RECENT ADVANCES IN
LONG WAVELENGTH SUPERCONTINUUM

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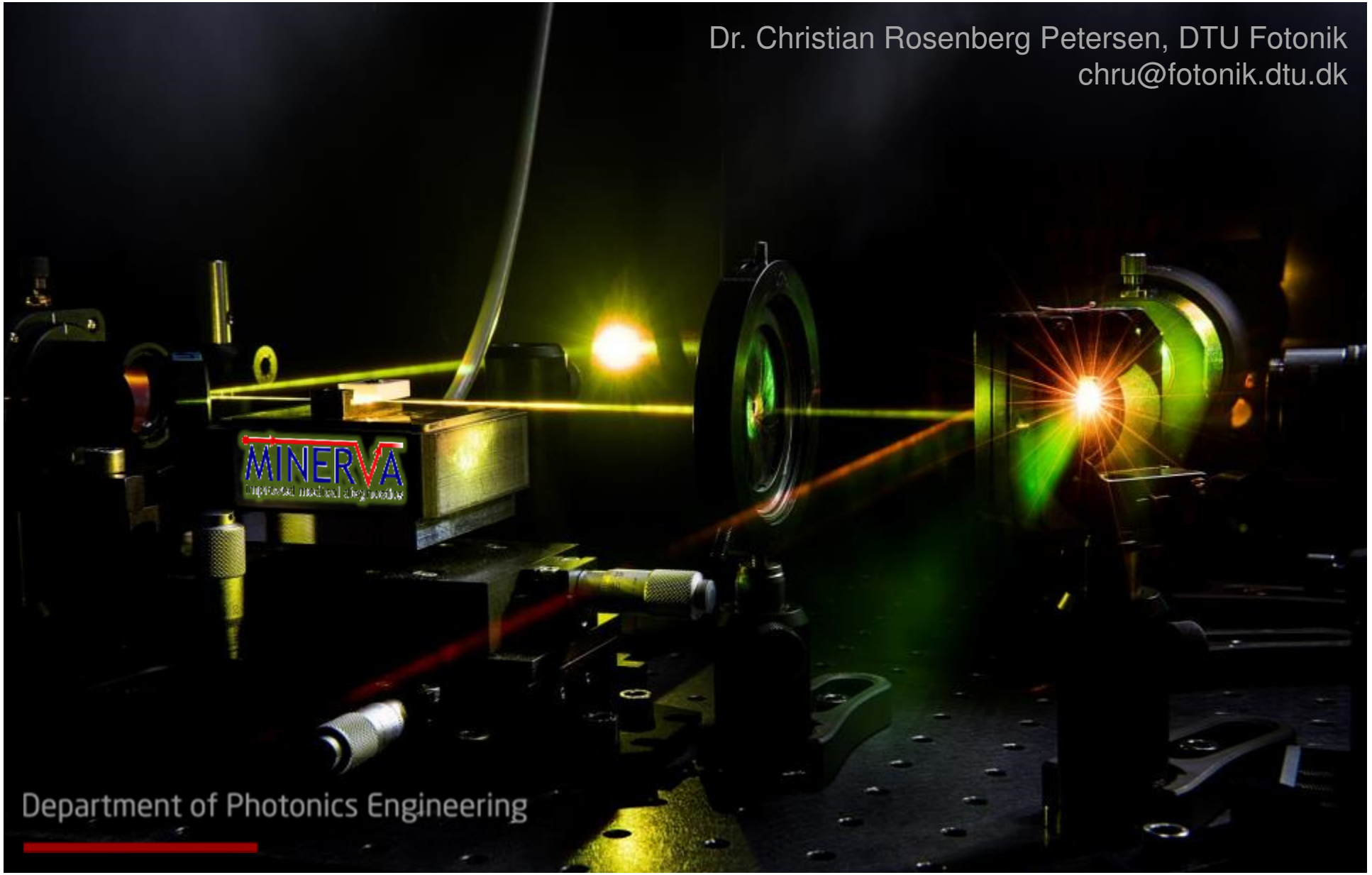

