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FOG femtosecond optics group

Versatile, all-fibre based sources

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Acknowledgements

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Organizers for invitation

The Group:

Sergei Popov
Ed Kelleher
Ben Chapman
Carlos Schmidt-Castellani
Meng Zhang
Robbie Murray
Tim Runcorn

Research support IPG Photonics

Outline

- Introduction
- All-fibre based systems
- Supercontinuum source for versatility ?
- Pulsewidth and repetition rate versatility
- Wavelength versatility via OPOs
- A universal short pulse source

Introduction

- Wavelength

Supercontinuum – 300 nm – 2300 nm psec/fsec pumping
Need ? - 20 mW /nm - implies 40W average power in continuum
- Direct generation with limited wavelength tunability – power scaling

- Repetition Rate

In supercontinuum, inherent jitter
Mode locked laser – fixed typical ranges 10MHz- 10GHz
- Employ direct modulation techniques and MOPFA configurations

- Pulsewidth

Supercontinuum pumped psec – dispersion and nonlinearity lead to a range of pulsewidths throughout the spectrum and jitter
- Compression techniques – selectable durations 20psec -100 fsec

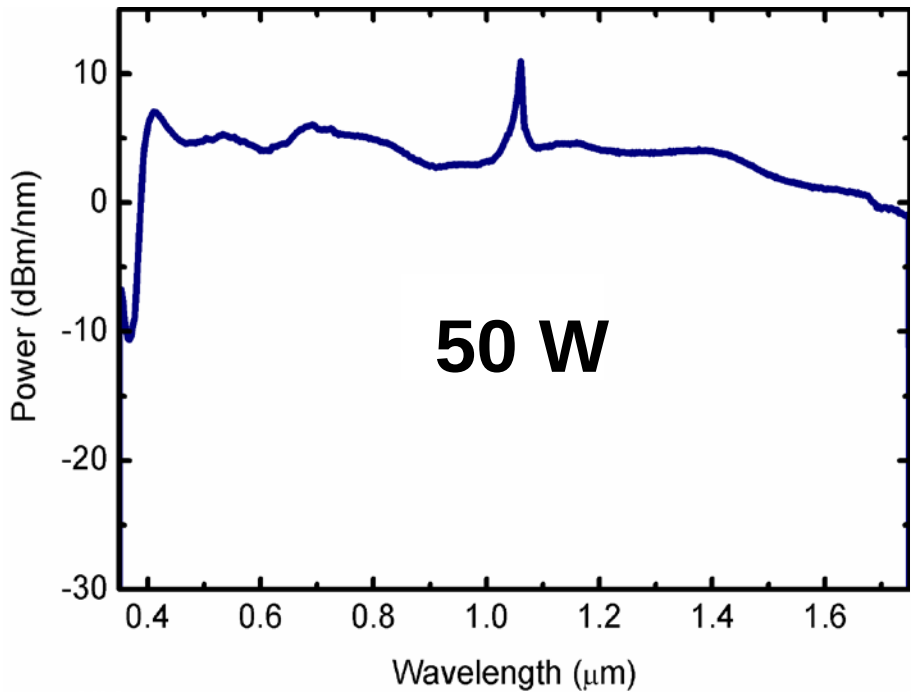
High Average Power Supercontinua

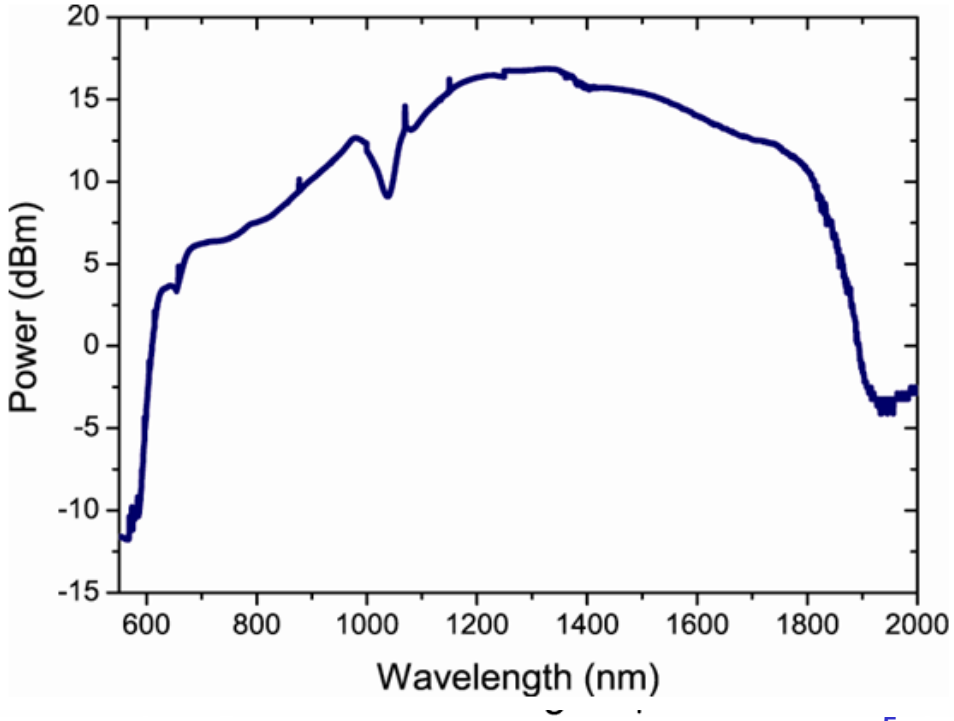
Average power in supercontinua 50W

Pumped by 100W average power picosecond Yb MOPFA

300W average power CW Yb fibre laser

In cw case spectral power density up to **100mW/nm**





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Picosecond pumped supercontinuum

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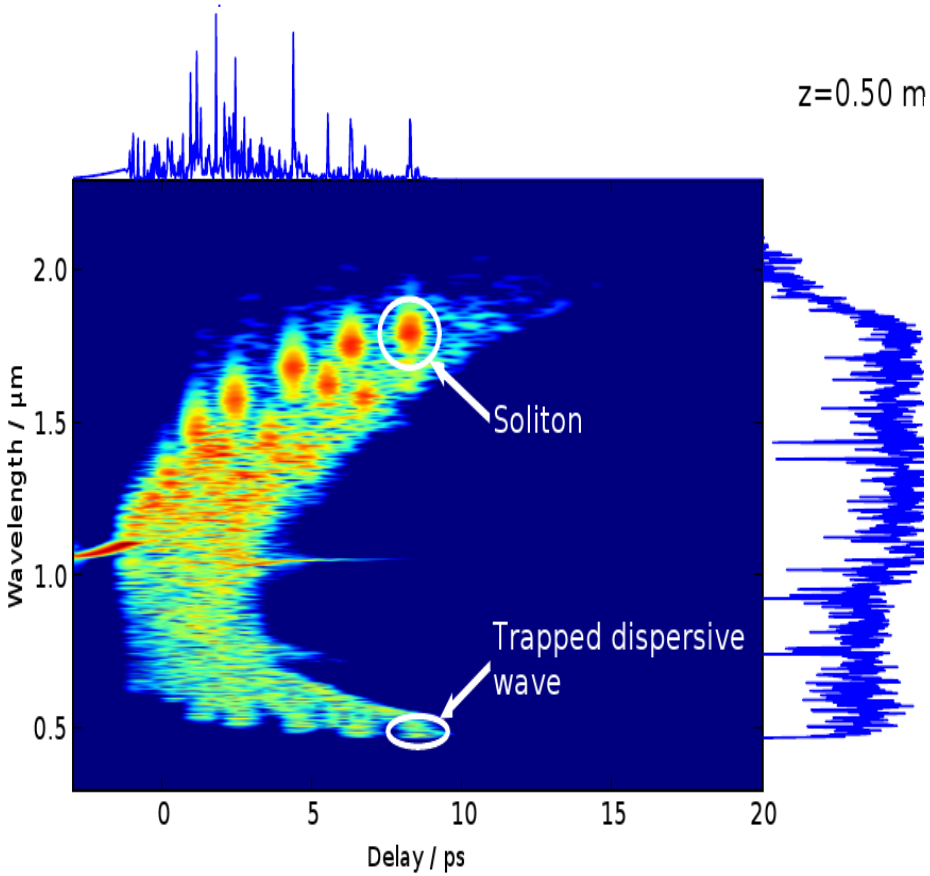
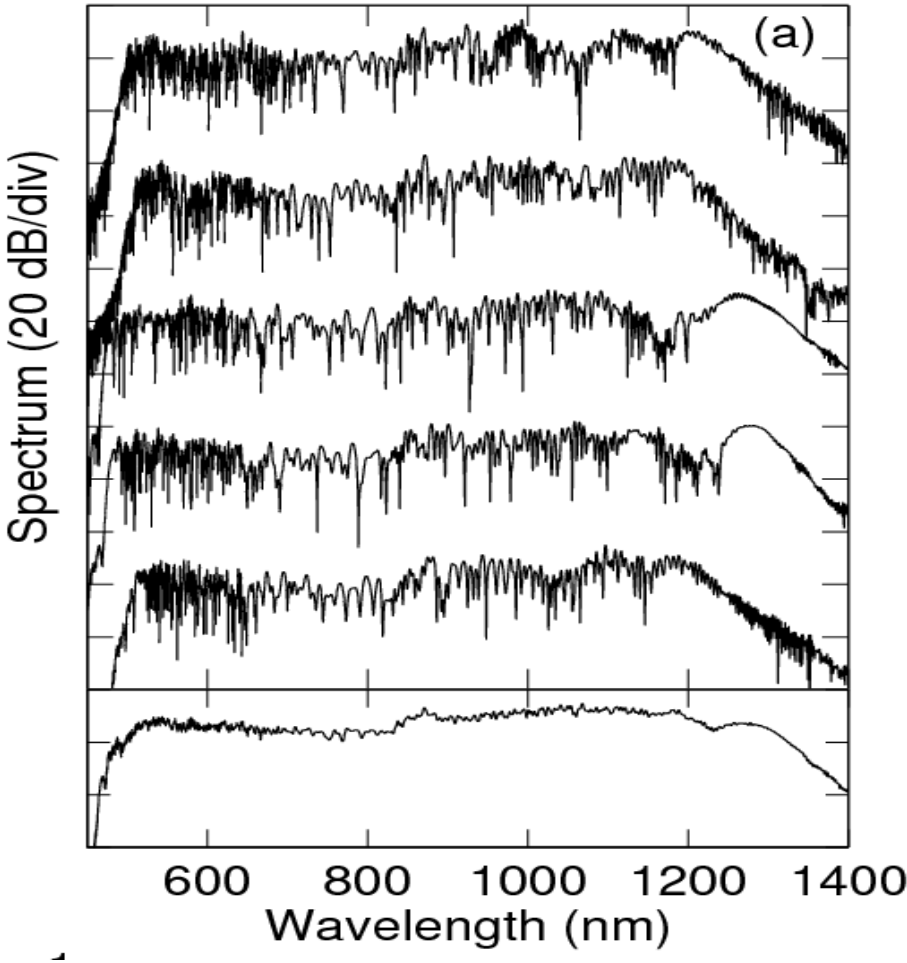
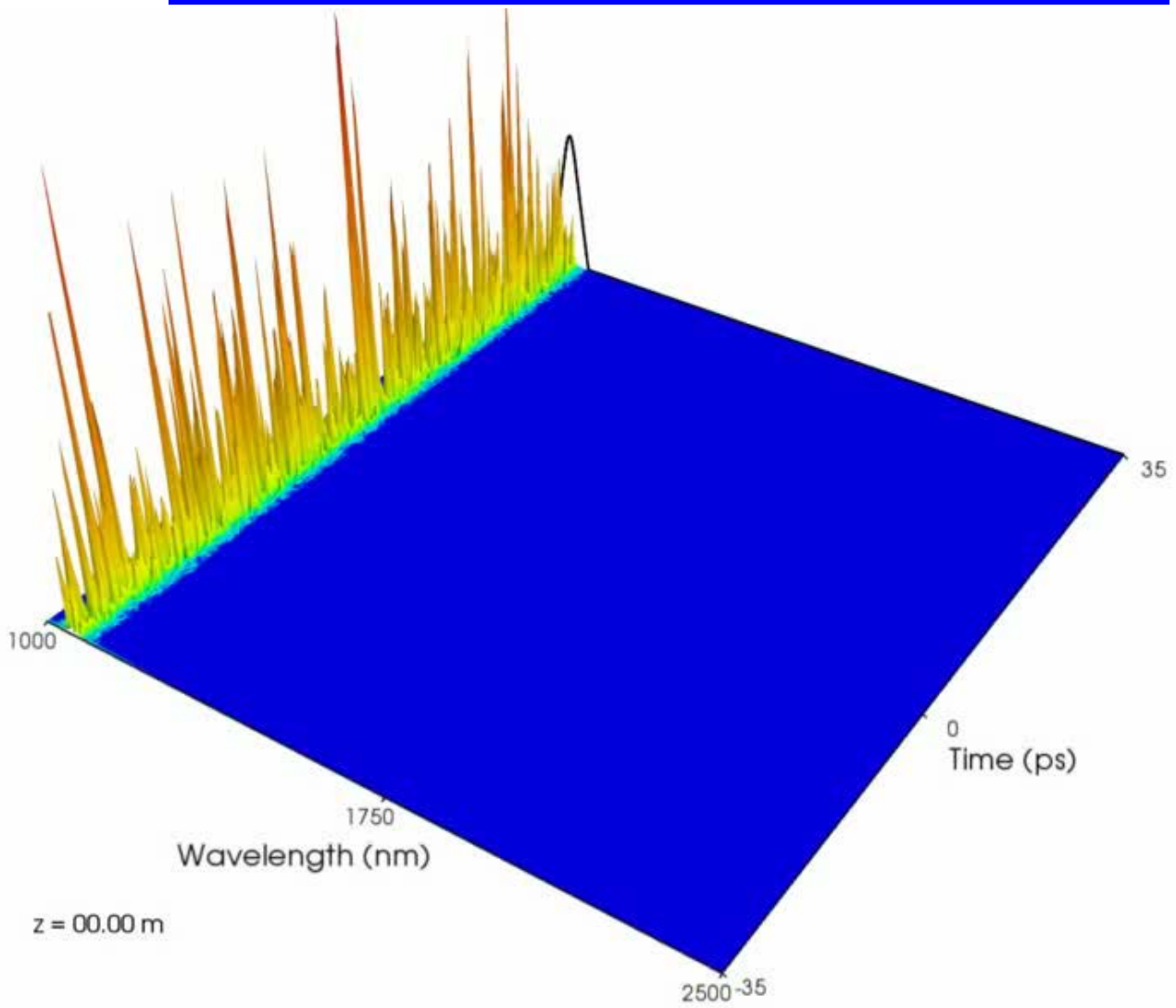
Initiated via modulational instability ~10kW pump

