Recent progress in broadband fiber-based mid-IR laser sources

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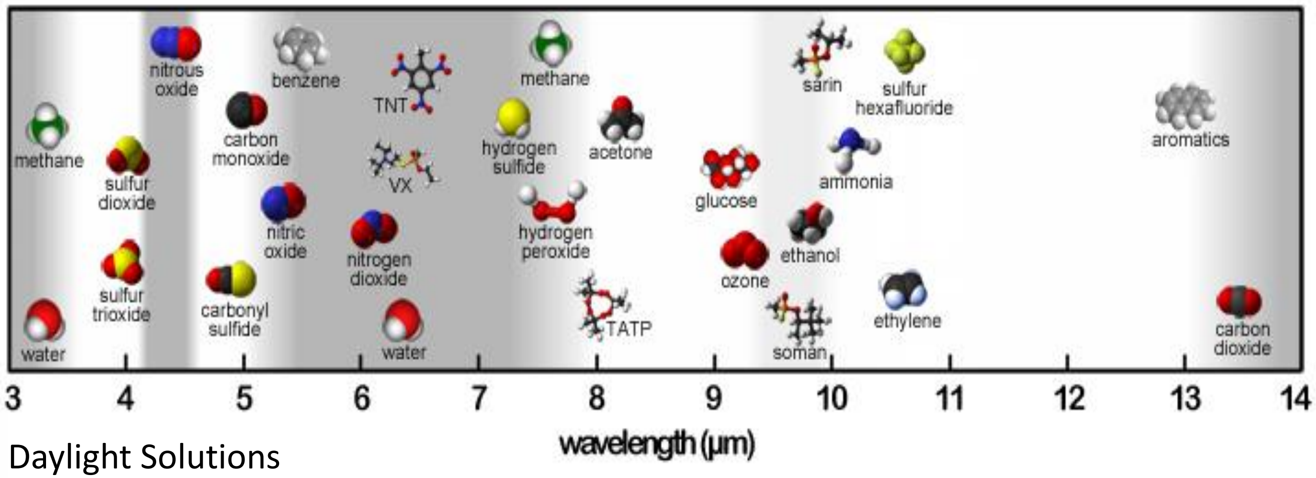
Laser&Fiber Electronics Group
Wroclaw University of Science and Technology

Vienna, 08.02.2018

Why mid-infrared?



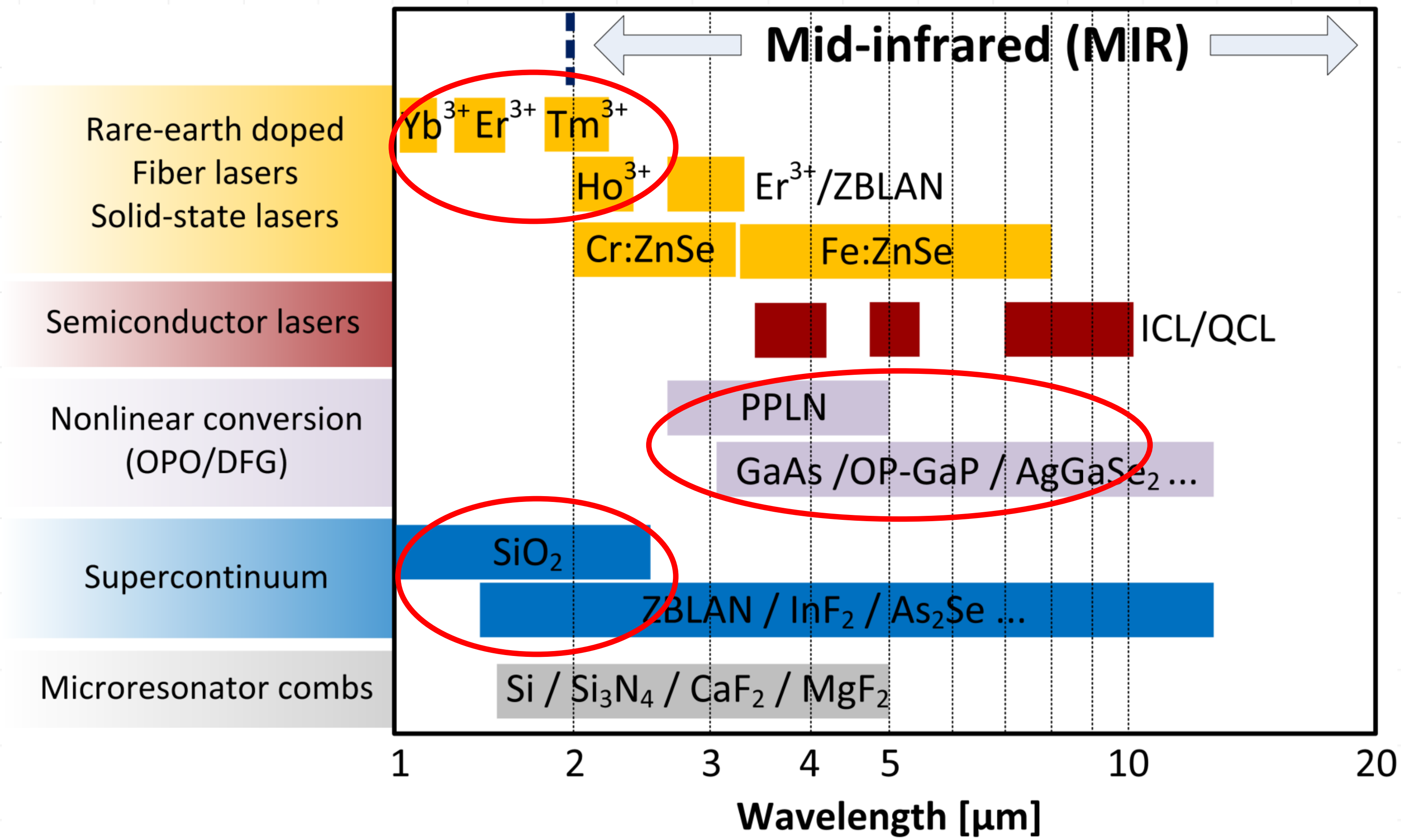
Daylight Solutions

Multiple absorption lines („fingerprints”)

- Greenhouse gases
- Toxic chemicals
- Explosives
- Disease markers
- Etc…

- Medicine (e.g. surgery, dermatology..)
- Micromachining and materials processing (e.g. plastics welding)
- Tool for basic science and R&D laboratories
- Etc…

Broadband mid-IR sources

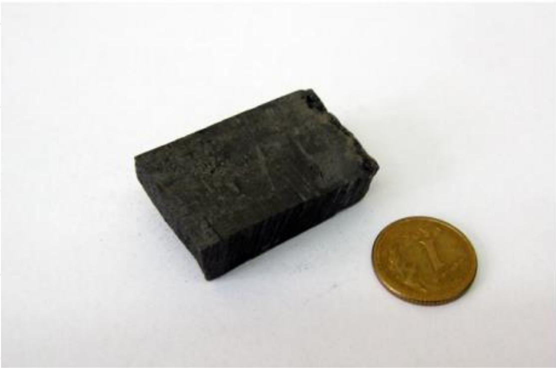


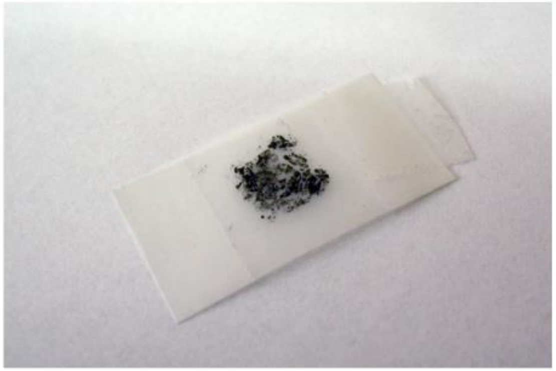
A. Schliesser, N. Picqué, T. W. Hänsch, "Mid-infrared frequency combs", Nature Photonics 6, 440-449 (2012).
C. W. Rudy, "Mid-IR Lasers: Power and pulse capability ramp up for mid-IR lasers", Laser Focus World 05/02/2014

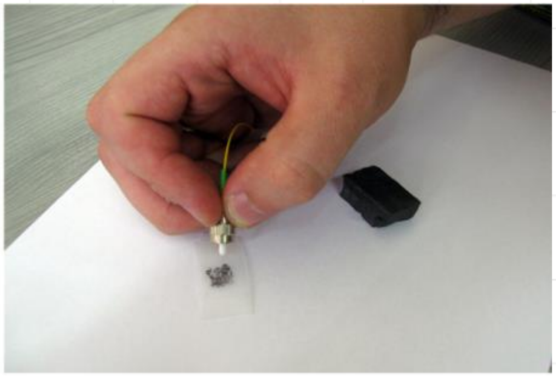
Outline

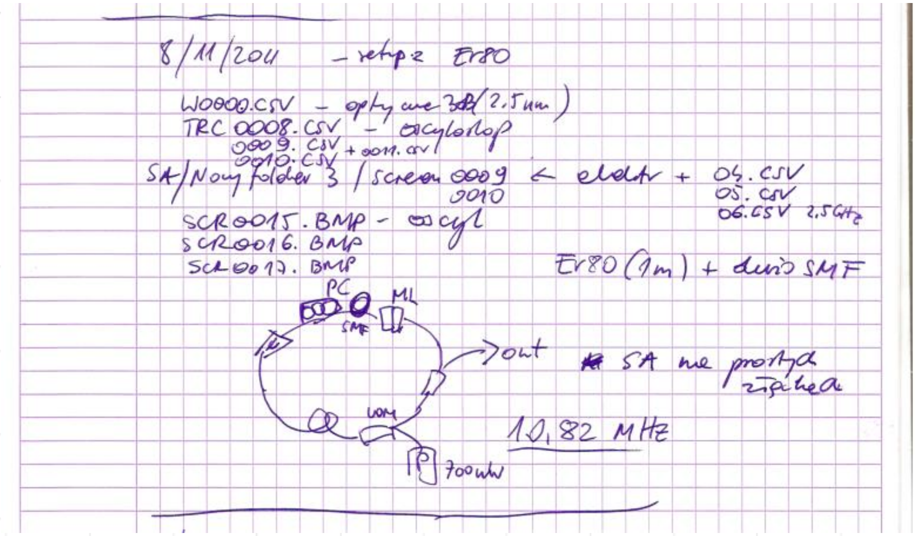
1) Mode-locked fiber lasers based on Thulium- and Holmium-doped fibers
2) Coherent supercontinuum generation pumped with femtosecond pulses at 1560 nm
3) Widely tunable all-fiber sources (1700 – 2100 nm) based on Raman-induced soliton self-frequency shift in highly nonlinear fibers
4) Mid-IR generation via difference frequency generation in nonlinear crystals (3-4 and 6-9 μm)