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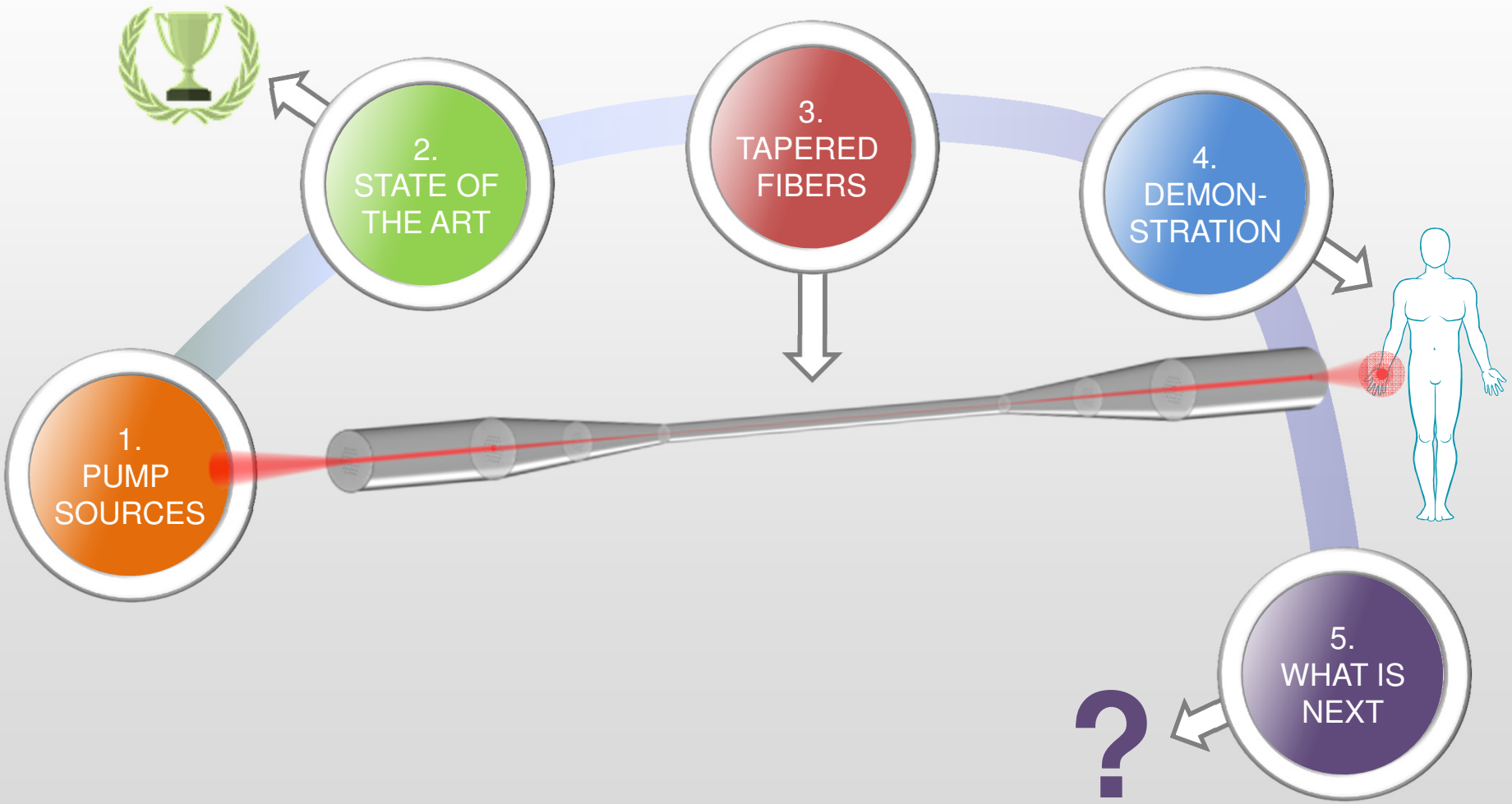


PUMP SOURCES

…In the mid-IR

CASCADE

[kæs'keɪd]

A series of components (fibers) the output of each of which serves as the input for the next.

FIBER LASERS

- Integrated
- Monolithic
- Compact
- 2.9 μm (emerging)
- 4-5 μm (development)

PARAMETRIC SOURCES

- Compact commercial systems available
- Tunable, 2.8-4.65 μm
- Free-space output
- Limited pump power

CASCADING

- Near-IR pumping
- Scalable in output power
- Much light is lost in near-IR

STATE OF THE ART

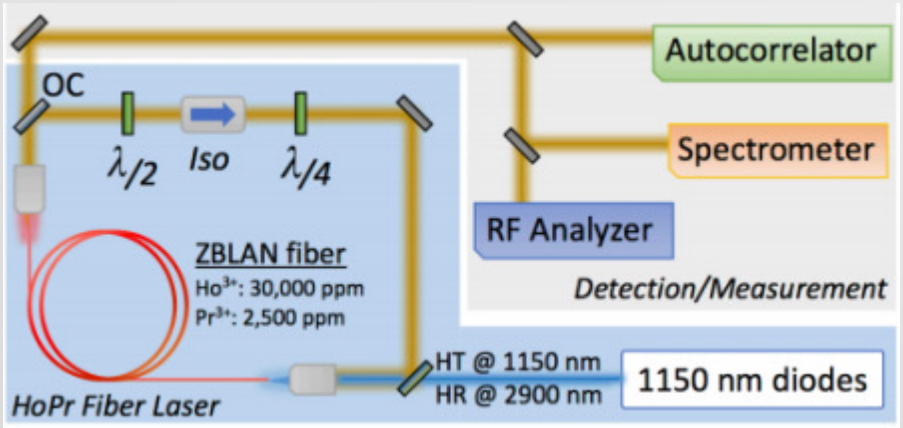
…above 5 µm

ALL-FIBER ZBLAN

components, such as couplers, FBGs, SESAMs, and polar-izers are slowly be-comming available, but are still in a de-velopment stage.

FIBER LASERS

- No results with supercontinuum above 5 µm pumped directly by fiber lasers.
- Recent talk at CLEO US on 2.9 µm Ho-Pr-doped ZBLAN fiber lasers presented 40 mW spanning 2-11.5 µm from a chalcogenide microwire (data not published).



