and output after 170 mm propagation in the suspended-core fiber, respectively.

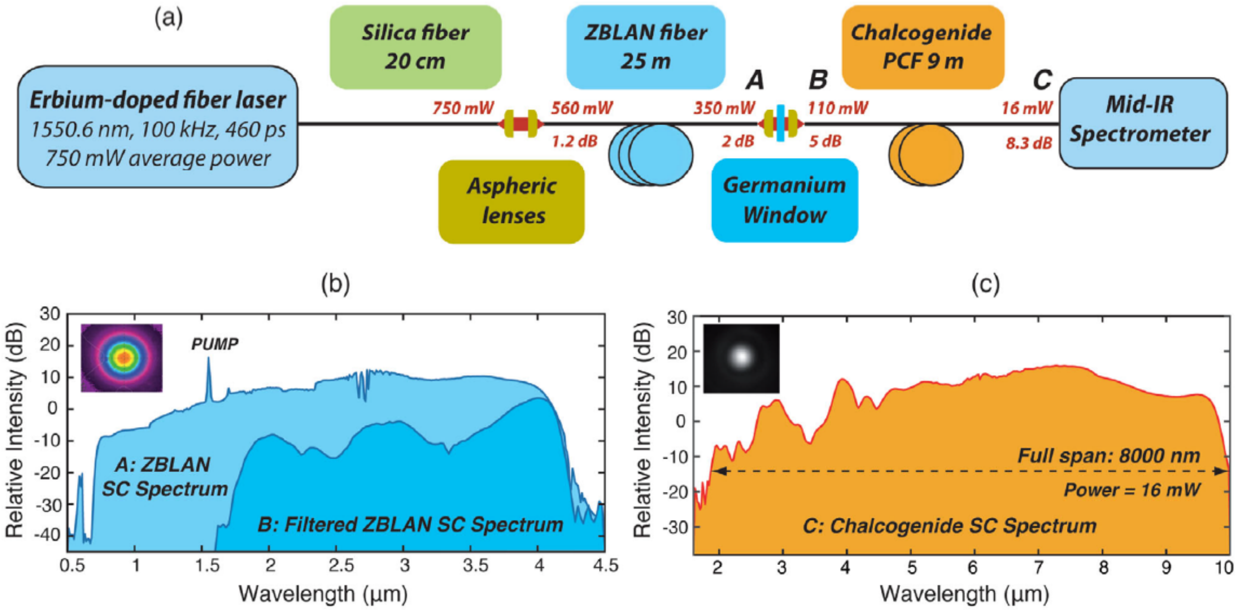


PUMPING SCHEMES

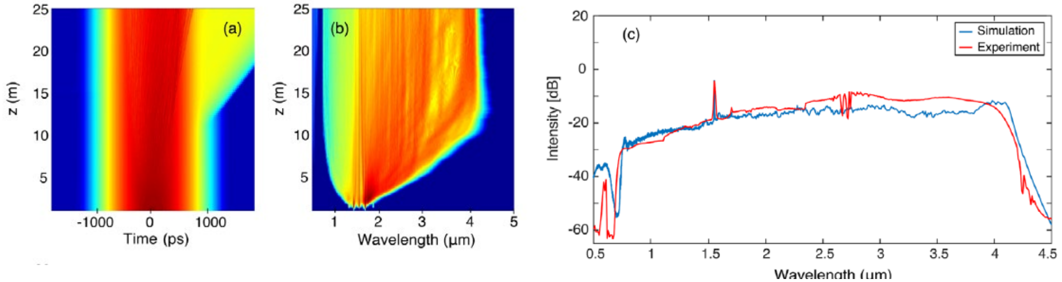
CASCADING

Cascaded generation

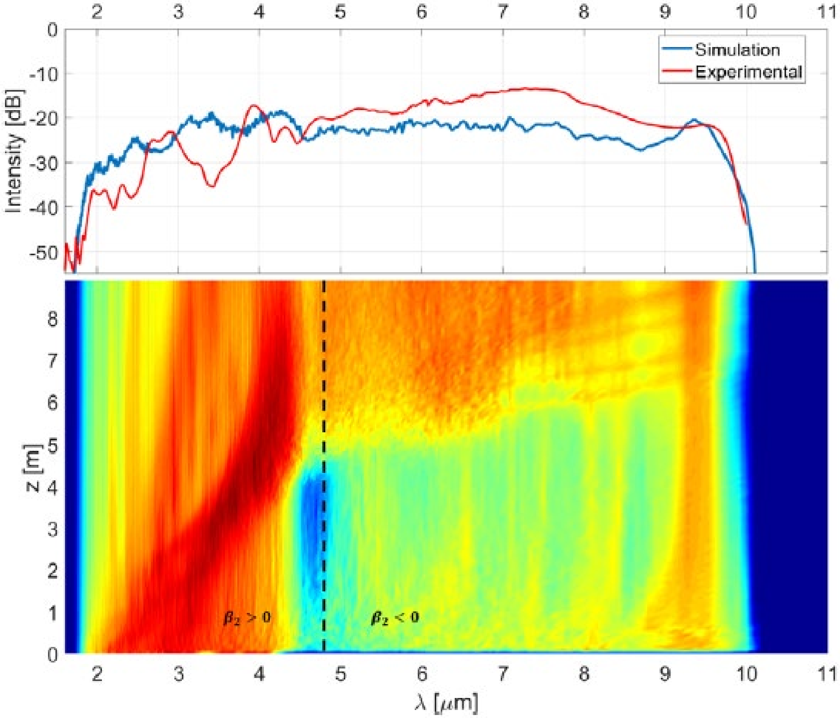
PULSE → **FIBER 1** → **FIBER 2** → ●●●



ZBLAN FIBRE



CHALCOGENIDE FIBRE



S. Venck, Laser Photonics Rev. 2000011 (2020).

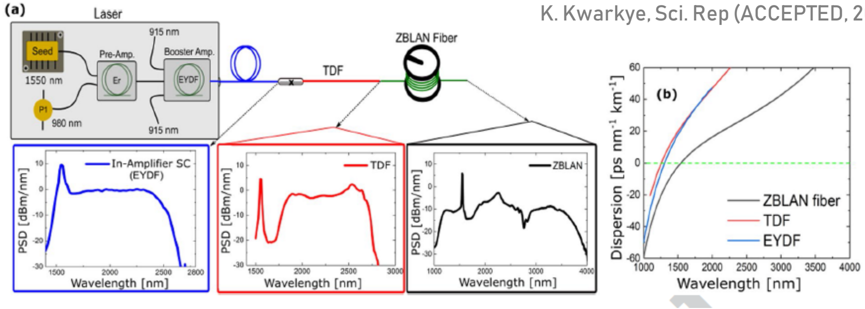
