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“Fibre lasers”

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Fibre Lasers – A very Brief History

- Snitzer 1964 Neodymium doped alkaline-glass fibre flashlamp pumped *(Koetser and Snitzer Applied Optics 3, 1182 (1964))*
- Stone and Burrus 1973 Neodymium doped silica glass fibre laser diode pumped *(Stone and Burrus App. Phys. Lett. 23, 388 1973)*
- Fabrication of low-loss optical fibres containing rare earth ions 1985. *(Poole, Payne and Fermann Electronics Letters 21, 737 (1985))*
- Q-switched Nd single mode fibre laser 1986 *(Alcock et al, Elect Lett. 22, 295 (1986))*
- Q-switched, mode locked Nd: fibre laser 1987 *(Alcock et al, IEE Proc 134 J, 183 (1987))*
- Yb-doped fibre laser 1988 *(Hanna et al. Elect. Lett. 24, 1111 (1988))*
- Erbium doped fibre amplifier 1987, developed 1987-1991, leading to telecoms boom *(Mears et al , Electronics Letters 23, 1026 (1987))*
- Sub picosecond passively mode locked fibre laser 1991 *(Duling, Optics Letters 16, 539 (1991))*
- Parallel combining and diode laser pumping dual clad fibre 1999 (IPG Photonics) leading to development of integrated, high power fibre lasers >50kW CW multimode and 10kW single mode.

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Advantages of Fibre Lasers

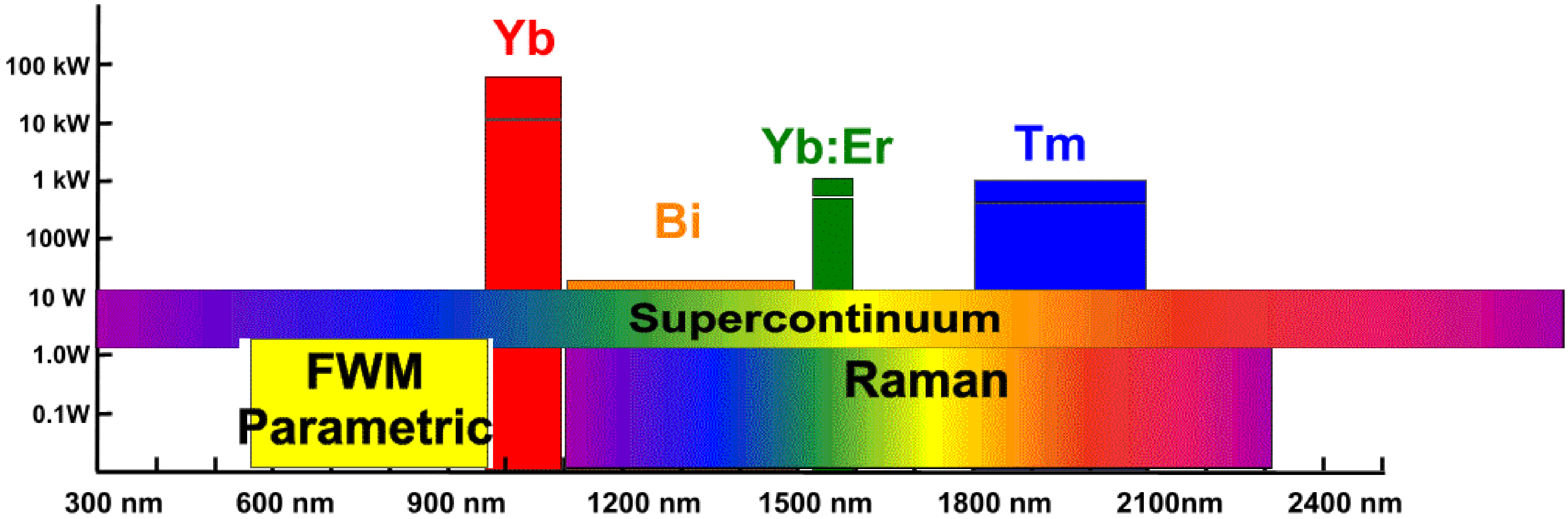
FOG femtosecond optics group

- Distributed high gain
- Low heat load
- Gain diversity from 1 to 2 μm – and beyond
- Pumping with high brightness/efficient semiconductor lasers
- High beam quality (currently 10kW at 1 μm diffraction limited)
- Electrical to optical efficiency up to 33%
- Mechanical stability and compactness due to all-fusion-spliced fibre designs
- Versatility in temporal format femtosecond to cw

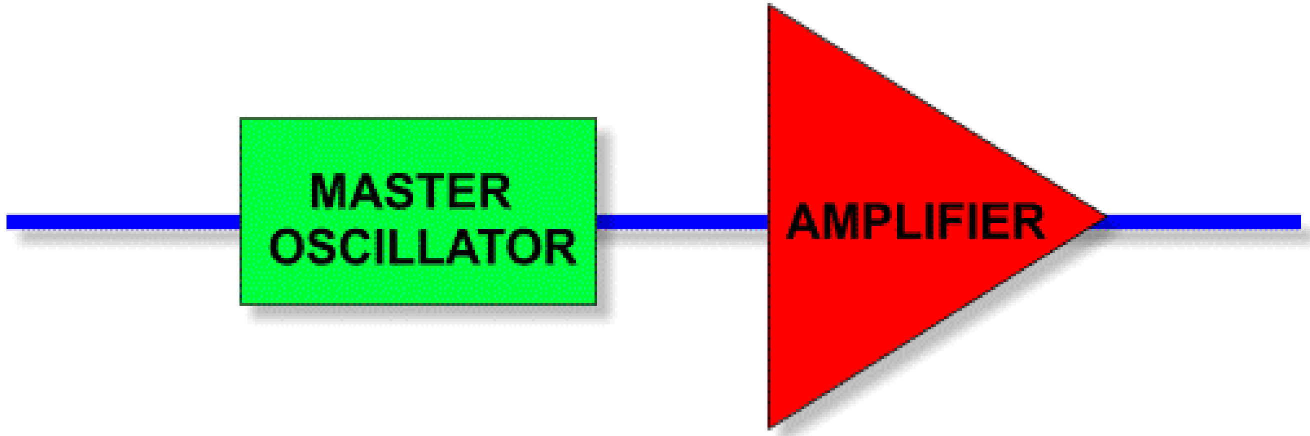
However!

- High energies and peak powers are limited in single mode format as compared to solid state gain media.

High power fibre lasers



MOPFA Technology



Master Oscillator

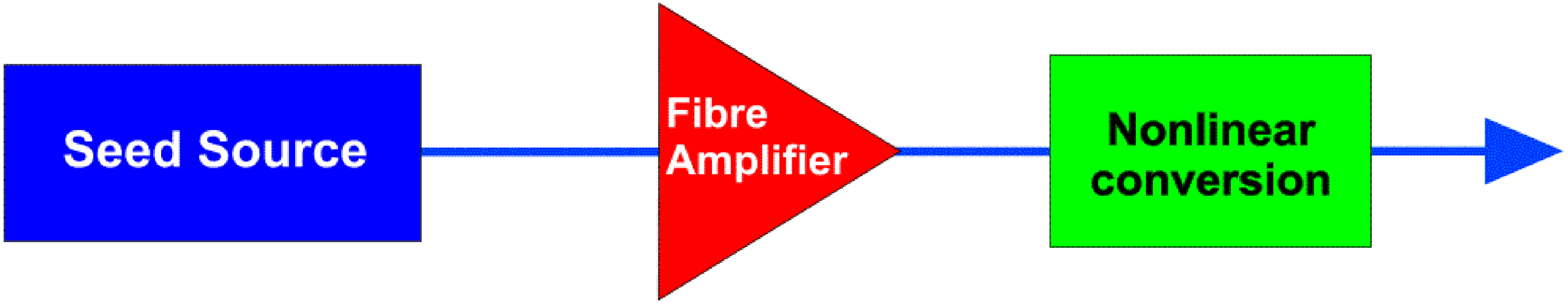
- Diode/fibre laser seeding
- Versatile parameter control
- Direct modulation
- Fibre integrated

High Power Fibre Amplifier

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

Key concept – Efficient power extraction from large mode area fibre amplifiers

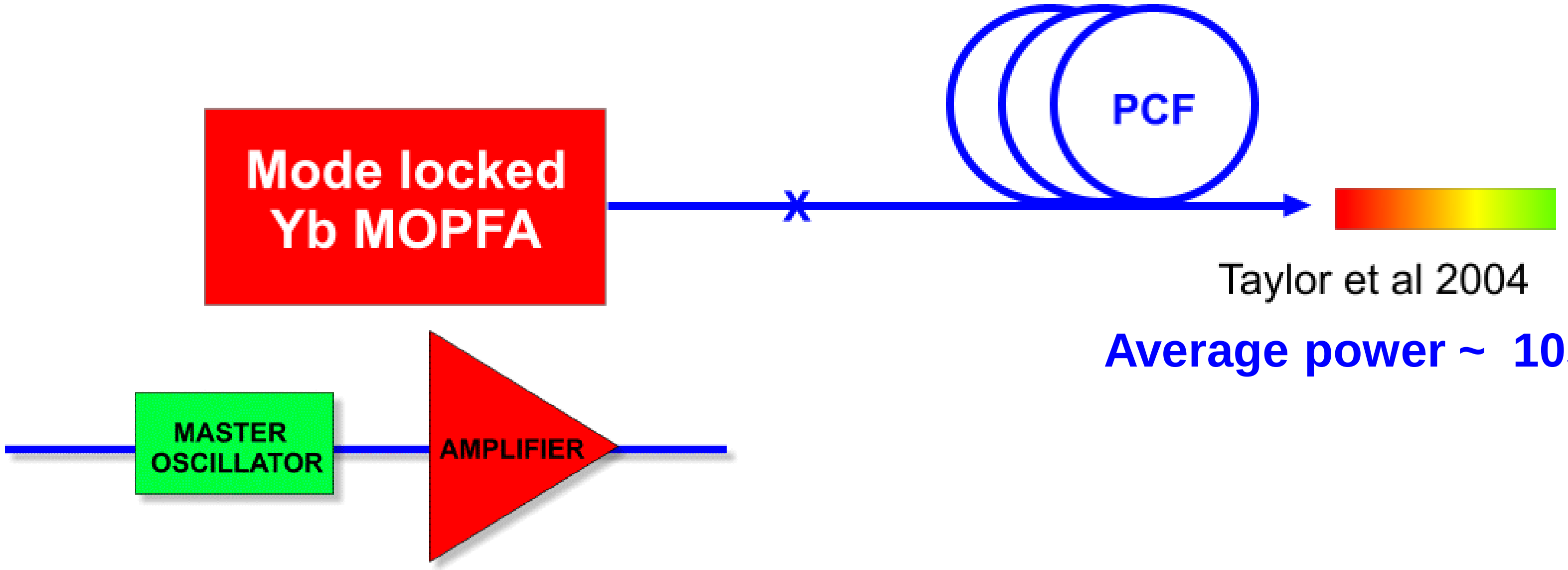
MOPFA plus non-linearity



Arsenal of Nonlinearities:-

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

High power supercontinuum sources



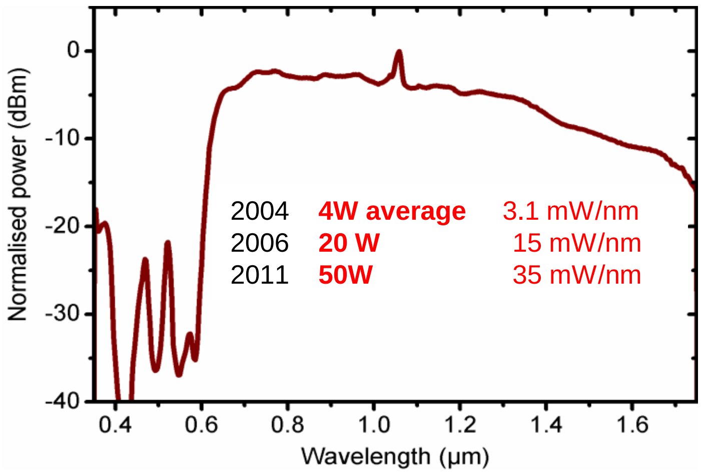
Taylor et al 2004

Average power ~ 10s W

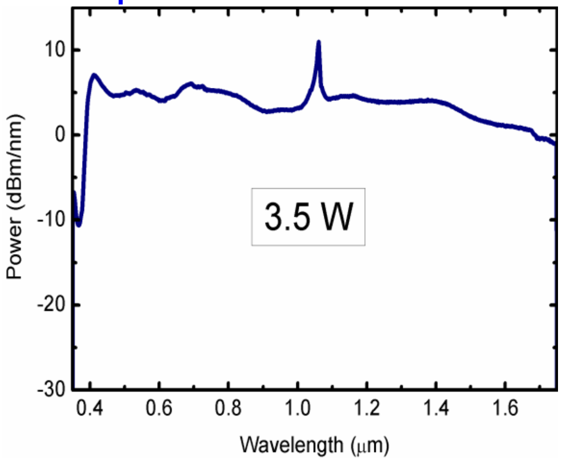
Advantages:-

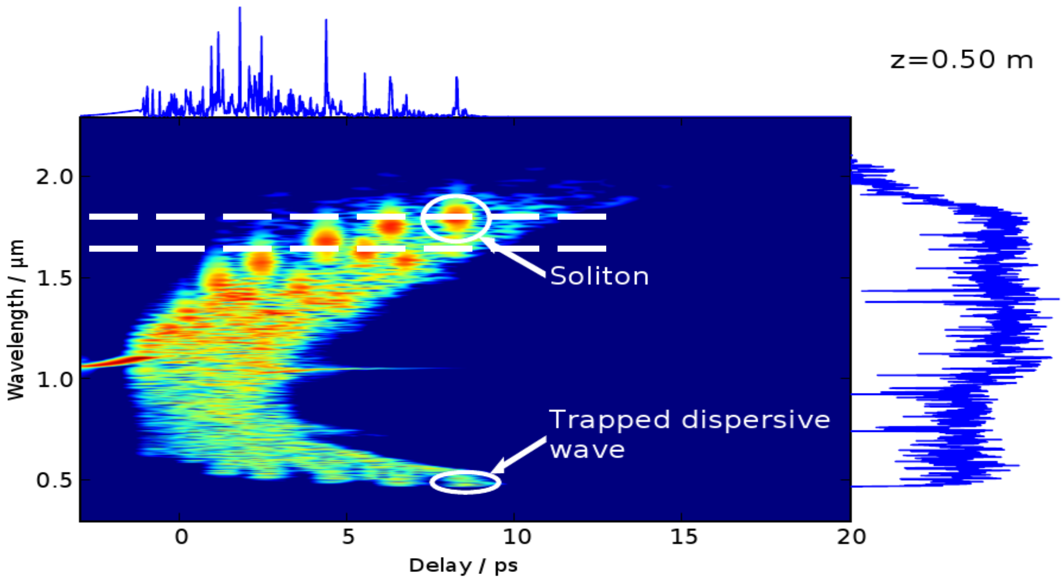
- **Fully fibre integrated**
- **Power scaling – spectral power densities 10s-100 mW/nm**
- **Control of pump wavelength – Yb, Er, Tm or Raman fibre lasers**
- **Precise control of fibre parameters**
  - ✓ **manipulate dispersion and group velocity matching**
  - ✓ **manipulate nonlinearity**

Dynamics of picosecond pumping



Operation down to 320 nm





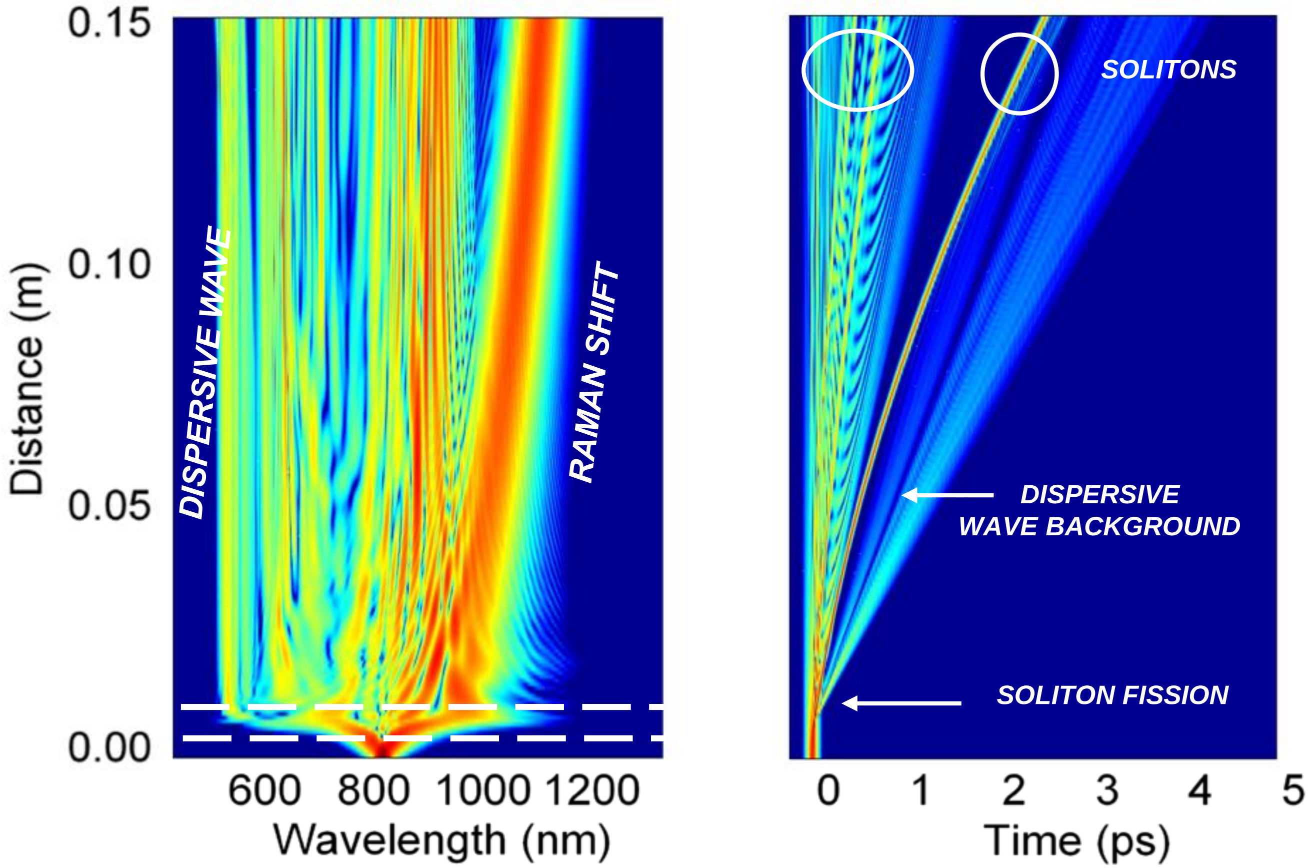
- **Identical dynamics for CW pumped systems - MI and noise 100 mW/nm**

Femtosecond pulse pumping

Dominated by soliton dynamics

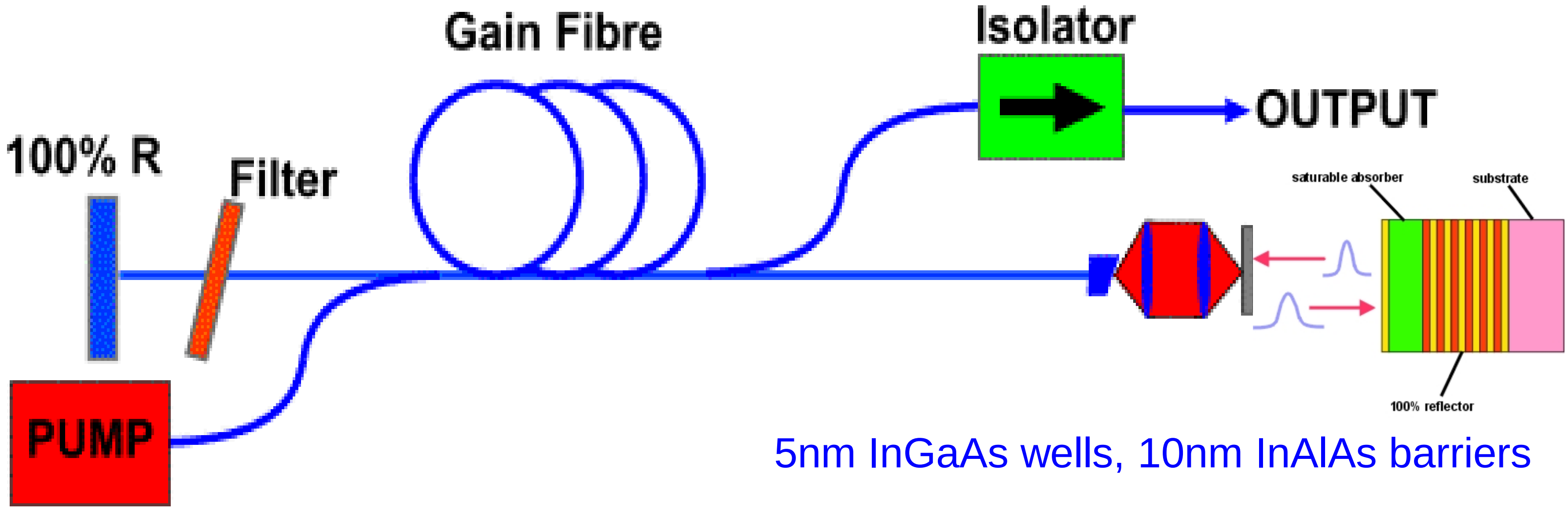
Dudley et al.

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

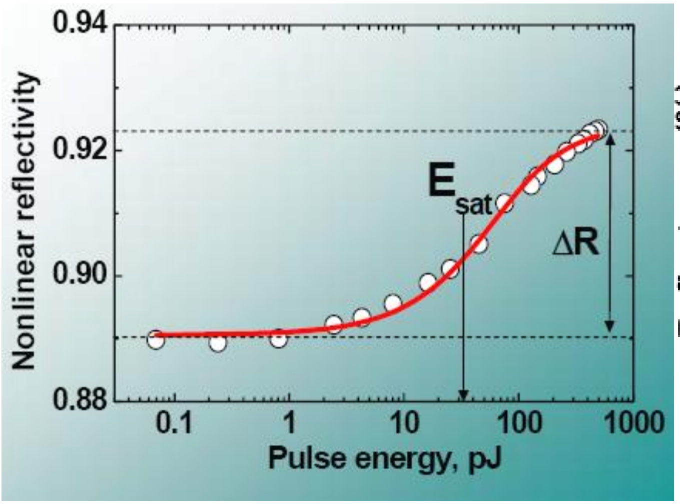


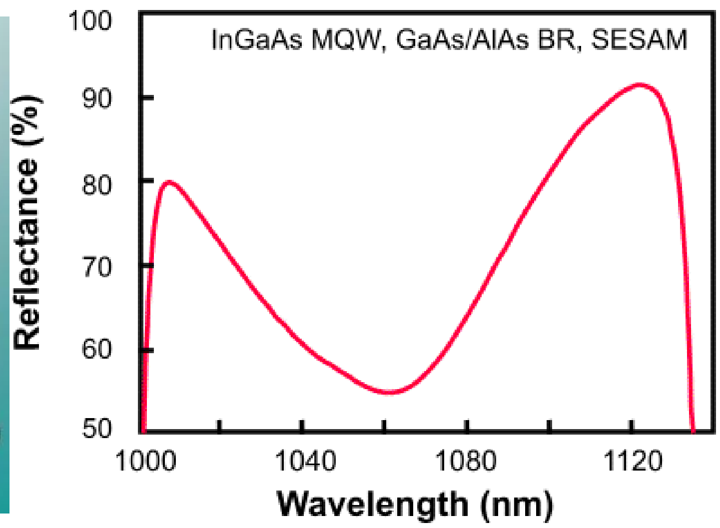
Alternatively – use all normal dispersion and use SPM

Passively mode locked lasers



5nm InGaAs wells, 10nm InAlAs barriers



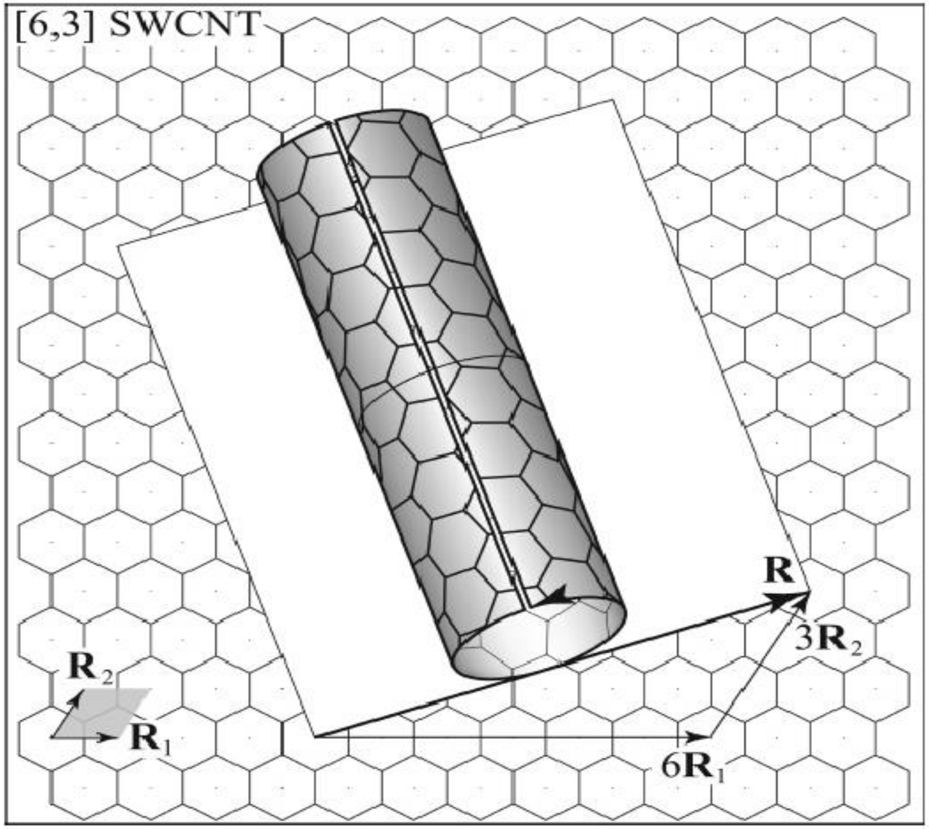


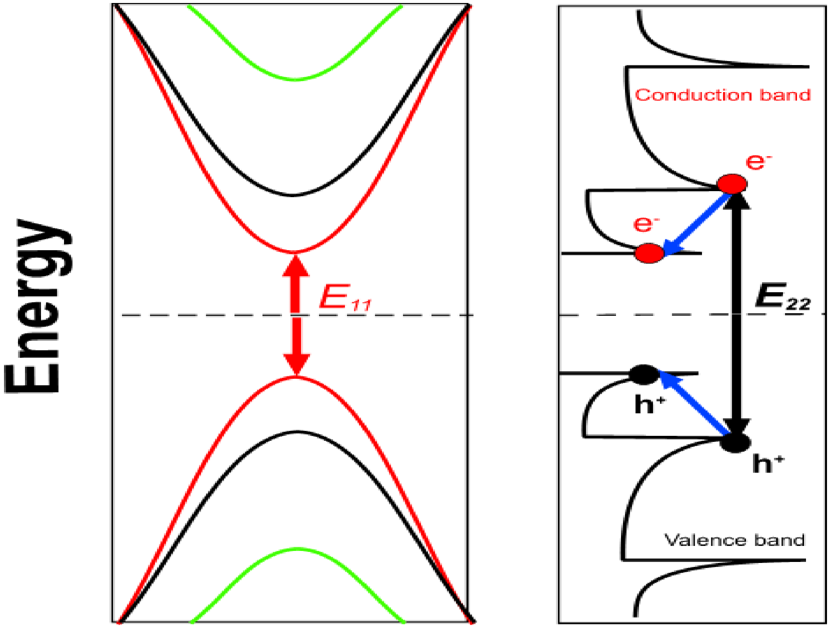
Dual recovery time:-
Fast , sub ps
intraband thermalization

Slower , 10's ps
carrier recombination

Carbon Nanotube Saturable Absorbers

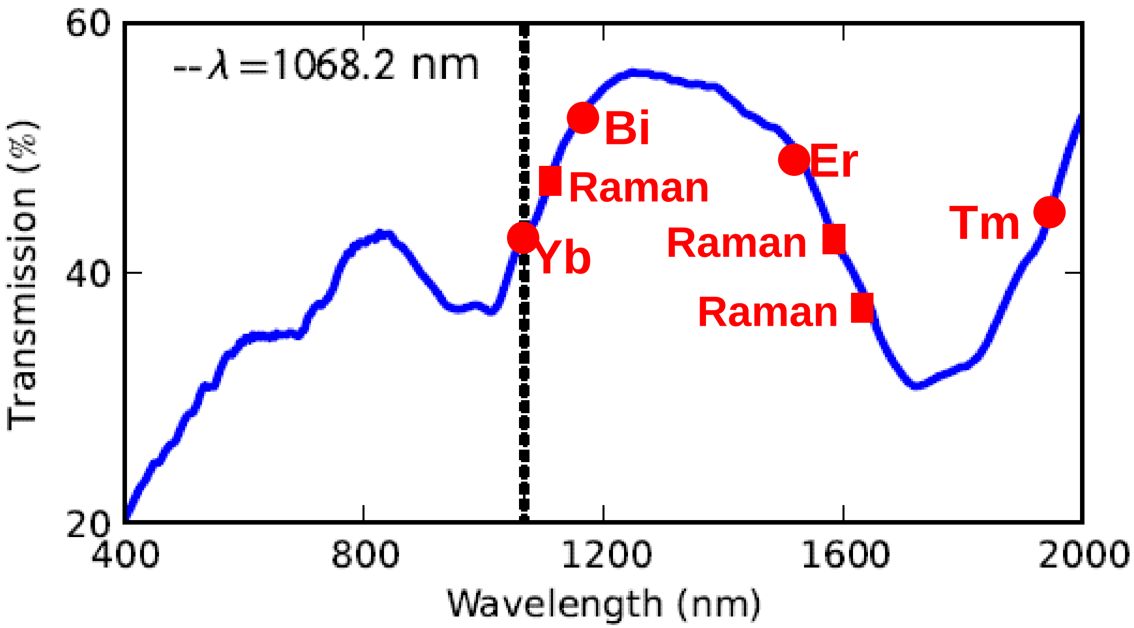
Grown by various techniques:-
Laser ablation
Arc discharge
CVD over catalyst ($Mg_{1-x}Co_xO$)
High pressure CO (~10g/day)





- Saturation fluence ~5 $MWcm^{-2}$
- 15 %-20% mod depth at 1.55 μm
- Problem – background loss   ~ few %

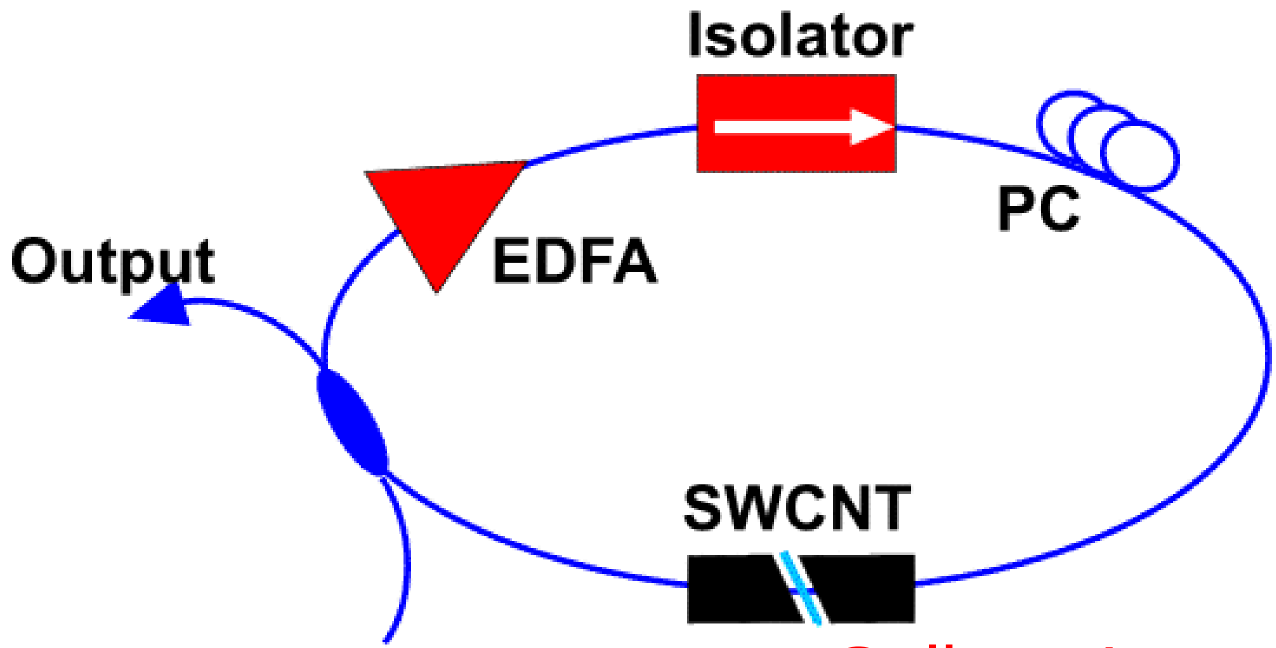
Carbon nanotube saturable absorbers



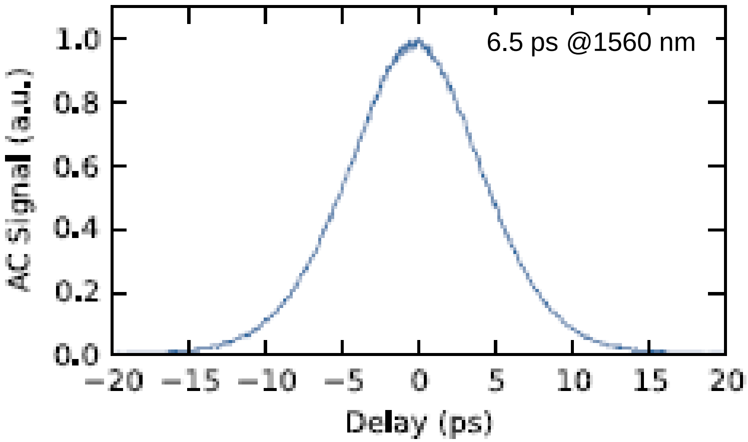
Transition	Modulation Depth	Saturation Intensity	Transition Lifetime
E_{11}	13%	~ 10 MW cm^{-2}	~ 400 fs
E_{22}	15%	~220 MW cm^{-2}	~ 40 fs