D. Hudson et al., "Ultrafast Fiber Lasers in the Mid-IR Water Vapor Window," CLEO, STu1K.1 (2017).

STATE OF THE ART

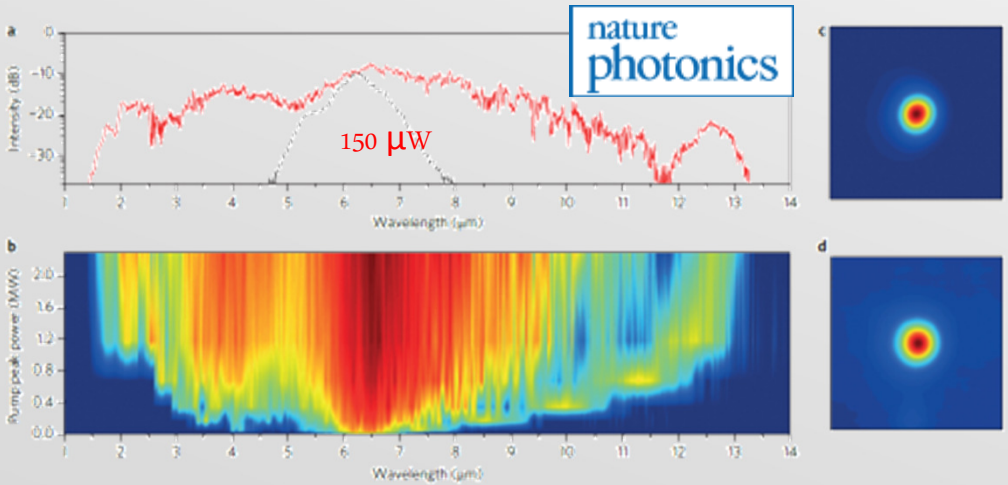
…above 5 µm

THE RECORD

has since been beaten, with de-monstrations of up to 15 µm by T. Cheng et al, Opt. Lett. 41, 2117-2120 (2016)

(kHz) PARAMETRIC SOURCES

- Massive beamlines with MW peak power (complex detection)
- Used in MINERVA record long-wavelength demonstration

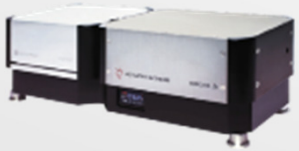


C. R. Petersen et al., "Mid-infrared supercontinuum covering the 1.4–13.3 µm molecular fingerprint region using ultra-high NA chalcogenide step-index fibre," Nat. Photonics **8**, 830–834 (2014).

STATE OF THE ART

…above 5 µm

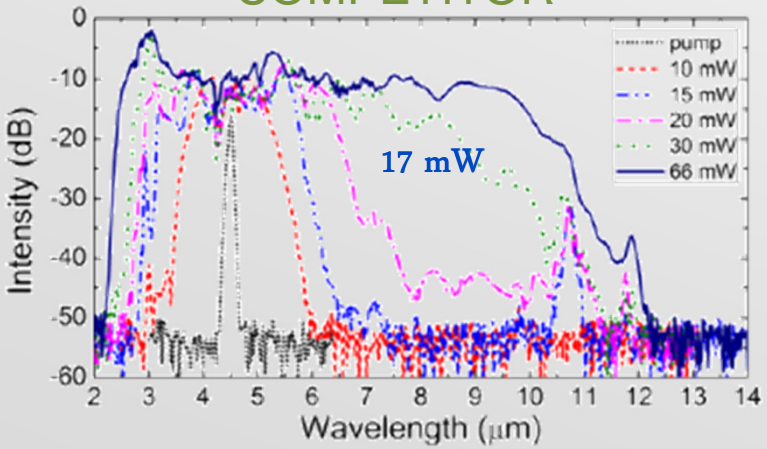
THE SINGLE PASS configuration is less efficient co-mpared to cavity-based designs, but is much si-mpler, compact, and robust.



(MHz) PARAMETRIC SOURCES

- Single pass configuration allow for very compact and robust sources.
- Can support reasonable average power and kW level peak power.
- Used to pump Ge-Sb-Se/Ge-Se step-index fiber with a core diameter of 6 µm and NA~1.1.

COMPETITOR



B. Zhang et al., "High Brightness 2.2–12 µm Mid-Infrared Supercontinuum Generation in a Nontoxic Chalcogenide Step-Index Fiber", J. Am. Ceram. Soc., **99**, 2565–2568 (2016).

