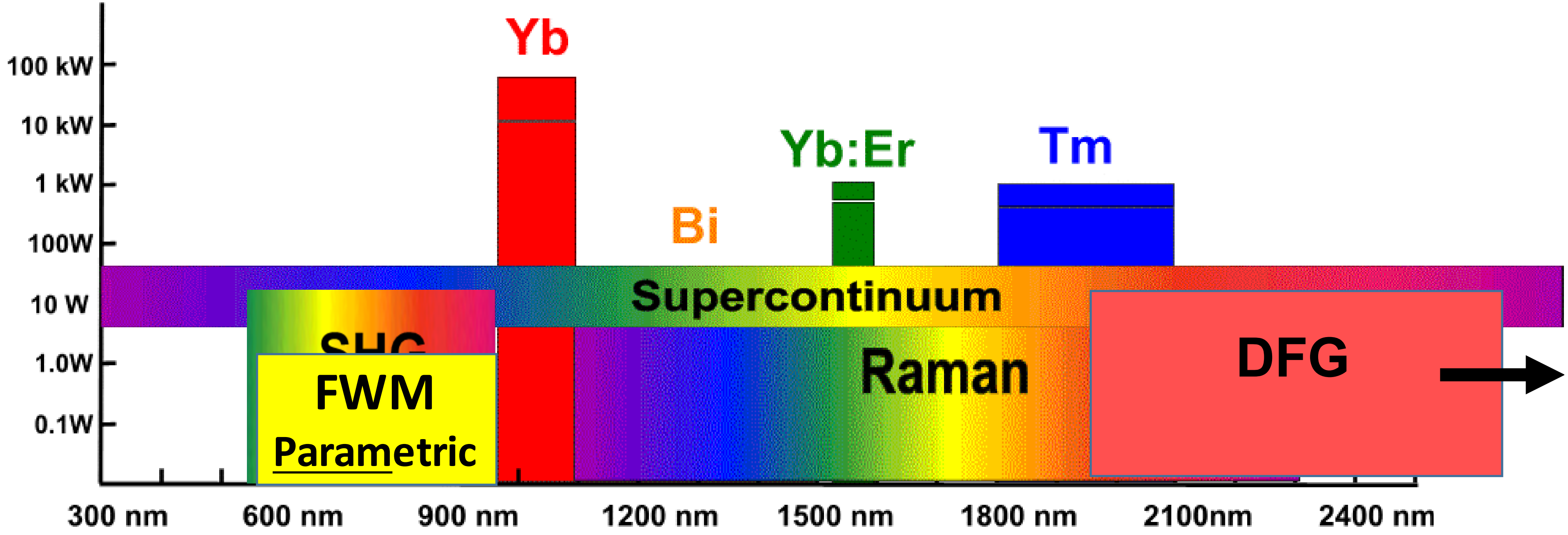
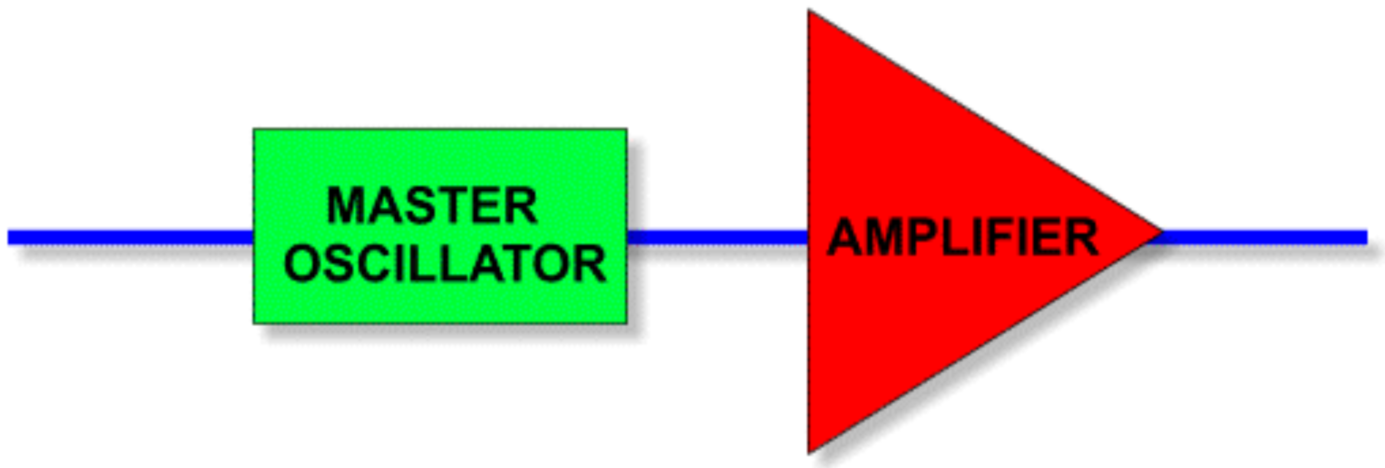
Silica fibre based sources and non-linear conversion



Imperial College London

MOPFA Technology

FOG femtosecond optics group



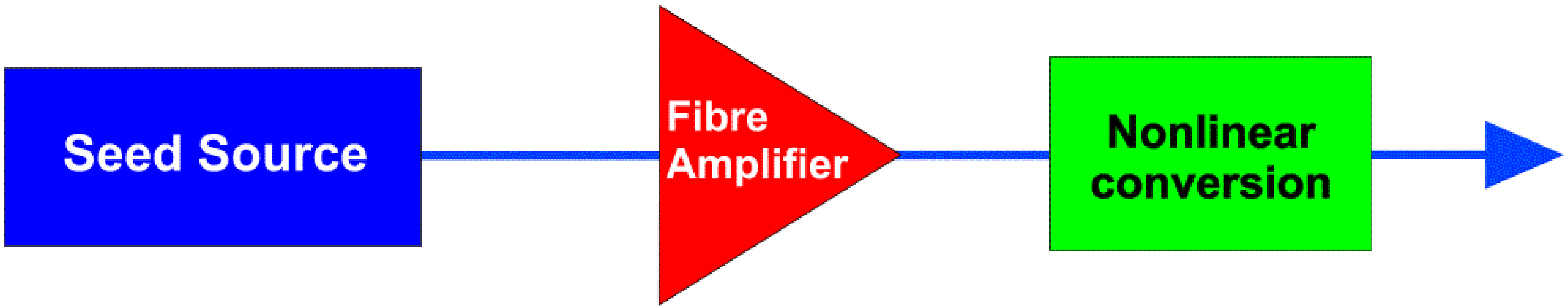
Master Oscillator

- Diode/fibre laser seeding
- Versatile parameter control
- Direct modulation
- Fibre integrated

High Power Fibre Amplifier

- High single pass gains
- Wavelength diversity
- High energy storage
- Fibre integrated

MOPFA + Nonlinearity

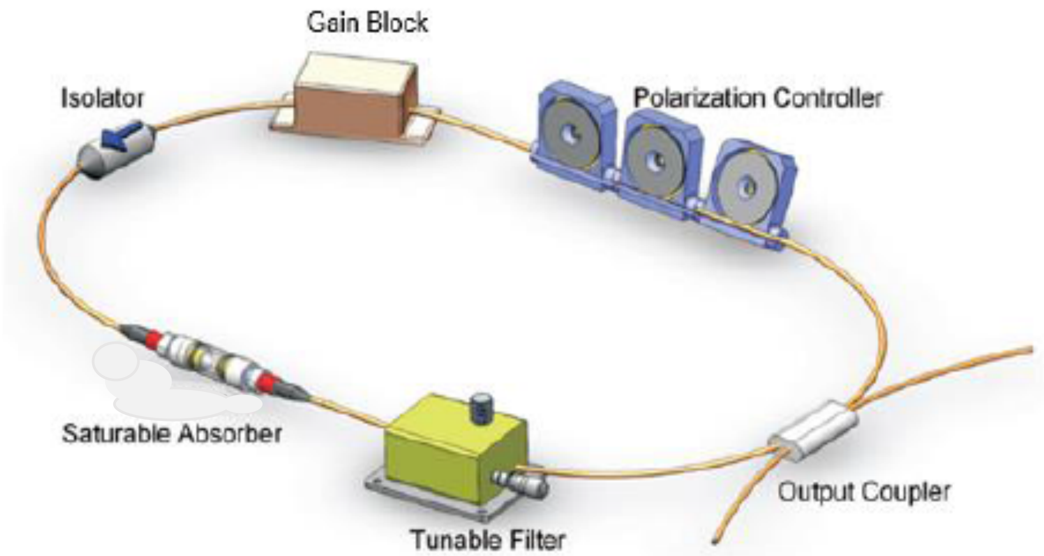


Arsenal of Nonlinearities:-

- SHG, SFG, THG, FHG (tandem SHG) in PP / bulk crystals
- Raman, SPM, FWM, soliton effects in optical fibres
- Supercontinuum generation

Seed Laser Systems

Passively mode locked fibre laser



Gain media :- Yb, Er, Tm, Raman

Saturable absorber - SESAM
Carbon nanotubes
Graphene
Transition metal dichalcogenides

Solid state saturable absorbers

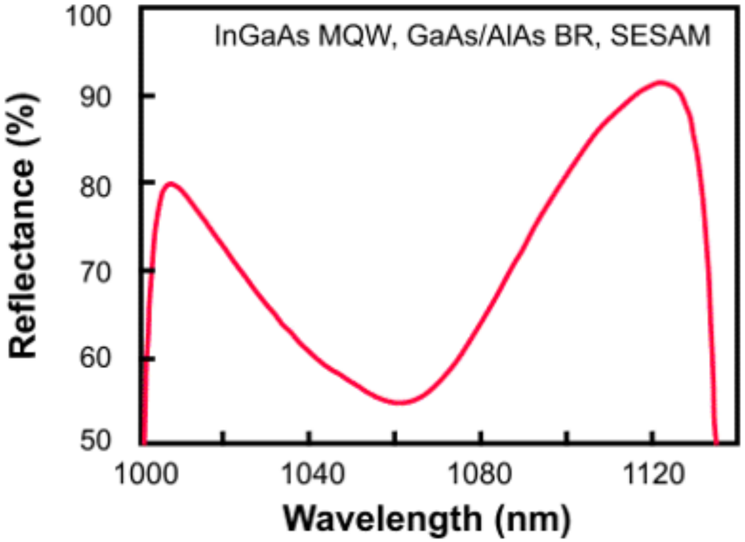
SESAMs

Saturation intensity ~ 50 $MWcm^{-2}$

Recovery time (variable) ~10 ps (carrier recombination)

< ps (intraband thermalization)

- Relatively expensive to manufacture
- Customized for each wavelength of operation



CARBON NANOTUBES

Absorption wavelength ~ 1.49d µm

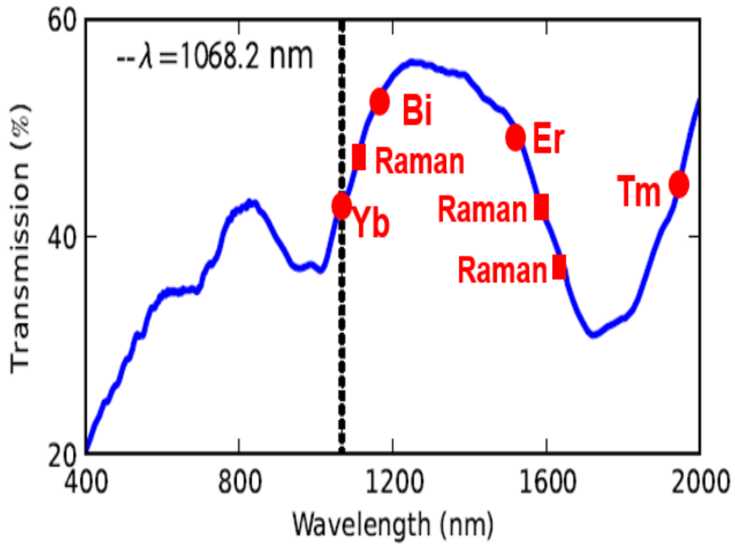
Saturation intensity ~ 10 $MWcm^{-2}$ (E_{11})

~ 200 $MWcm^{-2}$ (E_{22})

Recovery time (variable) ~ 500 fs (E_{11})

~ 50 fs (E_{22})

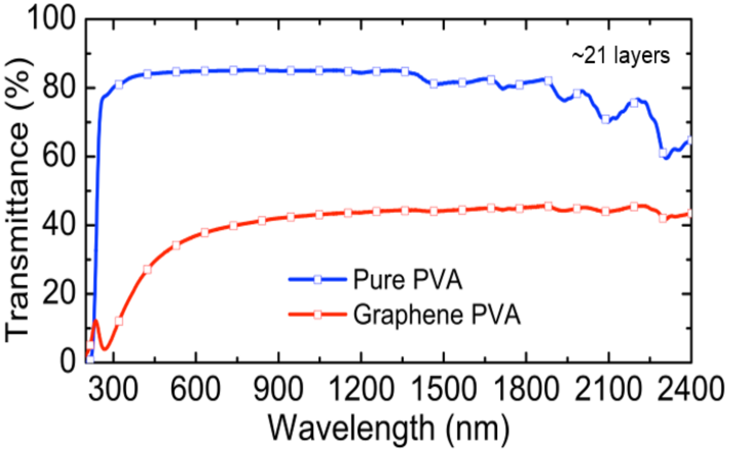
- Polymer host
- Resonant - but use mixture of tube diameters
- Increased non saturable loss



Solid state saturable absorbers

GRAPHENE

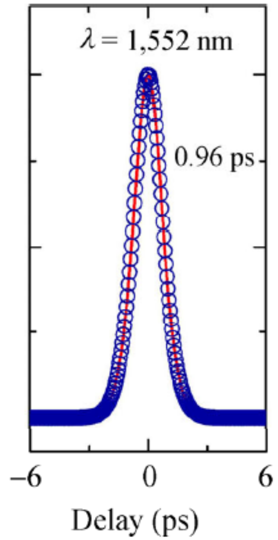
Absorption ~ 2.3% per layer
Saturation intensity ~ 10-200 $MWcm^{-2}$
Recovery times ~ 10 -100 fs thermalizing
~ <ps intra band phonon scatt



- Polymer host
- Lower non saturable loss than nanotubes
- Universal saturable absorber

OTHER 2D NANO-MATERIALS

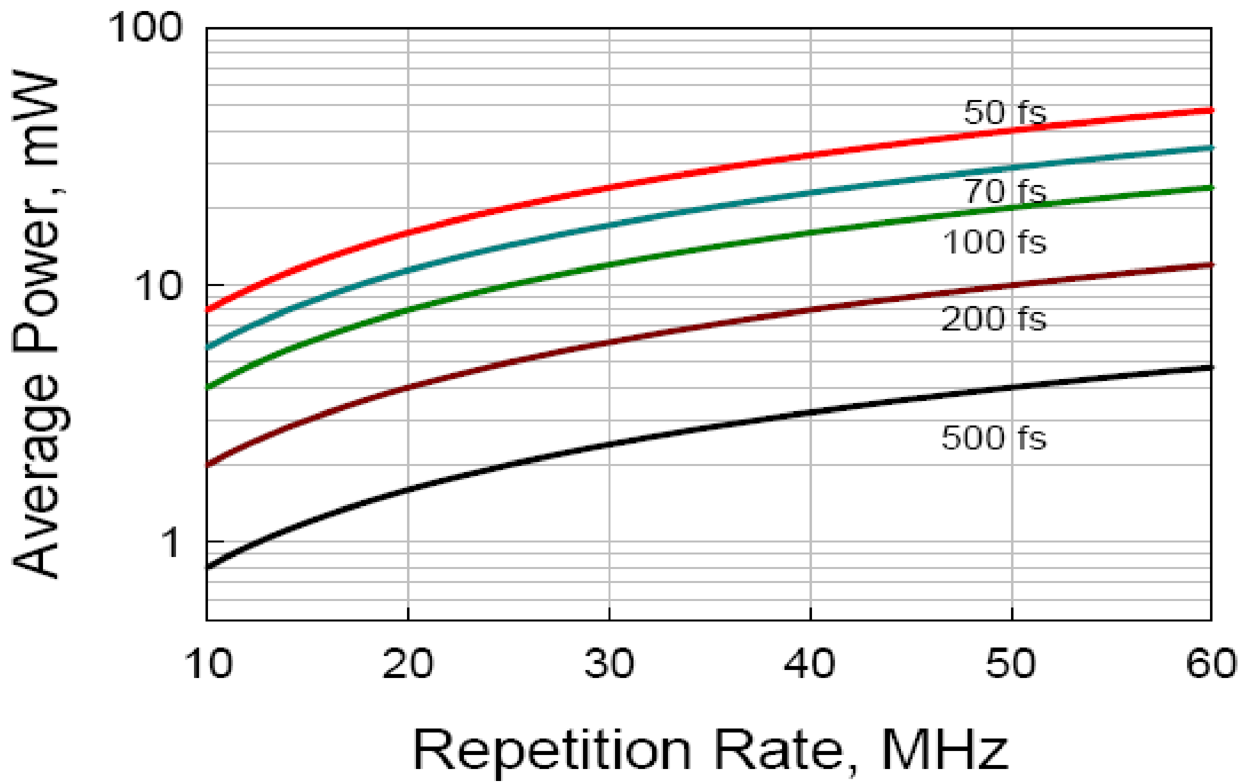
Metal dichalcogenides - MoS_2, $MoSe_2$, WS_2 etc
Saturation intensity ~ 1-150 $MWcm^{-2}$
Recovery times ~ 50 -100 fs



- Polymer host – damage
- Resonant - defect states vary bandgap
- High non saturable loss

Disadvantages - fixed repetition rates
- restricted flexibility of pulse durations
- soliton operation