Noise driven – temporal jitter – shot to shot instability

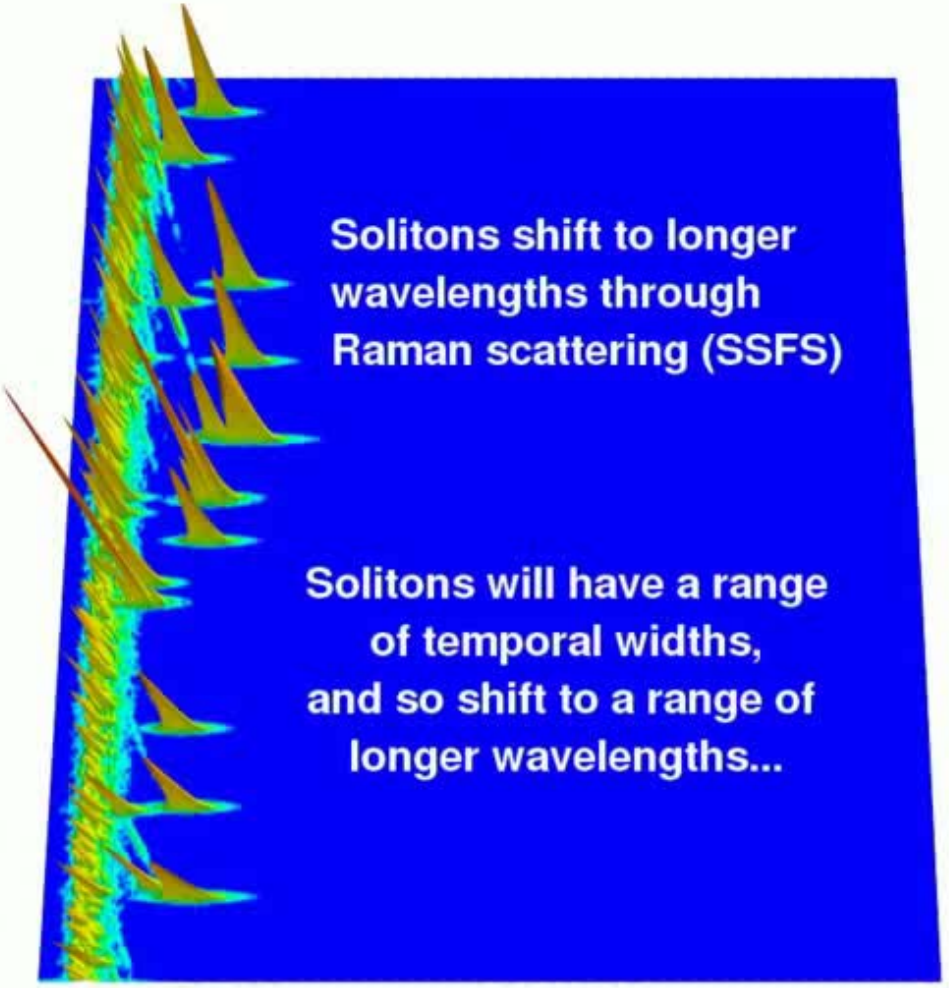




Supercontinuum Development



Supercontinuum Development



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Supercontinuum Development

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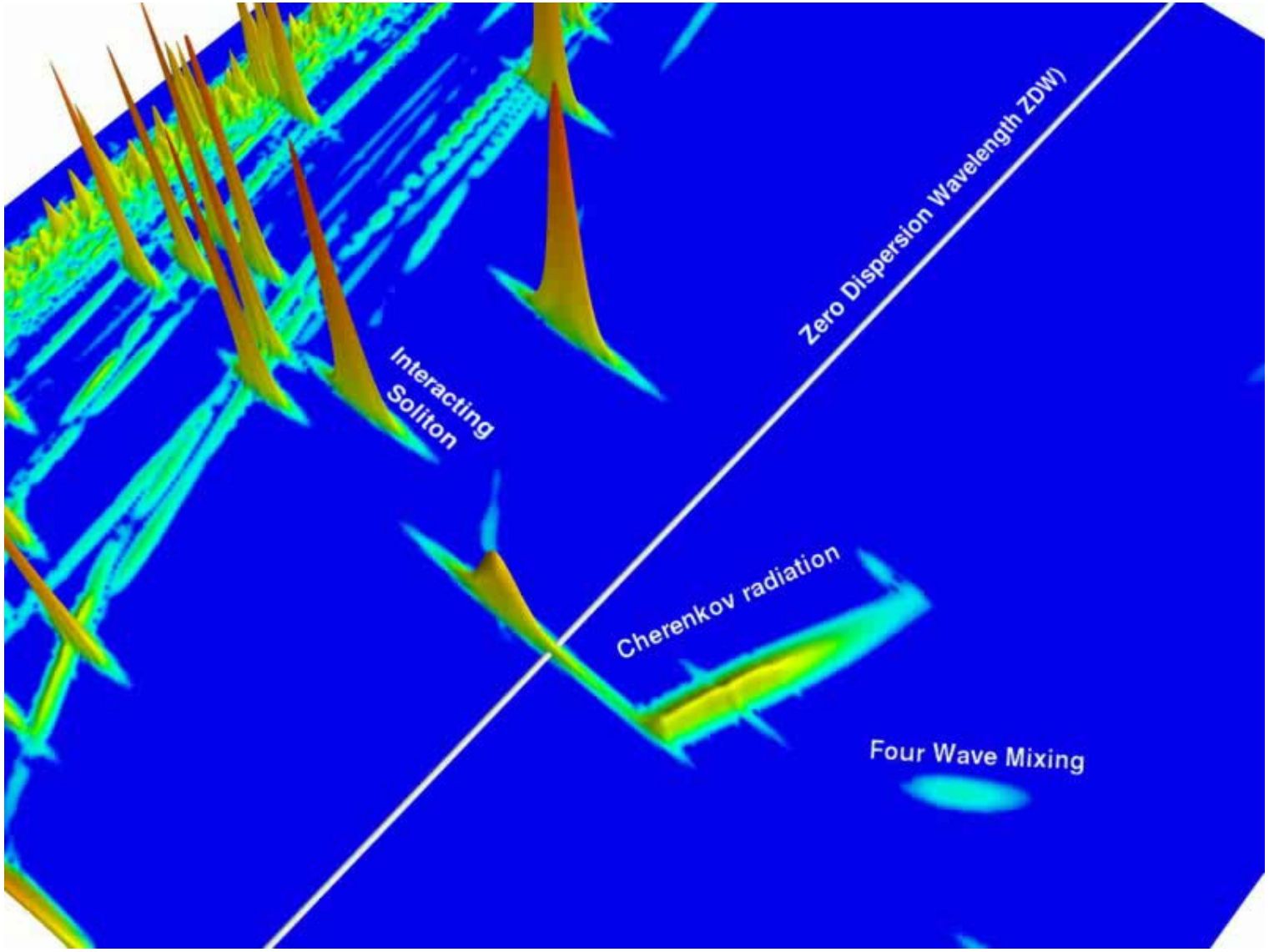
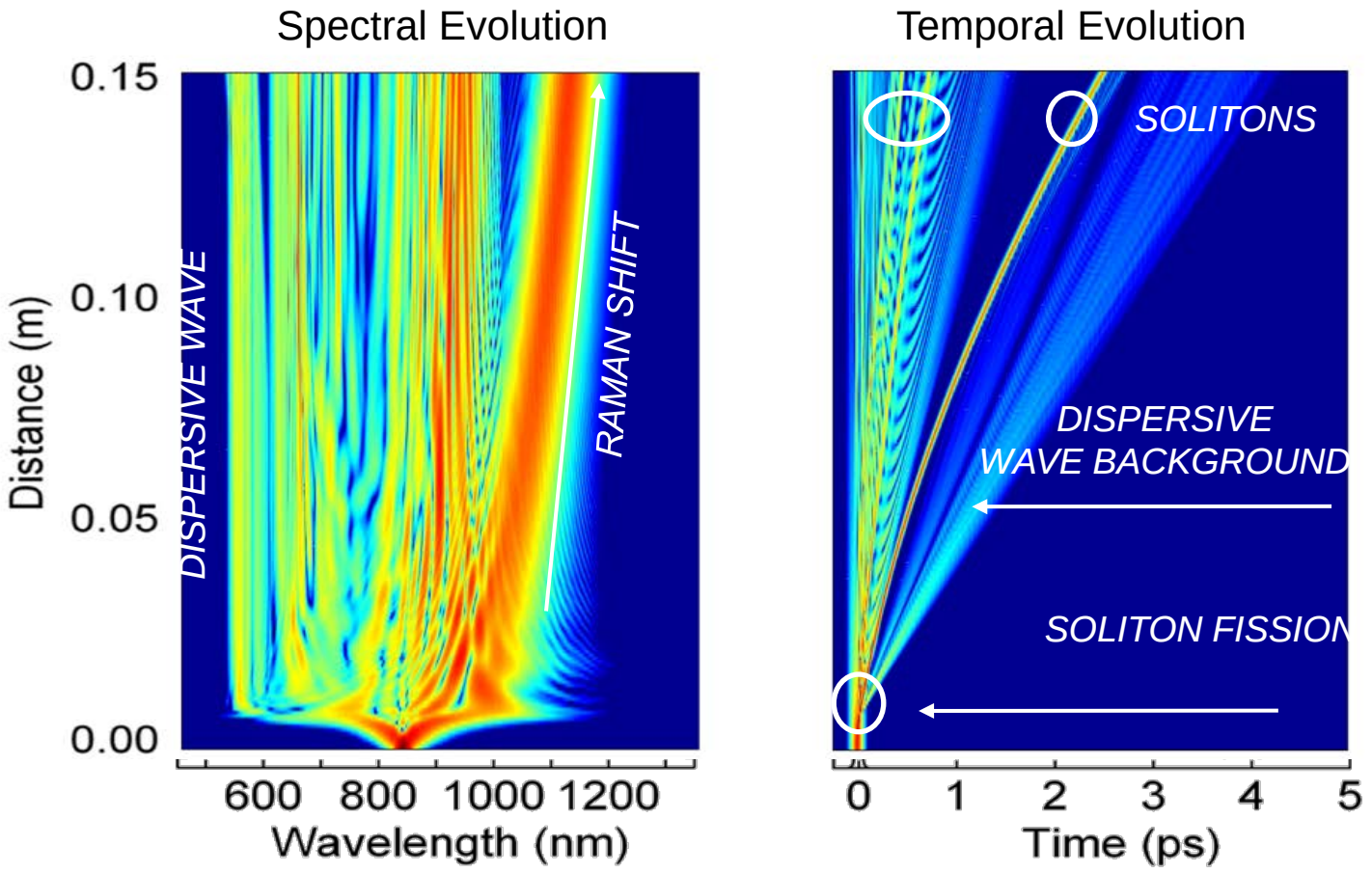


Femtosecond pumped supercontinuum

50 fsec, 835 nm, 0.5nJ, 10kW, 15 cm PCF, N=9 soliton



Solution:- Cut the fibre at point of maximum compression

note - you are using solitons

Solitons in fibre lasers

Balance of nonlinearity and dispersion

$$N = \sqrt{\frac{L_D}{L_{NL}}} = \sqrt{\frac{\gamma P \tau^2}{\beta_2}}$$

For N=1 pulse shape remains unchanged in lossless medium

Power required for a fundamental soliton in practical units

$$P = \left(\frac{1.763}{2\pi}\right)^2 \frac{A_{eff}\lambda^3}{n_2 c}\frac{D}{\tau^2} \qquad \text{ie} \qquad \tau \propto \frac{\beta}{\gamma E}$$

At 1550 nm, D= 17ps/nm/km, τ = 1ps, 100 MHz, STF

Soliton period ~20 m Soliton power ~ 30W (1.2mW @40MHz)

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Spectrally masked phase modulation

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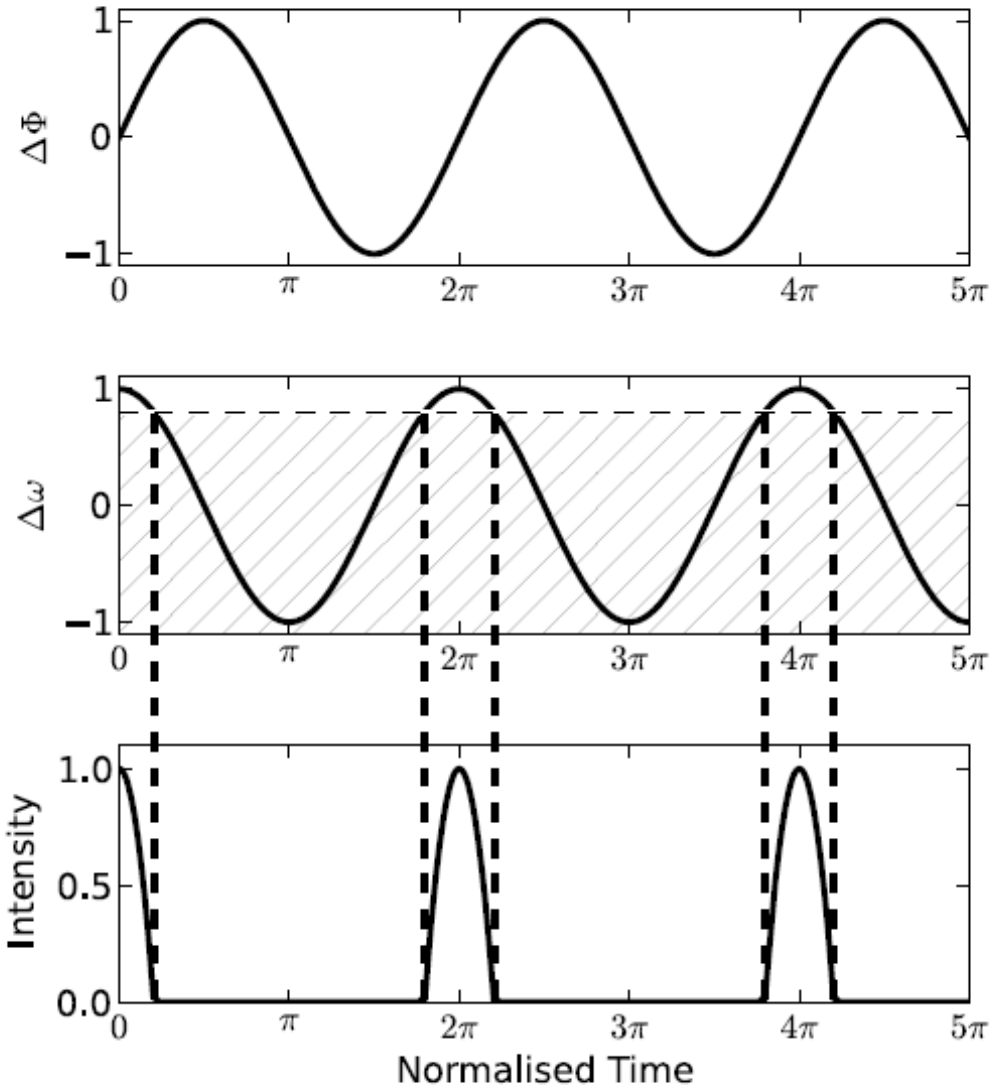
- Phase modulation gives rise to sinusoidal shift in optical frequency, amplitude dependent on applied voltage

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

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



Adiabatic Soliton Compression

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

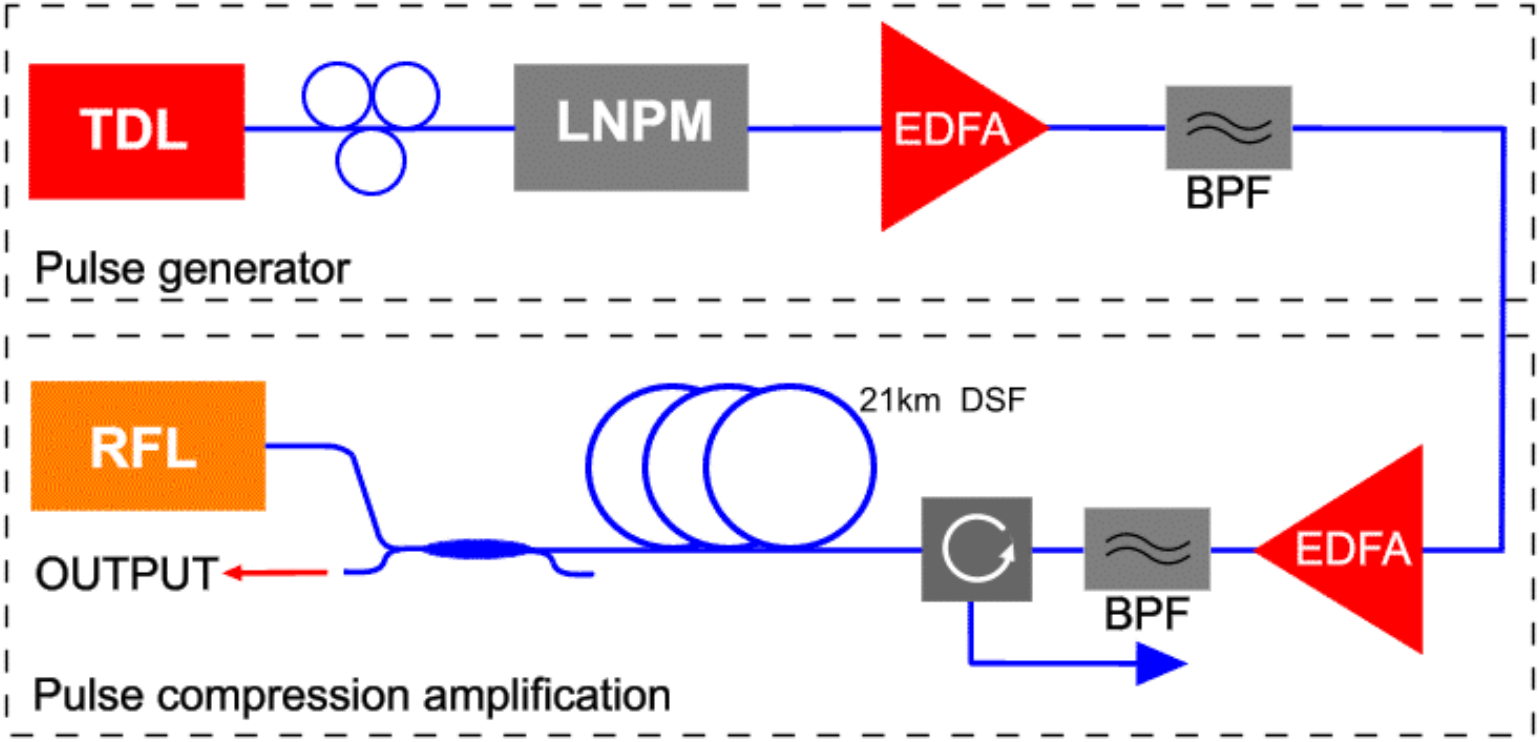
Advantages

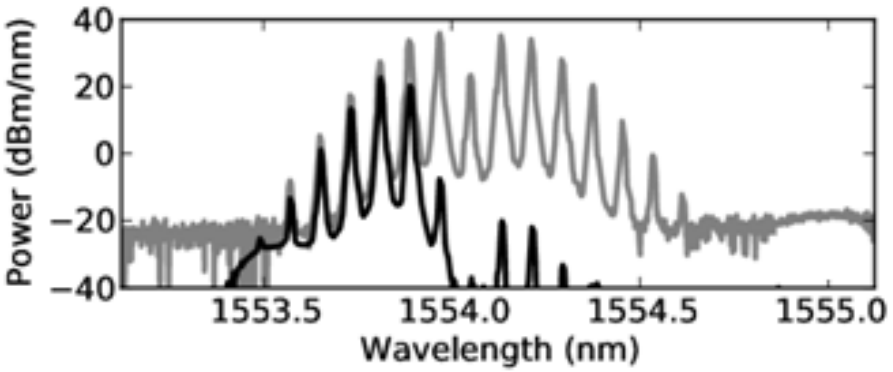
- Bandwidth-limited output
- Forgiving of input pulse shape
- Forgiving of taper / gain profile
- No alignment, robust, compact

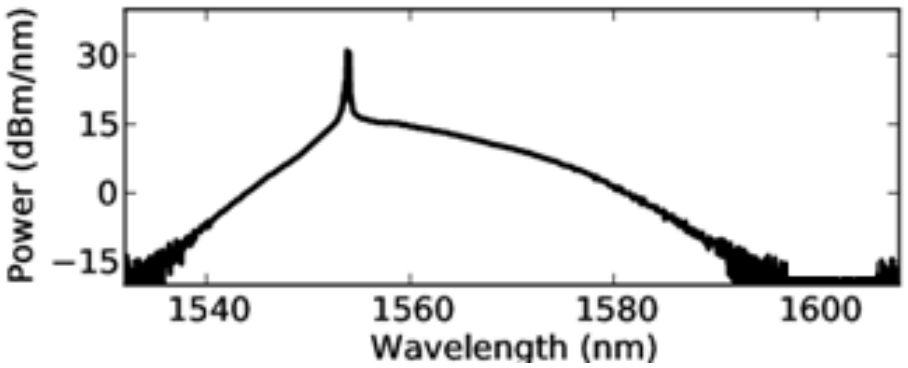
Disadvantages

- Need anomalous dispersion
- Pulse power fixed by dispersion

Pulse generation via phase modulation







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Gain-Compression Simulations

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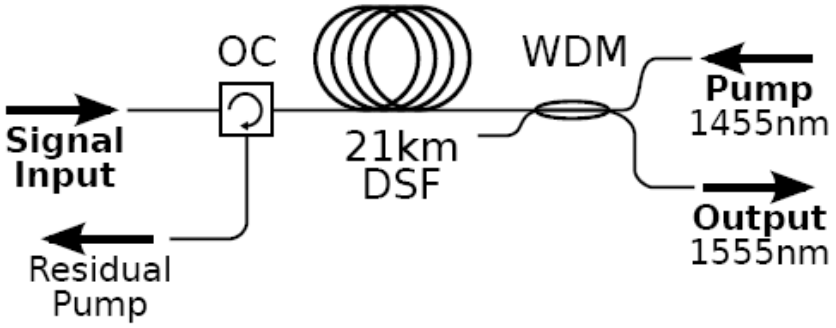
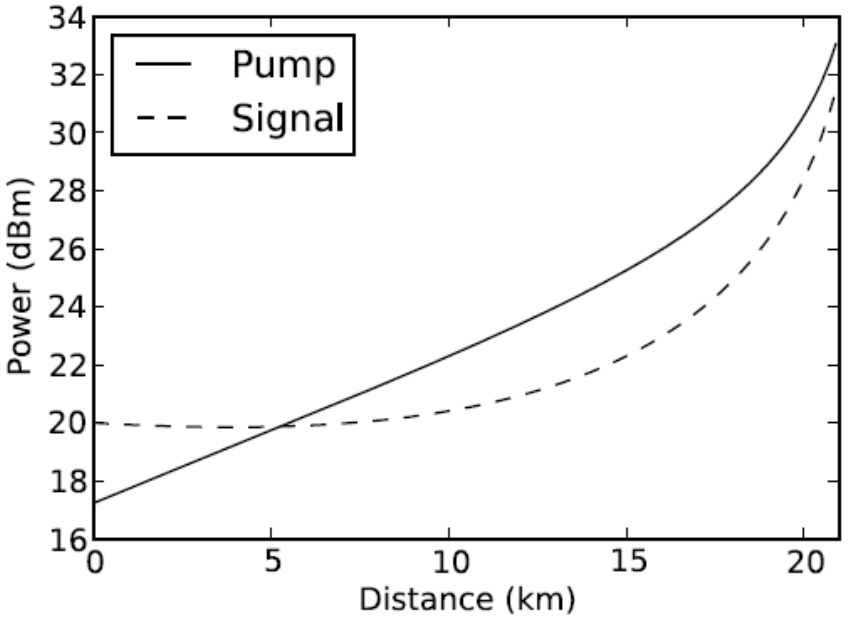
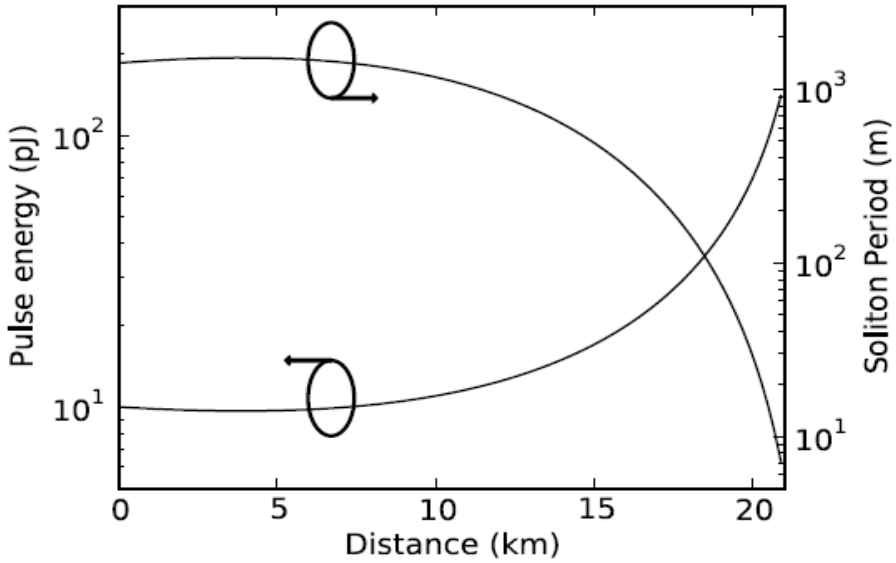
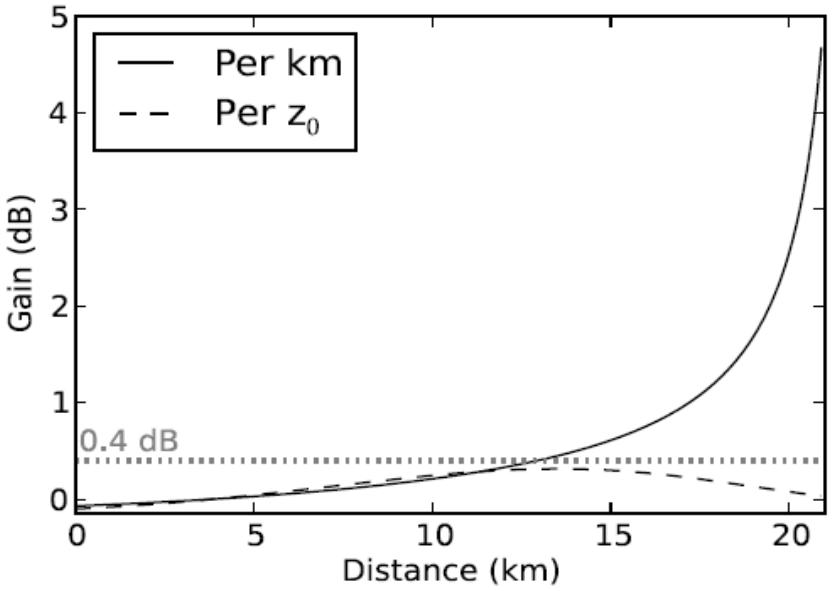
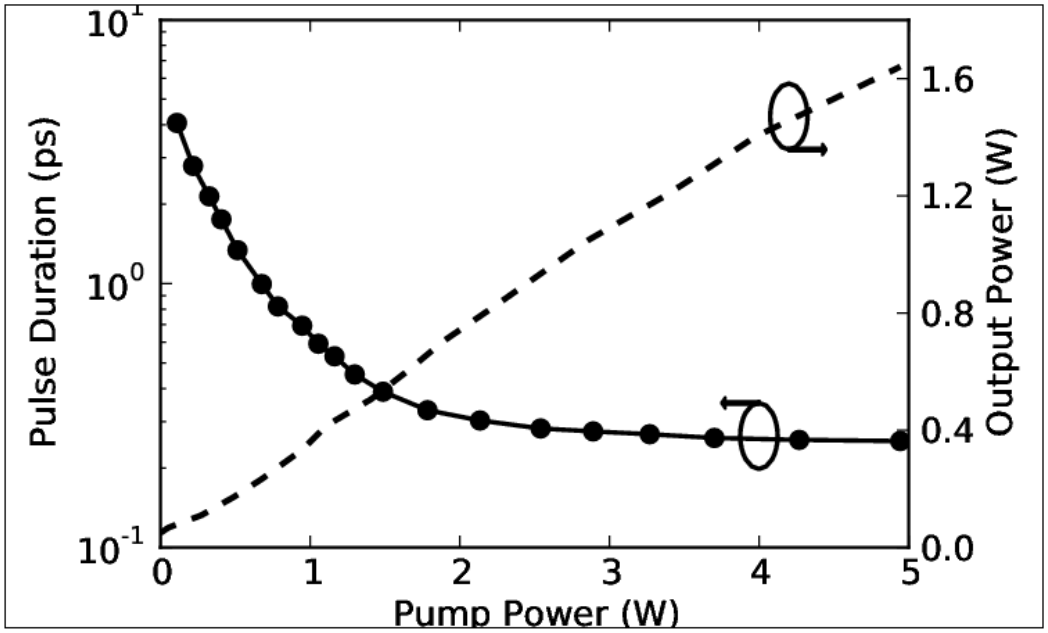


