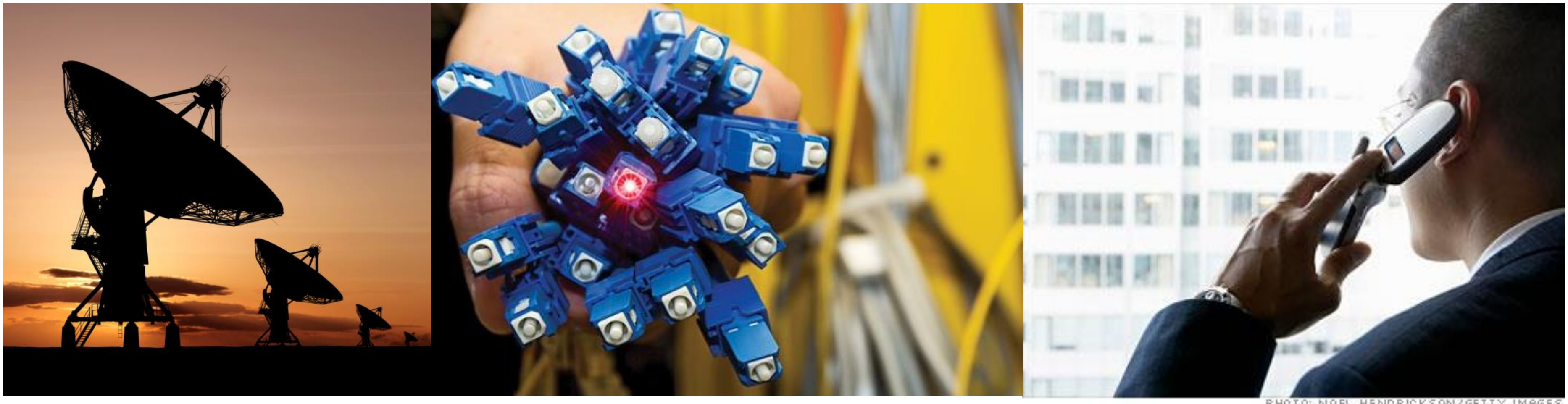


Research Interests

Photonics Applications in Communications and Sensing

Dr. Kavintheran Thambiratnam

Research is to see what everybody else has seen, and to think what nobody else has thought

- Albert Szent-Gyorgyi, Hungarian Biochemist, 1937 Nobel Prize for Medicine (1893-1986)

INTRODUCTION

Introduction

In this presentation, there are two primary research interests which are the focus and passion of the author, namely compact, highly-doped rare earth fibers for optical amplification and new approaches for the sensing and measurement of various biological parameters.

Thus, the first part of this presentation will focus on the Zirconia-Erbium Co-Doped Fiber, which provides all the benefits of a highly-doped fiber without the drawbacks typically associated with such fibers, such as incompatibilities with conventional Single-Mode Fibers.

The second part of this presentation will look at the initial work carried out to develop a minimally invasive means of detecting and measuring various biological parameters. This is the groundwork for the development of a non-invasive system, which is currently in progress.

ZREDF BASED OPTICAL AMPLIFIERS

The Need for Optical Amplification

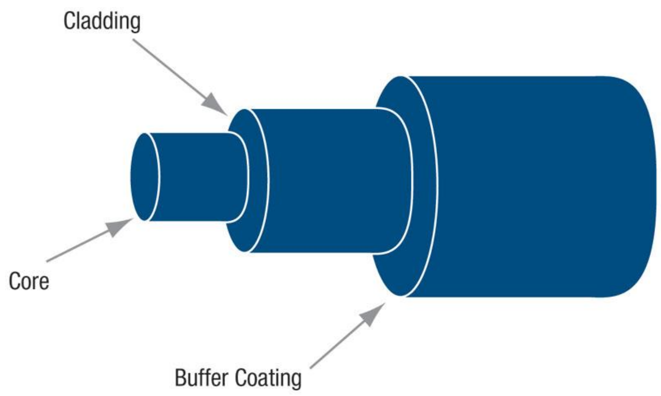
The Role of Optical Communication

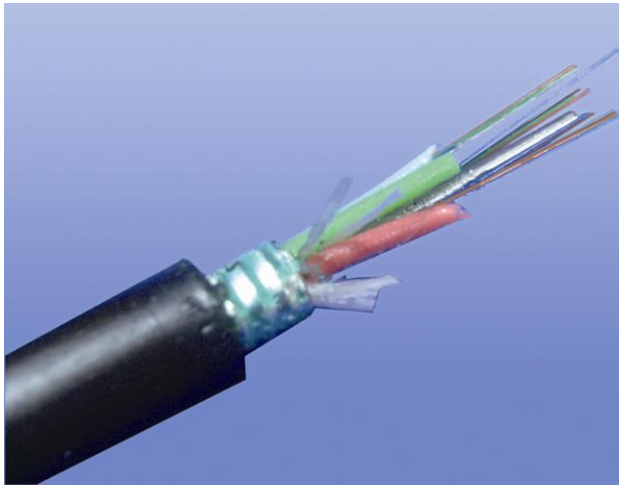
- Optical communications remains the fastest and most reliable means of communications today
- Optical fibers are transparent from between 1.0 µm to 1.6 µm, giving a total bandwidth of:

$$\Delta\lambda = \frac{c}{\lambda_1} - \frac{c}{\lambda_2} = 3.0x10^{14} - 1.1x10^{14} = 11\ \mathrm{THz}$$

By the Nyquist Criterion, one conversation requires 2 x 3kHz = 6 kHz for a telephone signal is from 100 Hz to 3 kHz. Thus the number of conversations that a fiber can carry:

$$N_f = \frac{1.1x10^{14}}{3x10^{3}} = 36\ \text{Billion!}$$

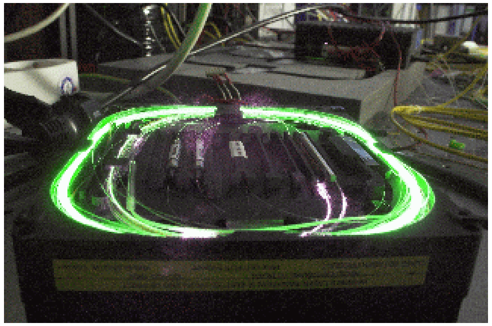




The Need for Optical Amplification

The Erbium Doped Fiber Amplifier (Cont.)

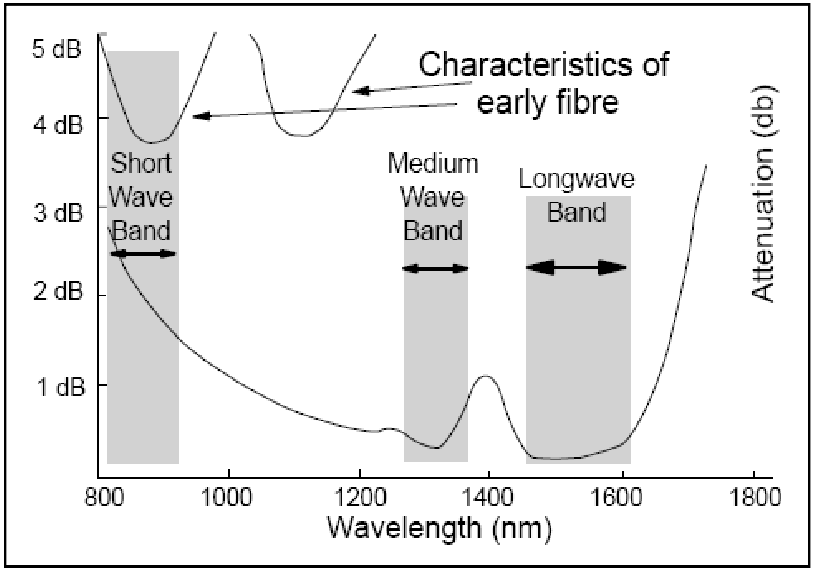
- Optical amplification is necessary to overcome intrinsic losses in optical fibers
- Typical fiber losses at 1.5 µm are ~0.2 dB/km (over 100 km, attenuation = 20 dB
- To overcome the problem, electronic regenerators are used to ‘rebuild’ the signal at certain points.
- However, regenerators have significant limitations: The are not wavelength transparent (cannot be multiplexed, very high cost-per-wavelength for practical systems), fragile and sensitive to environmental changes.
- The solution: the Erbium Doped Fiber Amplifier (EDFA), a fiber whose core is heavily doped with Erbium ions and works on the concept of stimulated emission

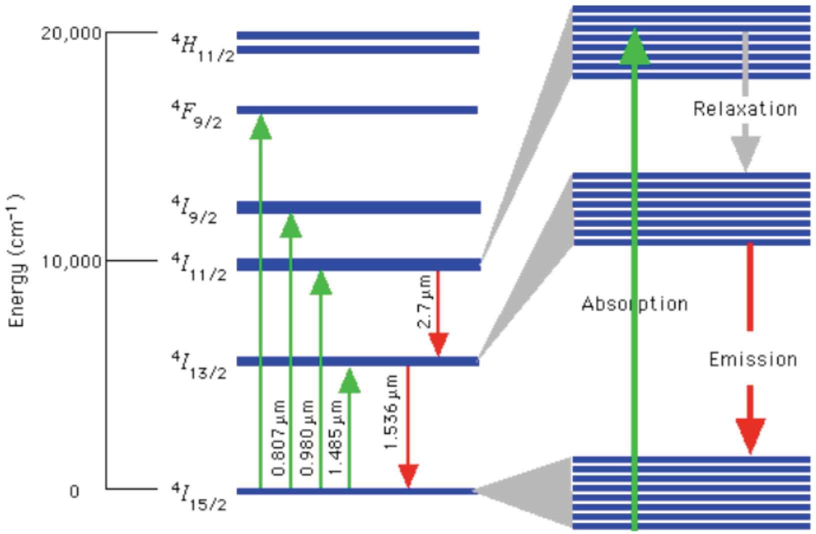


The Need for Optical Amplification

The Erbium Doped Fiber Amplifier (Cont.)

- Erbium is an excellent choice for an optical amplifier
- The quantum levels of Erbium ions (Er^{3+}) allow them to be stimulated to emit in the 1540 nm band (the band that has the least power loss in most silica-based fiber).
- Erbium's quantum levels also allow it to be excited by a signal at either 980 nm or 1480 nm (which silica-based fiber can carry without great losses)
- 980 nm pump sources are cheap and easy to produce, thus making Erbium Doped Fibers a suitable candidate for 1550 nm amplification





The Need for A Compact Optical Amplifier

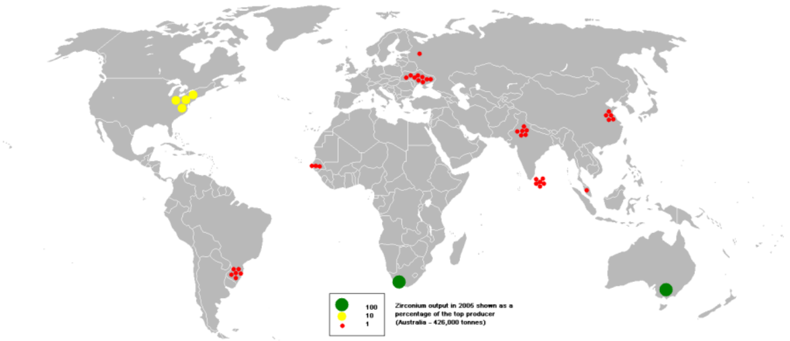
The Zirconia-Erbium Co-Doped Fiber Amplifier

- New challenge: to develop highly doped Erbium Doped Fibers for the development of compact and high powered laser sources.
- However, increasing the erbium dopant concentration leads to a number of detrimental effects:
    - *Cluster Formation* (the tendency of laser-active ions in laser gain media to form clusters in their host medium – this in turn promotes concentration quenching)
    - *Concentration Quenching* (where the dopant molecule quenches its own fluorescence at high concentration, e.g.. through radiation-less transfer of energy between identical molecules)
- Certain host materials / co-dopants such as Telluride and Bismuth allow for erbium ion concentrations to be increased without the effects of concentration quenching and clustering
- However, this brings a new set of problems – soft fibers that are hard to splice / incompatible with commercially available silica fibers, requiring pump wavelengths not commonly used by the industry

The Need for A Compact Optical Amplifier

The Zirconia-Erbium Co-Doped Fiber Amplifier (Cont.)