Average power operation with solitons

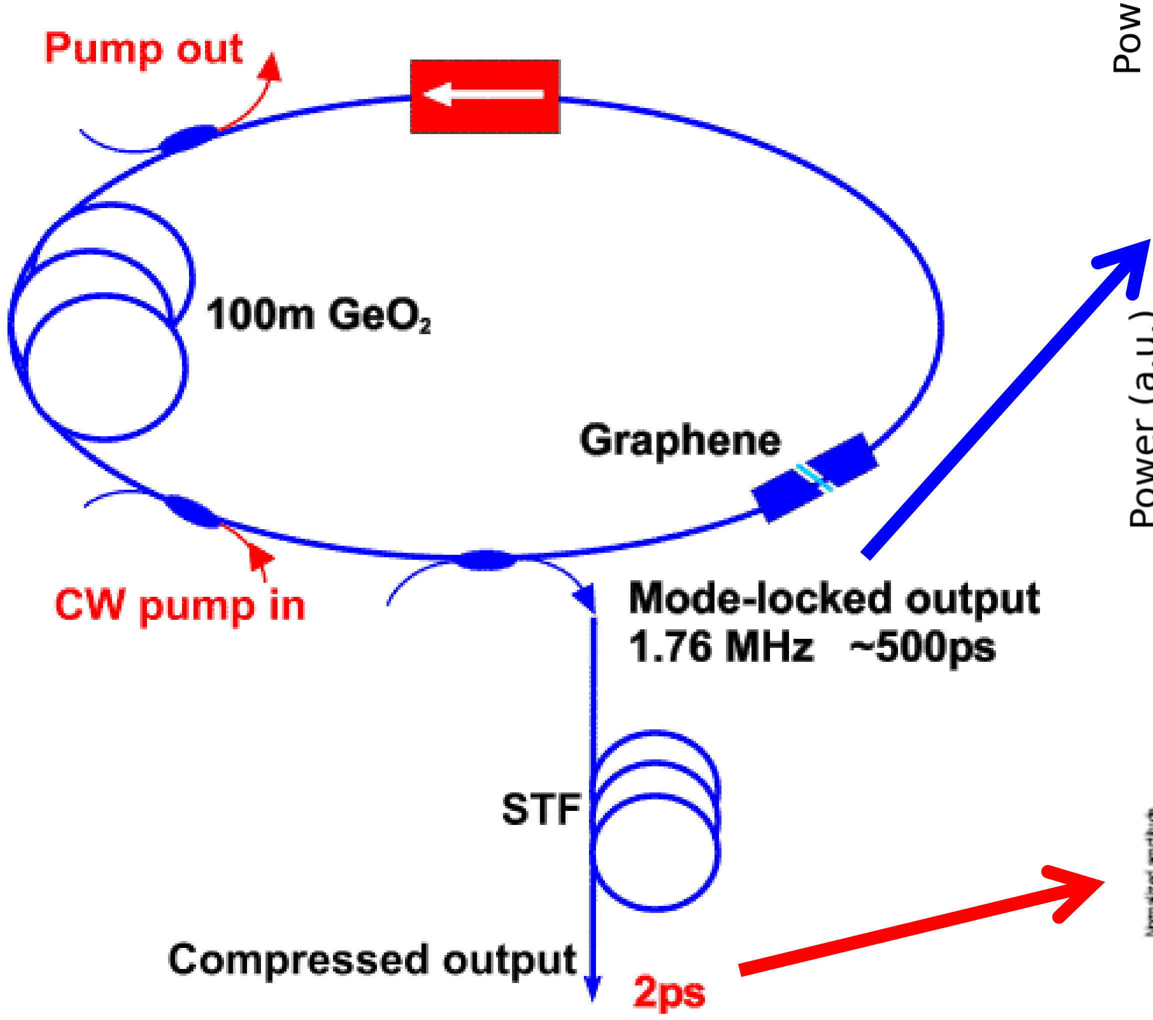


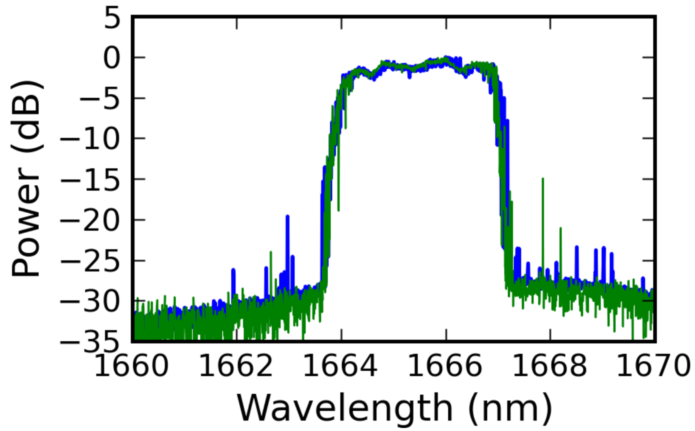
At repetition rates from a conventional fibre laser, for pulse durations in the 500fs-1ps regime only a few mw average power is required

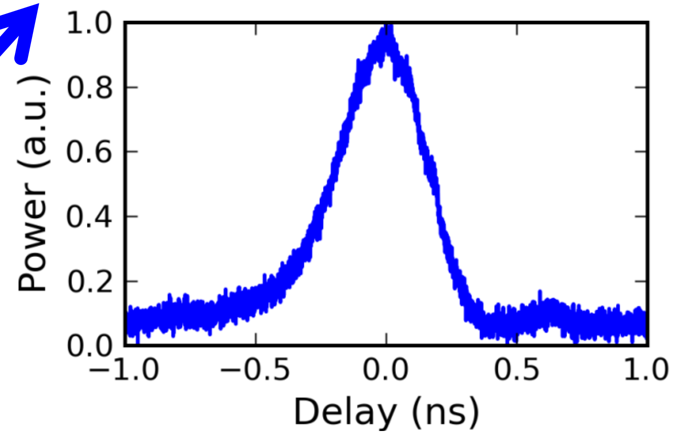
For follow on non-linear applications AMPLIFICATION (MOPFA) needed

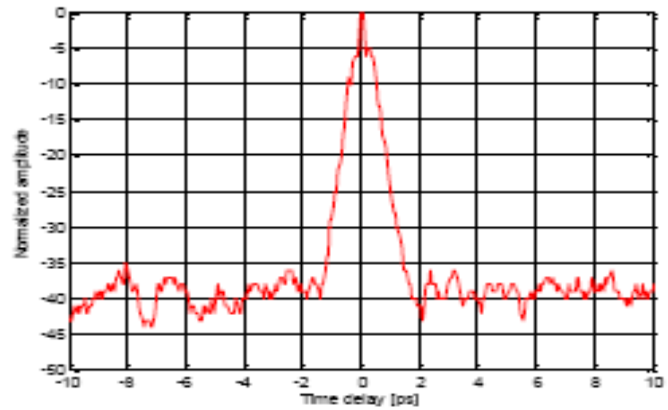
Universal Pulse Source

Raman gain pumped by cw Raman fibre laser
Graphene saturable absorber
Output wavelength determined by cw pump

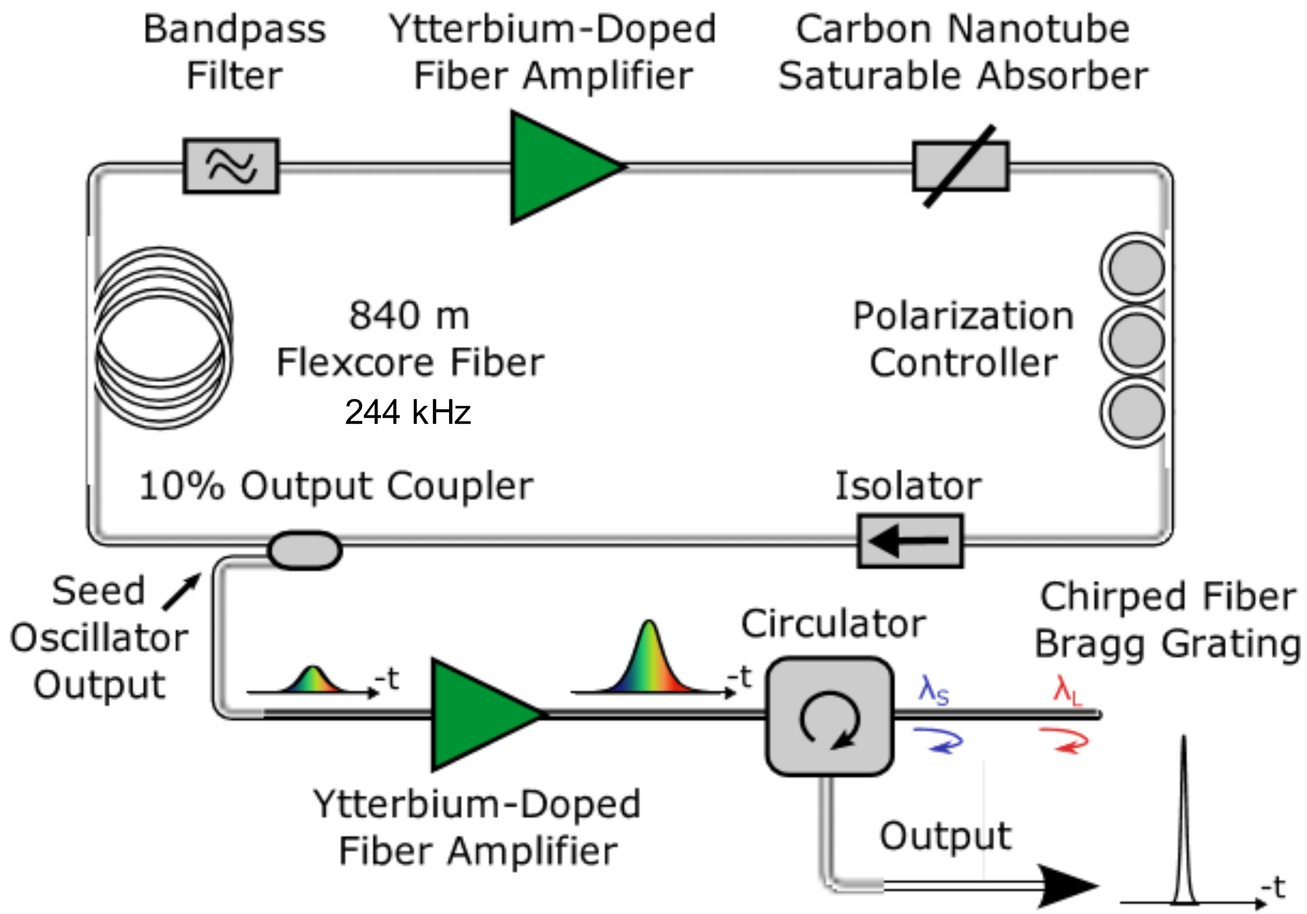


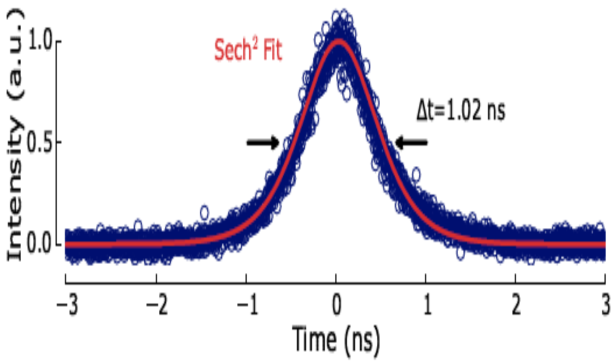


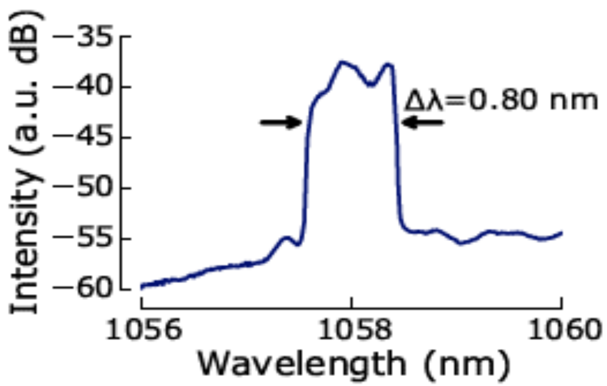




Normal dispersion, giant chirp fibre lasers







Giant chirp compensation – experimental

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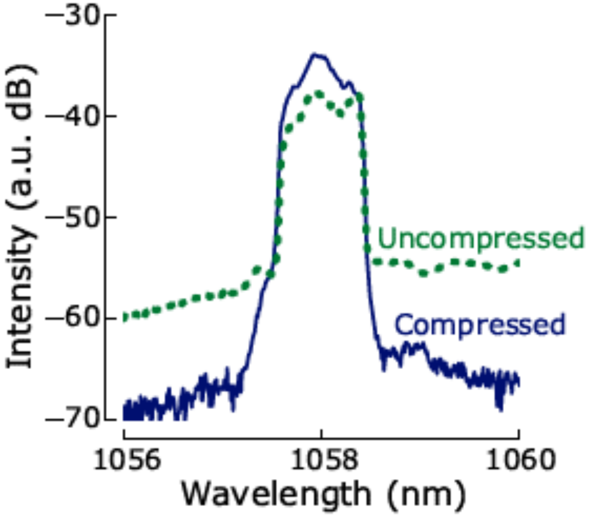
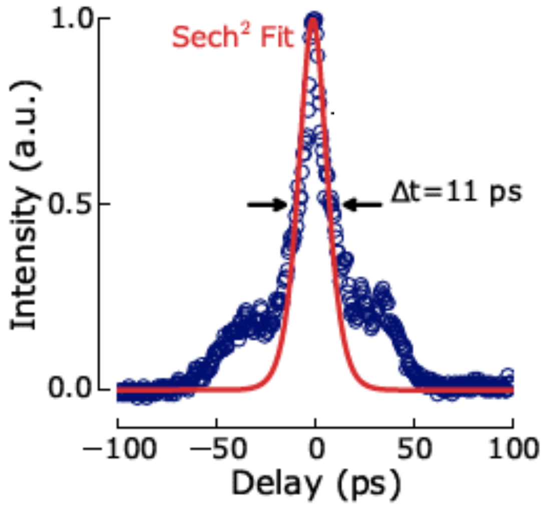
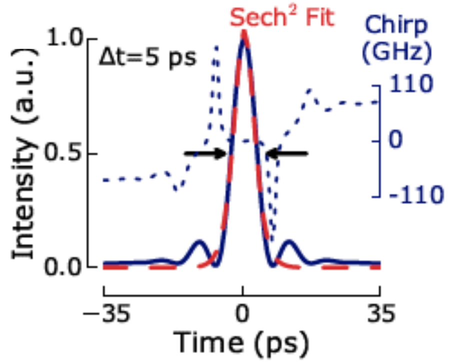
Mode locked input