PUMPING SCHEMES

SOLITON ALIGNMENT

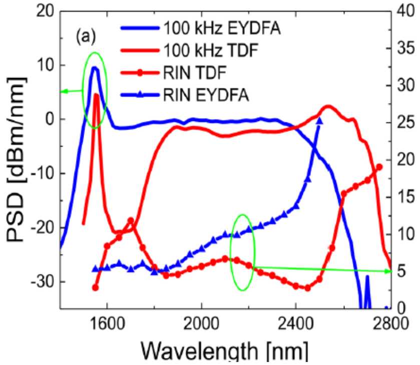
Combination
(in-amp. + casc.)

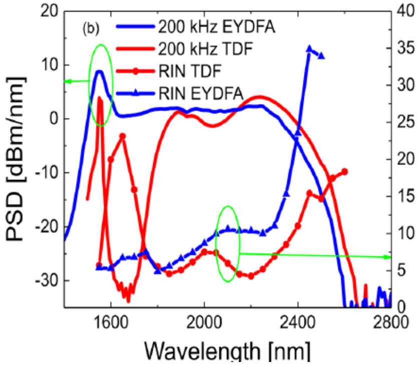
PULSE → **AMPLIFIER / FIBER** → **AMPLIFIER / FIBER** → ● ● ●

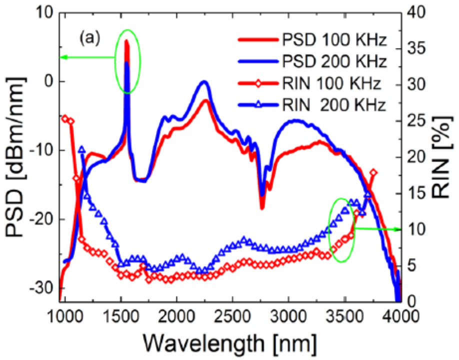
Accepted paper titled: “In-amplifier and cascaded mid-infrared supercontinuum sources with low noise through gain induced soliton spectral alignment”.