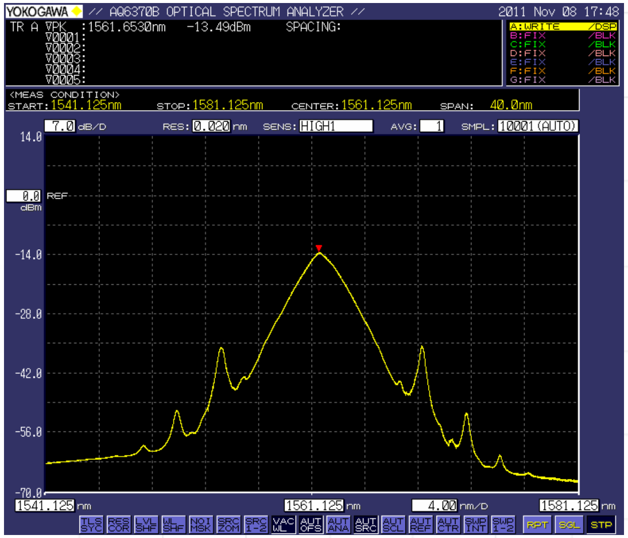
Our first experiments (Nov 2011)





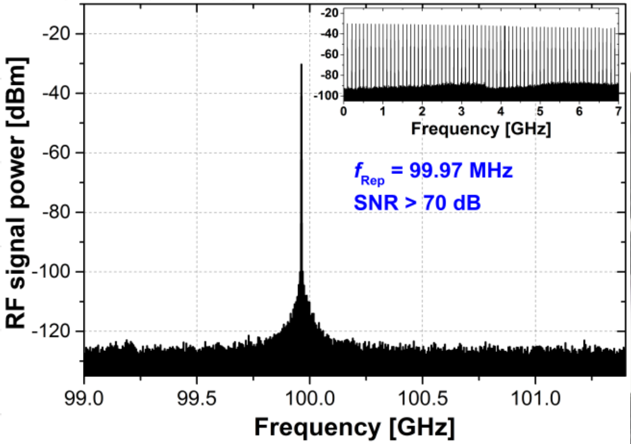


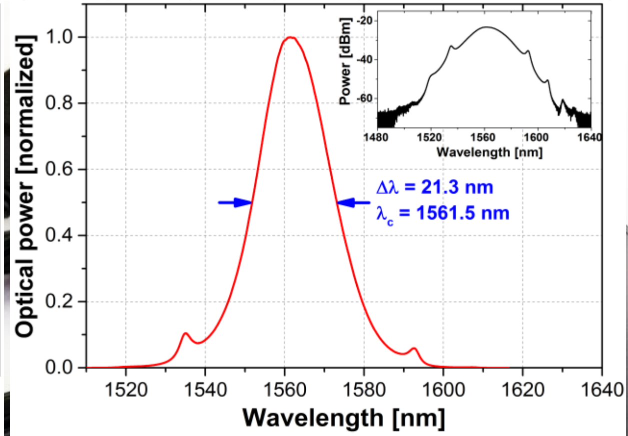


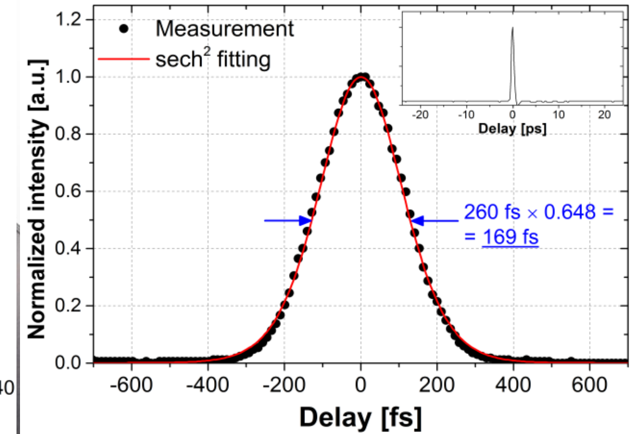


2015: prototypes of ultrafast lasers

Typical performance:





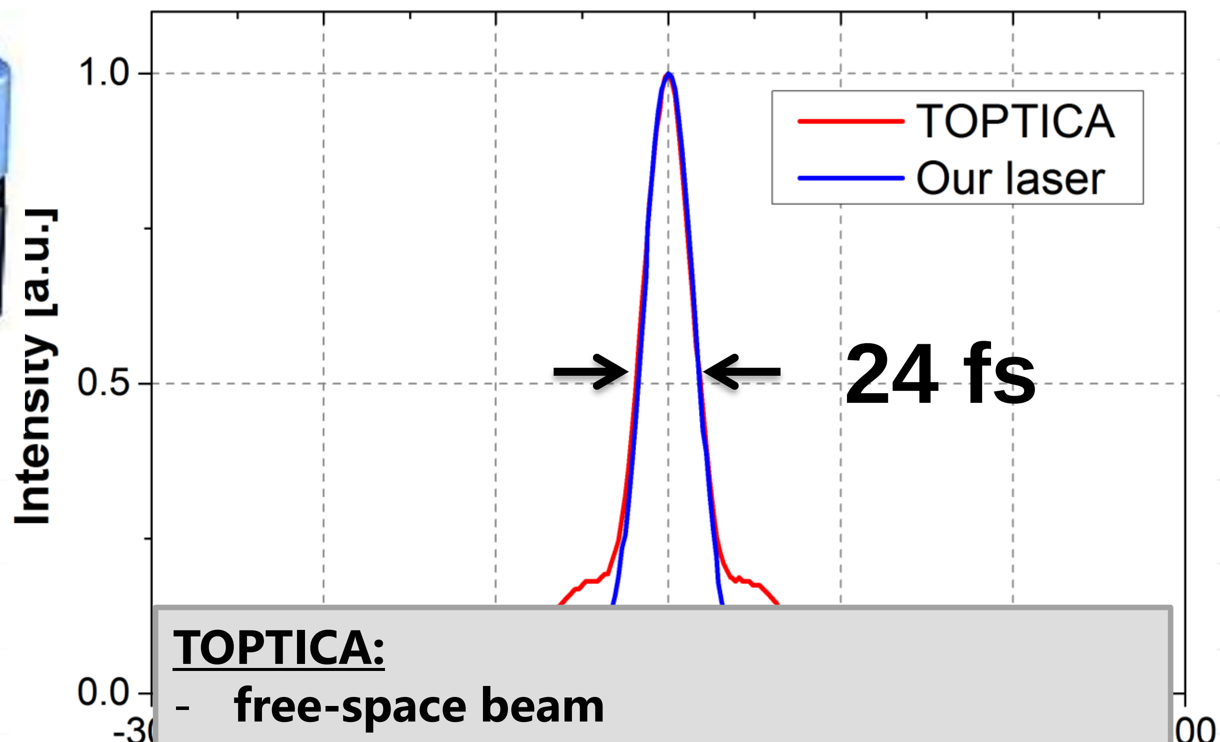


Wavelength: **1560 nm**
Bandwidth: **> 20 nm**
Pulse duration: **< 200 fs**
Repetition rates: **50**, **100**, **125 MHz**

J. Sotor, G. Soboń, K. Krzempek, G. Dudzik, K. M. Abramski, „Ultra-Graph" (NCBiR, GRAF-TECH), 2013-2015

Now: we're still upgrading

J. Sotor, G. Soboń, Laser Phys. Lett. 13, 125102(2016)

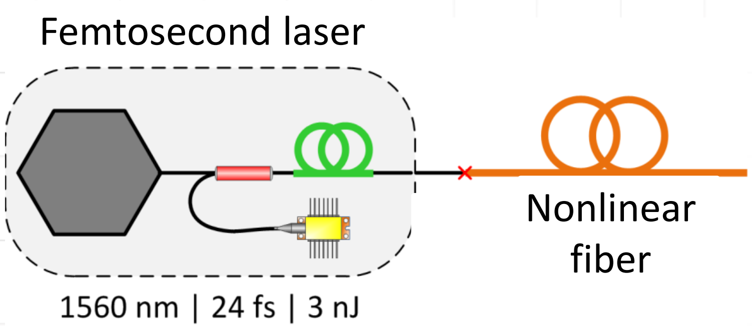


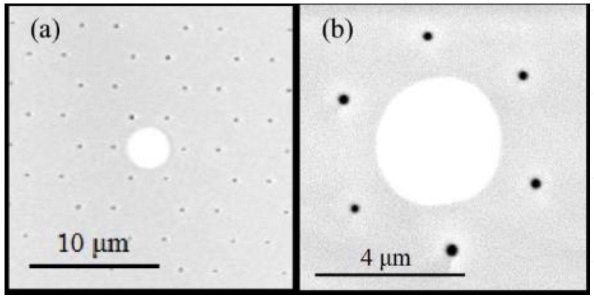
TOPTICA:

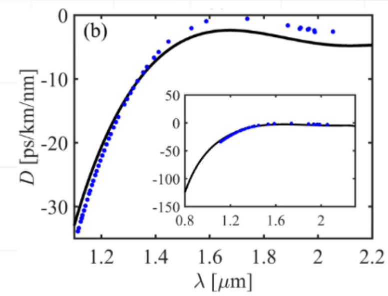
- free-space beam
- Bulk compressor inside
- 10 kg weight (laser) + 4.5 kg control unit
- 50-60 kEUR

All-in-fiber supercontinuum? No problem!