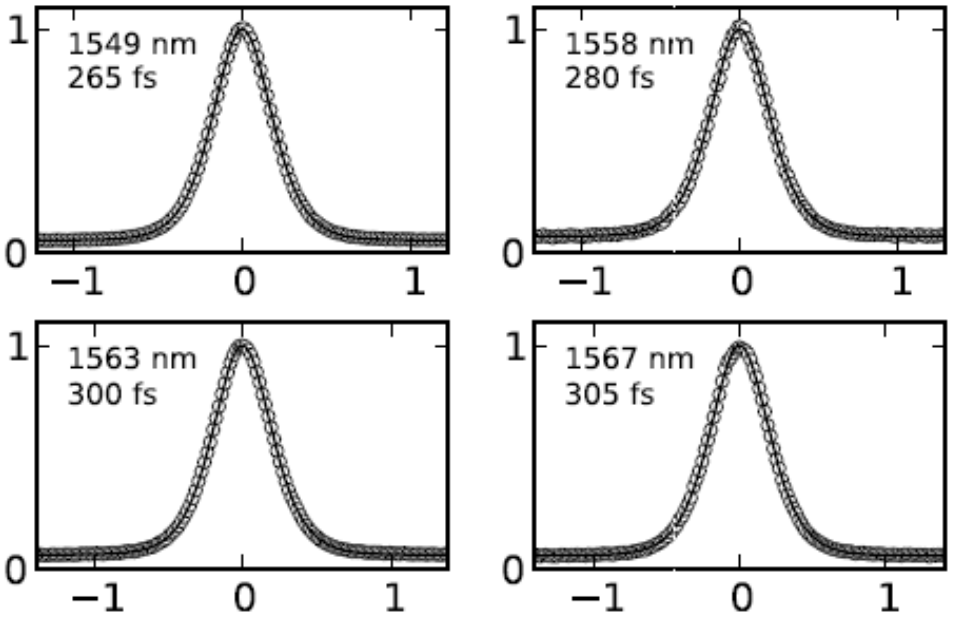






Pulse amplification and compression





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Alternative Wavelengths

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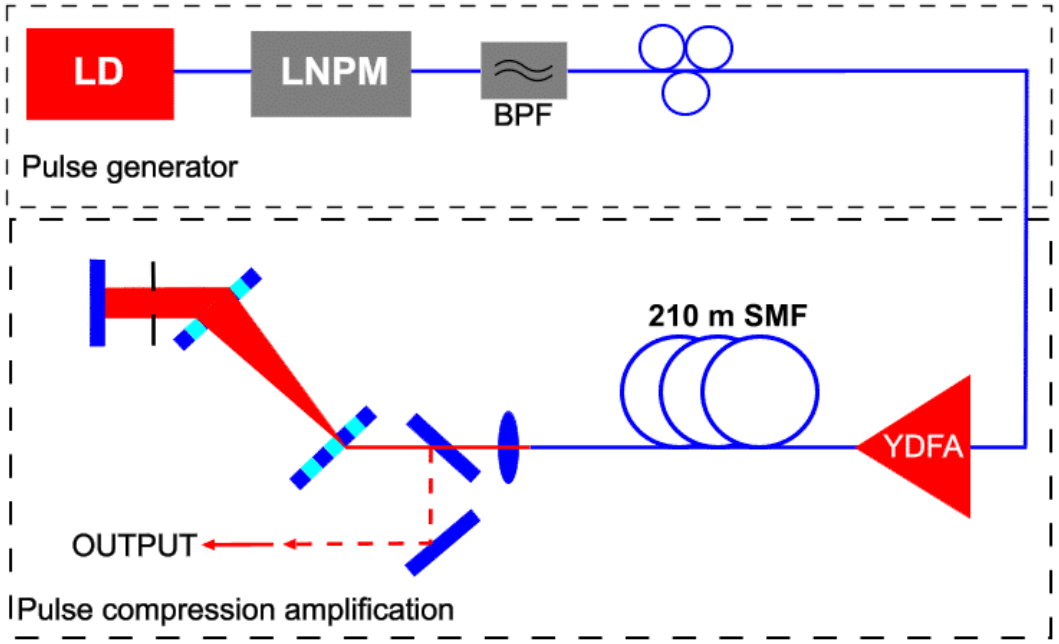
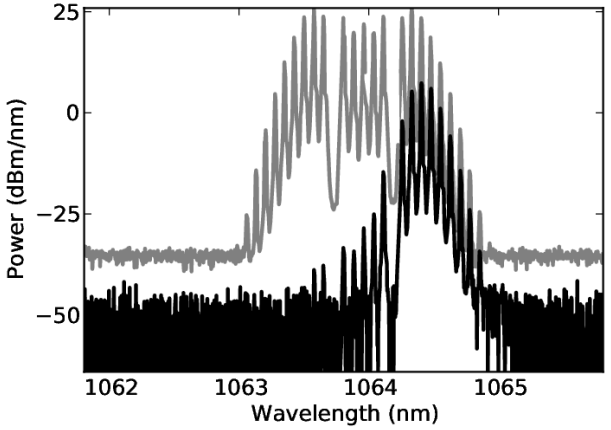
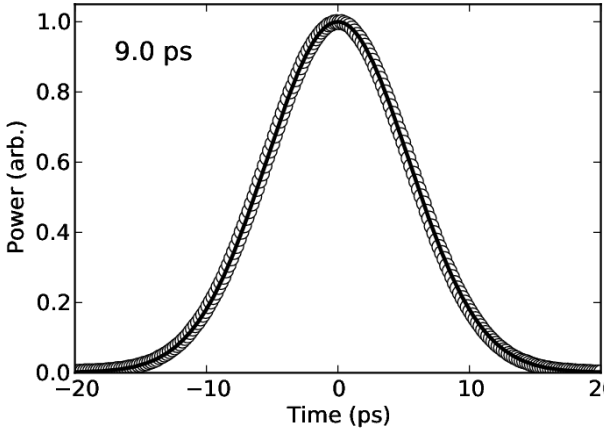
Tm ~ 1.98 μm
soliton shaping

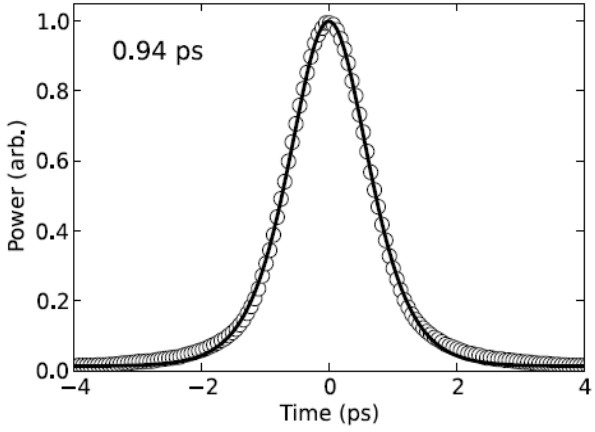
Yb ~ 1.06 μm
normal dispersion

Use : Bulk elements
PCF ? Not really
Air core PCF









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Compression in tapered PCF

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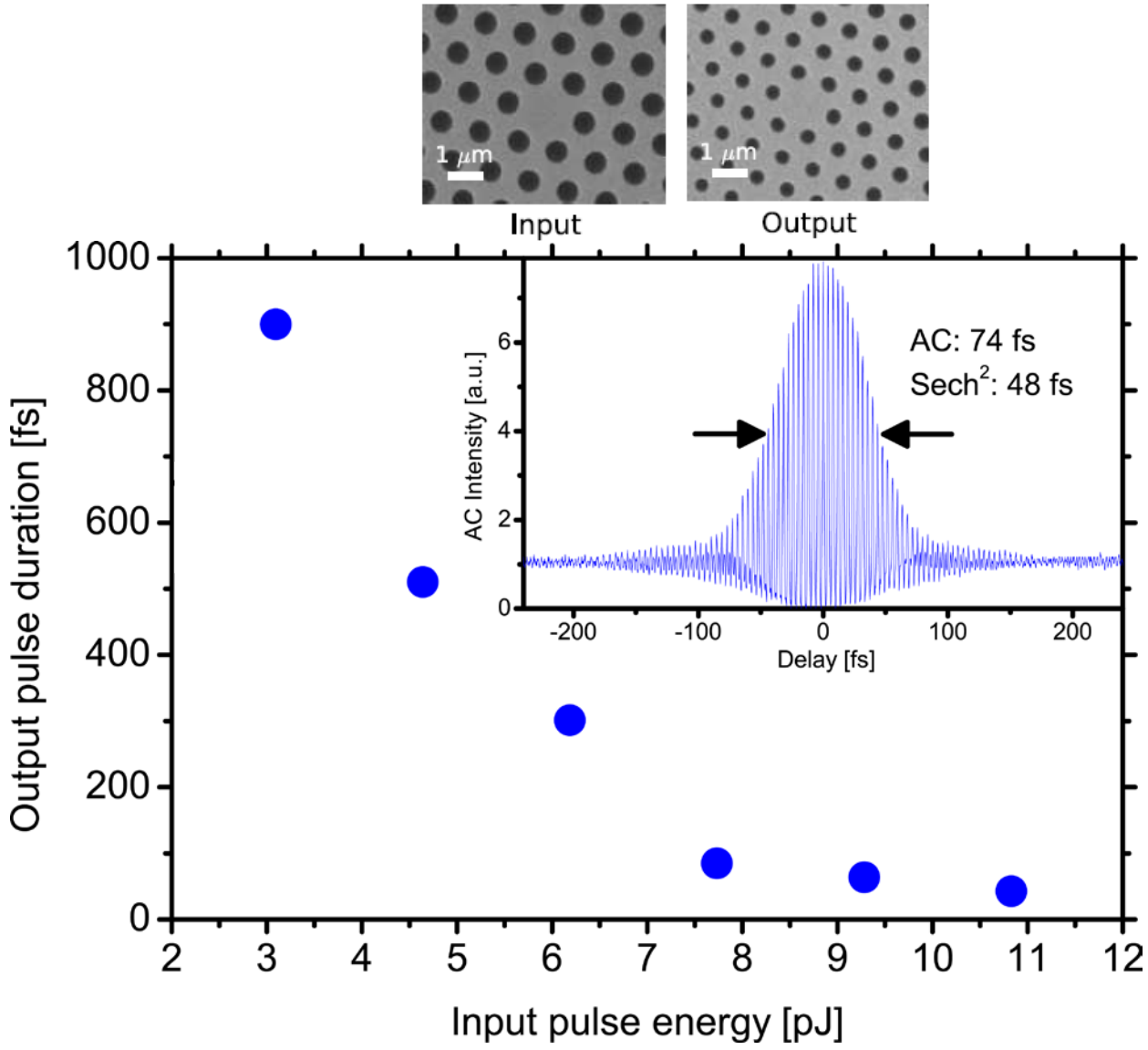
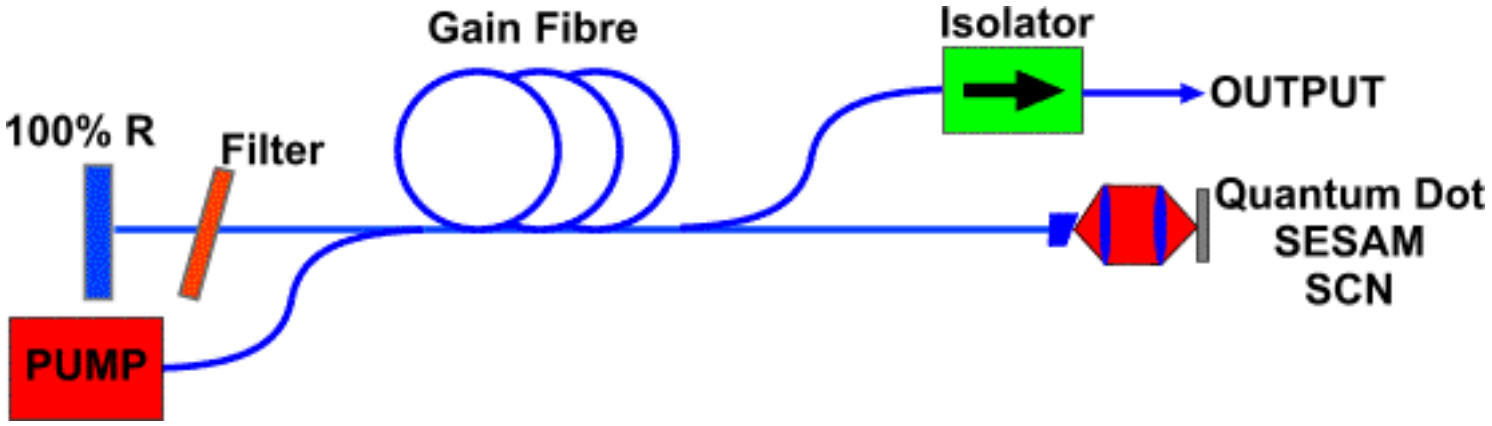


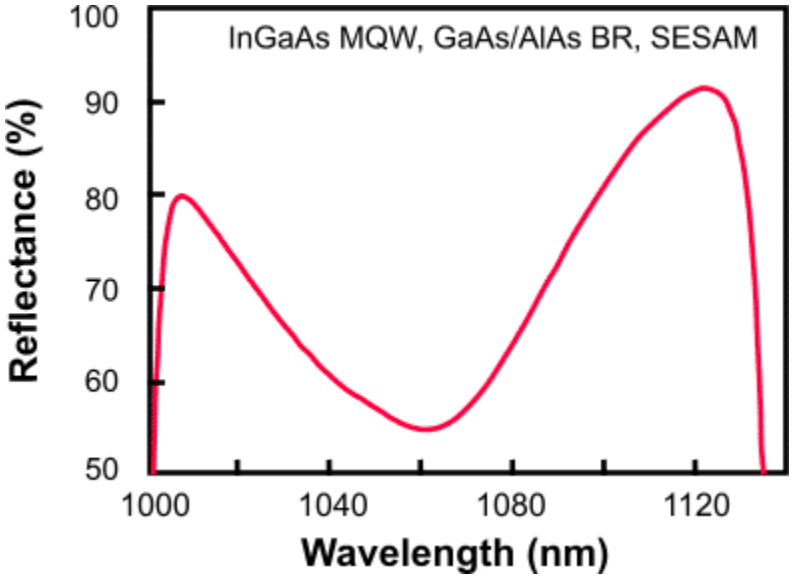
$$\tau_0 = \frac{2|\beta_2|}{\gamma E_s}$$

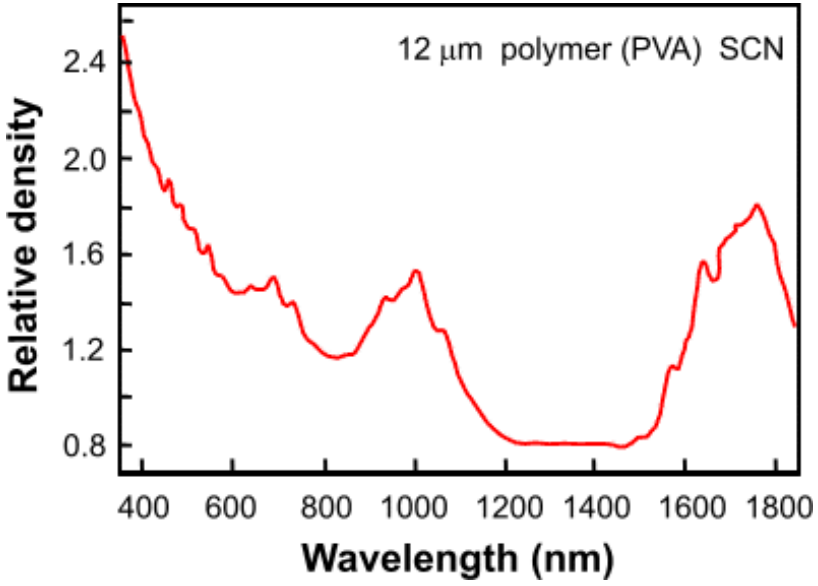
Parameters

- **Dispersion: ~30 to ~0 ps/nm/km**
- **Loss: 56 dB/km**
- **Length: 17 m**
- **d/Λ = 0.52-0.42**
- **Λ = 1.50 – 1.25 μm**