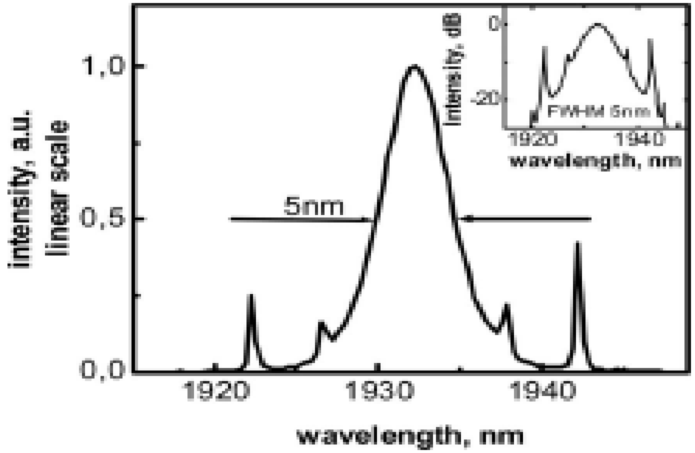
Improve wavelength versatility through use of - mixture of tubes – loss !!
- multiple wall tubes

CNT passively mode locked fibre lasers

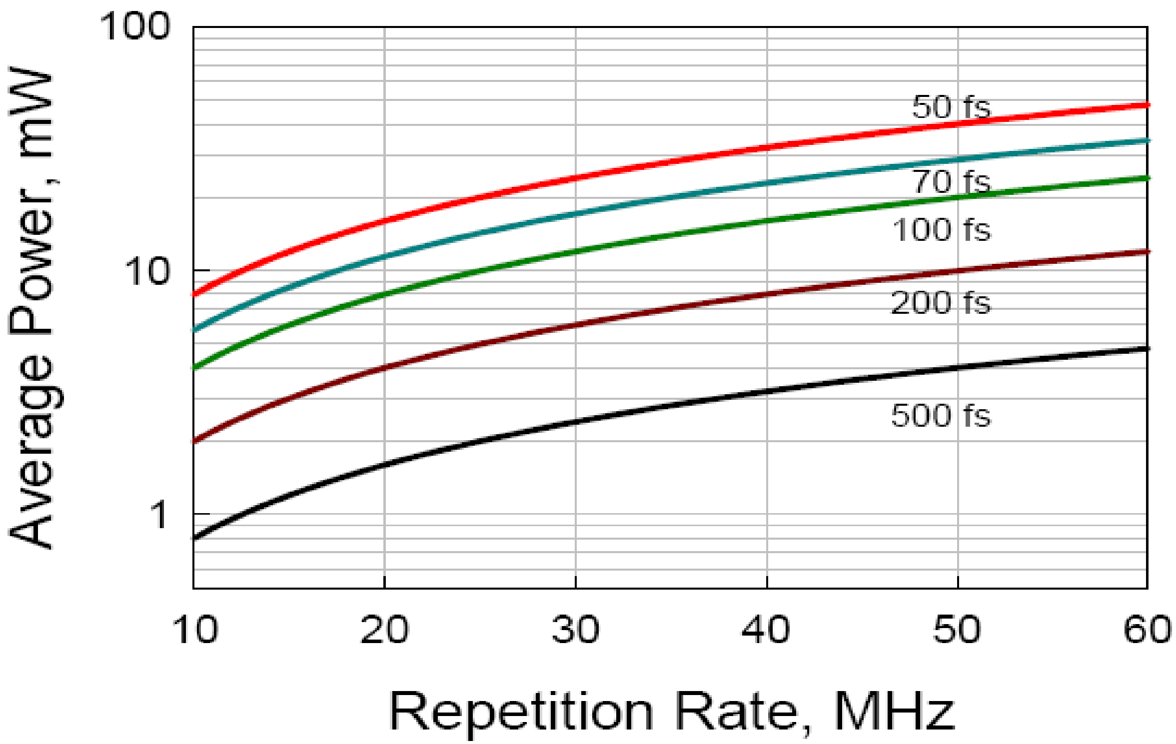


Solitons!





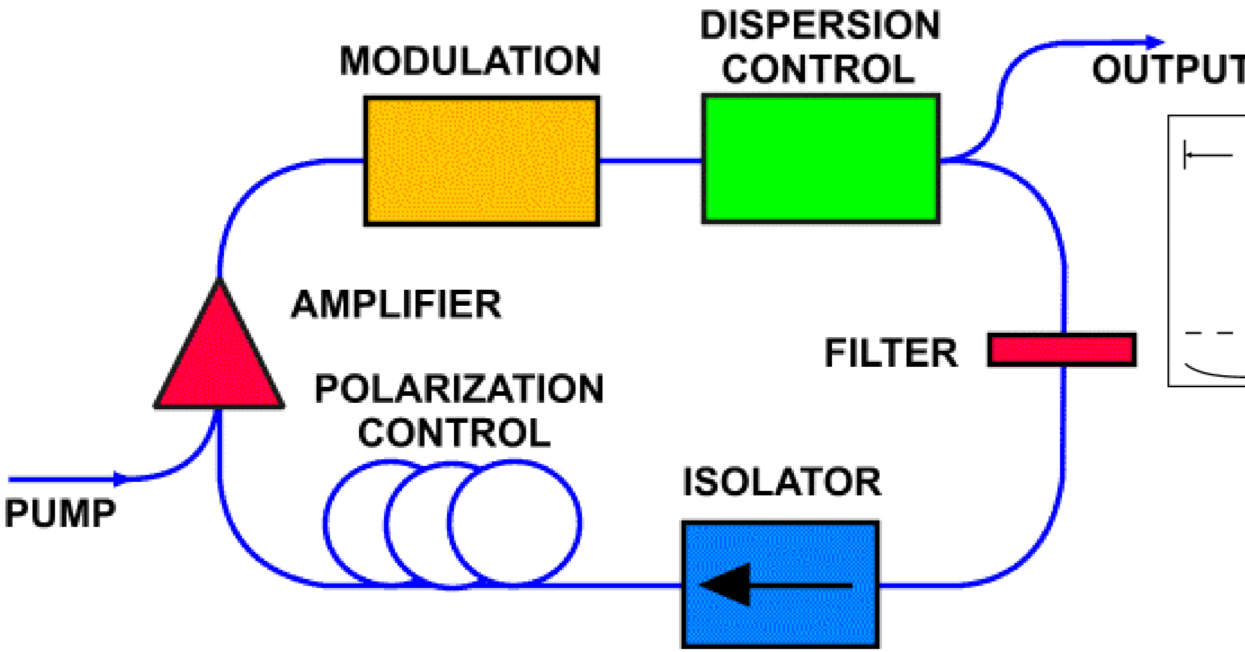
Power requirements for soliton

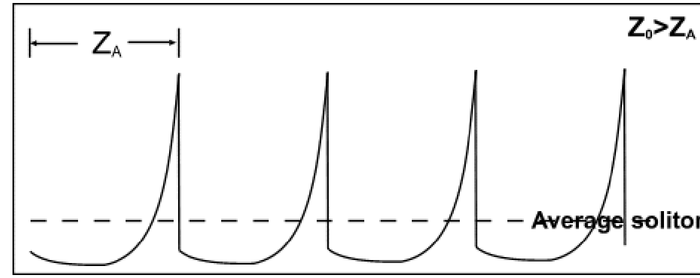


At repetition rates from a conventional fibre laser, for pulse durations in the 500fs-1ps regime only a few mw average power is required

For many applications AMPLIFICATION needed

Soliton fibre lasers

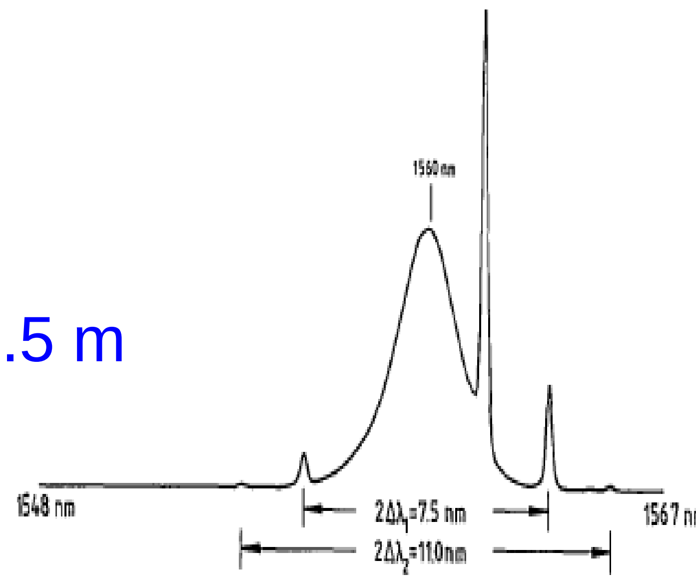




Soliton length $\approx 0.25\tau^2/D$

If τ = 500 fs, D = 5 ps/nm/km Z_0 ~ 12.5 m

Solitons will react and shed radiation



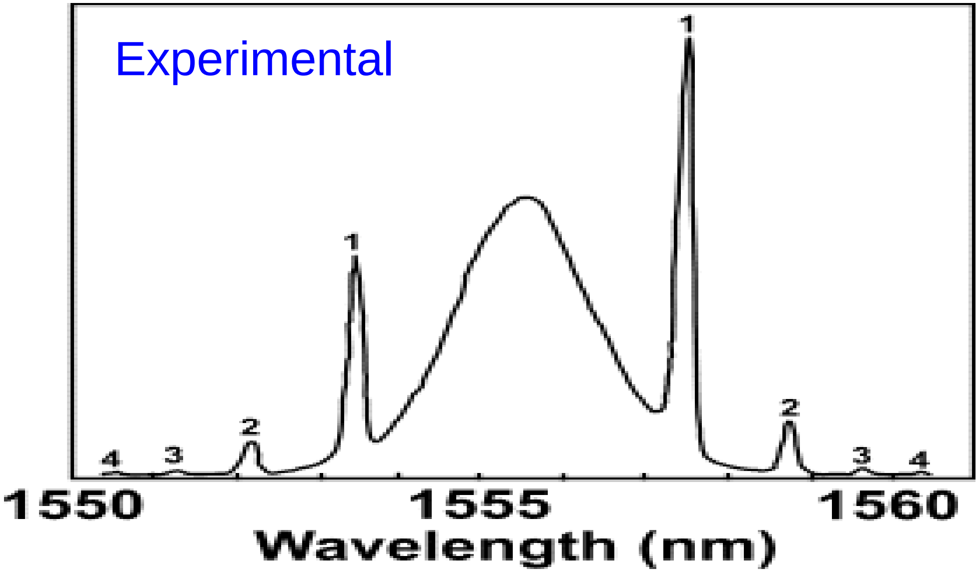
Spectral instability - sidebands

$nK_A = K_{SOL} + K_{DISP}$ gives $\frac{2\pi n}{Z_A} = \frac{1}{2} + \frac{\Delta\omega^2}{2}$

Rearranging

$$\Delta\lambda = \frac{\lambda^2}{2\pi c\tau}\sqrt{\frac{8nZ_0}{Z_A} - 1}$$

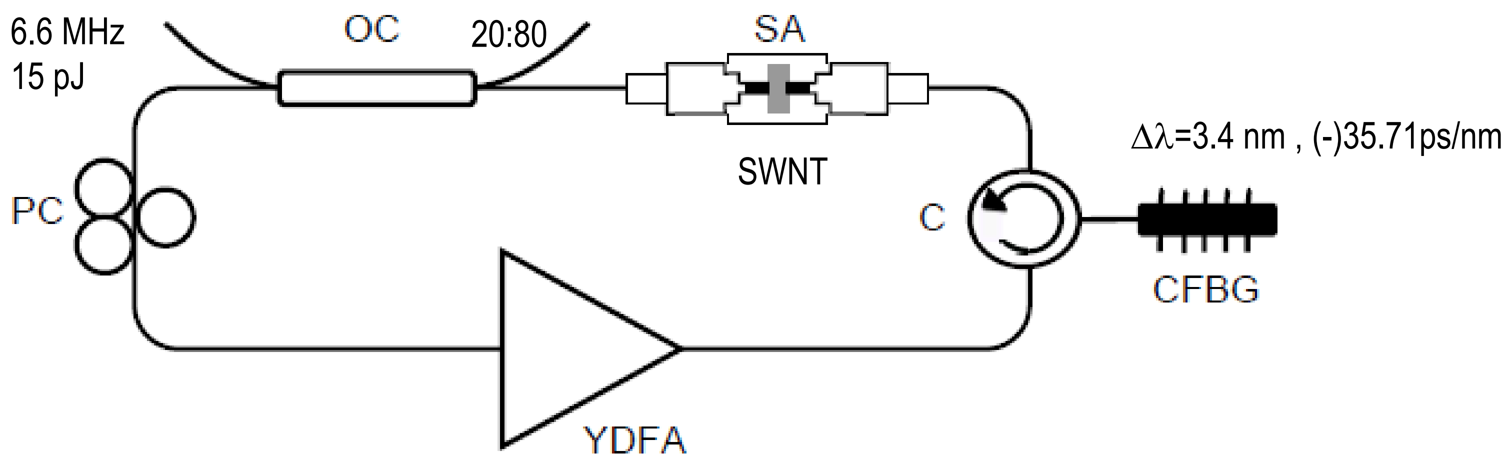
Kelly, Elect Lett. 28, 806 (1992)

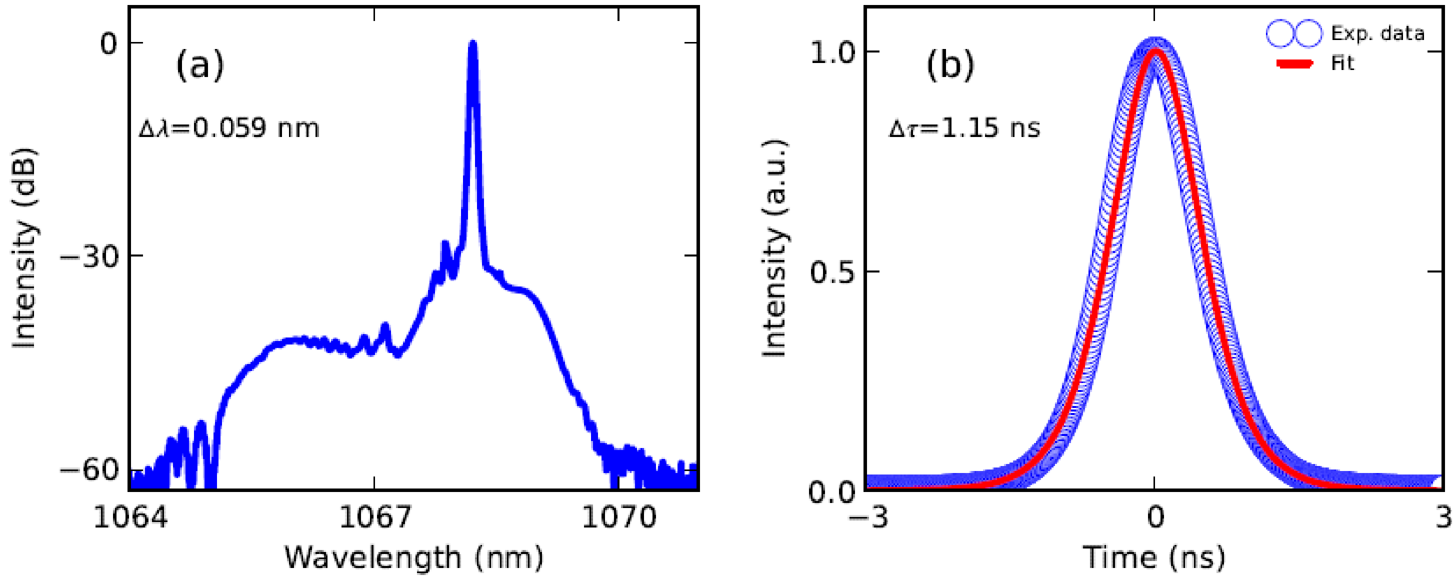


Sidebands:-

- Independent of power
- Non uniform distribution
- Determine “average” D
- Eliminate by filtering

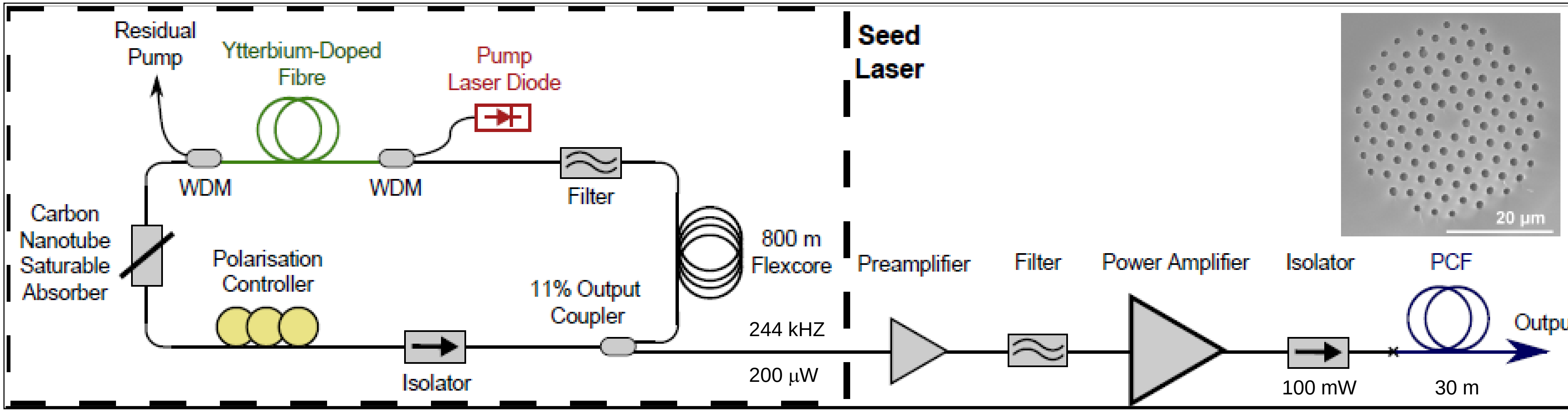
CNT passively mode locked fibre laser



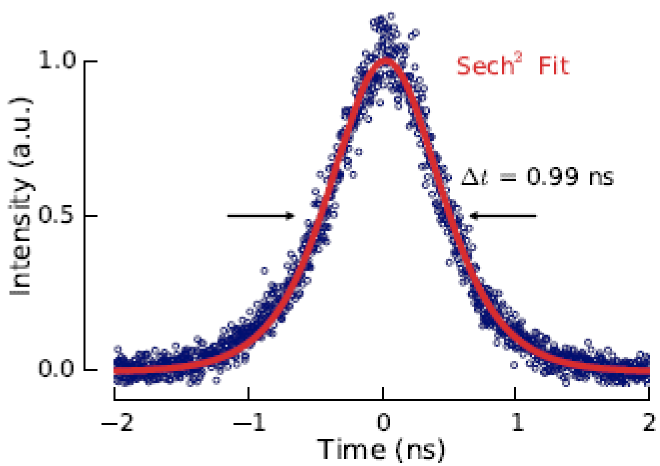


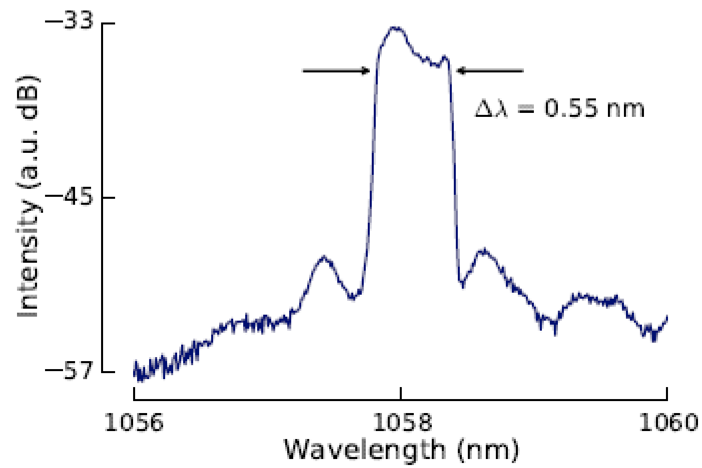
ΔνΔτ~18

Low repetition rate supercontinuum source

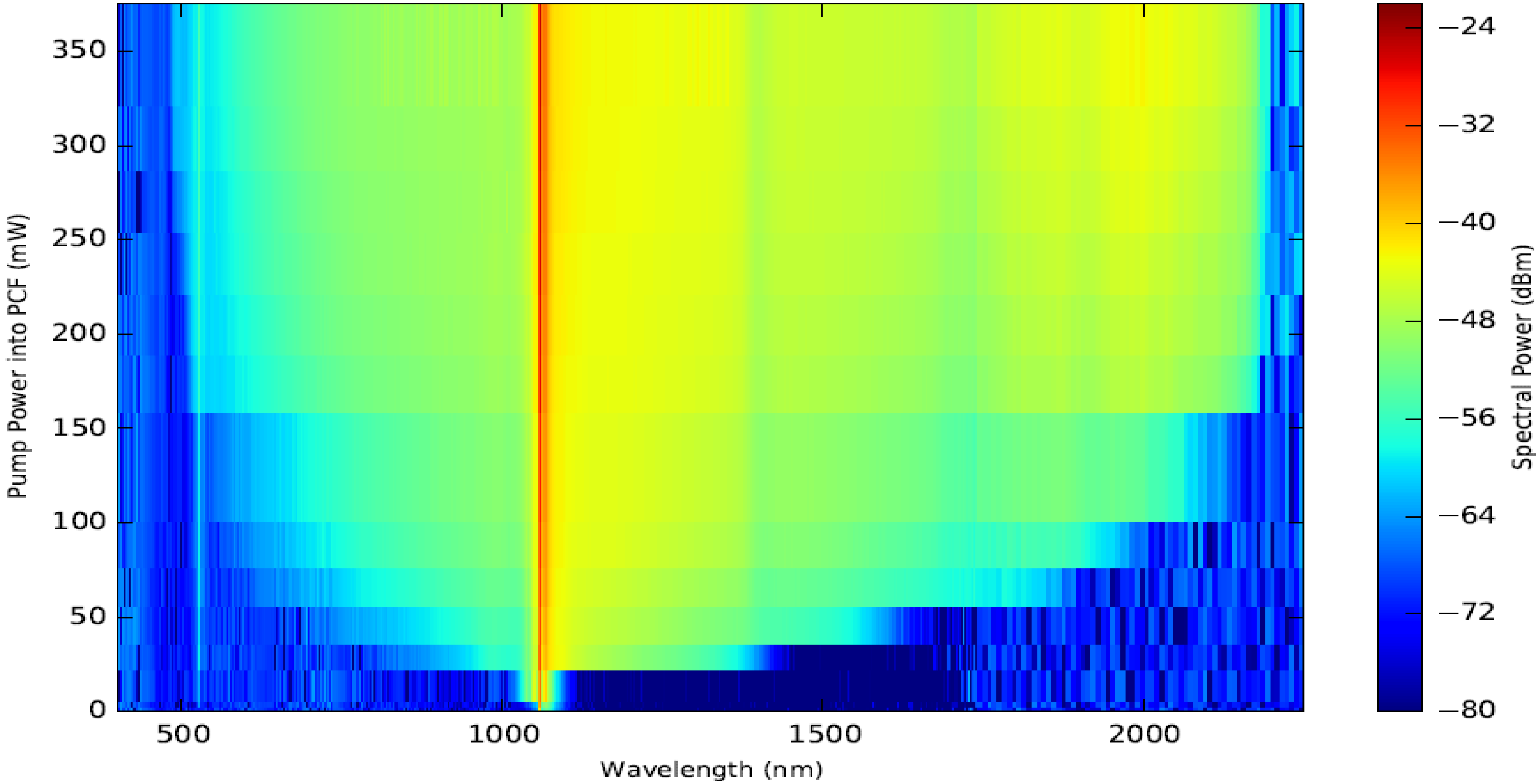


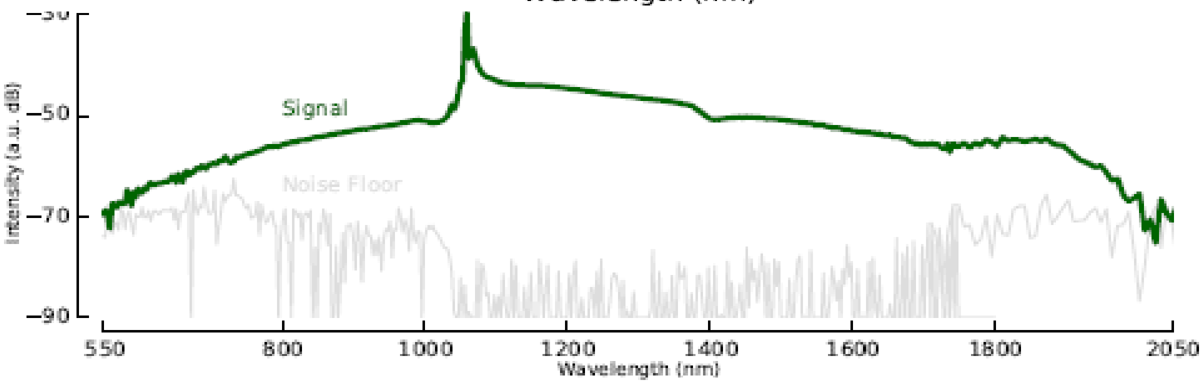
$\Delta\nu\Delta\tau \sim 143$





Low repetition rate supercontinuum source





87 mW pump power

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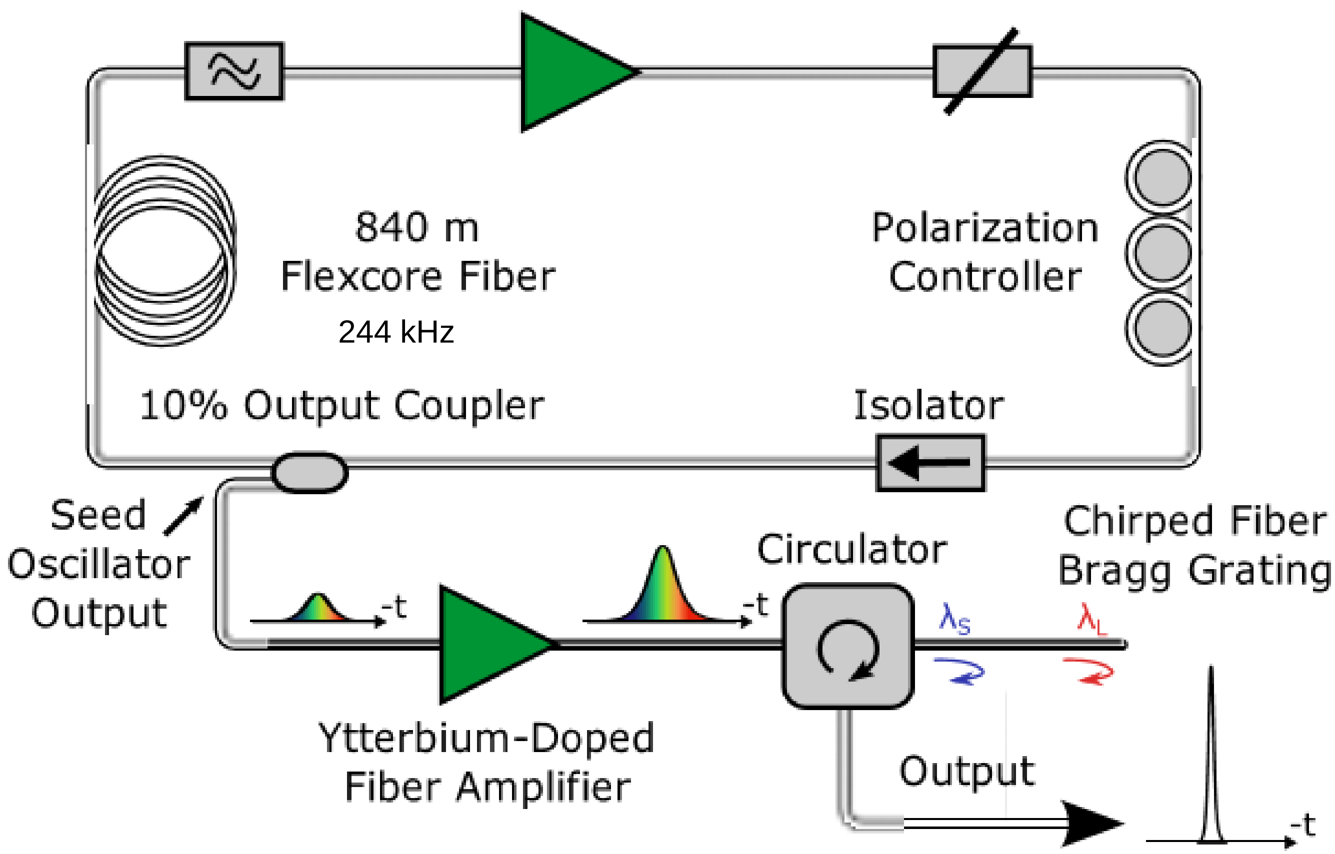
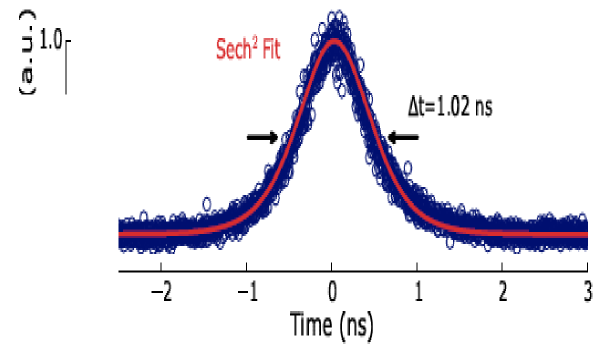
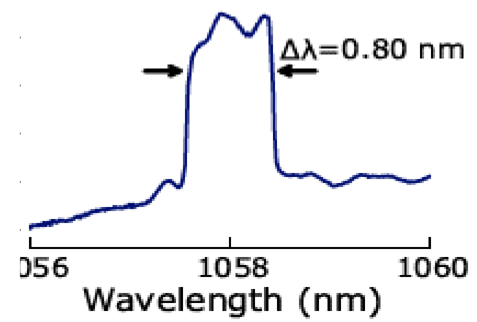
Giant chirp laser