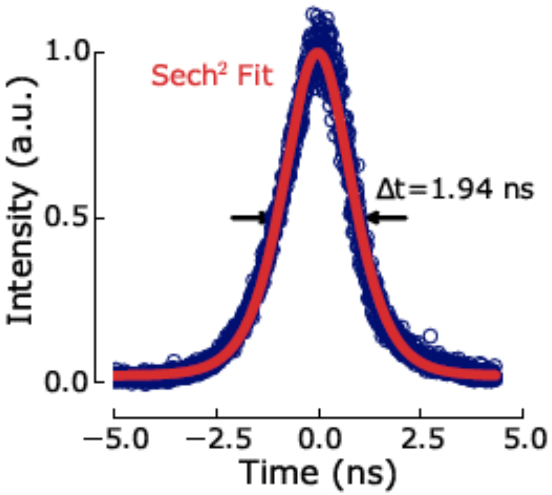


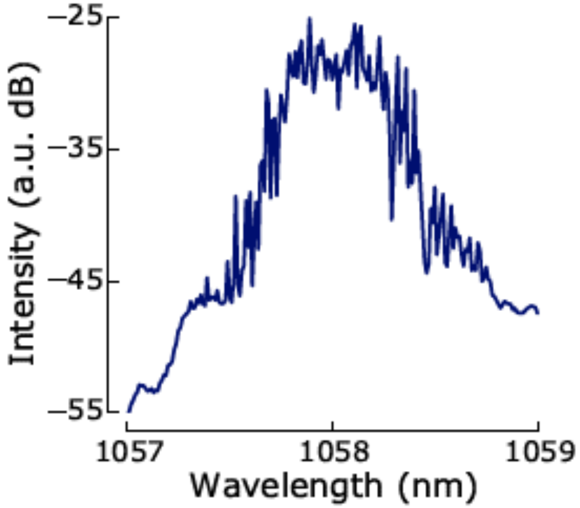


Predicted compression

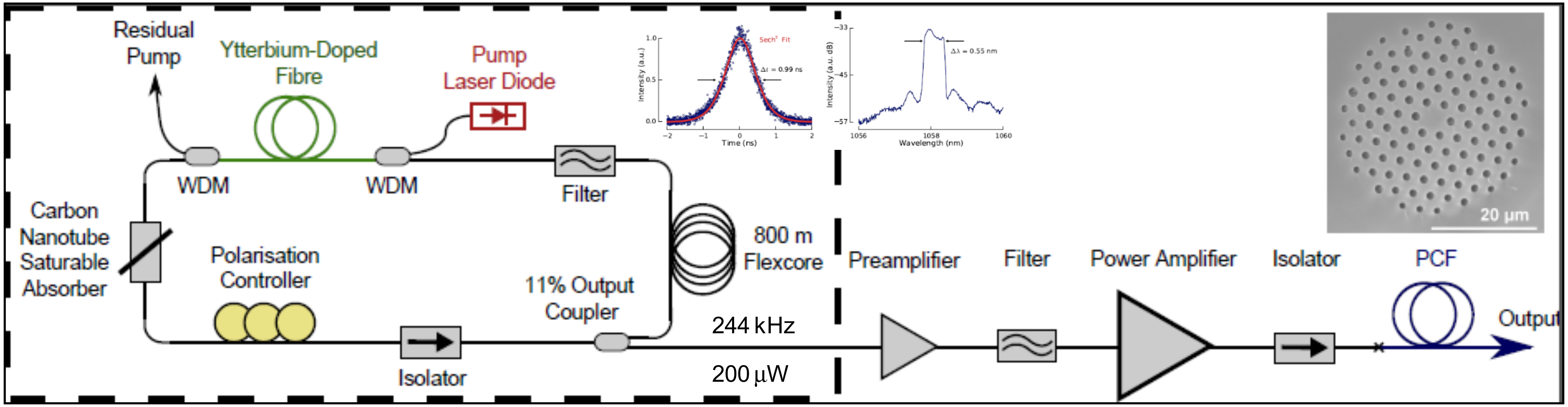


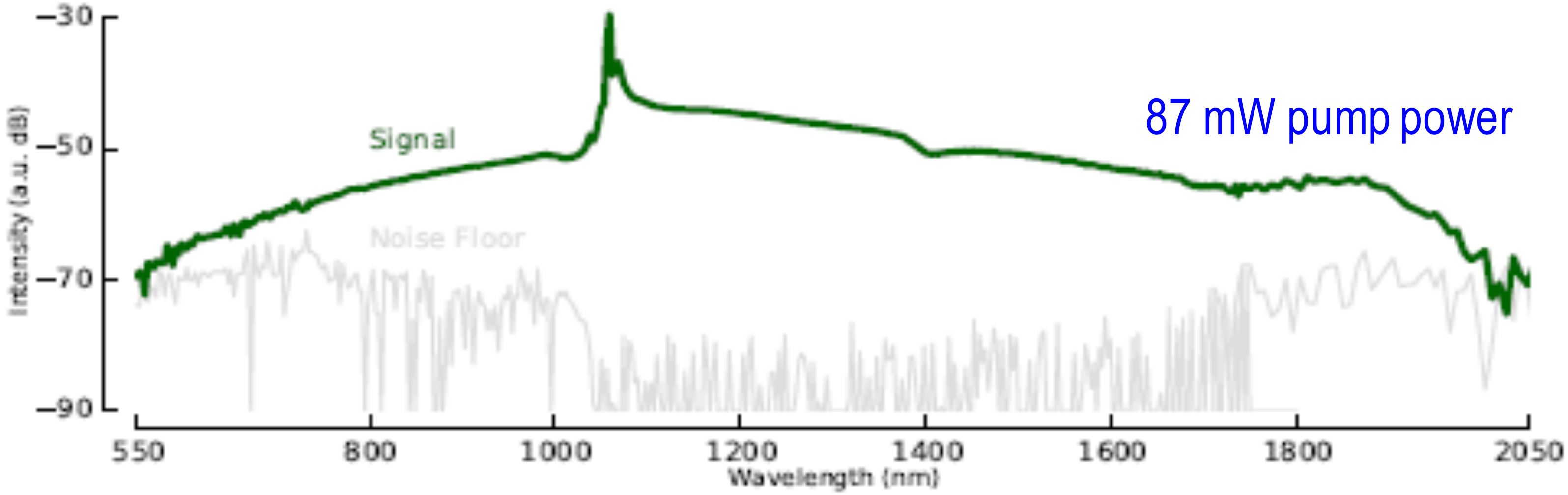
Noise burst input





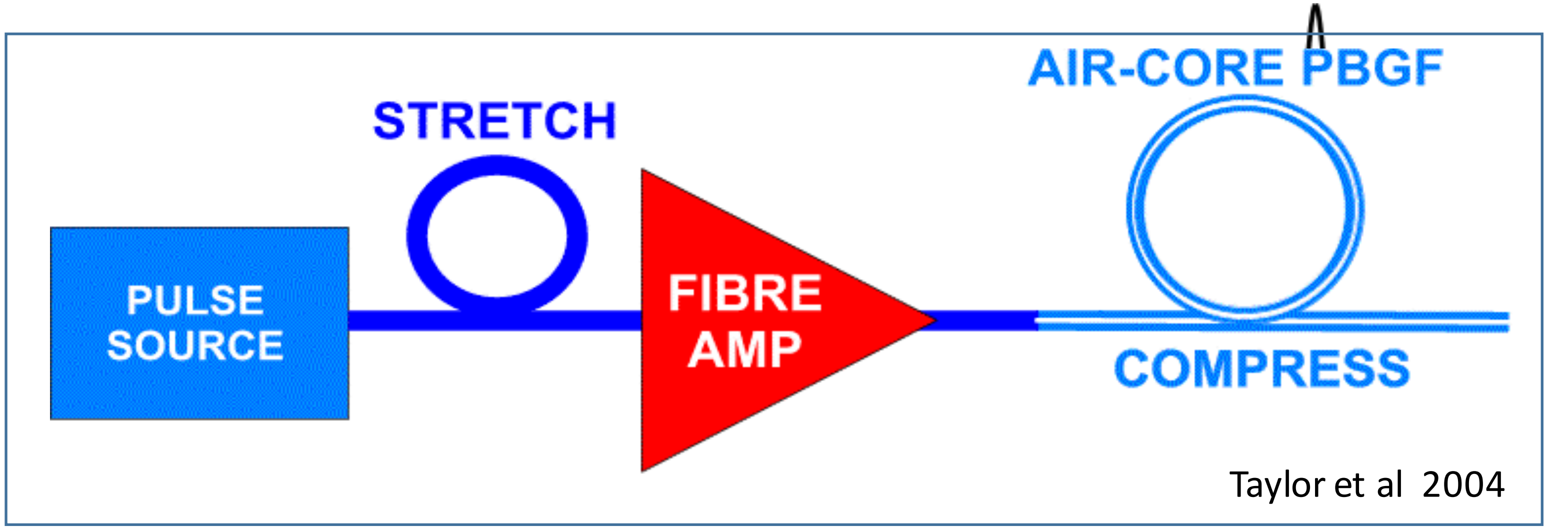
Low repetition rate supercontinuum source





87 mW pump power

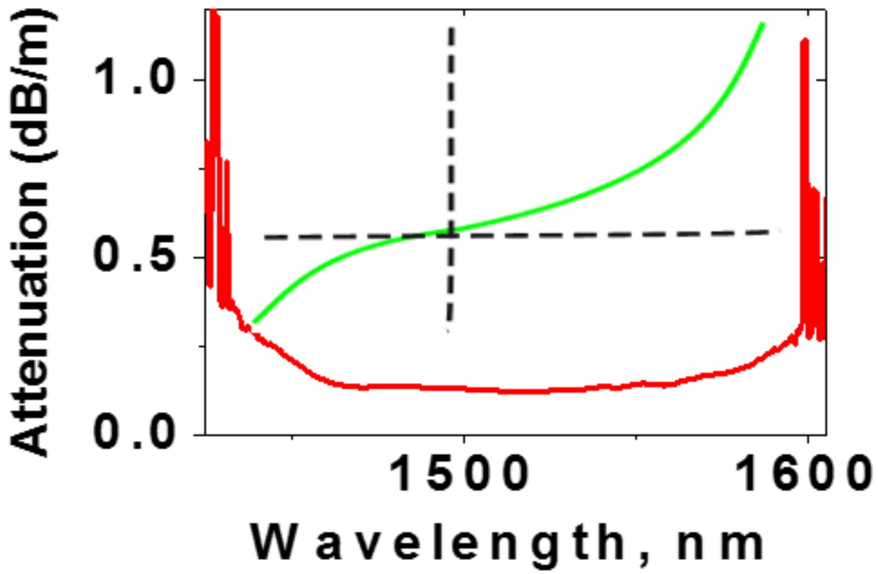
Chirped Pulse Amplification

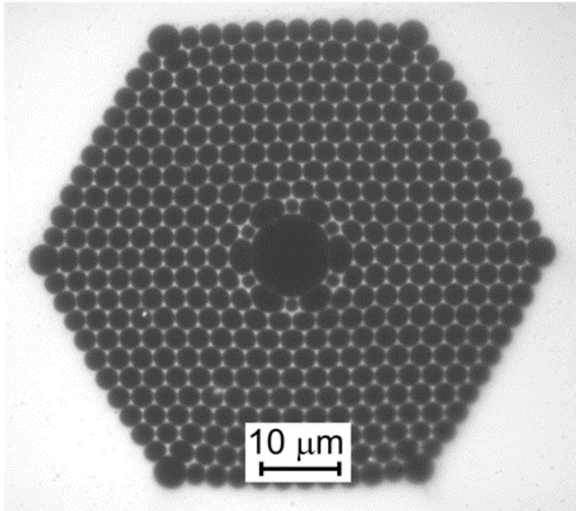


Demonstrated with
Yb, Yb:Er and Raman systems

Average powers ~ 10's W
Peak powers ~ 100kW
Raman Peak power ~ 1kW

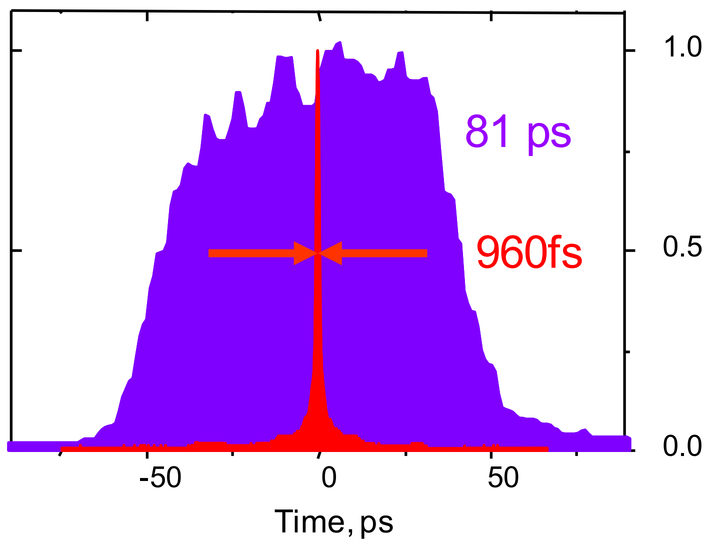
Air-Core Photonic Bandgap Fibre

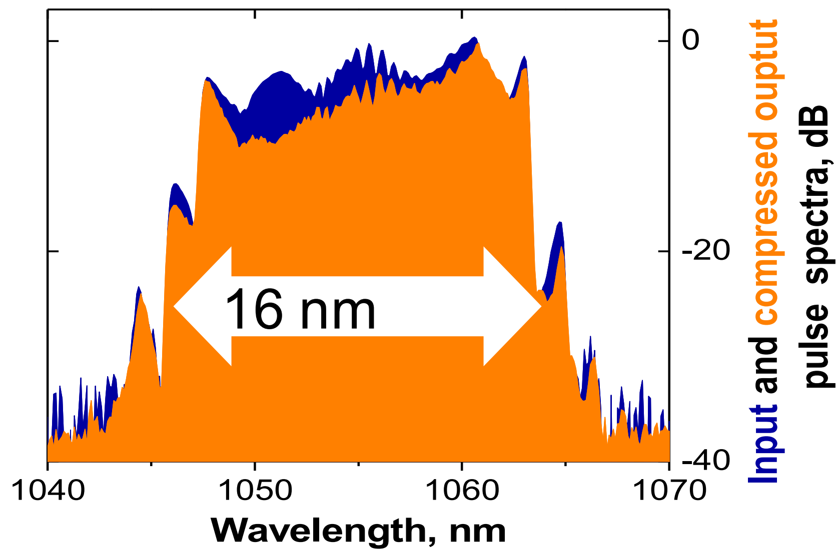




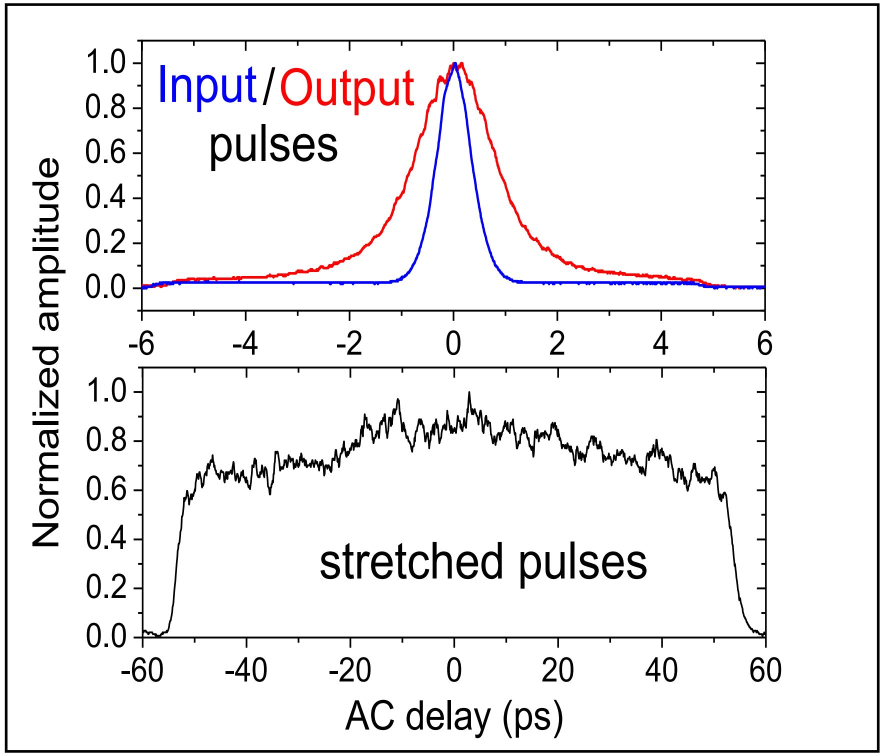
High waveguide dispersion

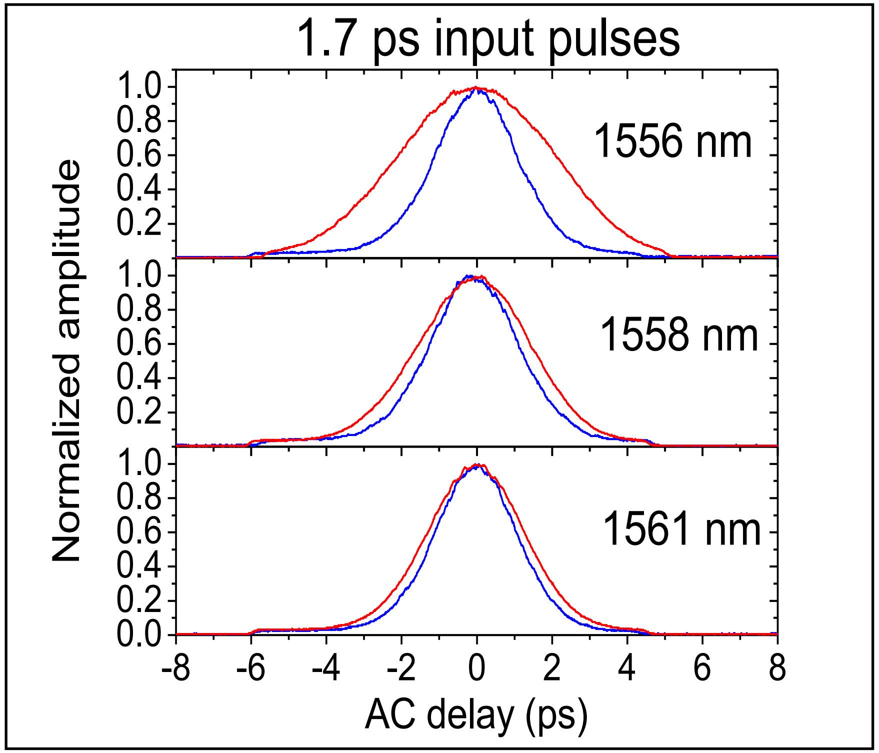
~1000 x lower nonlinear threshold





All-fibre CPA

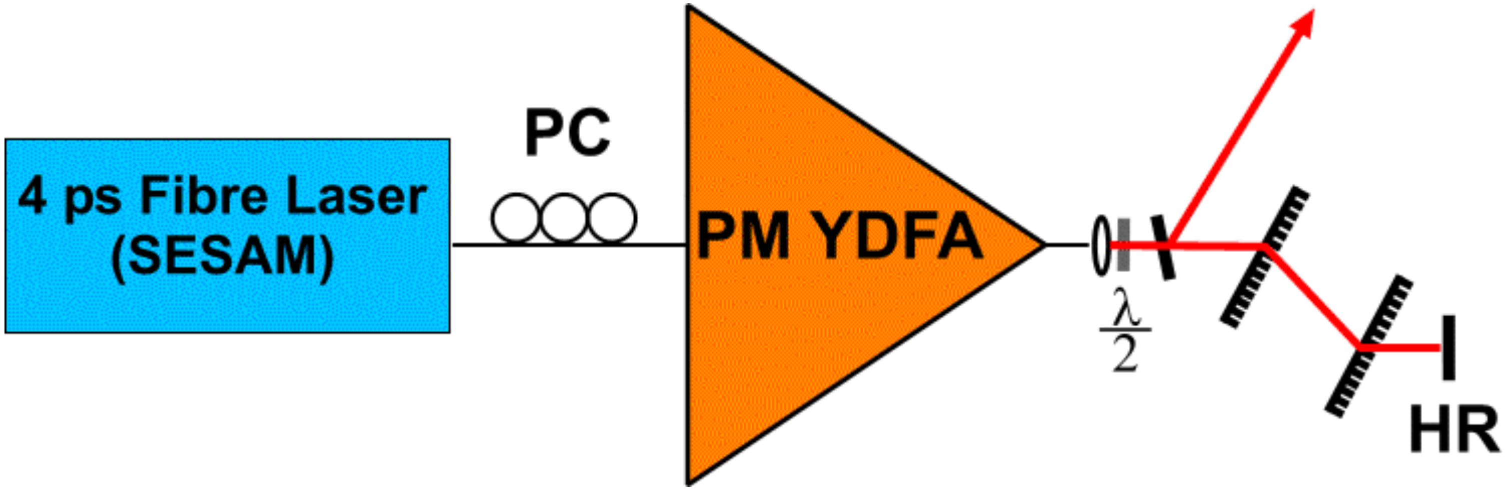




Problem: High order dispersion

Solution: Bulk elements – 100W, 100mJ, 500fs, 900kHz

Non-fibre CPA Femtosecond Compression



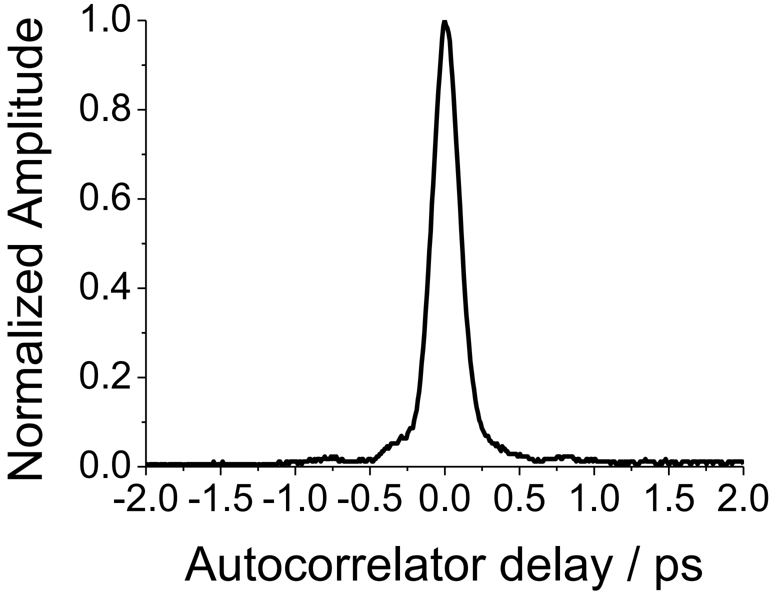
Power Amp Characteristics

- Polarization maintaining SMF
- Length: ~9 m, LMA ~10-12 μm
- Output power used: 4.3 W