HNLF fiber:
K. Tarnowski (WrUST)
P. Mergo (UMCS)

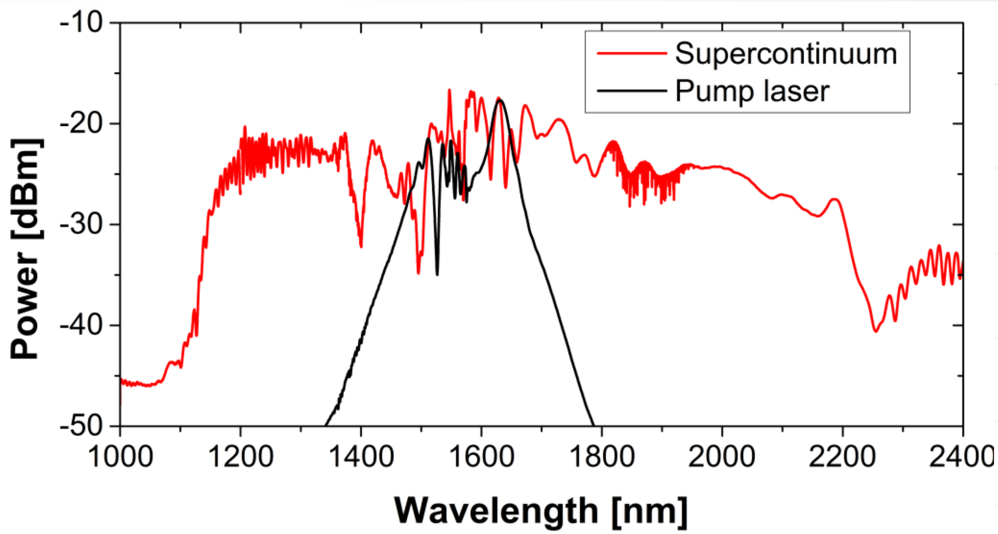






K. Tarnowski *et al.*, Opt. Express 24, 30523-30536 (2016)

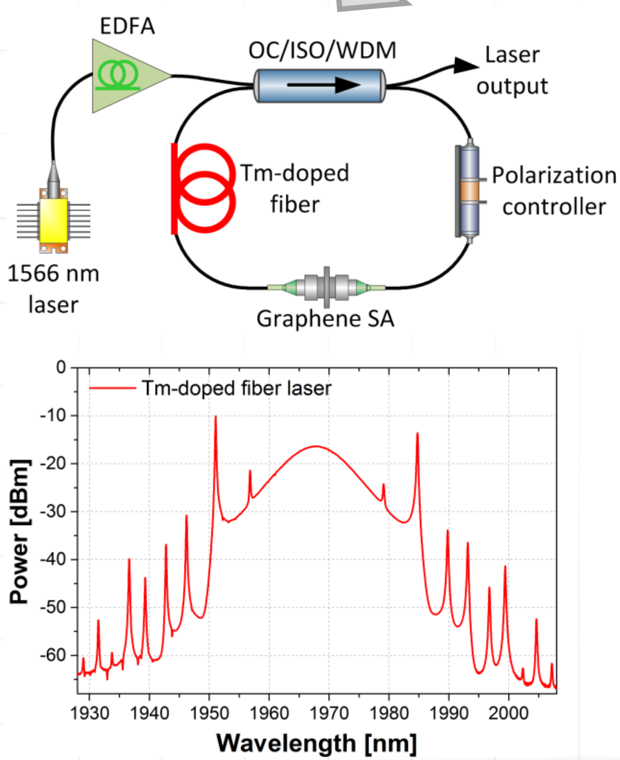
P_{in} = ~140 mW
P_{out} = ~30 mW

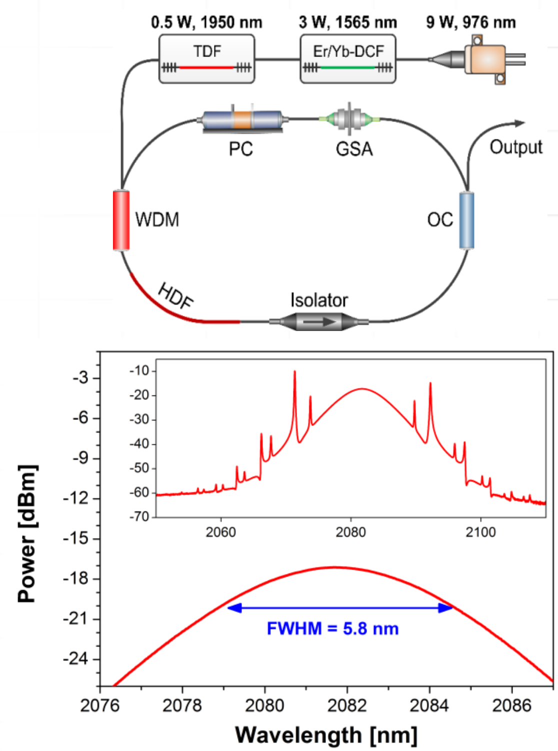


Towards new wavelengths

69 **Tm**
Thulium

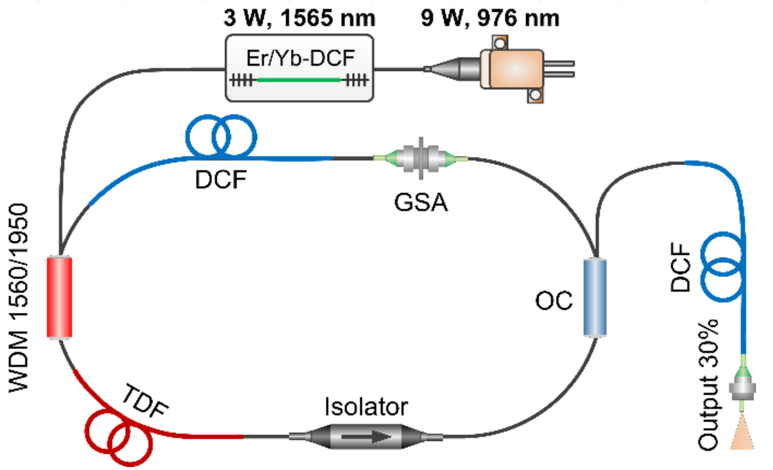
67 **Ho**
Holmium

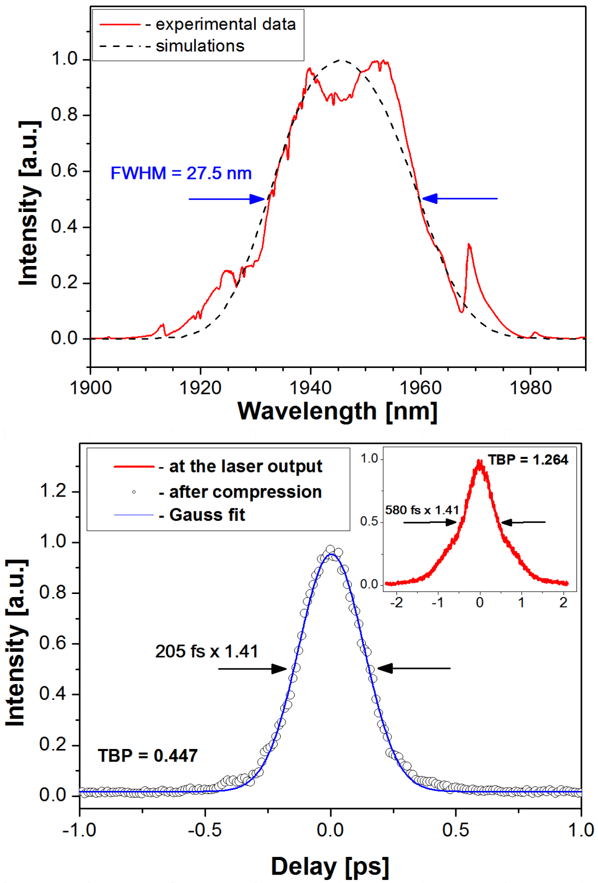




Femtosecond 1.9 µm (Tm^{3+}) lasers

- Dispersion-balanced lasers („*stretched-pulse*”)



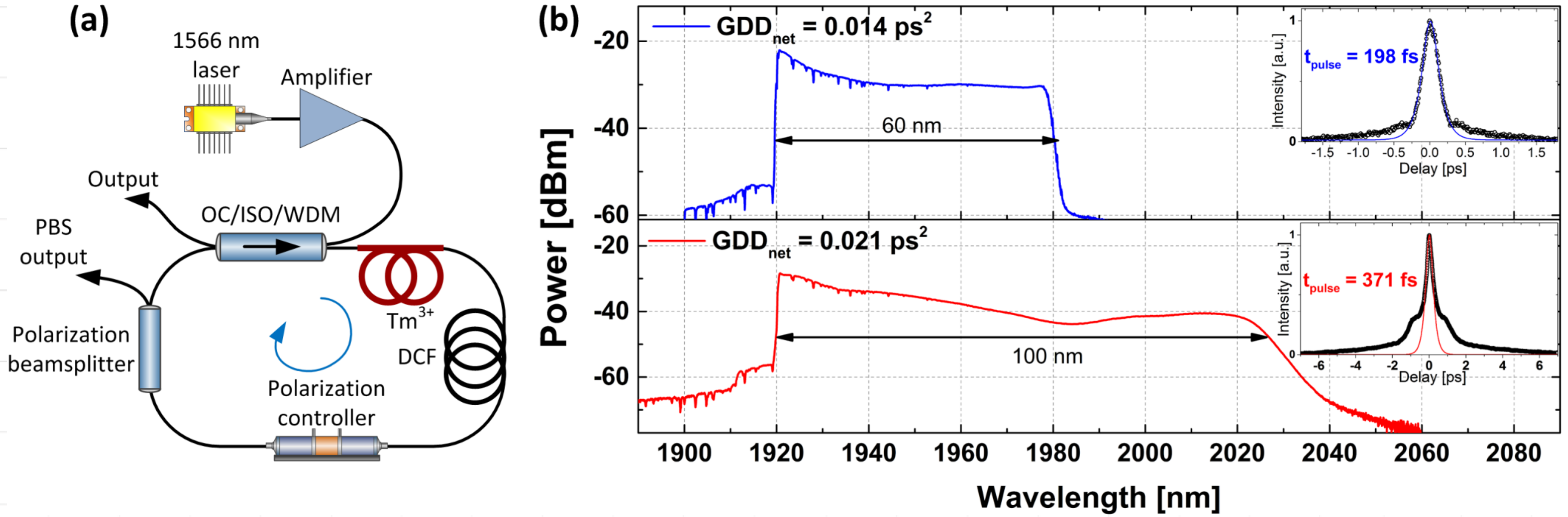


- Bandwidth: **27.5 nm** (FWHM)
- Pulse duration: **205 fs**
- Average power: **13 mW**
- Repetition rate: **60 MHz**