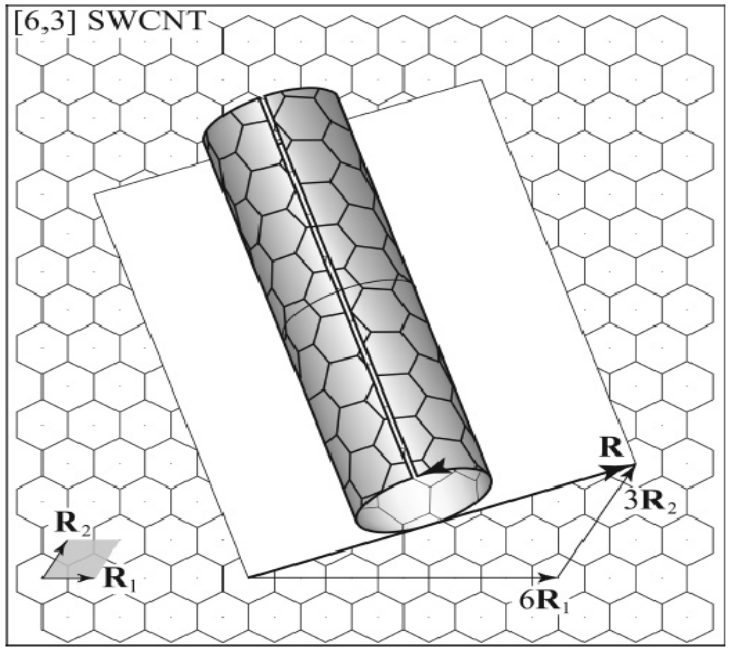
Passively mode locked fibre lasers

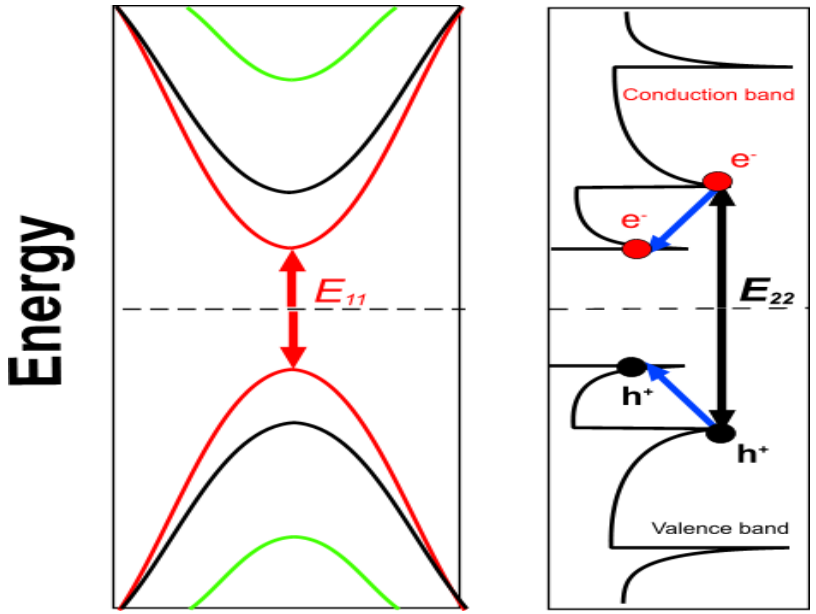




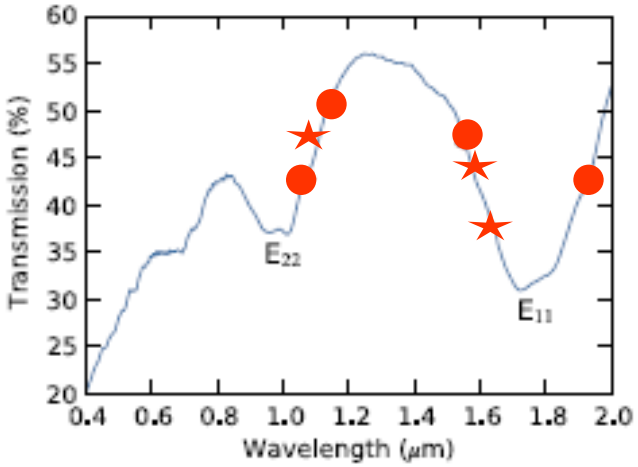


Carbon nanotube saturable absorbers

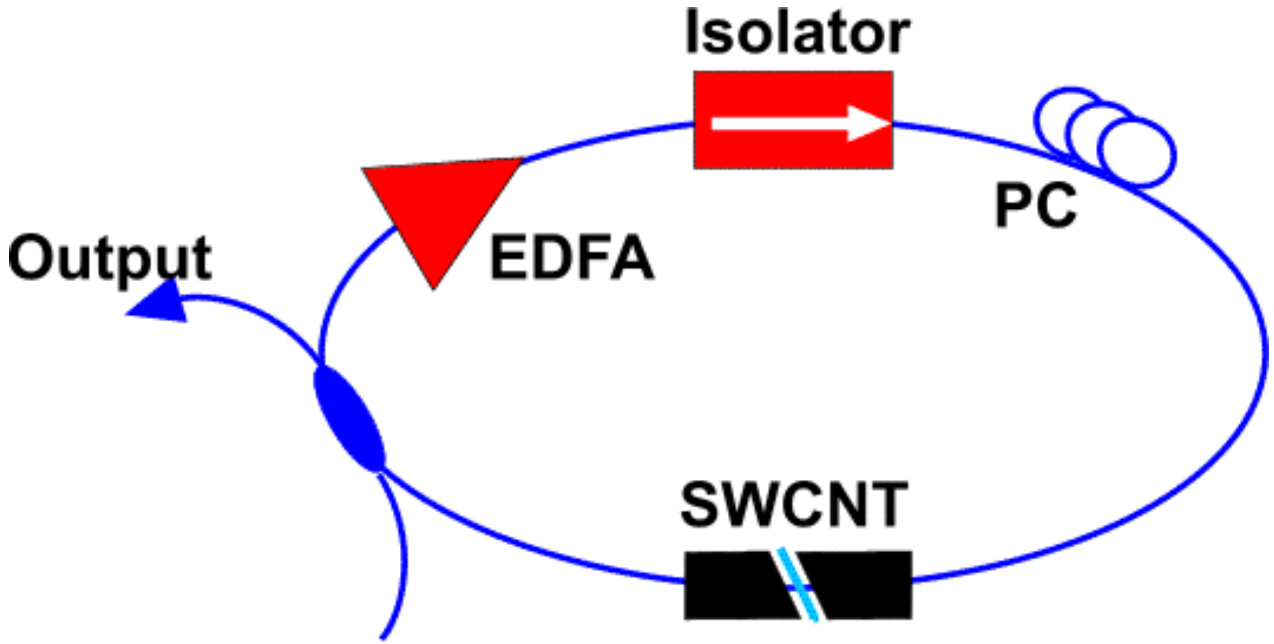




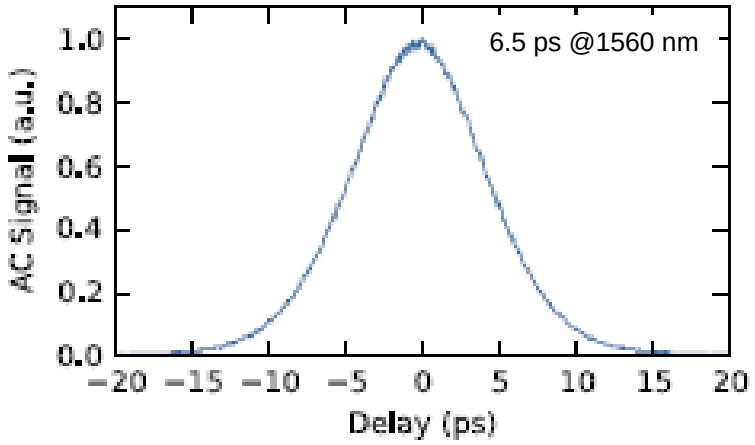
- **Saturation fluence ~5 MWcm^{-2}**
- **15 % mod depth at 1.55 μm**

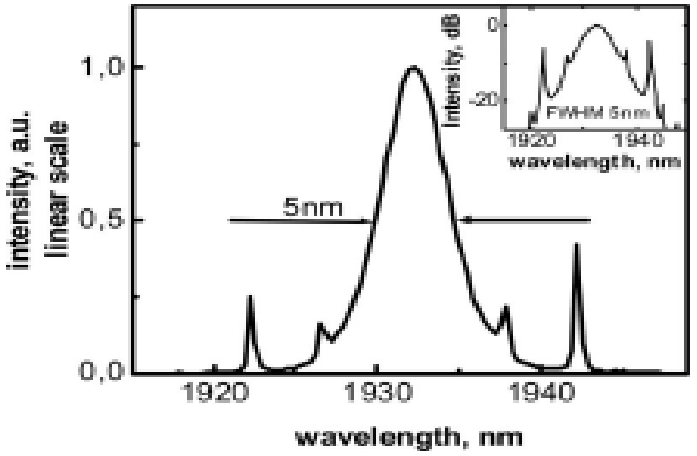


CNT passively mode locked fibre lasers

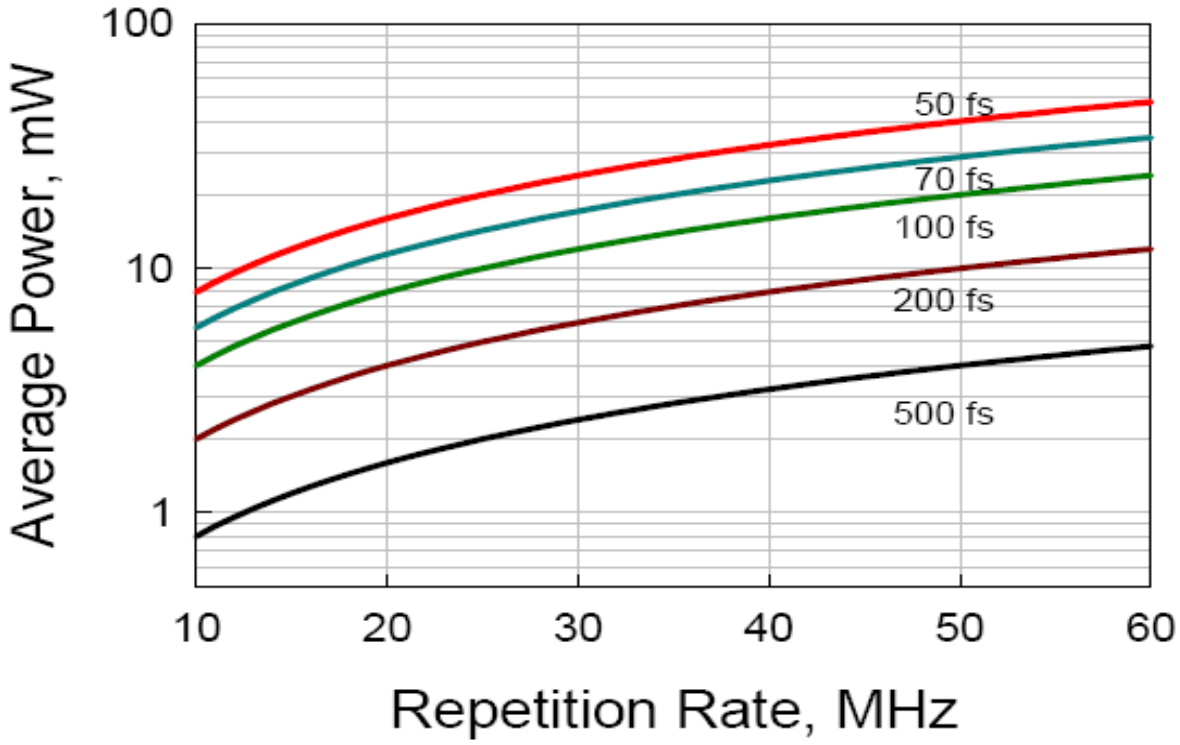


Solitons!





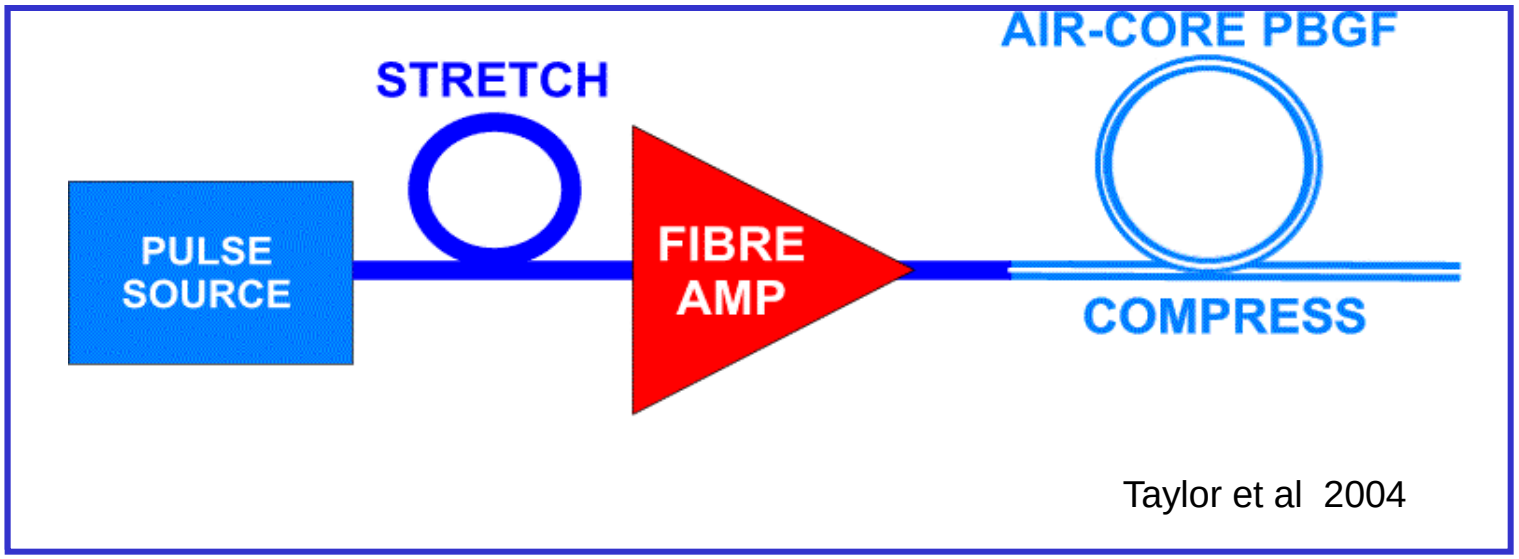
Power requirements for soliton



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 many applications AMPLIFICATION needed

Chirped Pulse Amplification



Demonstrated with
Yb, Yb:Er and Raman systems

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

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Air-Core Photonic Bandgap Fibre

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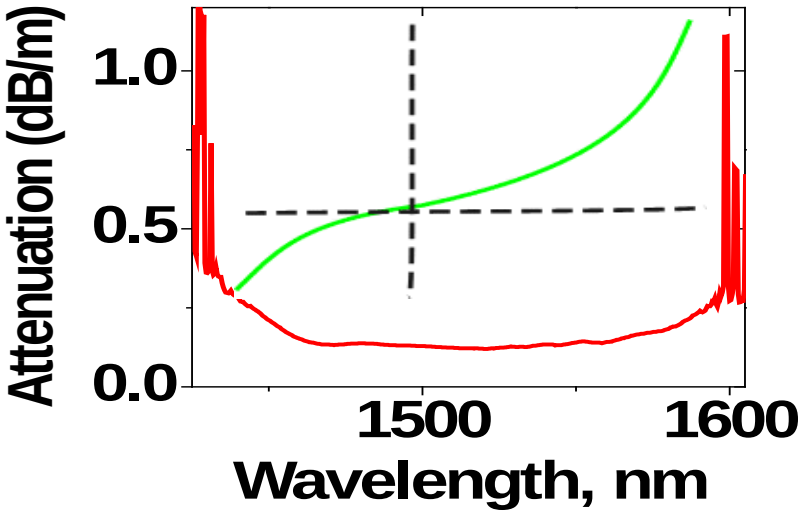
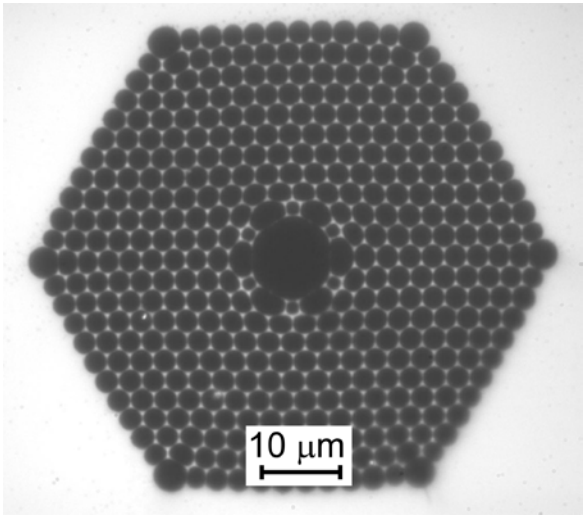
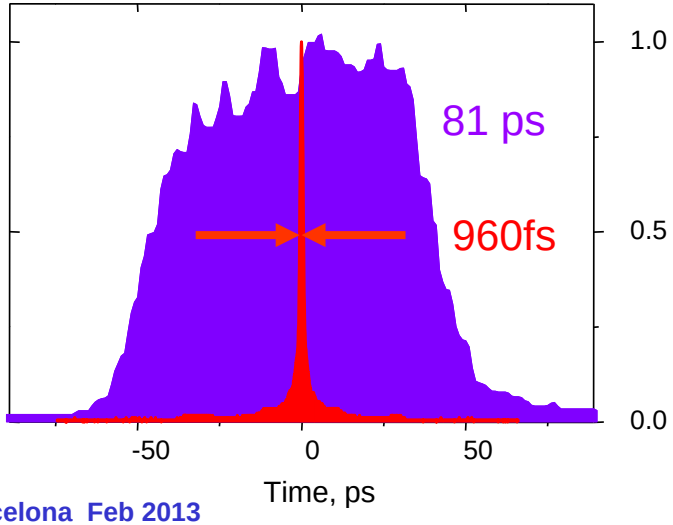
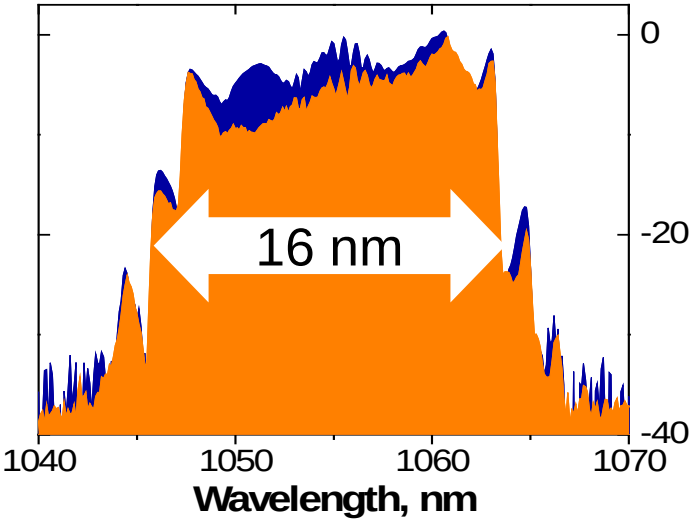