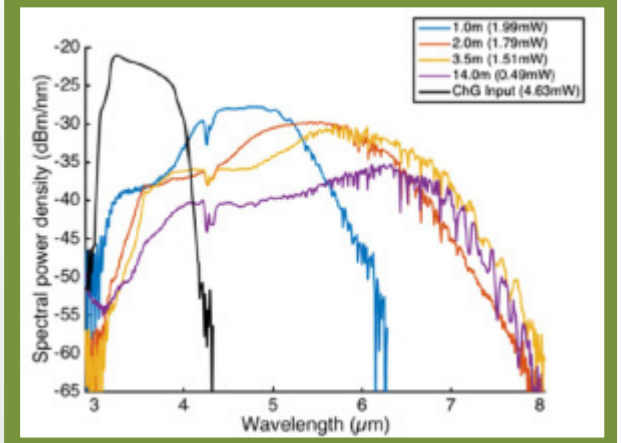
STATE OF THE ART

…above 5 µm

CASCADING

- Based on broadening in silica and then ZBLAN to around 4.3 µm (NKT source).
- First experimental result in chalcogenide fiber generated 6.5 mW up to 7 µm.
- Others have later demonstrated cascading using step-index fibers, generating 1.51 mW up to 8 µm.

COMPETITOR



L.-R. Robichaud et al., Opt. Lett. **41**, 4605-4608 (2016)

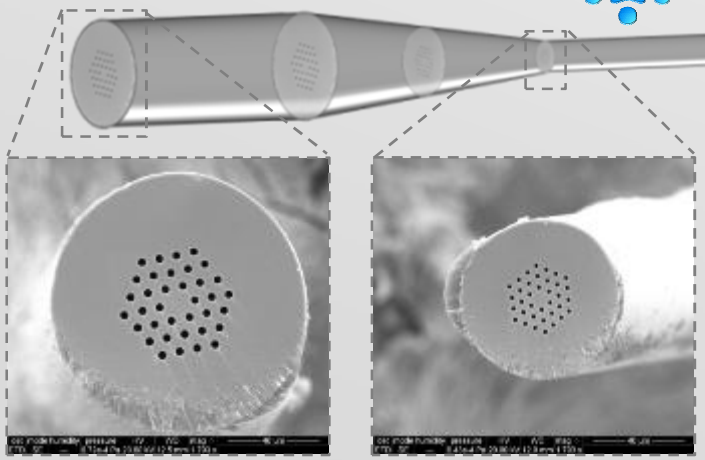
C. R. Petersen et al., "Spectral-temporal composition matters when cascading supercontinua into the mid-infrared," Opt. Express **24**, 749-758 (2016)

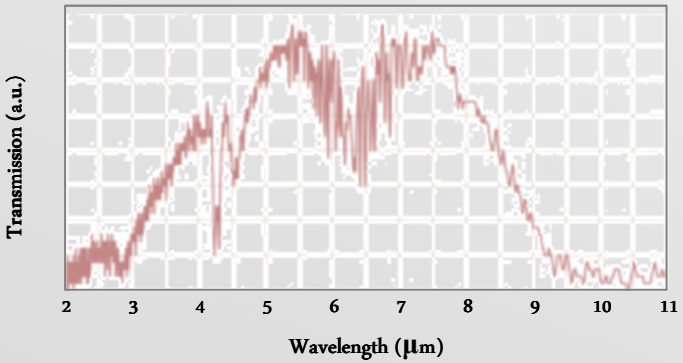
TAPERED FIBERS

PHOTONIC CRYSTAL FIBERS (PCF)

- Can be made single-mode at all wavelengths
- Can tailor the dispersion profile
- Ideal for tapering of high-index glasses
- Issue with confinement loss at long wavelengths
- Ge10As22Se68 can transmit beyond 9 μm, with a zero-dispersion wavelength around 3.6 μm for d/Λ = 0.5 and core diameter of 6.1 μm.

SelenOptics

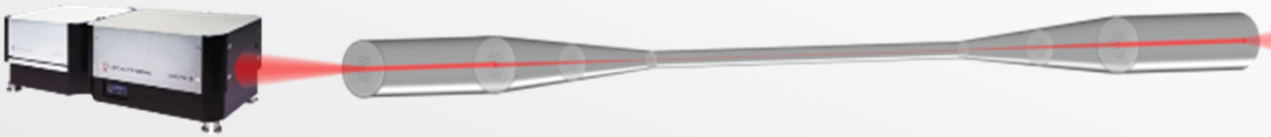


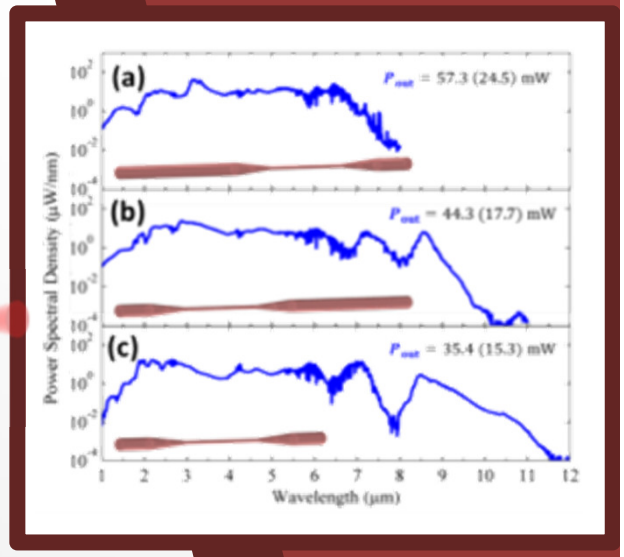


WE HAVE INVESTIGATED

- Different core diameters from 11.6 μm to 15.1 μm.
- Different d/Λ from 0.44 to 0.51
- Different lengths of fiber before and after the taper
- Different waist dia-meters from 5.9 μm to 8.0 μm.