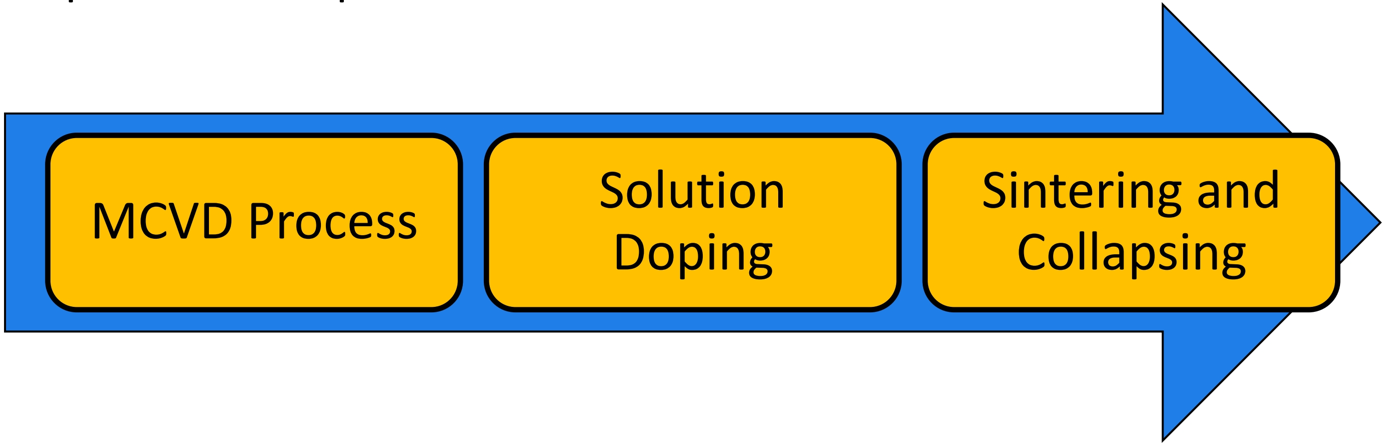
- Available solution: Zirconia Co-Dopants
- Zirconia is well known for its heat resistant properties, and already significantly applied as a ceramic
- Zirconia oxide (ZrO_2) is derived from Zirconium (Not Zirconia or Zircon!)
- ZrO_2 ions co-doped in silica fibers possess a high index of refraction that has been reported of around 1.45 over the visible and near infrared spectrum
- Zirconia co-doped fibers also have excellent mechanical strength and are chemical corrosion resistance as well as being non-hygroscopic, making them highly compatible with conventional silica fibers



Fabrication of the Zr-EDF

Fabrication of the Zirconia-Erbium Co-Doped Fiber

- Also known as ZrEDF
- Developed together with Dr. Mukul Paul of the Central Glass and Ceramic Research Institute (CGCRI), Kolkatta, India
- Three step fabrication process:



Fabrication process of the Zr-EDF comprising of the three main proceses (the MCVD process, the solution doping process and the sintering and collapsing process)

- Pre-fabrication - tube selection and preparation, while post-fabrication steps include fiber drawing

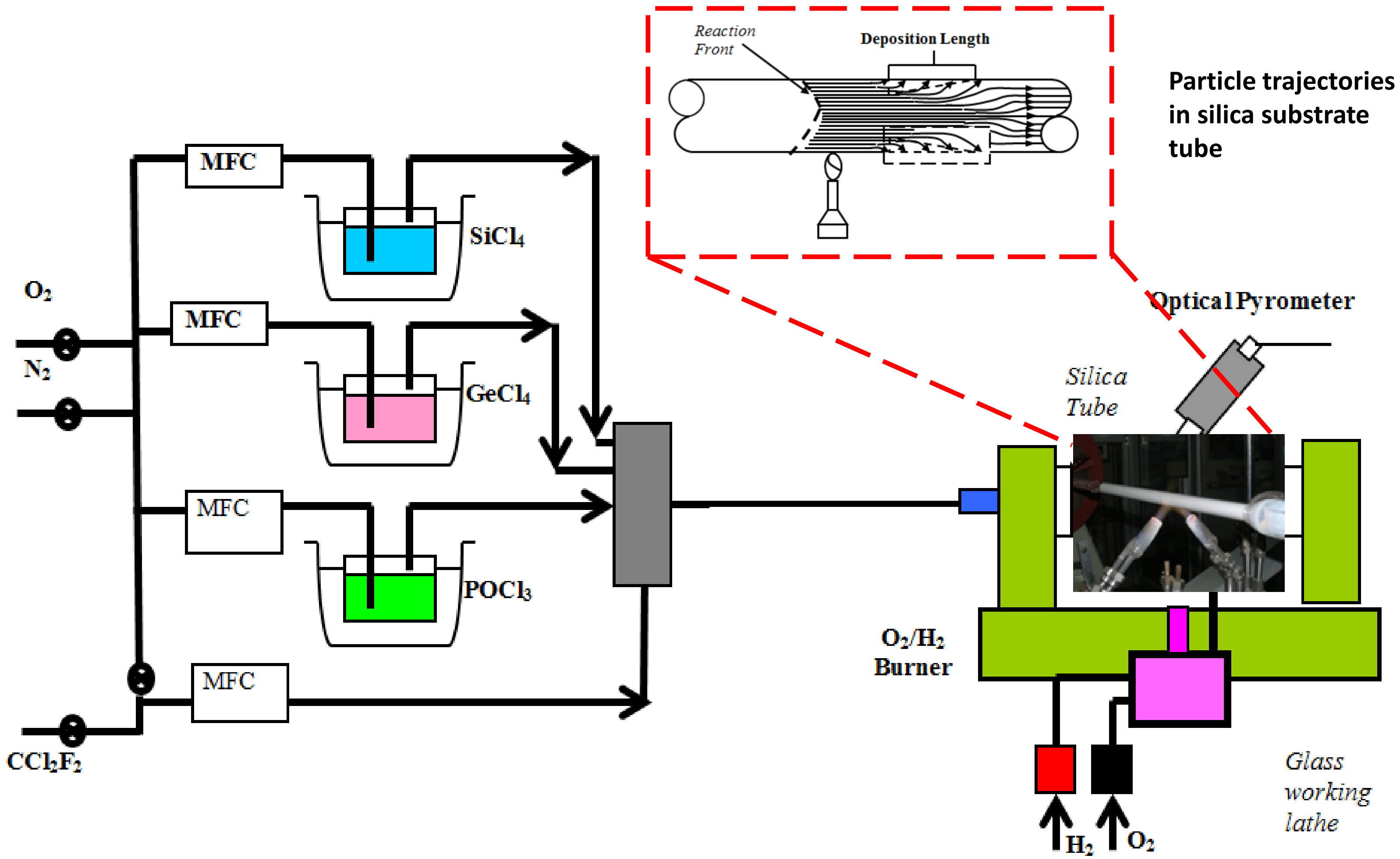
Fabrication of the Zr-EDF

Modified Chemical Vapor Deposition (MCVD) Technique

- Suitable for Research and Development (R&D) activities and also preform production on a commercial scale
- Reactant vapours such as $SiCl_4$, $GeCl_4$ & $POCl_3$ are bubbled by passing dry carrier oxygen gas through liquid bubblers which are kept at a constant temperature liquid-bath
- The tube is heated by a traversing oxy/hydrogen burner to temperature between 1500 and 2000^{0}C in the same direction as the interior gas flow
- A homogeneous gas phase reaction takes place and solid particles nucleate from the reaction products
- Particulates then deposit along the wall of the silica tube
- As the burner traverses further, the particulate layer is sintered and vitrified, forming a pore-free layer of glass with a thickness around 10 microns

Fabrication of the Zr-EDF

Modified Chemical Vapor Deposition (MCVD) Technique (Cont.)



MCVD process along with glass working lathe

Fabrication of the Zr-EDF

Solution Doping Technique

- Doping of Er_2O_3 into the yttria-aluminosilicate host material was done through solution doping process
- Small amounts of Y_2O_3 and P_2O_5 were added where both Y_2O_3 and P_2O_5 serve as a nucleating agent to increase the phase separation with generation of Er_2O_3 doped micro crystallites into the core matrix of optical fiber preform
- The glass formers incorporated by the vapor phase deposition process involve SiO_2 and P_2O_5 along with glass modifiers Al_2O_3 ZrO_2, and Y_2O_3 as well as the active medium Er_2O_3 incorporated by the solution doping technique using an alcoholic-water (1:5) mixture of suitable strength of $ErCl_3.6H_2O$, $AlCl_3.6H_2O$, $YCl_3.6H_2O$ and $ZrOCl_2$ $8H_2O$.
- Strength of $ErCl_3$ $6H_2O$ was varied from 0.005 M to 0.01 M
- Strength of $ZrOCl_2$, $8H_2O$ and $AlCl_3$ $6H_2O$ was adjusted from 0.1 M to 1.0 M