FOG femtosecond optics group

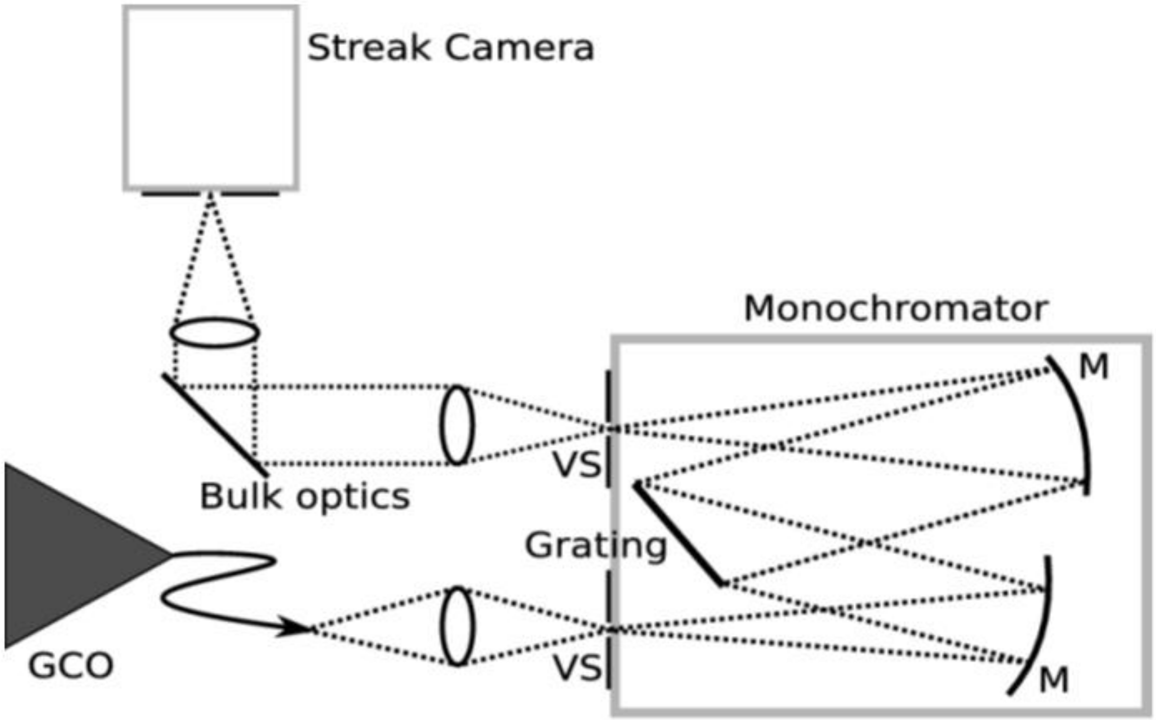




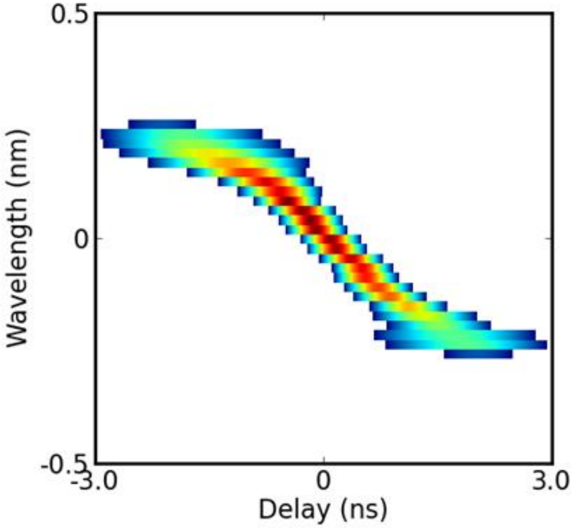


$\Delta\nu\Delta\tau \sim 219$

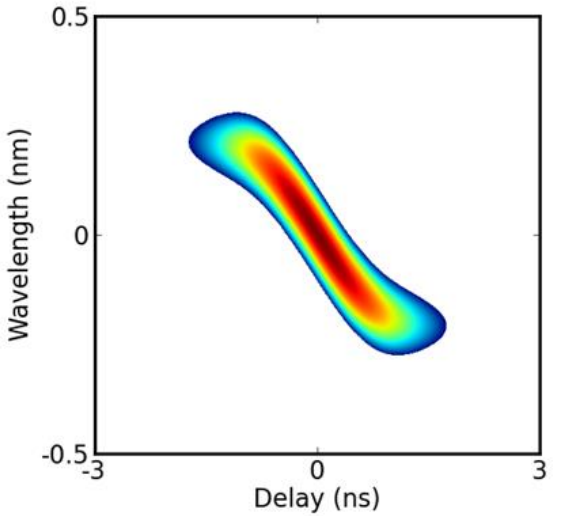
Chirp Measurement



Experimental



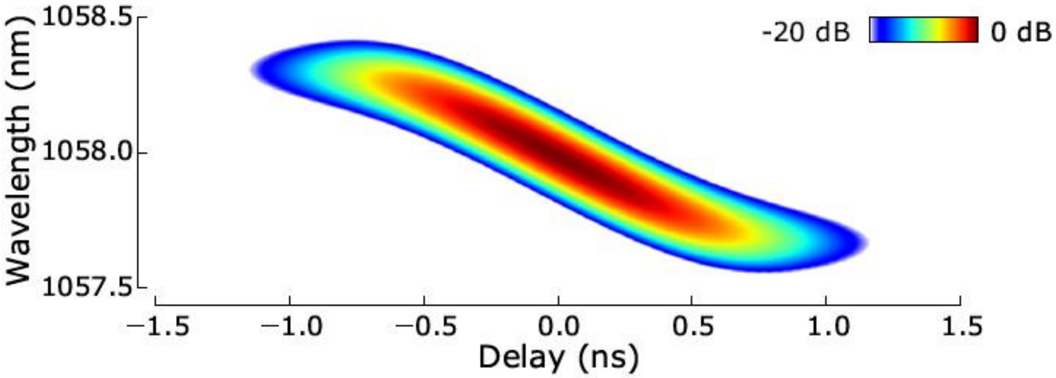
Model

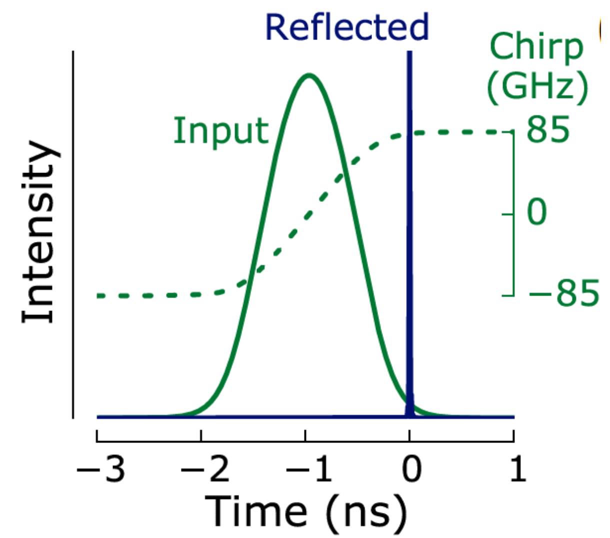


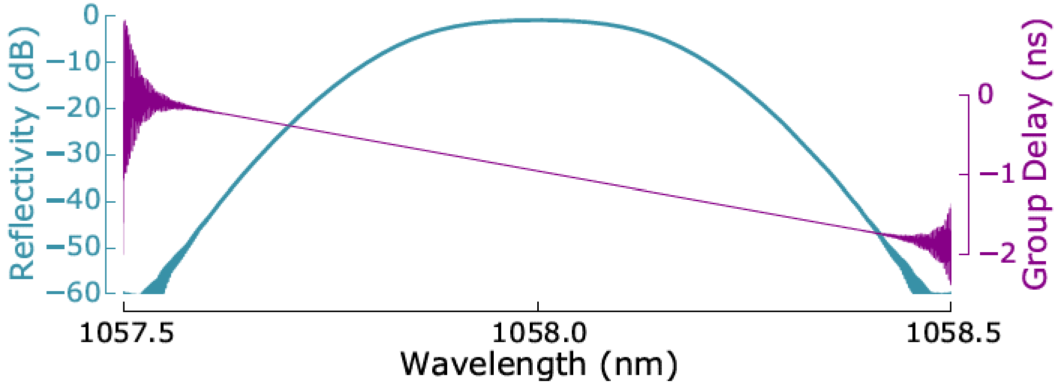
Compression ?

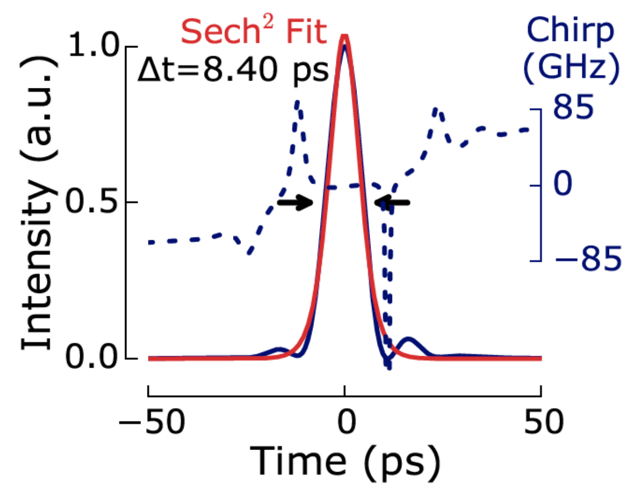
Required grating separation > 50 m

Giant chirp characterization - model







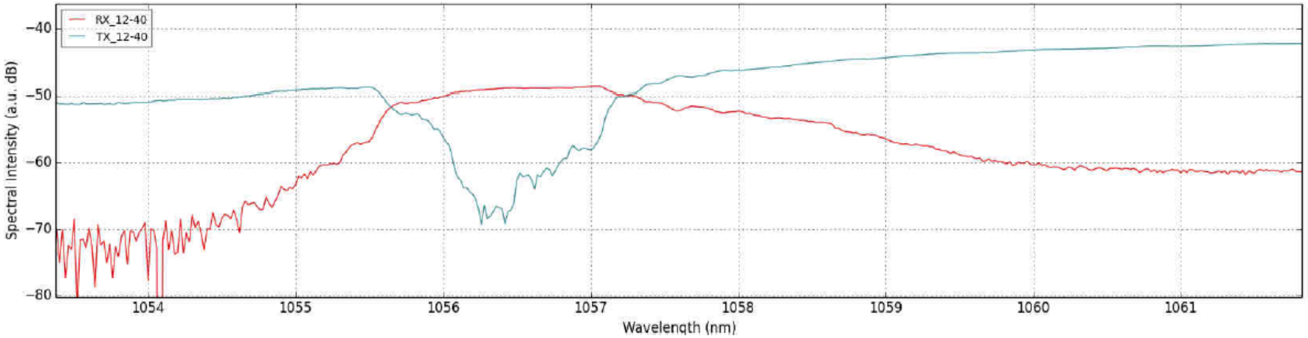


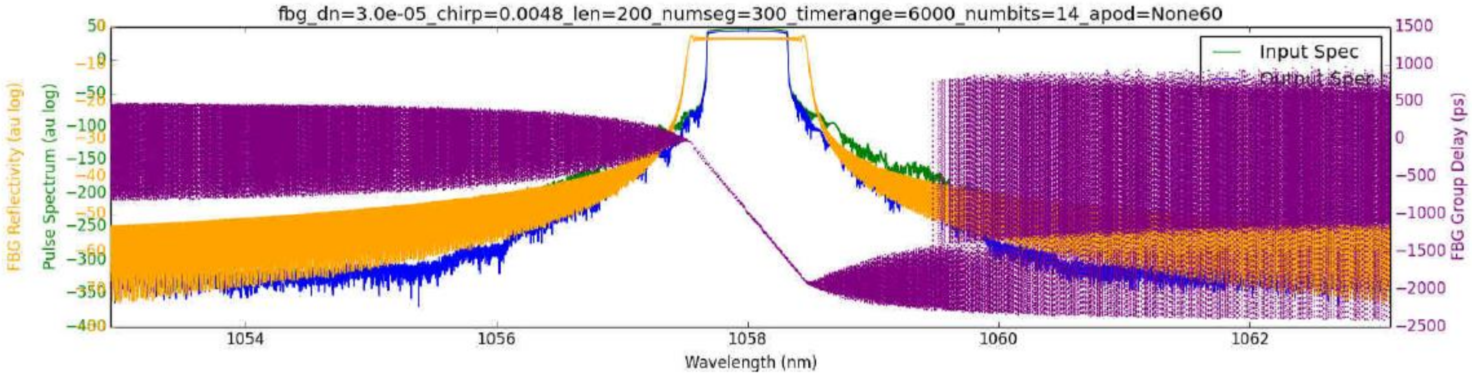
$n_0 = 1.45$ $\delta n = 5 \times 10^{-5}$ L= 200mm

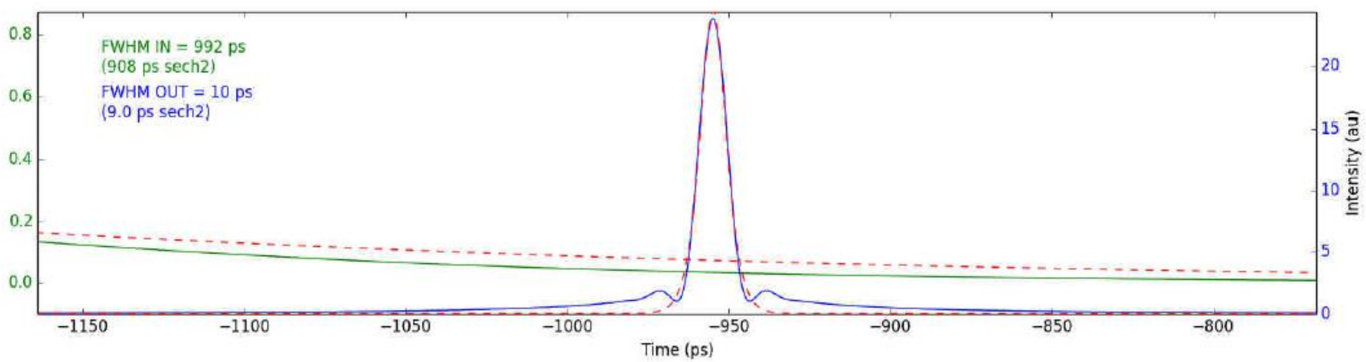
Gaussian apodization FWHM 60 mm

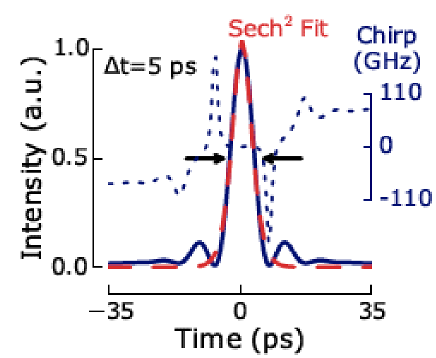
Giant chirp compression - improvements

n_0 =1.45 δn= 5 x10^{-5} L= 200mm
Gaussian apodization FWHM 60 mm



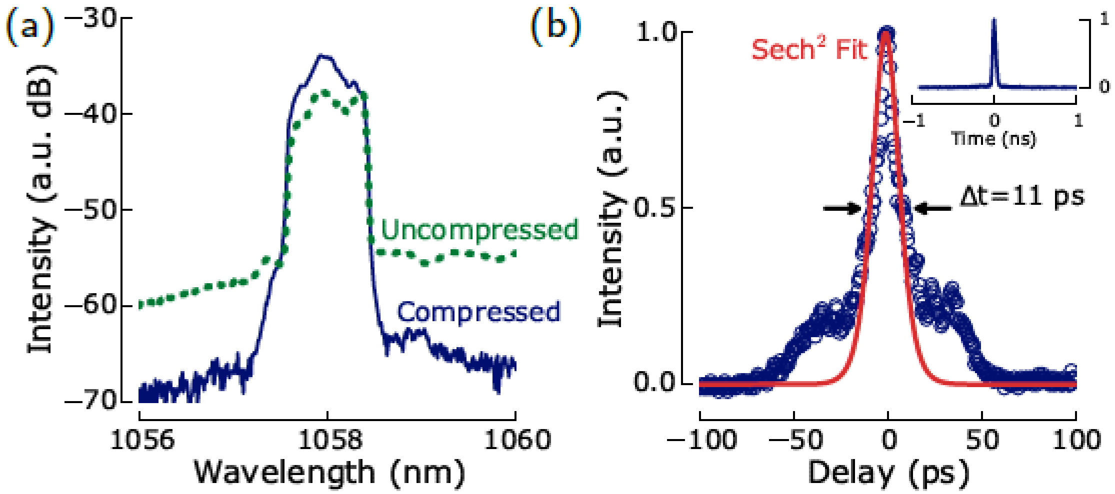




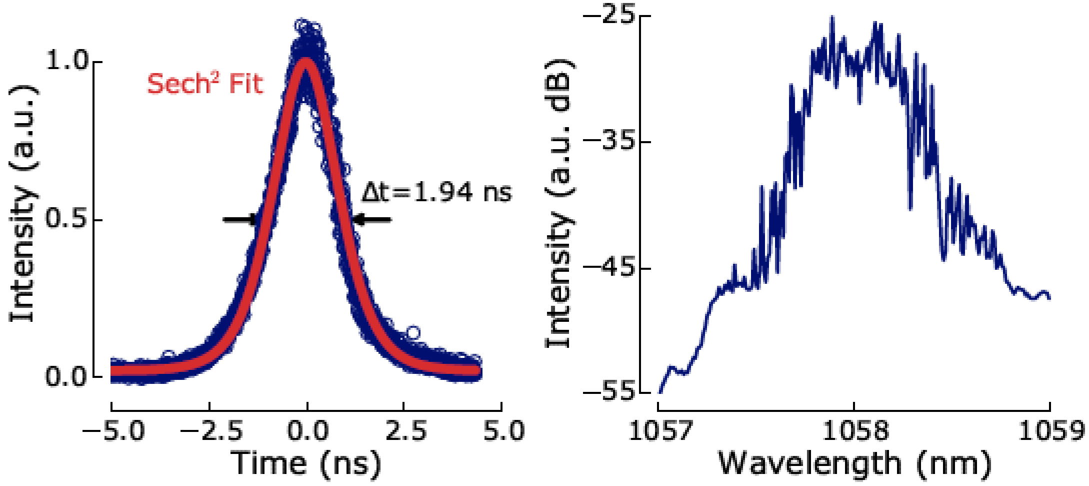


Giant chirp compensation – experimental

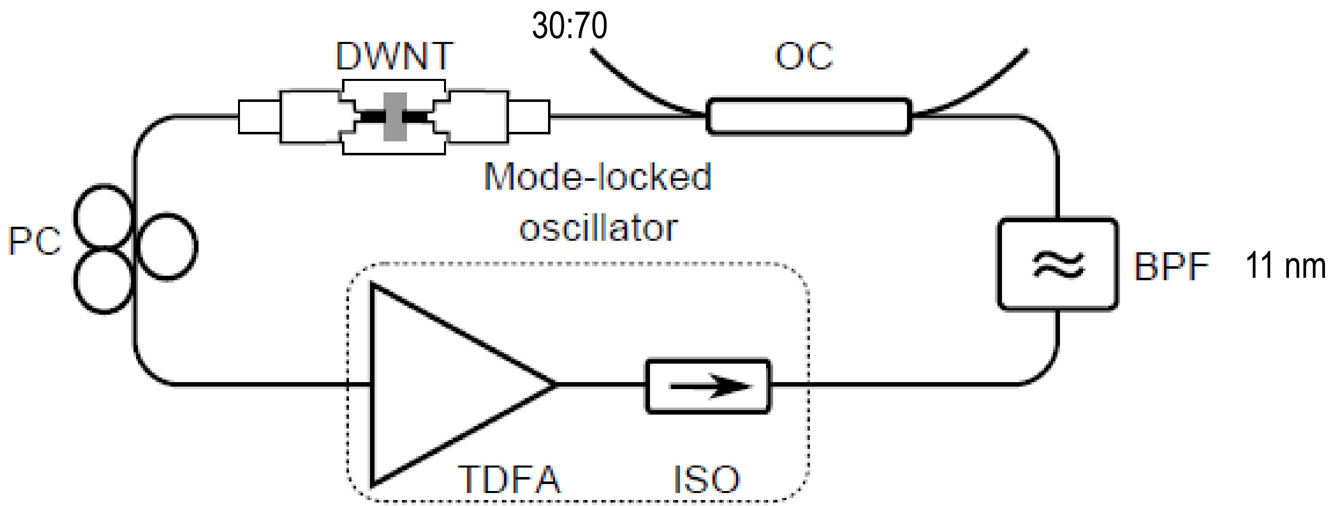
Mode locked

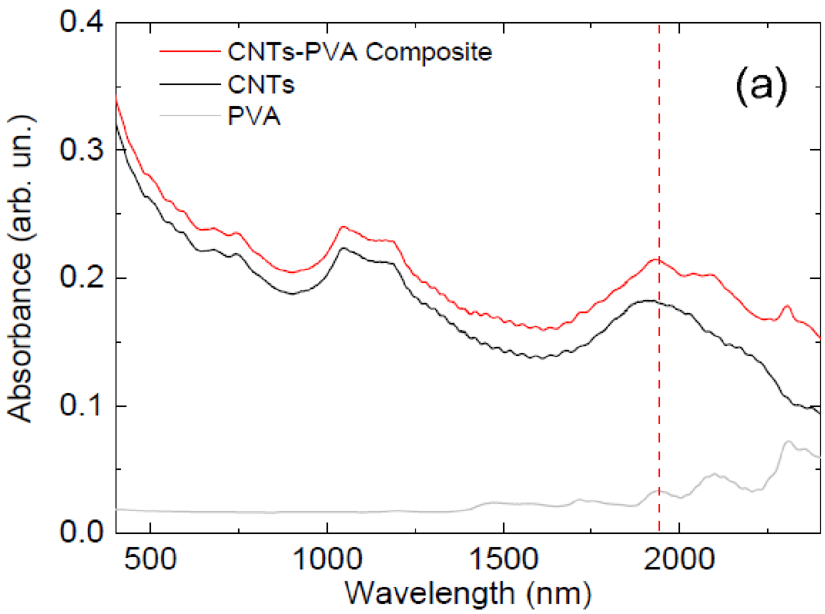


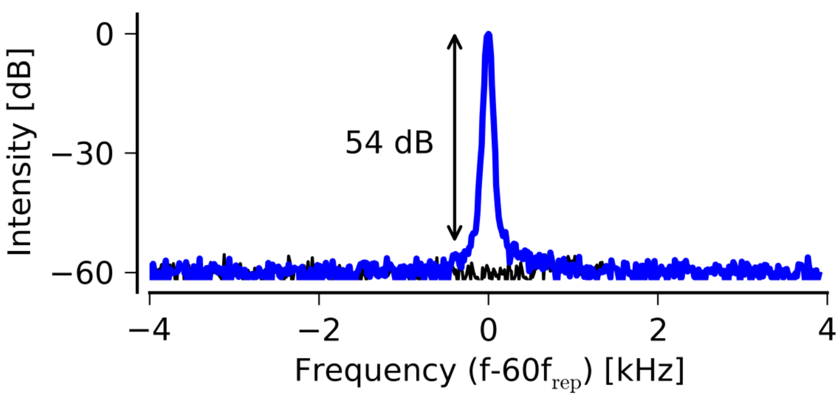
Noise burst



DWNT passively mode locked Tm fibre laser



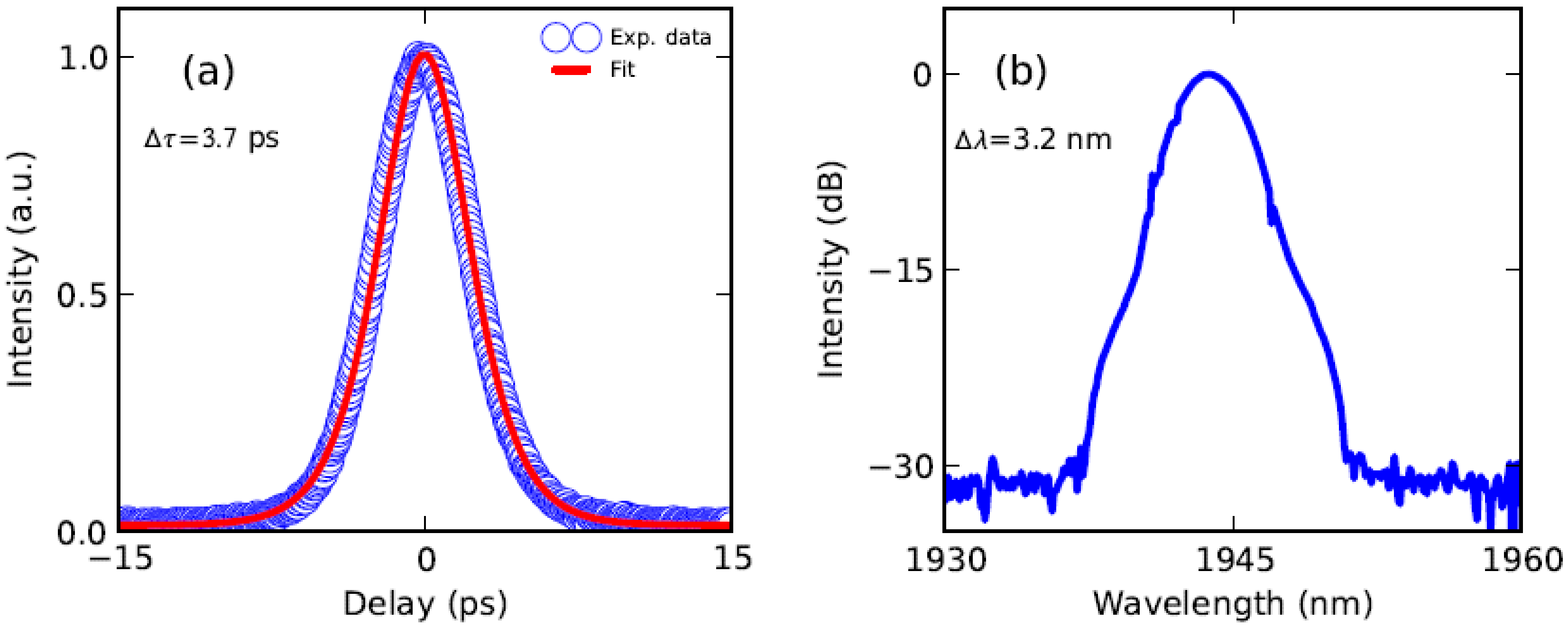




Abs. 1.75 – 2.15 µm:

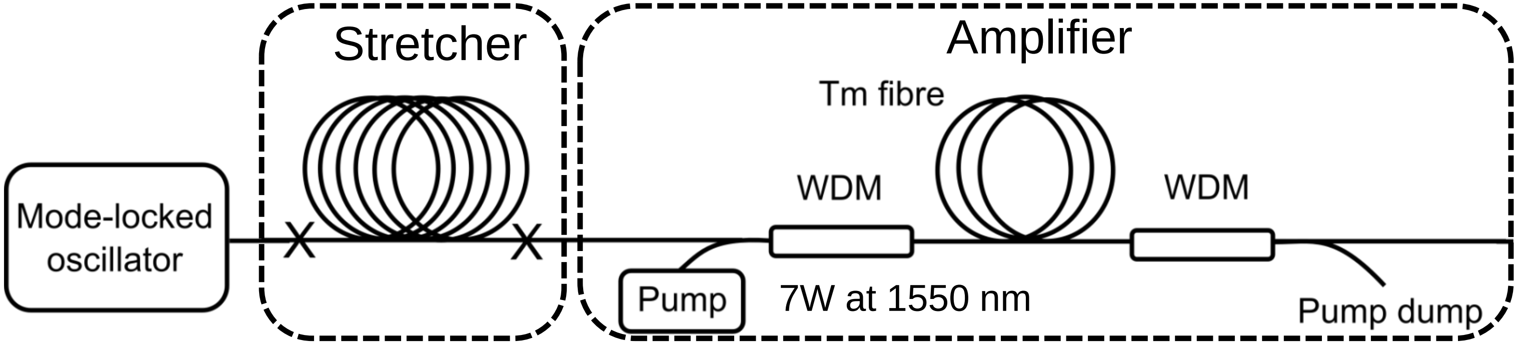
eh$_{11}$ of tubes **d = 1.5 – 1.8 nm**

Mode locked Tm fibre laser



- Fundamental cavity repetition frequency – **6.1 MHz**
- Centre wavelength – **1944 nm**, **Δλ = 3.2 nm**, **TBP = 0.94**
- Pulse duration – **3.7 ps**
- Single pulse energy – **0.6 nJ**

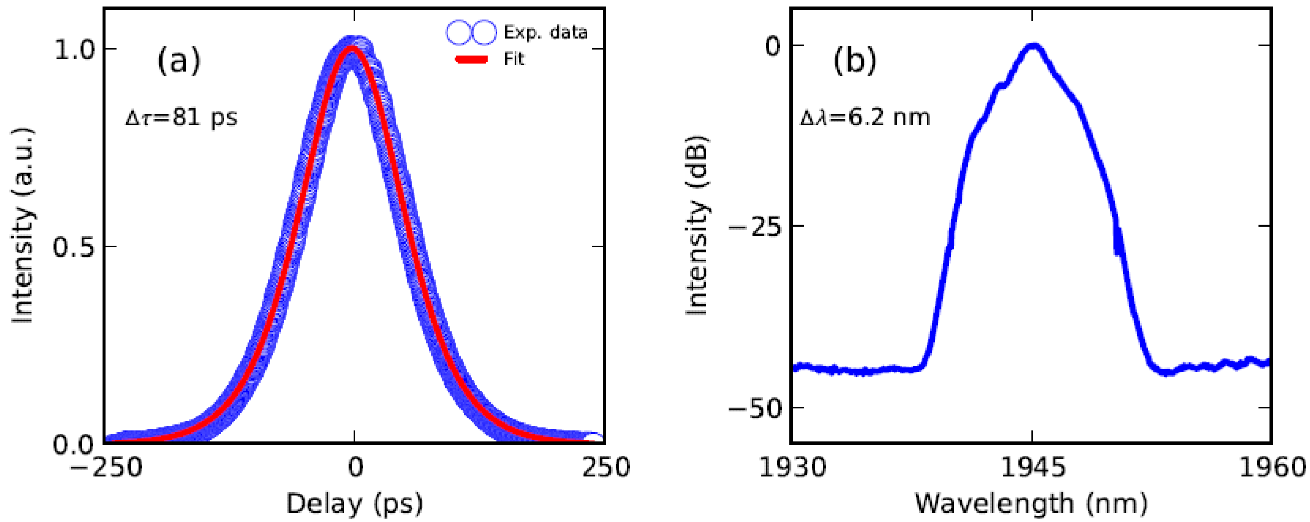
Tm CPA configuration



- Stretcher: **1250 m**, **GVD = 34 ps^2 km^{-1}** at 1.95 μm
- Amplifier: core-pumped single clad/mode Tm-doped fibre – **5.5 m**
- Limited gain to preserve pulse quality

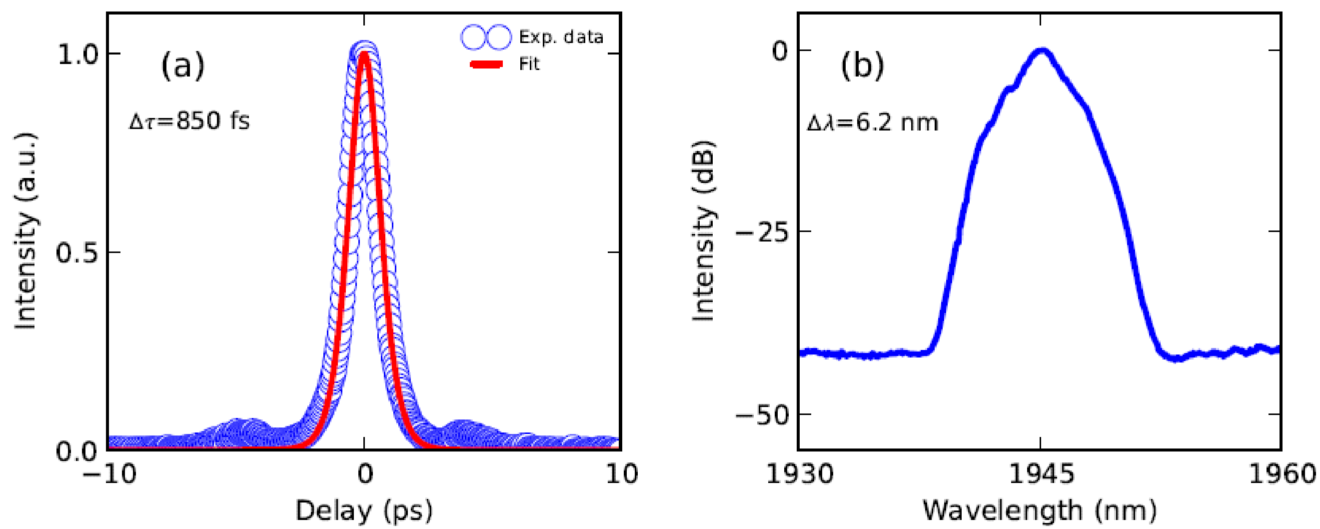
Tm CPA Characteristics

- 1945 nm, $\Delta\lambda$ = 6.2 nm
- Pulse duration 81 ps
- Pulse energy >22 nJ
- Peak power 304 W
- Average power 150mW

