Aston Institute of Photonic Technologies

Advances in Mid-infrared Mode-Locked Fibre Lasers

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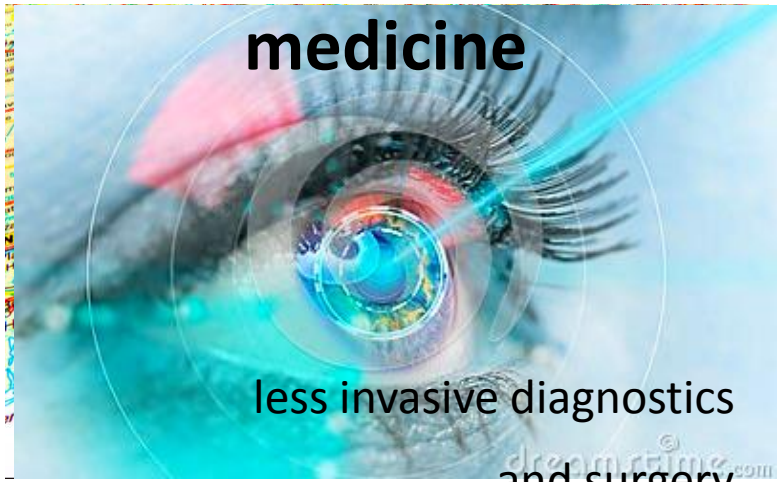
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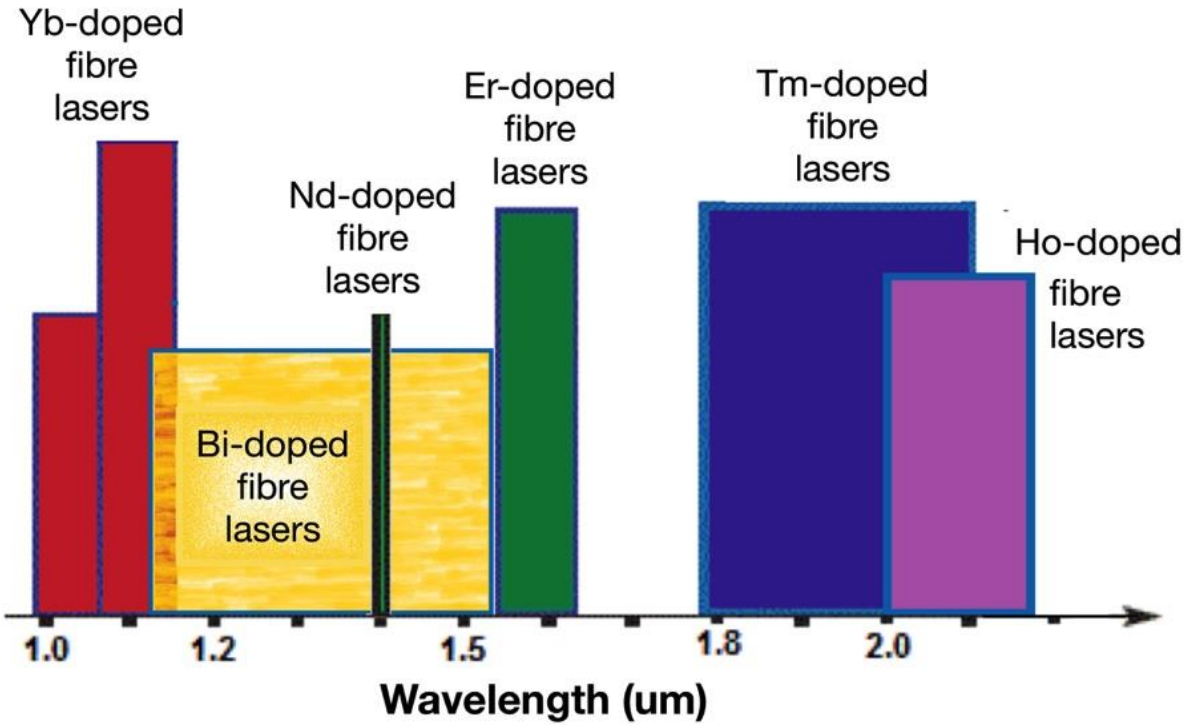
Outline

- State-of-art
- Direct Mid-IR laser generation
  - Rare-earth silica fibres
  - Rare-earth special fibres
  - Hollow-core fibres
- Mid-IR supercontinuum generation
- Conclusion