Fabrication of the Zr-EDF

Sintering and Collapsing

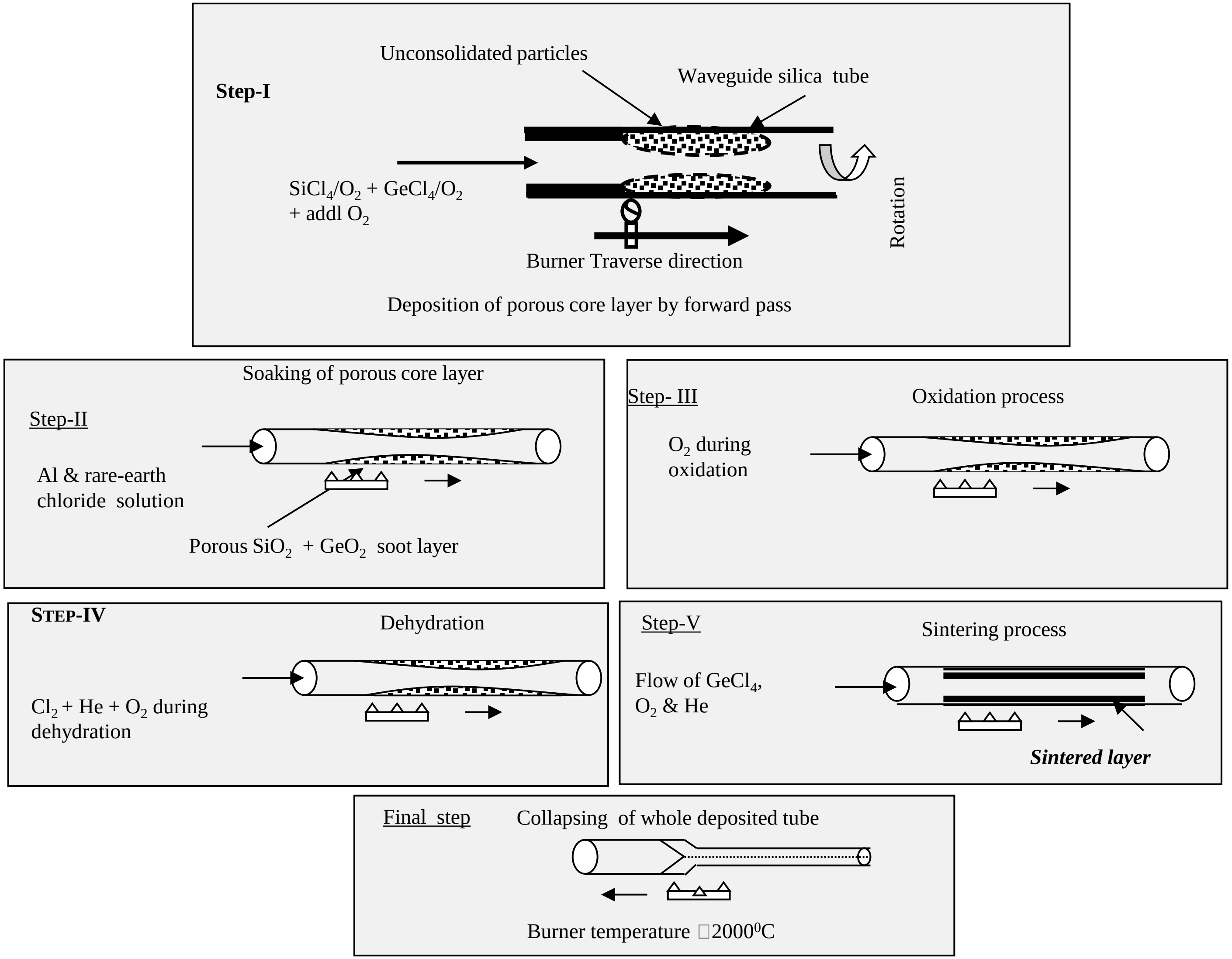
- Following solution doping, oxidation, dehydration and sintering is carried out before collapsing the rod:

  - *Oxidation - Done at 800^0C to 1000^0C in presence of excess O_2 to convert the halide or nitrate salts present in the pores into corresponding oxides*
  - *Dehydration – Carried out over 1 to 2 hours at a temperature of 900^0C*
  - *Sintering - Gradually heating the deposit within the tube with O_2 and He at 1100^0C for 3 hours in a closed furnace, under heating and cooling rates of 20^0C/min, to generate ErO_2 doped ZrO_2 rich micro-crystalline particles*

- To collapse the fiber, the preform is heated to around 2000^0C for only a few minutes (similar process for single mode fibers) and drawn using a drawing tower.

Fabrication of the Zr-EDF

Process Summary



Characterization of the Zr-EDF

Physical Characteristics

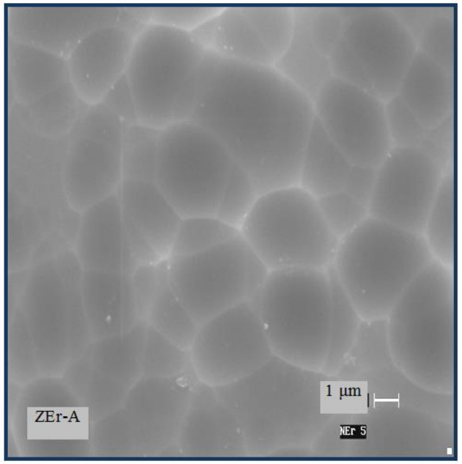
- Two preforms were fabricated, ZEr-A and Zer-B

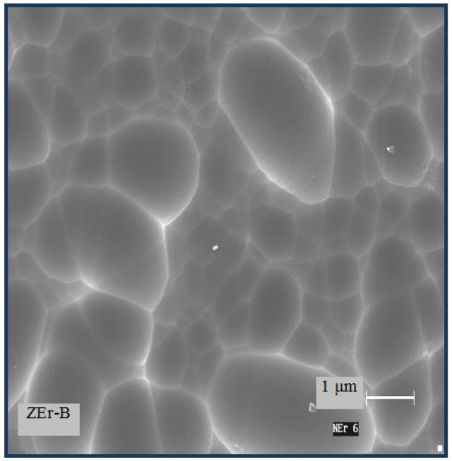
Preform No	Al_2O_3 (mole%)	ZrO_2 (mole%)	Er_2O_3 (mole%)
ZEr-A	0.25	0.65	0.155
ZEr-B	0.24	2.10	0.225

Dopant concentrations confirmed using Electron Probe Micro-Analysis (EPMA)

Fiber Number	Core composition	Core Diameter	Fiber type	NA	A-eff	RI of core
ZEr-A	$SiO+Al_2O_3+P_2O_5$-ZrO_2-$Y_2O_3+Er_2O_3$	10.5	Circular core with normal resin	0.17	87 μ^2	1.46625
ZEr-B	$SiO+Al_2O_3+P_2O_5$-ZrO_2-$Y_2O_3+Er_2O_3$	10.0	Circular core with normal resin	0.20	75μ^2	1.47025

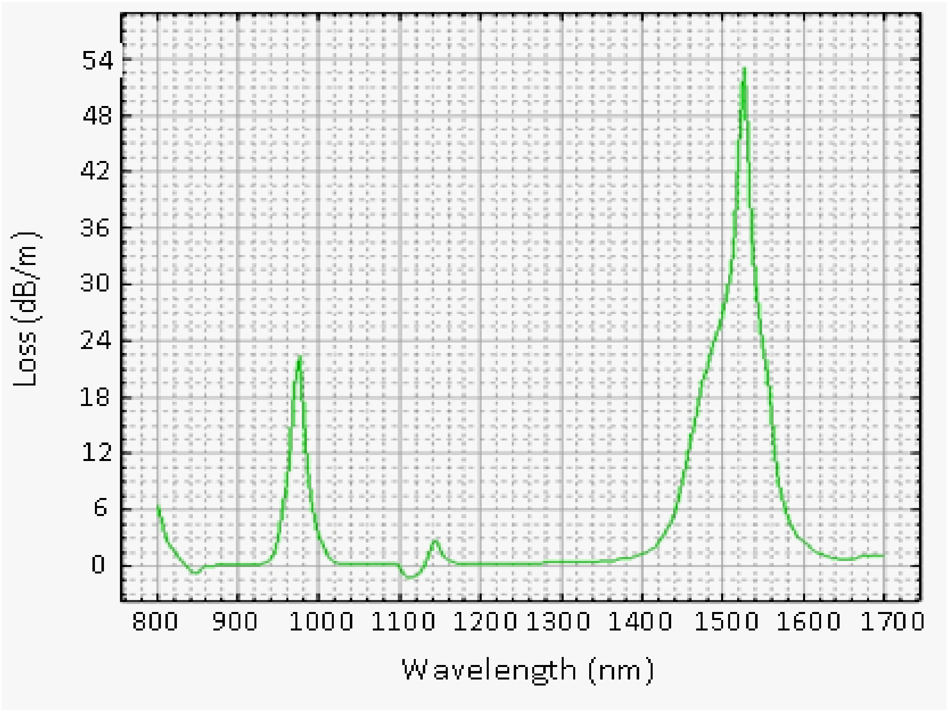
Morphology of the core region of some preform samples was studied using Field-Emission Gun Scanning Electron Microscopy (FEGSEM)



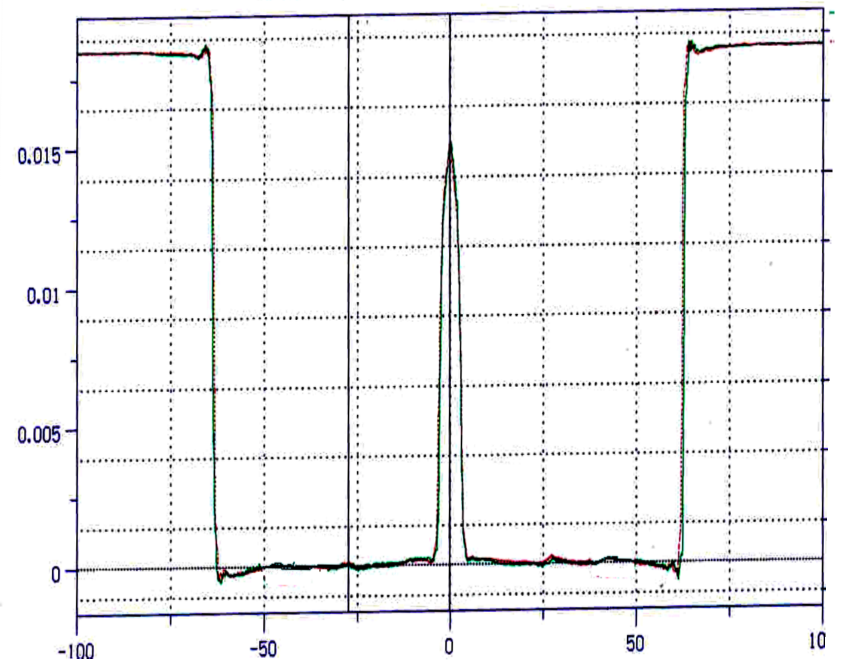


Characterization of the Zr-EDF

Attenuation and Refractive Index



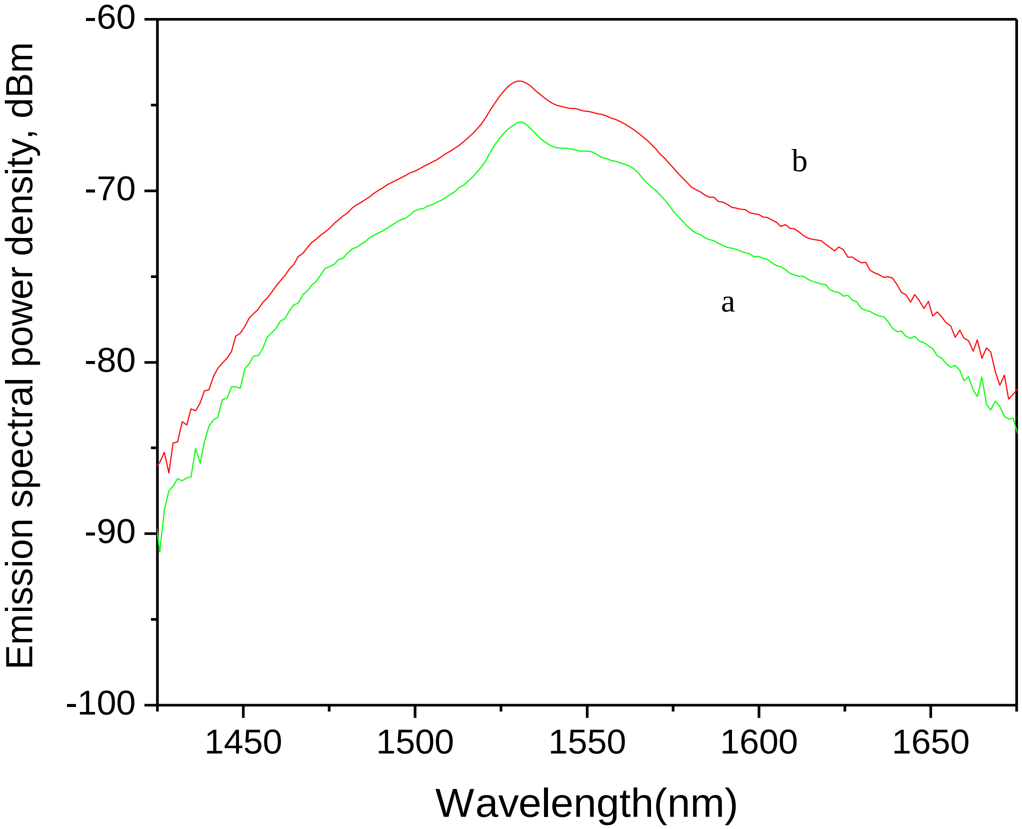
Spectral attenuation curve of fiber (ZEr-B)