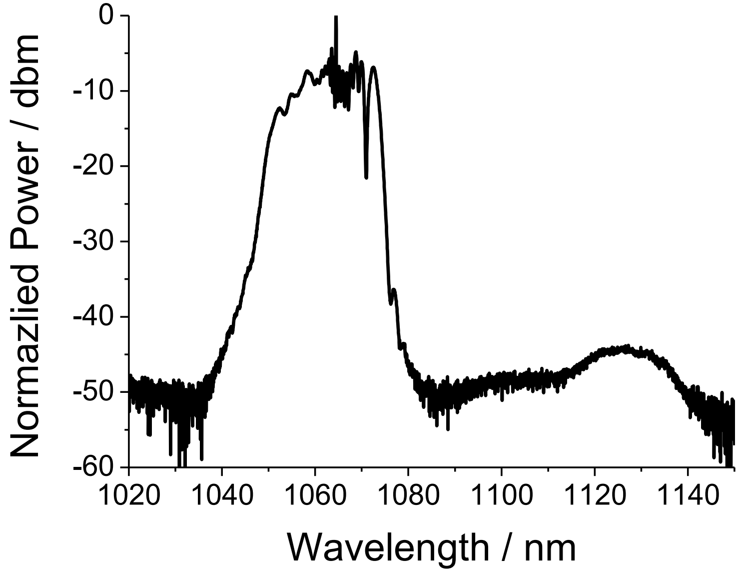
Transmission Gratings

- Pitch: 800 nm
- Separation: 14 mm
- Total loss (x2 pass): 2.3 dB

Non-fibre CPA: Compression - 2

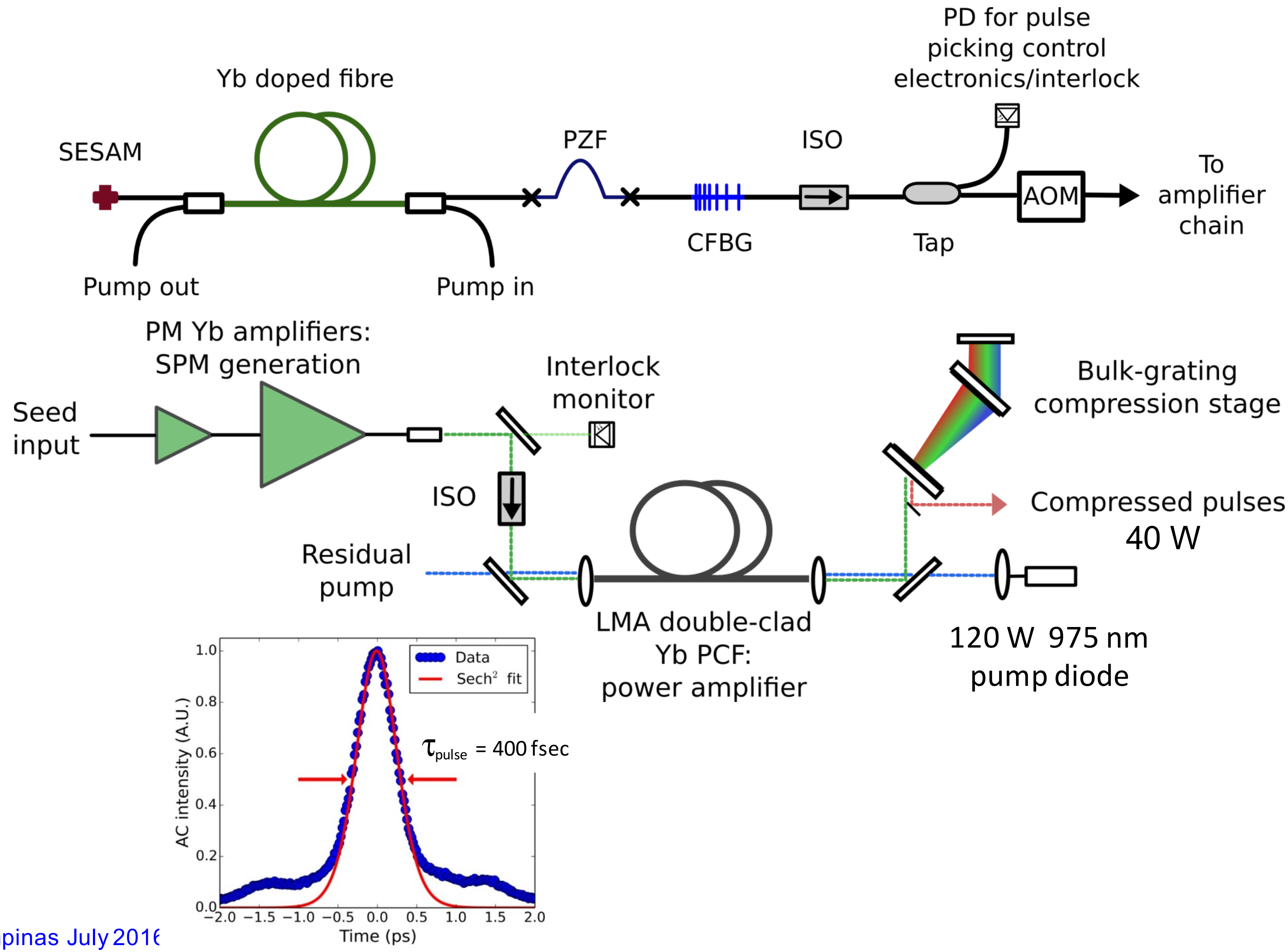


- 140 fs pulses
- 270 kW peak power
- 2.5 W average power



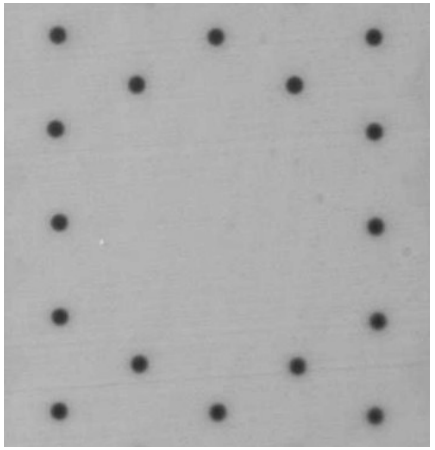
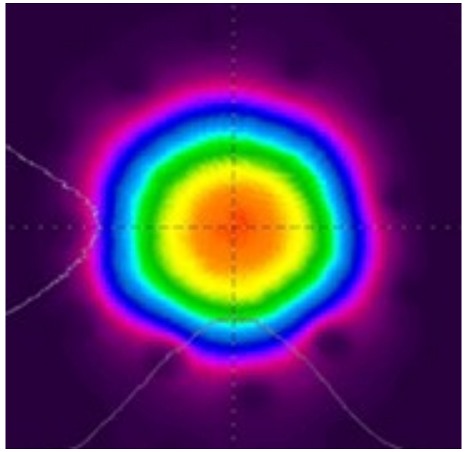
- 10dB bandwidth: 16.5 nm
- Limited by onset of Raman

Yb - MOPFA

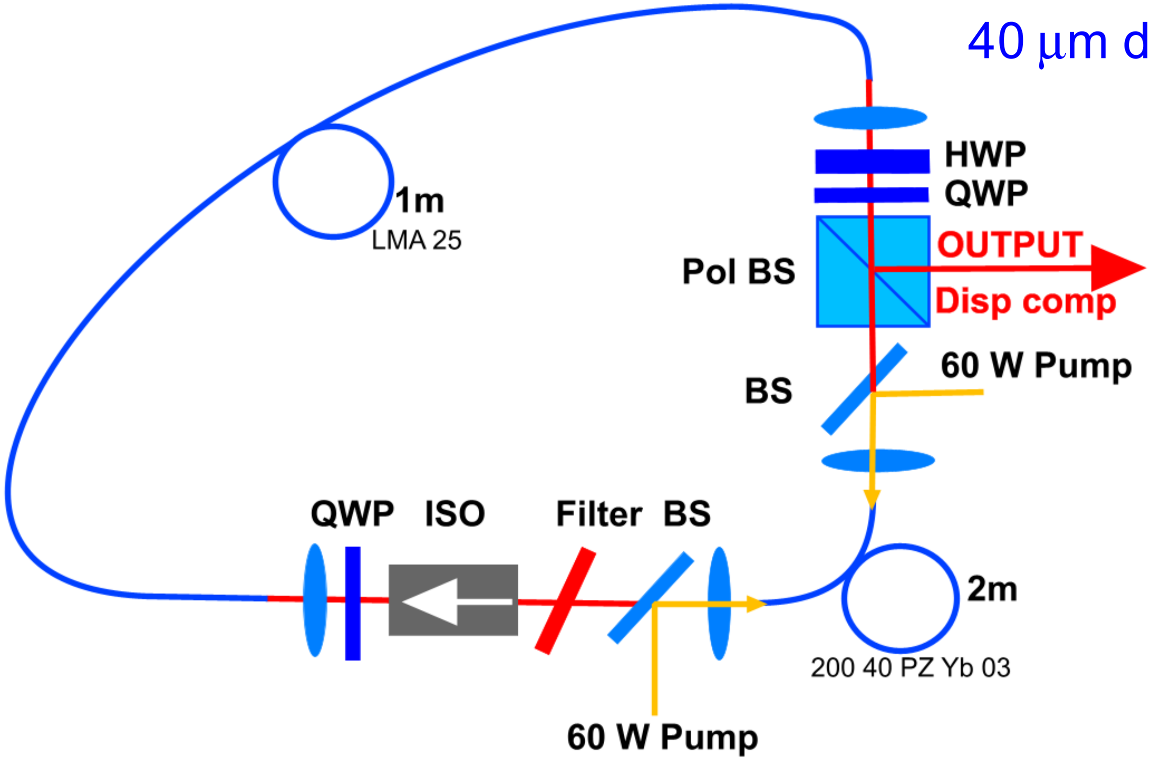

PD for pulse picking control electronics/interlock
Yb doped fibre
SESAM
PZF
ISO
AOM
To amplifier chain
CFBG
Tap
Pump out
Pump in
PM Yb amplifiers: SPM generation
Seed input
Interlock monitor
Bulk-grating compression stage
ISO
Compressed pulses 40 W
Residual pump
LMA double-clad Yb PCF: power amplifier
120 W 975 nm pump diode
Data
Sech² fit
τpulse = 400 fsec
AC intensity (A.U.)
Time (ps)
1.0
0.8
0.6
0.4
0.2
0.0
−2.0 −1.5 −1.0 −0.5 0.0 0.5 1.0 1.5 2.0

High Power Scaling - Oscillators

Amplifier	Yb-doped LMA PCF
Pump	120 W multi-mode
Efficiency	20 %

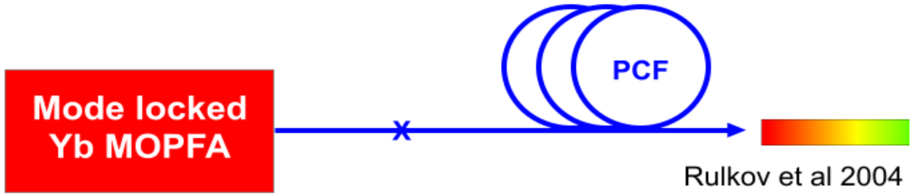



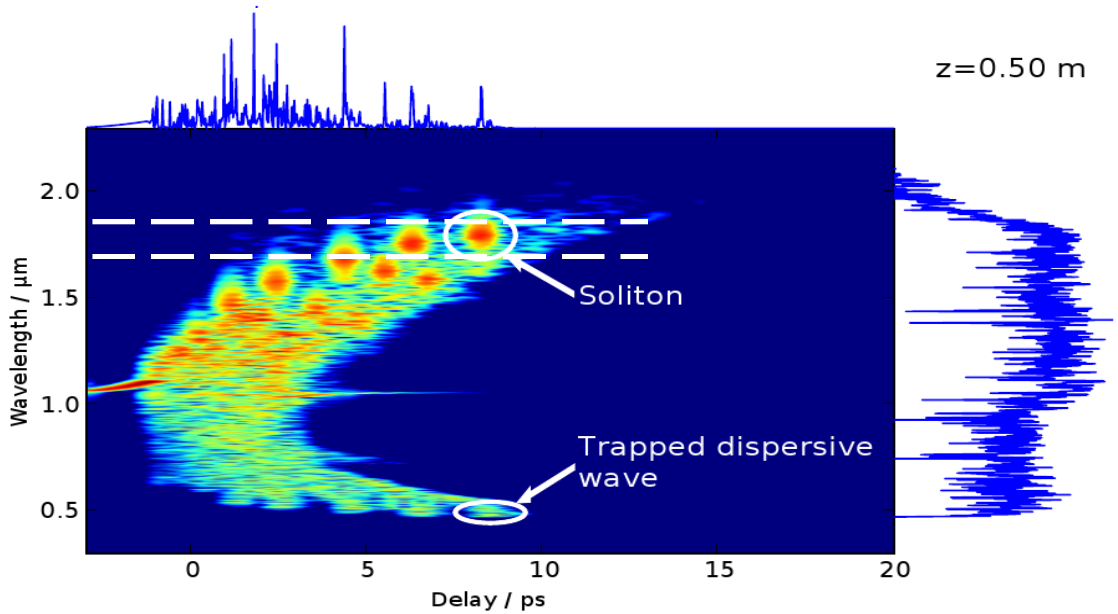
40 µm diameter, 200 µm inner cladding



Pulse duration	120 fs
Pulse energy	~ 0.5 µJ
Rep. rate	~ 50 MHz
Average power	30 W
Peak power	>4.5 MW

Supercontinua - picosecond pumping





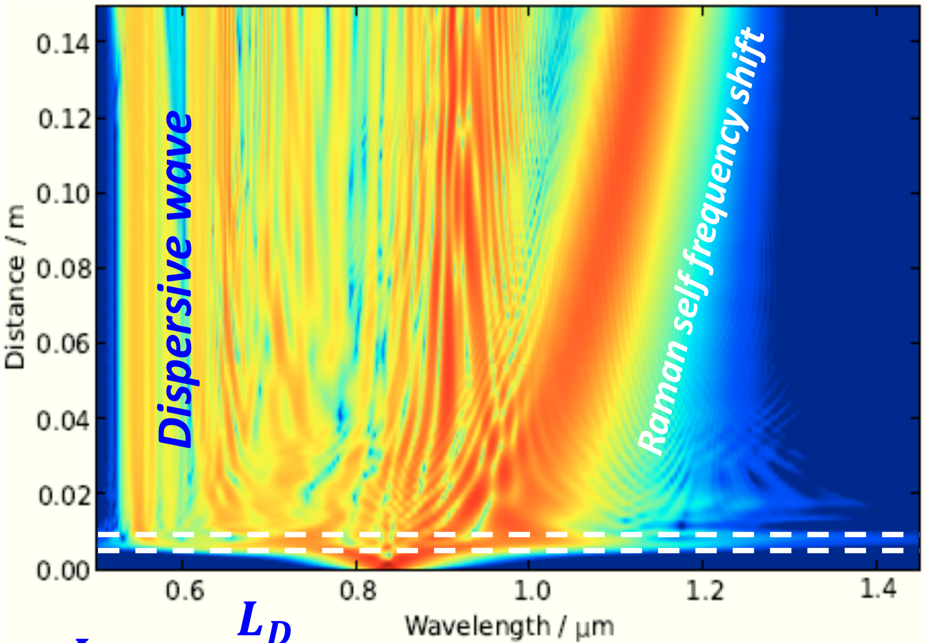
- **Identical dynamics for CW pumped systems - MI and noise**

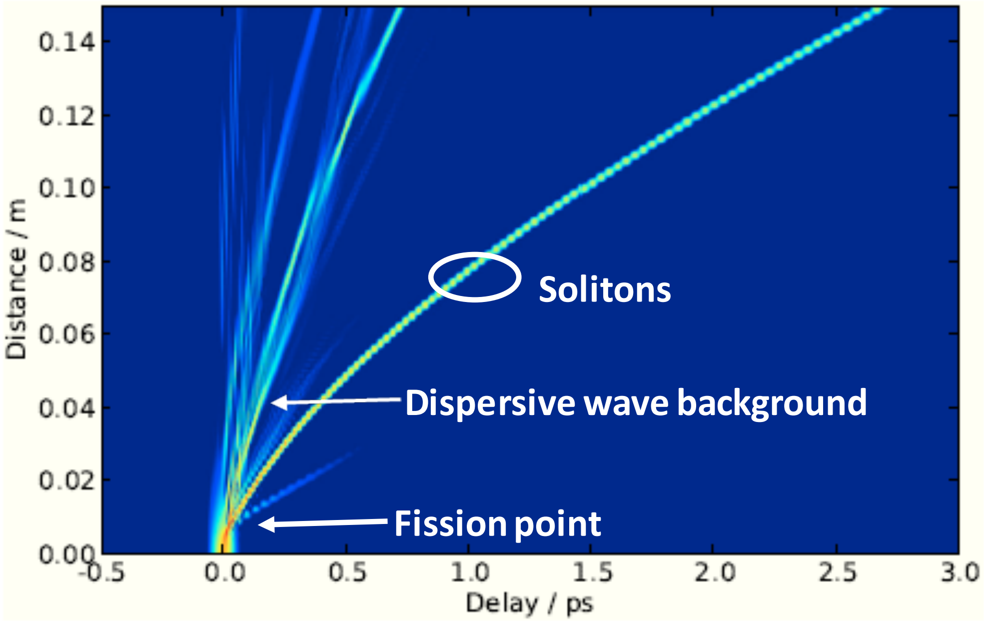
  100 mW/nm

Supercontinua - femtosecond pumping

Dominated by soliton dynamics

50 fs pulse , 830 nm, 10 kW peak power, N=9, 15 cm PCF





$$L_{fiss} = \frac{L_D}{N}$$

Alternatively – use normally dispersive fibre and SPM

- but still at fixed repetition rates
- relatively inefficient source of tunable radiation