State of the art

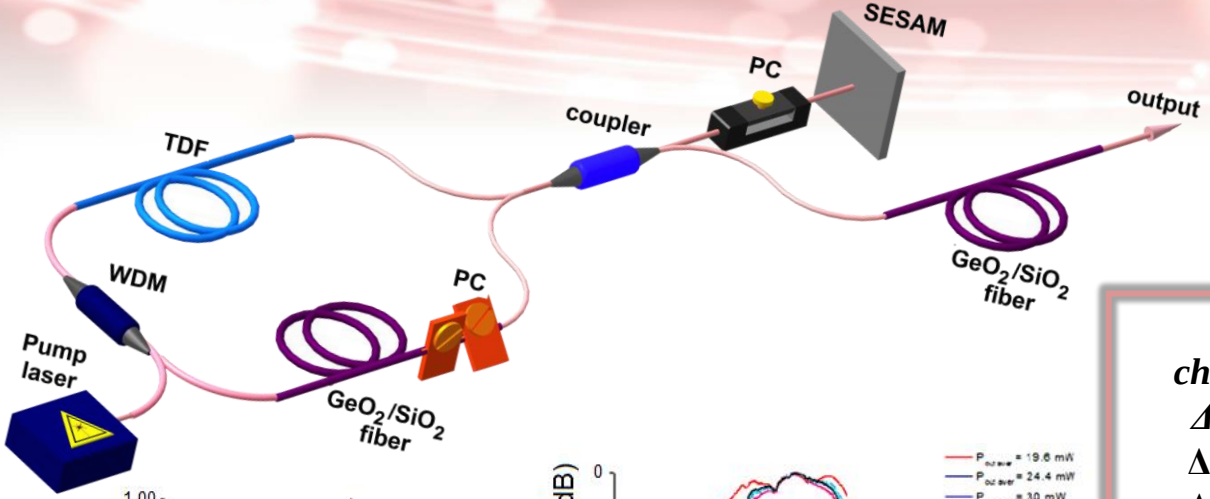


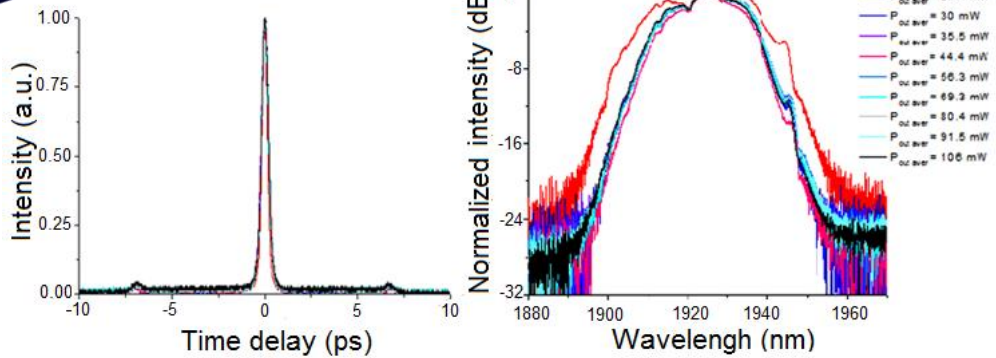
State of the art



Tm-doped Fiber Laser with NALM

1. State-of-art
2. Direct generation
2.1 Tm-fibre laser
2.2 ZBLAN fibre lasers
2.3 Hollow-core fibre lasers
3. SC generation
4. Conclusion





Output characteristics

$\Delta\tau_p \approx 300$ fs,

$\Delta\lambda = 23.5$ nm

$\Delta\nu \cdot \Delta\tau = 0.39$

$P_{aver\ MAX} = 106$ mW

$E_{MAX} = 2$ nJ

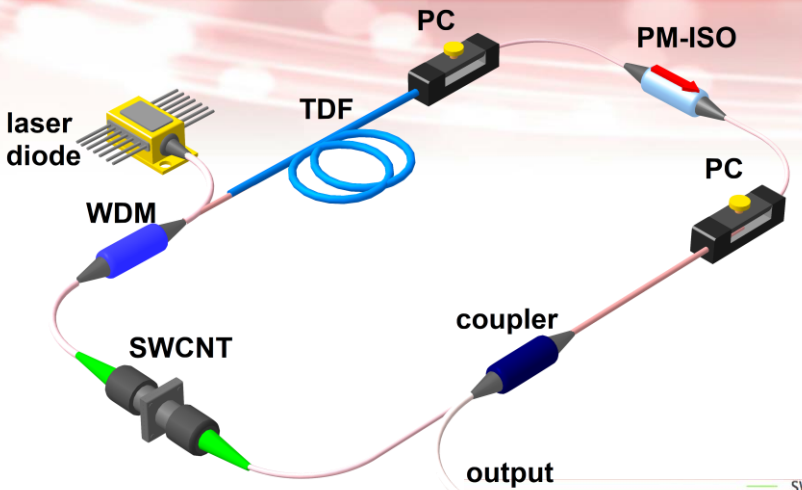
$P_{peak\ MAX} = 3.7$ kW

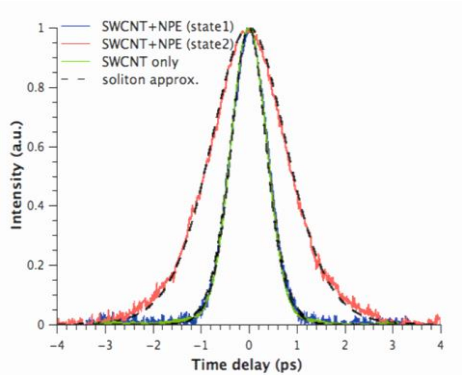
$\eta = 14\%$

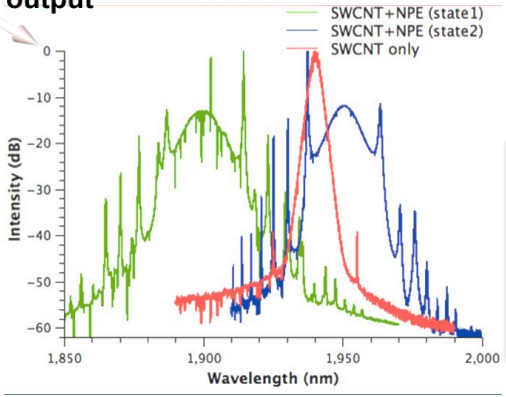
M. Chernysheva et al. "SESAM and SWCNT mode-locked all-fibre thulium-doped lasers based on the nonlinear amplifying loop mirror ", IEEE J. Selected Topics in Quantum Electronics 20(5), 448, 2014

Ring Tm-doped Fiber Laser with NPE

1. State-of-art
2. Direct generation
2.1 Tm-fibre laser
2.2 ZBLAN fibre lasers
2.3 Hollow-core fibre lasers
3. SC generation
4. Conclusion