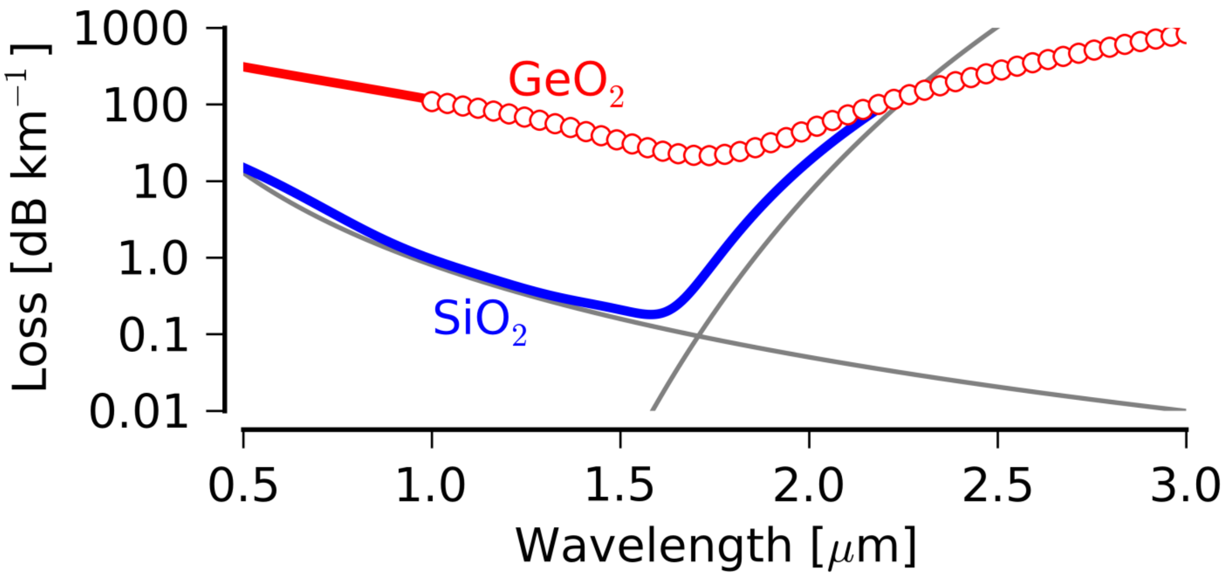


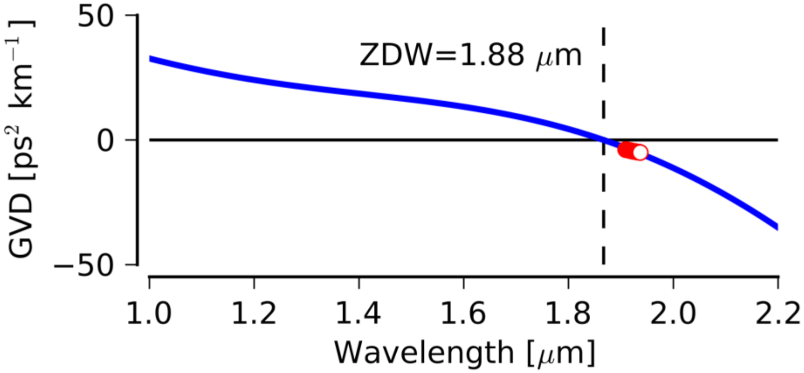
Post gratings

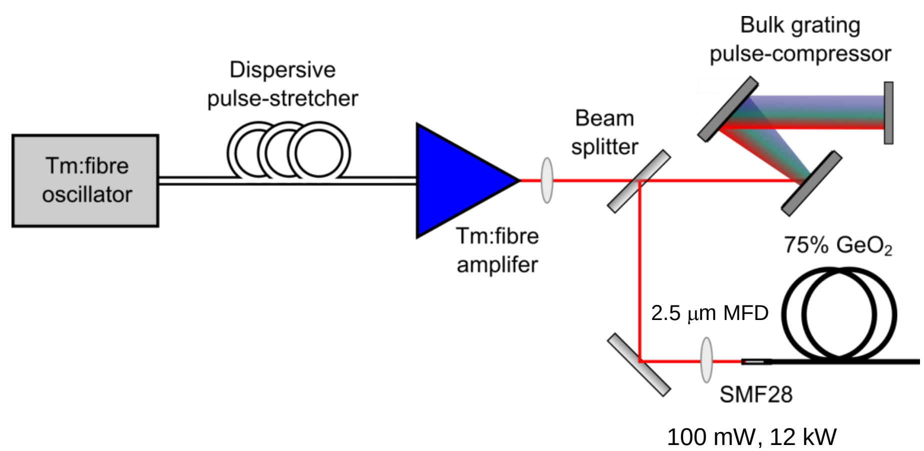
- Pulse duration 850 fs
- Peak power 12 kW
- Average power 100mW



Advantage of Ge doped fibres

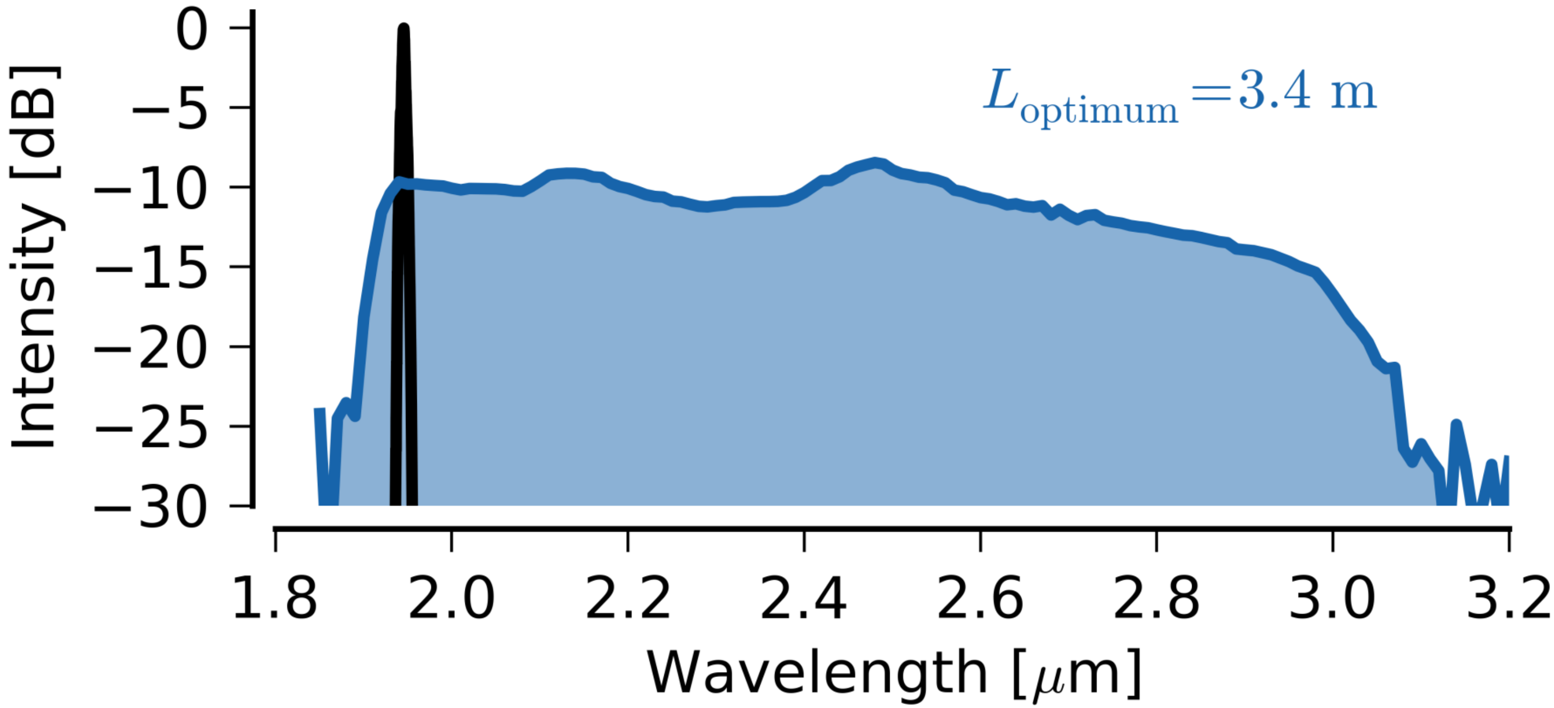






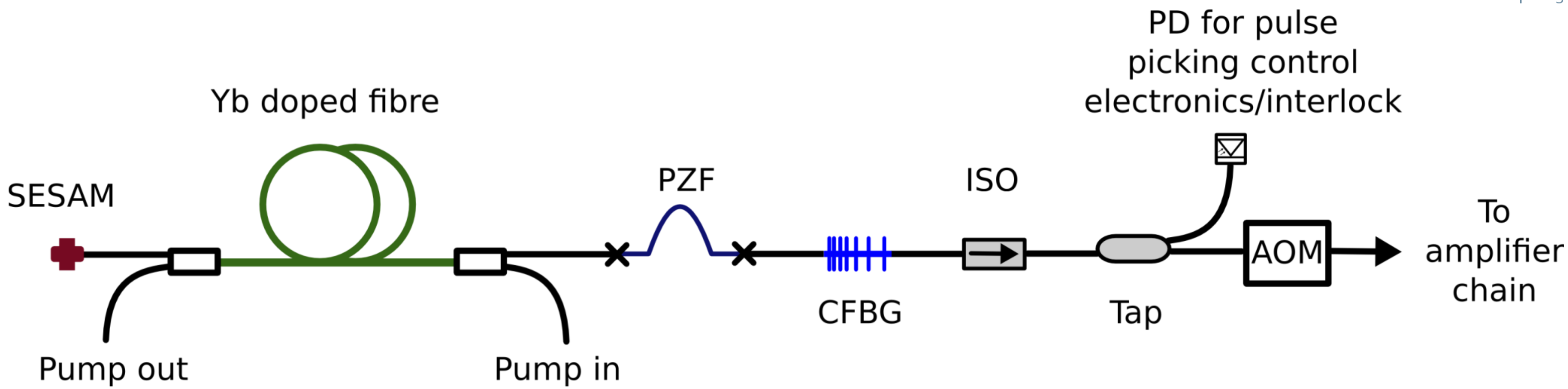
IR supercontinuum optimization

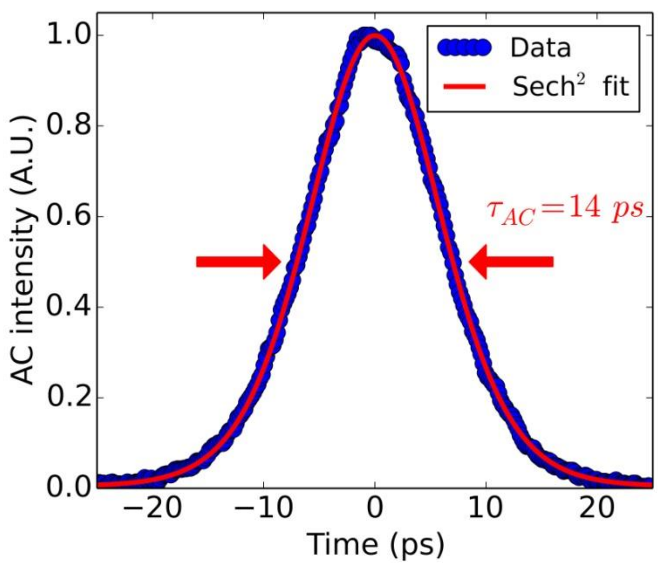
Pump N~100   Modulational instability dominated dynamics

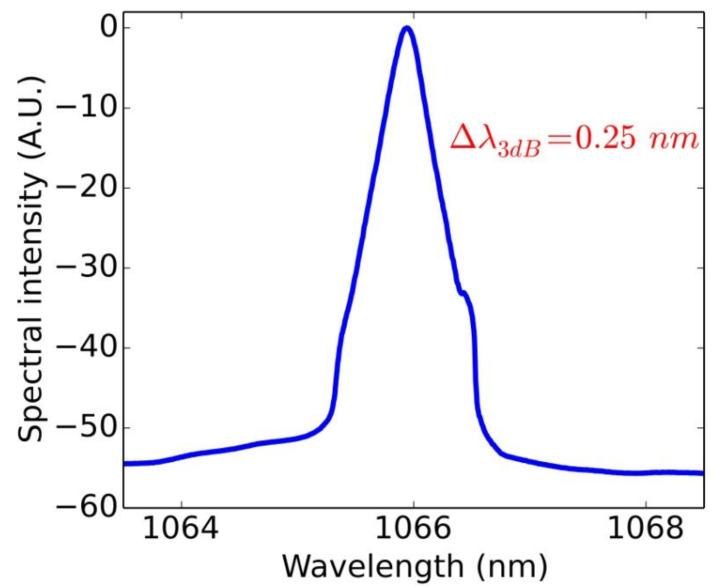


With increased power scaling – hence shorter (~cm) fibre length)
- spectral extension to 4.5 μm should be possible

Yb CPA - Oscillator

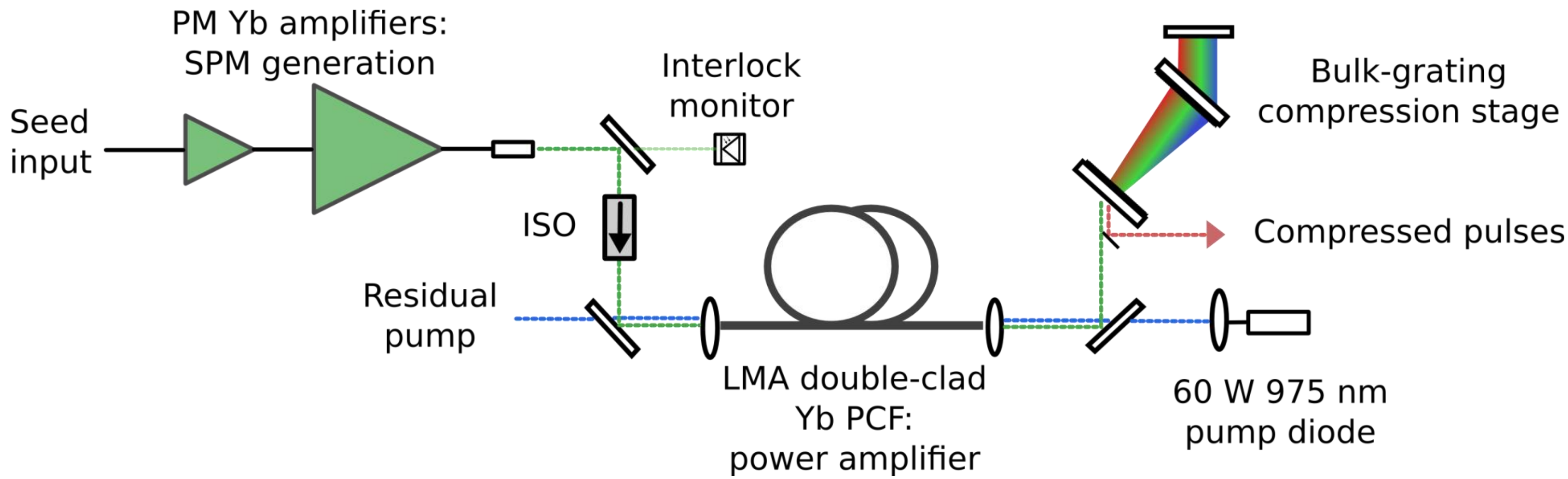


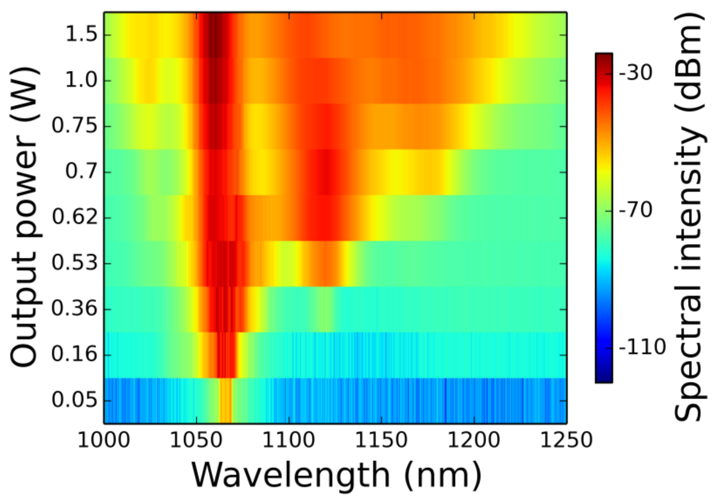


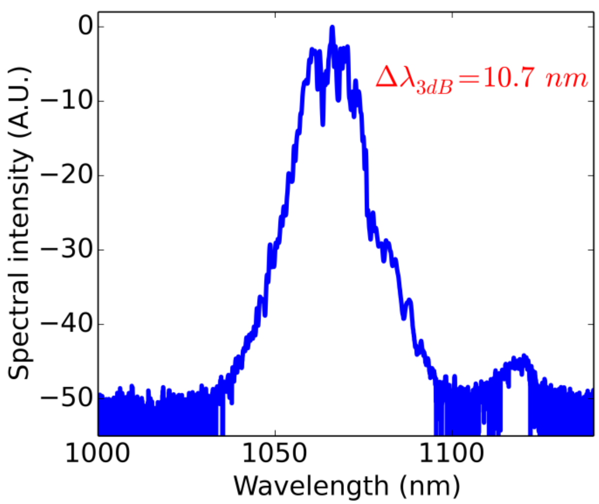


- Linear PM SESAM mode locked cavity, f_{rep}= 28 MHz, P_{av} = 6mW, τ_{pulse} = 9 ps
- 5% tap coupler provides signal for pulse picking control electronics and interlock circuitry
- AOM used to pick repetition rate down to 5 MHz or below

YB CPA –Pre-Amps

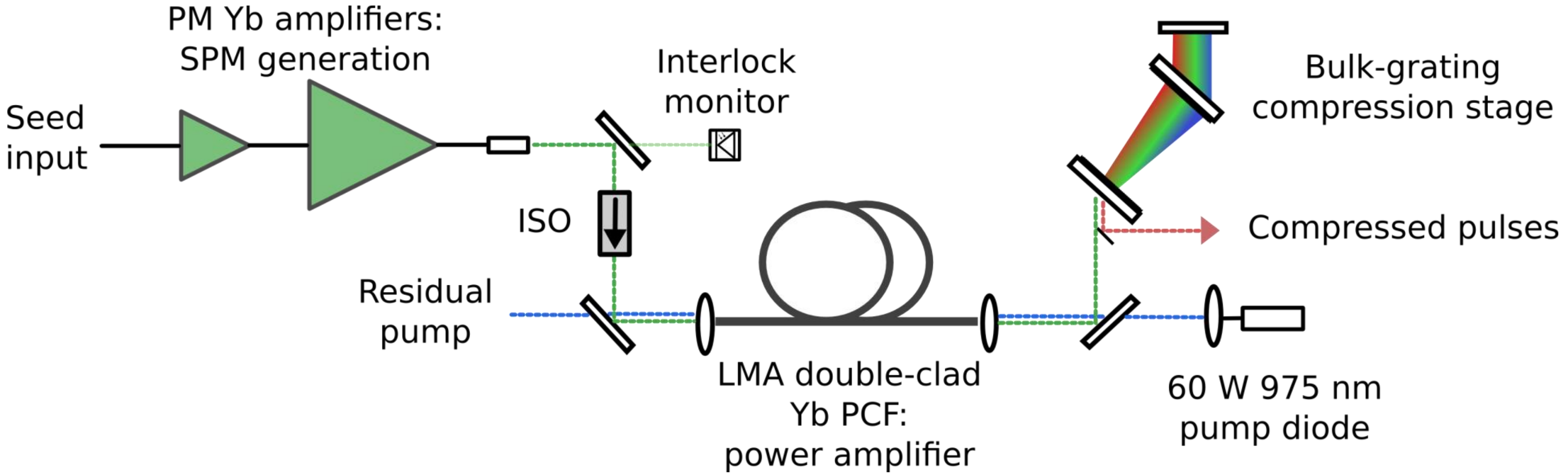


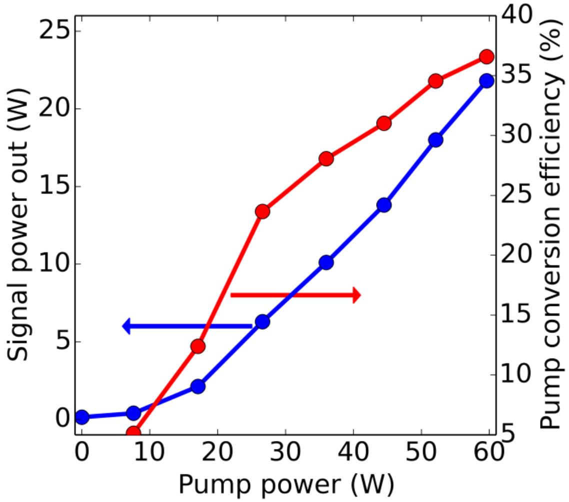


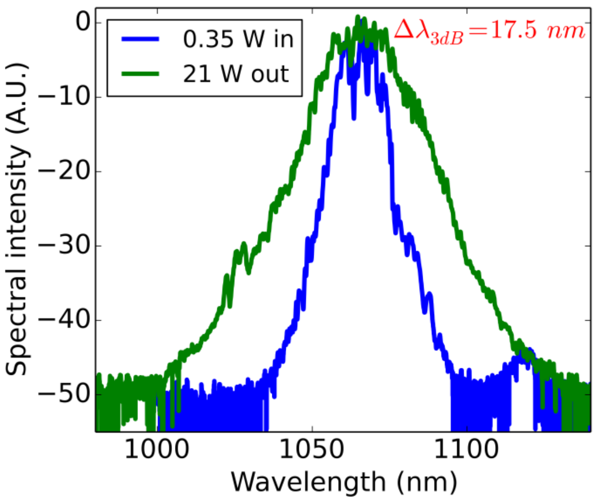


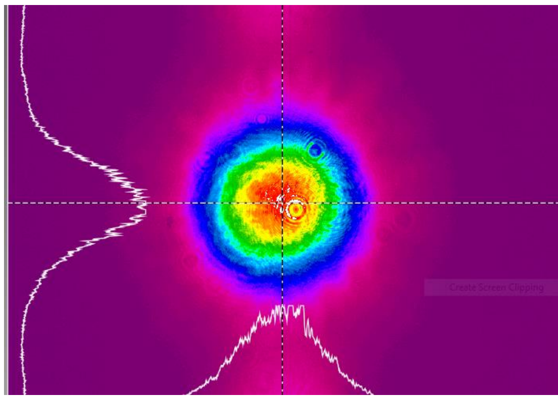
- Use two Yb pre-amplifiers to generate bandwidth through SPM
- Spectral evolution with increasing power – must prevent onset of Raman
- Stop at ≈ 350 mW average power at 5 MHz, 40x increase in spectral bandwidth

YB CPA –Power Amp



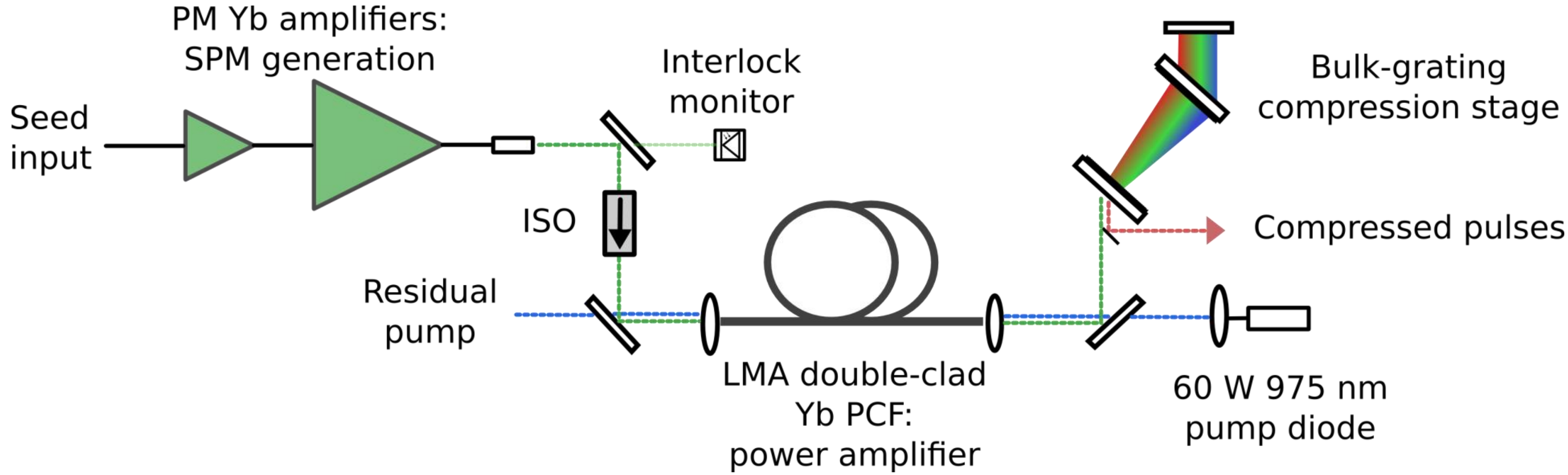


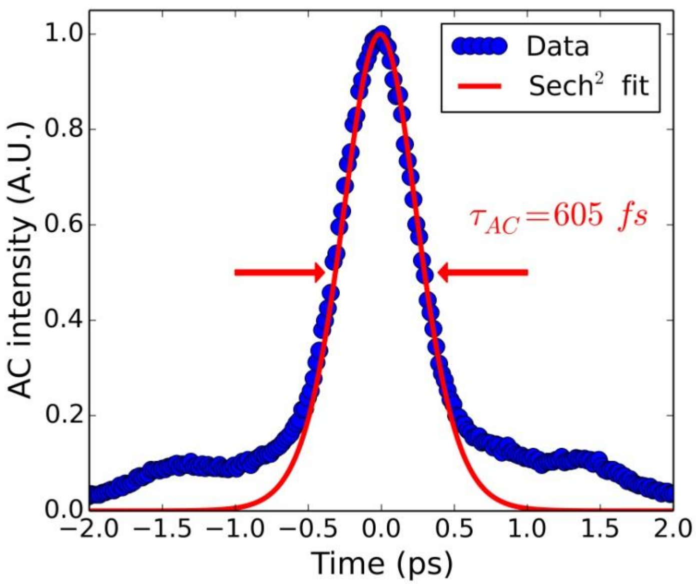




- Double clad Yb doped LMA polarising PCF – NKT Photonics. MFD 31 μm at 1064 nm
- Counter pumped with 60 W IPG 975 nm diode, ~10 dB/m absorption at 976 nm
- Conversion efficiencies > 35%, output powers > 20W, pump power limiting power scaling

Yb CPA - Recompression





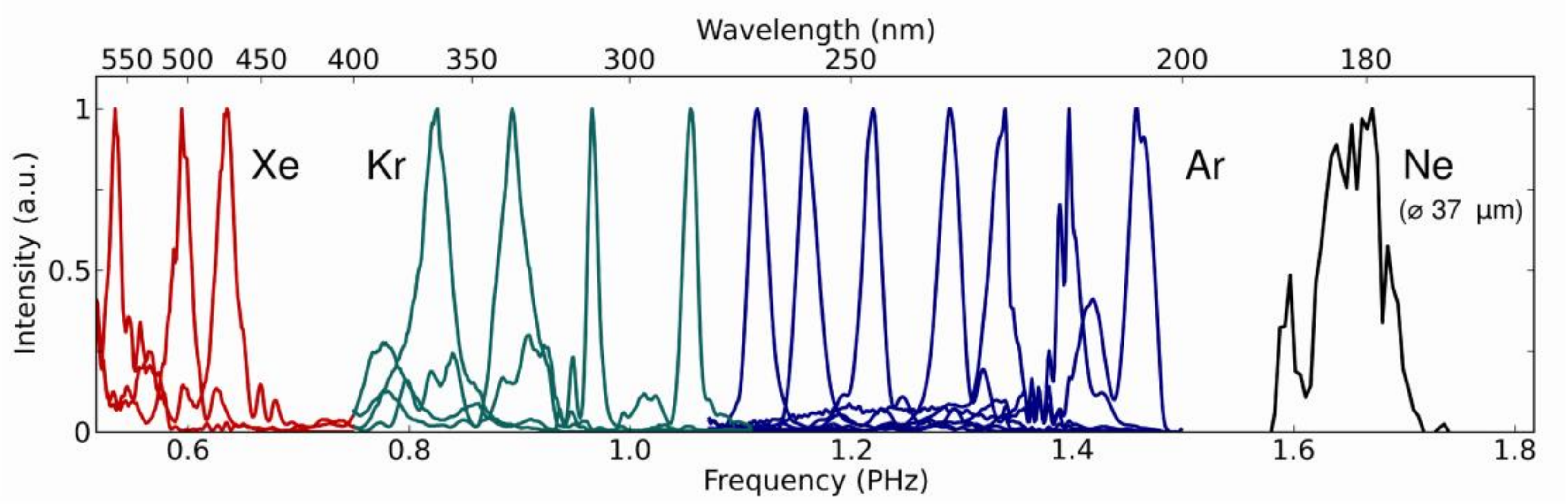
- Compression at 28 MHz, sub 400 fs
- Transmission gratings – 1250 lp/mm.
- 200 fs @ 5 MHz with 20 W average power
- Application to tunable vuv in gas filled pcf

Short Wavelength Extension

Mak et al Optics Express 21, 10942 (2013)
Gas-filled Kagome PCF, 10s cm , 40fs, μJ, 800nm

Dispersive wave emission in the uv

5% conversion



Graphene

Graphene production :-

Micromechanical cleavage

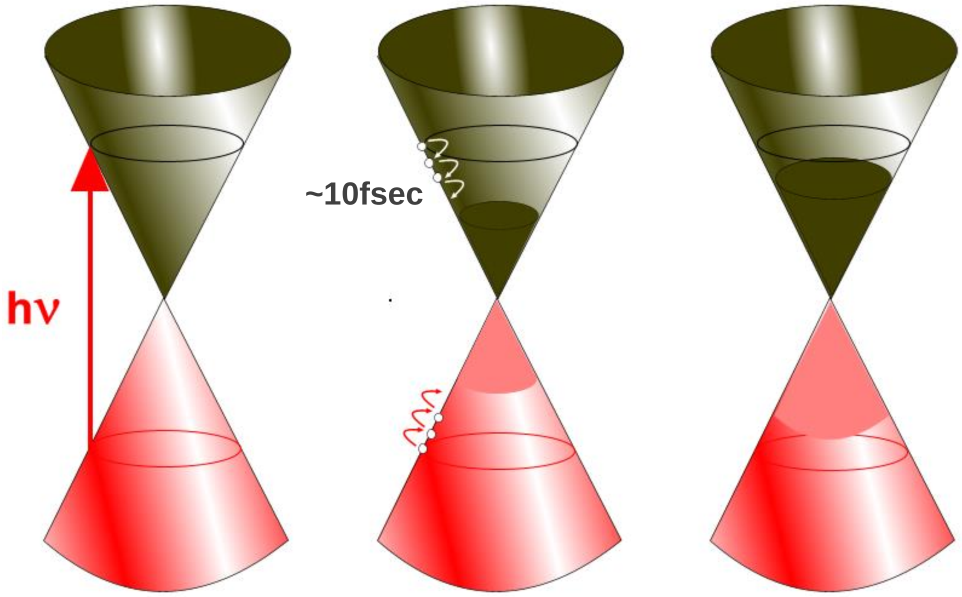
CVD of hydrocarbons

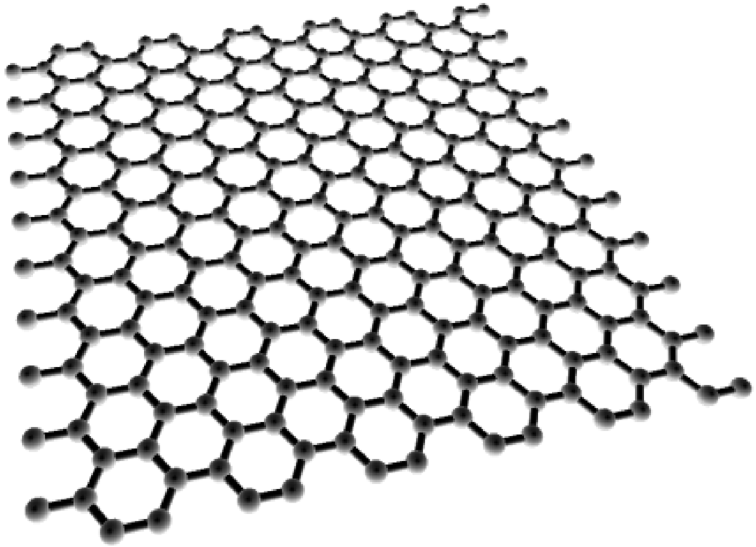
Carbon segregation from silica carbide

Chemical synthesis from polyaromatic hydrocarbons

Liquid phase exfoliation –

graphite + sodium deoxycholate – sonicate, settle, centrifuge (17000g), select from dispersion, add to PVA, centrifuge , ~40-50 μm film