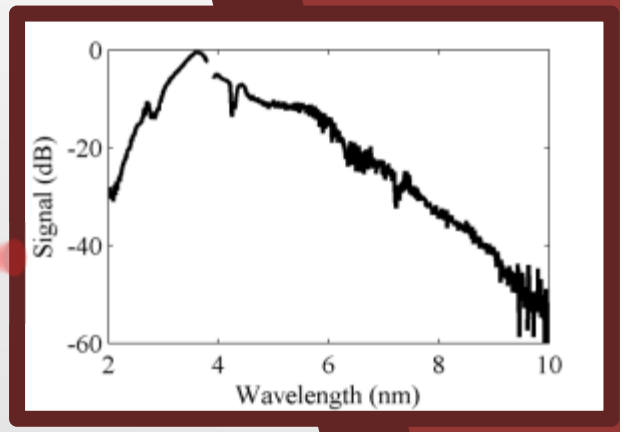
TAPERED FIBERS





OPA RESULTS

- Pumping at 4 μm we achieved 57.3 mW from 1-8 μm, and 35.4 mW from 1-11.5 μm by varying the length of uniform fiber before and after the tapered section.

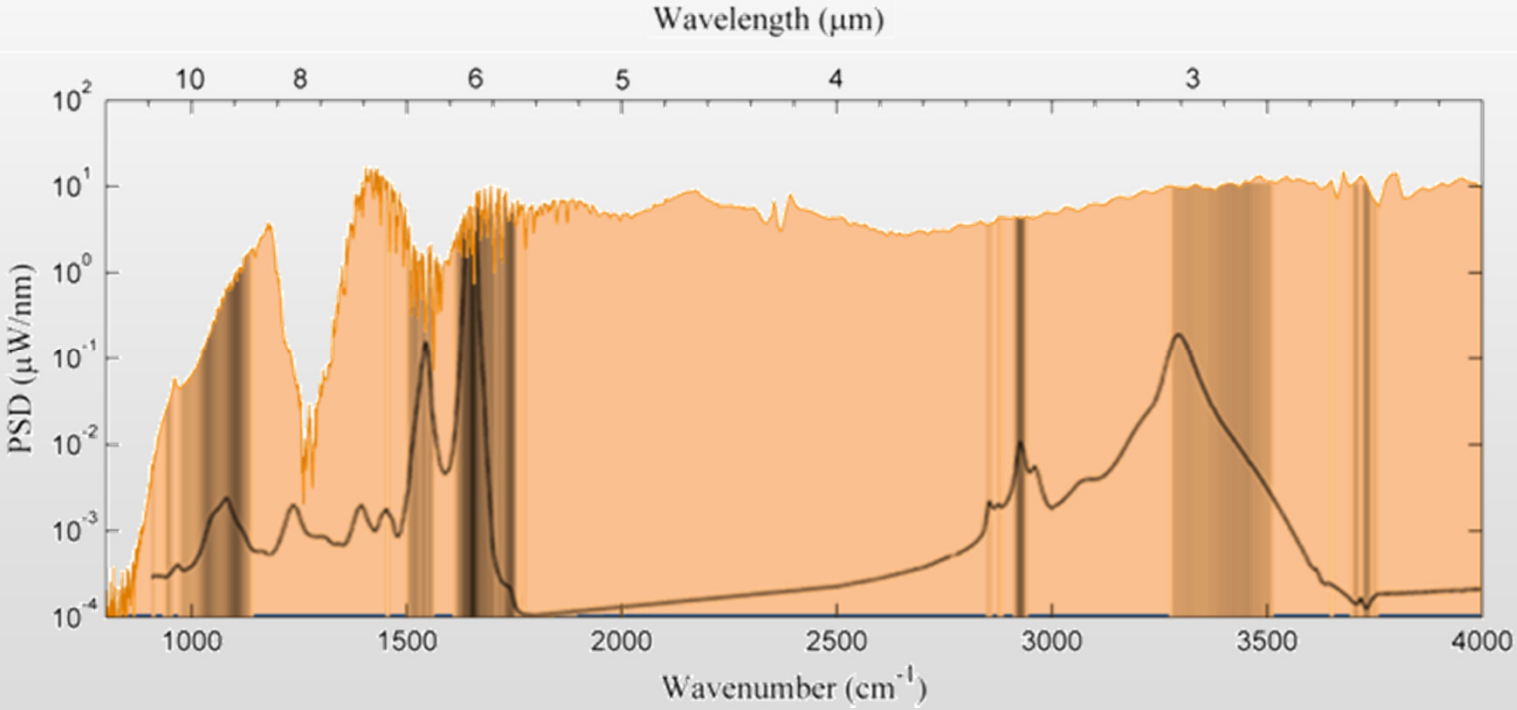


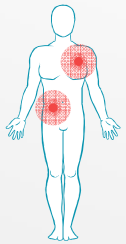
CASCADING RESULT

- We obtained 9 mW from 2-9 μm, thus improving on the state of the art.
- This result was obtained using first trial tapers made, so we expect to improve on power and bandwidth.