J. Sotor *et al.*, Opt. Letters 42, 1592 (2017)

Femtosecond 1.9 µm (Tm^{3+}) lasers

- Normal-dispersion lasers („*dissipative soliton*”)



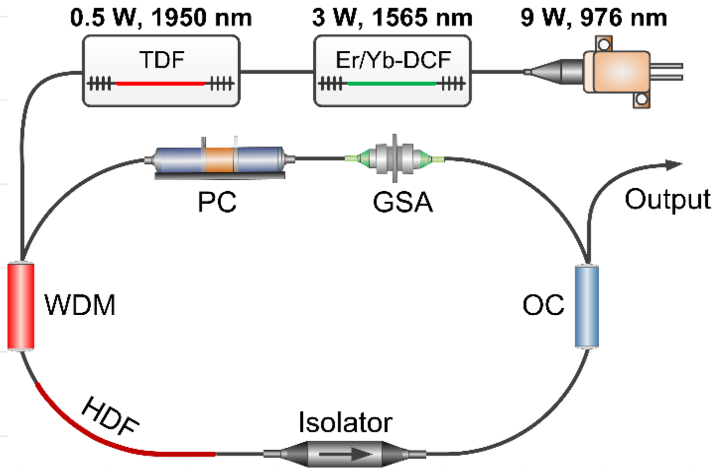
- Bandwidth: >**60 nm** (10 dB)
- Pulse duration: **198 fs**
- Average power: **9 mW**
- Repetition rate: **20 MHz**

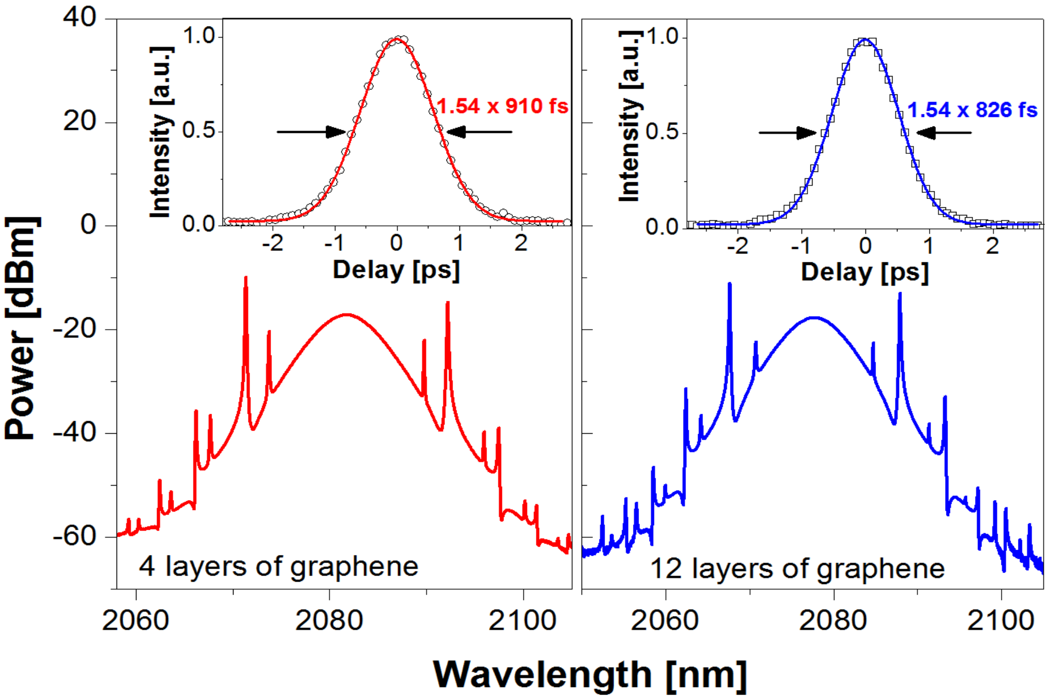
Broadest optical spectra generated from a Tm-doped fiber laser so far

G. Soboń et al., Opt. Express 24, 6156-6161 (2016)

Femtosecond 2.1 µm (Ho^{3+}) lasers

- Anomalous-dispersion lasers (conventional soliton)



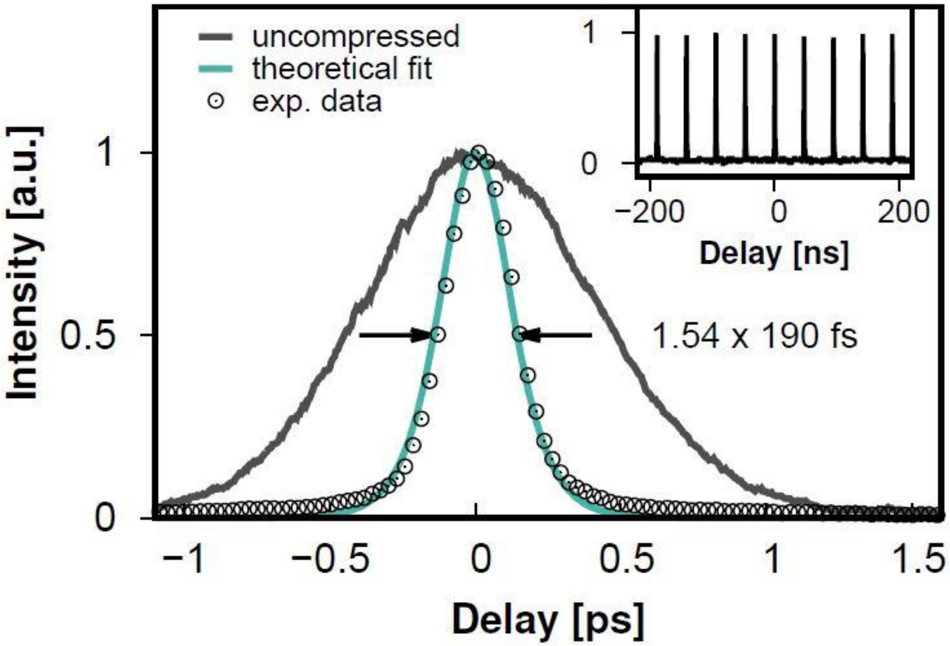


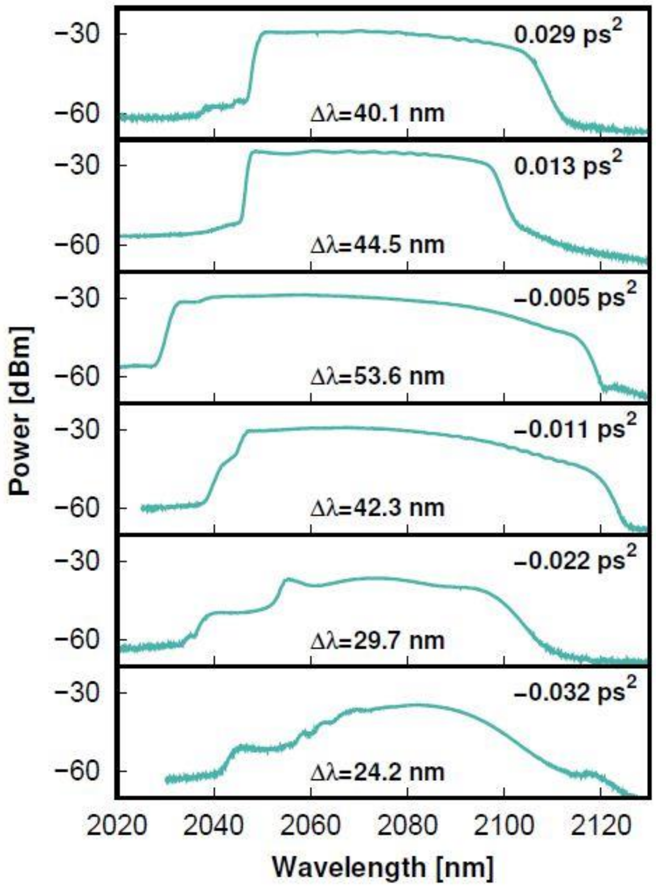
- Central wavelength: **2081 nm**
- Bandwidth: **6 nm**
- Pulse duration: **830 fs**
- Average power: **6 mW**
- Repetition rate: **38 MHz**

J. Sotor *et al.*, Opt. Letters 41, 2592 (2017)

Femtosecond 2.1 µm (Ho^{3+}) lasers

- Balanced-dispersion cavity





- Max. Bandwidth: **53.6 nm** (FWHM)
- Pulse duration: **190 fs**
- Average power: **54 mW**
- Repetition rate: **21 MHz**

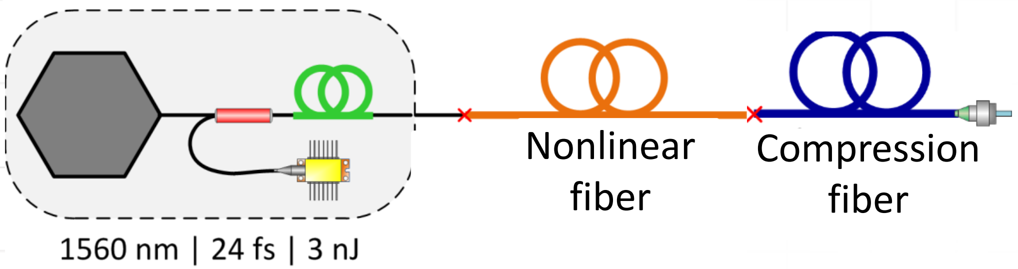
M. Pawliszewska *et al.*, Opt. Lett. 43, 38-41 (2018)

Soliton self-frequency shift

Soliton self-frequency shift (SSFS)

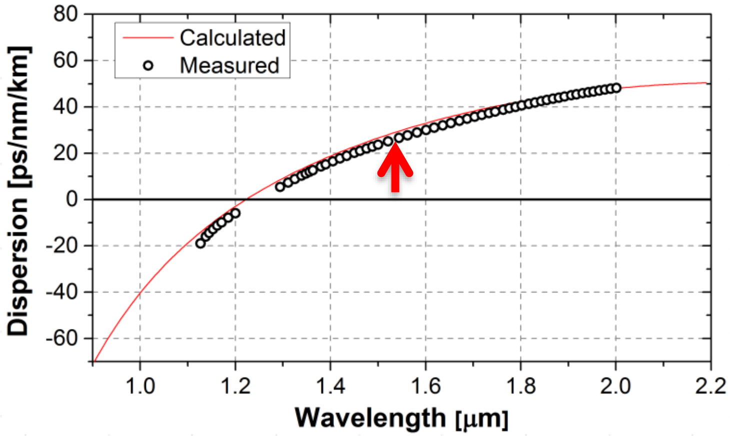
F. M. Mitschke, L. F. Mollenauer, "Discovery of the soliton self-frequency shift", Opt. Lett. **11**, 659-661 (1986)

Alternative to Tm-/Ho- mode-locked lasers!