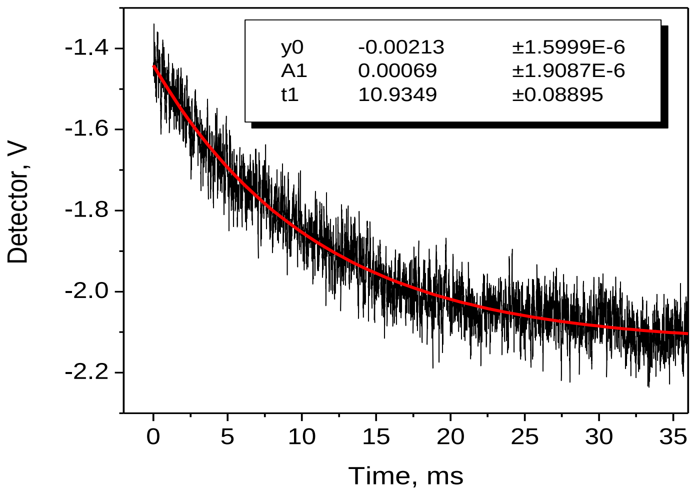


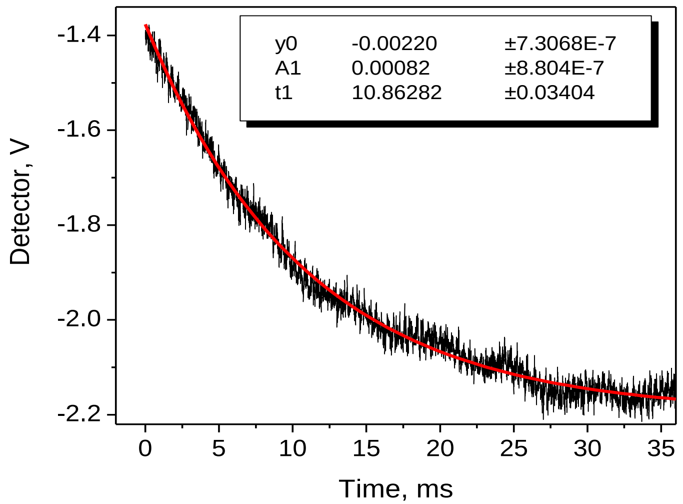
Refractive index profile of fiber (ZEr-B)

Characterization of the Zr-EDF

Fluorescence





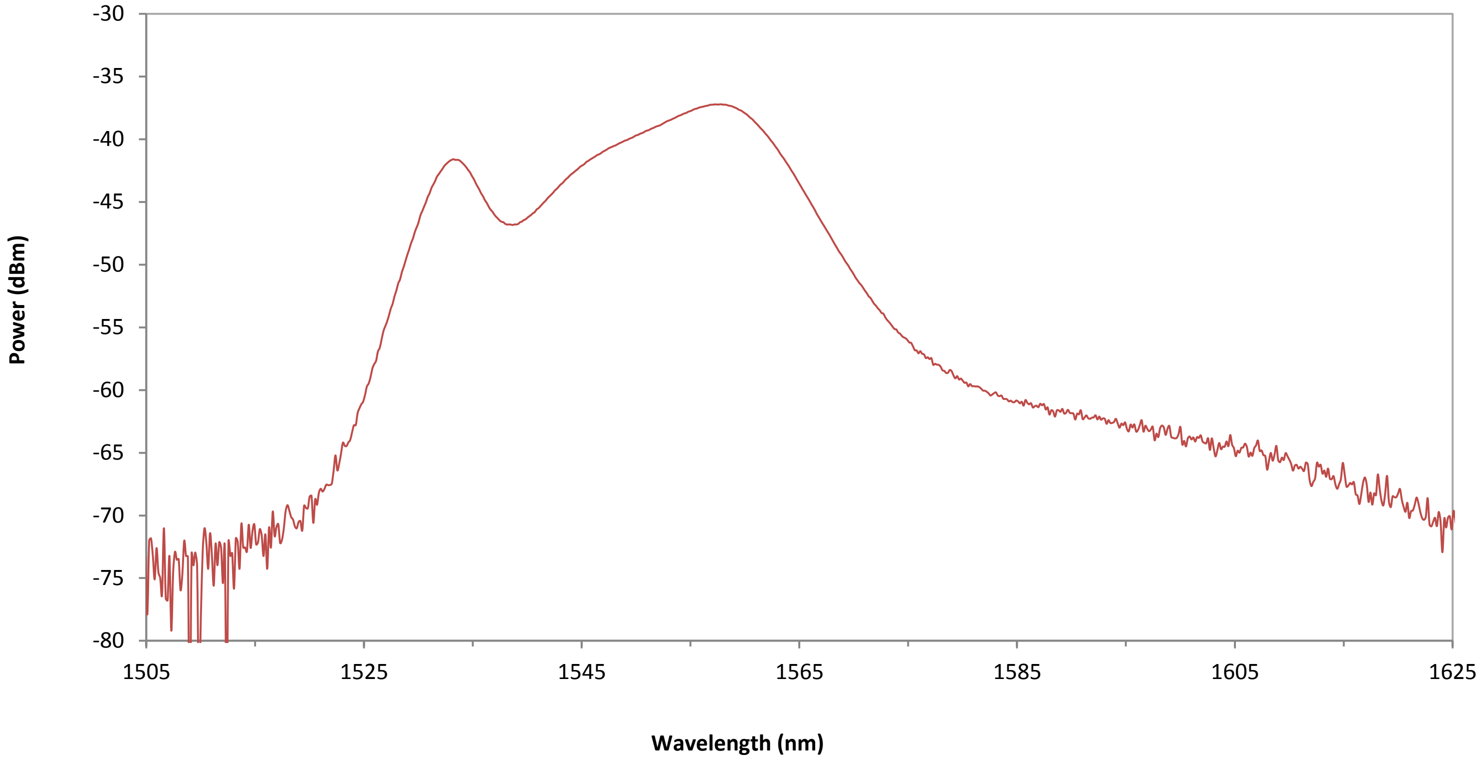


Fluorescence curves of (a) fiber ZEr-A and (b) fiber ZEr-B at a pump power level of 100 mW. (above)

The fluorescence decay curve of two ZrEDFs: ZEr-A (left, above) and ZEr-B (left, below) at a pump power level of 100 mW.

Characterization of the Zr-EDF

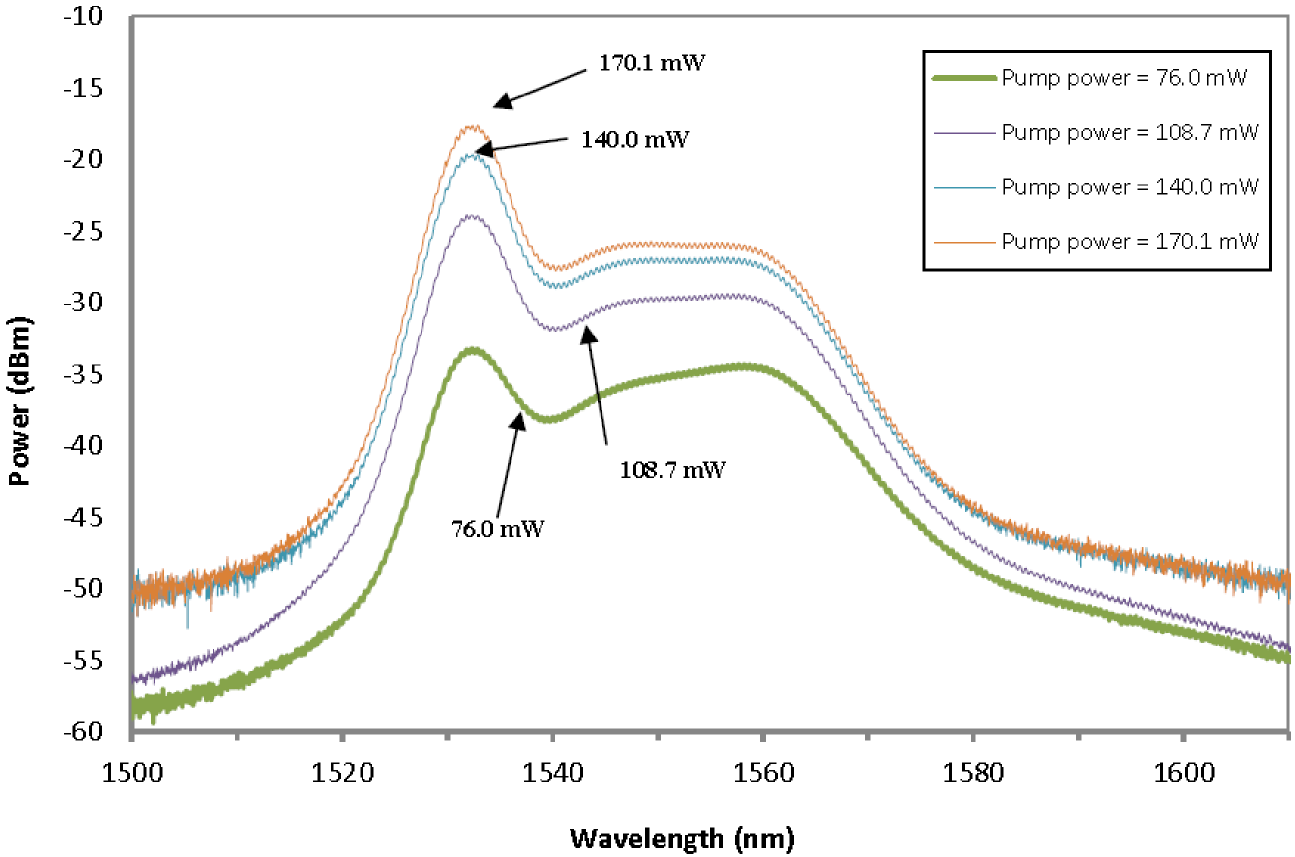
Amplified Spontaneous Emission (ASE)



- Broad Amplified Spontaneous Emission (ASE) from1525 nm to more than 1605 nm
- Peak at 1535 nm, as expected in Erbium Doped Fibers
- In silica based Erbium Doped Fibers, ASE decreases after 1535 nm
- In ZrEDF nearly flat plateau stretching from 1528 to 1568 nm