ENOUGH POWER AND BANDWIDTH FOR

THE FIRST DEMONSTRATION





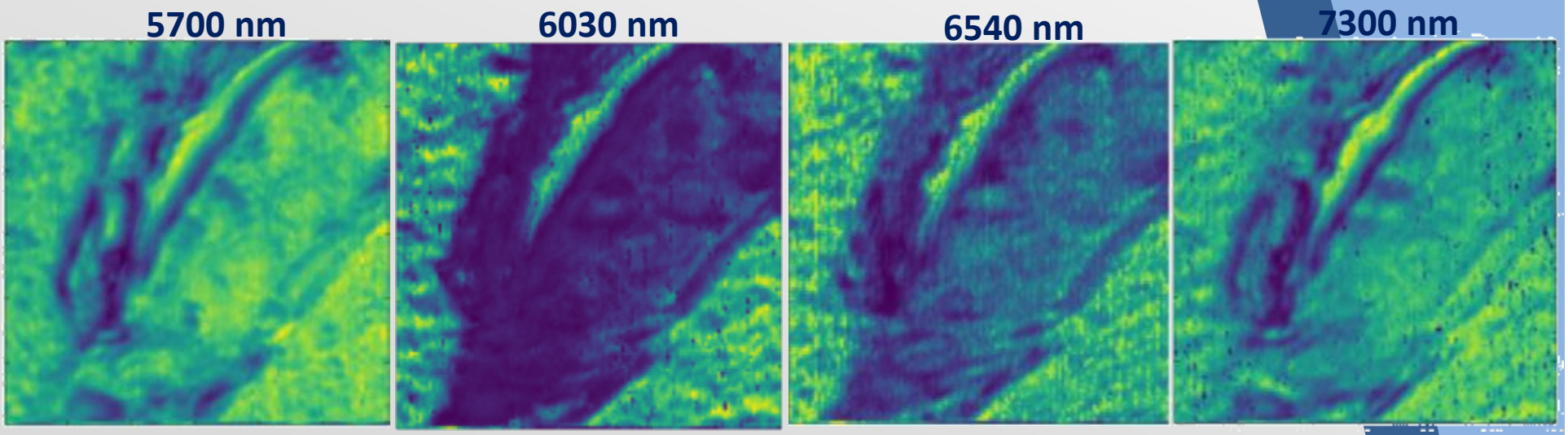
DEMONSTRATION USING SUPERCONTINUUM

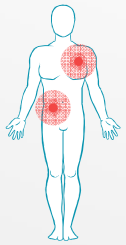
FIRST DEMONSTRATION

- Used a fully connectorized tapered fiber to interface with a scanning system (Nikola's talk later)
- Scanned using several filtered wavelengths of interest.
- First demonstration of imaging using supercontinuum above 5 µm.

THE SAMPLE

was a 10 µm section of parafinized colon tissue fixed on CaF2 substrate.