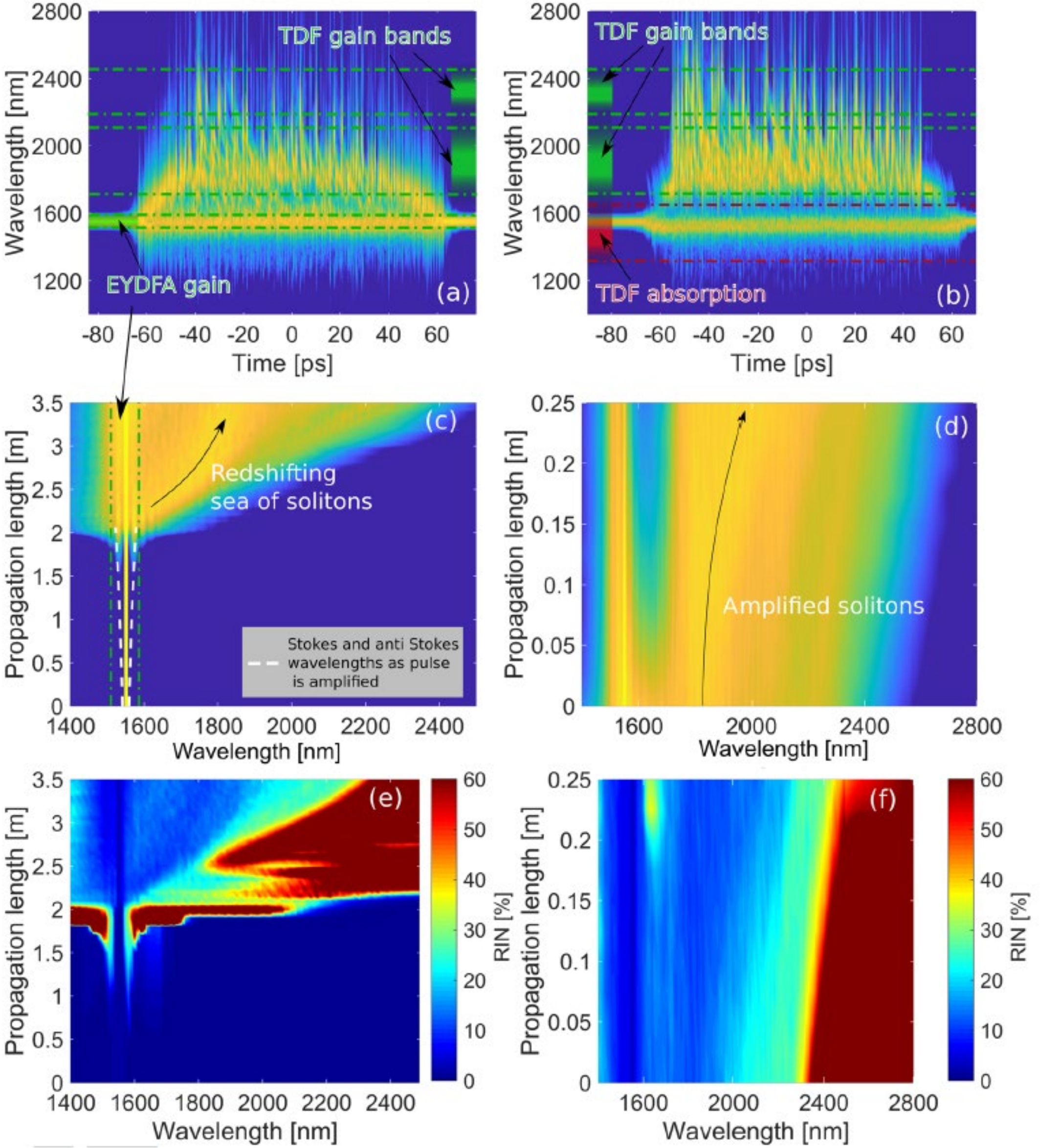


K. Kwarkye, Sci. Rep (ACCEPTED, 2020).

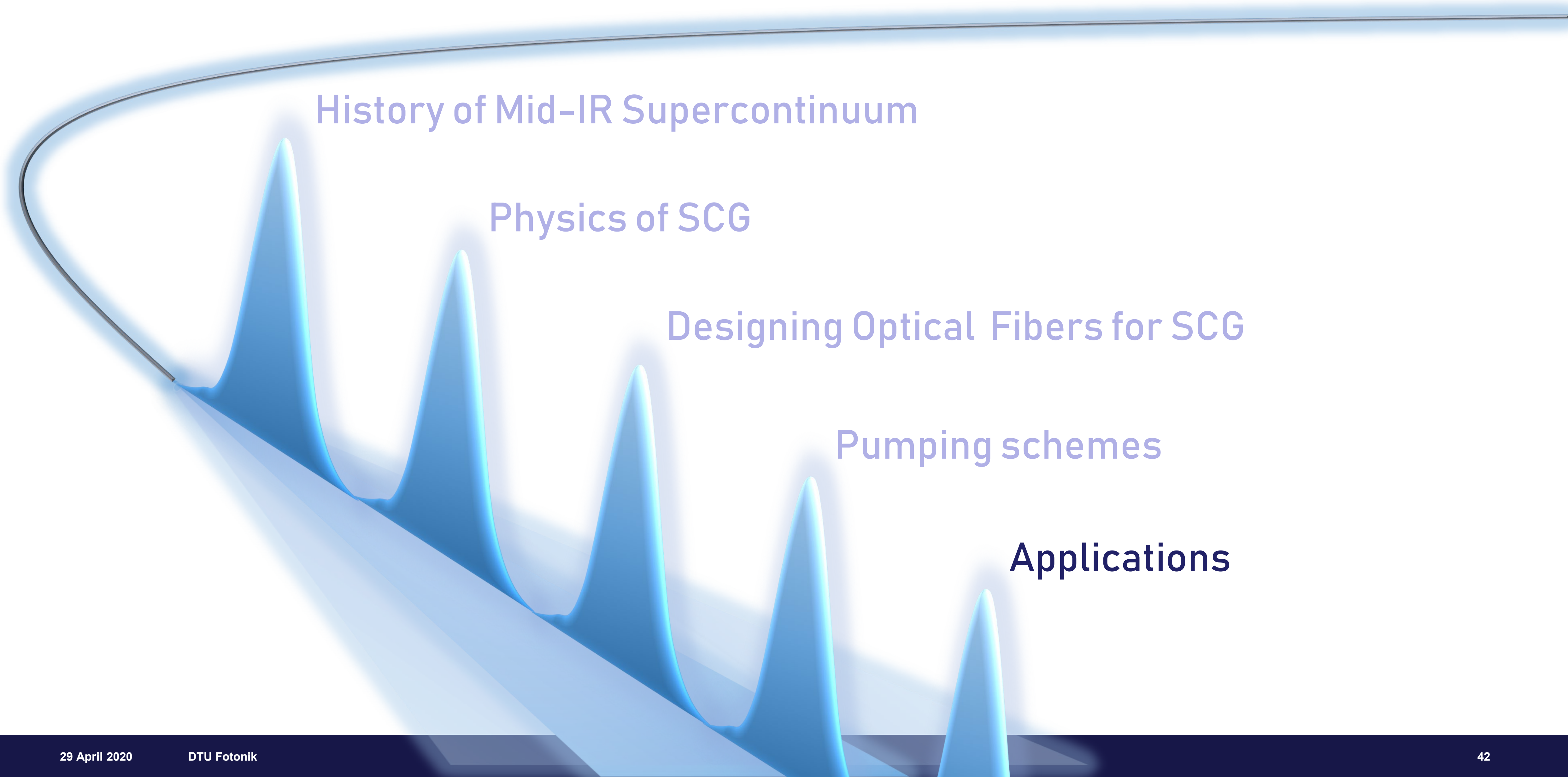








OUTLINE



- History of Mid-IR Supercontinuum
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APPLICATIONS

COMPARING APPLES AND PEARS

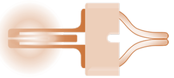
SC is often compared to traditional broadband sources of IR radiation, such as thermal sources and synchrotrons. However, there are some key differences.

SUPERCONTINUUM SOURCE

- Compact, portable, turn-key device
- Flexible optical fiber output
- Tunable pulse duration and repetition rate
- Covers 2-10 microns (5000-1000 cm^{-1})
- >4 orders of magnitude brighter than Globars

