“Fibre lasers”

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[www.femto.ph.ic.ac.uk](http://www.femto.ph.ic.ac.uk)
Fibre Lasers – A very Brief History

● Snitzer 1964 Neodymium doped alkaline-glass fibre flashlamp pumped (Koetser and Snitzer Applied Optics 3, 1182 (1964))


● Fabrication of low-loss optical fibres containing rare earth ions 1985. (Poole, Payne and Fermann Electronics Letters 21, 737 (1985))


● 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.
Advantages of Fibre Lasers

- Distributed high gain
- Low heat load
- Gain diversity from 1 to 2 $\mu$m – and beyond
- Pumping with high brightness/efficient semiconductor lasers
- High beam quality (currently 10kW at 1 $\mu$m 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

- Yb
- Yb:Er
- Tm
- Bi
- Supercontinuum
- Raman
- FWM
- Parametric
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
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

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

Average power ~ 10s W

Taylor et al 2004
Dynamics of picosecond pumping

2004 4W average  3.1 mW/nm
2006  20 W       15 mW/nm
2011  50W       35 mW/nm

Operation down to 320 nm

• Supercontinuum initiated by modulation instability
• Generates > 100 kW power fundamental solitons from ~10 kW pump
• A cascade of four wave mixing processes extends the continuum to visible
• Further extension due to soliton–dispersive wave interactions

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

GAIN
LOSS
DISPERSSION
MODULATION
PULSE NARROWING
SPECTRAL NARROWING

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$_x$O)
- 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

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

<table>
<thead>
<tr>
<th>Transition</th>
<th>Modulation Depth</th>
<th>Saturation Intensity</th>
<th>Transition Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{11}$</td>
<td>13%</td>
<td>$\sim 10 \text{ MW cm}^{-2}$</td>
<td>$\sim 400 \text{ fs}$</td>
</tr>
<tr>
<td>$E_{22}$</td>
<td>15%</td>
<td>$\sim 220 \text{ MW cm}^{-2}$</td>
<td>$\sim 40 \text{ fs}$</td>
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</table>
CNT passively mode locked fibre lasers

Solitons!

6.5 ps @1560 nm
At repetition rates from a conventional fibre laser, for pulse durations in the 500fs-1ps regime only a few mw average power power is required. For many applications AMPLIFICATION needed.
Soliton length \( \approx 0.25 \tau^2/D \)

If \( \tau = 500 \text{ fs} \), \( D = 5 \text{ ps/nm/km} \) \( Z_0 \approx 12.5 \text{ m} \)

Solitons will react and shed radiation
Spectral instability - sidebands

\[ nK_A = K_{\text{SOL}} + K_{\text{DISP}} \]

Rearranging

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

\[ \frac{2\pi n}{Z_A} = \frac{1}{2} + \frac{\Delta \omega^2}{2} \]

Kelly, Elect Lett. 28, 806 (1992)

Sidebands:-

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

Experimental
CNT passively mode locked fibre laser

6.6 MHz
15 pJ

SWNT

Δλ=3.4 nm, (-)35.71 ps/nm

(a) Δλ=0.059 nm

(b) Δτ=1.15 ns

ΔνΔτ~18
Low repetition rate supercontinuum source

\[ \Delta v \Delta \tau \sim 143 \]

Sech\(^2\) Fit

\[ \Delta t = 0.99 \text{ ns} \]

\[ \Delta \lambda = 0.55 \text{ nm} \]
Low repetition rate supercontinuum source

87 mW pump power
Giant chirp laser

Bandpass Filter

Ytterbium-Doped Fiber Amplifier

Carbon Nanotube Saturable Absorber

840 m Flexcore Fiber

244 kHz

10% Output Coupler

Polarization Controller

Isolator

Seed Oscillator Output

Ytterbium-Doped Fiber Amplifier

Circulator

Chirped Fiber Bragg Grating

Output

\( \Delta \nu \Delta \tau \approx 219 \)

\( \Delta t = 1.02 \text{ ns} \)

\( \Delta \lambda = 0.80 \text{ nm} \)