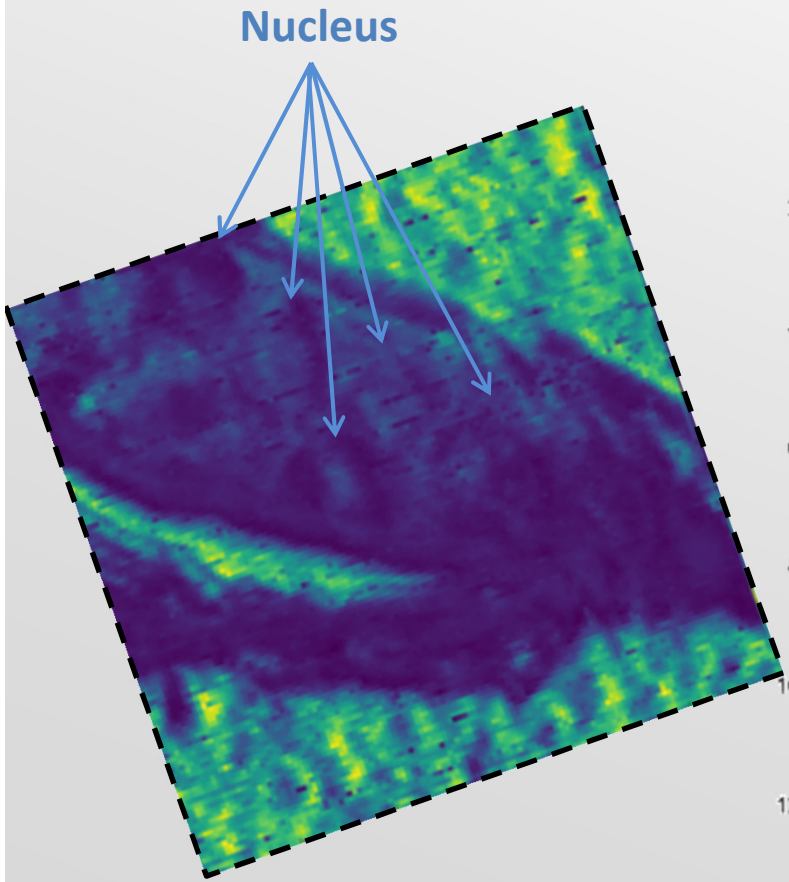


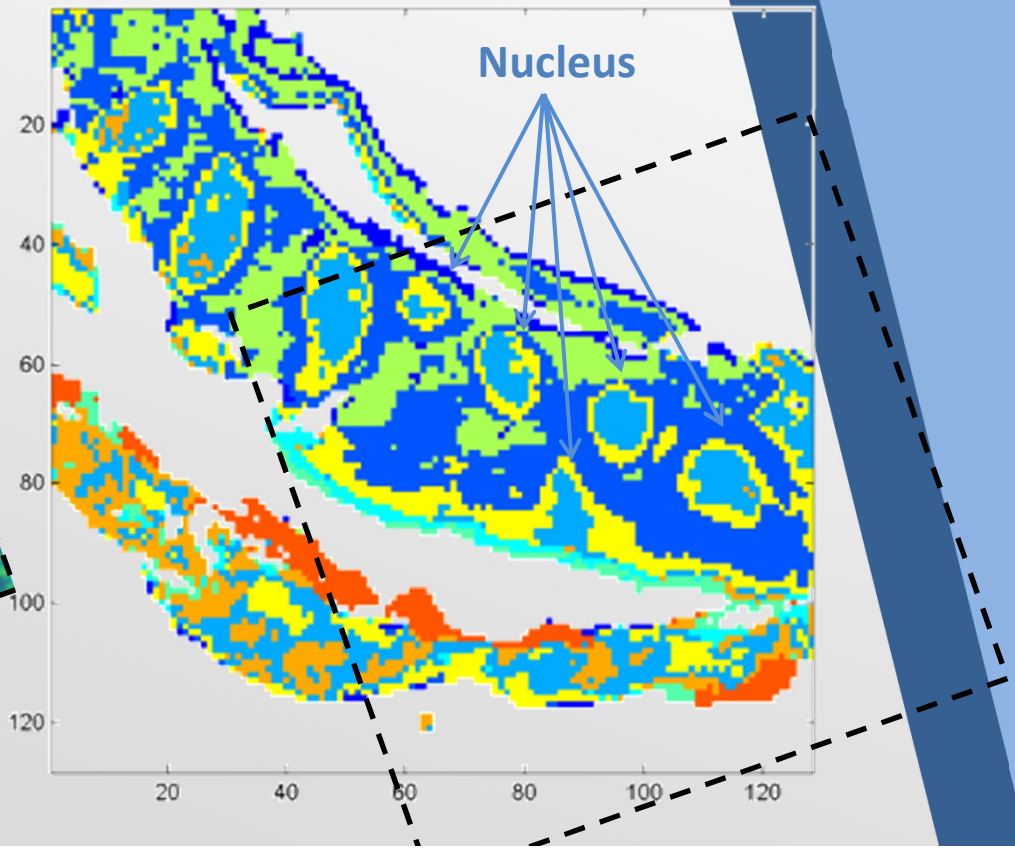


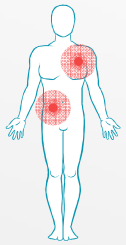
DEMONSTRATION
USING SUPERCONTINUUM

COMPARED TO FT-IR STATE OF THE ART

- Features are visible from raw data



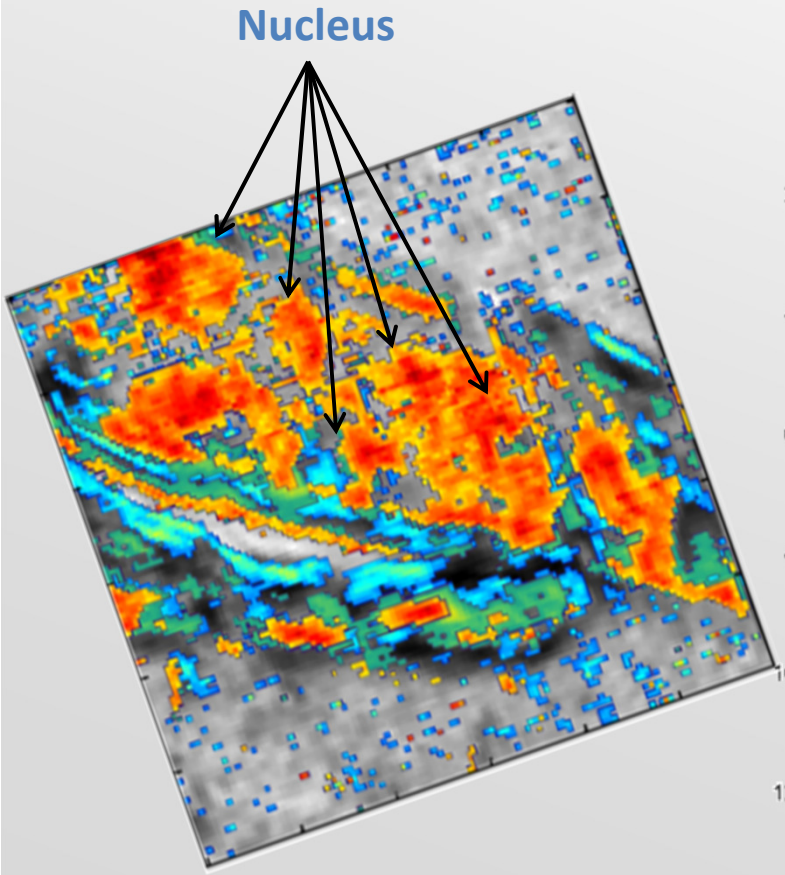


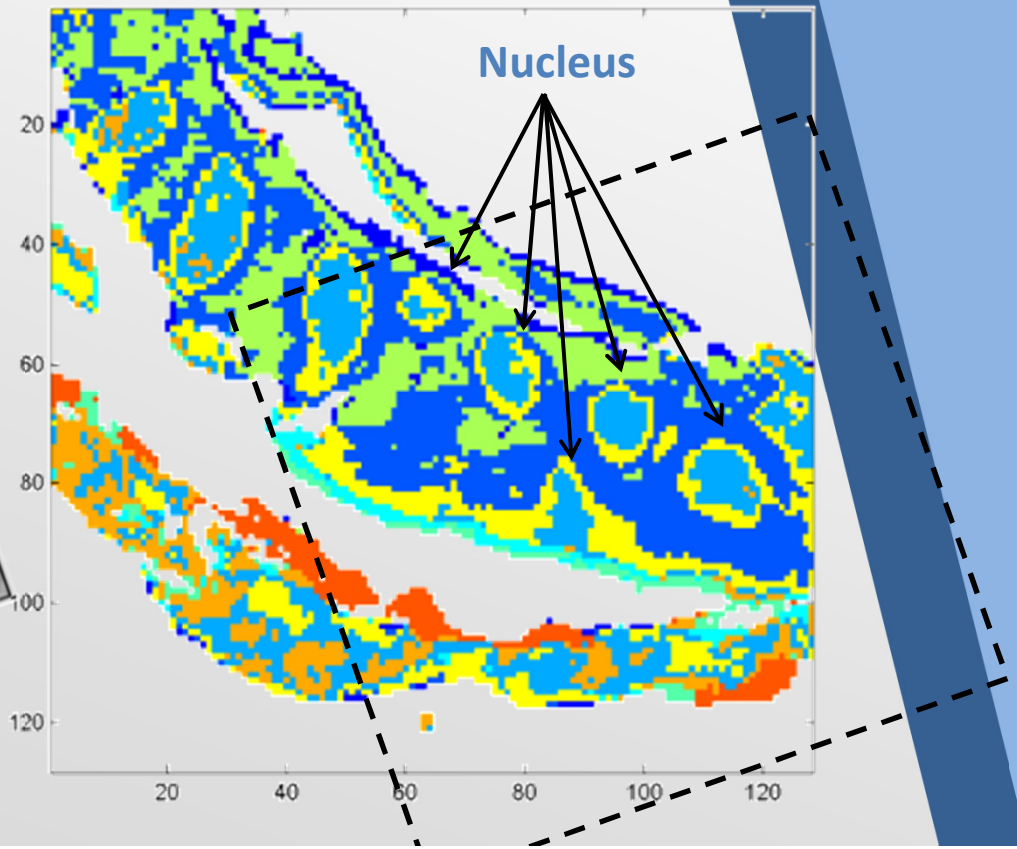


DEMONSTRATION
USING SUPERCONTINUUM

SPECTRAL ABSORPTION MAP

- ORANGE=6030 nm, GREEN=6450 nm, BLUE=7300 nm.





? WHAT IS NEXT

…for long wave supercontinuum?

LESSONS LEARNED

- Applications should utilize the laser-like properties of supercontinuum.
- Qualitative methods, like imaging, may be better suited for long wave supercontinuum.

SOURCES

- Improve cascading
- 2.9 μm fiber lasers

FIBERS

- Te-based fibers
- Multi-material fibers

APPLICATIONS

- Optical Coherence Tomography

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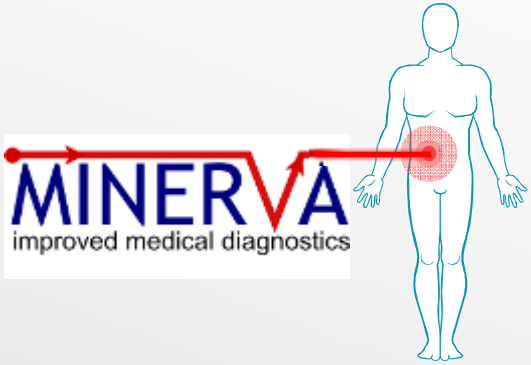

THANK YOU FOR YOUR ATTENTION

ANY QUESTIONS?

DTU Fotonik
Department of Photonics Engineering