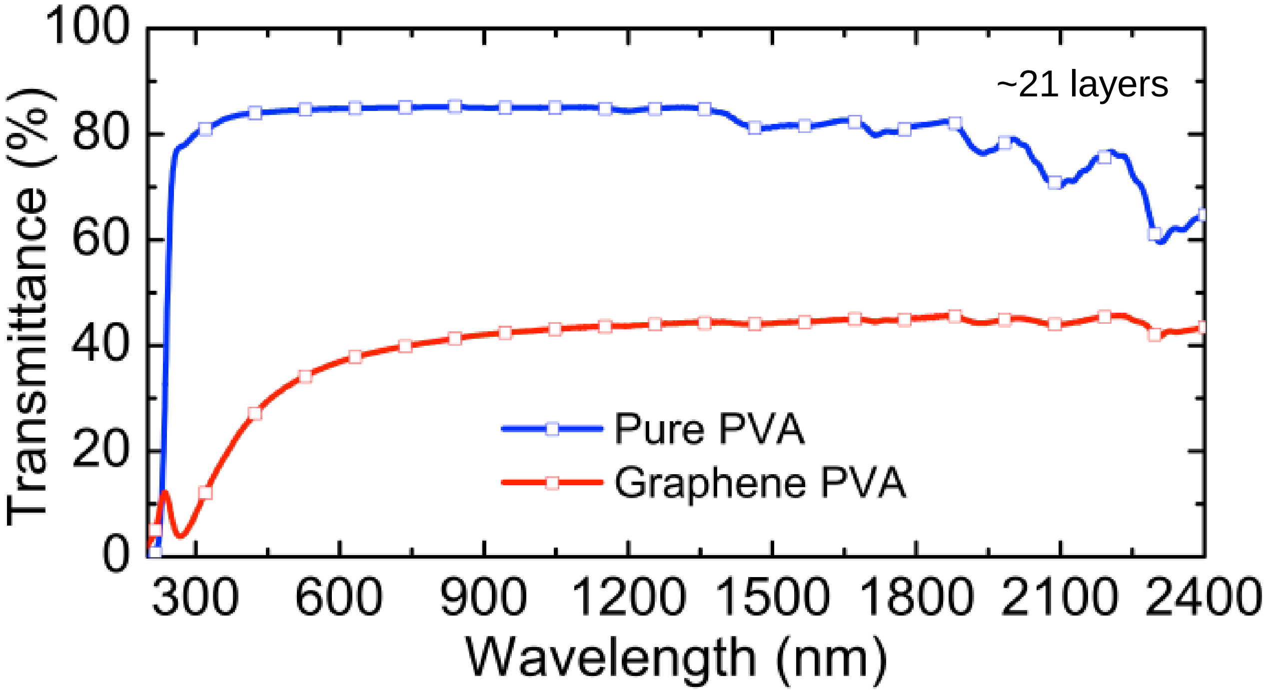




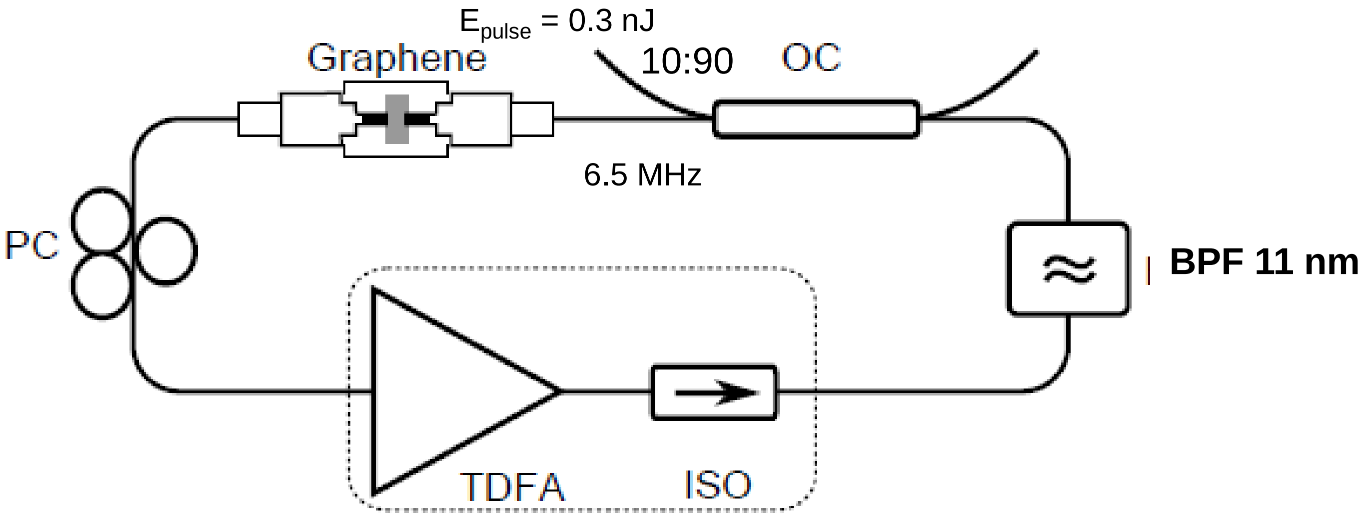
Graphene saturable absorbers

Graphene advantages:-

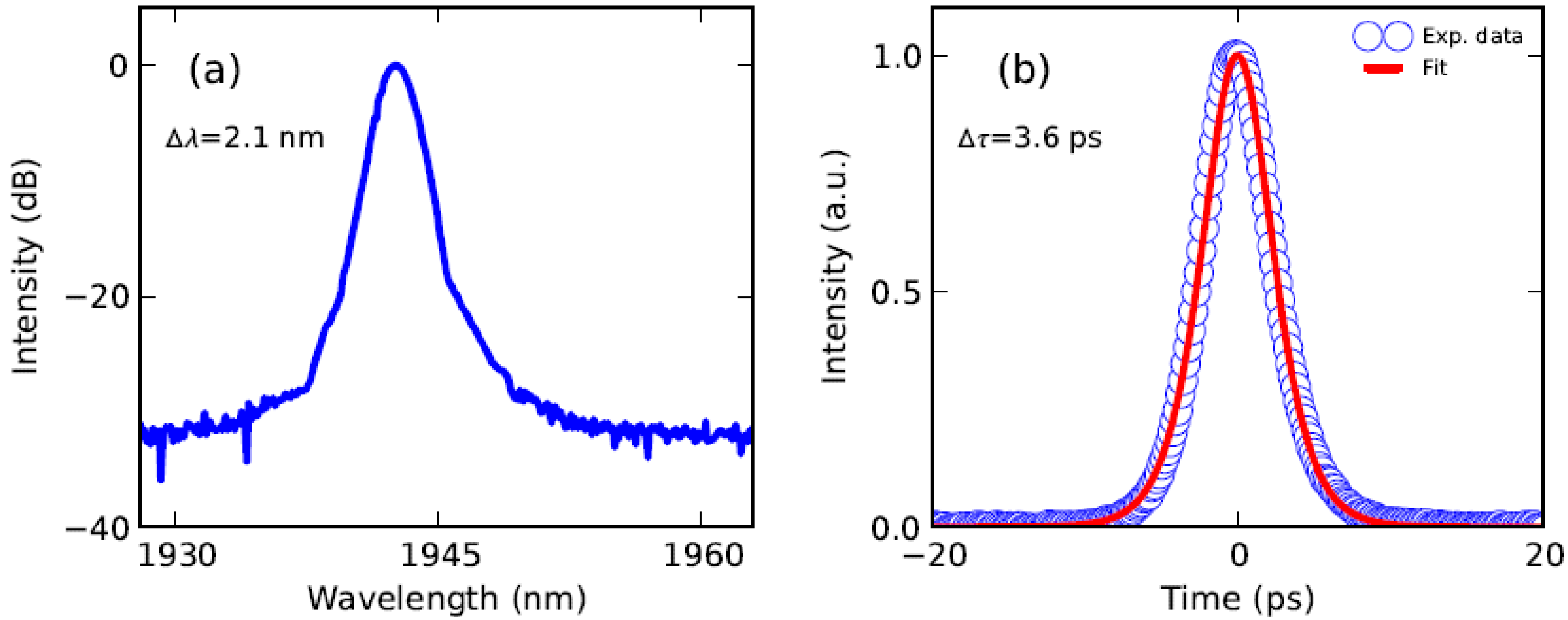
Point band gap structure – easy fabrication - CVD
No need for bandgap engineering – UNIVERSAL SATURABLE ABSORBER
Low non-saturable loss
Broad absorption – tuning range – controlled modulation depth
Low threshold for saturable absorption ~10s MWcm^{-2}
Ultrafast recovery time ~200fsec
Absorption ~ 2.3% per layer (0.3nm)



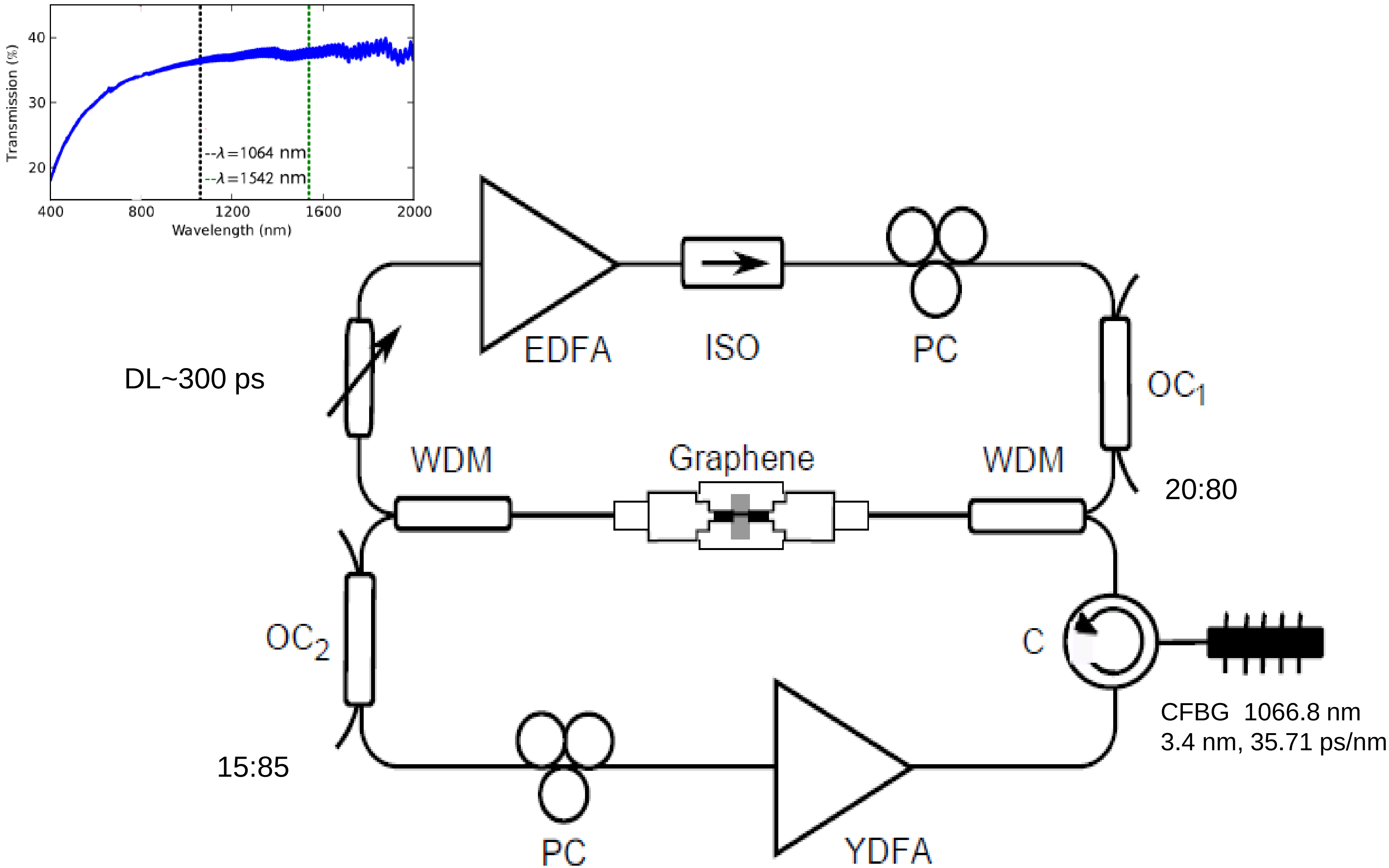
Tm fibre laser – graphene saturable absorber



$\Delta\nu\Delta\tau$ = 0.59.



Graphene – Dual Cavity Mode-locking



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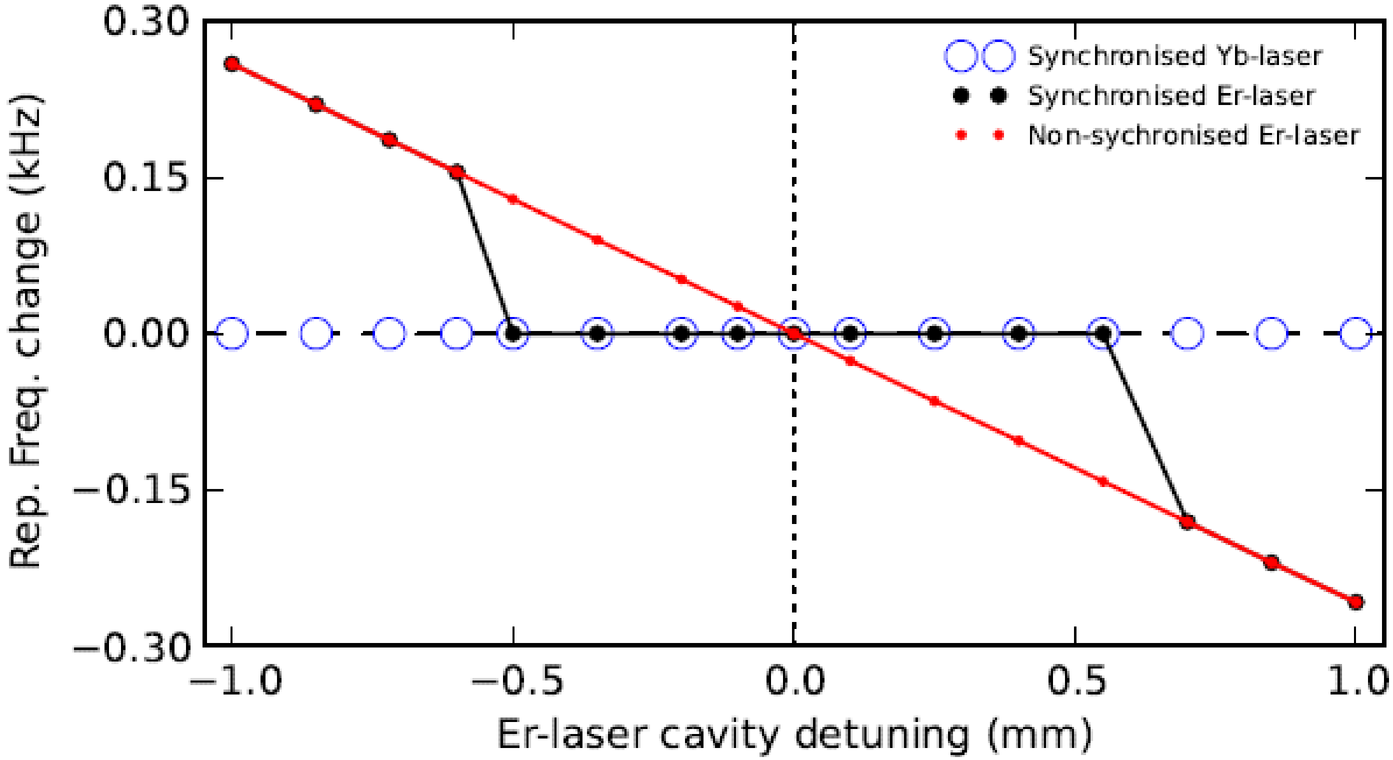
Coupled cavities

FOG femtosecond optics group

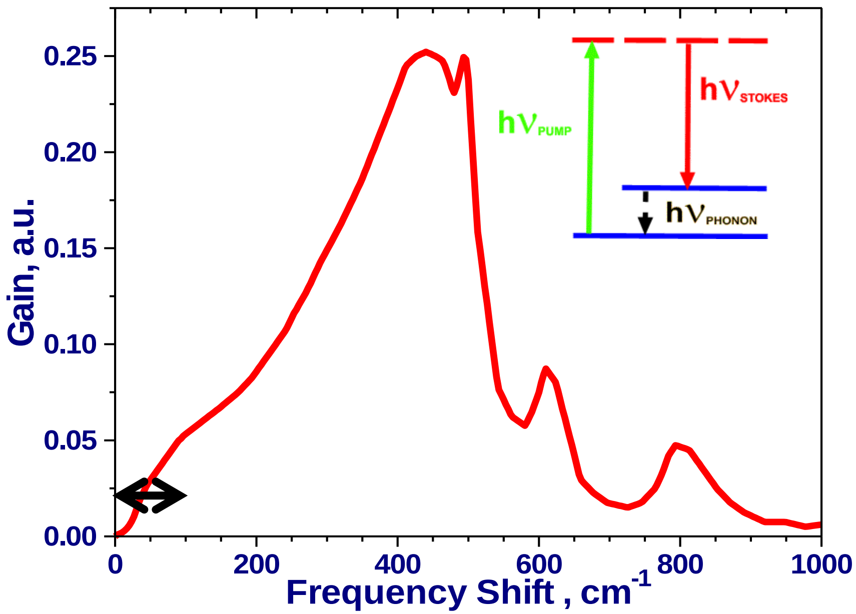


- Fundamental syn. cavity repetition frequency – **7.2 MHz**
- Yb-laser – **1066 nm**, **Δλ = 0.27 nm**, **pulse duration = 4.4 ps**
- Er-laser – **1542 nm, Δλ = 2.22 nm**, **pulse duration = 1.12 ps**

Cavity mismatch allowable ~1mm

Raman Gain

Stolen et al. App.Phys. Lett. 22, 276 (1973)



Raman gain:

Present in all fibres

Coupling via optical phonons

Fast response

Gain at any wavelength

Max at ~13Thz (60-100nm)

Polarisation dependent

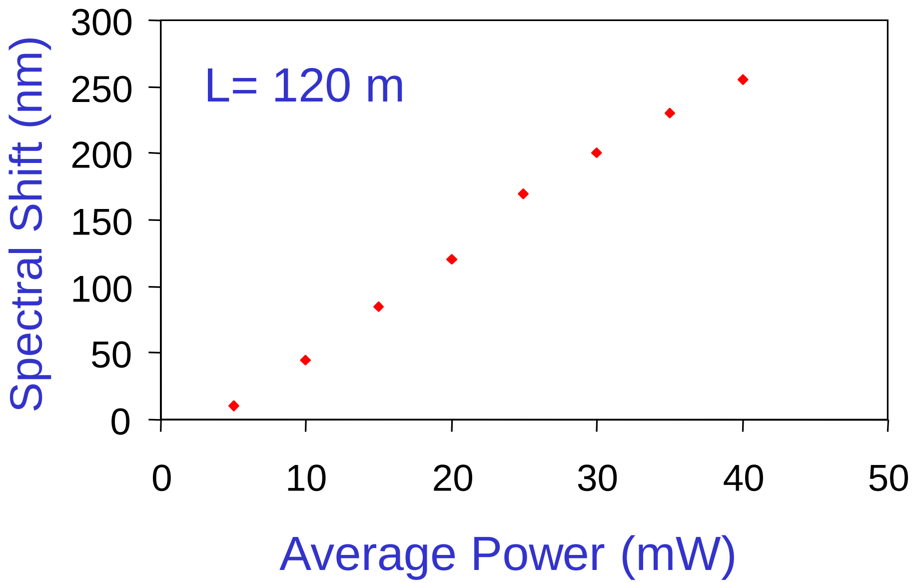
Broad gain (not flat!)

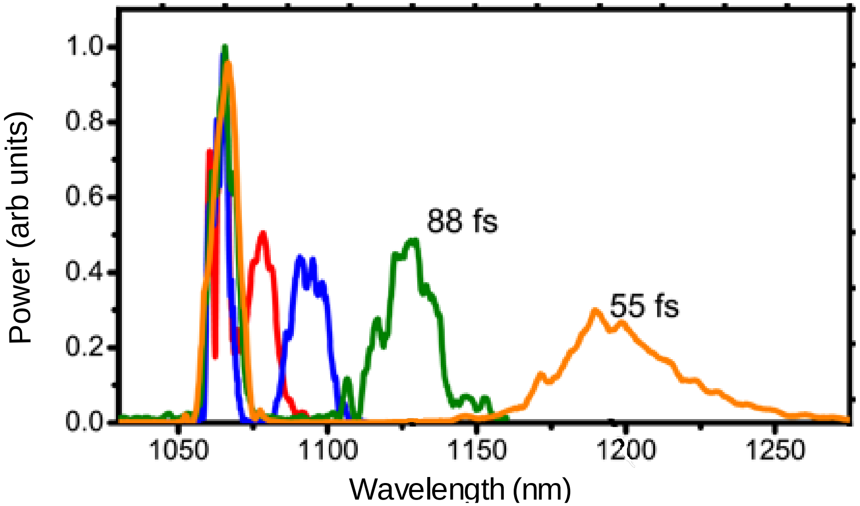
Raman self interaction

Dianov et al. JETP Lett. 41, 294 (1985)
Mollenauer et al. Opt. Lett. 12, 659 (1986)

$$\frac{d\nu}{dz} = \tau^{-4}$$

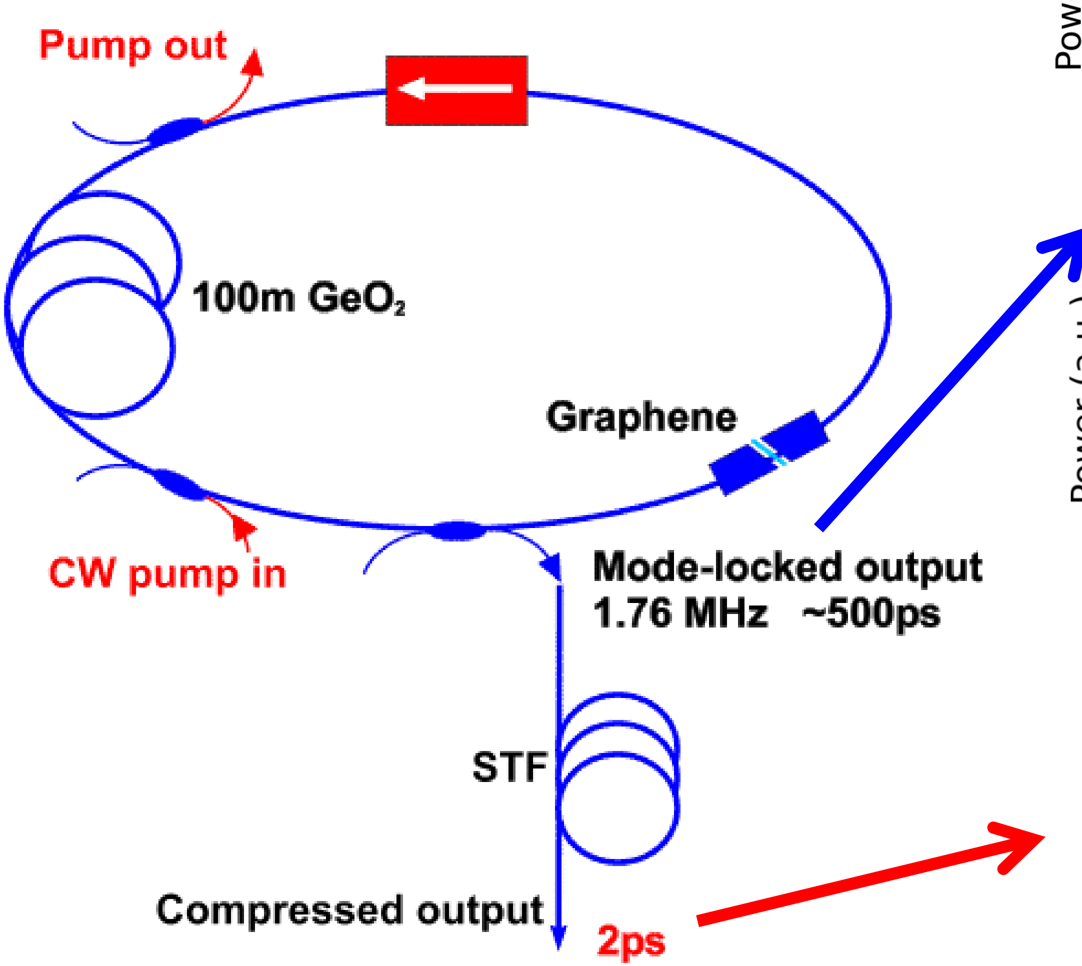
Input wavelength 1540 nm up to 1.6kW

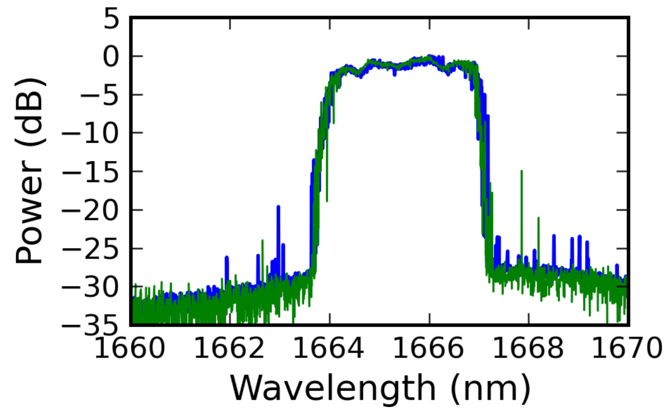


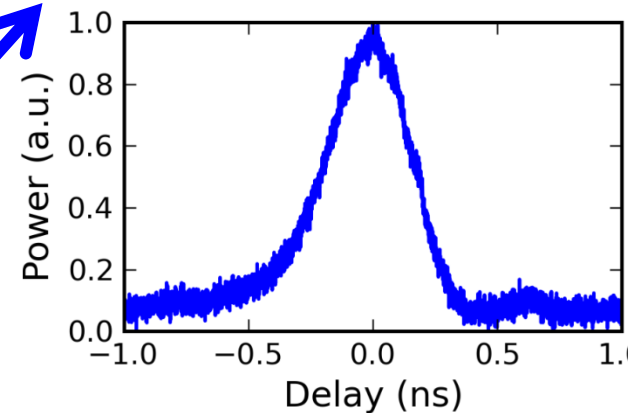


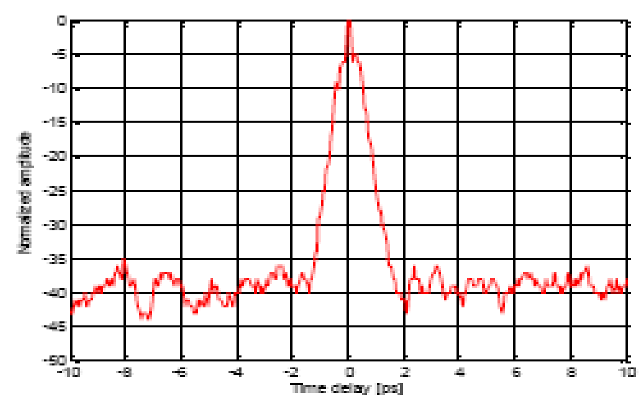
Universal Pulse Source

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

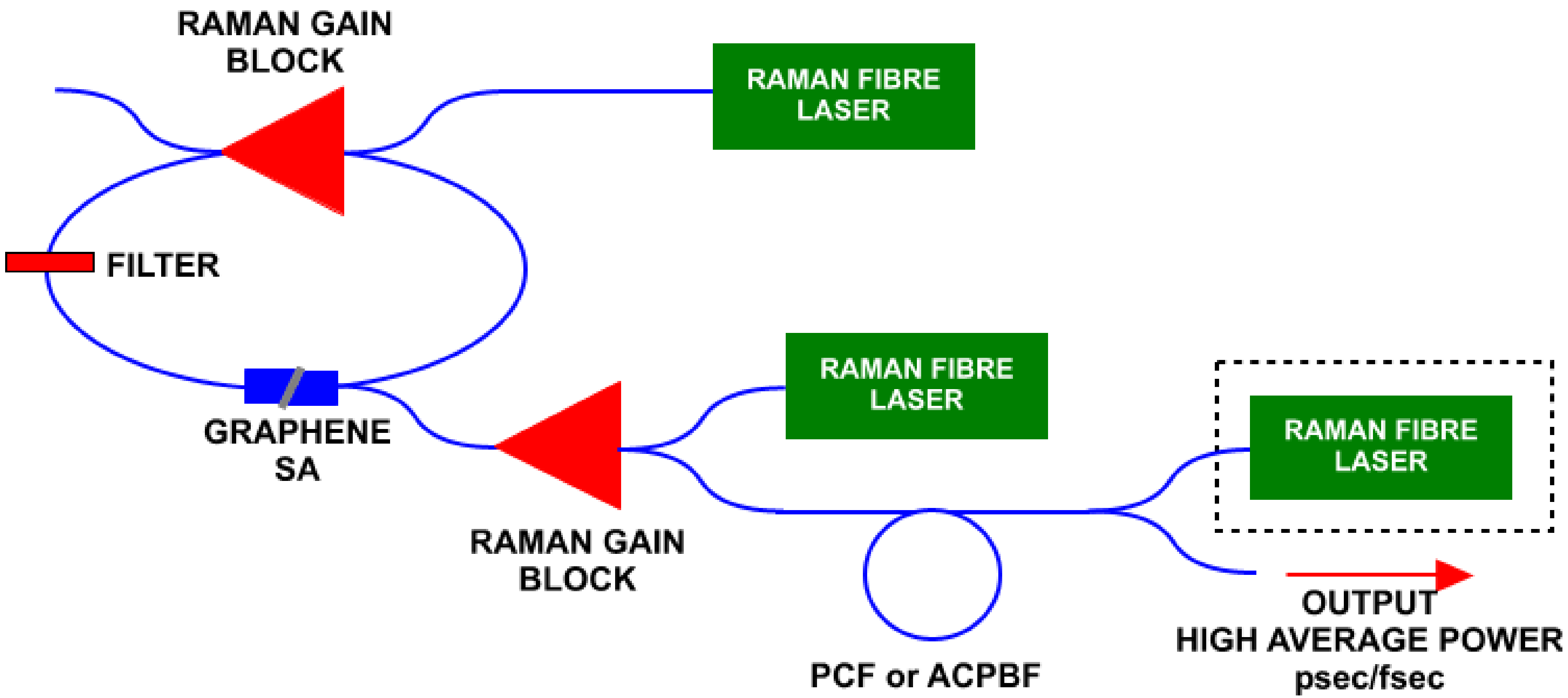








Universal short pulse source

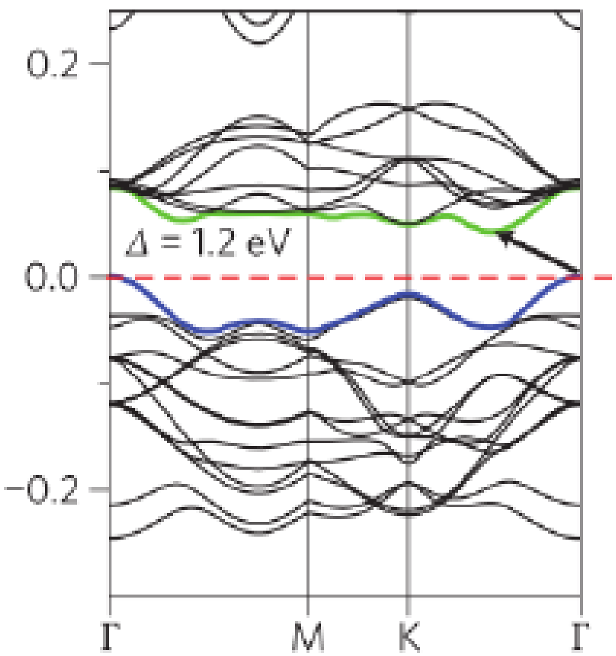


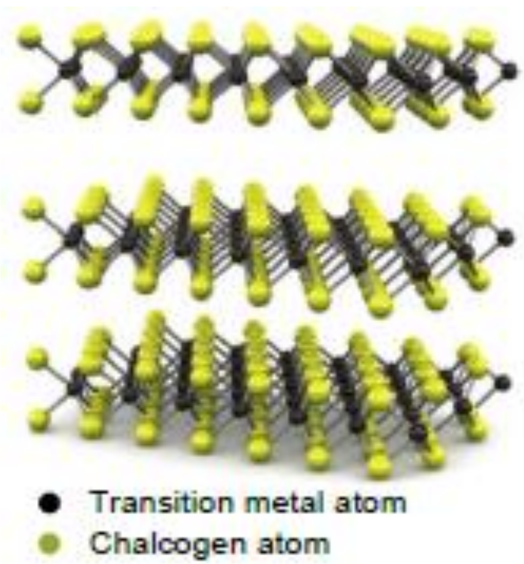
Raman gain based
All building blocks are in place

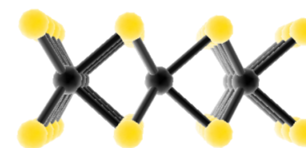
Molybdenum disulphide stacked molecular layers