Output characteristics

$\Delta\tau_p \approx 600$ fs,

$\Delta\lambda = 8.17$ nm

$\Delta\nu \cdot \Delta\tau = 0.316$

$P_{aver\ MAX} = 312$ mW

$E_{MAX} = 4.08$ nJ

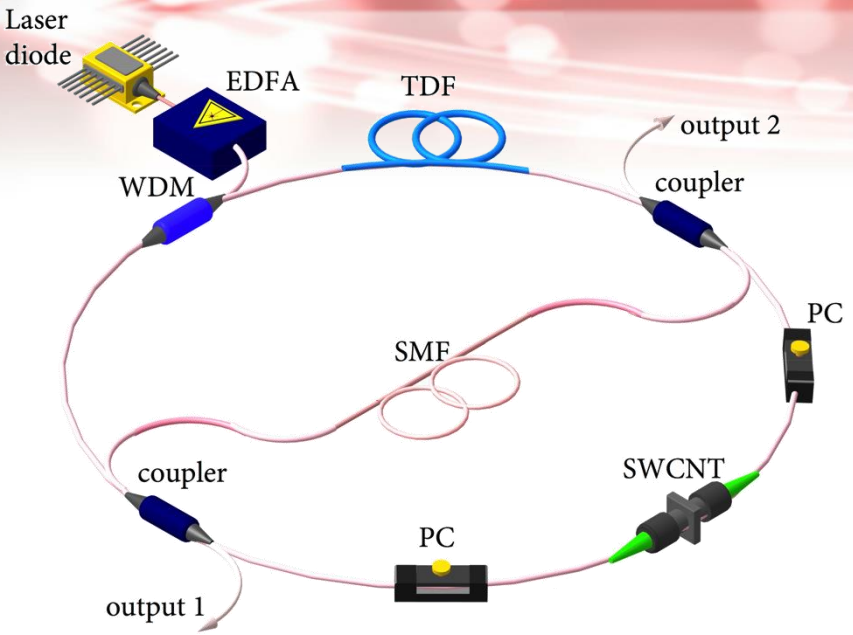
$P_{peak\ MAX} = 4.88$ kW

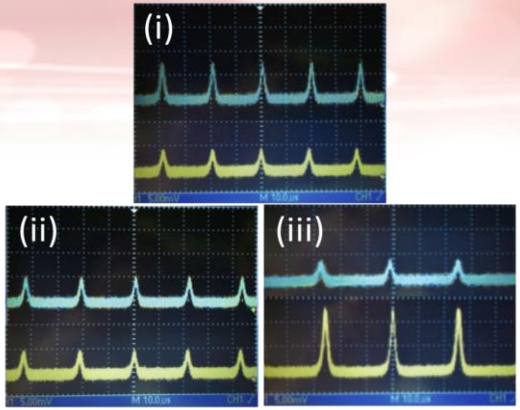
$\eta = 32\%$

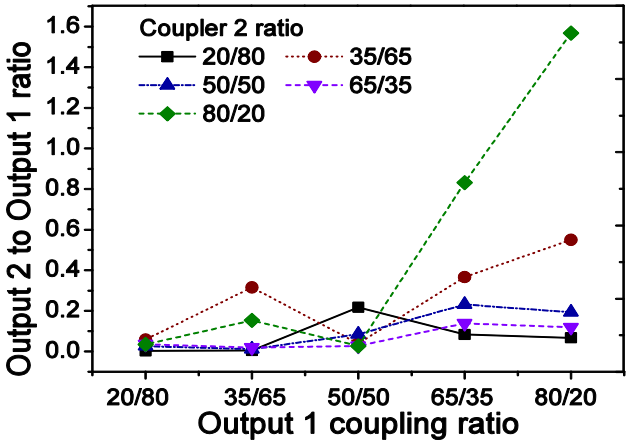
M. Chernysheva et al. "Higher-order soliton generation in hybrid mode-locked thulium-doped fibre ring laser", IEEE J. Selected Topics in Quantum Electronics 20(5), 425, 2014

Q-switched Yin-Yang Tm-doped Fiber Laser

1. State-of-art
2. Direct generation
2.1 Tm-fibre laser
2.2 ZBLAN fibre lasers
2.3 Hollow-core fibre lasers
3. SC generation
4. Conclusion