Spectrally masked phase modulation

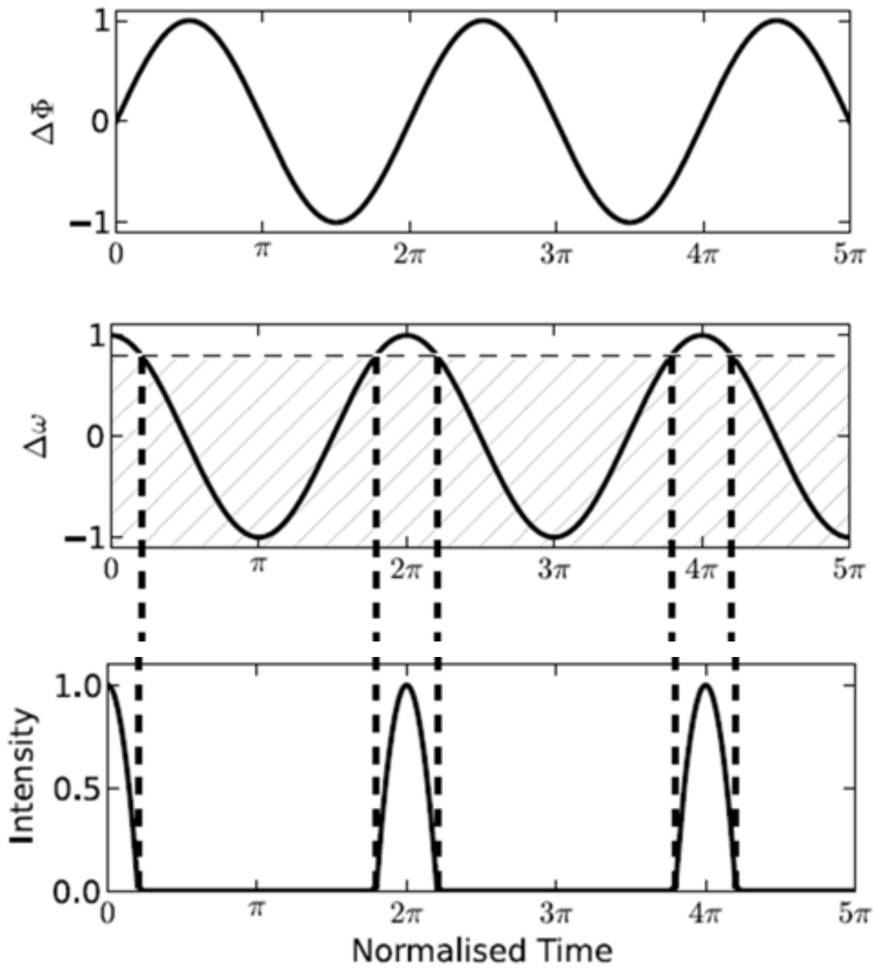
Mamyshev Opt Lett. 19, 2074 (1994)

Wavelength, repetition rate and pulsewidth versatility of seed source

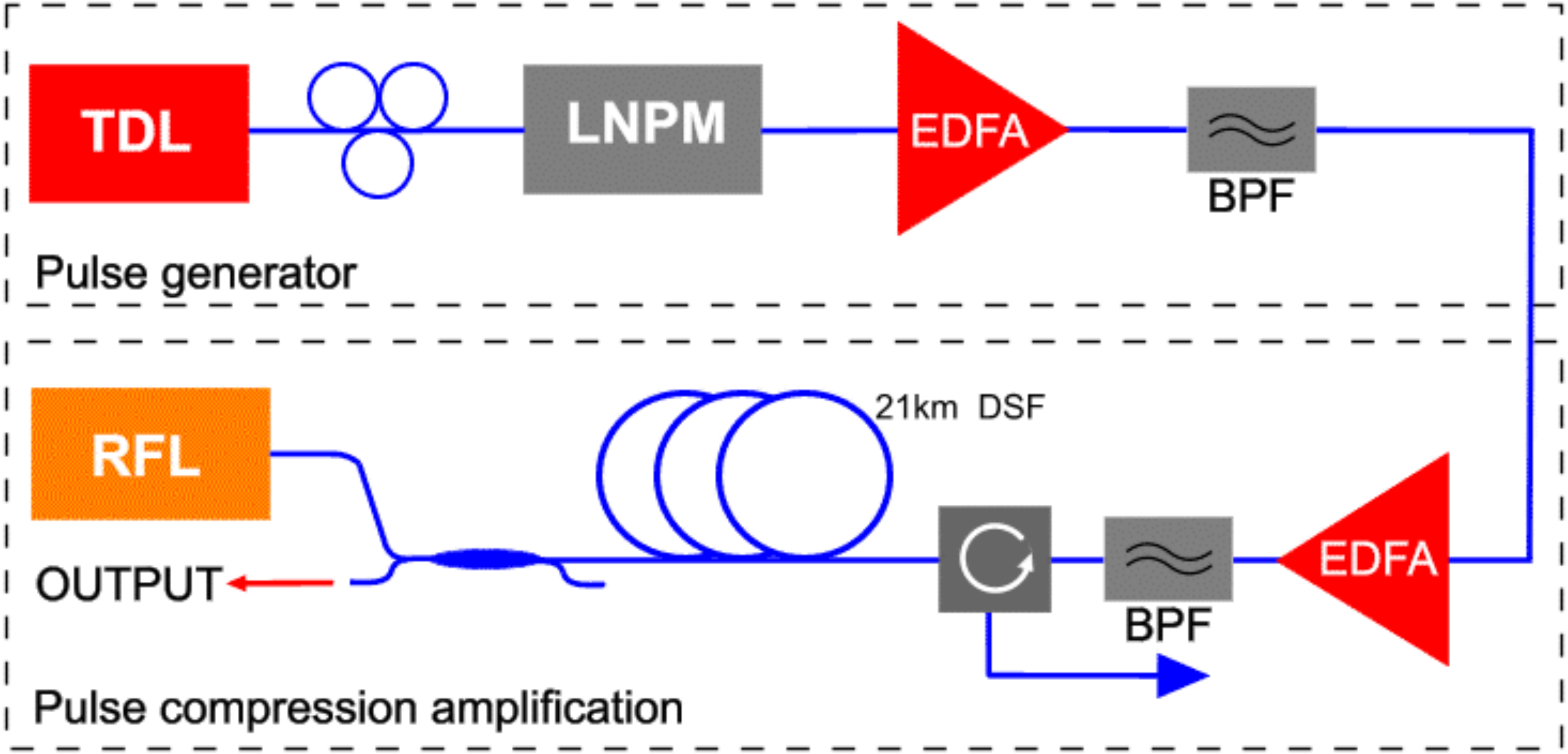
- Phase modulation gives rise to sinusoidal shift in optical frequency, amplitude dependent on applied voltage

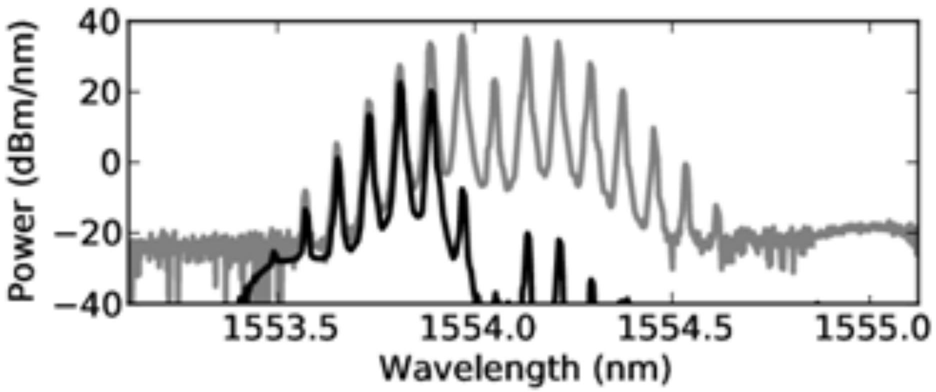
- Application of spectral mask (band pass filter) removes everything except frequency extreme

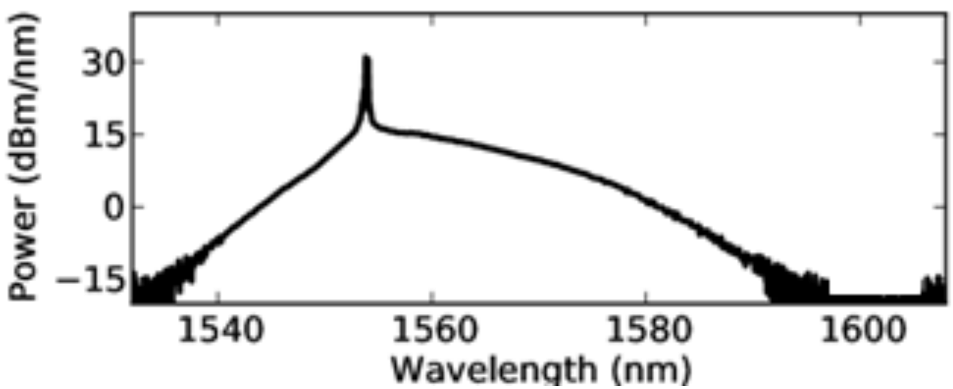
- Results in pulse train at the repetition rate of the modulation



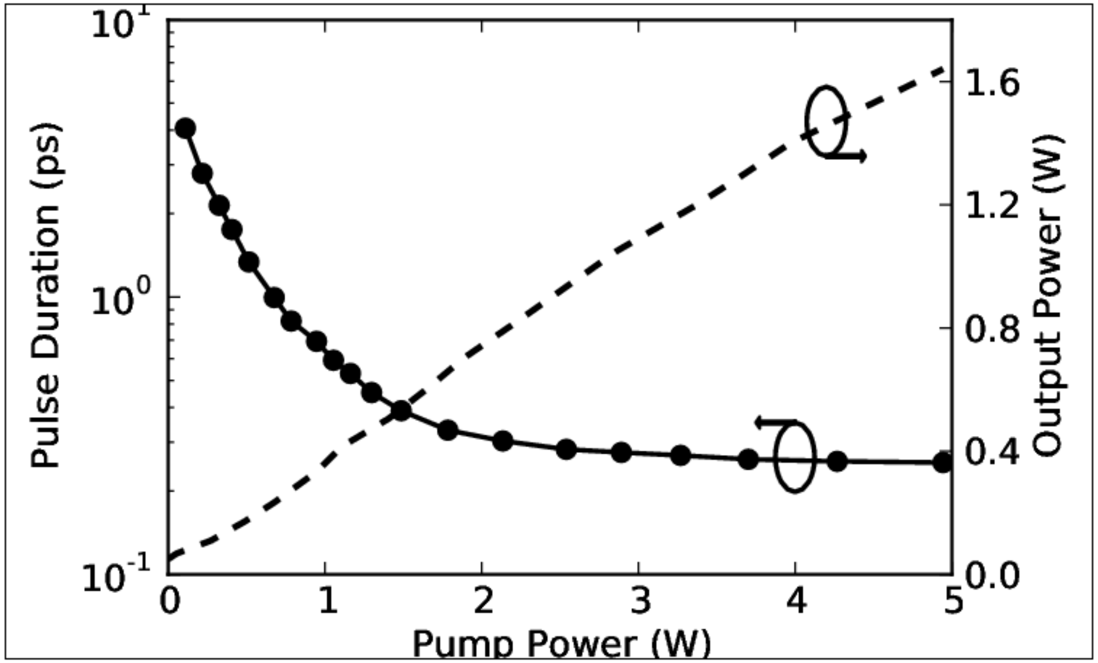
Selectable pulse width generation – Experimental



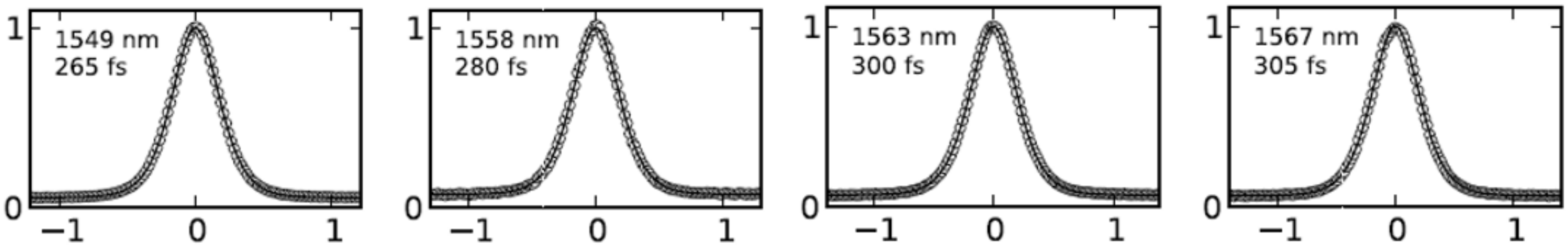




Pulse amplification and compression



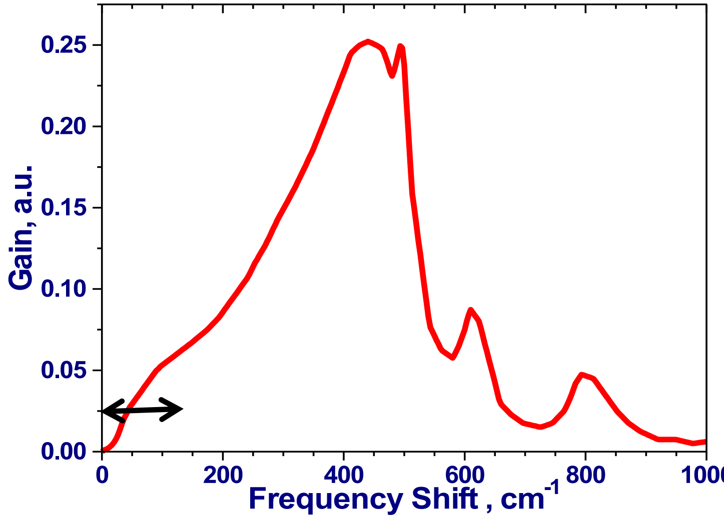
$$\tau_0 = \frac{2|\beta_2|}{\gamma E_s}$$

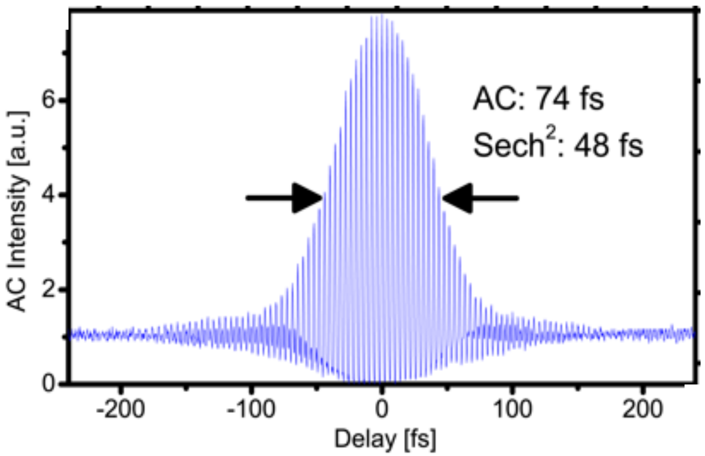


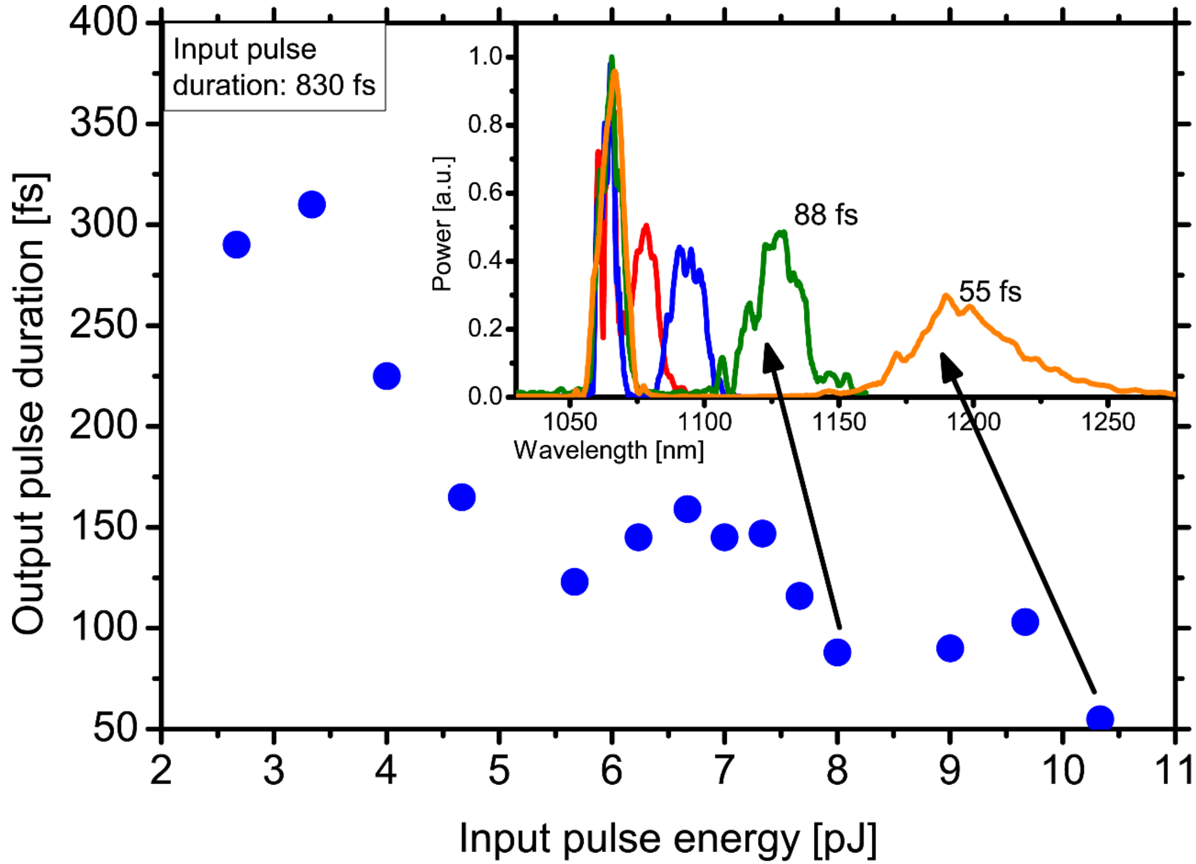
- Needs anomalous dispersion
- Pulse energy limited by soliton requirements
- Pulse duration range limited by soliton dynamics
- Greater flexibility – cw seed plus in-line amplitude modulator