Single metal layer between two layers of chalcogen atoms

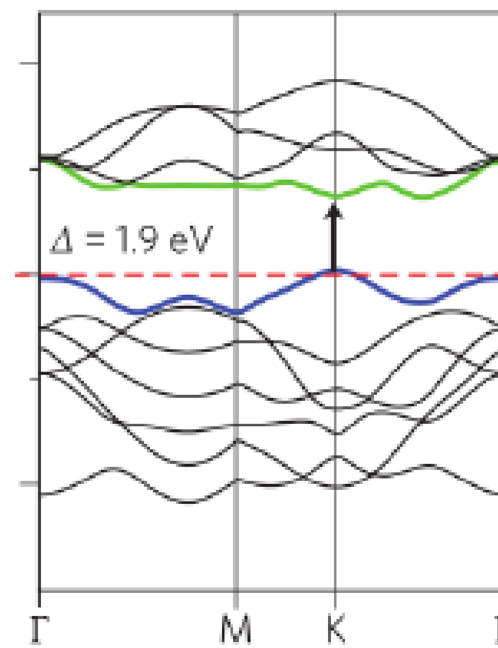
MoS_2 bulk







MoS_2 monolayer



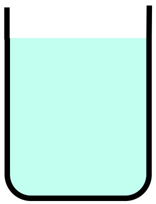
MoS_2 manufacture - LPE

MoS_2 powder

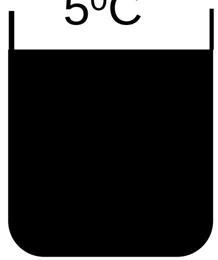
+ sodium deoxycholat

+

water

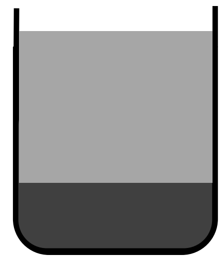


5^0C



Ultrasonication

2hrs



Centrifugation

1hr

TEM

+

PVA Pellets

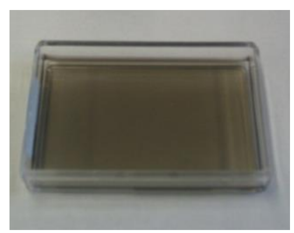
Centrifuge

Mixing

Mixture dried

in oven

20^0C



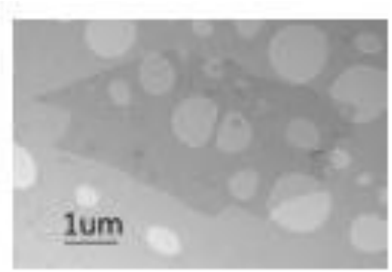
30-40 μm

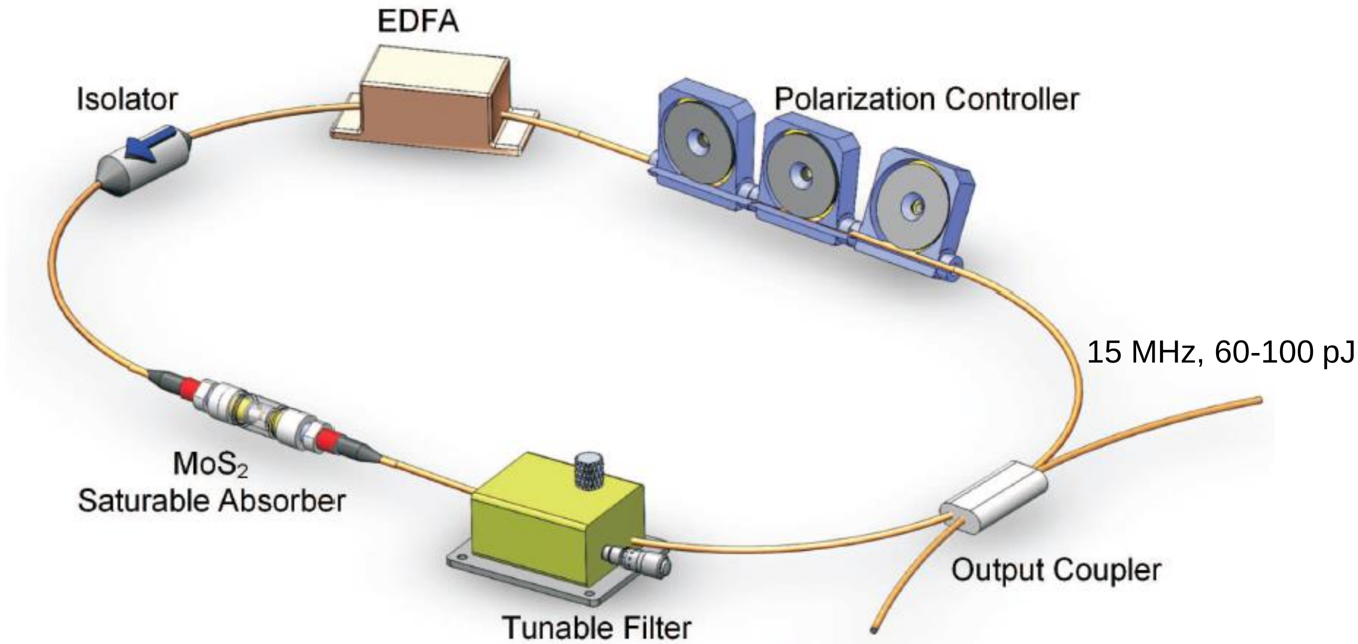
Nanomaterial

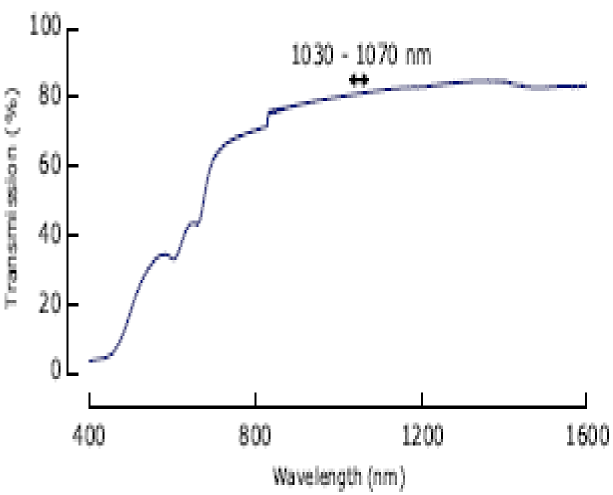
PVA composite

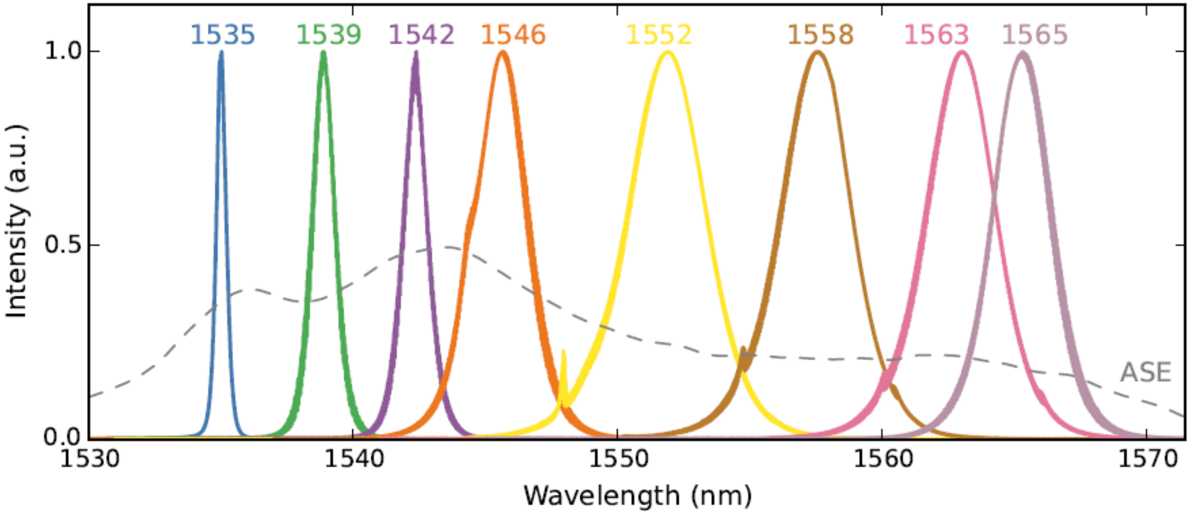
- Picosecond (~100) recovery time interband, ~30 fs intraband
- $\Psi^{(3)} \sim$ 1.5 x 10^{-14} esu (~ 2x graphene)

MoS $_2$ mode-locked Er fibre laser

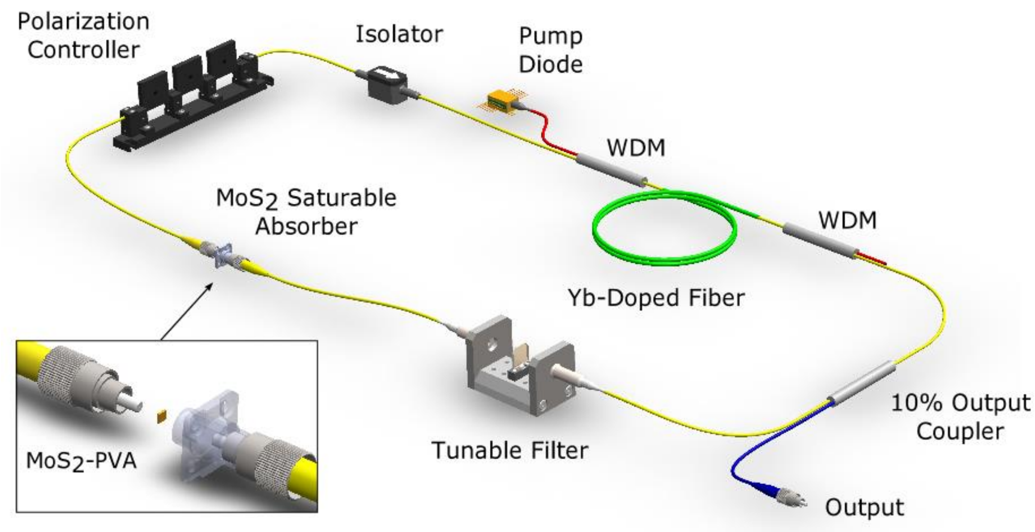


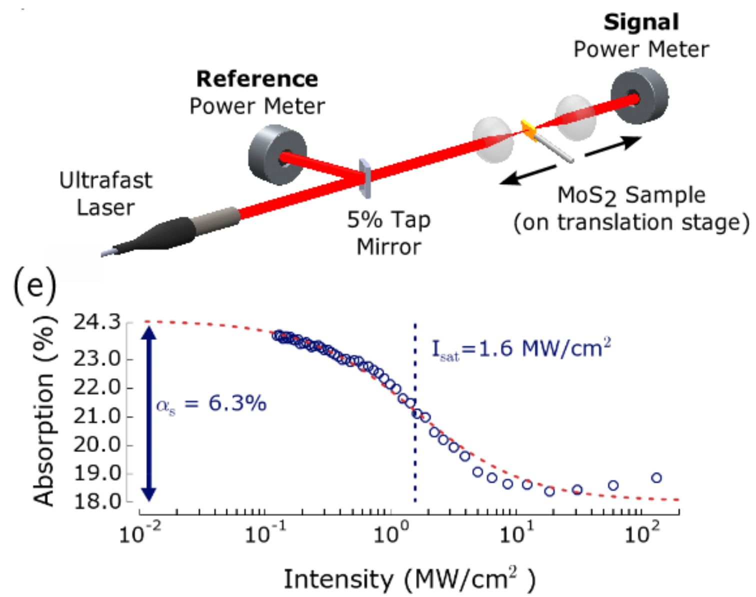


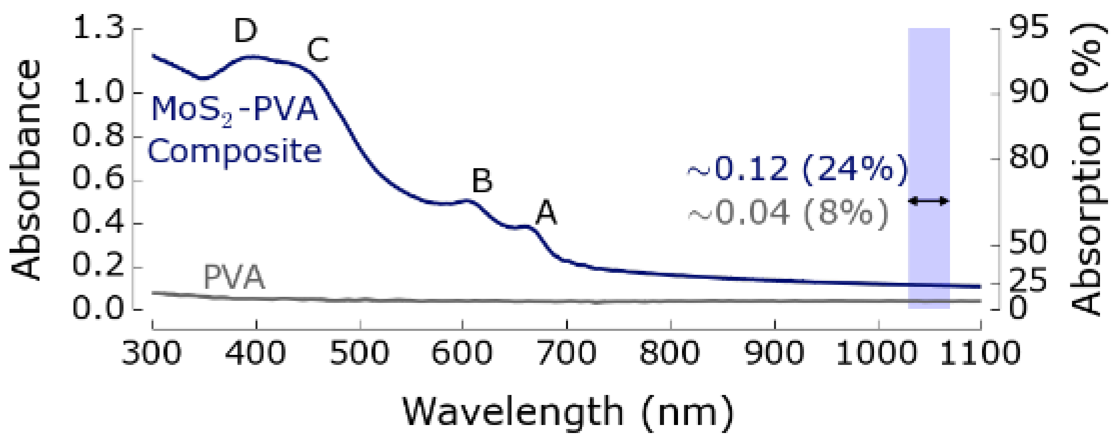




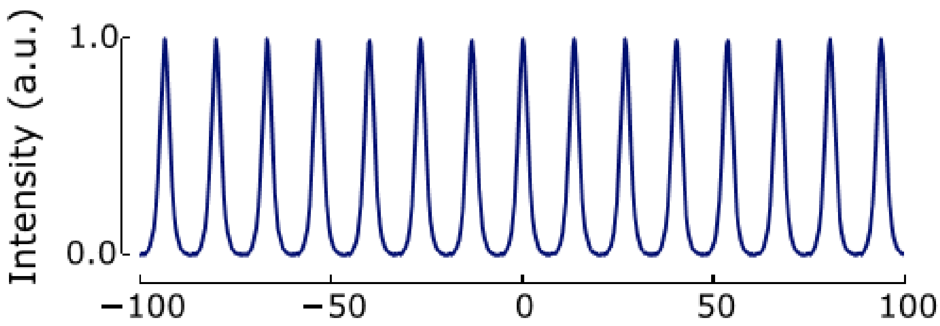
MoS_2 Q-switched Yb fibre laser

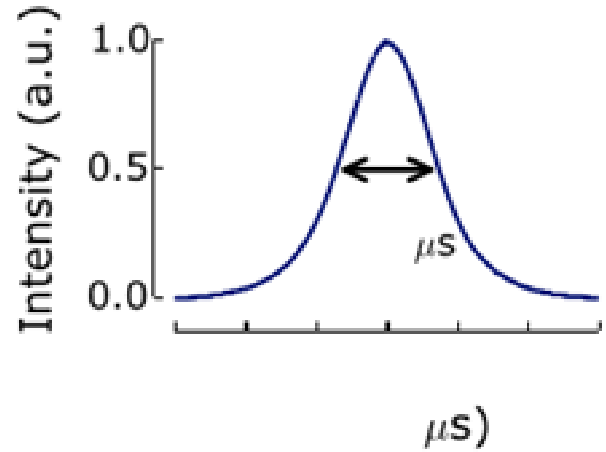


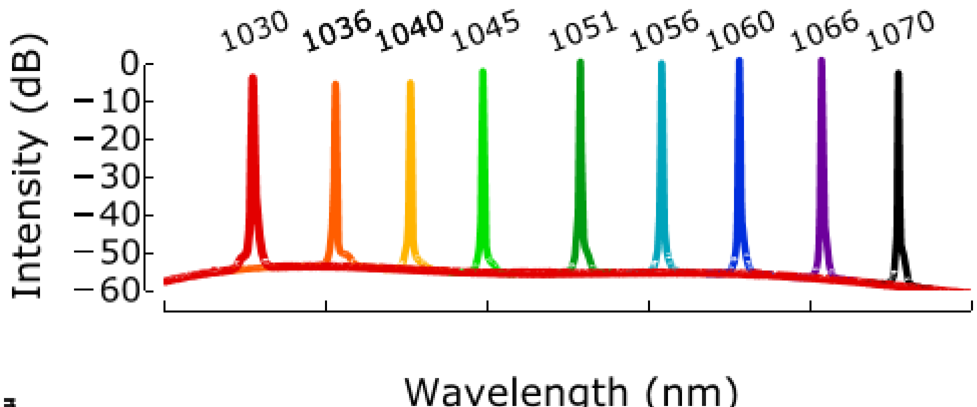


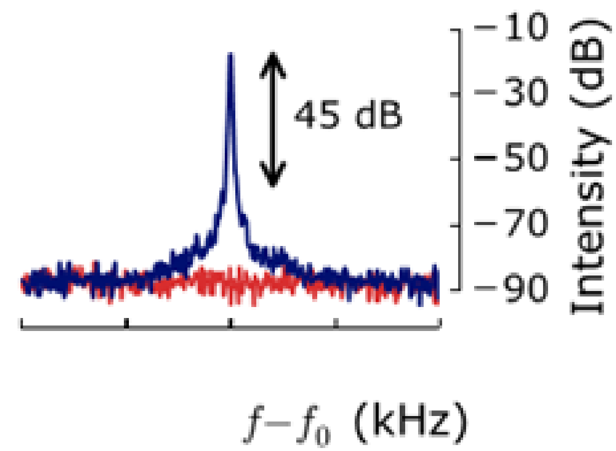


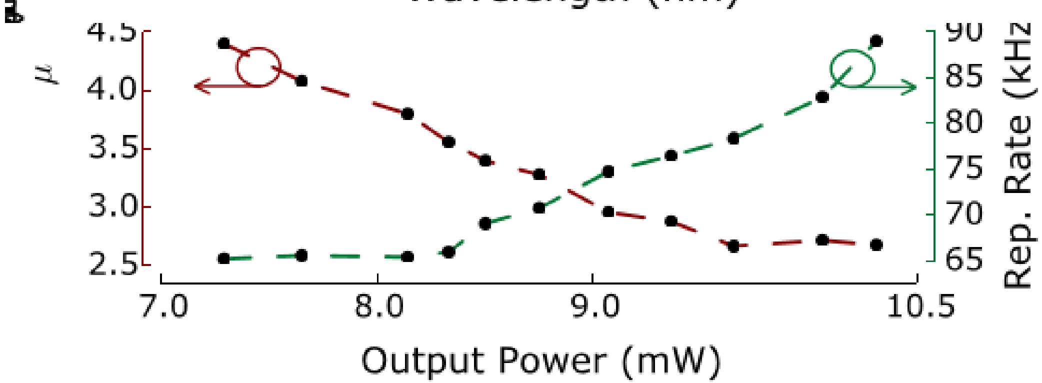
MoS $_2$ Q-switched Yb fibre laser







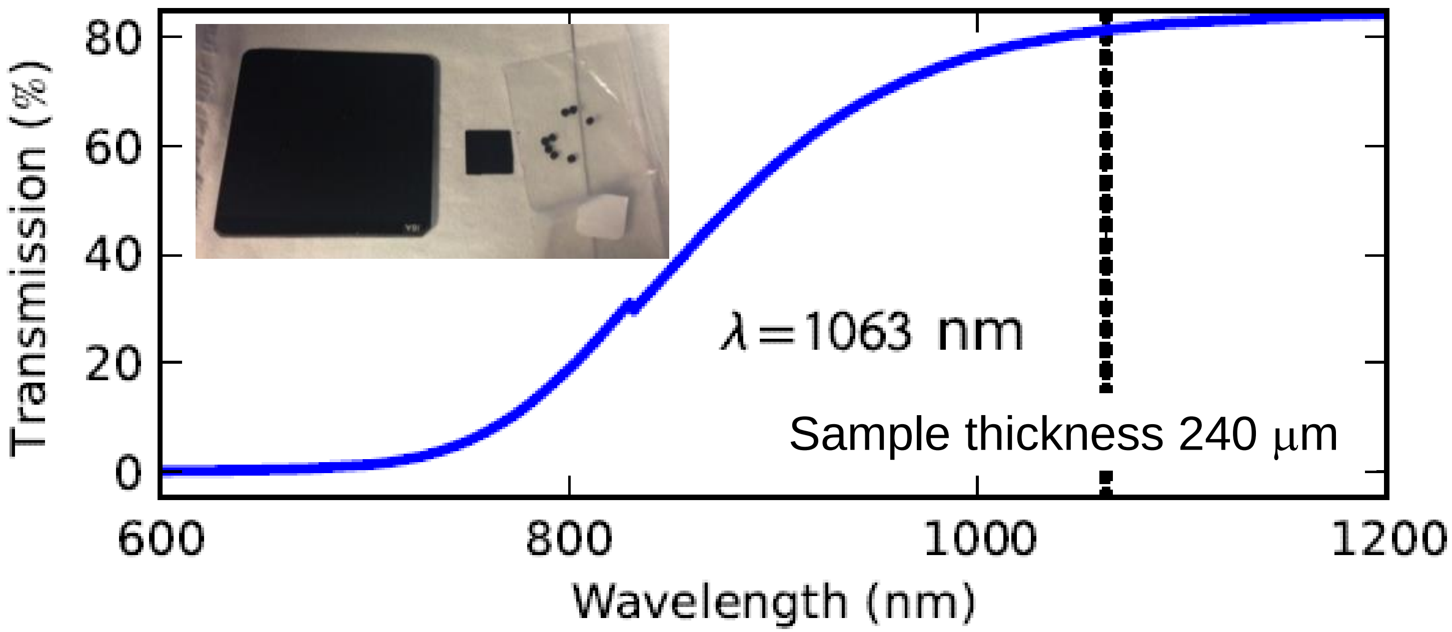




Ionically doped glass saturable absorbers

- High damage threshold
- Low cost !
- Used as early as 1964 for Q switching ruby lasers

Schott RG1000 CuInSSe



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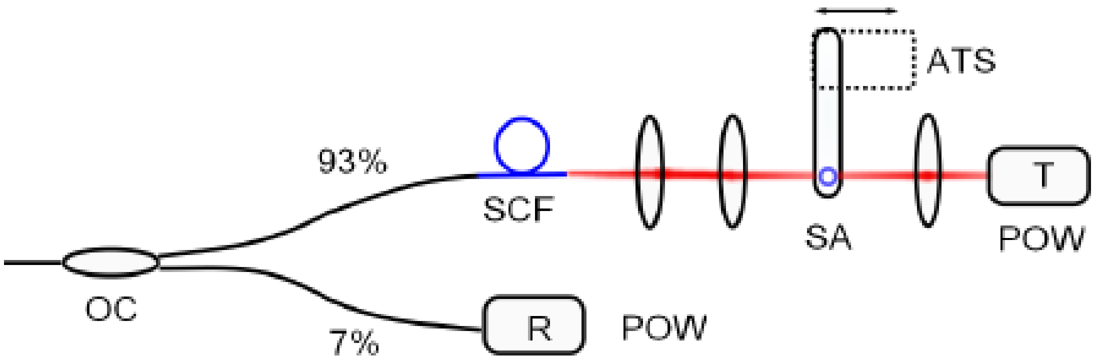
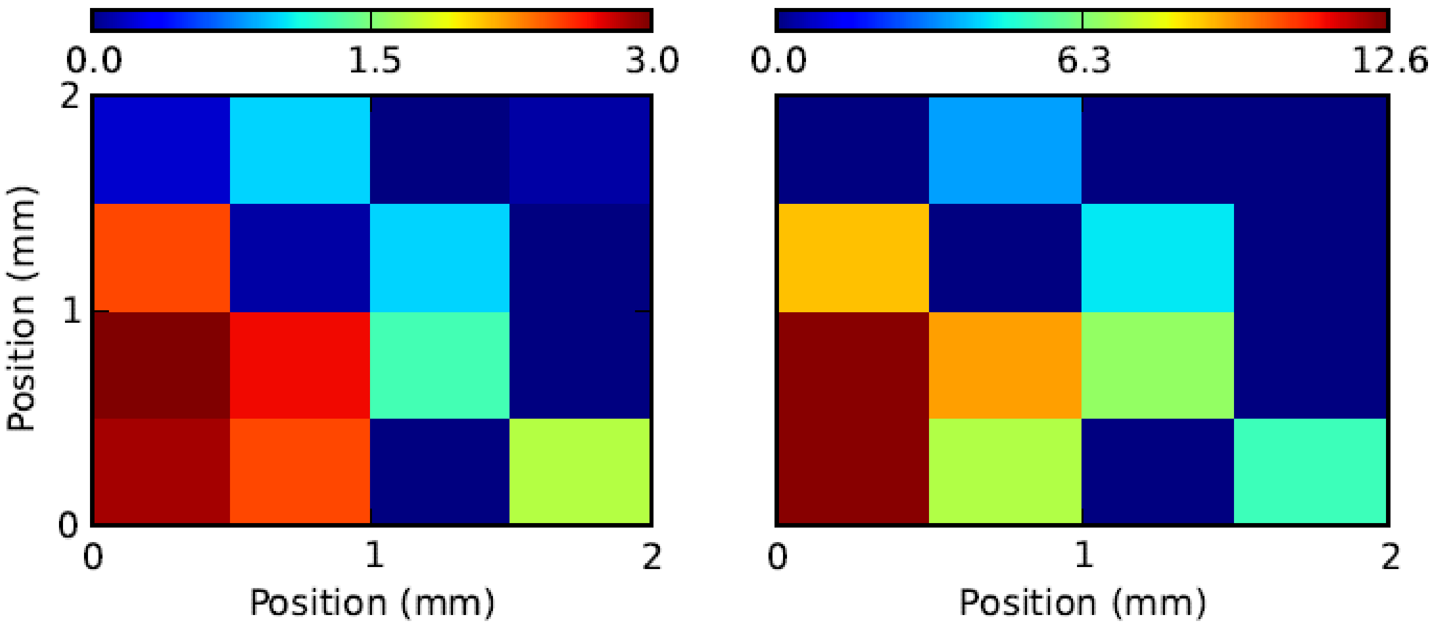
Z scan measurement of RG1000

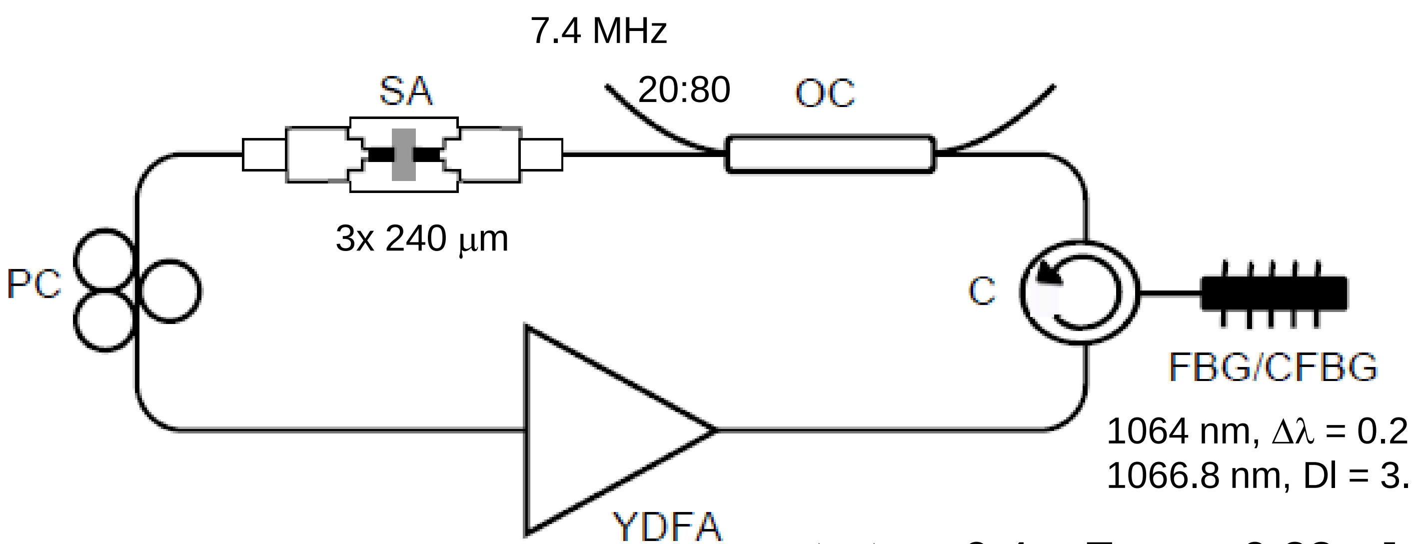
FOG femtosecond optics group





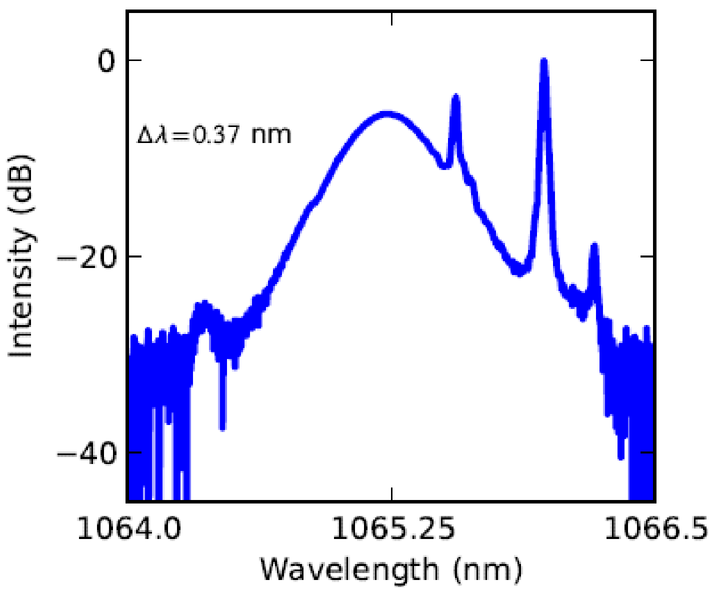
(a) Modulation depth (b) Saturation fluence

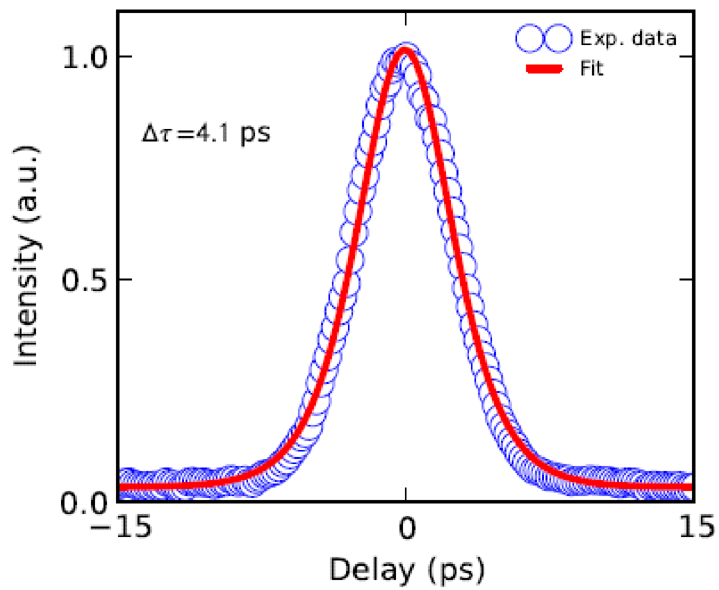
Ionically doped glass SA application



1064 nm, Δλ = 0.2 nm
1066.8 nm, Dl = 3.4 nm, -21.6ps[2]

$\Delta\nu\Delta\tau = 0.4$ $E_{pulse} = 0.28$ pJ



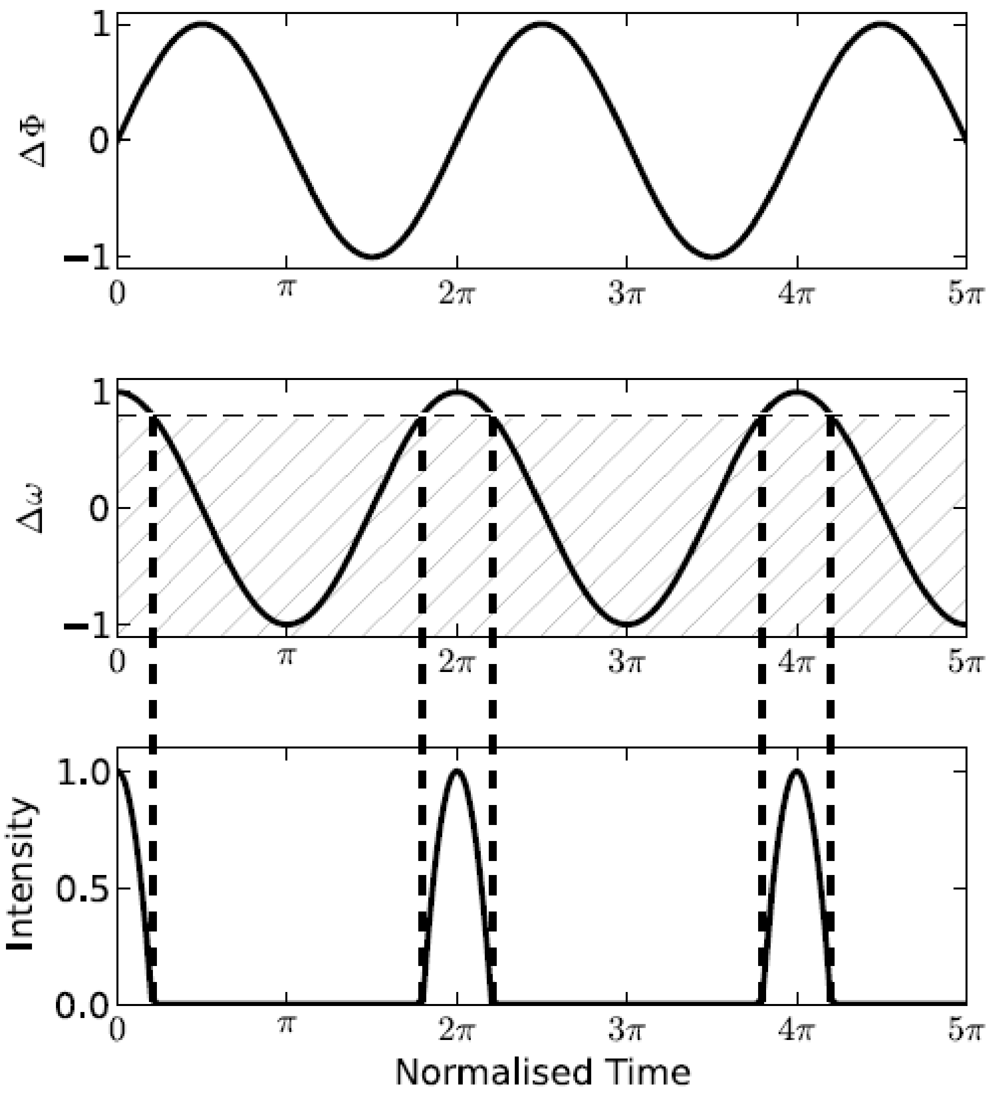


Spectrally masked phase modulation

- 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



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Adiabatic Soliton Compression