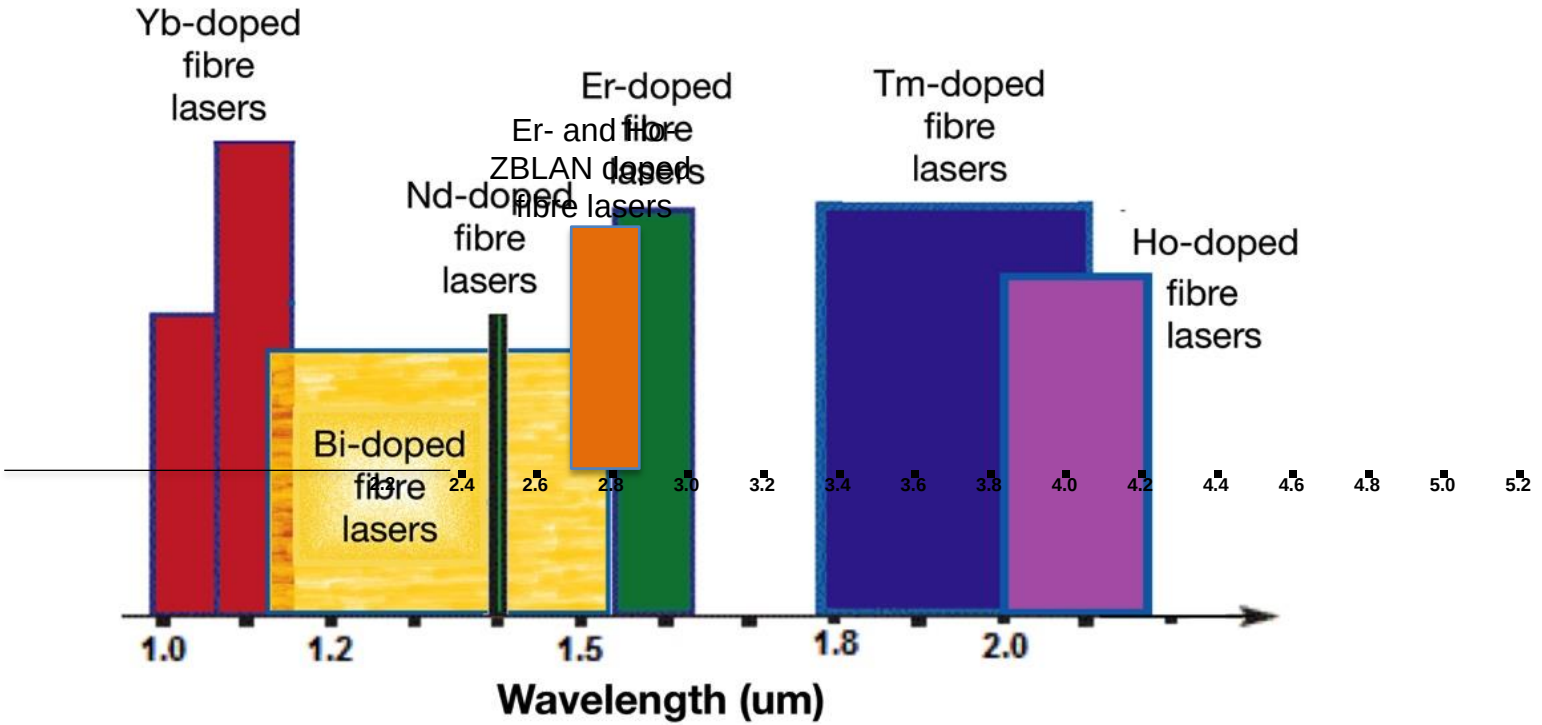


Output characteristics
$\Delta\tau_p \approx 0.9$ us,
$f = 20$ kHz

$P_{aver} = 197$ mW
$E = 1.7$ uJ
$P_{peak} = 1.9$ W
$\eta = 34\%$

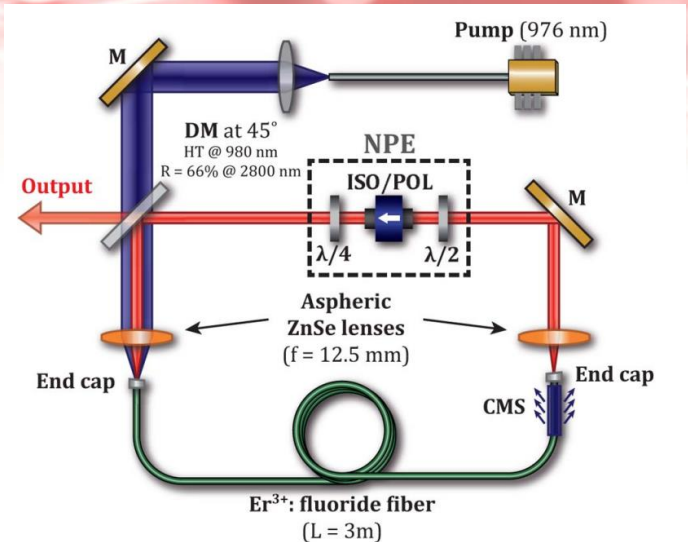
M. Chernysheva et al. "High power Q-switched thulium doped fibre laser using carbon nanotube polymer composite saturable absorber " Scientific Reports, 24220, 2016

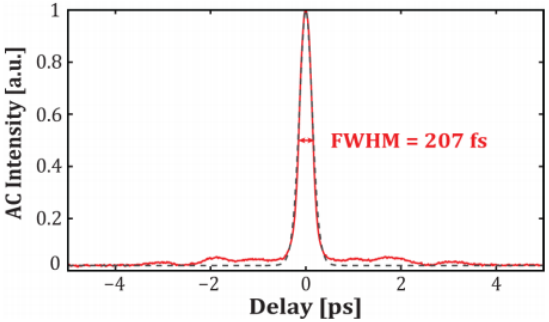
State of the art



Er-doped Fluoride Fiber Laser

1. State-of-art
2. Direct generation
2.1 Tm-fibre laser
2.2 ZBLAN fibre lasers
2.3 Hollow-core fibre lasers
3. SC generation
4. Conclusion