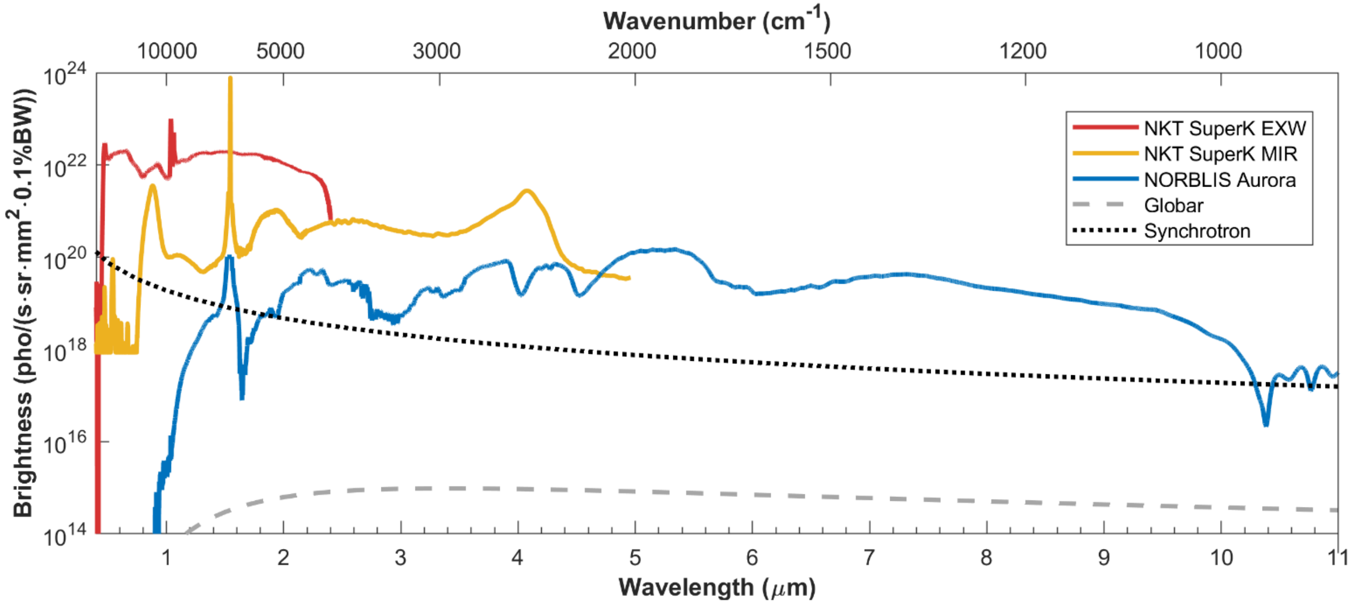
SYNCHROTRON BEAMLINE

- Massive, stationary, shared facility
- Free-space beam output
- Fixed pulse duration and repetition rate
- Covers hard X-ray to microwaves
- >2 orders of magnitude brighter than Globars



GLOBAR THERMAL SOURCE

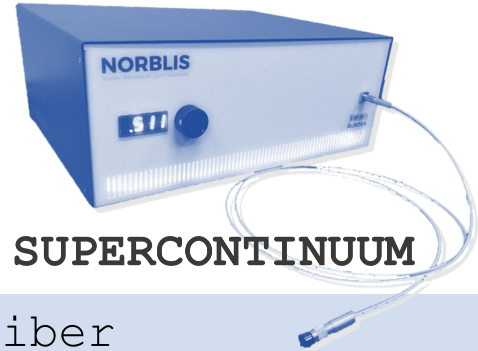
- Very compact and cheap
- Omni-directional output
- Continuous radiation
- Covers 2-25 microns infrared (5000-400 cm^{-1})
- Low brightness



APPLICATIONS

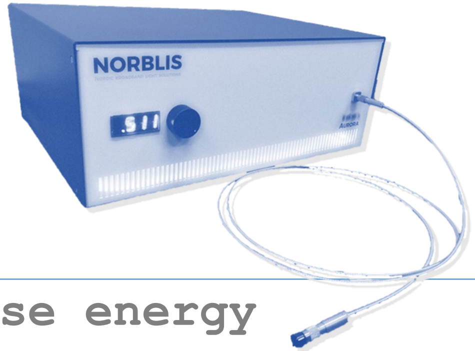
FAIR COMPARISON

To assess the potential of SC in an application it is more fair to compare against competing commercial technologies.



	SUPERCONTINUUM	**EC-QCL**	**PARAMETRIC SOURCES**
Output	Fiber	Free-space	Free-space
Scan speed	Full spectrum in single shot (~µs)	250ms step and settle or 100ms free scanning	2s step and settle
Power spectral density	Medium	Very high	High
Pulse energy	High	Low	Very high

APPLICATIONS



Advantages

- **High pulse energy**
  - Photo-acoustic spectroscopy/imaging
- **High peak power**
  - Nonlinear microscopy
- **Fast and broadband acquisition**
  - Upconversion micro/spectroscopy
  - FTIR spectroscopy/microscopy
  - Optical Coherence Tomography

Advantages

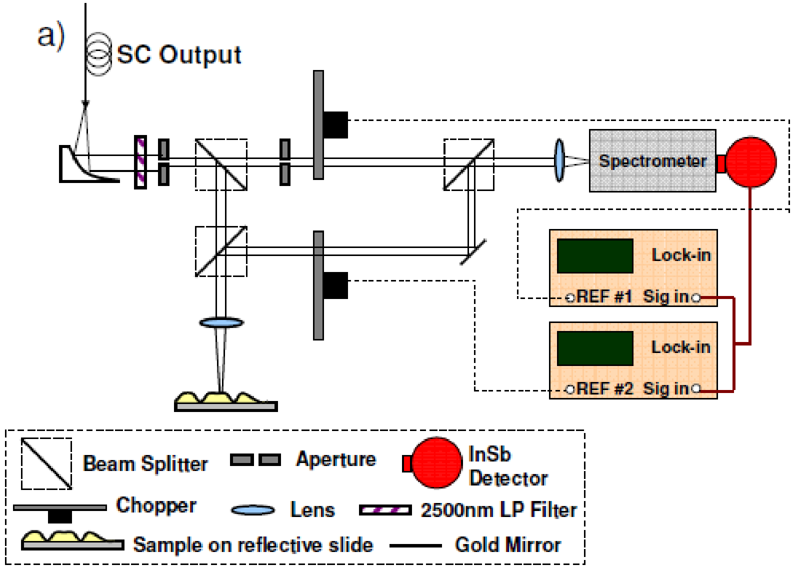
- **High power spectral density**
  - Scanning IR microscopy
  - Defense applications
- **Fast scanning, narrow line**
  - Sparse wavelength spectroscopy
  - Photo-thermal microscopy
  - Coherent Raman microscopy