Characterization of the Zr-EDF

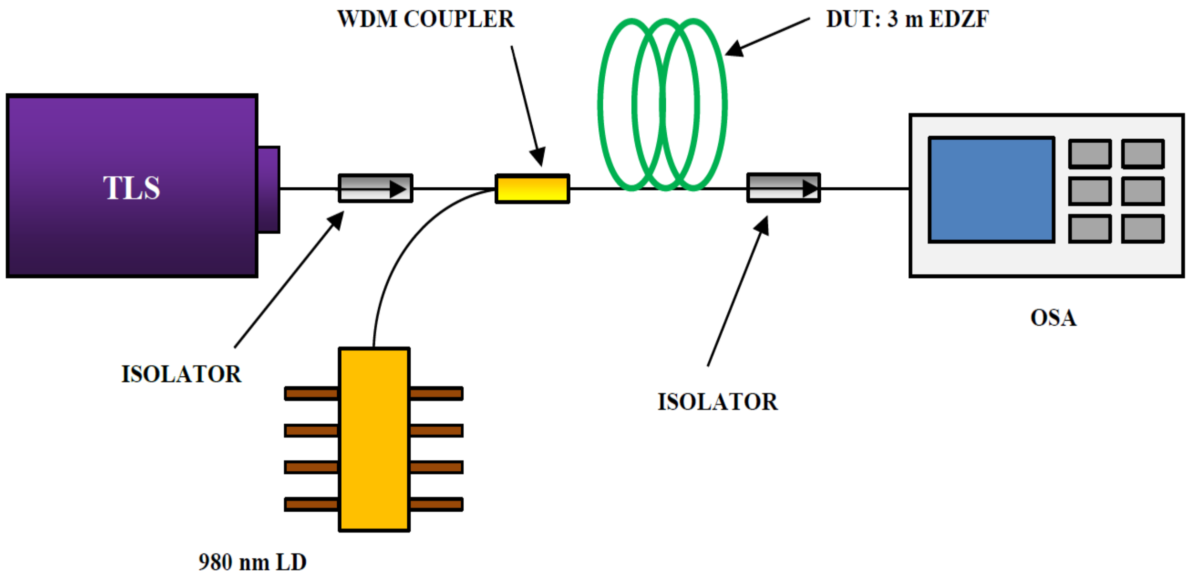
Amplified Spontaneous Emission (ASE) (Cont.)



- ASE generated by the ZrEDF is similar in many aspects to conventional EDF
- Lasing lines at the 1530 nm region are not observed under all pumping powers indicating that the ZrEDF is not yet fully pumped.

Characterization of the Zr-EDF

Experimental Setup for Gain and Noise Figure (NF) Measurement

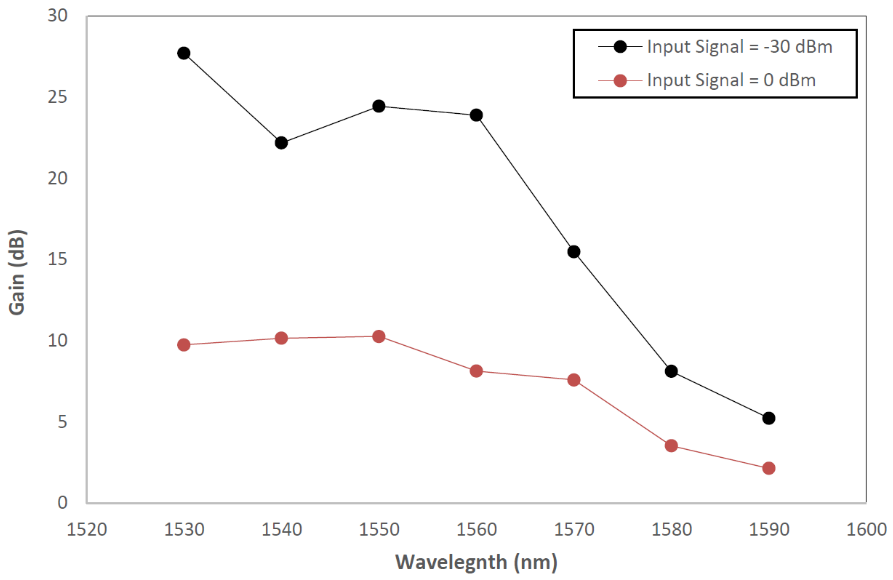


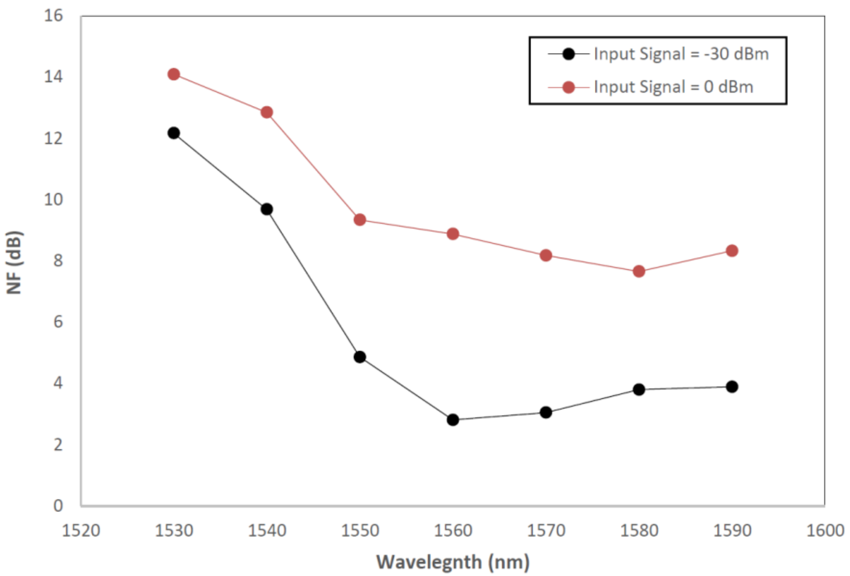
Schematic diagram for measuring gain and NF of the ZrEDF

- The test signal is generated by TLS 1 at a wavelength range of 1460 nm to 1640 nmand an average output power of 12.8 dBm.
- A 3 m long ZrEDF (Zer-B) with a dopant concentration of 3880 ppm/wt is used as the Device Under Test (DUT)
- Pump power of the system is 170.01 mW, and test signal set at 0 dBm and -30 dBm for high and low signal testing respectively.

Characterization of the Zr-EDF

Gain and Noise Figure (NF) of the ZrEDF



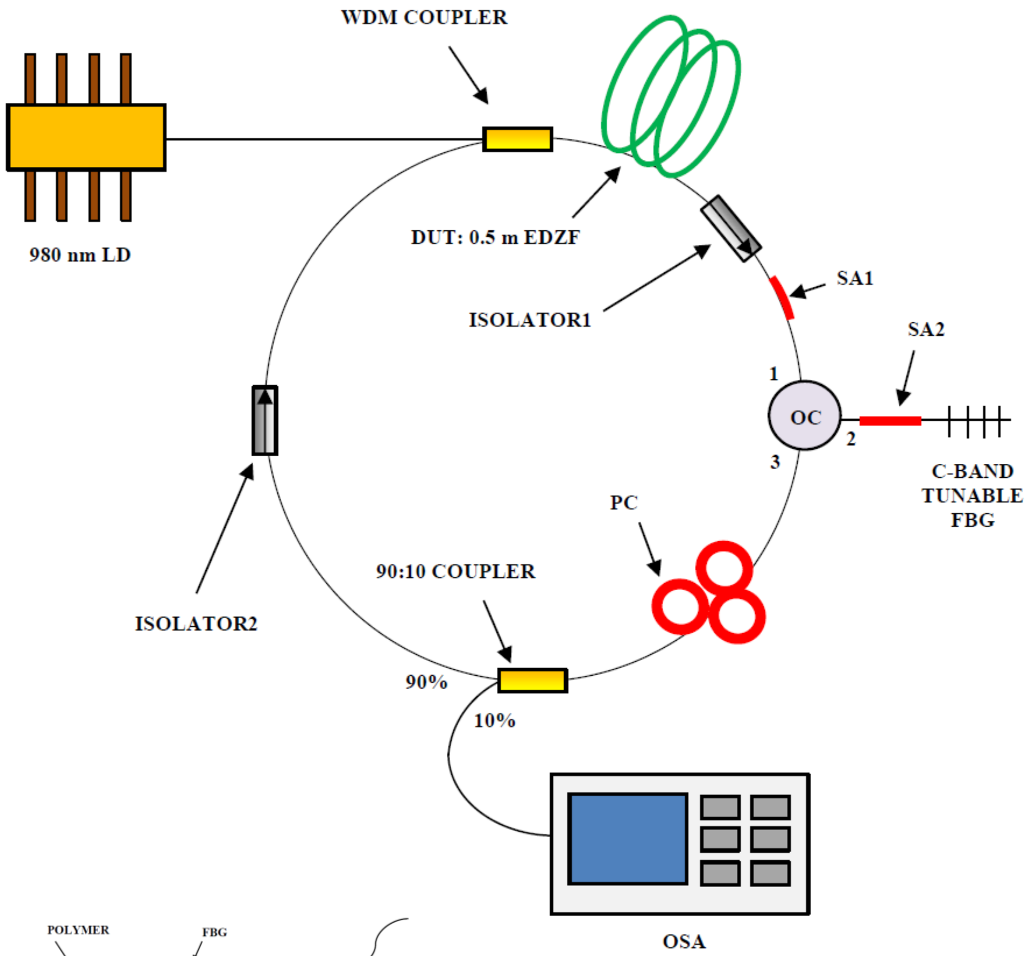


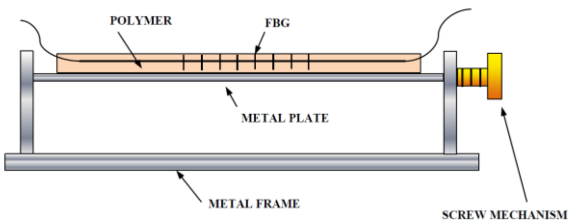
Above left: gain, output right: noise figure

- High gain levels achieved, ranging from approximately 28.0 dB near the central region of 1530 and between 22.0 to 25.0 dB between 1535 nm and 1560 nm for Low input signal
- Flat gain of about 10 dB from 1520 nm to 1560 nm for High input signal
- Relatively similar NF profiles for High and Low signals, from between 14 to 12 dB at 1530 nm and dropping to about 10 dB and 3 dB for High and Low signals respectively