FOG femtosecond optics group

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

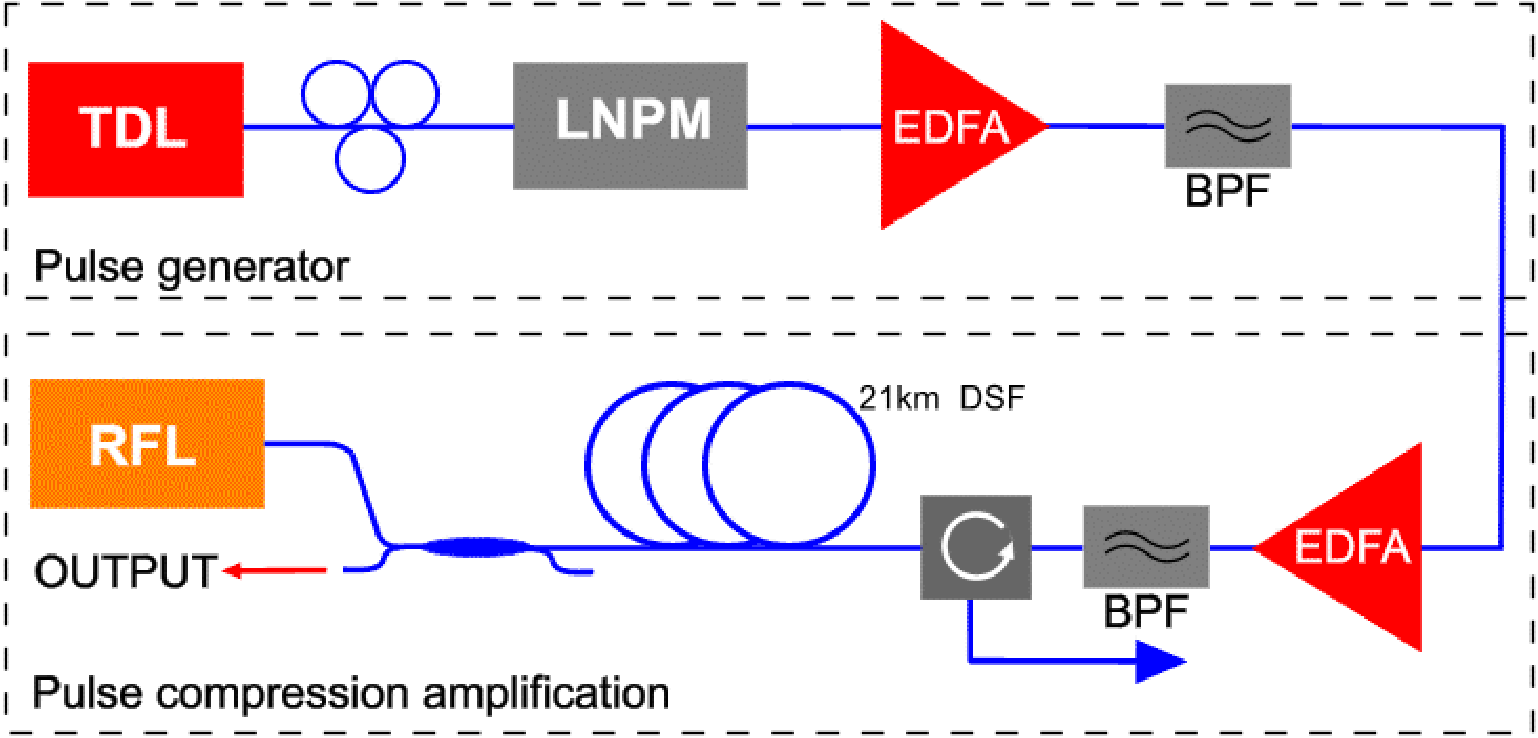
Advantages

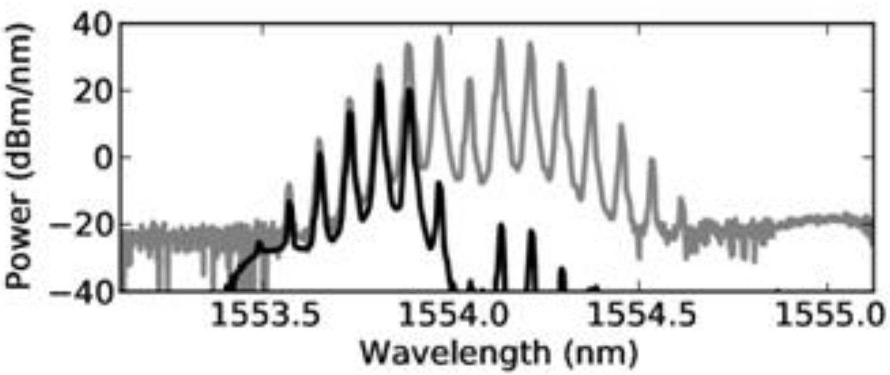
- Bandwidth-limited output
- Forgiving of input pulse shape
- Forgiving of taper / gain profile
- No alignment, robust, compact

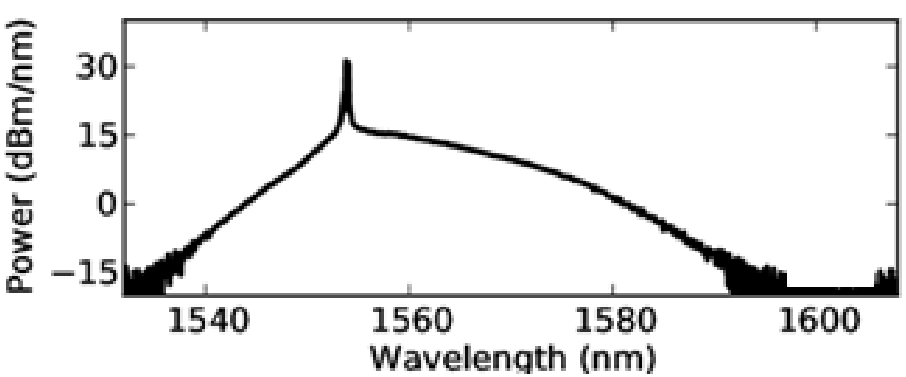
Disadvantages

- Need anomalous dispersion
- Pulse power fixed by dispersion

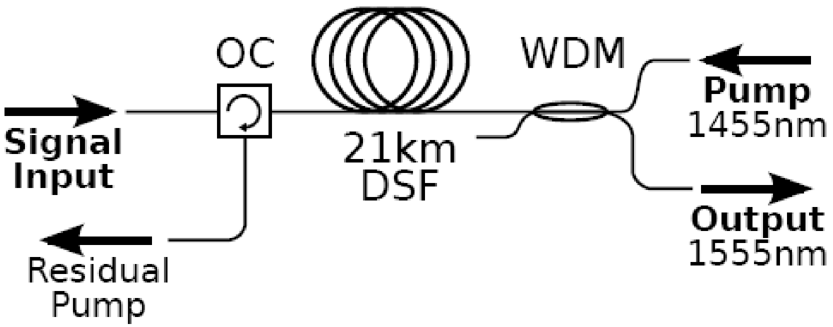
Pulse generation via phase modulation

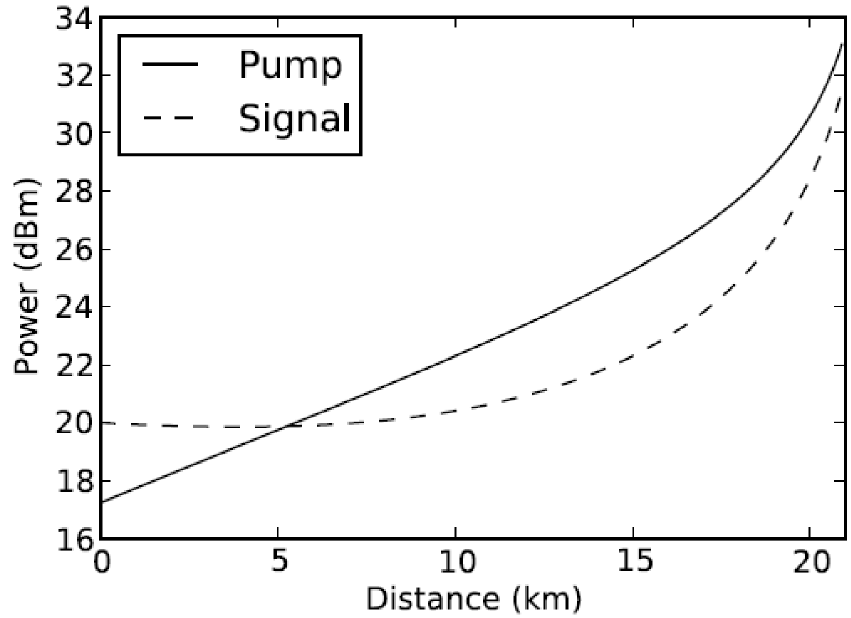


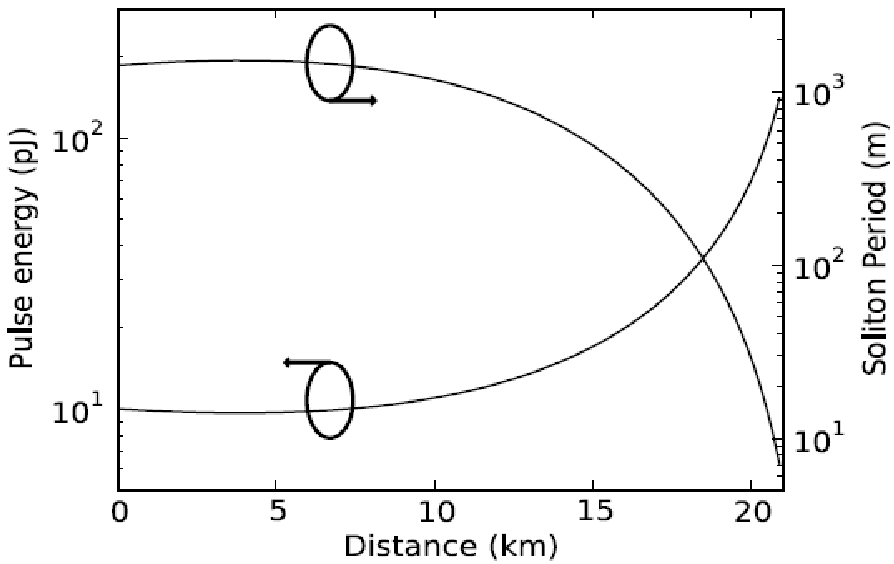


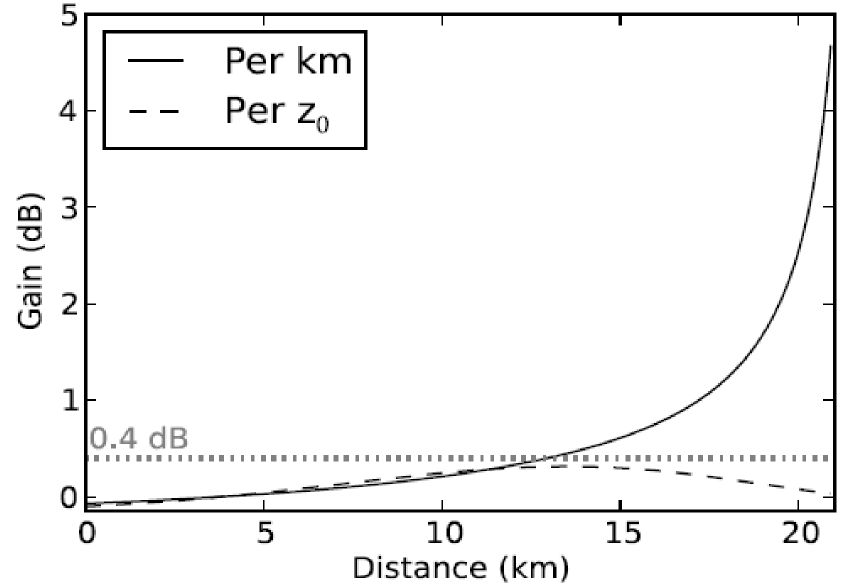


Gain-Compression Simulations

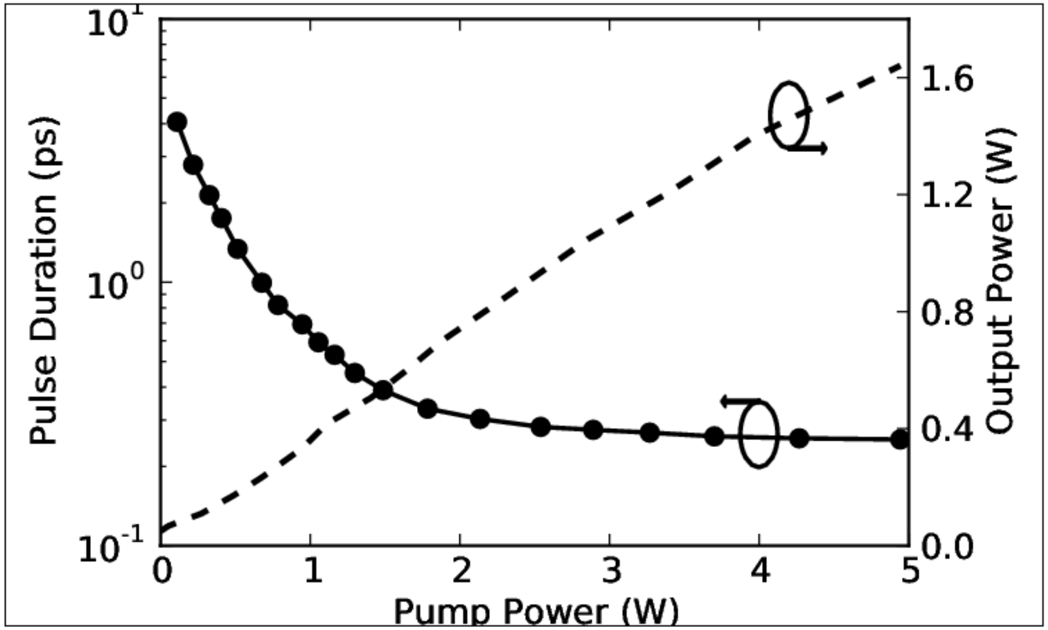


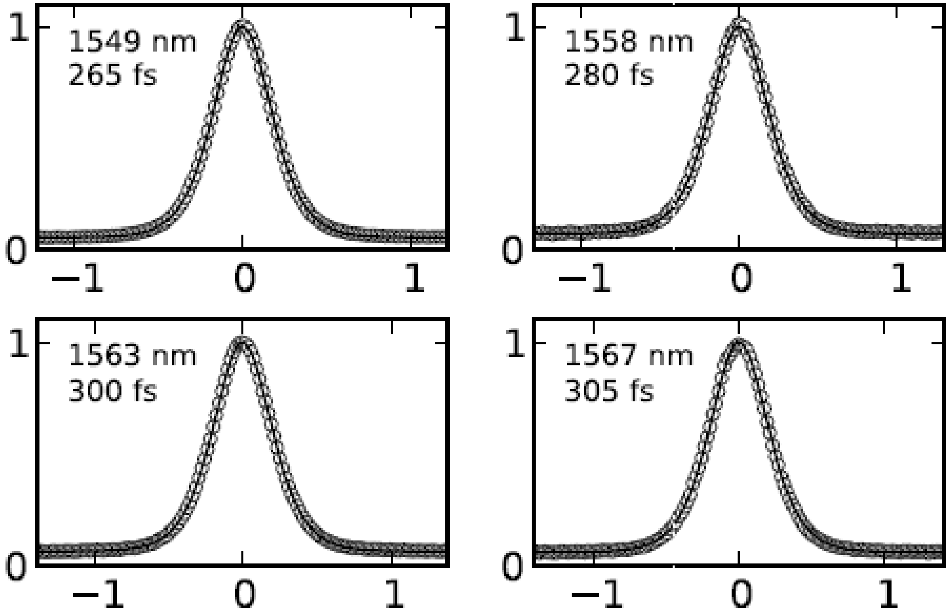






Pulse amplification and compression



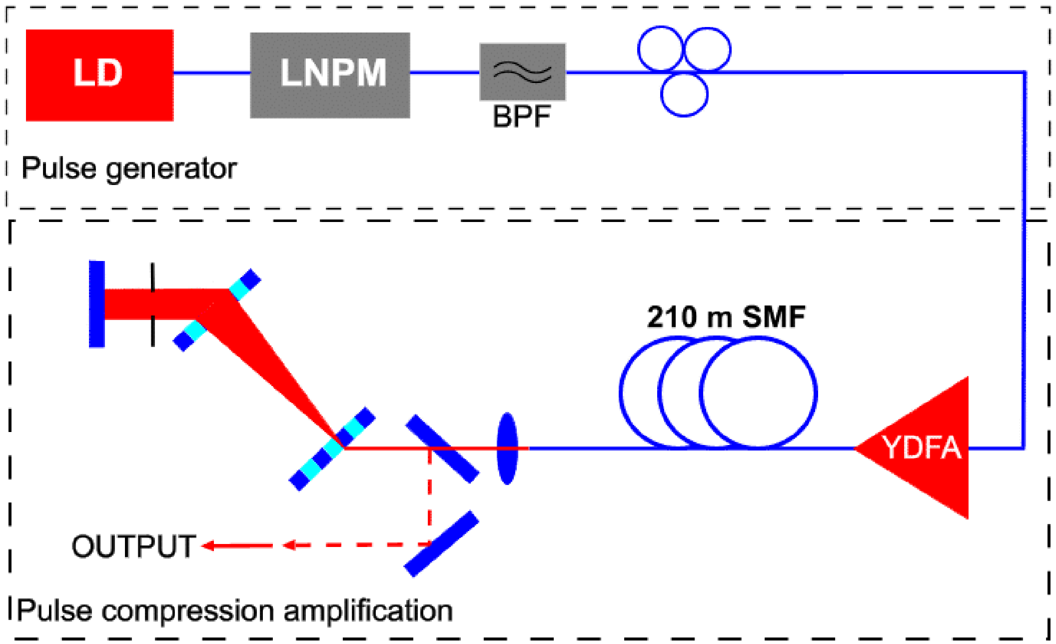


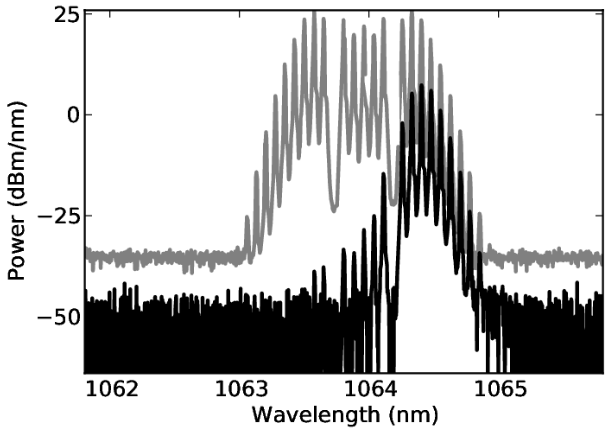
Alternative Wavelengths

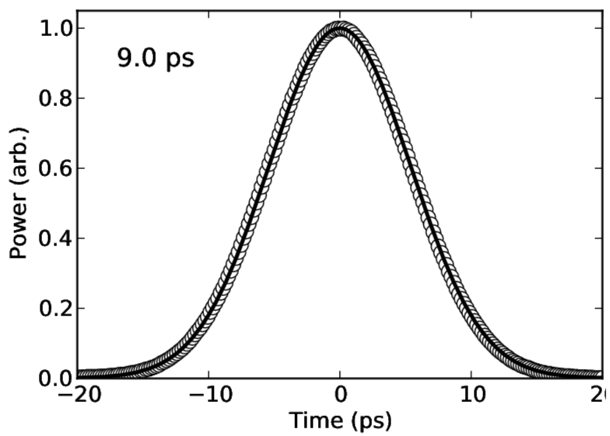
Tm ~ 1.98 μm
soliton shaping

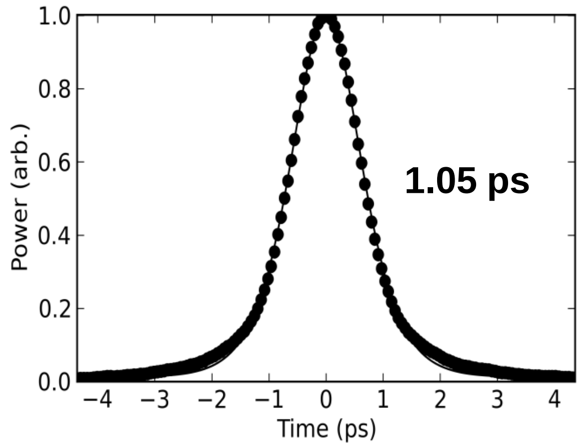
Yb ~ 1.06 μm
normal dispersion

Use : Bulk elements
PCF ? Not really
Air core PCF

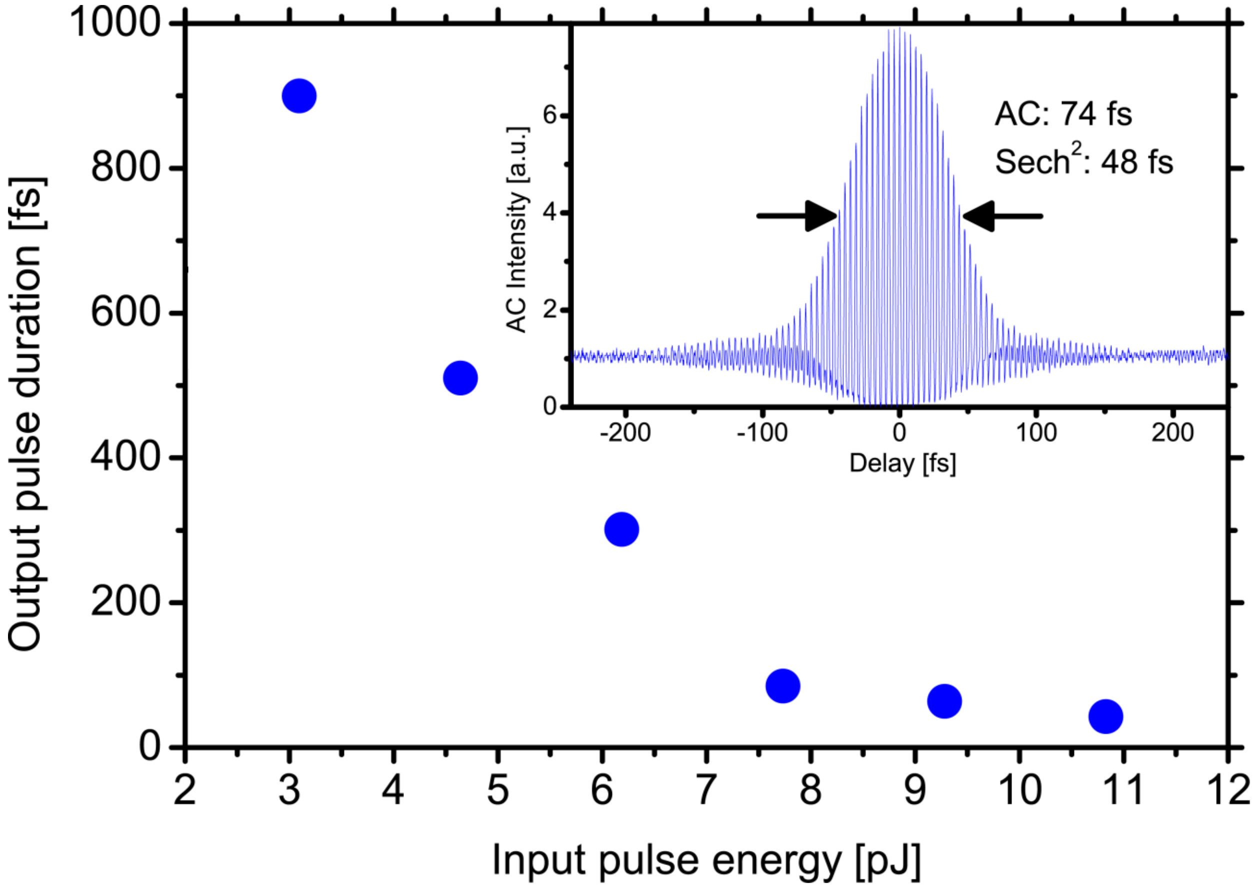








Compression in tapered PCF

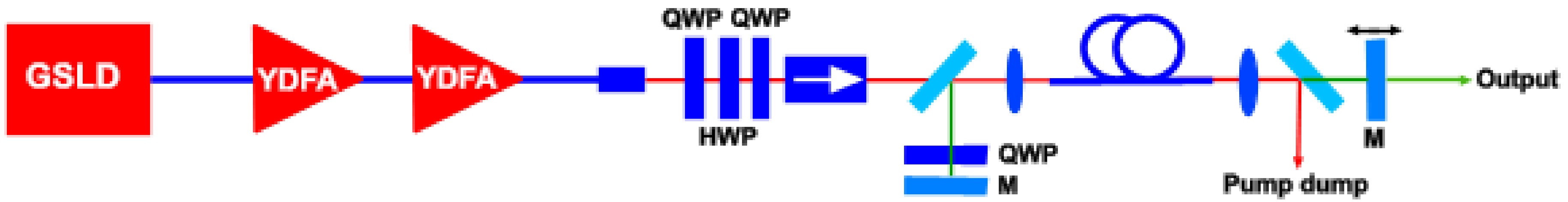


$$\tau_0 = \frac{2|\beta_2|}{\gamma E_s}$$

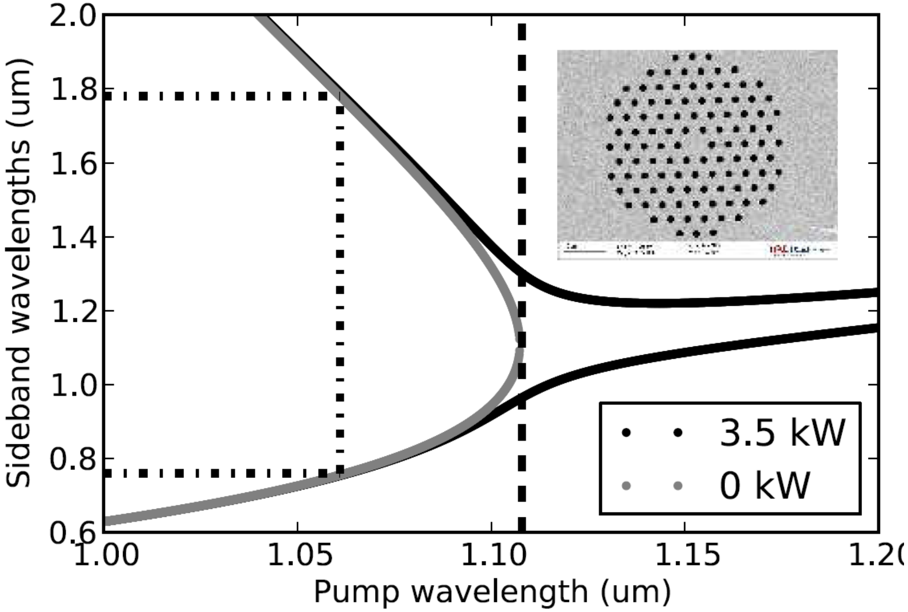
Parameters

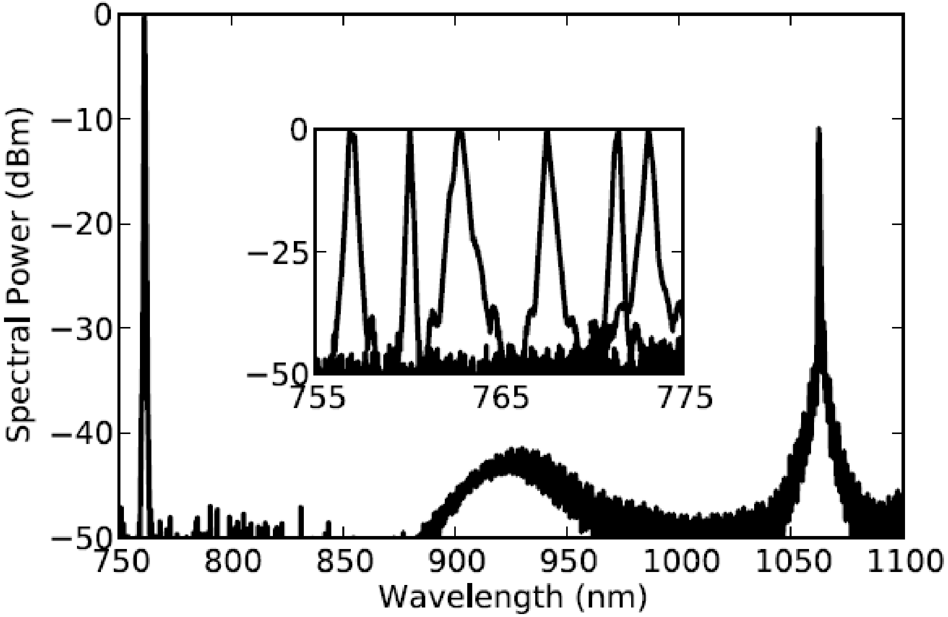
- **Dispersion: ~30 to ~0 ps/nm/km**
- **Loss: 56 dB/km**
- **Length: 17 m**
- **d/Λ = 0.52-0.42**
- **Λ = 1/50 – 1.25 μm**

PCF Optical Parametric Oscillator

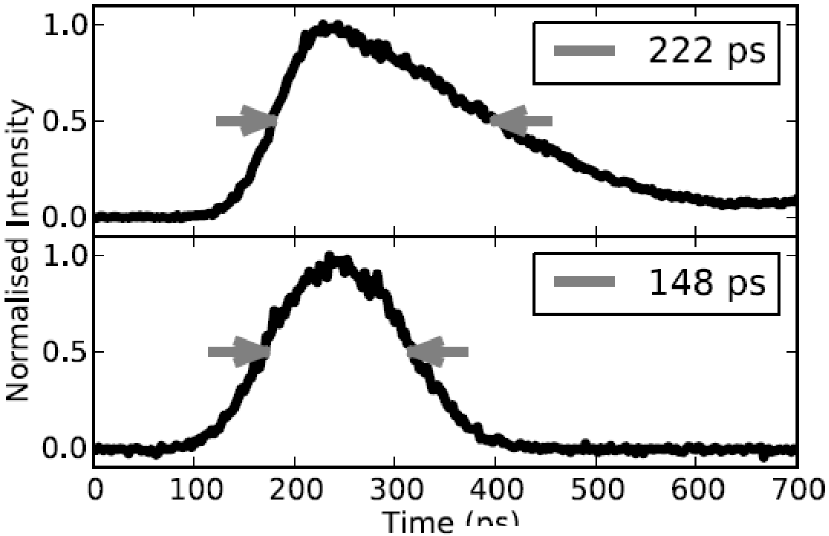


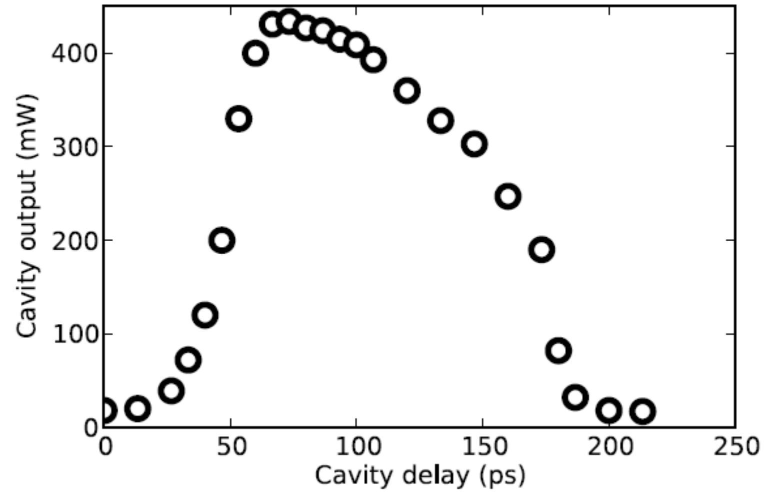
Pump - gain switched DFB at ~ 20 MHz (17.984MHz) Amplified ~ 14W (3.5kW peak)
PCF - ~2.6 m