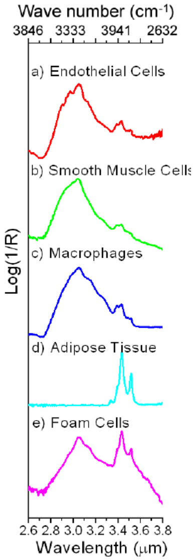
APPLICATIONS

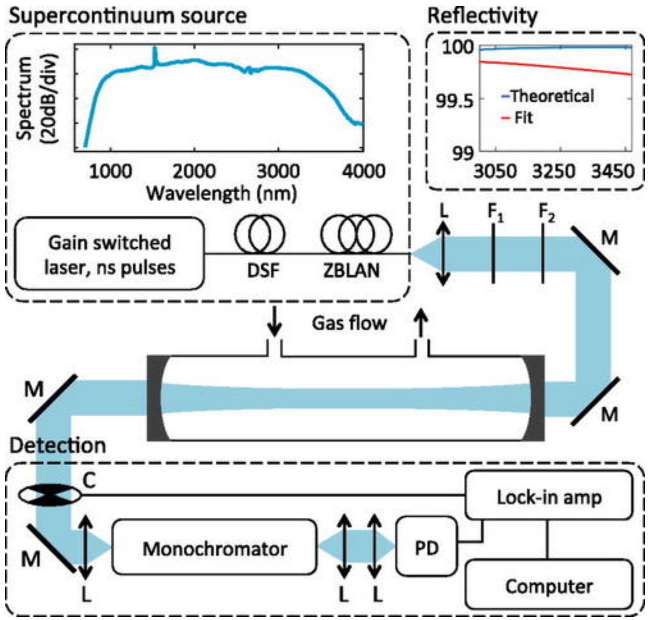
2009: DUAL-BEAM SPECTROSCOPY

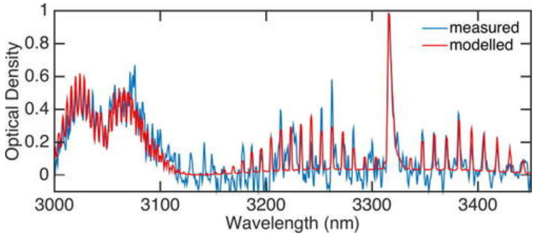
Shortly after the first demonstration of SCG in ZBLAN fiber, the same group published results with spectroscopy. A dual-beam modality was chosen to greatly reduce the noise of the otherwise very noisy SC source.

K. Ke et al., Optics Express 17, 12627-12640 (2009)









2017: CAVITY-ENHANCED SPECTROSCOPY.

Utilizing the coherent beam properties to improve the sensitivity. Although their detection was slow, the broadband instantaneous spectrum of SC has potential for monitoring fast processes.

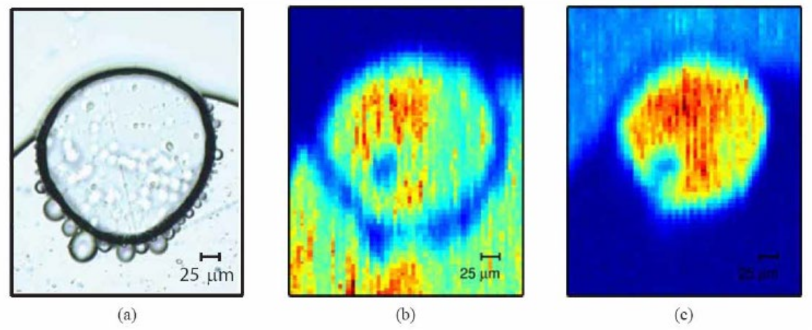
C. Amiot et al., Appl. Phys. Lett 111, 061103 (2017).