Characterization of the Zr-EDF

Experimental Setup for ZrEDF as a Single-Longitudinal Mode Fibre Laser



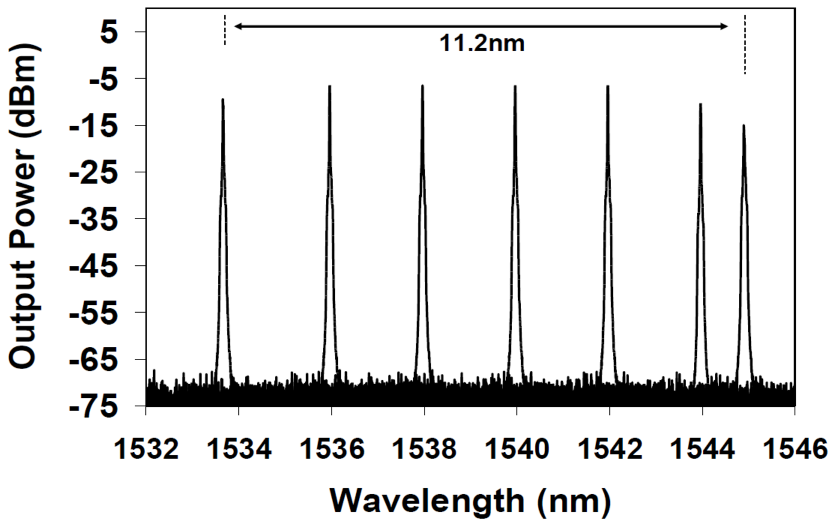


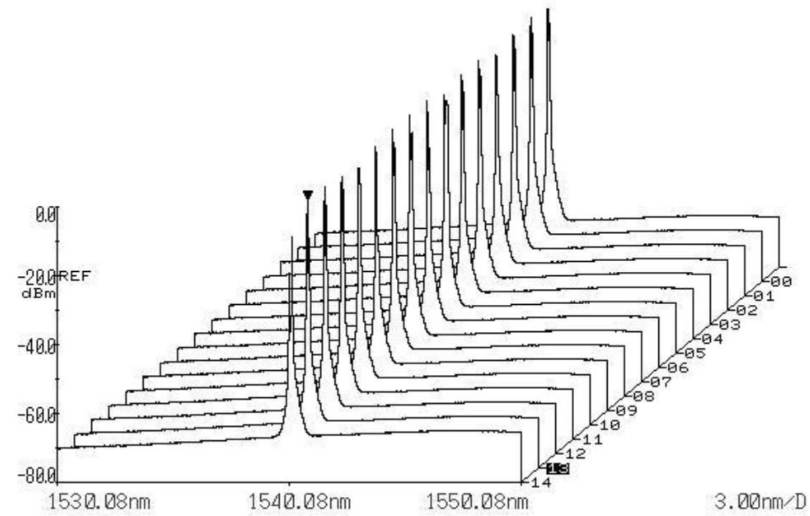
- The high dopant concentration of the ZrEDF allows for a fibre lasers with a short cavity length, thereby realizing SLM operation
- Two Saturable Absorbers (Sas) used, consisting of short EDFs with dopant concentrations of 900 ppm/wt and absorption of 5.0 dB/m at 1530 nm. SA1 is 3 cm long, SA2 is 6 cm long
- 980 nm pump with maximum output power of 80 mW is used.
- A C-band Tunable Fibre Bragg Grating (reflectivity 99%, bandwidth 0.1 nm)

Schematic diagram for an ZrEDF based SLM Laser (above) and C-band TBFG (left)

Characterization of the Zr-EDF

The ZrEDF as a Single-Longitudinal Mode Fibre Laser



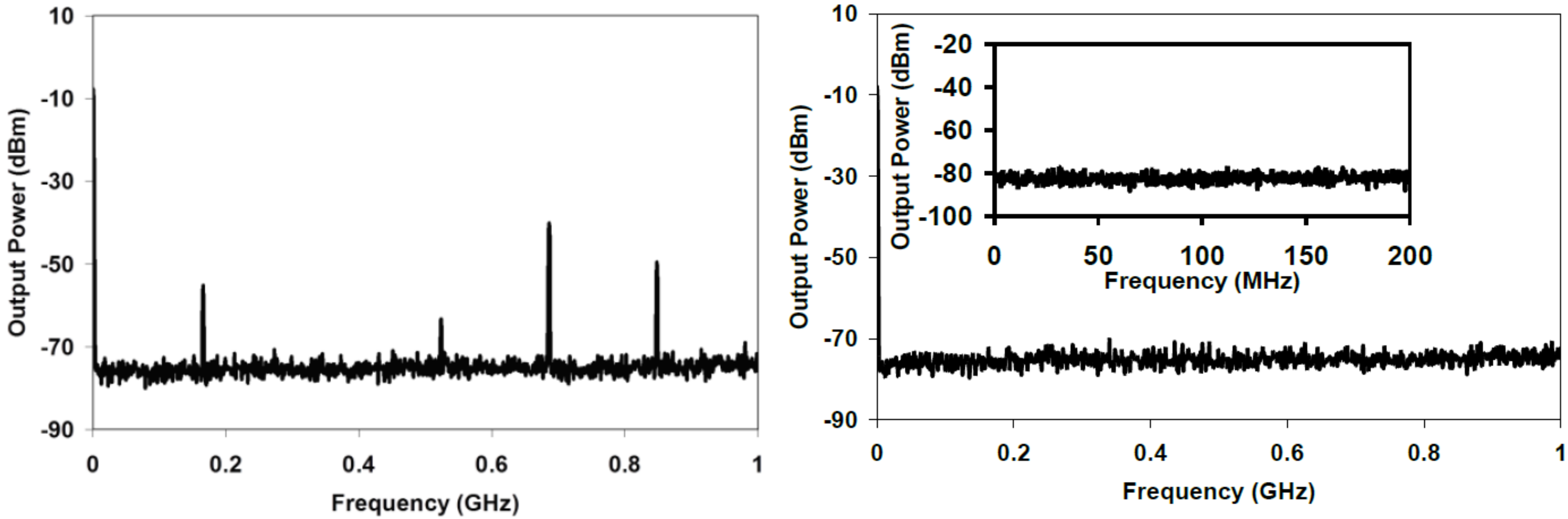


Above left: Output power against wavelength, output right: stability measurement

- The SLM laser has a tuning range of approximately 11.2 nm from 1533.8 nm to 1545.0 nm with a peak wavelength around 1540.0 nm.
- The Output power for 5 wavelengths is above -10.0 dBm, with another two wavelengths having a power of above -15.0 dBm
- The average SNR for the proposed laser is quite stable, with a value of more than 50 dB
- Measurement of the power at 10 minute intervals over 2 hours show high stability and almost no power fluctuation

Characterization of the Zr-EDF

The ZrEDF as a Single-Longitudinal Mode Fibre Laser (Cont.)

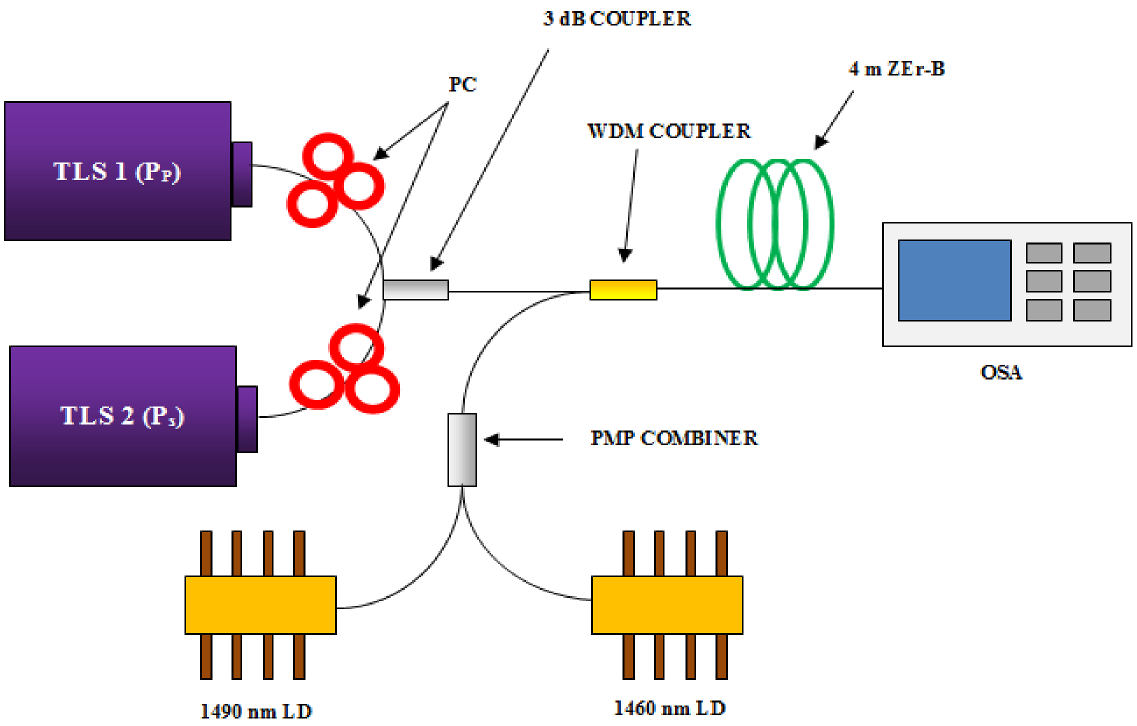


Above left: RFSA spectrum without SAs, output right: RFSA spectrum with SAs

- Radio Frequency Spectrum Analysis (RFSA) of the laser output shows competing modes in the cavity due to constructive interference.
- By adding SA1 and SA2, these modes can be suppressed so that only he highest powered mode can propagate in the cavity

Characterization of the Zr-EDF

Characterization of ZrEDF Non-Linearity using Four-Wave-Mixing Effect

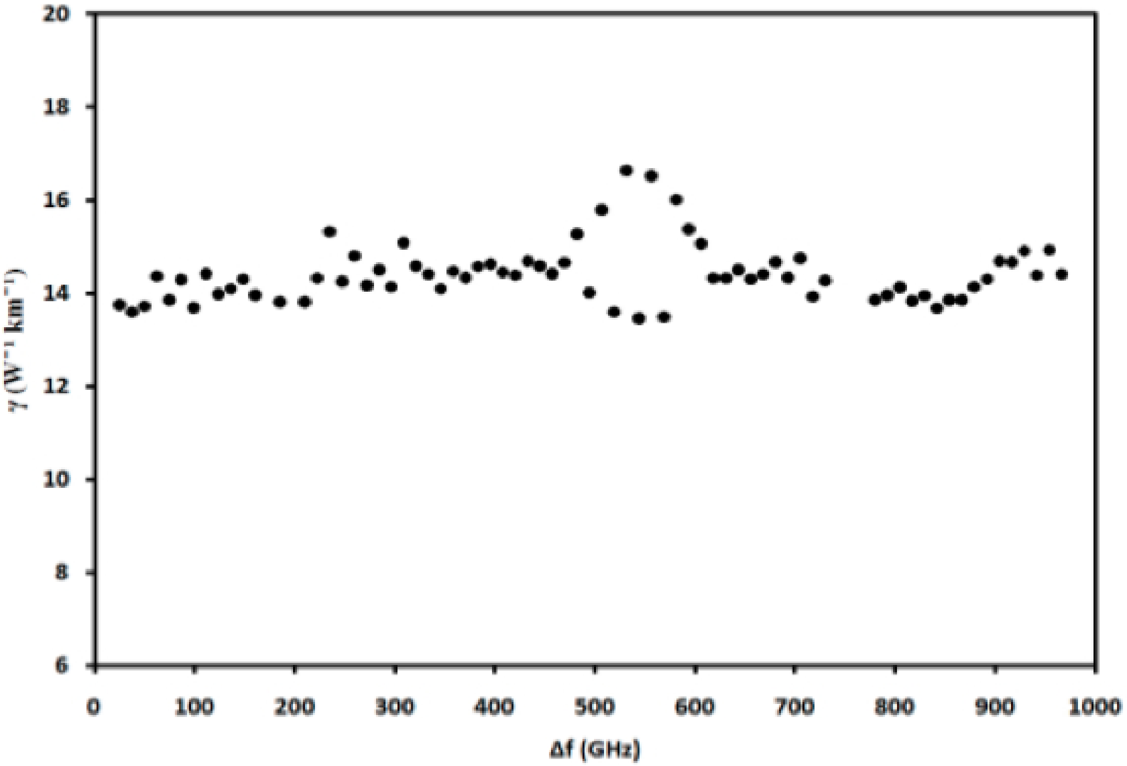


Schematic diagram for generating FWM effects in the ZrEDF.