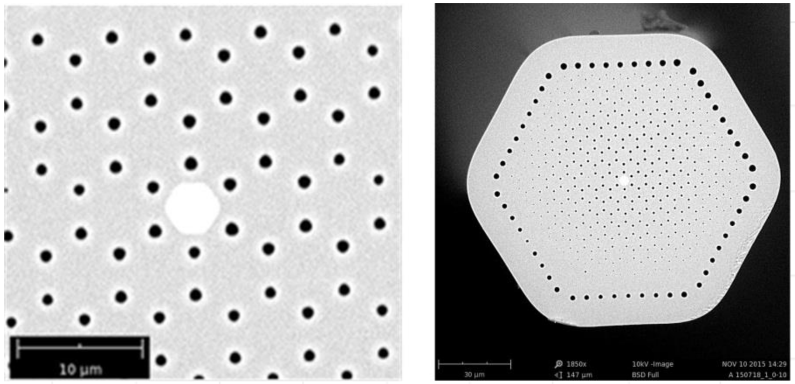


Fiber: dr Paweł Mergo, UMCS Lublin

Dispersion profile of the used nonlinear fiber:

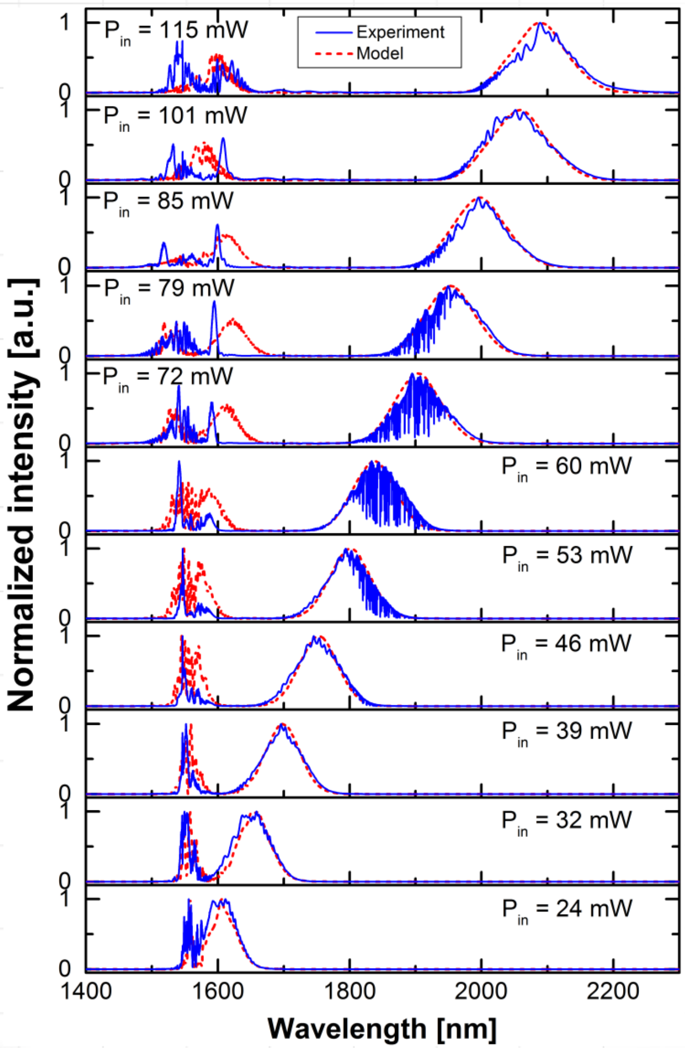


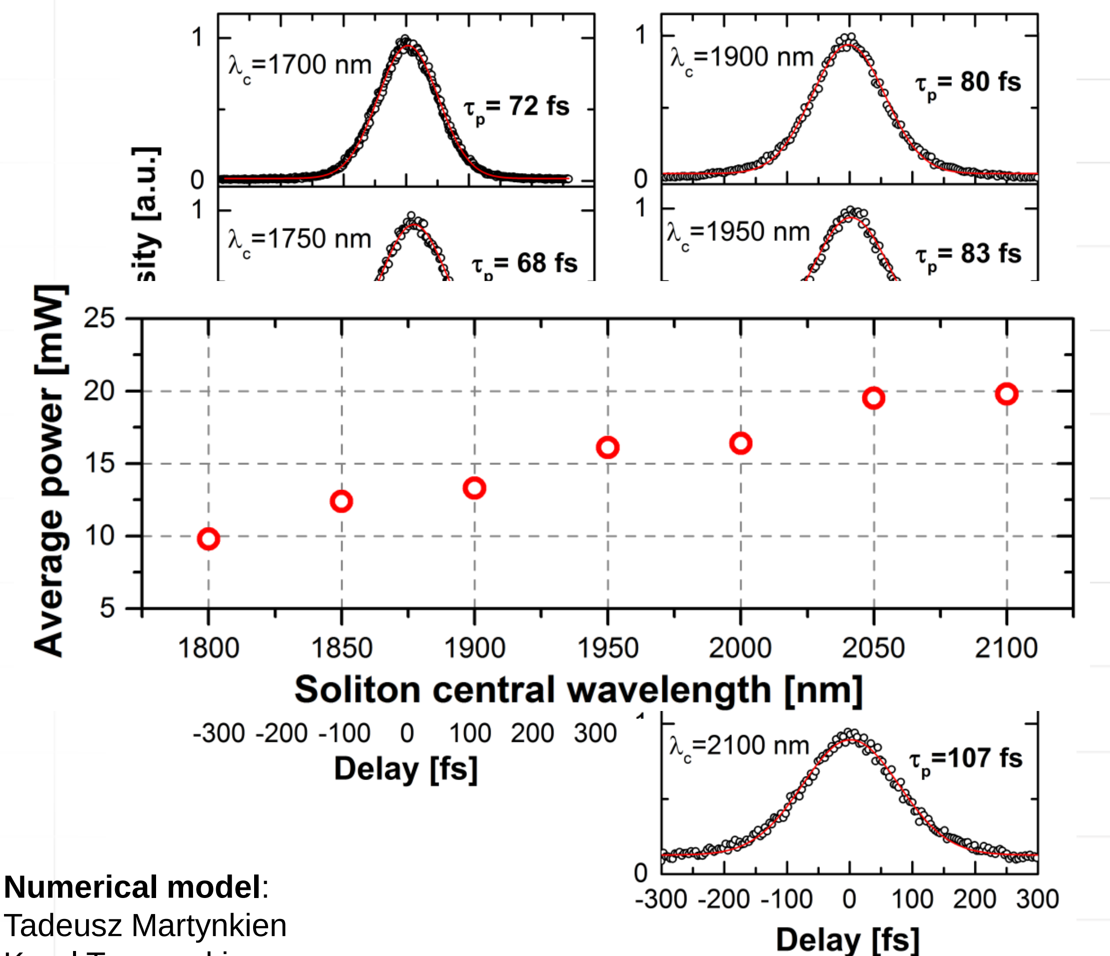
Fiber SEM images:



J. Sotor, G. Soboń, Laser Phys. Lett. 13, 125102(2016)
G. Soboń *et al.*, Photonics Research 5, 151-155 (2017)

SSFS source (1700 – 2100 nm)

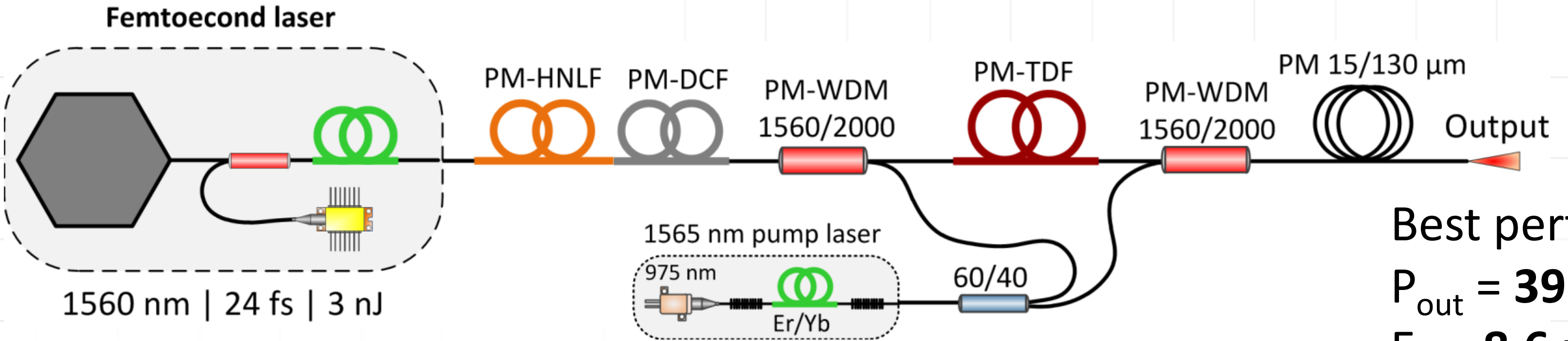




Numerical model:
Tadeusz Martynkien
Karol Tarnowski
(Physics, Wrocław Univ. Technol.)