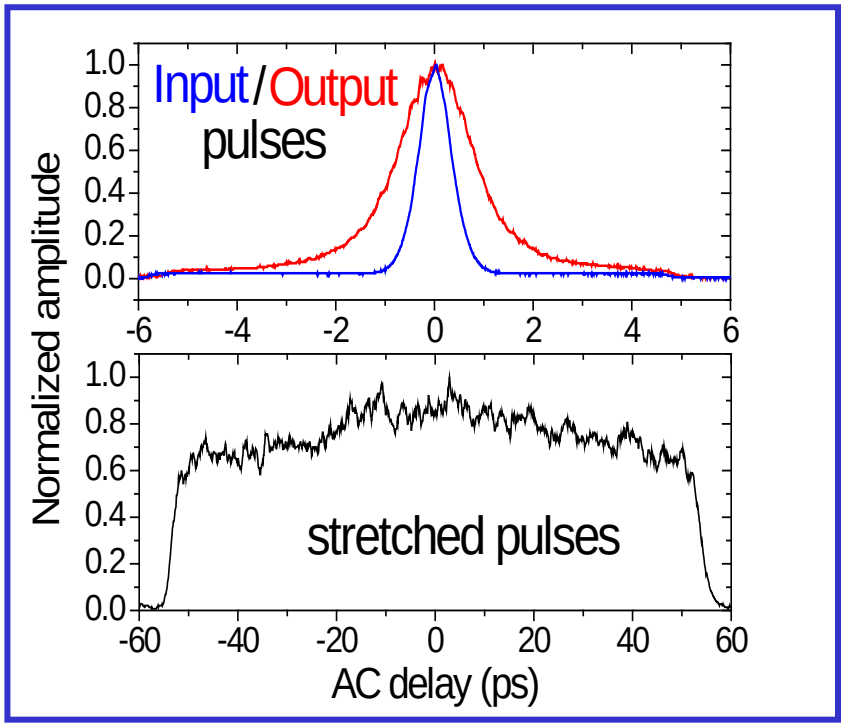
High waveguide dispersion

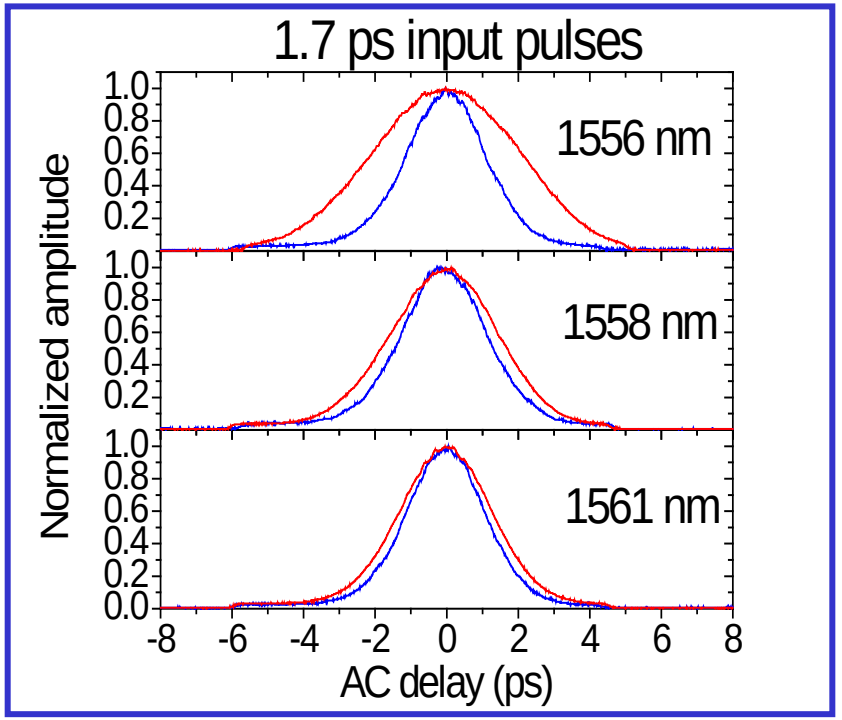
~1000 x lower nonlinear threshold





All-fibre CPA





Problem: High order dispersion

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

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Non-fibre CPA Femtosecond Compression -1

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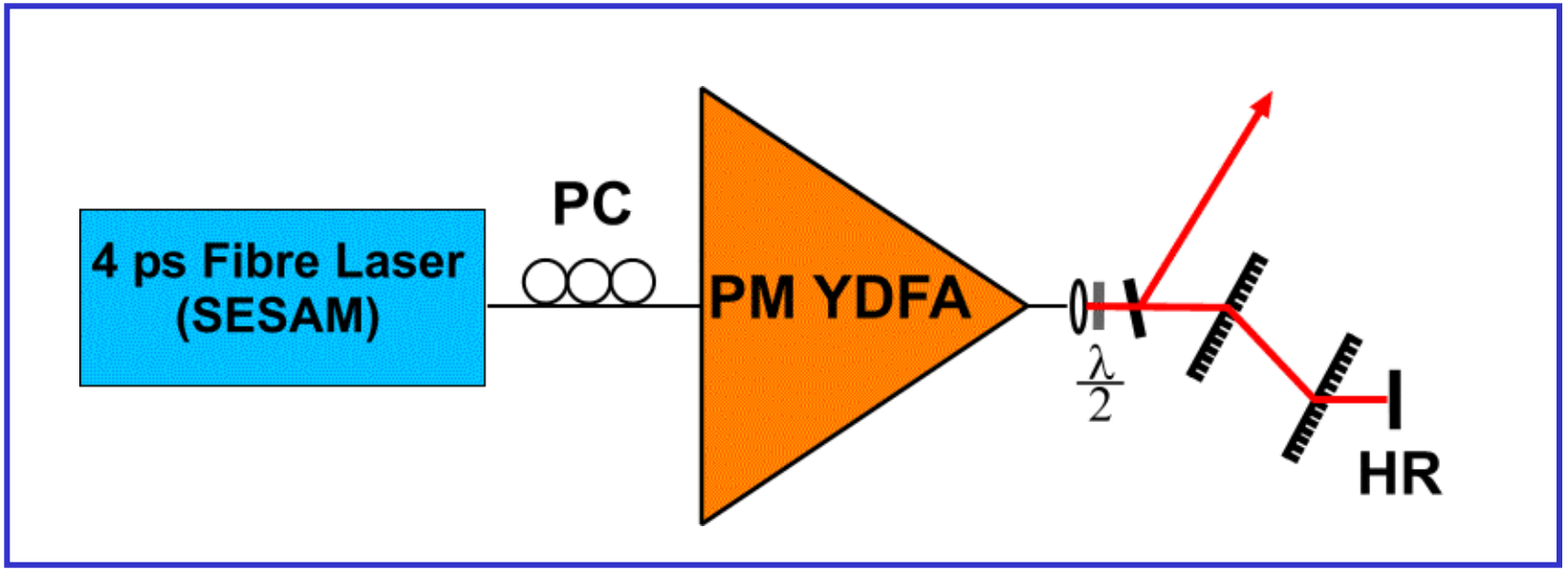


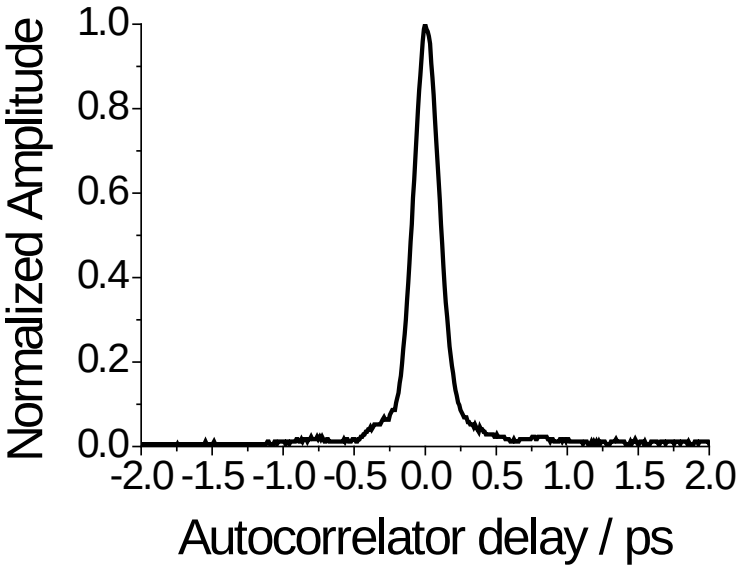
Power Amp Characteristics

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

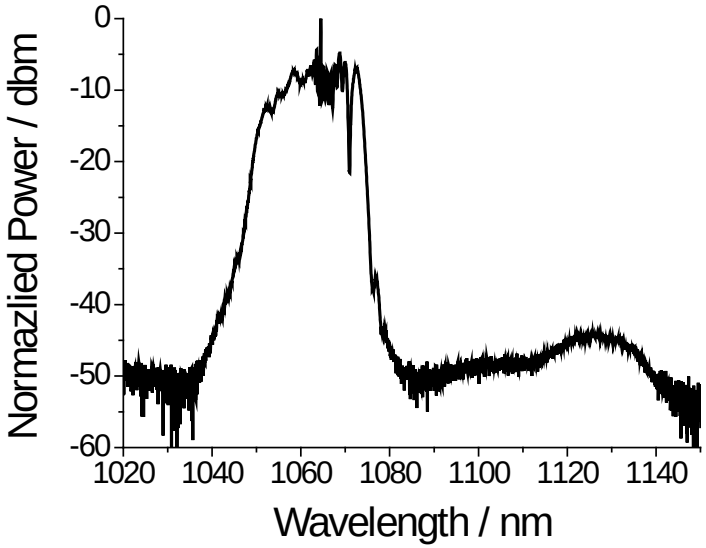
Transmission Gratings

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

Non-fibre CPA: Compression - 2



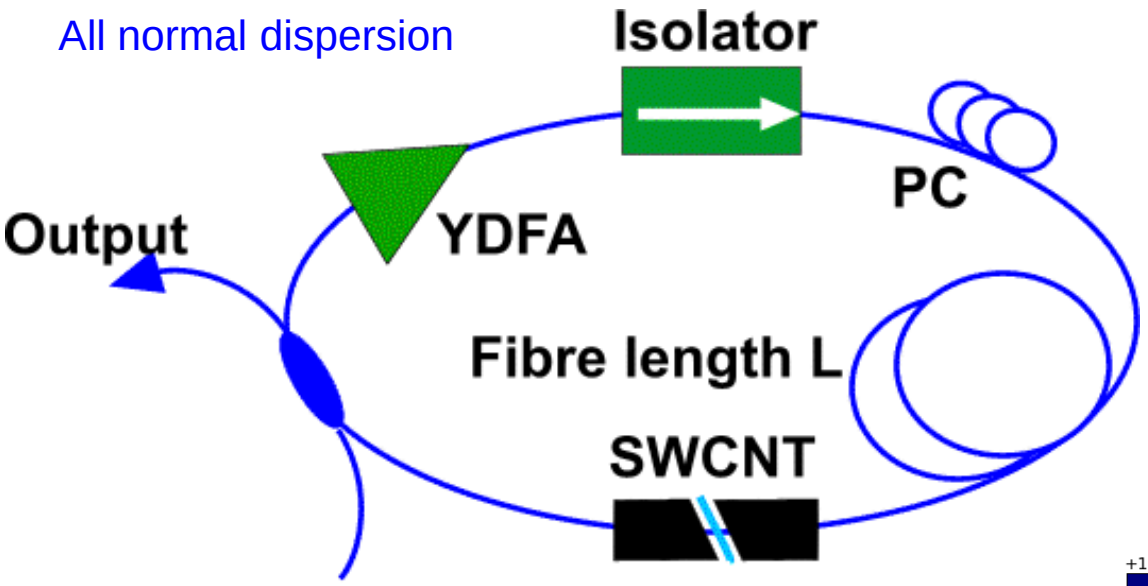
- 140 fs pulses
- 270 kW peak power
- 2.5 W average power

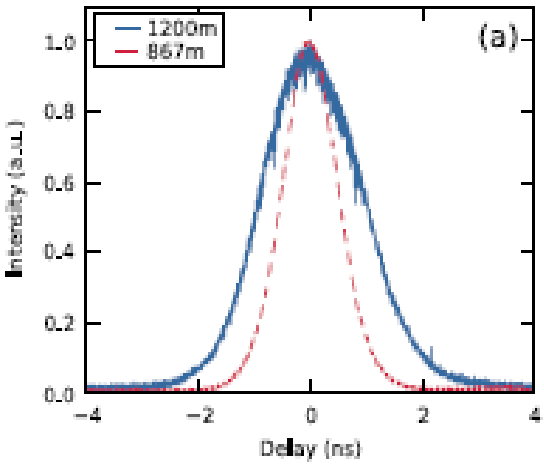


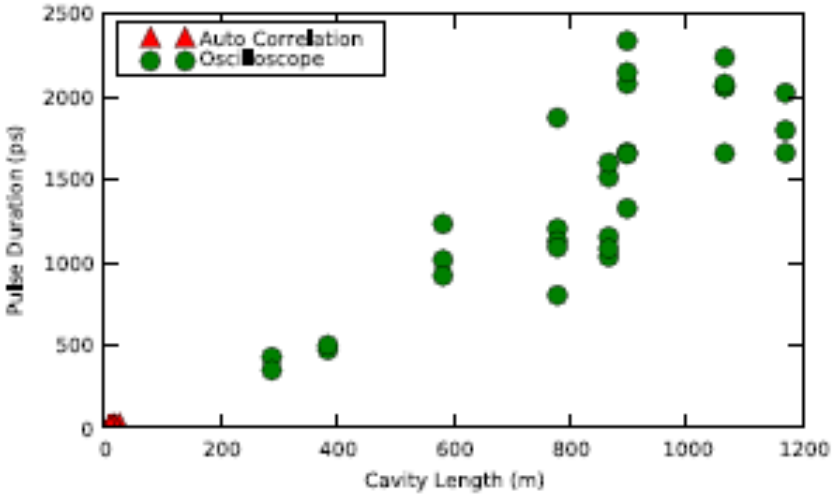
- 10dB bandwidth: 16.5 nm
- Limited by onset of Raman

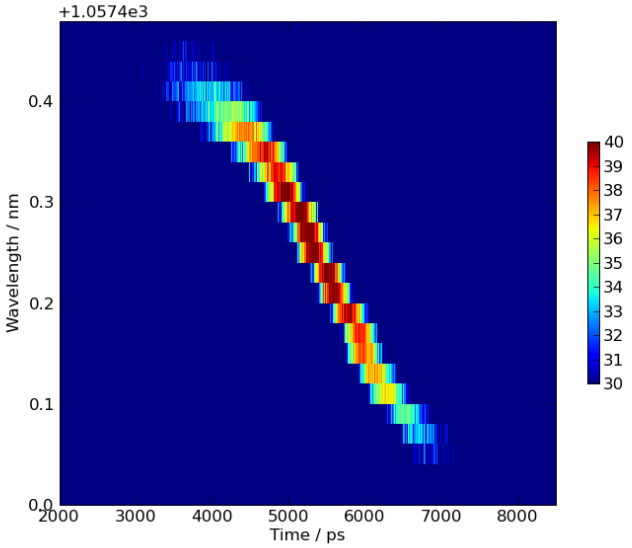
Long, stretched-pulse, mode locked regime

All normal dispersion









0.52nm, 2 ns, > 600 times transform limit!

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Gallery of Results

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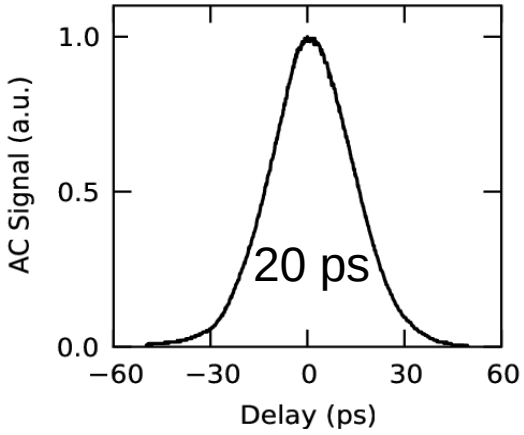
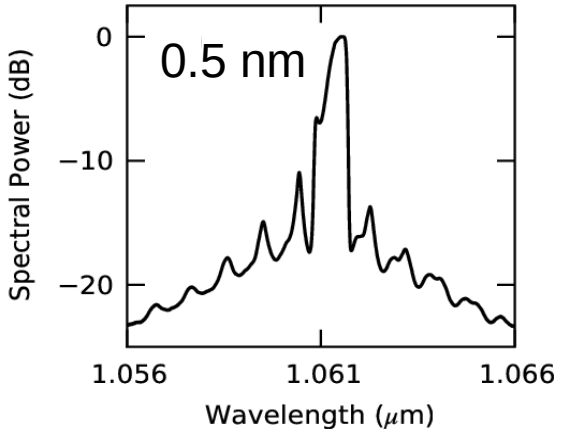
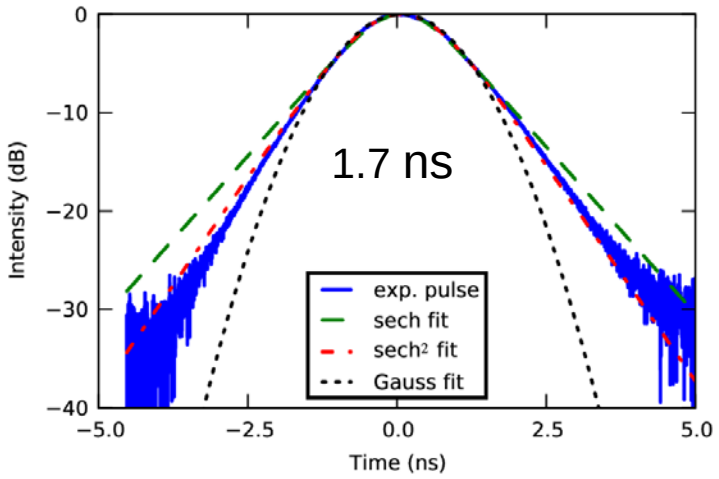
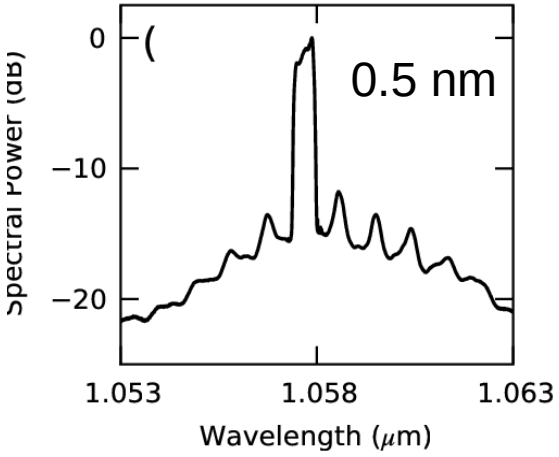




Cavity length 10m
Rep. rate 21 MHz
Dispersion -0.3 ps nm^{-1}





Cavity length 1200m
Rep. rate 177 kHz
Dispersion -36 ps nm^{-1}

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High Power Scaling

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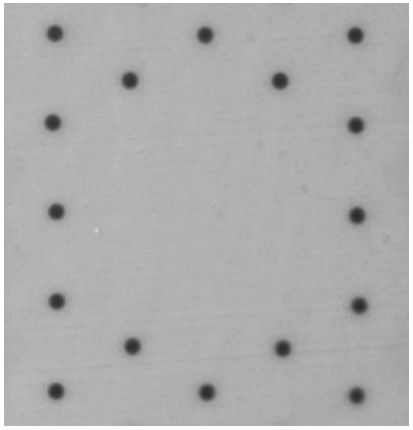
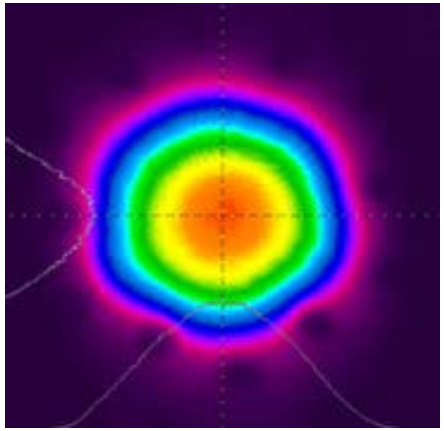
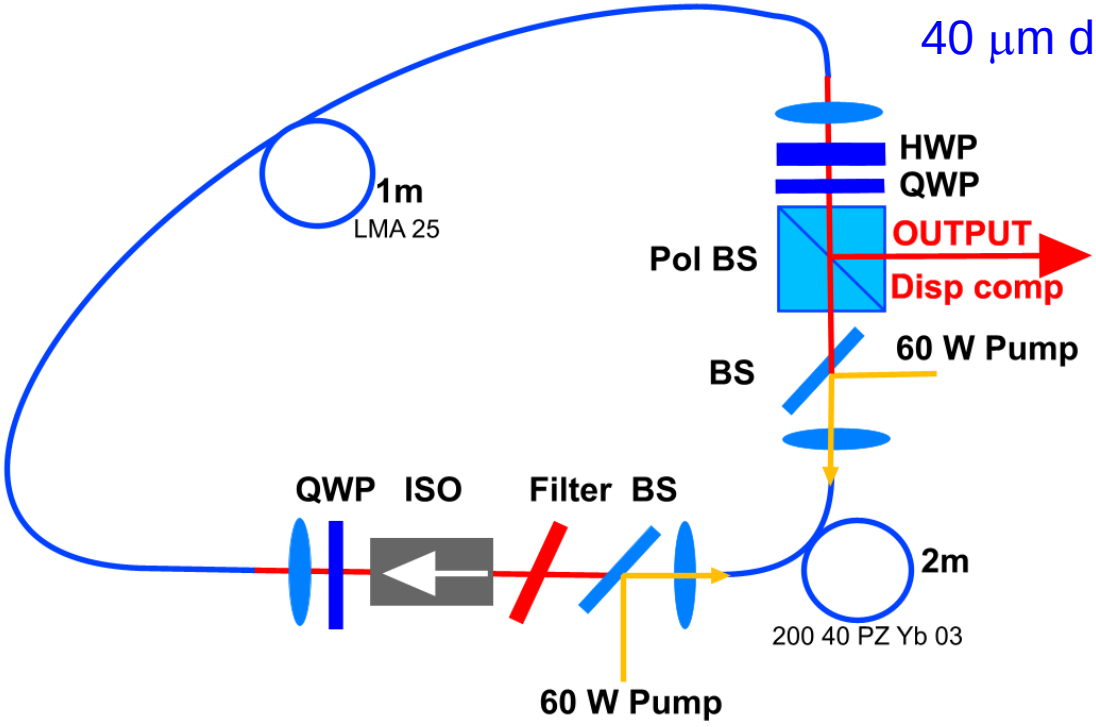
Amplifier	Yb-doped LMA PCF
Pump	120 W multi-mode
Efficiency	20 %