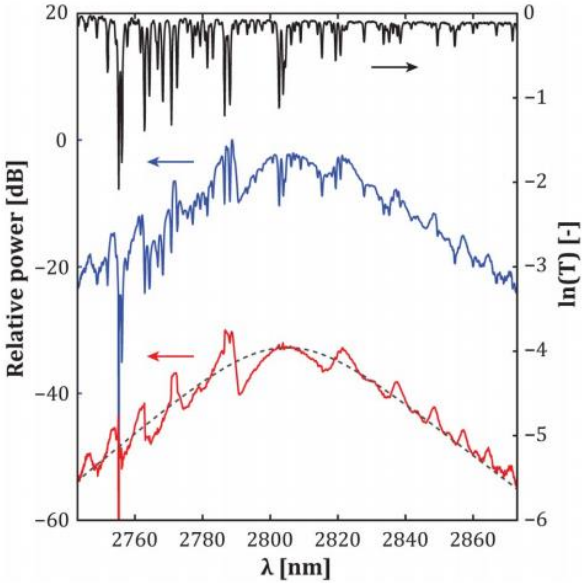
Output characteristics

$\Delta\tau_p \approx 207$ fs,

$P_{aver} = 44$ mW

$E = 0.8$ nJ

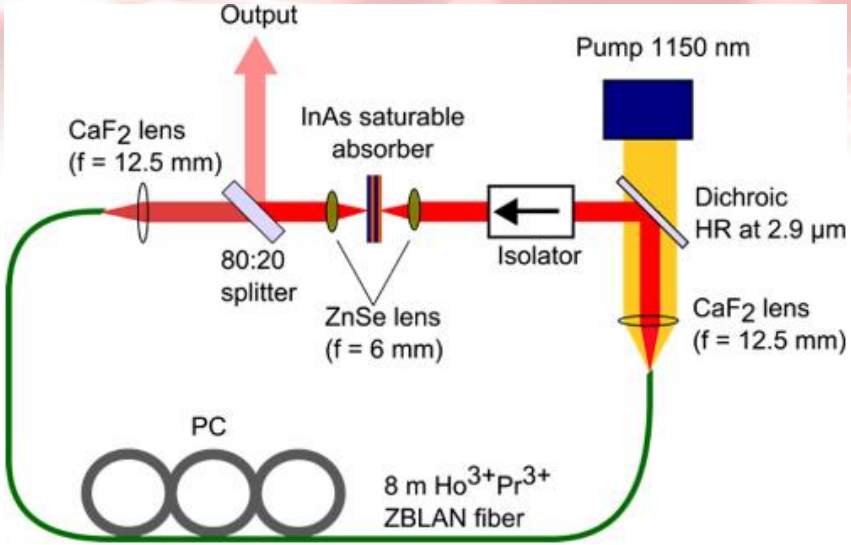
$P_{peak} = 3.5$ kW

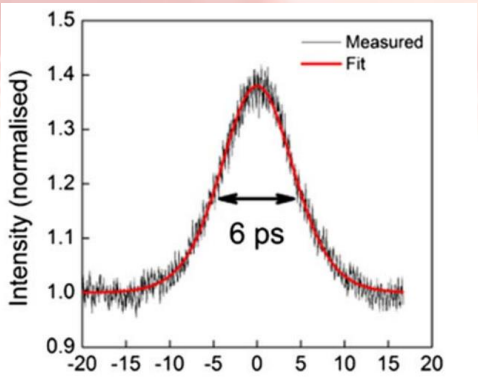


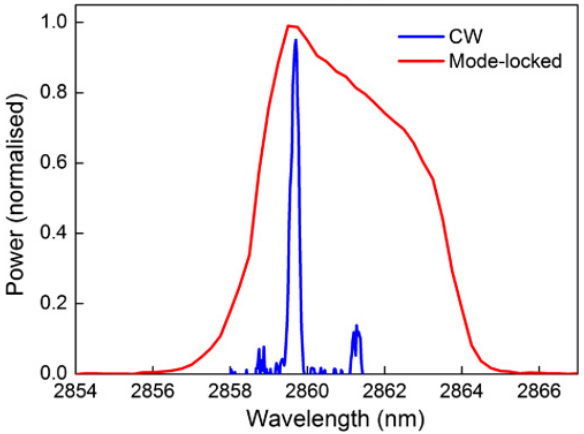
S. Duval et al. "Femtosecond fiber lasers reach the mid-infrared," Optica 2, 623-626 (2015)

Ho-doped Fluoride Fiber Laser

1. State-of-art
2. Direct generation
2.1 Tm-fibre laser
2.2 ZBLAN fibre lasers
2.3 Hollow-core fibre lasers
3. SC generation
4. Conclusion







Output characteristics

$\Delta\tau_p \approx 6$ ps,

$P_{aver} = 70$ mW

$E = 12.6$ nJ

$P_{peak} = 465$ W

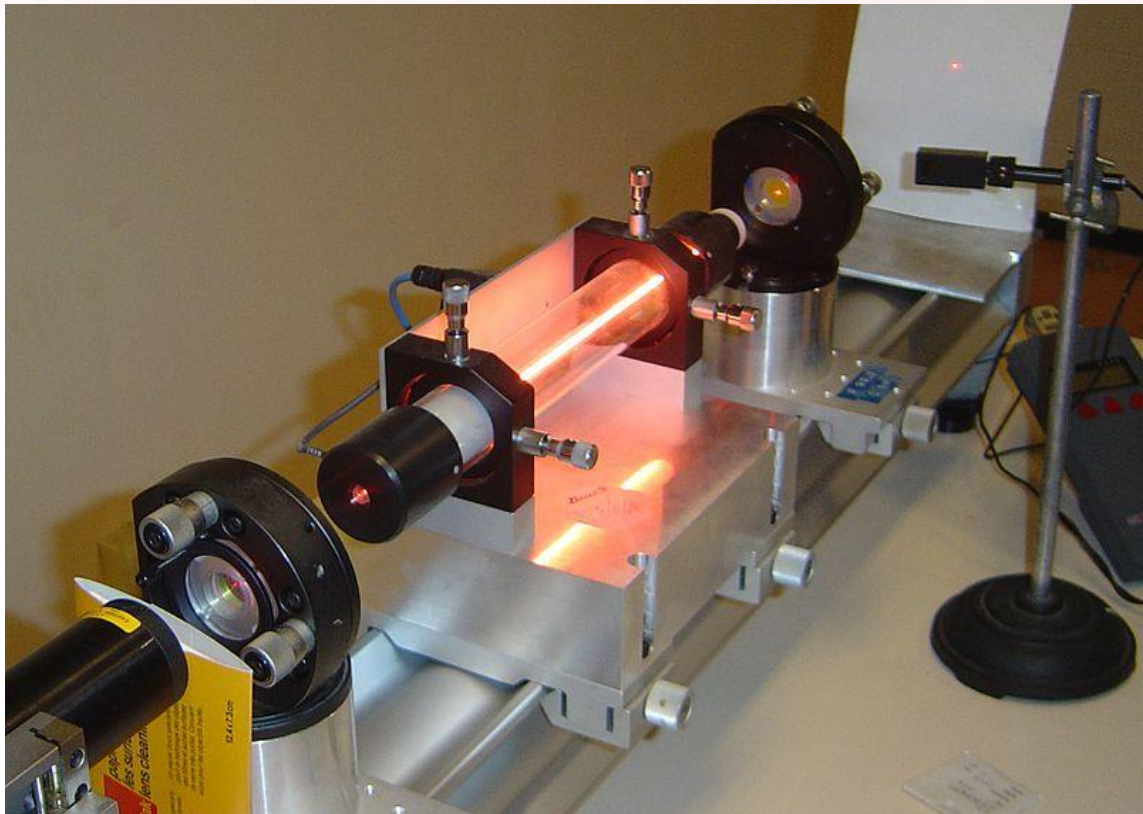
Tomonori Hu, Darren D. Hudson, and Stuart D. Jackson, "Stable, self-starting, passively mode-locked fiber ring laser of the 3 μm class," Opt. Lett. 39, 2133-2136 (2014)