G. Soboń *et al.*, Photonics Research 5, 151-155 (2017)

Amplification of SSFS

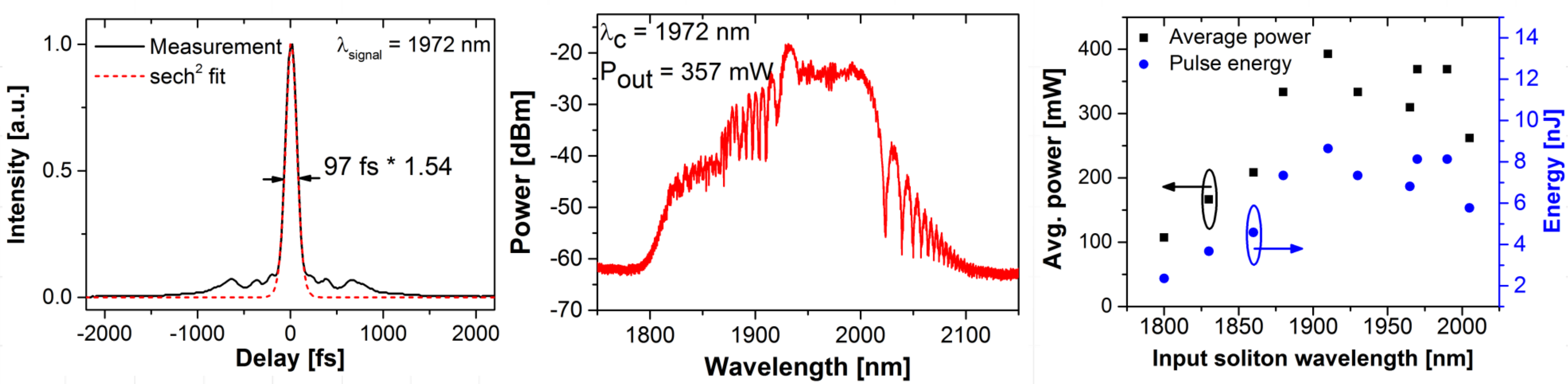


Best performance:

P_{out} = **395 mW**

E_p = **8.6 nJ**

t_p = **99 fs**



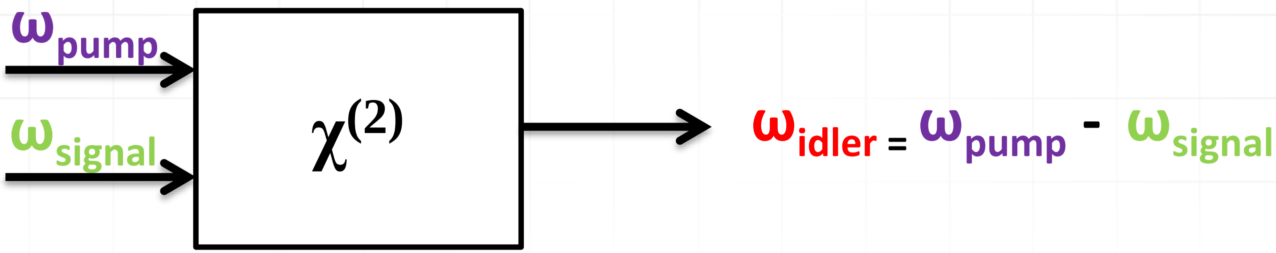
J. Sotor *et al.*, CLEO Pacific Rim 2017 , G. Soboń *et al.*, submitted to CLEO 2018

Why SSFS can be better than a Tm/Ho-laser?

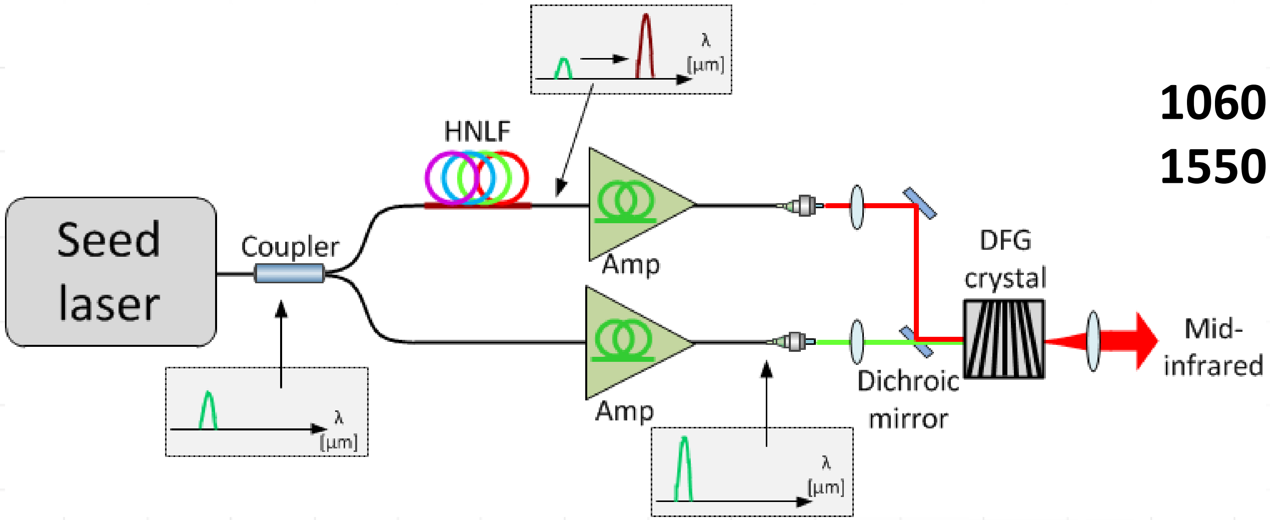
- Tm-doped and Ho-doped fibers are much more expensive than Er-doped fibers (300-500 US $/m vs. 60-70 US $/m)
- Complicated pumping scheme
  - Tm:fiber → pumping at 1565 nm
  - Ho:fiber → pumping at ~1.9 µm
- No tunability
- Dispersion compensation required (PM DCF for 2 µm: 200 US $ /m)

Difference frequency generation

Difference frequency generation

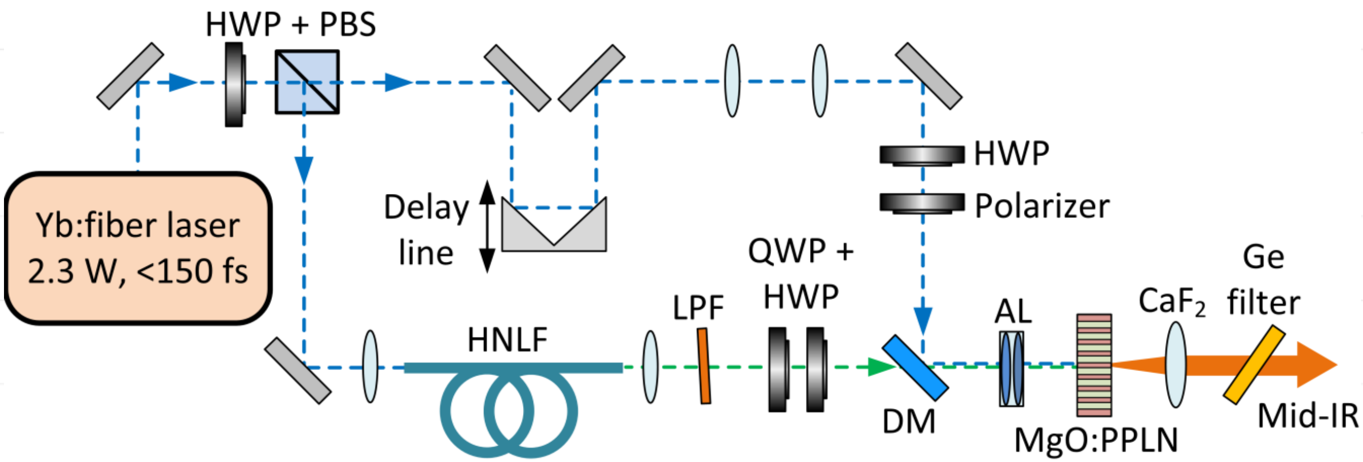


- Two sparate pulsed lasers → synchronization required (might be complex)
- But... both interacting beams might originate from one master laser! → **SSFS**



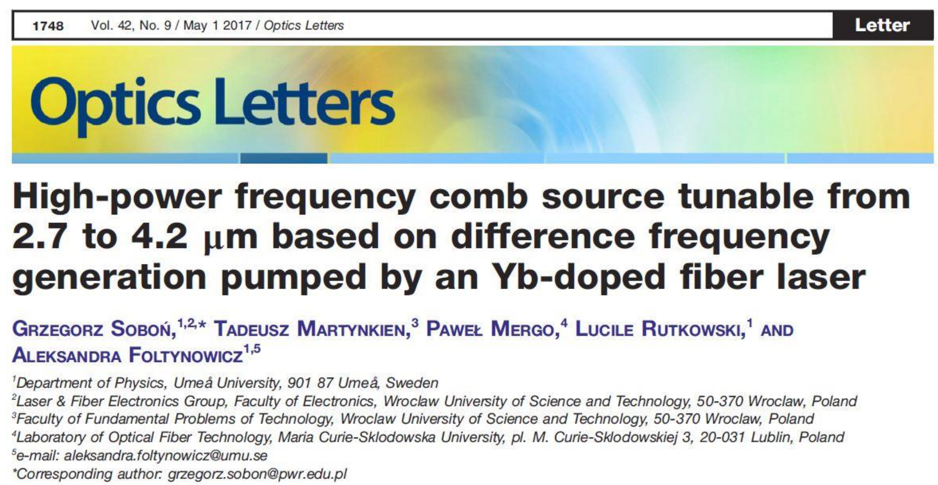
1060 + 1550 nm → ~3.3 μm
1550 + 1950 nm → ~7.5 μm

Short-wave (3–4 μm) mid-IR generation



237 mW!