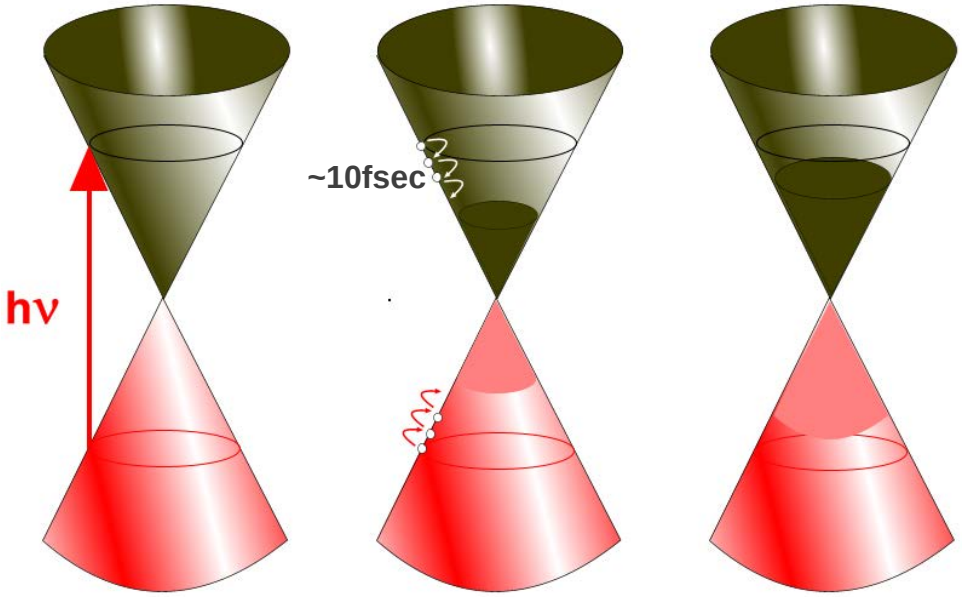


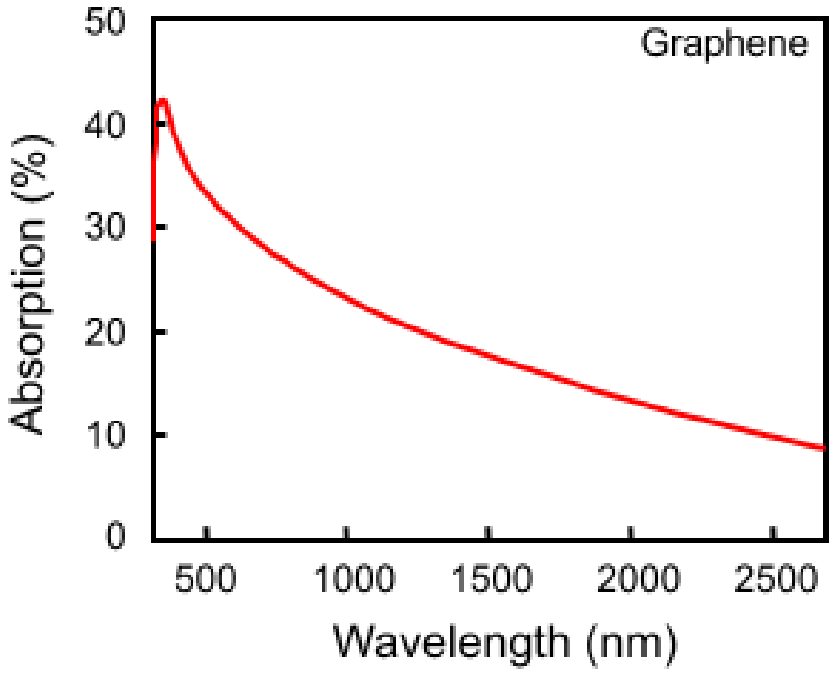
40 μm diameter, 200 μm inner cladding



Pulse duration	100 fs
Pulse energy	~ 0.5 μJ
Rep. rate	~ 50 MHz
Average power	30 W
Peak power	>4.5 MW

Graphene saturable absorbers





Graphene advantages:-

- Point band gap structure – easy fabrication - CVD
- No need for bandgap engineering – UNIVERSAL SATURABLE ABSORBER
- Low non-saturable loss
- Broad absorption – tuning range –controlled modulation depth
- Low threshold for saturable absorption ~0.7MWcm^{-2}
- Ultrafast recovery time ~200fsec

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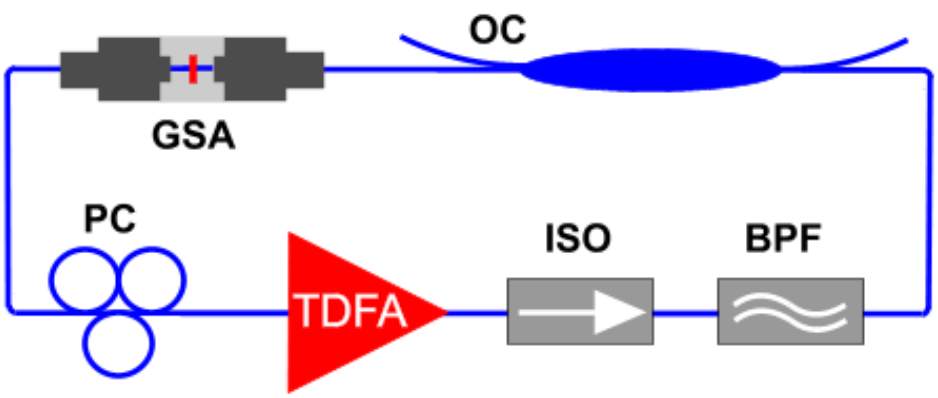
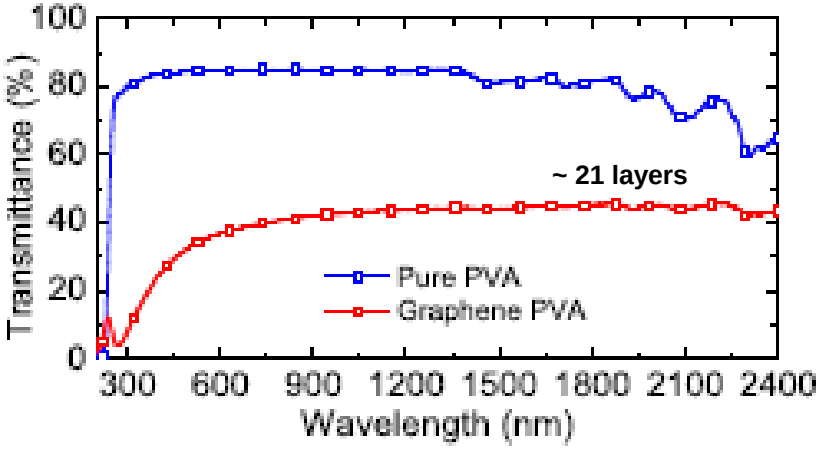
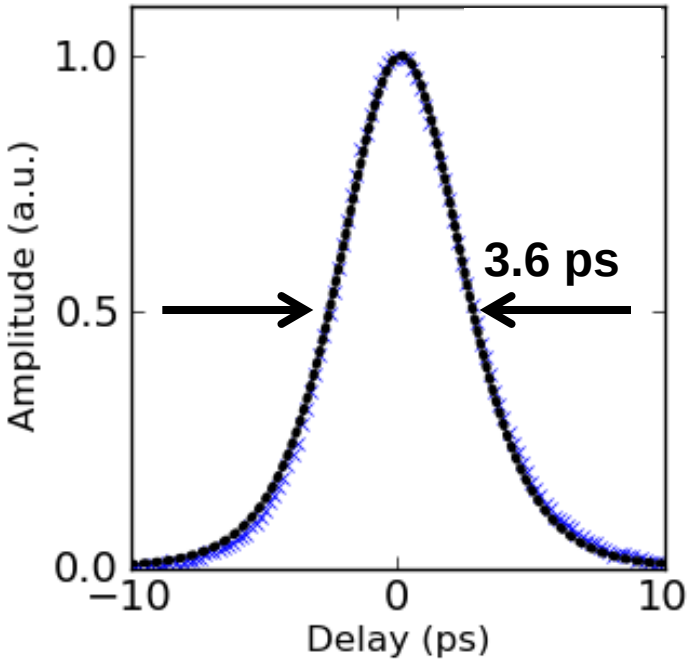
Graphene passively mode locked lasers -Tm

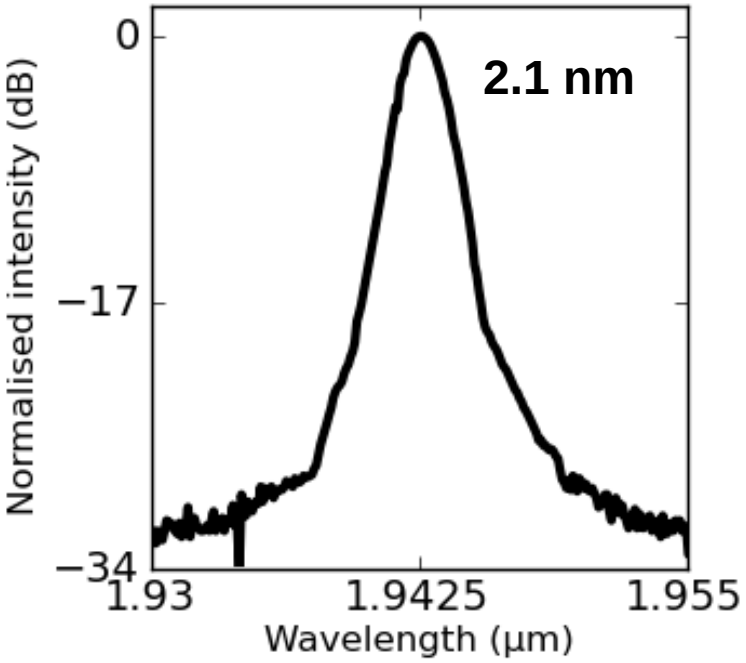
femtosecond optics group

Thullium

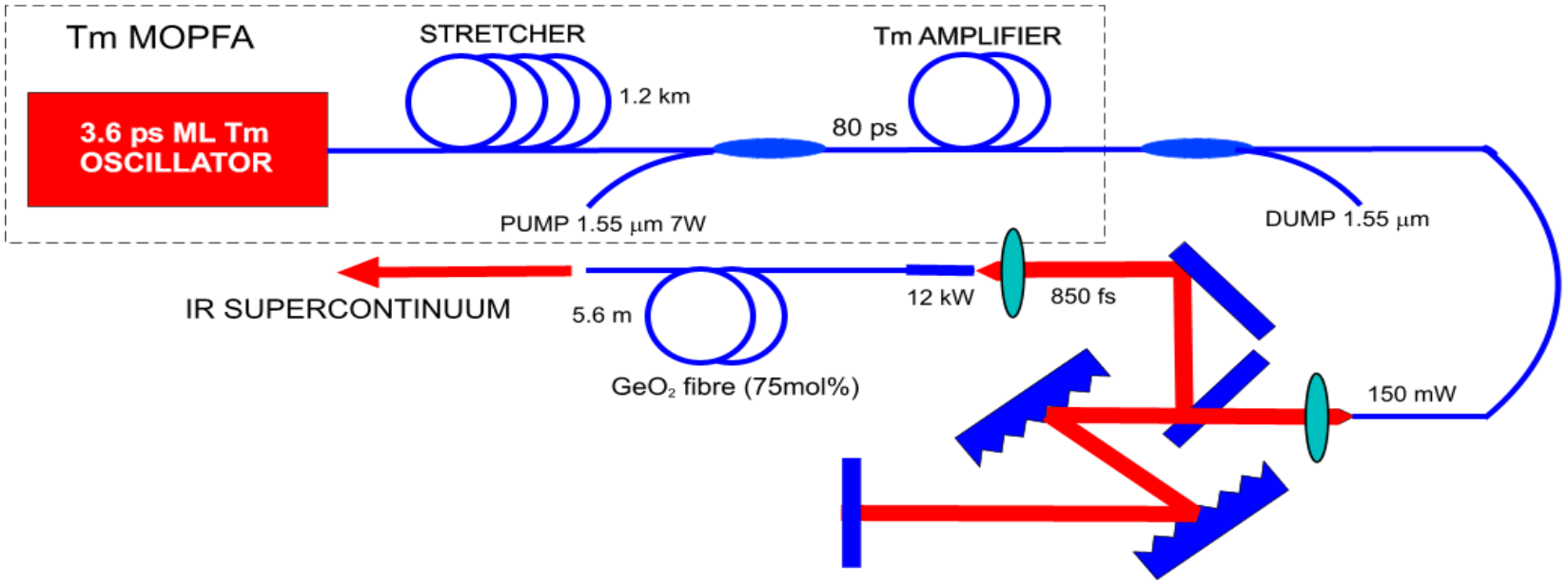


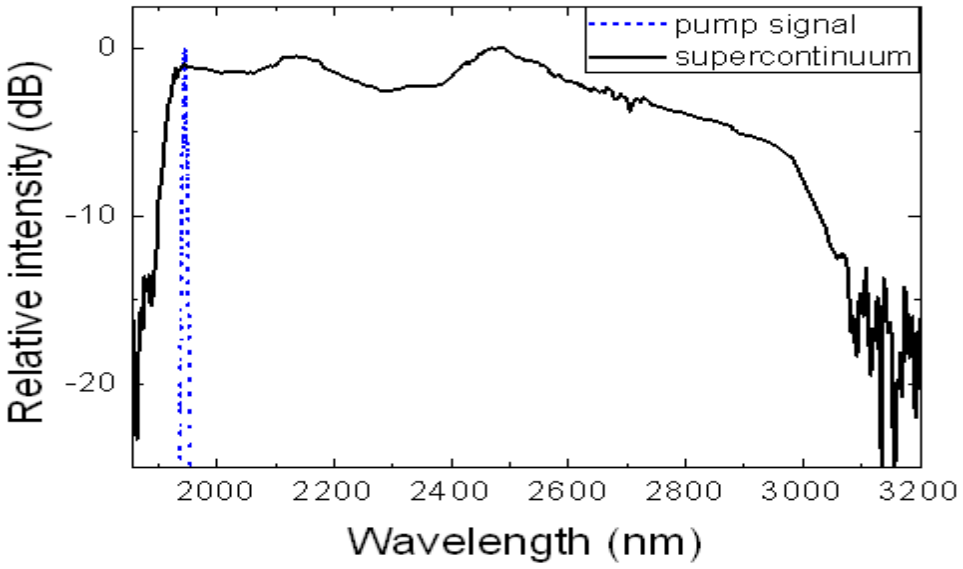






IR Supercontinuum Generation





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Graphene passively mode locked lasers

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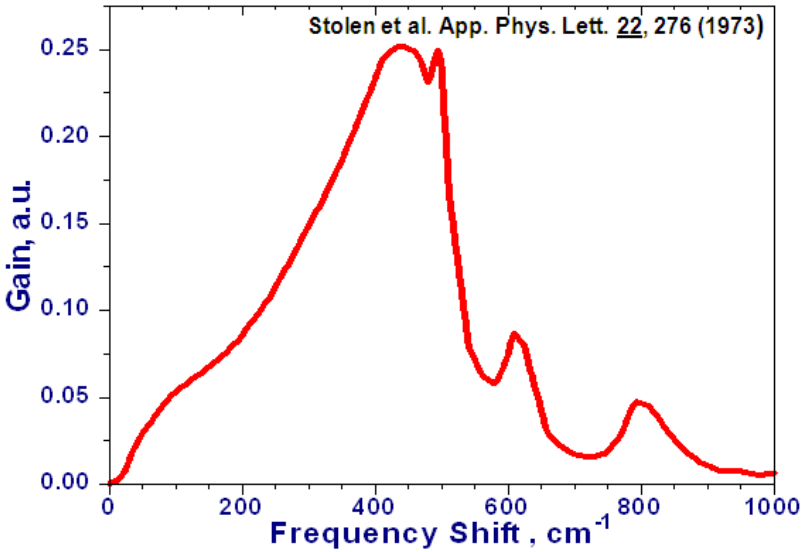
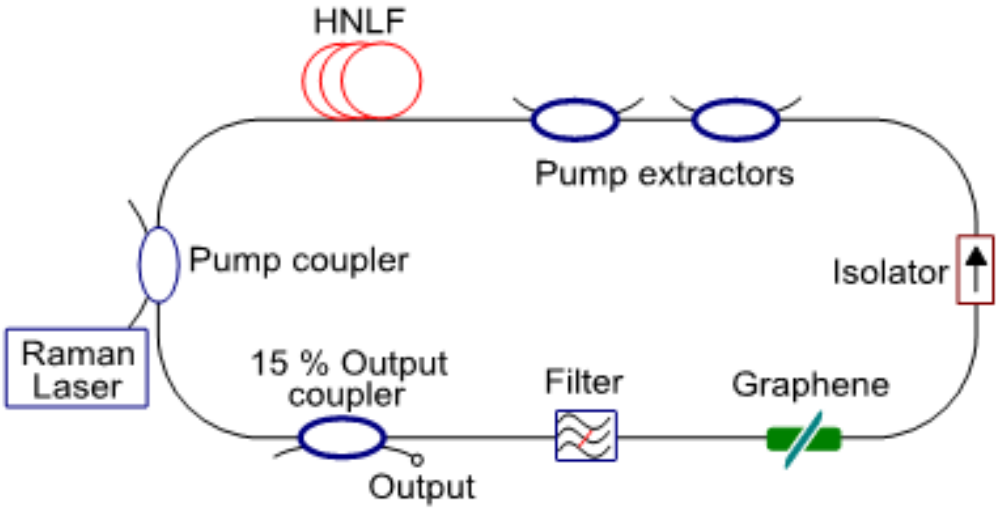
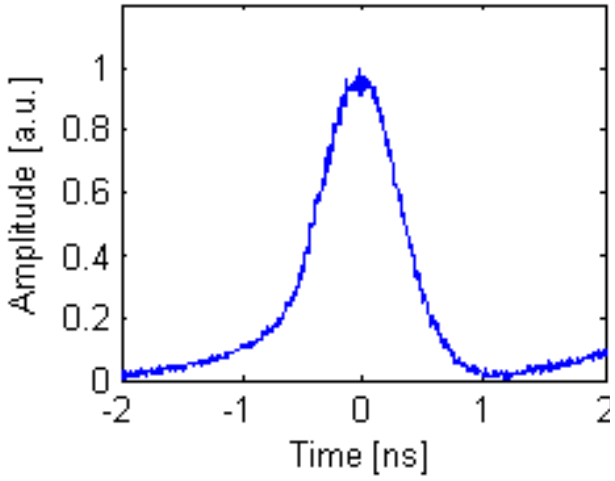
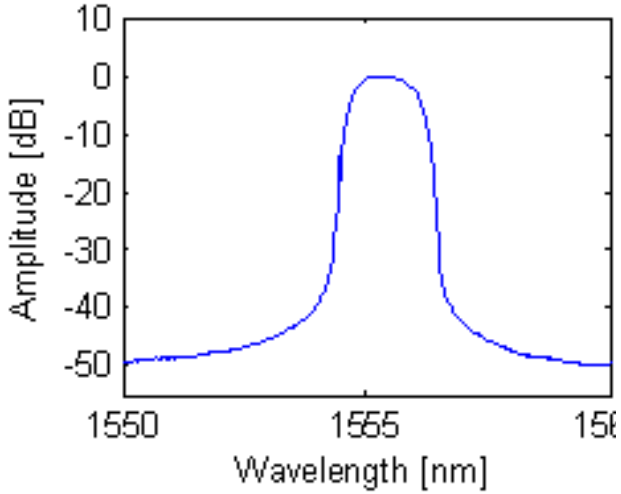
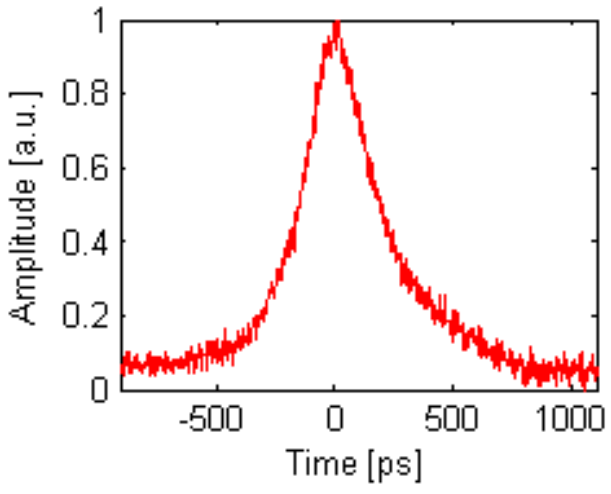
Raman