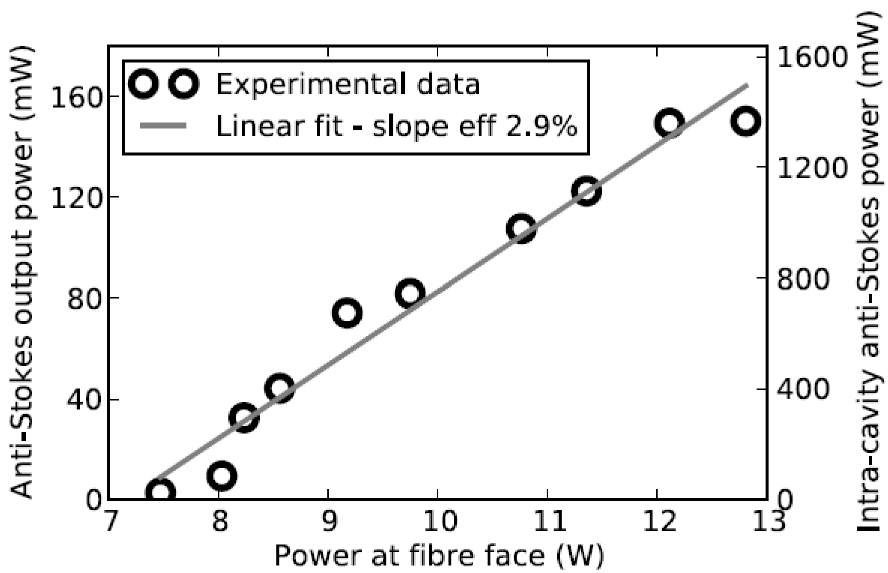




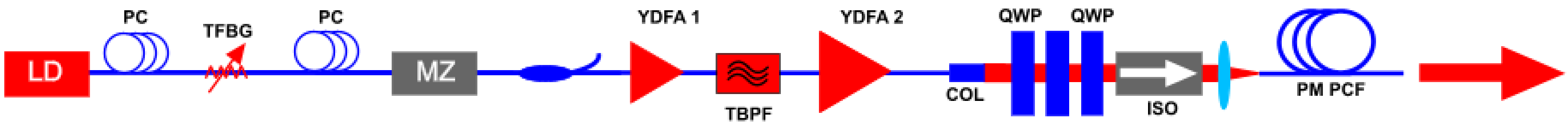
Optical Parametric Oscillation

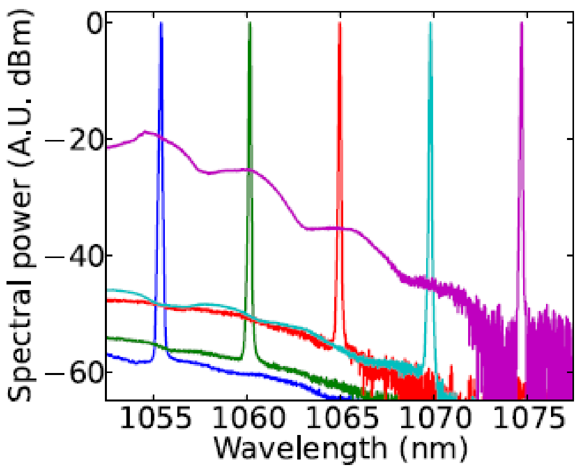


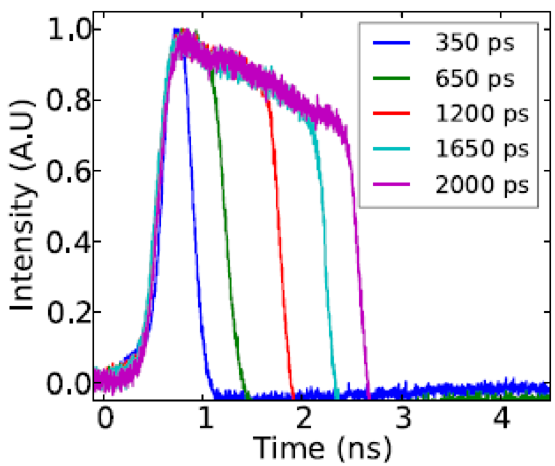


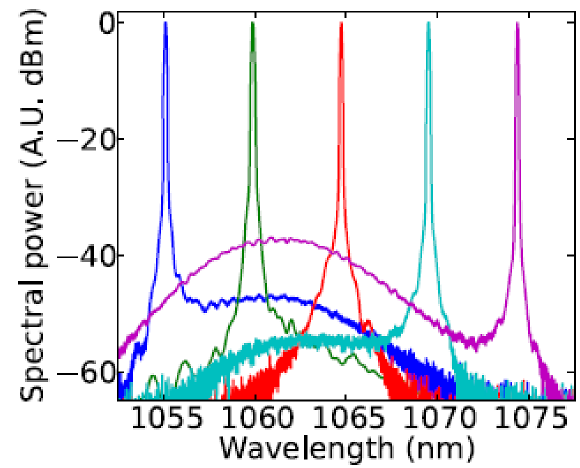


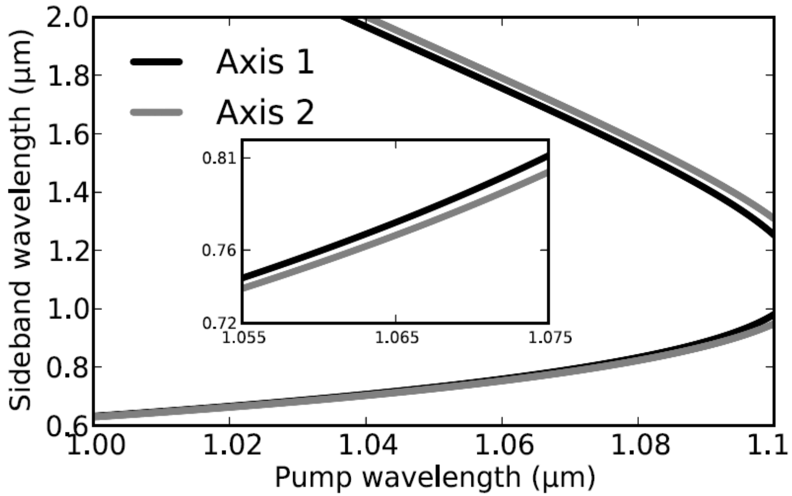
Single Pass Parametric Generation

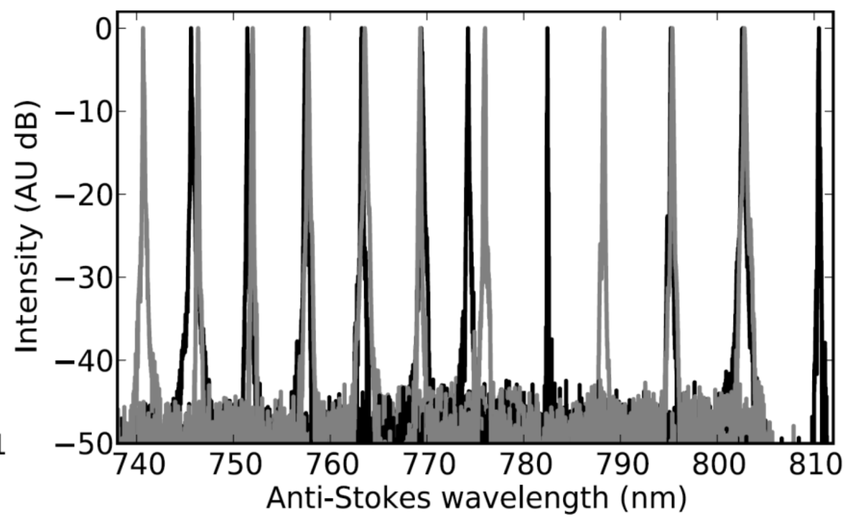












740-810 nm

0.2-1.5 ns

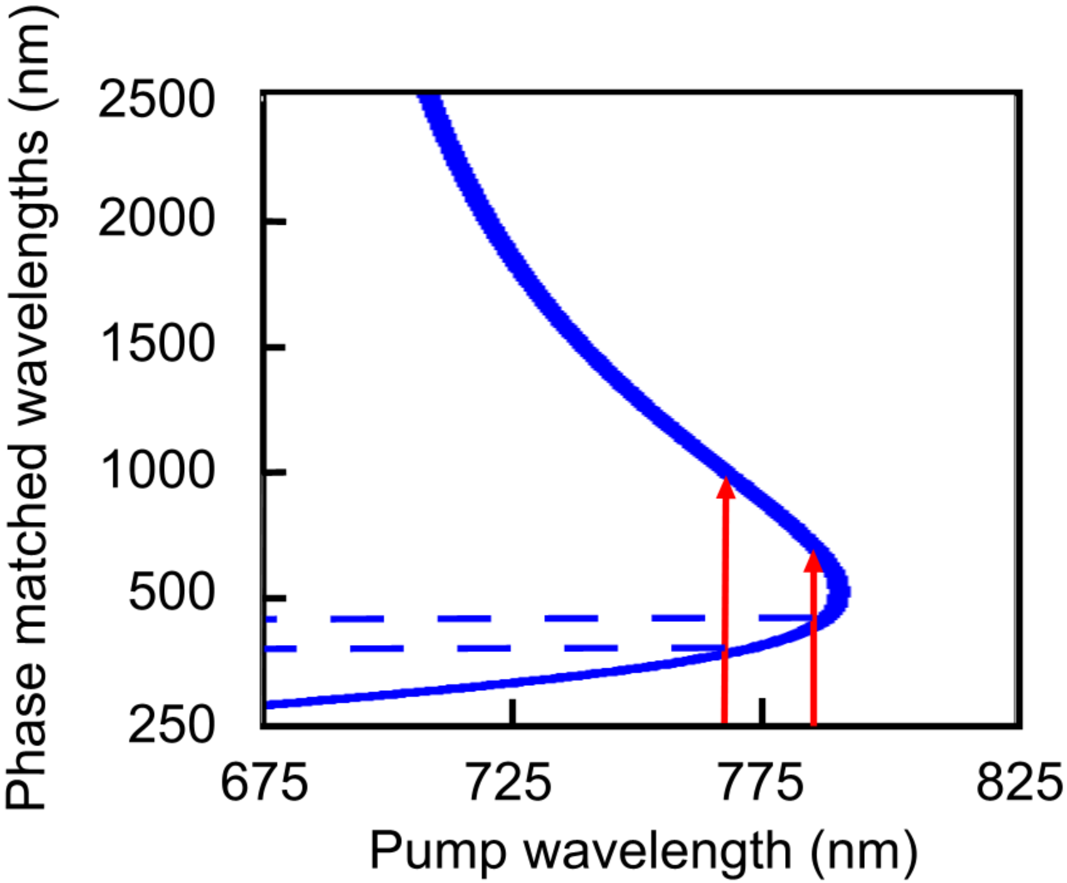
1-30 MHz

15% efficiency

~ 1W average

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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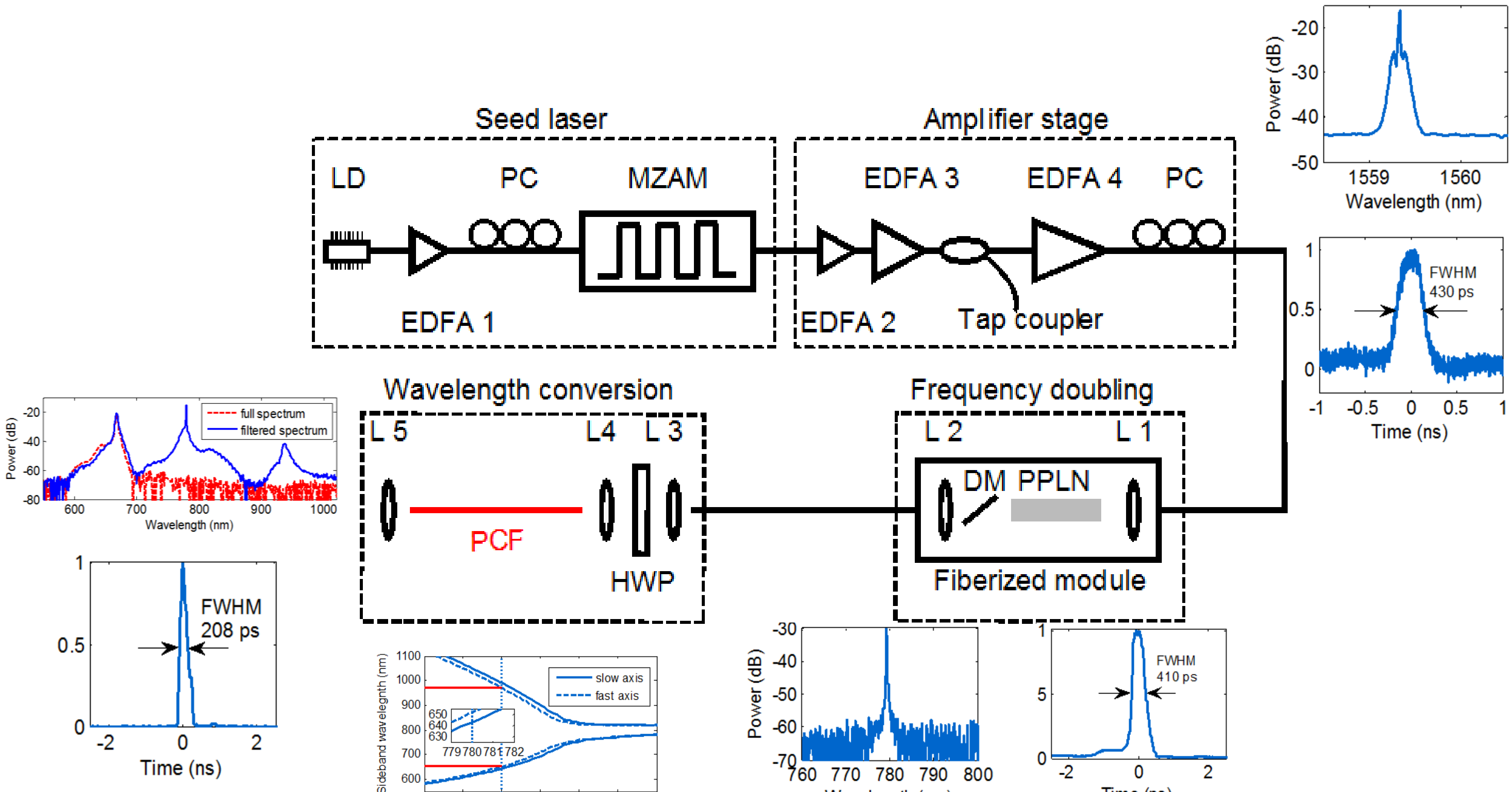
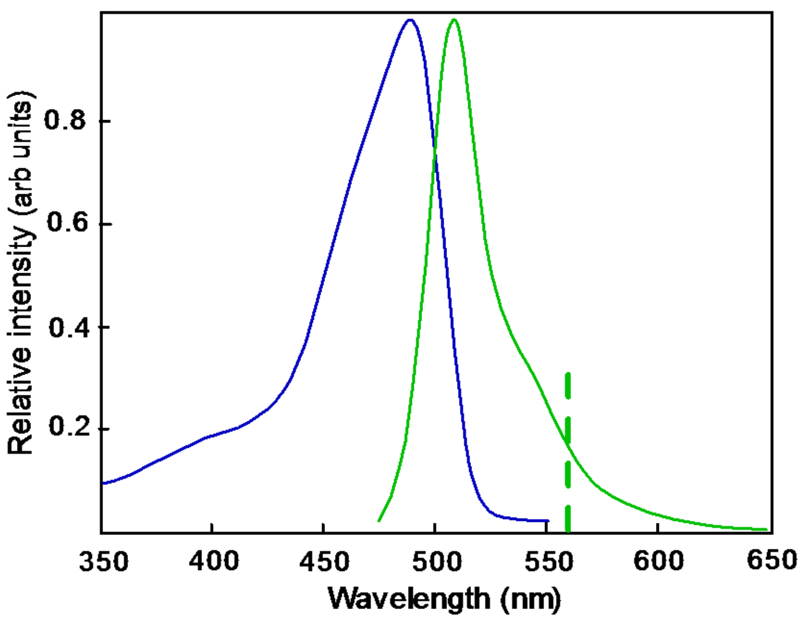
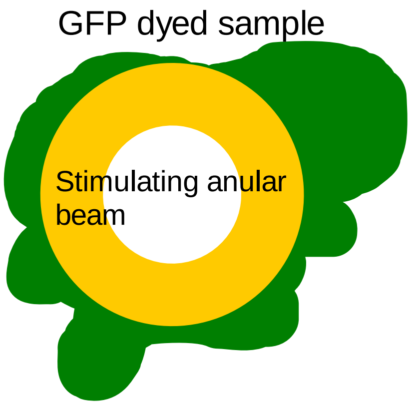


400 mW, 660 nm, 3.3nm

Visible sources for STED

- 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
- Typically use SHG of sync-pumped OPO pumped by femtosecond Ti:Sapphire or spectral selection from supercontinuum

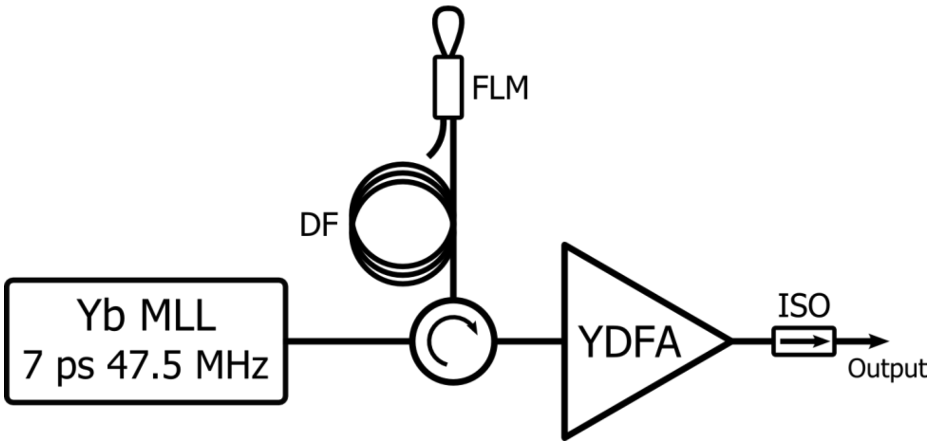


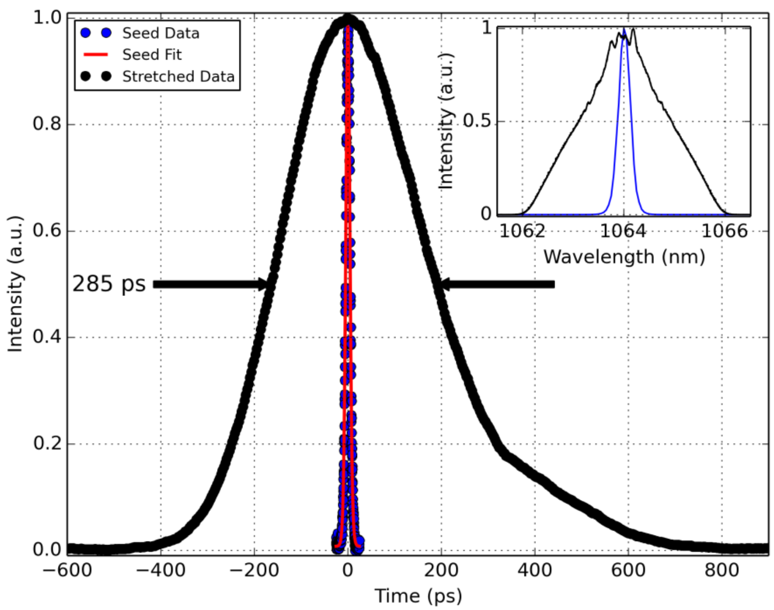


$$\Delta r = \frac{0.44\,\lambda}{NA\sqrt{1+\frac{I_{STED}}{I_{SAT}}}}$$

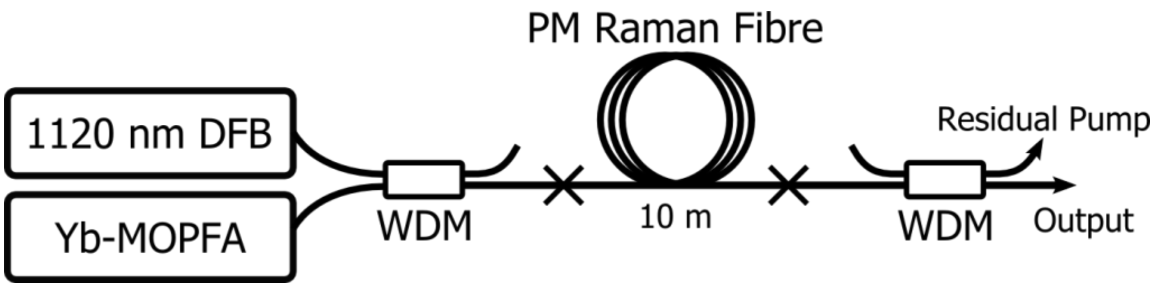
Yb-Fibre MOPFA

- Passively mode-locked Yb-fibre oscillator, 7 ps pulses at 47.5 MHz centred on 1064 nm
- Pulses stretched to 285 ps by double-passing normally dispersive fibre
- SPM aids dispersive broadening
- Amplified to 10 W average power with random polarisation state





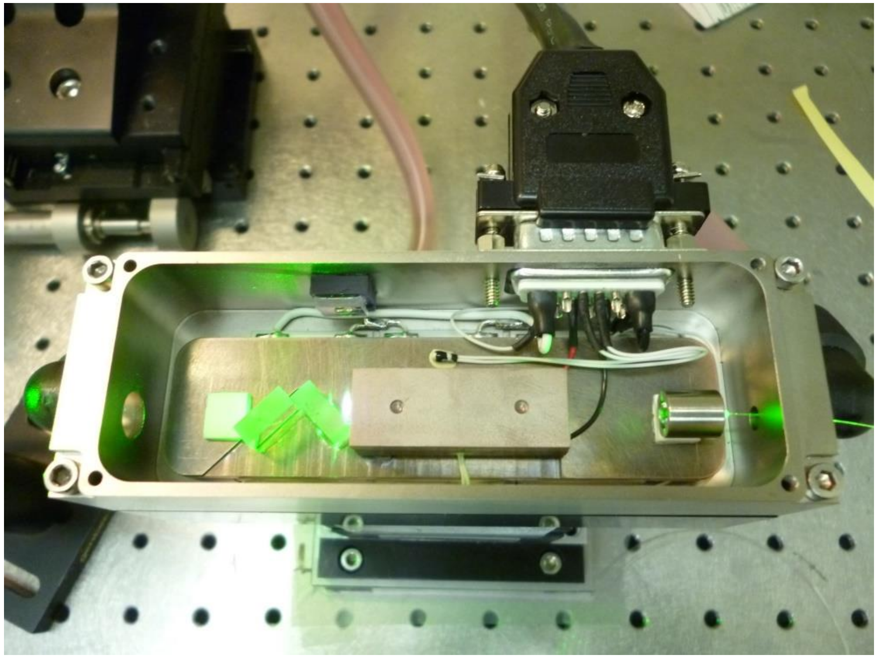
Raman Conversion to 1120 nm



- CW narrowline (< 10MHz) distributed feedback laser diode seed at 1120 nm
- Raman amplification in 10 m length of PM Raman fibre to 1.8 W in 200 ps pulses
- 74% conversion of pump to 1120 nm
- Linearly polarised (PER 14 dB) output

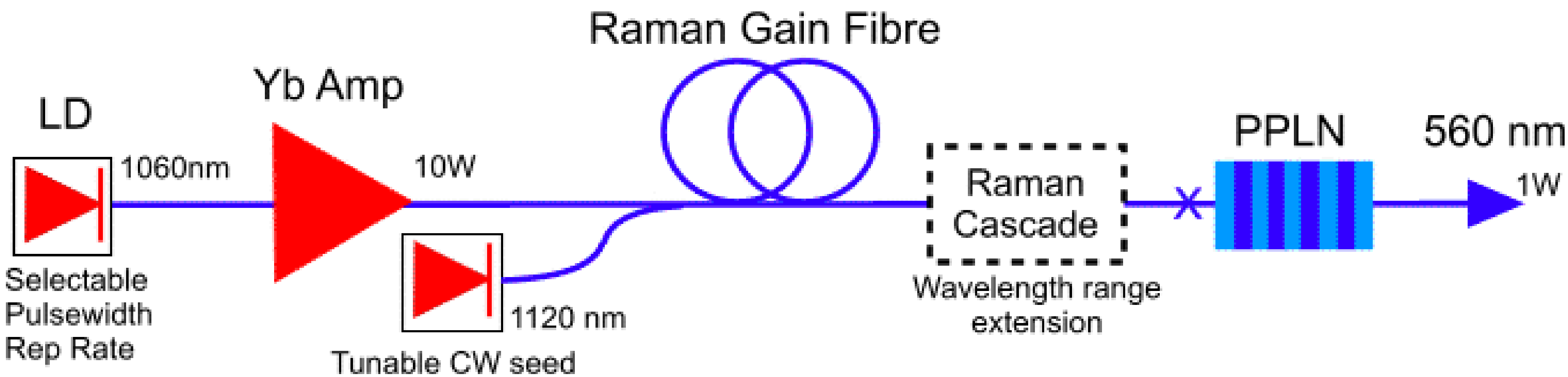
SHG Module

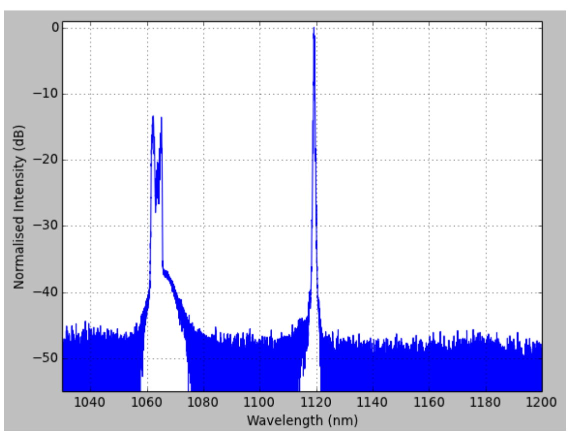
- 15 mm long PPLN crystal in copper oven
- Single aspheric to focus fibre input to 65 µm waist
- Optics bonded to TEC controlled base plate
- Up to 500 mW of 560 nm generated with 25% efficiency

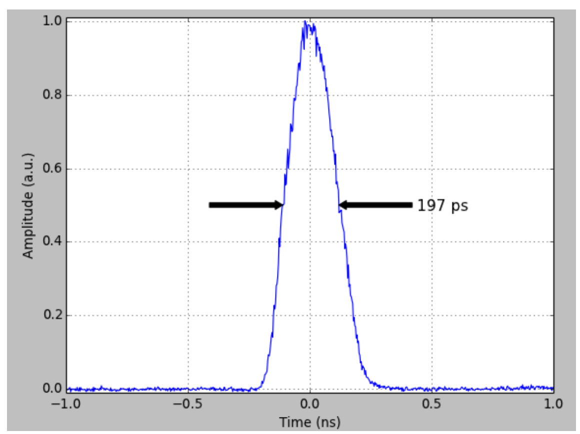


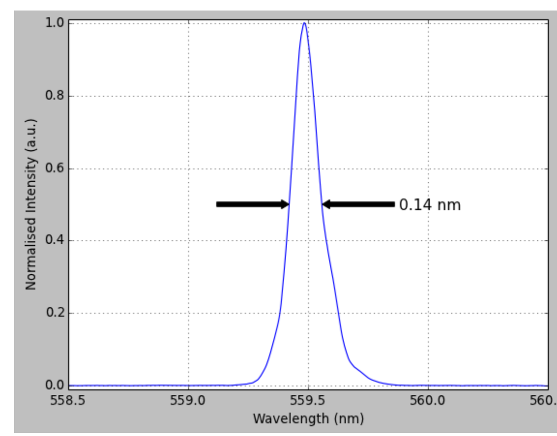
High-power – Visible sources

Frequency doubled, cw-seeded Raman fibre amplifiers for wavelength, pulsewidth and repetition rate selectivity

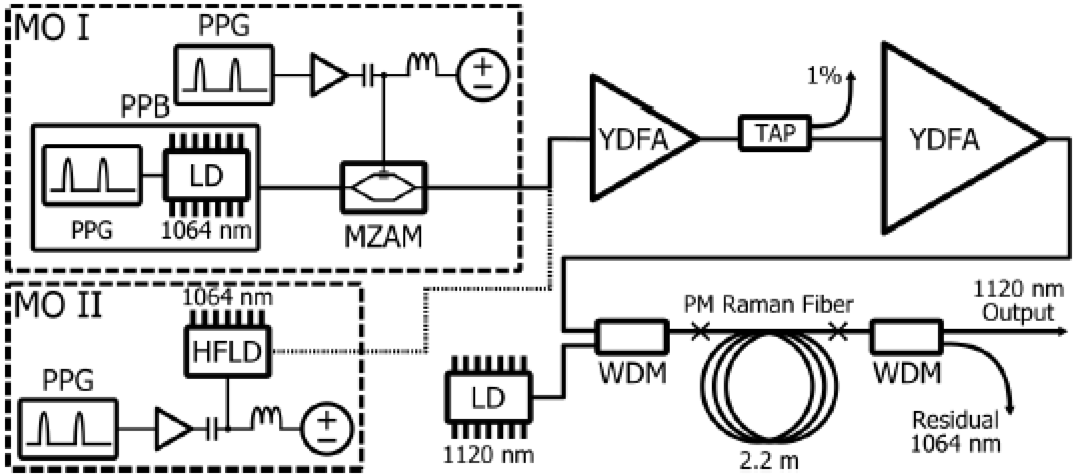


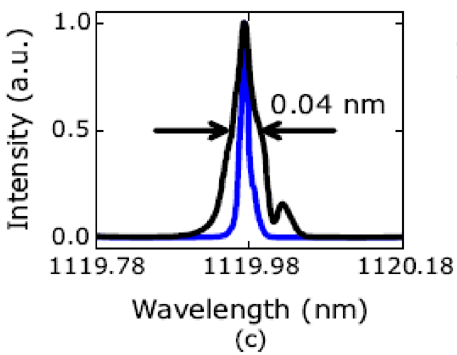


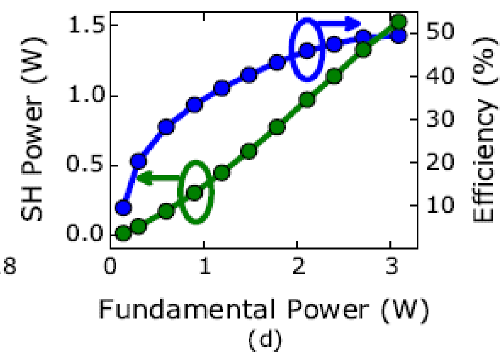


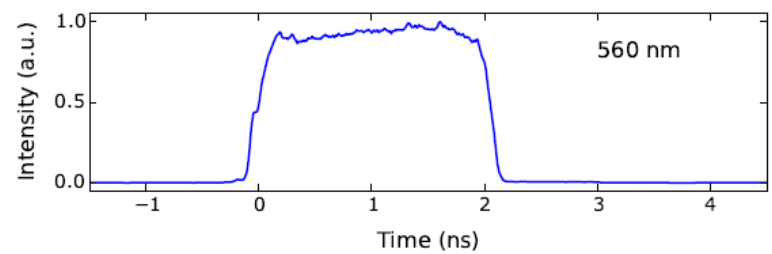


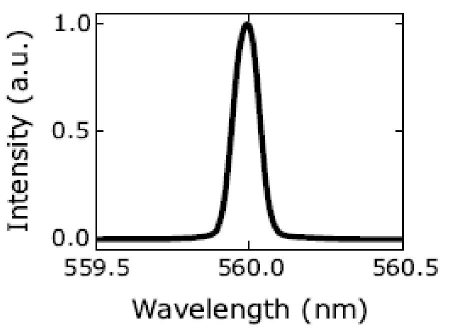
Versatile fibre Raman source at 560 nm

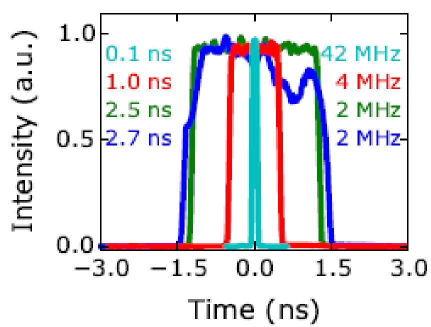


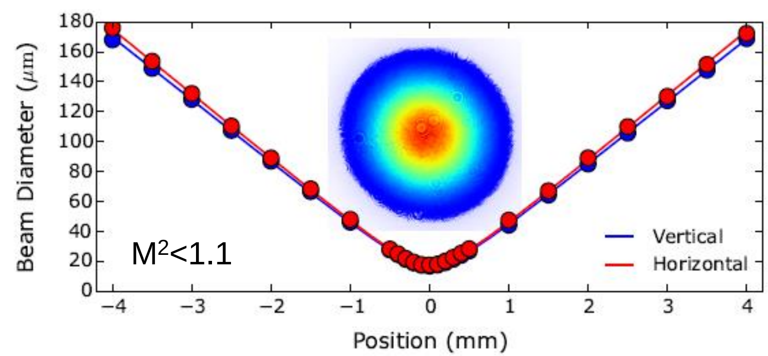












Summary

- As a result of technological advances fibre lasers are dominating the industrial laser market
- Continuous wave operation up to 10 kW single mode, 50 kW multimode
- Pulse durations down to 20 fs
- MOPFA geometries for added versatility (pulse duration and repetition rate) and power scaling
- MOPFA plus nonlinearity for spectral versatility covering 180 nm – 13 μm

High power fibre laser – fibre fuse