- **Pump laser**: Yb:fiber, 2.3W, <150 fs, 1040 nm (Menlo Systems)
- **Nonlinear crystal:** MgO:PPLN, 3 mm-thick (Covesion)
- **Up to 1.4 W of pump at the crystal**
- **Most powerful PPLN-based DFG with broadest reported tuning range**


1748 Vol. 42, No. 9 / May 1 2017 / *Optics Letters* **Letter**

Optics Letters

High-power frequency comb source tunable from 2.7 to 4.2 μm based on difference frequency generation pumped by an Yb-doped fiber laser

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[2]*Laser & Fiber Electronics Group, Faculty of Electronics, Wroclaw University of Science and Technology, 50-370 Wroclaw, Poland*
[3]*Faculty of Fundamental Problems of Technology, Wroclaw University of Science and Technology, 50-370 Wroclaw, Poland*
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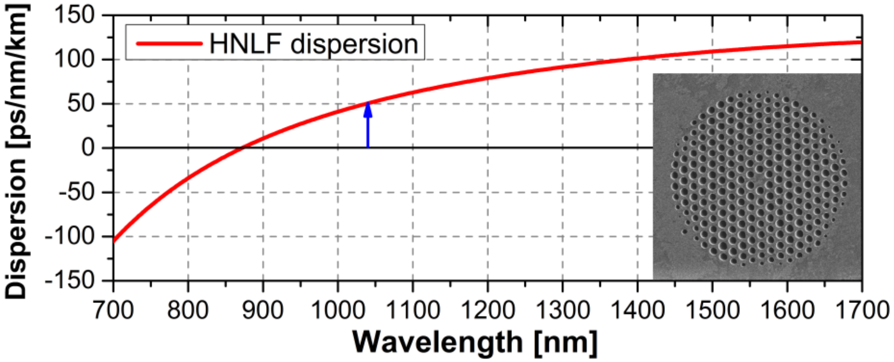
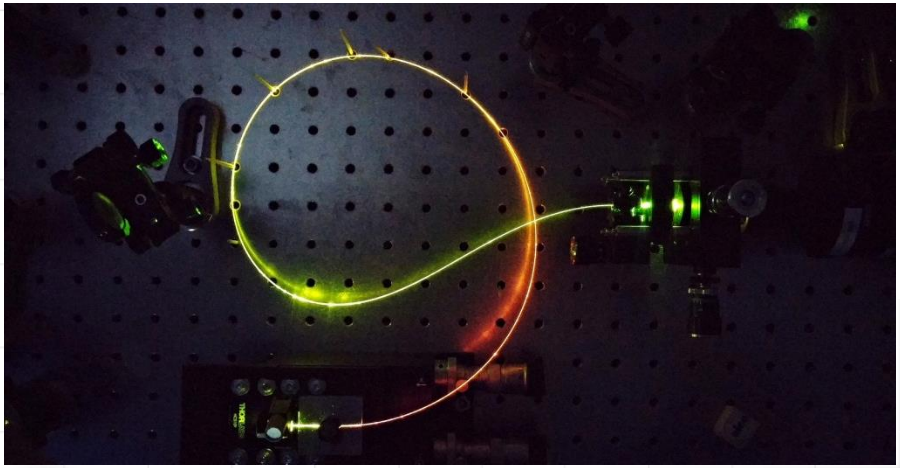
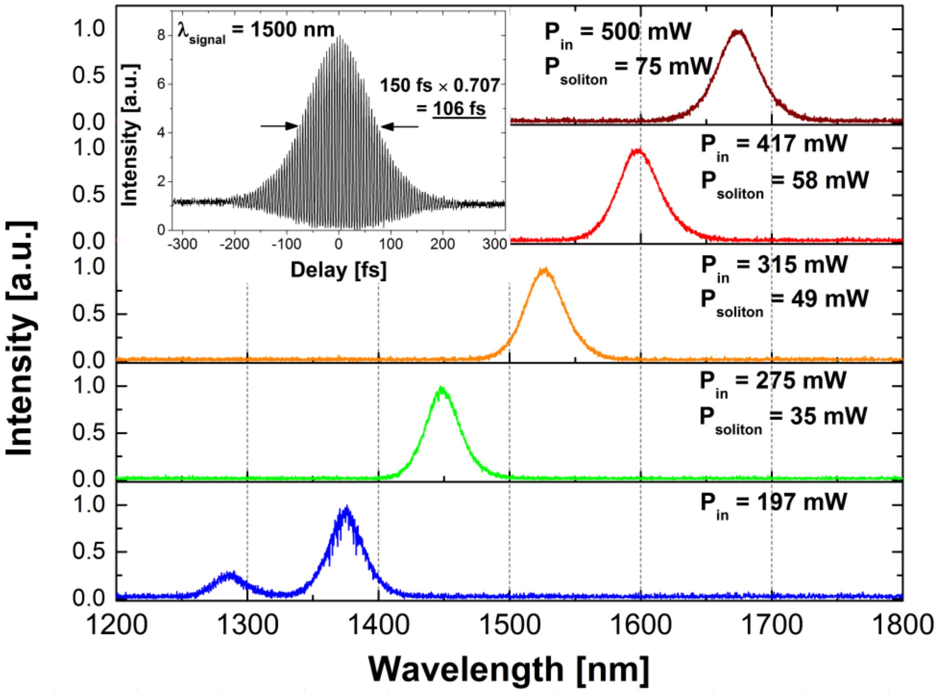
[5]*e-mail: aleksandra.foltynowicz@umu.se*
**Corresponding author: grzegorz.sobon@pwr.edu.pl*