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Passive Raman Mode-Locking

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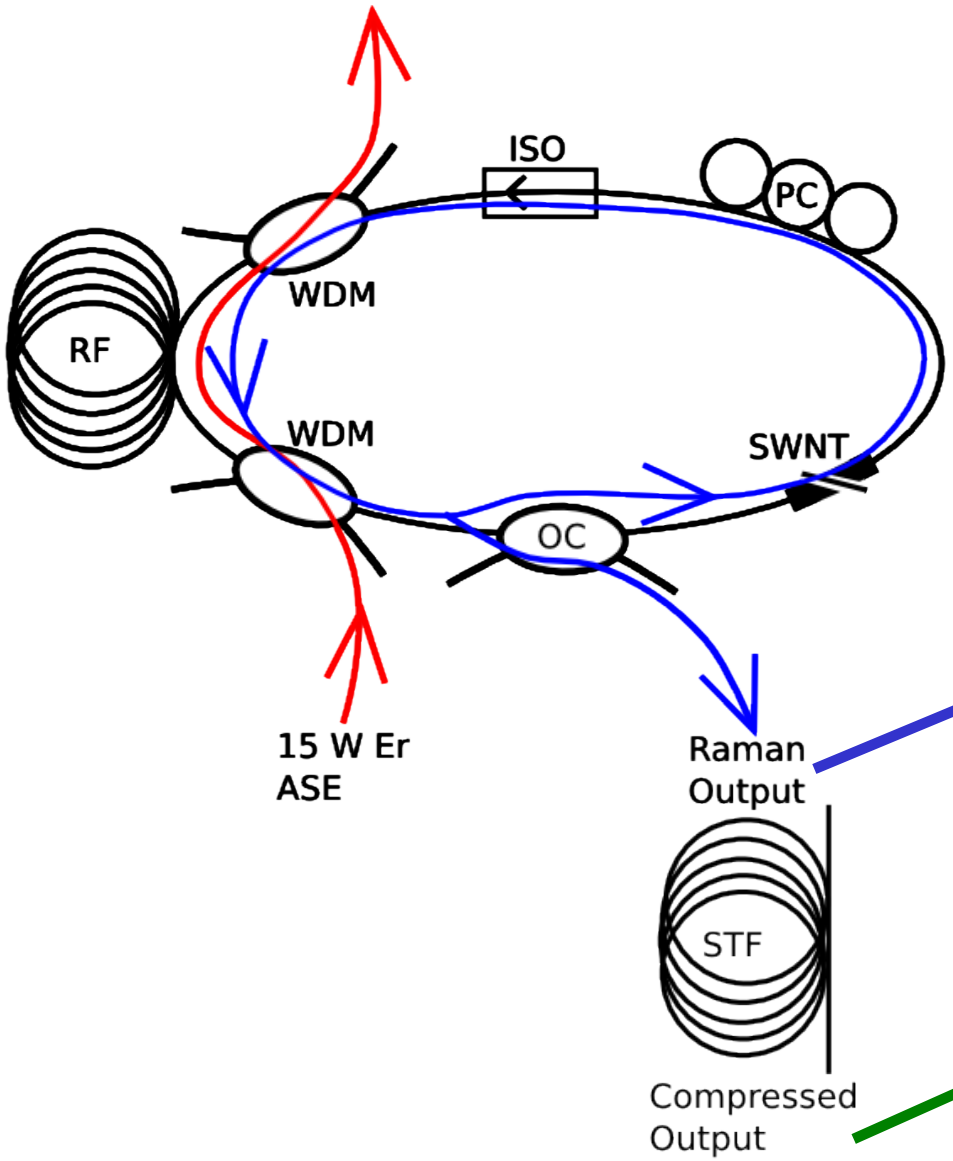
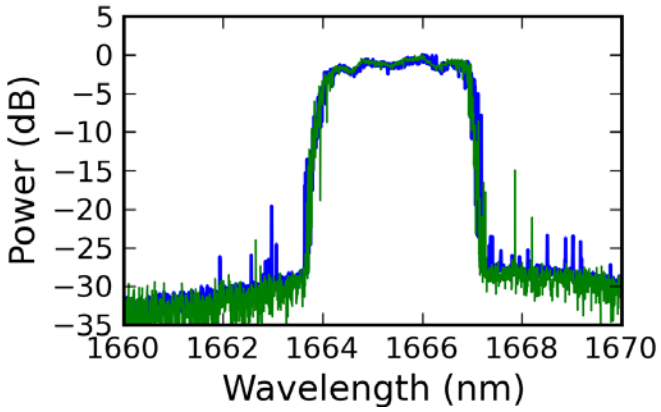
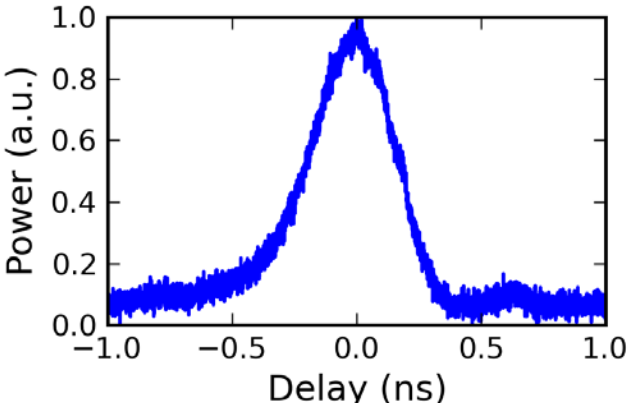
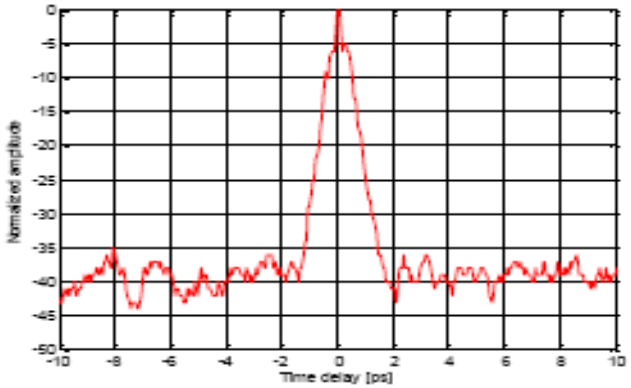
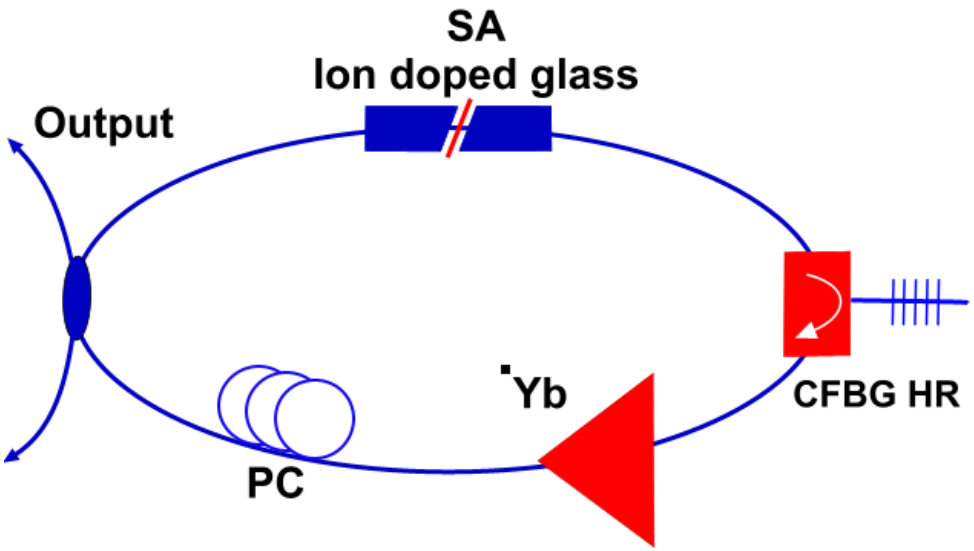


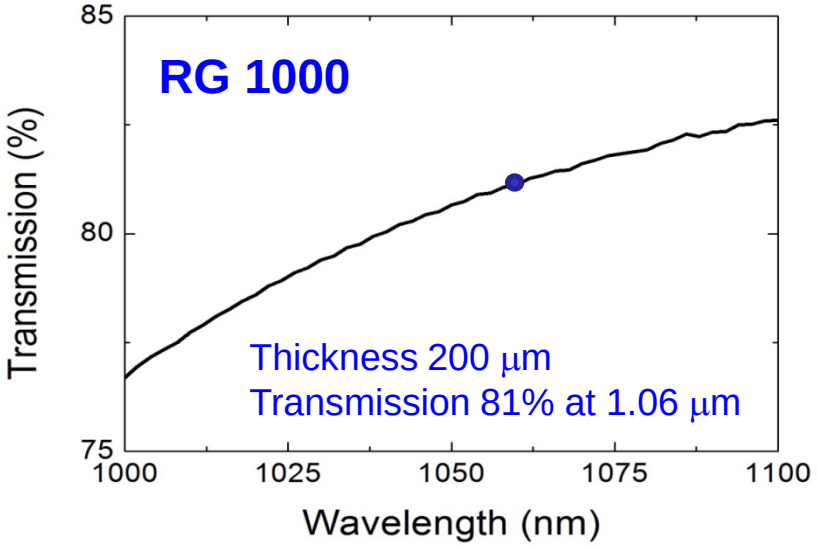


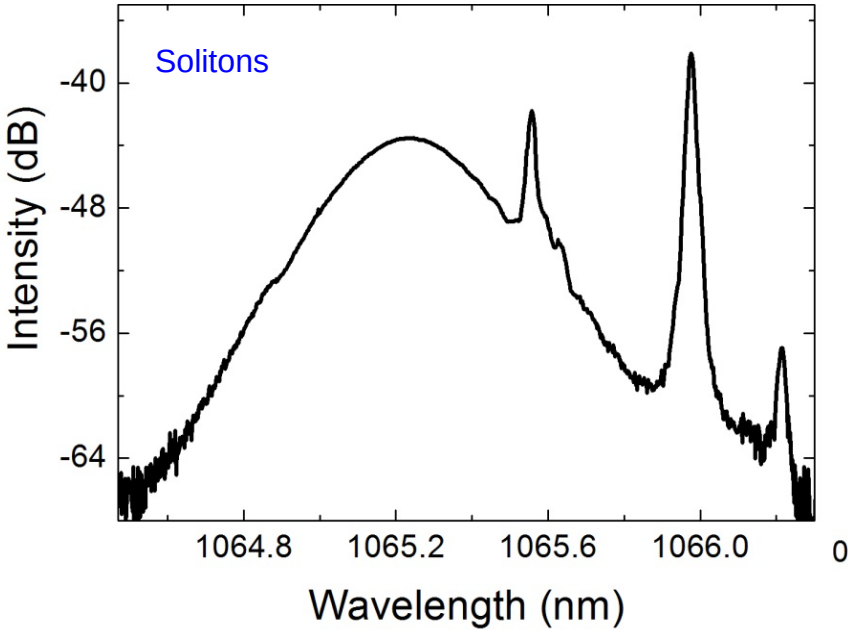


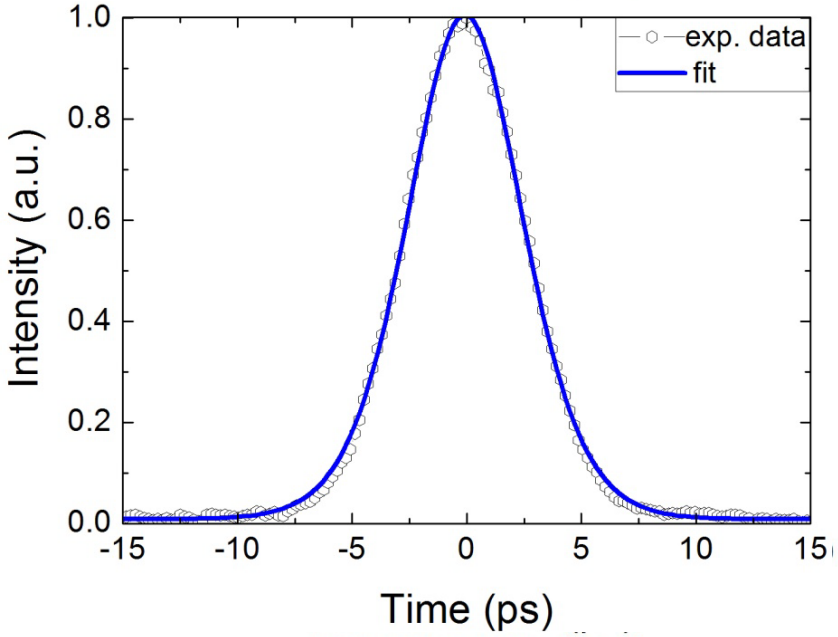


Ionically doped glass saturable absorber

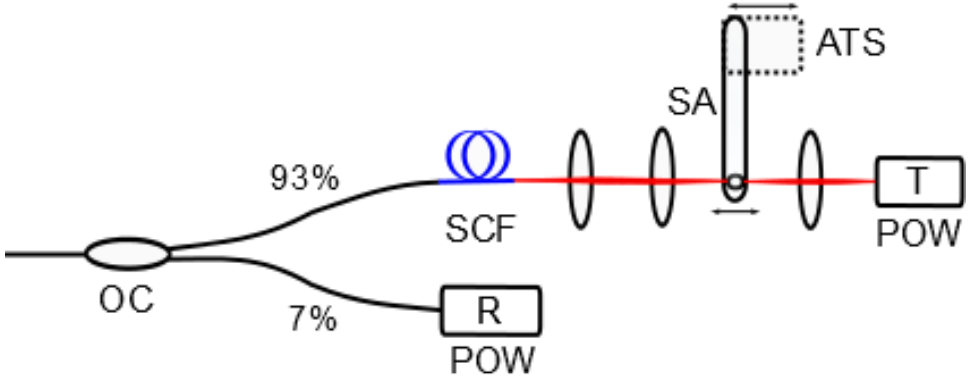






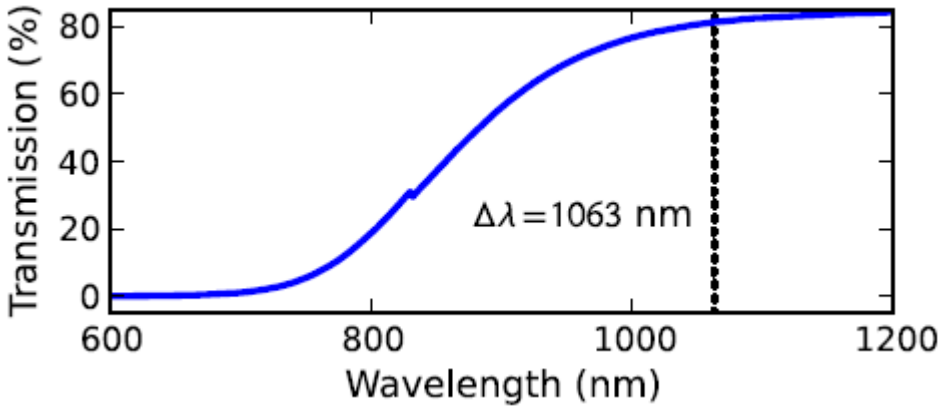


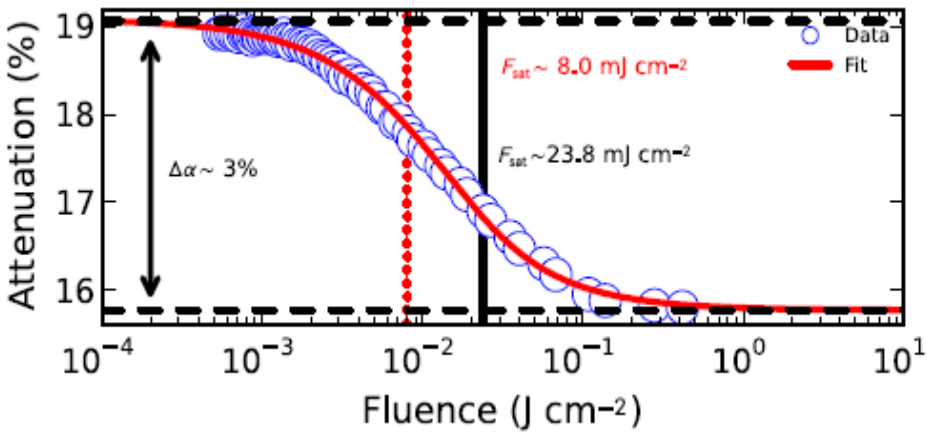
Ionically doped glass saturable absorber

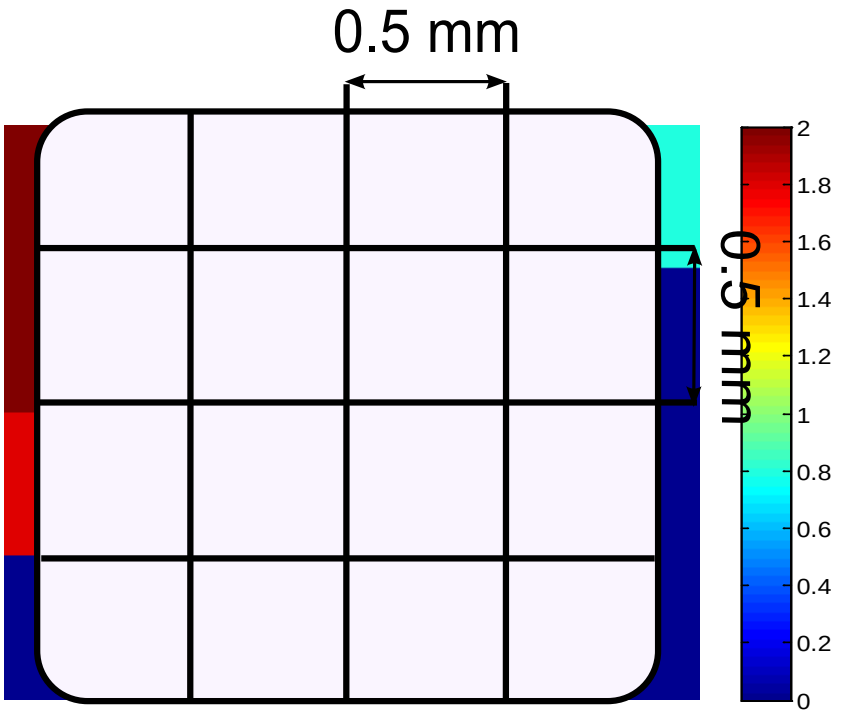


For each sample (200 μm thick)