Self Raman interaction (SSFS) in tapers

- **Dispersion: ~40 to ~10 ps/nm/km**
- **Loss: 25 dB/km @ 1.06 μm PCF**
- **Length: 40 m**

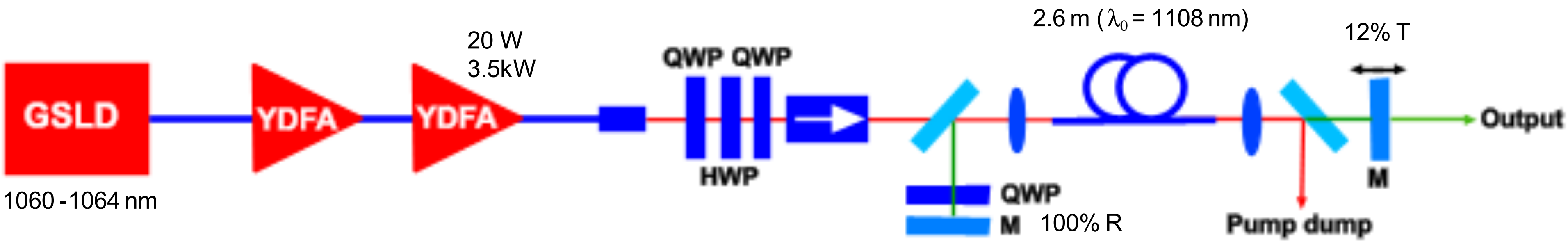


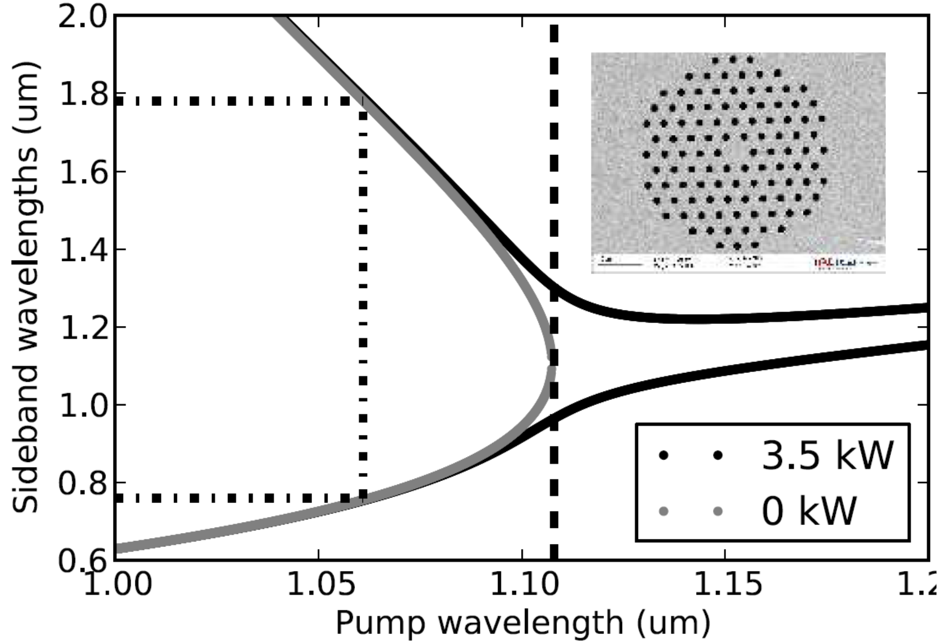


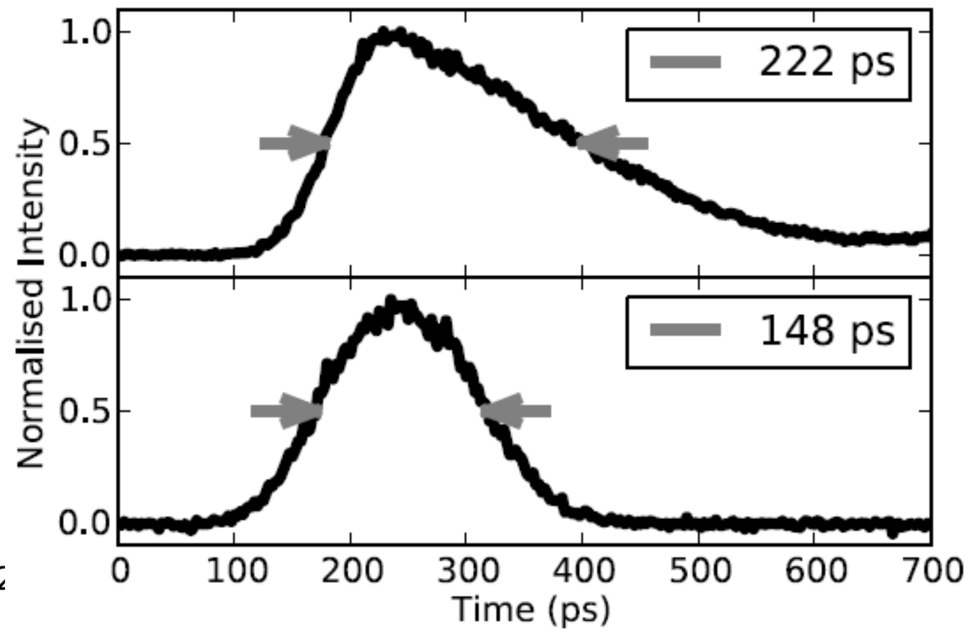


PCF Optical Parametric Oscillators

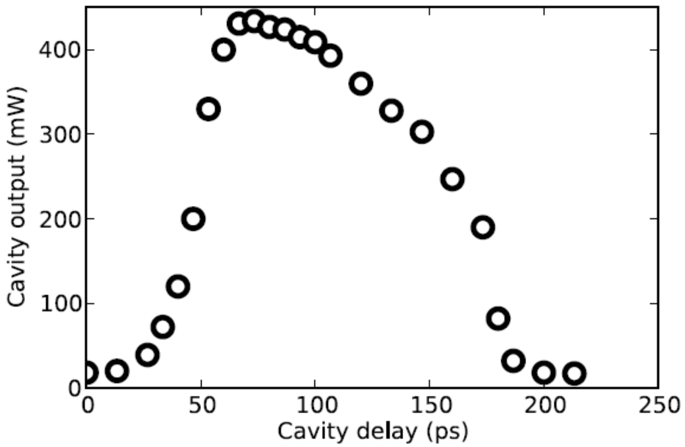
Advantages :- Lower thresholds
Tunable outputs

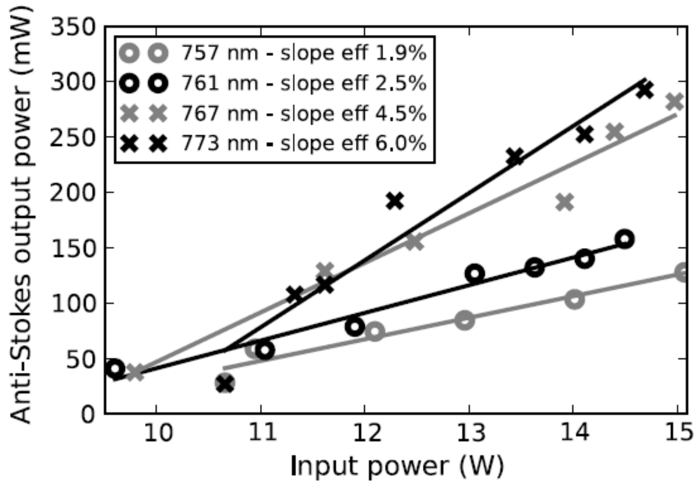


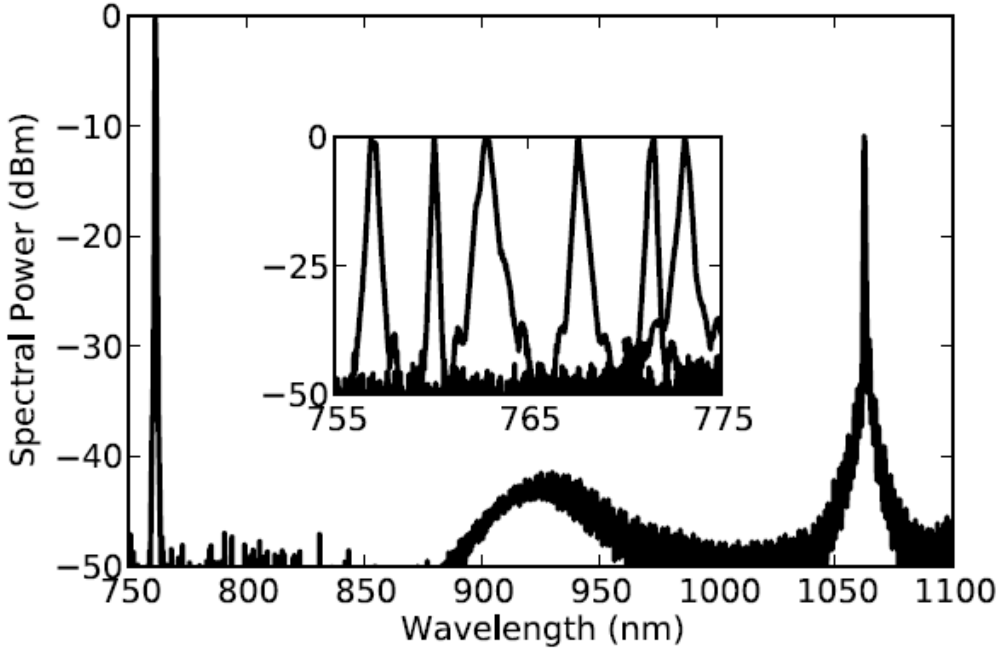




Synchronously pumped PCF OPO

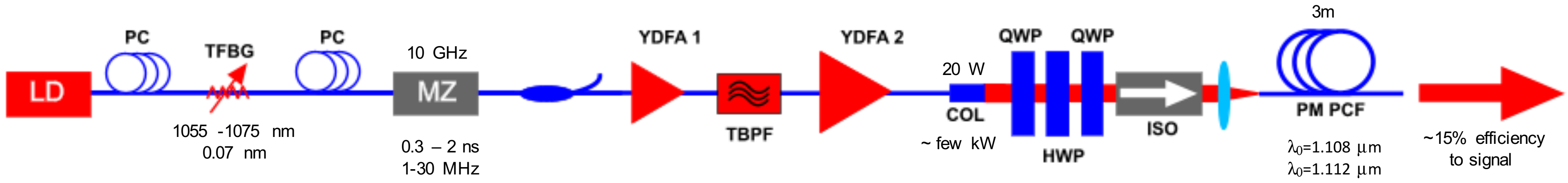


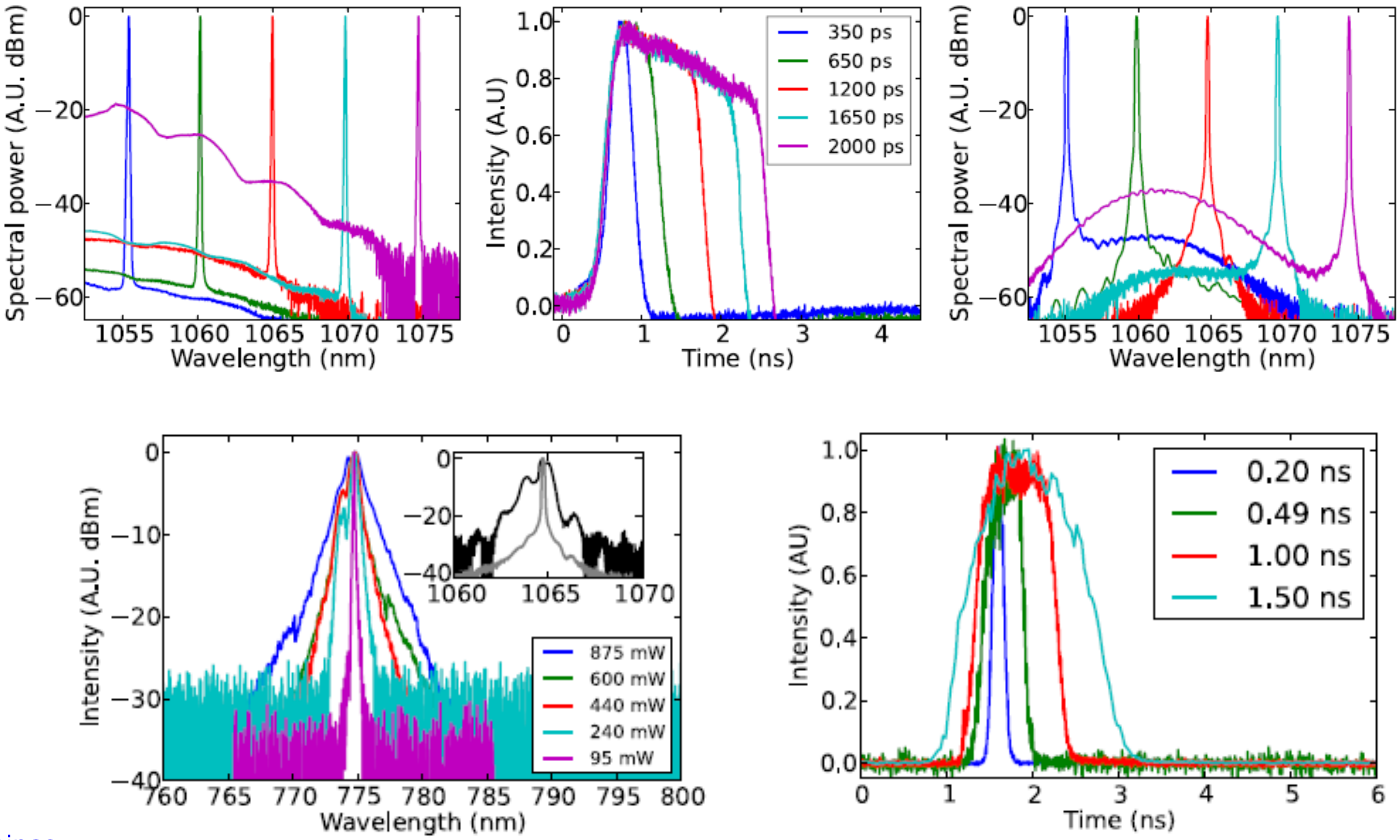




Problem - cavity synchronisation
variation of repetition rate

Single Pass Optical Parametric Generation

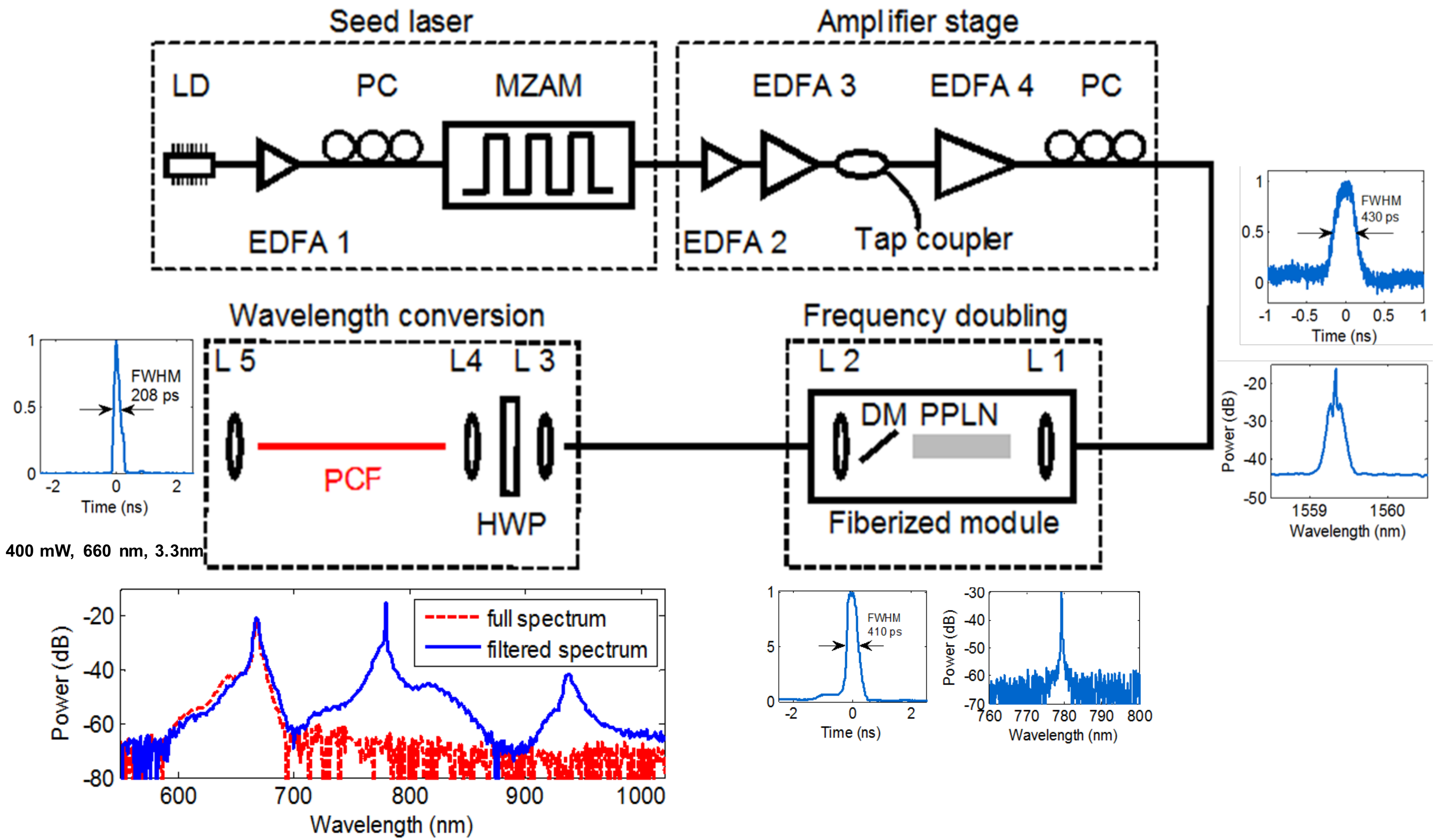




Imperial College London

Visible optical parametric generation

FOG femtosecond optics group



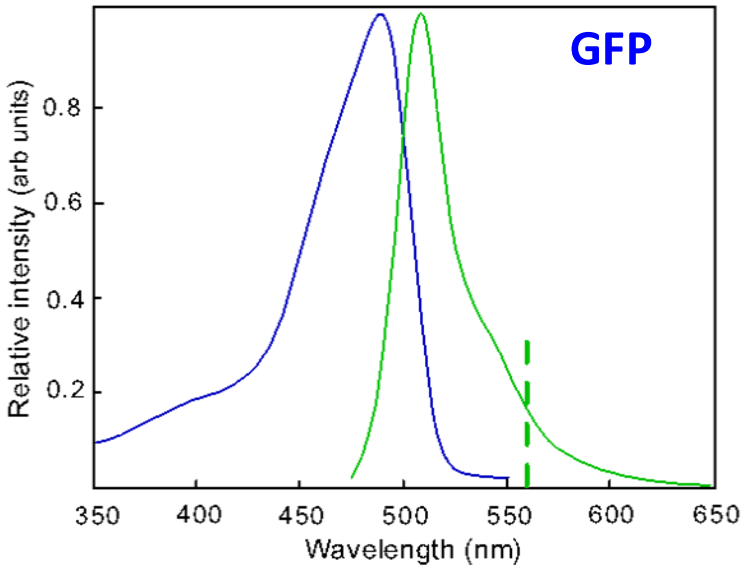
Problems : Power scaling, shorter wavelength operation, dispersion control, small core