State of the art

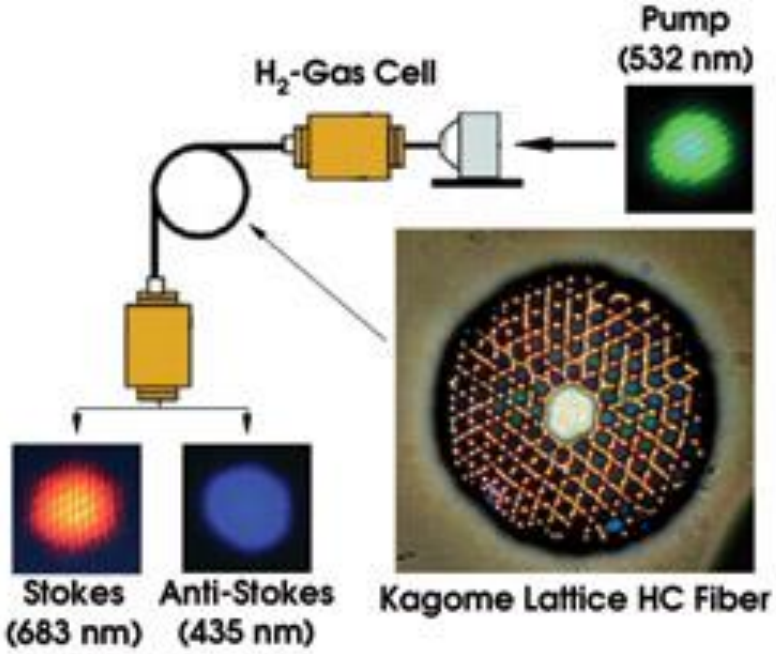
1960 William R. Bennett demonstrated of the first gas laser, the Helium–neon laser

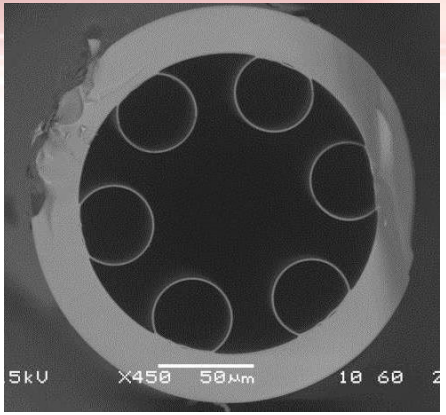
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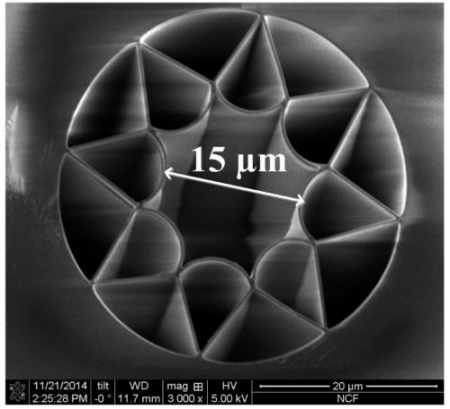
gas lasers didn't find wide application range