- Signal P1, is generated by TLS 1 at a fixed wavelength of 1560 nm and an average output power of 12.8 dBm.
- Ps is generated from TLS2 with a wavelength varying from 1552 nm to 1557 nm at an average power level of 10.8 dBm.
- A 4 m long ZEr-B fiber with an Erbium concentration of 3000 ppm is used.
- Core refractive index value of 1.466 and an effective area of 87 μm2 along with a propagation loss, α of 0.68 dB/m.

Characterization of the Zr-EDF

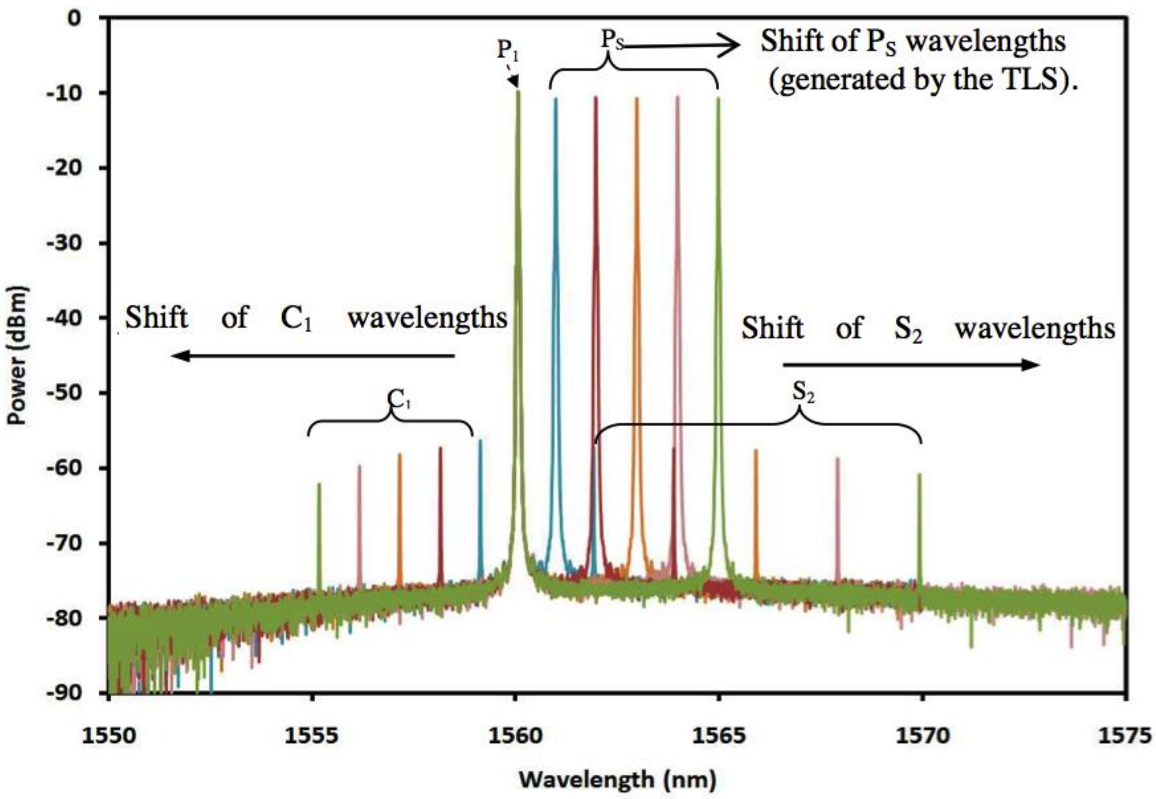
Four-Wave-Mixing (FWM) Effect in the ZrEDF



- The incorporation of ZrO_2 ions in the silica fiber allows the ZrEDF to exhibit non-linear optical properties
- Measurement of the ZrEDF provides a non-linear coefficient of $14W^{-1}km^{-1}$

Characterization of the Zr-EDF

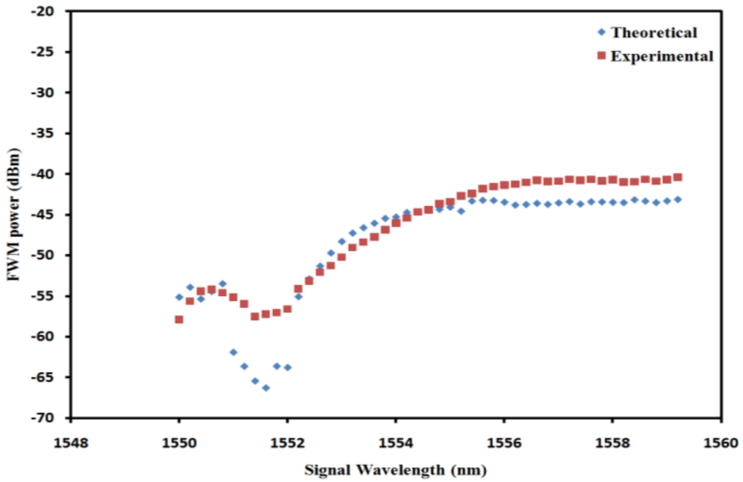
Four-Wave-Mixing (FWM) Effect in the ZrEDF (Cont.)

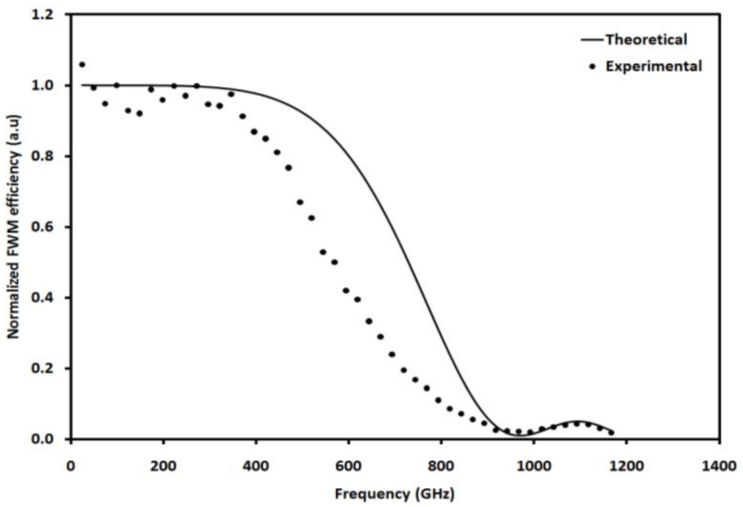


- The FWM effect occurs when Er^{3+} ions are suppressed by 980 nm pumping
- Idlers obtained for two propagating wavelengths correspond to predicted FWM idler values
- Average idler peak power of ~ -60 dBm for pump and signal wavelengths of ~ -10 dBm

Characterization of the Zr-EDF

Four-Wave-Mixing (FWM) Effect in the ZrEDF





The power of the converted signal is initially low at about -58 dBm, reaching a power of approximately -45 dBm at a wavelength of 1557 nm.

The normalized FWM efficiency against the input signal frequency efficiency remains relatively the same, with fluctuations of about 0.5 units.

However, above 400 GHz, the FWM efficiency begins to drop, reaching almost 0 at 1000 GHz in agreement with the theoretical predictions for the ZrEDF fiber.

A chromatic dispersion and slope dispersion value of 28.45 ps/nm.km and 3.63 $ps/nm^2.km$ respectively is obtained for the fiber.

FWM conversion efficiency versus wavelength detuning (above left) and Normalized FWM efficiency against the input signal frequency (below left)

The Zr-EDF as a Pulse Laser

Passive Pulse Generation

- Pulsed outputs can be generated in a fibre laser by either active or passive modulation
- Saturable Absorbers (SAs) and Semiconductor Saturable Absorption Mirrors (SESAMs) have high potential as passive modulators
- Used to generate mode-locked or Q-switched pulses
- Mode-locking generates ultra-fast pulses of typically less than 1 ns, useful for optical communications
- Q-switched is used for systems requiring longer pulses, such as range-finding and sensing
- Two approaches – Single-Walled Carbon Nanotubes (SWCNTs) and graphene as SAs for generating passively pulsed lasers.

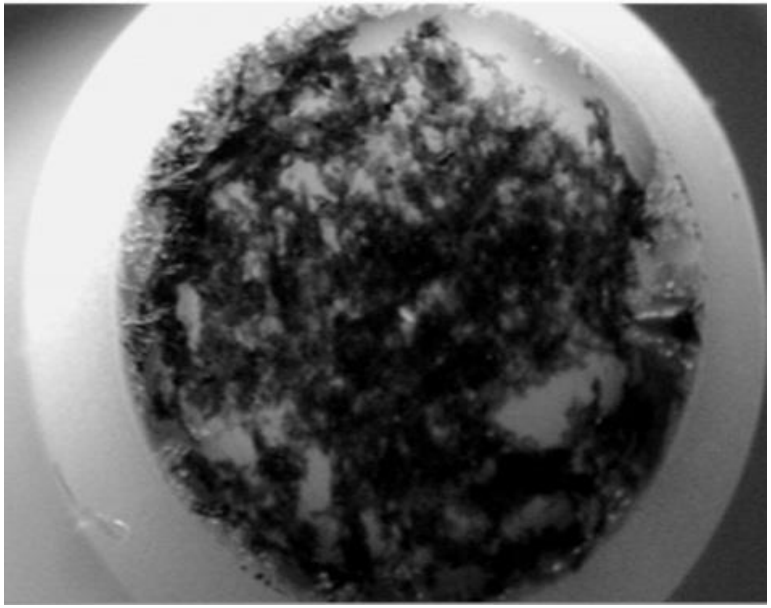
The Zr-EDF as a Pulse Laser

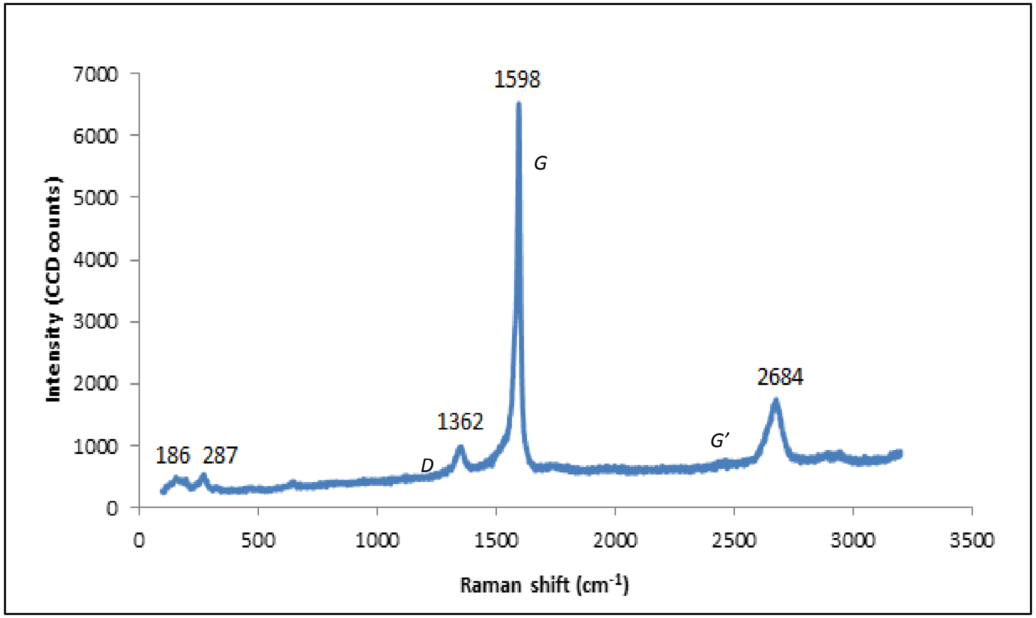
Fabrication of SWCNT / PEO SA for Passive Q-Switching

- Using a Saturable Absorber formed by sandwiching a Single Walled Carbon Nanotube / Polyethylene Oxide (SWCNT/PEO) composite in between two fibre ferrules
- Easy to fabricate – suspension of commerciality available SWCNTs in a PEO mix
- SWCNTs obtained from Cheap Tubes Inc, between 3 to 30 μm in length and diameters of between 1 to 3 nm.
- PEO and Sodium Dodecyl Sulfate (SDS) solutions with average molecular weights of 1 x 10^6 g/mol and 288.38 g/mol are obtained from Sigma-Aldrich, and combined with the SWCNTs to form the SWCNT/PEO composite.
- The SWCNT, in a 1% SDS solution, is ultrasonically dispersed at 50 W for a period of 30 minutes and then forms the composite by solution casting.
- Resulting composite is then formed onto the fibre ferrule by dropping the liquid solution and allowing it to dry in air over a period of 24 hours.