2.7 – 4.2 µm coherent DFG source

- Signal for DFG: nonlinear frequency shift

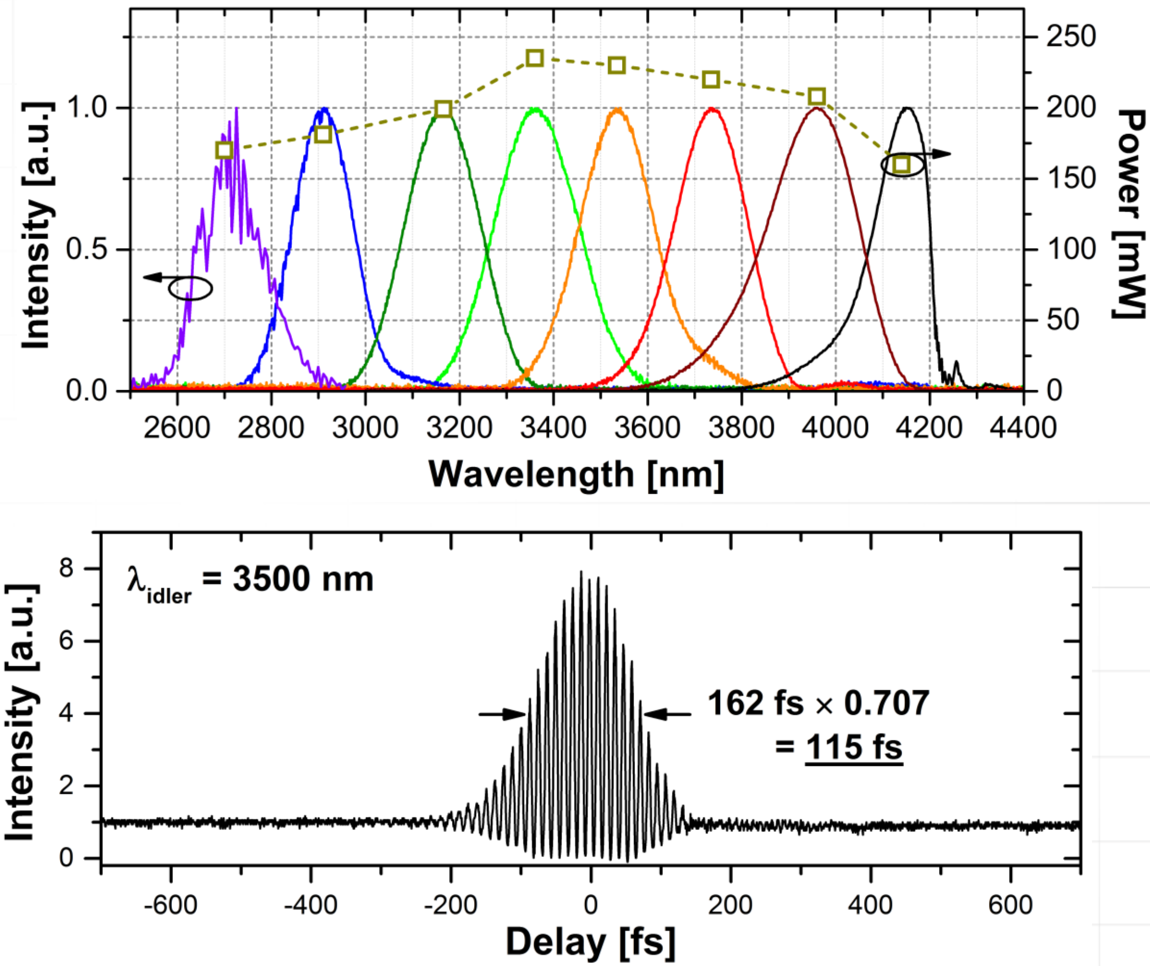




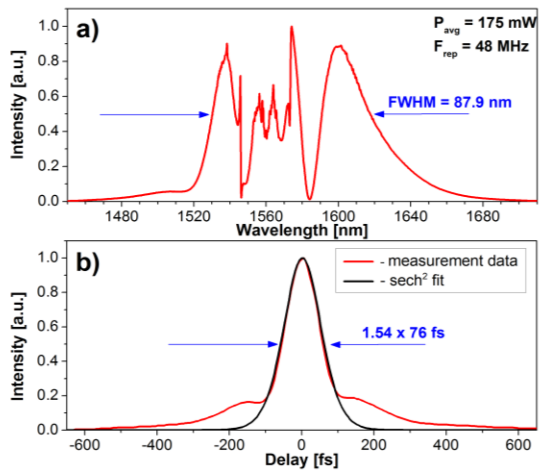


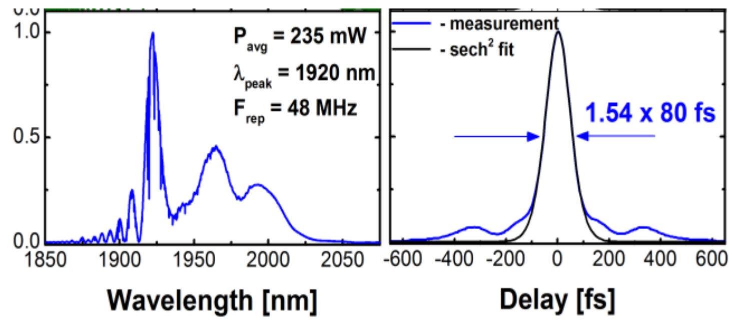
2.7 – 4.2 µm coherent DFG source

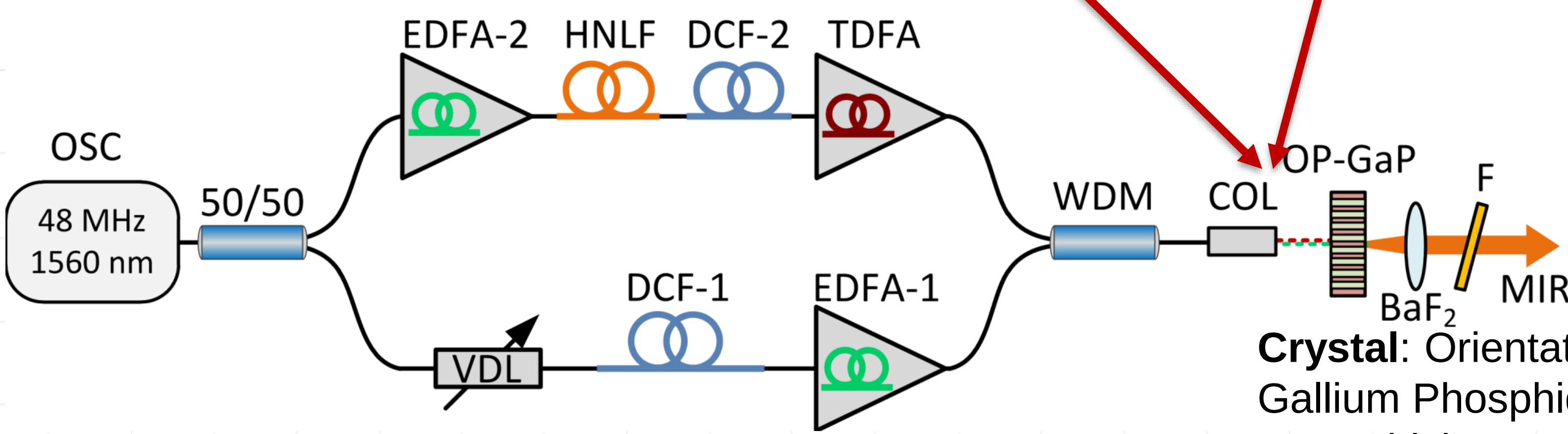
- Tuning range:
  - ✓ **2.7 – 4.2 µm** (signal tuning: 1350-1650 nm)
- Output power:
  - ✓ Max. **237 mW**
  - ✓ > **160 mW** in the entire tuning range
- Mid-IR pulse duration:
  - Min. **115 fs** (@3500 nm)
  - < **200 fs** in the entire tuning range
- Confirmed coherence



G.Soboń, T.Martynkien, P.Mergo, L.Rutkowski, A.Foltynowicz, Opt. Lett. **42**, 1748-1751 (2017)





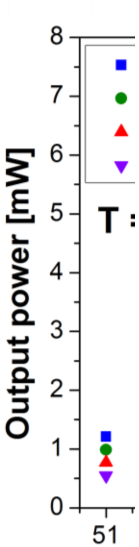


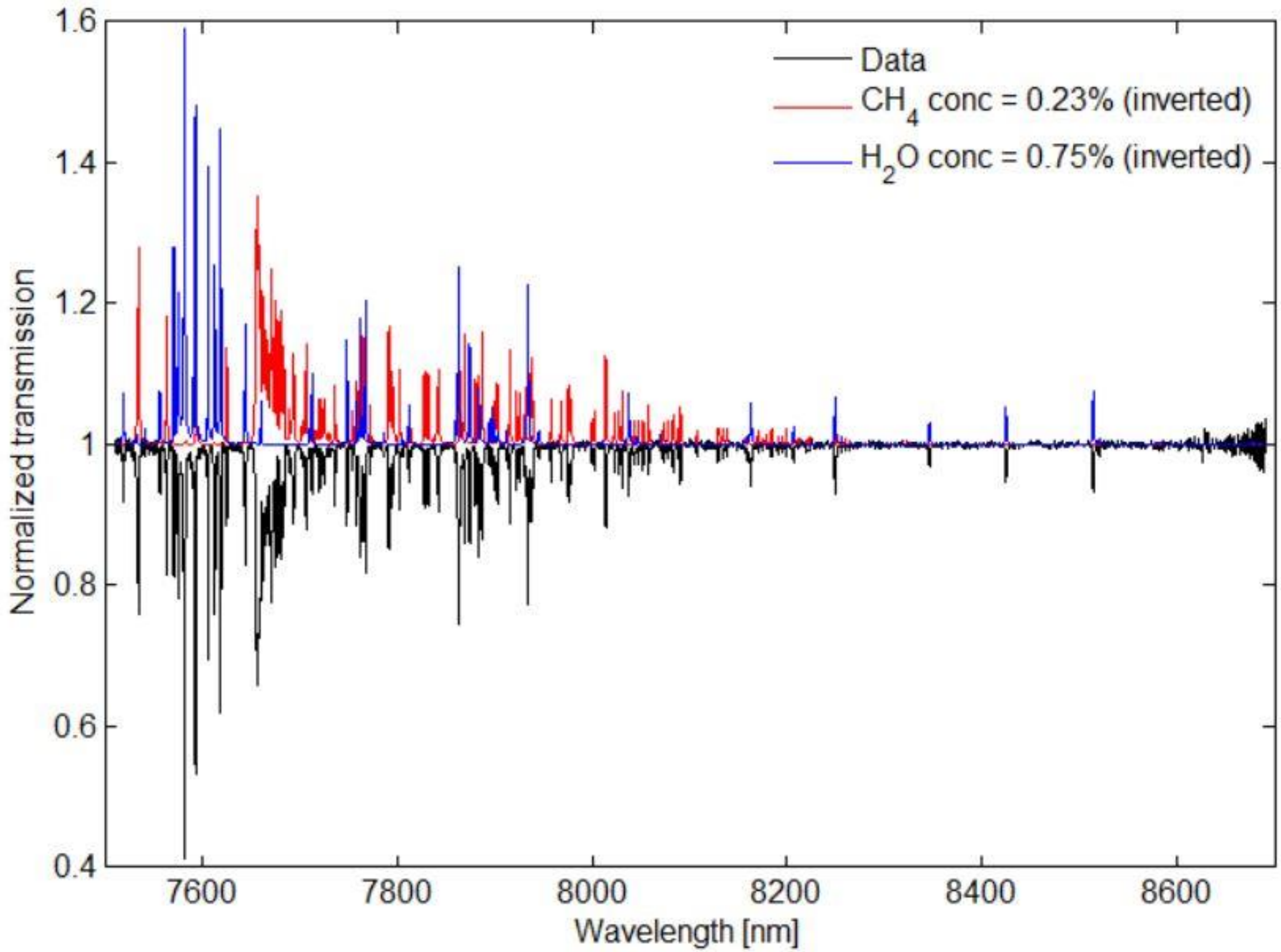
Crystal: Orientation-patterned Gallium Phosphide (**OP-GaP**)
3 mm thick
BAE Systems

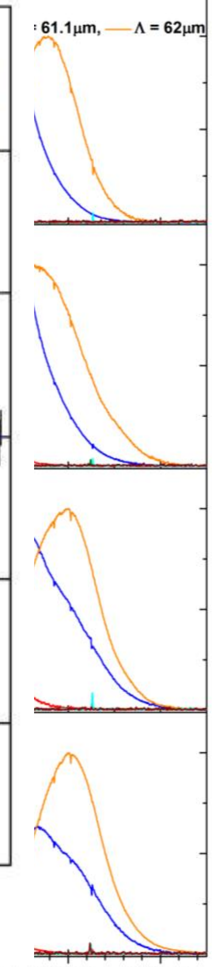
J. Sotor et al., in preparation

6 – 9 µm all-fiber DFG

- Broad t
- Up to **7.**
- All-fiber
- Exceptio







J. Sotor et al., in preparation

Summary

- Mode-locked fiber lasers based on Thulium- and Holmium-doped fibers with graphene as saturable absorber
- Coherent supercontinuum generated in normal-dispersion fibers, pumped with femtosecond pulses at 1560 nm (also all-in-fiber!)
- Widely tunable all-fiber sources (1700 – 2100 nm) based on Raman-induced soliton self-frequency shift in highly nonlinear fibers – interesting alternative to Tm-/Ho-doped fiber lasers
- Mid-IR generation via difference frequency generation in nonlinear crystals: widely-tunable 3-4 and 6-9 µm sources

Collaboration

Wrocław Univ. of Science and Technology

- Tadeusz Martynkien (fiber design, modeling)
- Karol Tarnowski (fiber design, modeling)

Umeå Universitet, Department of Physics, Sweden

- Aleksandra Foltynowicz
- Lucile Rutkowski

(3-4 µm DFG)

Maria Curie-Skłodowska University, Lublin

- Paweł Mergo (nonlinear fiber fabrication)

Czech Academy of Sciences, Prague

- Pavel Peterka
- Jakub Cajzl
- Pavel Peterka
- Pavel Honzátko
- Ivan Kašík

(Fabrication of Ho-doped fibers)

Institute of Electronic Materials Technology

- Włodzimierz Strupiński
- Iwona Pasternak
- Aleksandra Krajewska

(graphene fabrication)

- Ryszard Buczyński
- Mariusz Klimczak

(supercontinuum)

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- DEC-2014/13/D/ST7/02143 (SONATA)

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i Szkolnictwa Wyższego

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- IP2015 073774 (Iuventus Plus)

WALLENBERG
ACADEMY
FELLOWS

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(KAW 2015.0159)