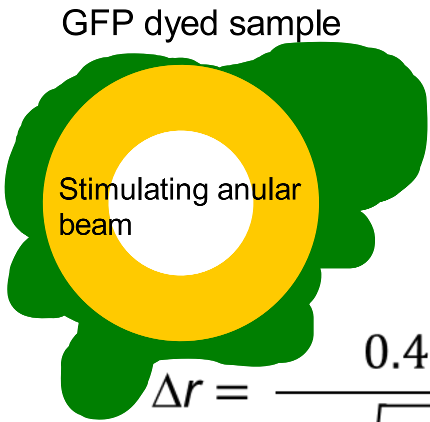
Visible sources for Microscopy

Vast array of fluorophores used as labels in differing imaging techniques such as PALM, STORM, STED, RESOLFT

Eg. STED – excitation/dexcitation requirements 405 nm - 750 nm

- Green fluorescent protein (GFP) can be introduced and expressed in many biological samples
- Non-phototoxic allows in-vivo intrinsic labelling of cells
- Emission peak at 510 nm, suitable for depletion at 560 nm
- Increasing the peak power increases the resolution improvement





$$\Delta r = \frac{0.44\,\lambda}{NA\sqrt{1+\frac{I_{STED}}{I_{SAT}}}}$$

Ideal source for GFP STED application

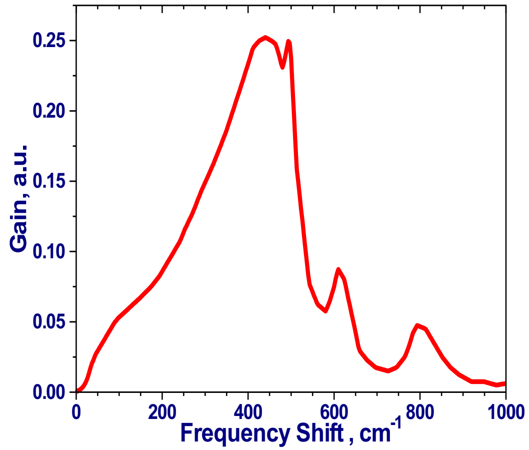
- Central wavelength around 560 nm
- High pulse energy for good resolution ~ 35 pJ
- ‘Enough’ average power
- 0.1-2 ns pulse duration
- Low MHz repetition rate
- Diffraction limited beam quality
- Polarised
- Compact, efficient and turn-key

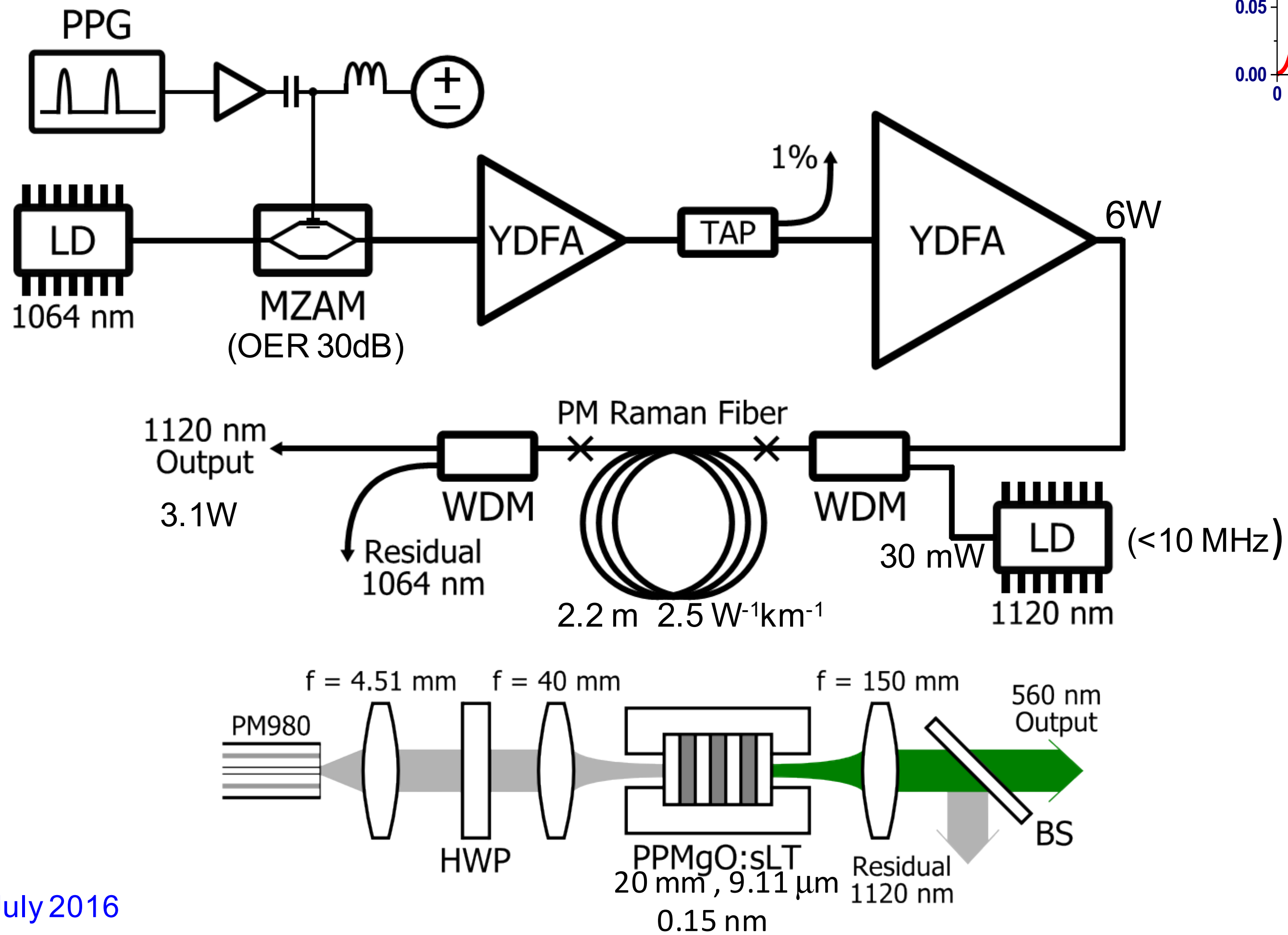
Fibre laser pumped supercontinuum

- Compact
- 9 mW/nm 560 nm(10 nm, 90 mW, 80 MHz ~ 1 nJ)
- 1% optical efficiency from 20 W pump
- ~10s ps fixed duration (structure?)

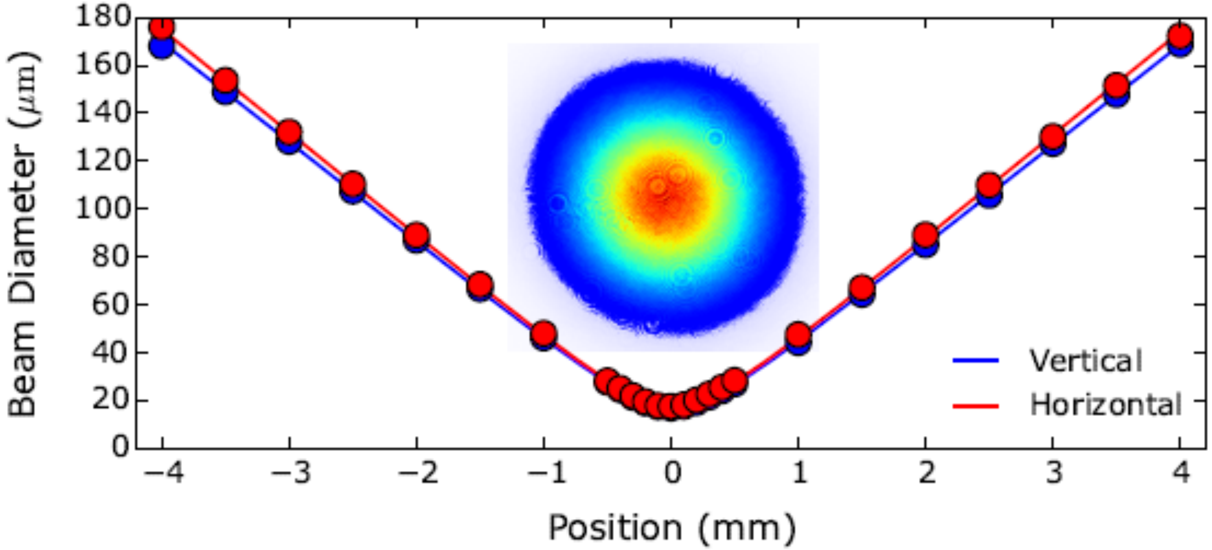
Raman based pulse sources

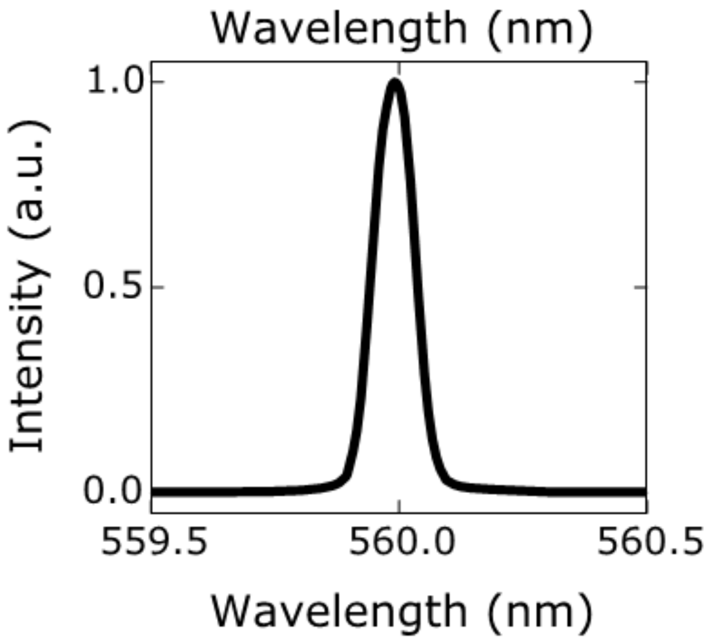
- Pulses generated and amplified at 1064 nm
- Raman amplifier shifts to 1120 nm
- Frequency doubled to 560 nm

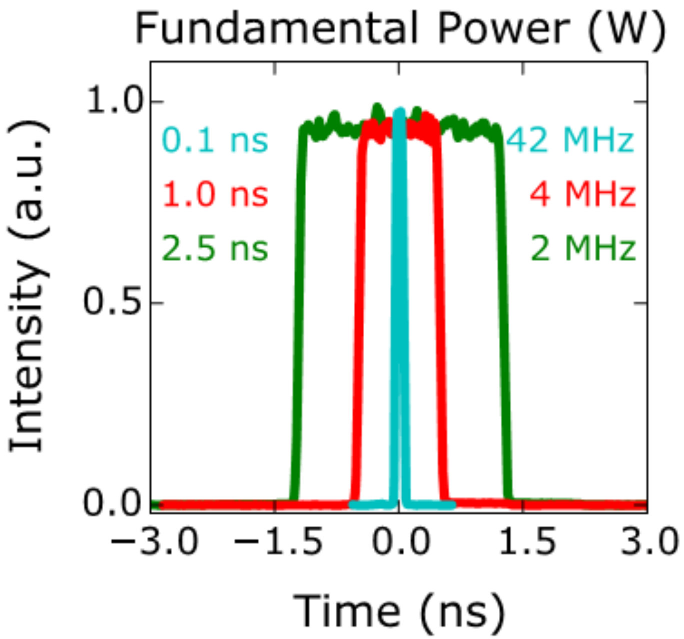




560 nm source characteristics

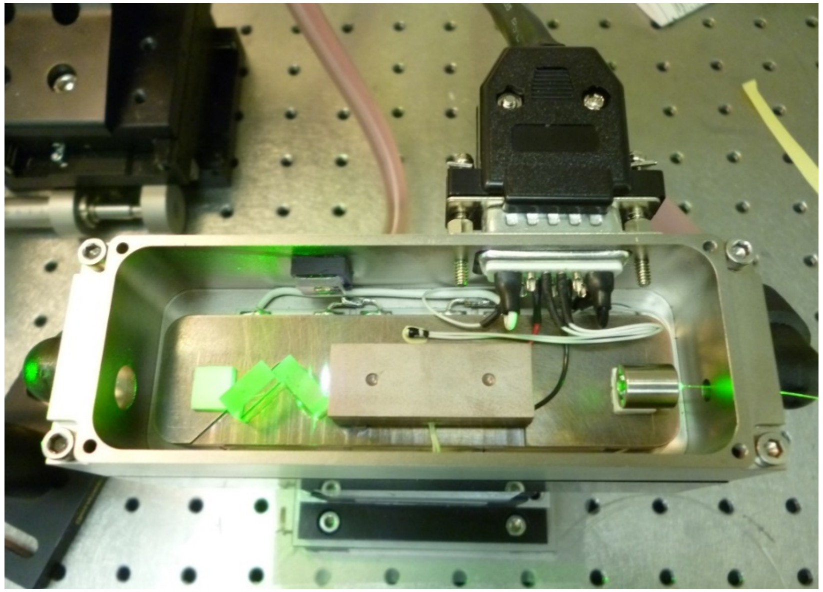




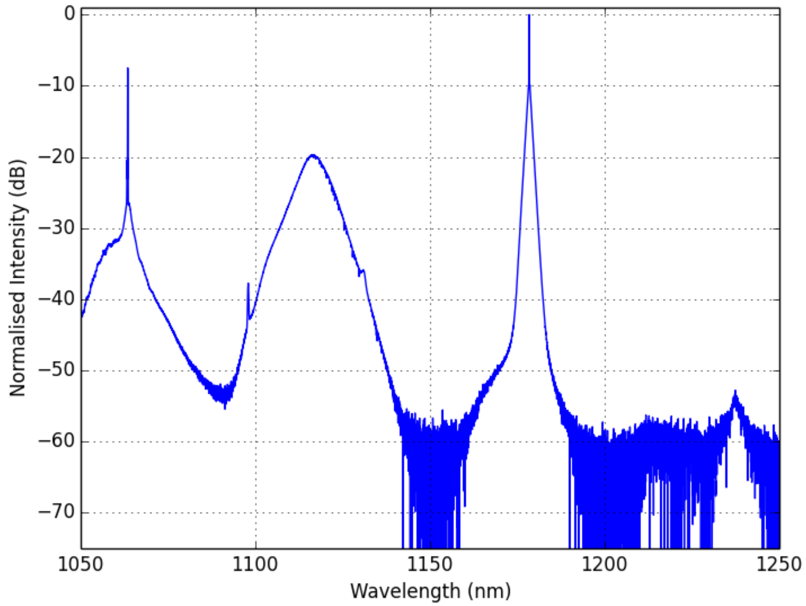


Improvements and developments

- Single aspheric to focus fibre input to 65 μm waist
- Optics bonded to TEC controlled base plate
- Up to 2 W of 560 nm generated with 50% efficiency
- Gooch and Housego

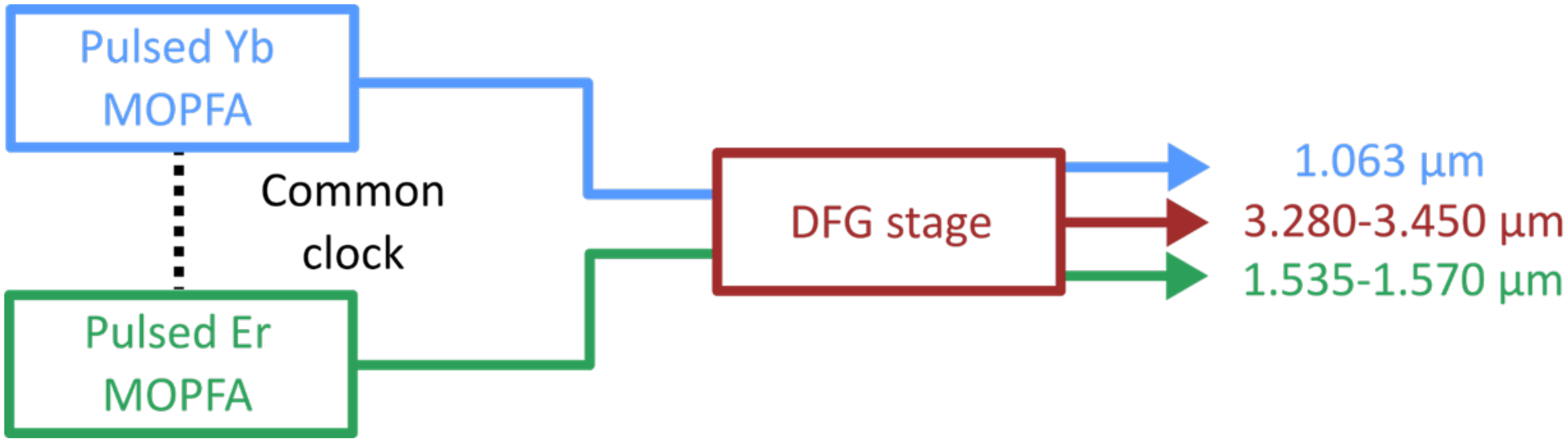


- Raman gain ~ 30 nm at 1 μm
- Pumps are tunable
- Cascade
- SHG of Yb, Er + Raman 488-900 nm
- SFG 325-490 nm
- Above 2 μm ?