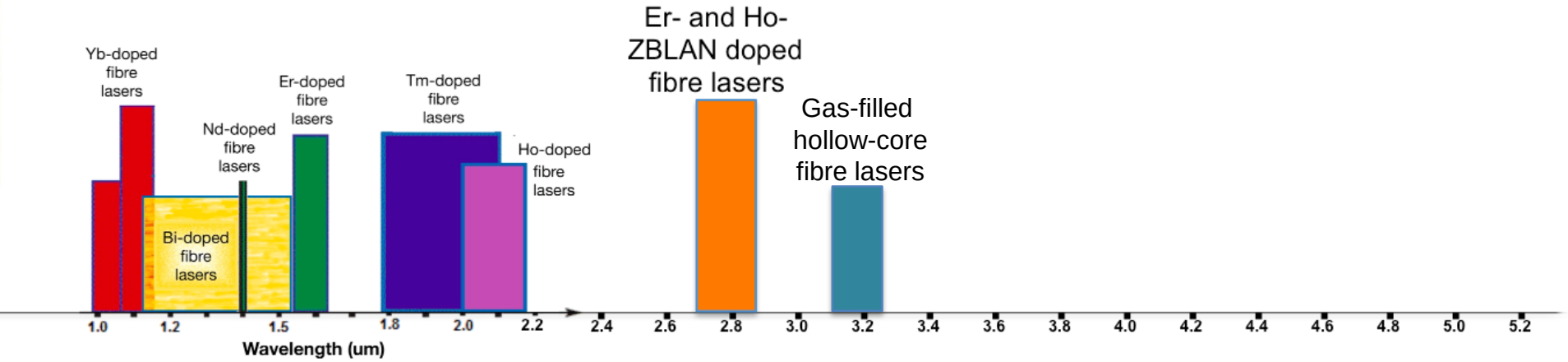
State of the art





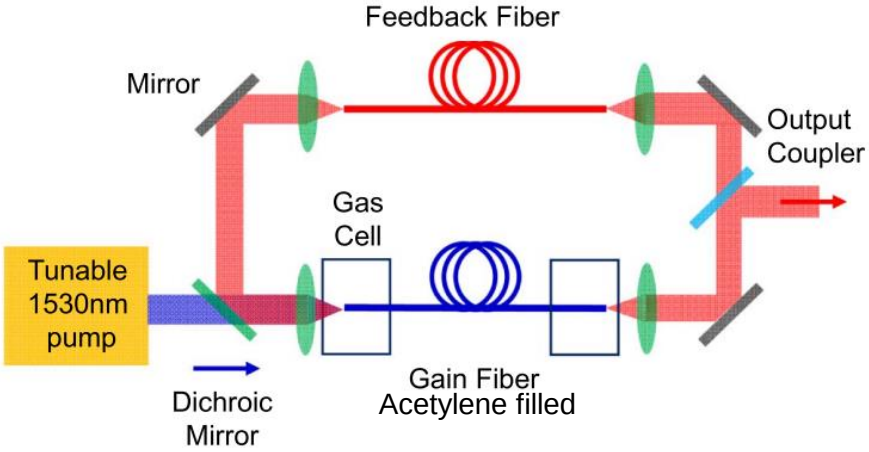


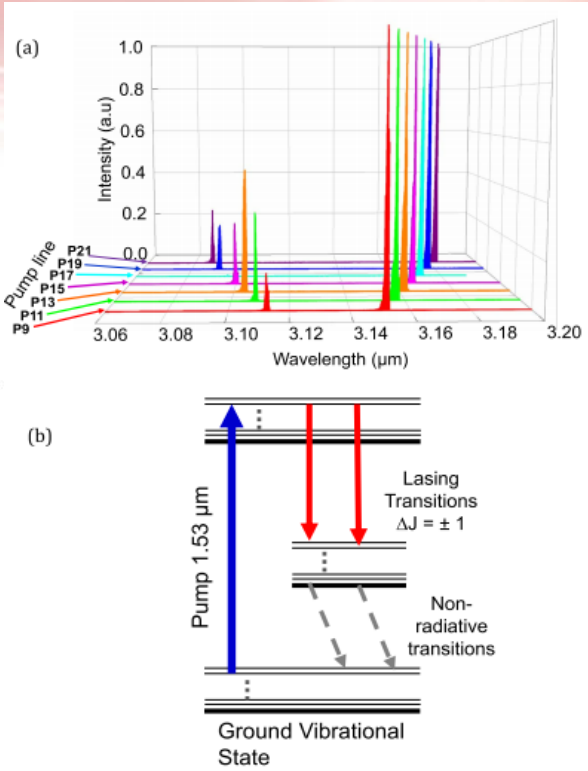
State of the art



Gas-filled Hollow-core Fiber Laser

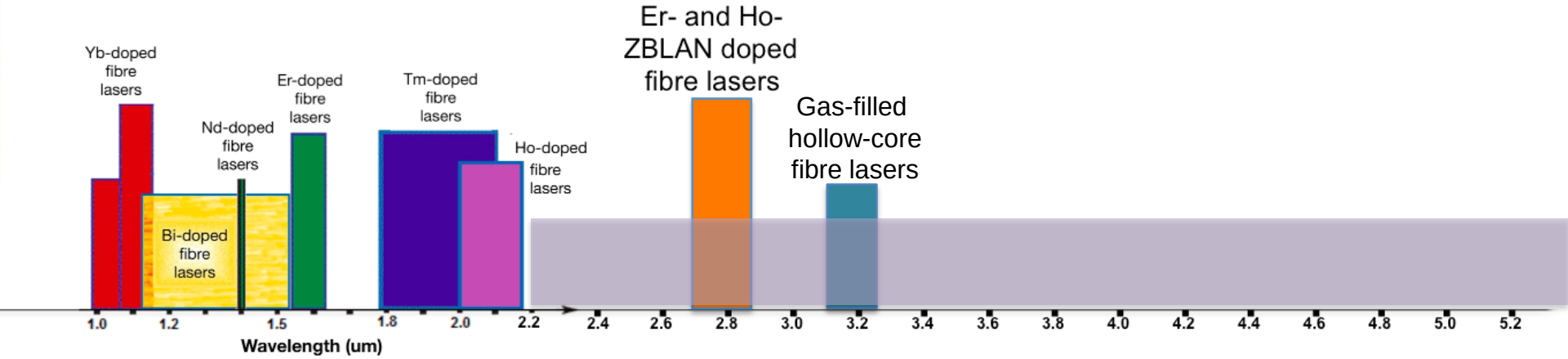
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4. Conclusion





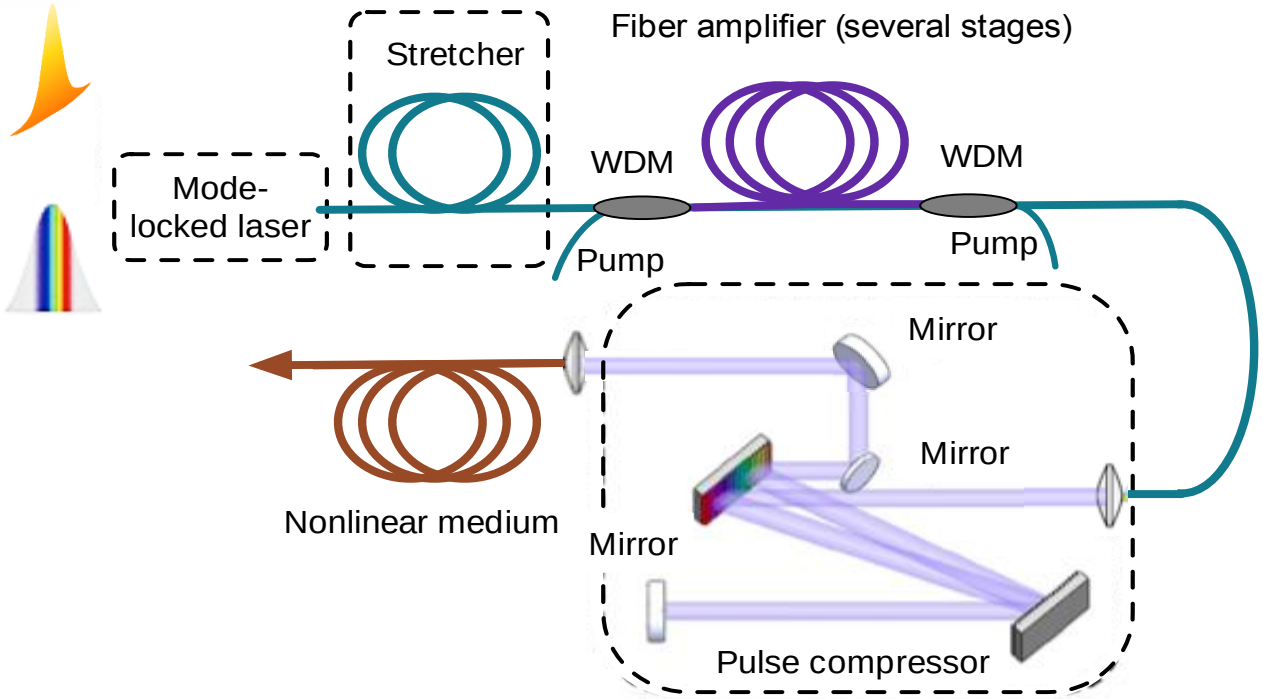
M. R. Abu Hassanet al., "Cavity-based mid-IR fiber gas laser pumped by a diode laser," Optica 3, 218-221 (2016)