\( \text{Sect}^2 \text{ Fit} \)
Chirp Measurement

Compression?
Required grating separation > 50 m
\[ n_0 = 1.45 \quad \delta n = 5 \times 10^{-5} \quad L = 200\text{mm} \]

Gaussian apodization FWHM 60 mm
Giant chirp compression - improvements

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

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: 
$e h_{11}$ of tubes $d = 1.5 – 1.8$ nm
Mode locked Tm fibre laser

- Fundamental cavity repetition frequency – 6.1 MHz
- Centre wavelength – 1944 nm, $\Delta \lambda = 3.2$ nm, TBP = 0.94
- Pulse duration – 3.7 ps
- Single pulse energy – 0.6 nJ
• Stretcher: **1250 m**, \( \text{GVD} = 34 \text{ ps}^2 \text{ km}^{-1} \) at 1.95 \( \mu \text{m} \)

• 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 150 mW

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

$L_{\text{optimum}} = 3.4 \text{ m}$
- Linear PM SESAM mode locked cavity, \( f_{\text{rep}} = 28 \, \text{MHz} \), \( P_{\text{av}} = 6 \, \text{mW} \), \( \tau_{\text{pulse}} = 9 \, \text{ps} \)
- 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
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
- 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
• 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

![Graph showing dispersive wave emission in the uv spectrum for different gases (Xe, Kr, Ar, Ne).](image-url)
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
- 10:90 OC
- 6.5 MHz
- BPF 11 nm

\[ E_{\text{pulse}} = 0.3 \text{ nJ} \]

\[ \Delta \lambda = 2.1 \text{ nm} \]

\[ \Delta \tau = 3.6 \text{ ps} \]
Graphene – Dual Cavity Mode-locking

DL~300 ps

CFBG 1066.8 nm
3.4 nm, 35.71 ps/nm
Coupled cavities

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

Cavity mismatch allowable ~1mm

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)

\[ \frac{dv}{dz} = \tau^{-4} \]

Input wavelength 1540 nm up to 1.6kW

L = 120 m

Average Power (mW)

Spectral Shift (nm)

Power (arb units)

Wavelength (nm)
Universal Pulse Source

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

Pump out

100m GeO$_2$

Graphene

CW pump in

Mode-locked output
1.76 MHz ~500ps

Compressed output
2ps
Universal short pulse source

Raman gain based
All building blocks are in place
Transition metal dichalcogenides

Molybdenum disulphide stacked molecular layers
Single metal layer between two layers of chalcogen atoms

MoS\(_2\) bulk

MoS\(_2\) monolayer
**MoS\(_2\) manufacture - LPE**

1. MoS\(_2\) powder + sodium deoxycholate + water
2. Ultrasonication 2hrs
3. Centrifugation 1hr
4. Centrifuge Mixing
5. Mixture dried in oven 20\(^\circ\)C
6. TEM

Nanomaterial PVA composite

- Picosecond (~100) recovery time interband, ~30 fs intraband
- \(\Psi^{(3)} \sim 1.5 \times 10^{-14}\) esu (~2x graphene)
**MoS\textsubscript{2} mode-locked Er fibre laser**

![Diagram of MoS\textsubscript{2} mode-locked Er fibre laser](image)

- **EDFA**
- **Isolator**
- **Polarization Controller**
- **MoS\textsubscript{2} Saturable Absorber**
- **Tunable Filter**
- **Output Coupler**

**Parameters:**
- **15 MHz**
- **60-100 pJ**

**Graphs:**
- *Transmission (%) vs. Wavelength (nm)*
- *Intensity (a.u.) vs. Wavelength (nm)*

**Notes:**
- 1030 - 1070 nm
- Wavelength range from 1530 to 1570 nm
- Intensity peaks indicating mode-locked operation
- ASE (Amplified Spontaneous Emission) indicated

*Photonics@be  Oostduinkerke May 2015*
MoS$_2$ Q-switched Yb fibre laser
MoS$_2$ Q-switched Yb fibre laser

Intensity (a.u.)

Intensity (dB)

Intensity (a.u.)