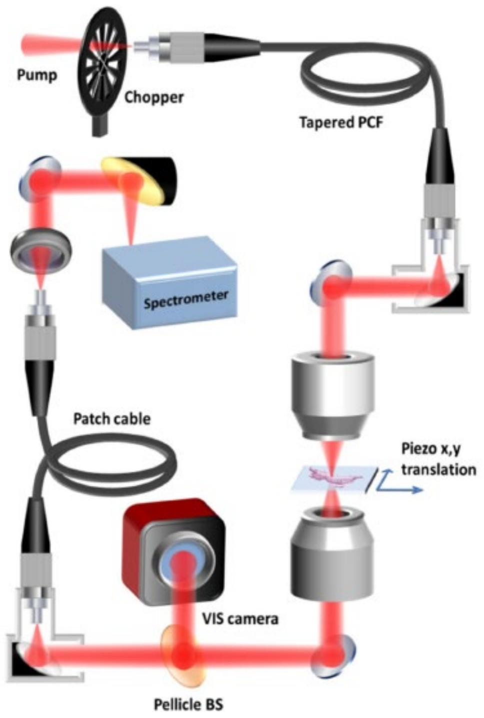
APPLICATIONS

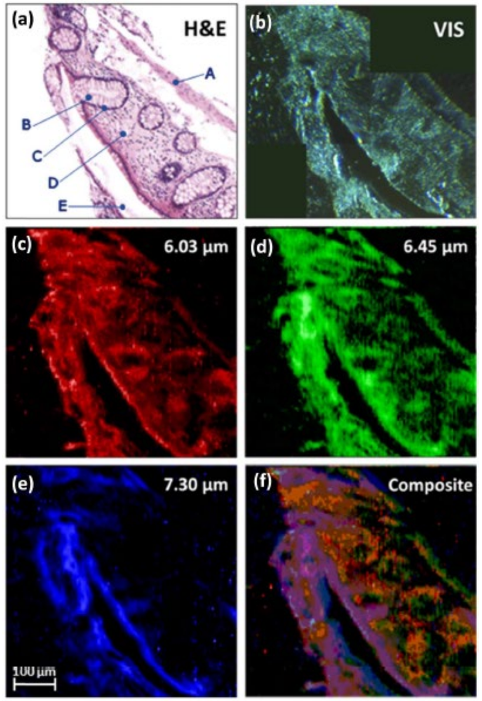
2012: MICROSCOPY (3.2-3.6 µm)

ZBLAN-based SC used for visualizing oil and water based on chemical absorption features.

A simple proof-of-concept study.







2018: IR MICROSCOPY (5.7-7.3 µm)

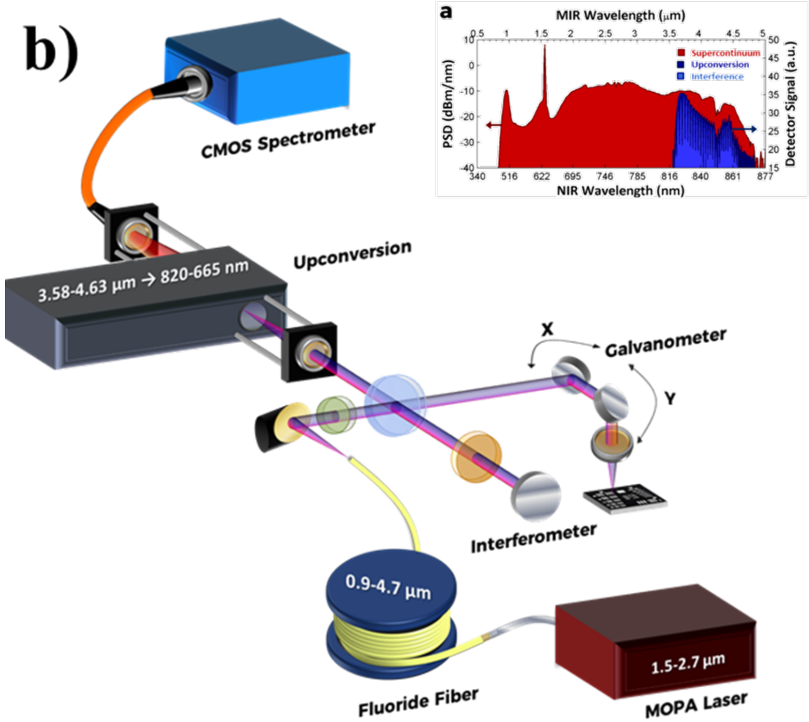
Chalcogenide-based SC used for visualizing a human colon tissue sample at different characteristic wavelengths. The goal was to obtain similar information to the sample exposed to chemical H&E staining.