Mid-infra red sources

- Rare earth doped fluoride fibre lasers
- Quantum cascade lasers
- OPOs – but cavity configuration, alignment, fixed repetition rates…
- DFG – offers a simple single pass solution, both cw and pulsed but lower efficiency , higher thresholds

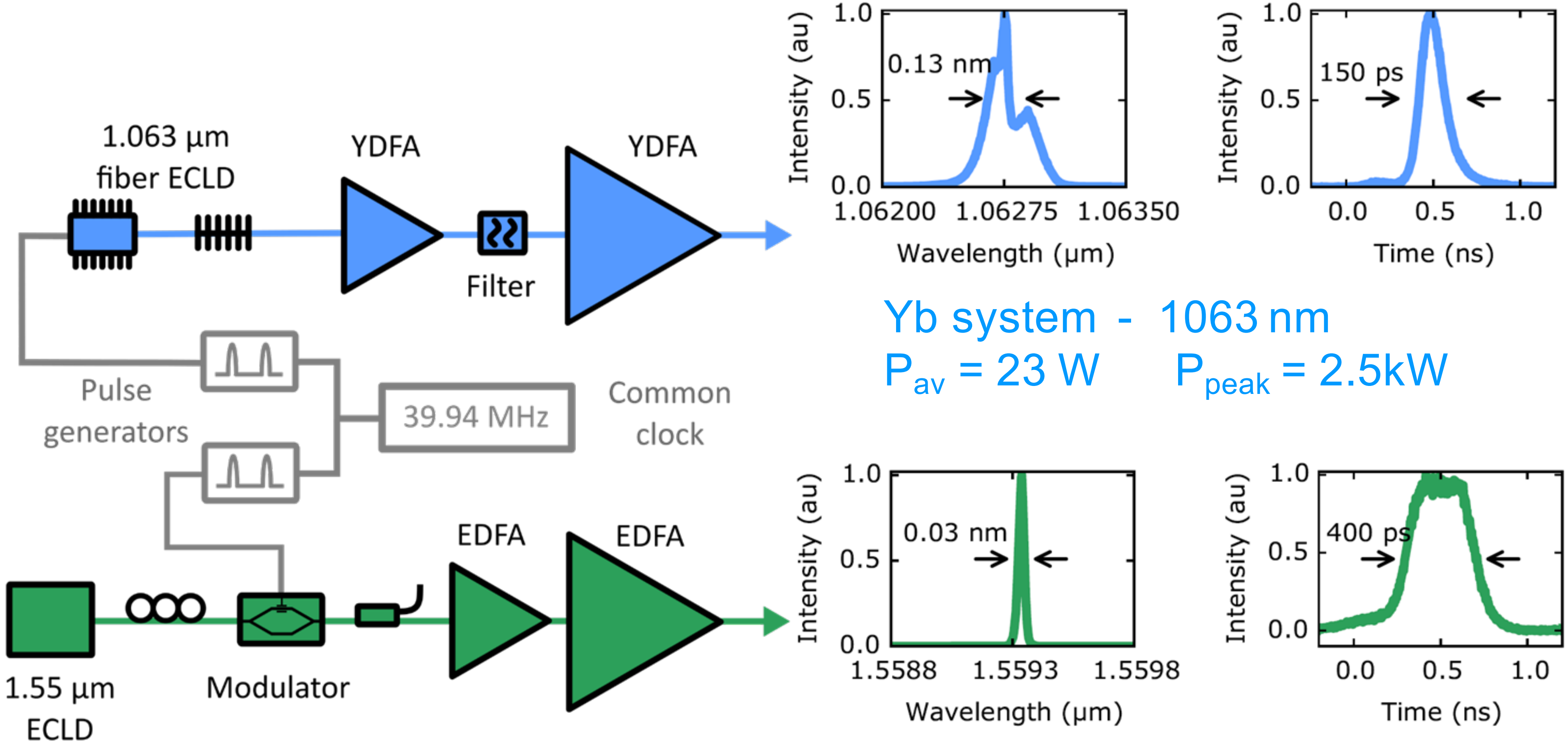


Advantages of DFG with pulsed seeding rather than cw

- Lower peak pump power requirement
- High pump conversion possible
- Temporal tuning of pulses by time slip of pump and seed

but greater system complexity

DFG - Pump and Signal MOPFAs



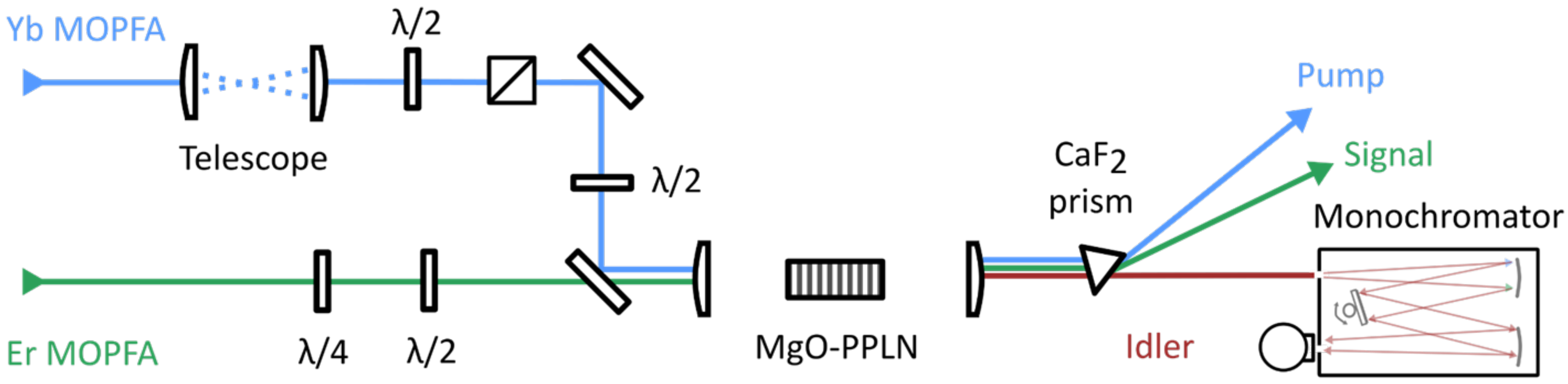
Yb system - 1063 nm

P_{av} = 23 W P_{peak} = 2.5kW

Er system - 1535 – 1570 nm

P_{av} = 2.1W P_{peak} = 0.1kW

DFG in PPLN



Match spot sizes in crystal ($1/e^2$ = 150 μm)

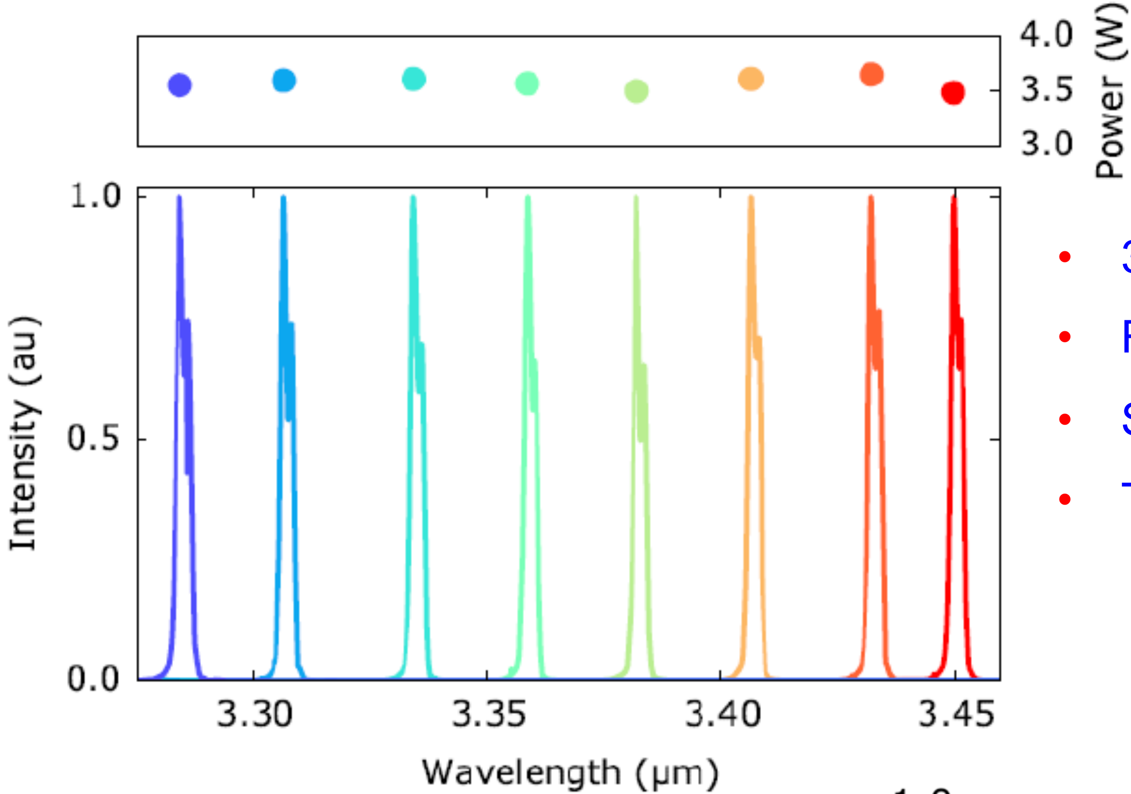
40 x 10 x 1 mm MgO-doped PPLN (Covesion UK)

Max pump intensity 28 MW/cm^2

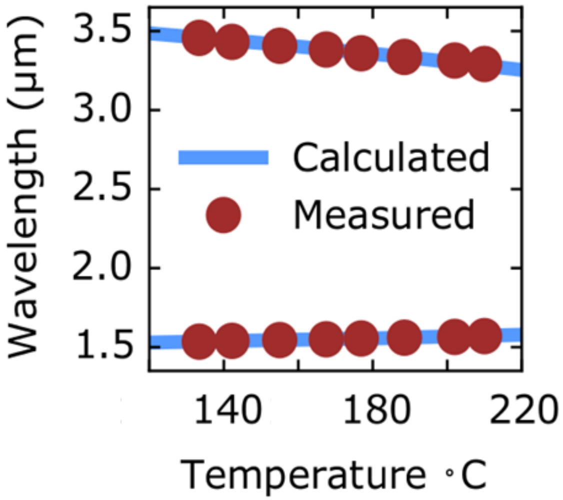
Typical damage thresholds ≈ 0.1-1 GW/cm^2

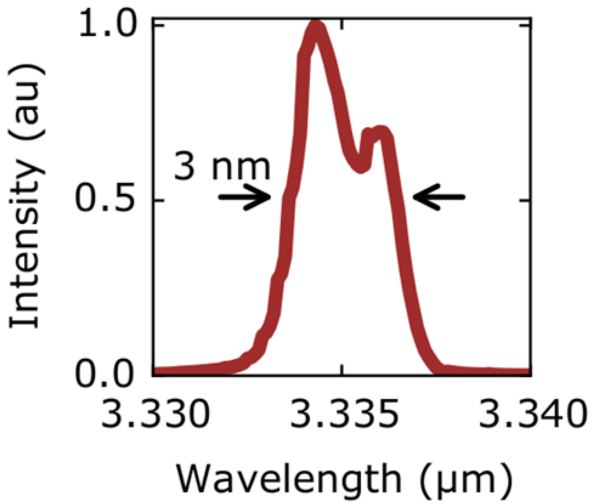
Grating period Λ = 29.98 μm

Tunable mid-IR generation through DFG

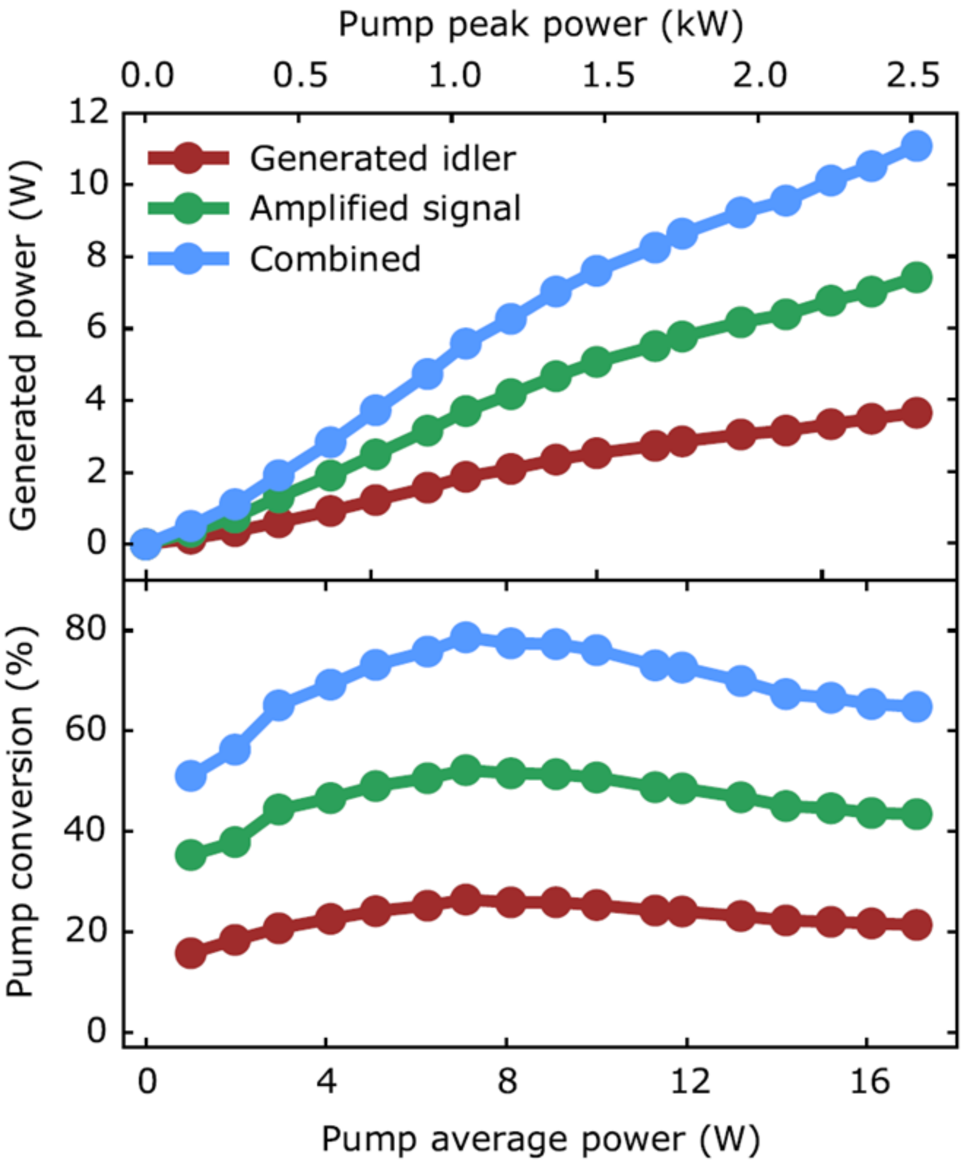


- 3.28 – 3.45 μm
- Restricted by Er (signal) gain band
- Signal 1535 – 1570 nm
- Temperature 130-210 ^{0}C



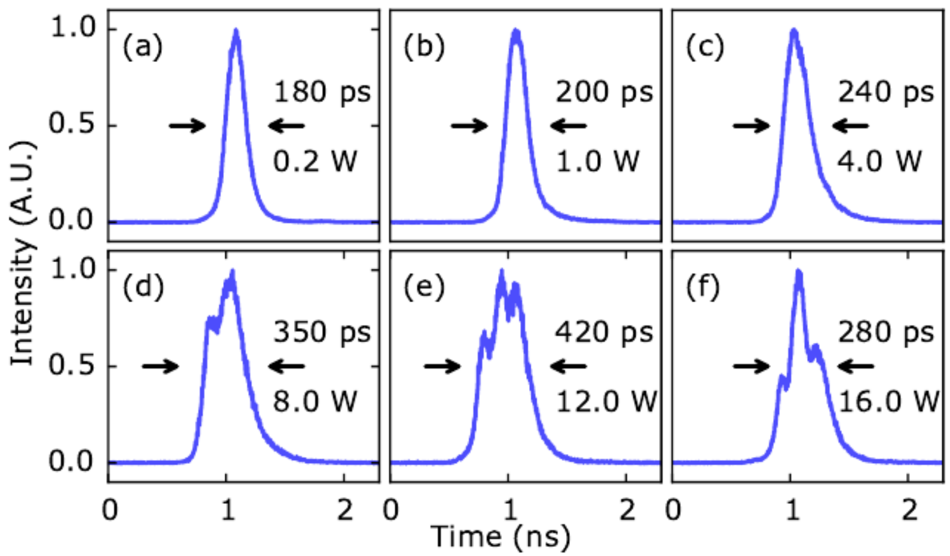


DFG conversion efficiency



Conversion roll off ?

- Thermal effects
  no distortion pump alone
- Photorefractive effects/nonlinear
  green induced absorption
- Back conversion



Wavelength extension with DFG

Tm (2.0 μm) - Er (1.5 μm) = 6.8 μm

Yb (1.06 μm) –Yb:Raman (1.24 μm)= 7.5 μm

Yb (1.06 μm) - Yb:Raman (1.3 μm) = 5.7 μm

Yb (1.06 μm) -Yb:Raman (1.4 μm) = 4.4 μm