State of the art



Supercontinuum generation

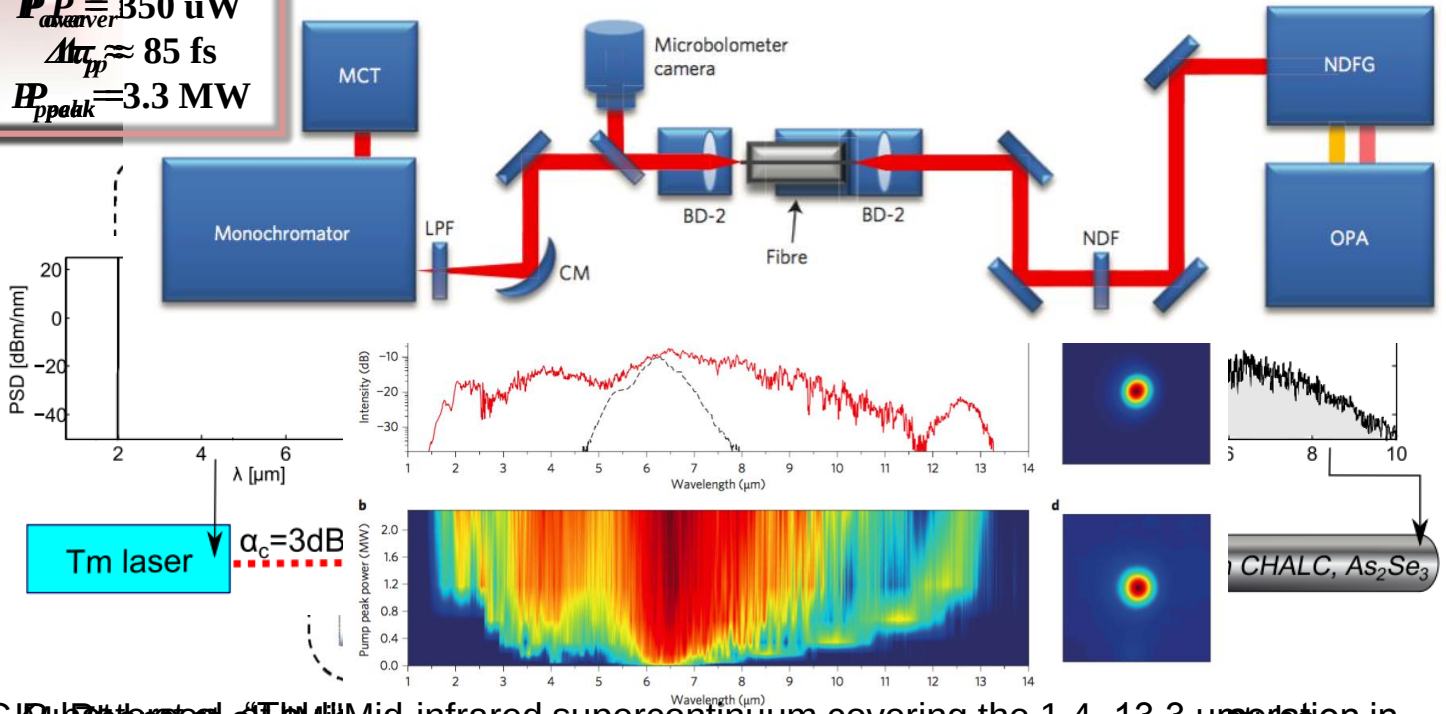
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4. Conclusion



Mid-IR supercontinuum

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2.1 Tm-fibre laser
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2.3 Hollow-core fibre lasers
3. SC generation
4. Conclusion

$P_{average}$ = 350 uW
$\Delta\tau_{fp}$ ≈ 85 fs
P_{peak} =3.3 MW



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," Nature Photonics 8.11 (2014): 830-834.

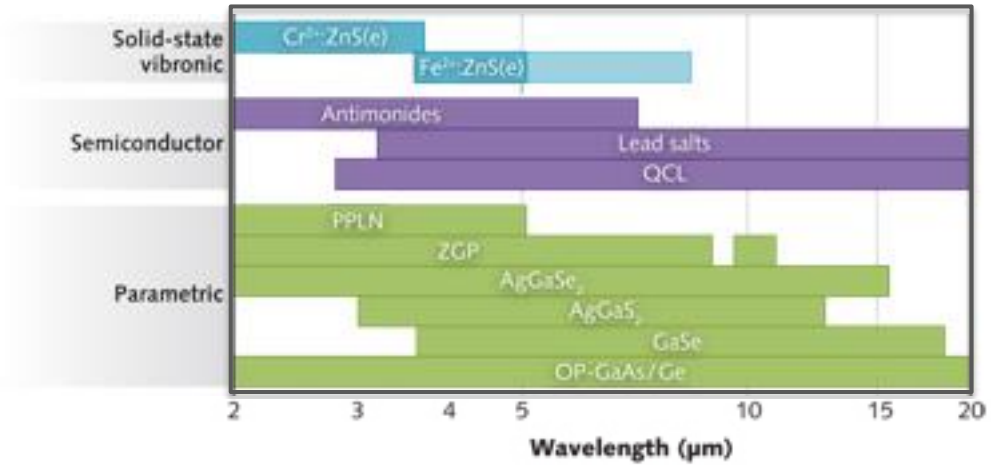
M. Zhang et al., "Mid-infrared Raman coherent frequency comb from a fibre-coupled quantum cascade laser," Optica 6.6 (2019): 796-797.

J. Hu et al., "1.9 μm, 10 W monolithic laser diode pumped Tm fiber laser with parasitic-wavelength-suppressed single-mode output," Optics Express 28, 23 (2020): 34325-34332.

Conclusion

1. State-of-art
2. Direct generation
2.1 Tm-fibre laser
2.2 ZBLAN fibre lasers
2.3 Hollow-core fibre lasers
3. SC generation
4. Conclusion

Mid-IR Fiber Lasers are not the only obvious solution. What are we up against?



Conclusion

1. State-of-art
2. Direct generation
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4. Conclusion

What is to be developed or improved?

• Novel glass matrixes, structures and design of optical fibres to :

- create optical gain in Mid-infrared;
- control intracavity dispersive parameters;
- achieve sufficient nonlinear characteristics.

• Direct modulation

Fast, miniature, low power consumption modulators

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Thank you for your attention!