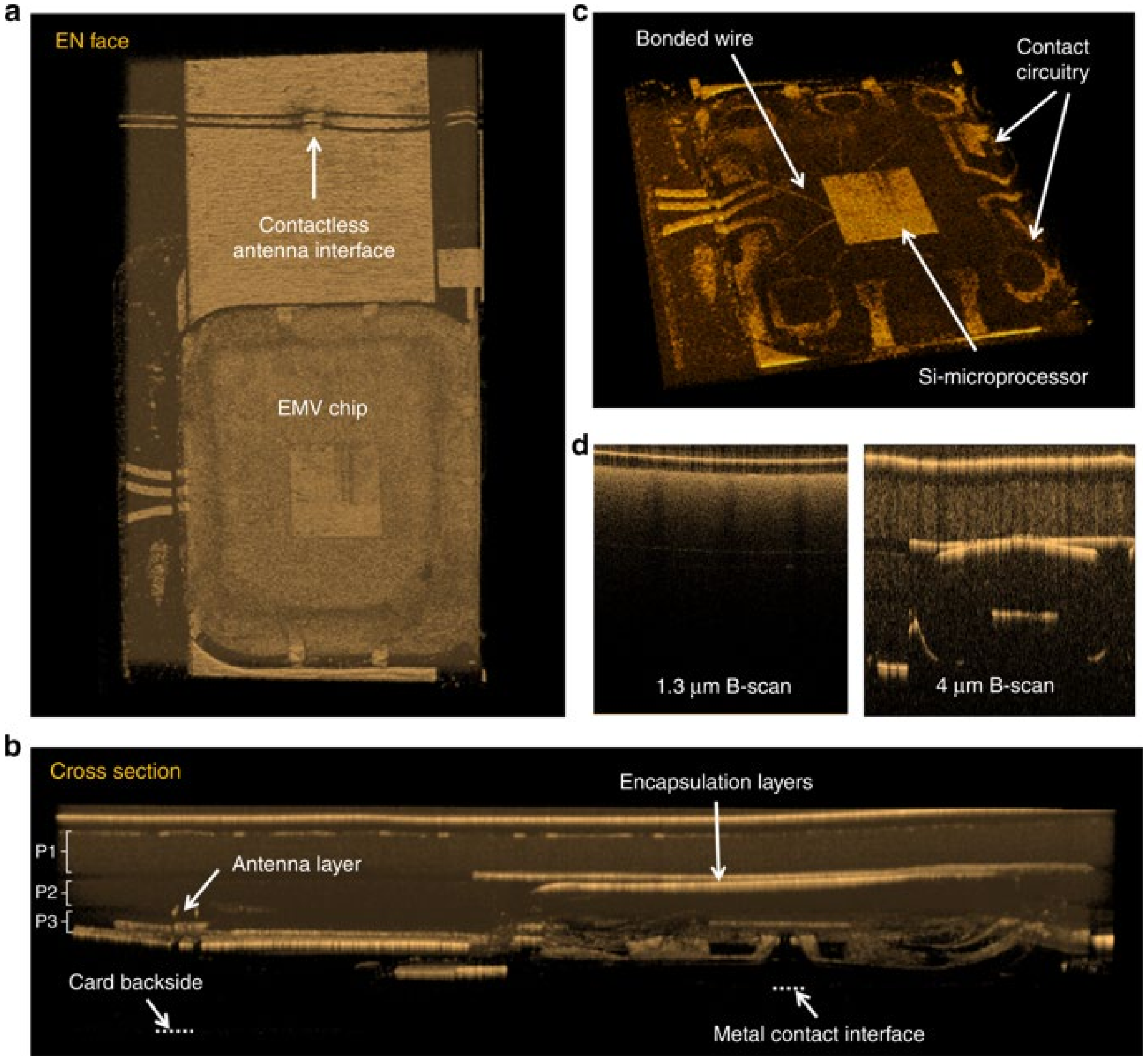
However, currently QCLs are ahead of SC in this application, with commercial products already on the market. To properly utilize SC and to compete with QCLs, the detection must be fast and parallelized to compete.

APPLICATIONS

2019: OPTICAL COHERENCE TOMOGRAPHY

Combining mid-IR SC with upconversion enabled fast and high-resolution mid-IR OCT. In OCT the resolution is proportional to the bandwidth of the source, which is why SC is ideal.





NORBLIS

www.norblis.com

Small Danish university spin-out

DTU Fotonik
Department of Photonics Engineering

Founded in 2018

Mission

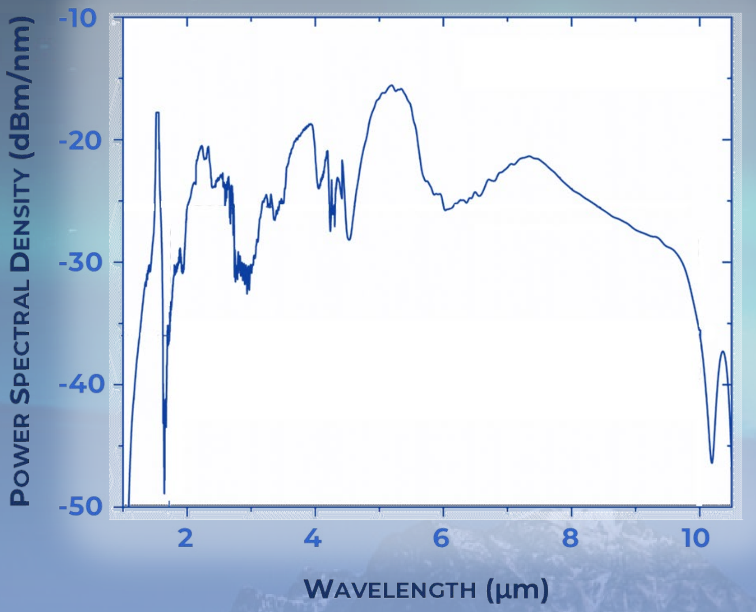
"To push super-continuum and applications further into the mid-IR."

"Create broadband mid-IR light sources that are compact, robust, and reliable."

crpetersen@norblis.com

NORBLIS

Nordic Broadband Light Solutions



crpetersen@norblis.com

www.norblis.com

THANK YOU FOR YOUR ATTENTION!

If you have additional questions I can be reached at chru@fotonik.dtu.dk