- Modulation depth—2%
- Saturation Intensity—2.2 GW/cm^2







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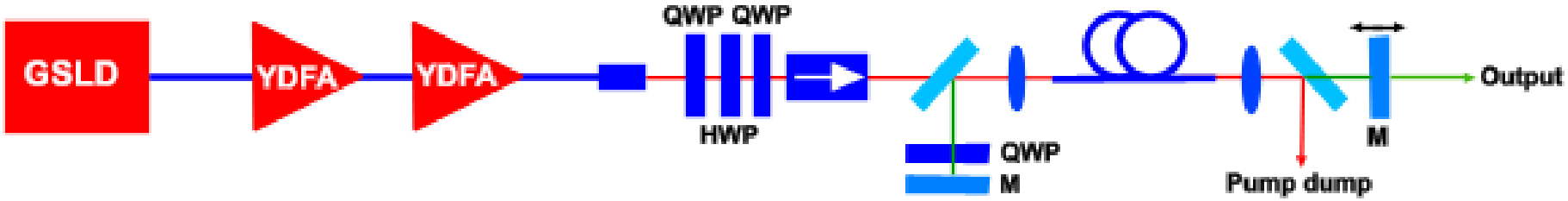
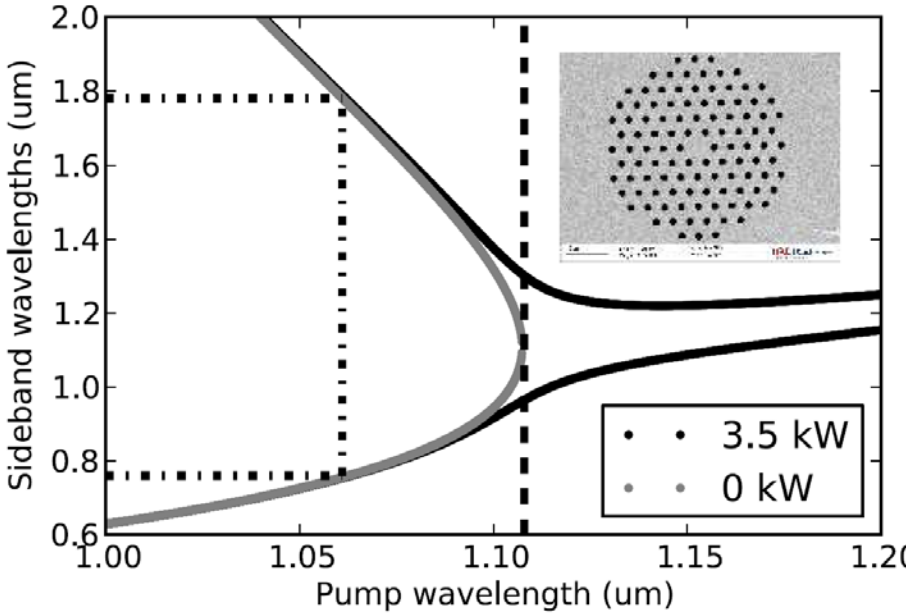
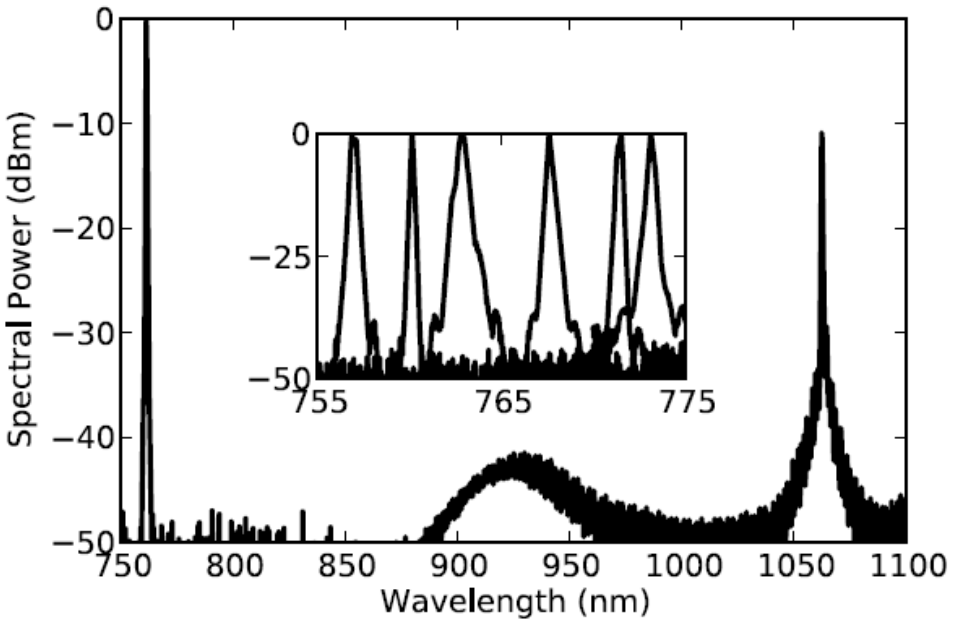
PCF Optical Parametric Oscillator

FOG femtosecond optics group



Pump - gain switched DFB at ~ 20 MHz (17.984MHz) Amplified ~ 14W (3.5kW peak)
PCF - ~2.6 m





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Optical Parametric Oscillation

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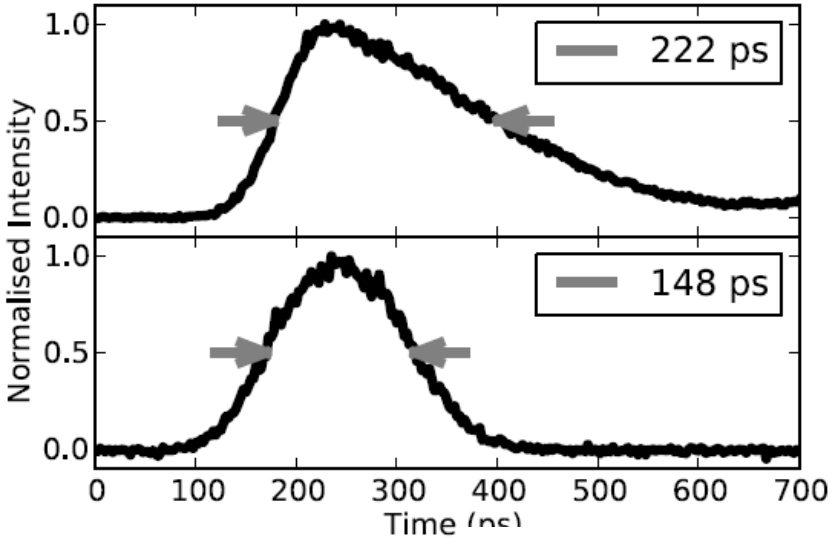

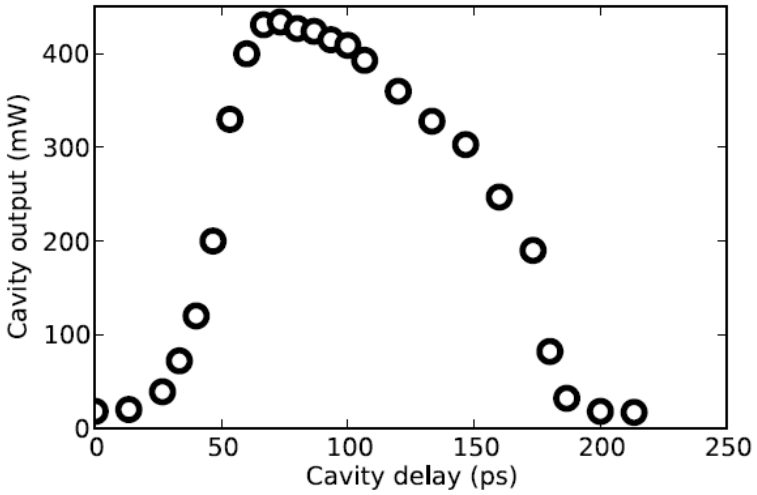

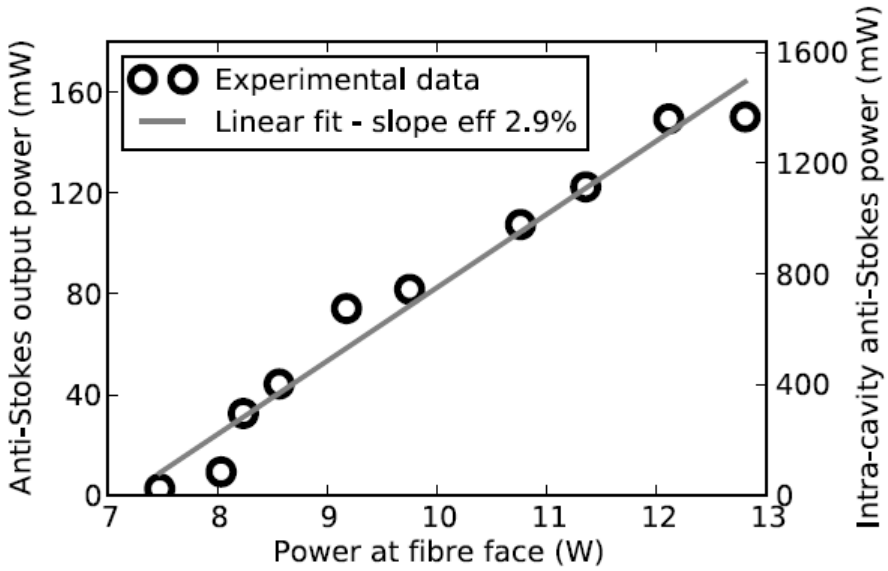

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Single Pass Parametric Generation

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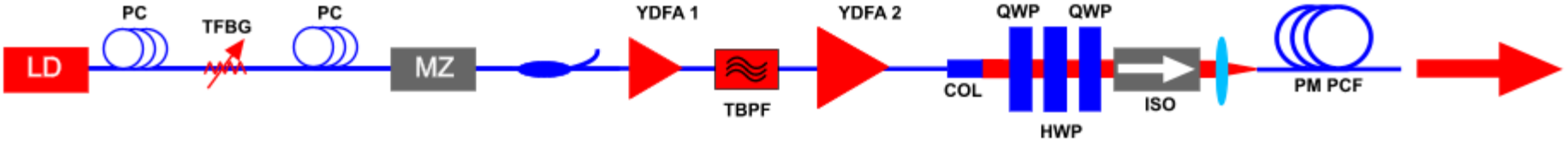
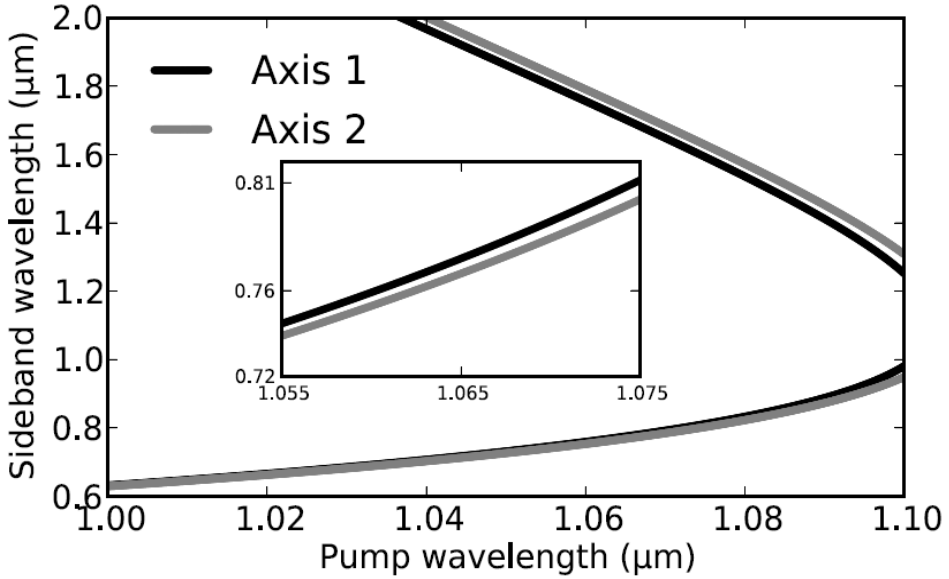
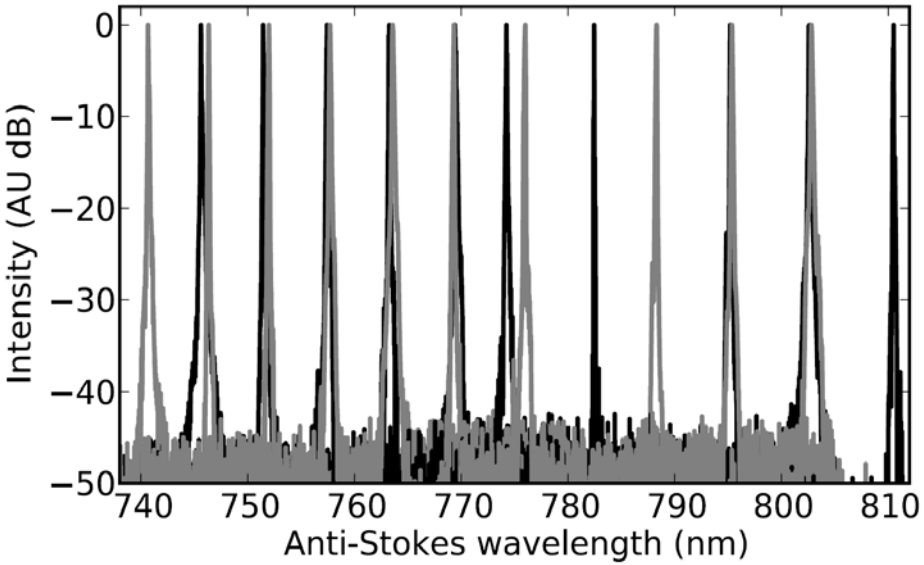




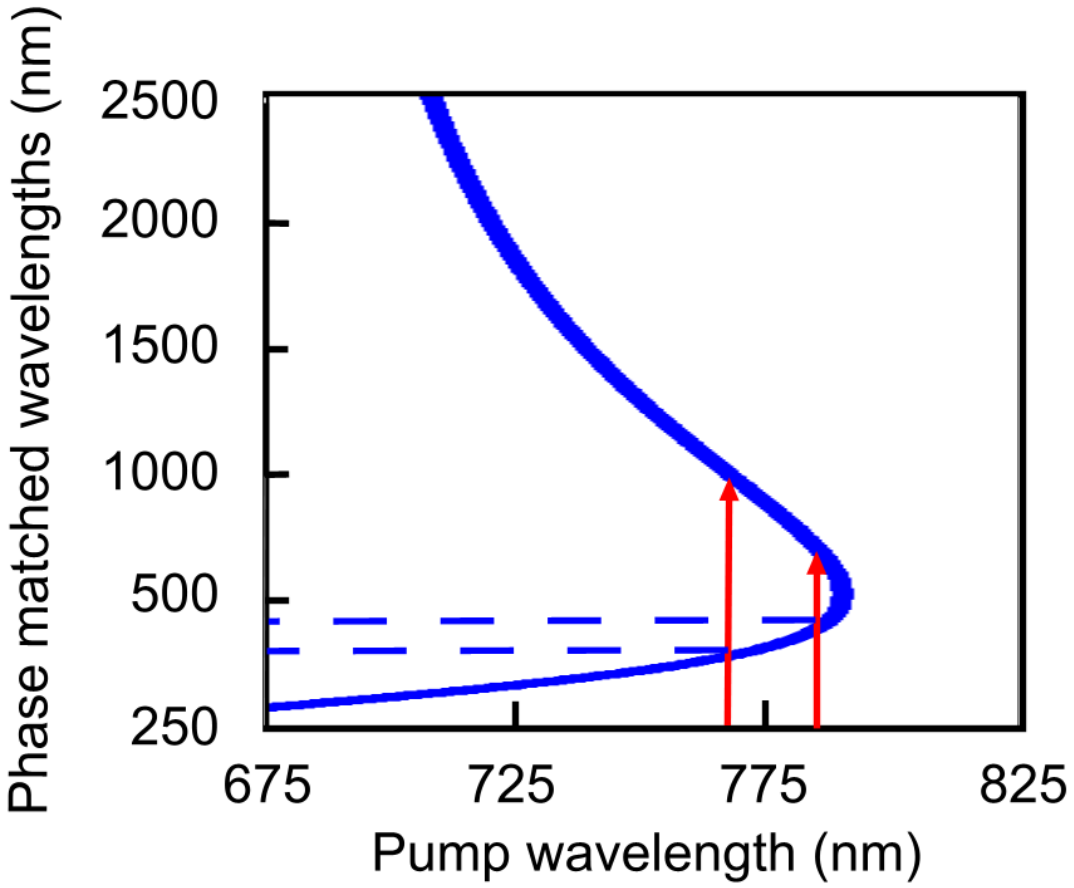


Curent development –Visible

PCF dispersion zero 795 nm

Pump tunable frequency doubled picosecond Er-MOPFA

767 nm- 785 nm produces 390-460 nm



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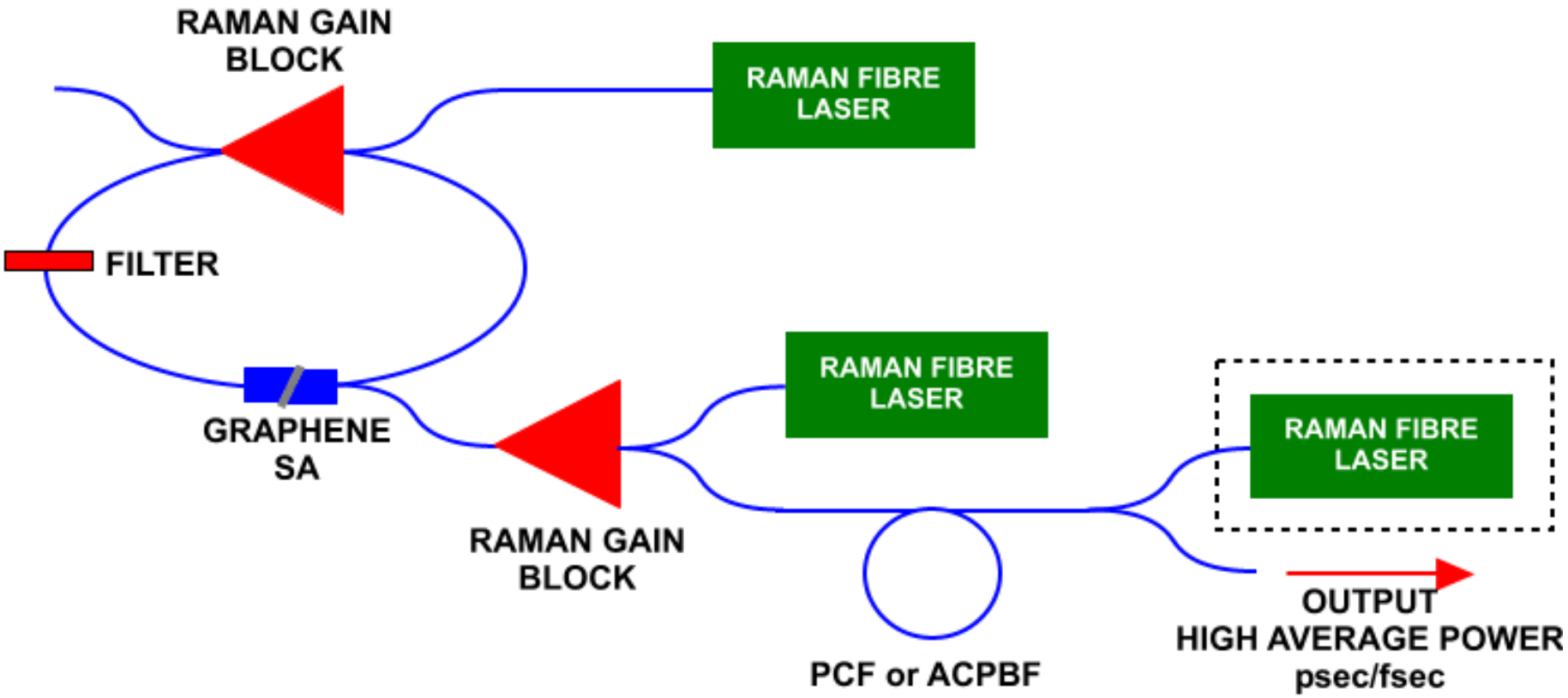
Universal short pulse source

FOG femtosecond optics group



Raman gain based
All building blocks are in place

Summary

Fibre based systems are providing versatility in

- Wavelength
- Pulse duration
- Repetition rate

Further simplification are in development

- All-fibre configurations
- Single systems providing the above characteristics