Intensity (dB)

Wavelength (nm)

Output Power (mW)

Rep. Rate (kHz)

$f-f_0$ (kHz)

45 dB
Ionically doped glass saturable absorbers

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

**Schott RG1000 CuInSSe**

Sample thickness 240 µm
Z scan measurement of RG1000

(a) Modulation depth
(b) Saturation fluence
Ionically doped glass SA application

7.4 MHz

1064 nm, $\Delta \lambda = 0.2$ nm
1066.8 nm, $Dl = 3.4$ nm, -21.6 ps

$\Delta v \Delta \tau = 0.4$  $E_{\text{pulse}} = 0.28$ 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
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

Pulse generator

Pulse compression amplification

21km DSF

BPF

EDFA
Gain-Compression Simulations

Diagram:
- Signal Input
- Residual Pump
- OC
- WDM
- Pump 1455 nm
- 21 km DSF
- Output 1555 nm

Graphs:
- Power (dBm) vs. Distance (km)
- Pulse energy (pJ) vs. Distance (km)
- Soliton Period (m) vs. Gain (dB)
- Per km vs. Per z₀

Note: 0.4 dB
Pulse amplification and compression

\begin{align*}
\text{Pulse Duration (ps)} & \quad \log_{10}(W) \\
10^{-1} & \quad 0.4 \\
10^{0} & \quad 0.8 \\
10^{1} & \quad 1.2 \\
10^{2} & \quad 1.6
\end{align*}

\begin{align*}
Pump \ Power \ (W) & \quad \text{Output Power (W)} \\
0 & \quad 0.4 \\
1 & \quad 0.8 \\
2 & \quad 1.2 \\
4 & \quad 1.6
\end{align*}

- 1549 nm, 265 fs
- 1558 nm, 280 fs
- 1563 nm, 300 fs
- 1567 nm, 305 fs
**Alternative Wavelengths**

\( \text{Tm} \sim 1.98 \, \mu\text{m} \)

Soliton shaping

\( \text{Yb} \sim 1.06 \, \mu\text{m} \)

Normal dispersion

Use: Bulk elements  
Air core PCF? Not really

![Diagram of pulse generator and fiber optic components](image)

- **LD**  
- **LNPM**  
- **BPF**  
- **210 m SMF**  
- **YDFA**

**Graphs:**

- **Top graph:**
  - X-axis: Wavelength (nm)  
  - Y-axis: Power (dBm/\text{nm})

- **Bottom left graph:**
  - X-axis: Time (ps)  
  - Y-axis: Power (arb.)  
  - Label: 9.0 ps

- **Bottom right graph:**
  - X-axis: Time (ps)  
  - Y-axis: Power (arb.)  
  - Label: 1.05 ps
Compression in tapered PCF

Parameters

- Dispersion: \( \sim 30 \) to \( \sim 0 \) ps/nm/km
- Loss: 56 dB/km
- Length: 17 m
- \( d/\Lambda = 0.52-0.42 \)
- \( \Lambda = 1/50 – 1.25 \ \mu m \)

\[ \tau_0 = \frac{2|\beta_2|}{\gamma E_s} \]
Pump - gain switched DFB at $\sim 20$ MHz (17.984MHz) Amplified $\sim 14$W (3.5kW peak)
PCF - $\sim$2.6 m
Optical Parametric Oscillation

- Normalised Intensity vs Time
  - 222 ps
  - 148 ps

- Cavity output vs Cavity delay (ps)

- Anti-Stokes output power vs Power at fibre face (W)

- Intra-cavity anti-Stokes power (mW)

- Experimental data
  - Linear fit - slope eff 2.9%
Single Pass Parametric Generation

Wavelength (nm)

Time (ns)

Spectral power (A.U. dBm)

Intensity (A.U.)

740-810 nm
0.2-1.5 ns
1-30 MHz
15% efficiency
~ 1W average

Photonics@be  Oostduinkerke May 2015
PCF dispersion zero 795 nm
Pump tunable frequency doubled picosecond Er-MOPFA
767 nm- 785 nm produces  390-460 nm
Current development – Visible

PCF dispersion zero 795 nm
Pump tunable frequency doubled picosecond Er-MOPFA

400 mW, 660 nm, 3.3 nm
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

![Graph showing relative intensity vs. wavelength with typical emission peaks at 510 nm for GFP.]

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

$M^2 < 1.1$
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