The Zr-EDF as a Pulse Laser

Fabrication of SWCNT / PEO SA



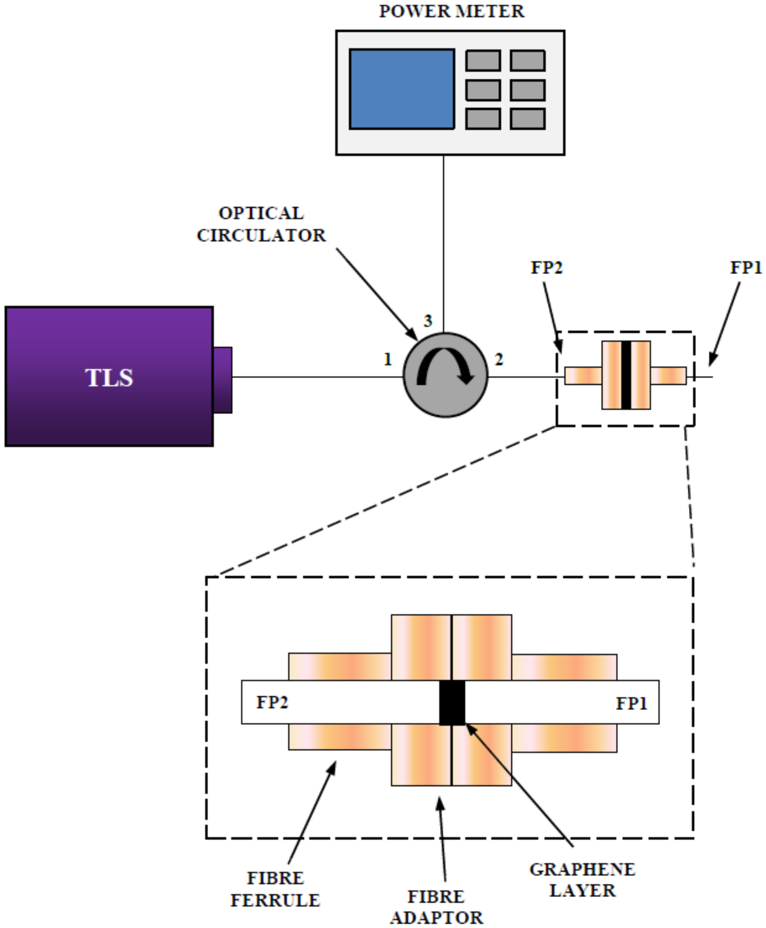


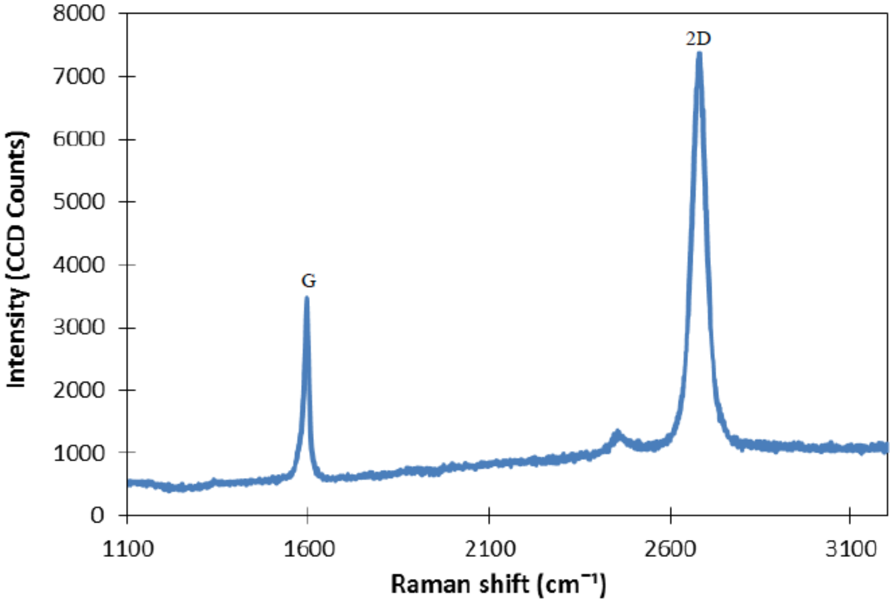
(above left) SWCNT/PEO composite polymer deposited on the face of the fiber ferrule, and (above right) the Raman spectroscopy taken indicating the Single-Walled Carbon Nanotube layer.

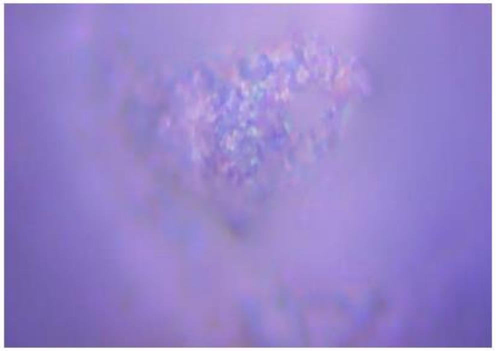
- Raman spectroscopy shows G at 1598 cm^{-1}, D at 1362 cm^{-1} and G' at 2684 cm^{-1}, thus indicating it is a single-walled carbon nanotube (Dresselhaus et. al.)
- Peaks at 186 cm^{-1} and 287 cm^{-1} are in the Radial Breathing Modes (RBM), which correspond to the nanotube diameter and occur at low wavenumbers (Wang et. al.)

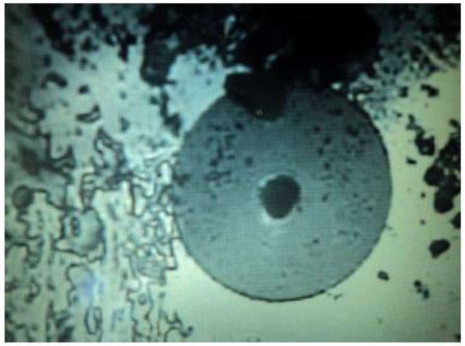
The Zr-EDF as a Pulse Laser

Fabrication of Graphene SA









Above left: Optical deposition technique. Above right (top): Raman spectrum of graphene, Above right (below): Spot image of graphene layer on the left, and image of fibre ferrule with graphene layer taken from a fibre probe on the right.

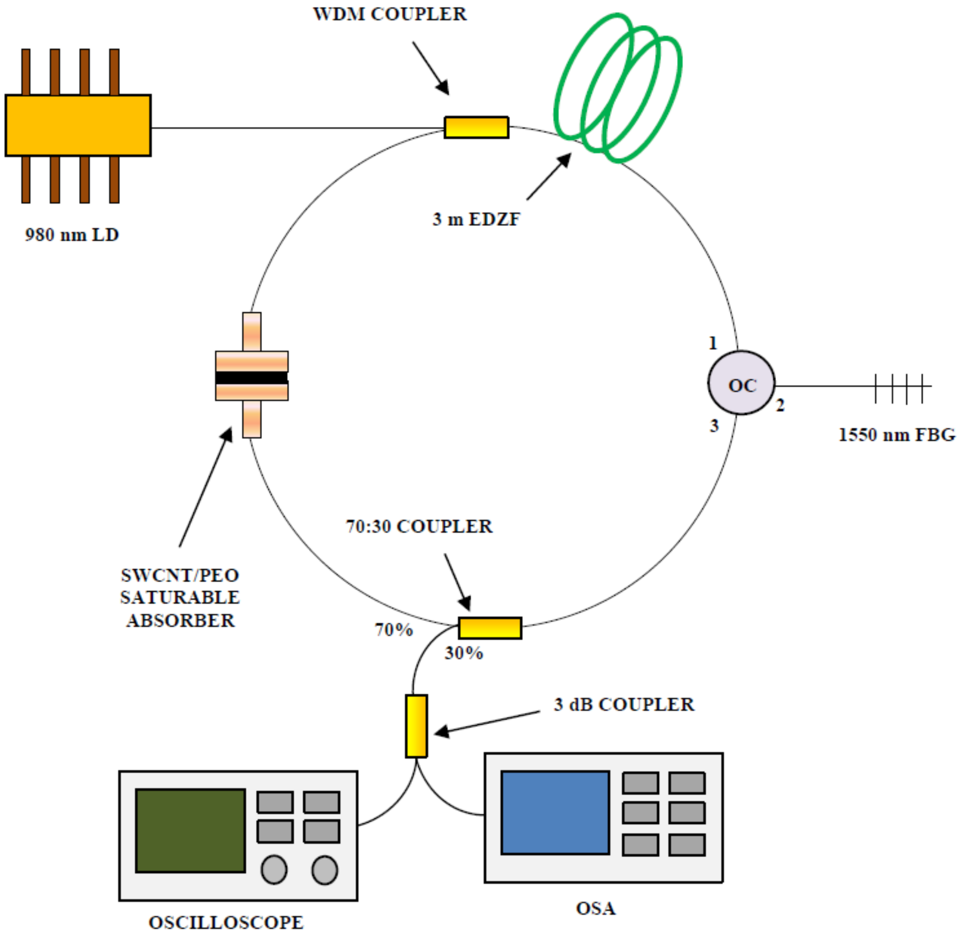
The Zr-EDF as a Pulse Laser

Fabrication of Graphene SA

- The graphene based saturable absorber is formed by optically depositing graphene flakes onto the face of a fibre ferrule
- Graphene flakes are obtained from Graphene Research Ltd suspended in an N-Methyl Pyrrolidone (NMP) solution
- The average particle size of 550 nm and average flake thickness of 0.35 nm
- Power of the TLS signal is set at 11 dBm at 1550 nm for 3 minutes
- Reflection of 4.1% affirms deposition of graphene layer (0.1% attributed to Fresnel reflection, and another 4.0% attributed to the reflection from the graphene layer)
- Analysis of deposited layer carried out using Renishaw InVia Raman spectrometer at 532 nm (2.33 eV) over a period of 10s with a grating value of 1800 lines/mm
- Charge Coupled Device (CCD) with a 100× objective lens and numerical aperture of 0.8 is used together with the Raman spectrometer, giving the system a spot size of 0.5 μm.
- Two intensity peaks at 1597 cm^{-1} and 2684 cm^{-1} are seen, corresponding to the G and 2D peaks respectively (580 cm^{-1} and 2700 cm^{-1})
- The ratio of G to 2D does not exceed 1, showing an almost single layer of graphene was formed.

The Zr-EDF as a Pulse Laser

Q-switched ZrEDF / SWCNT Fibre Laser

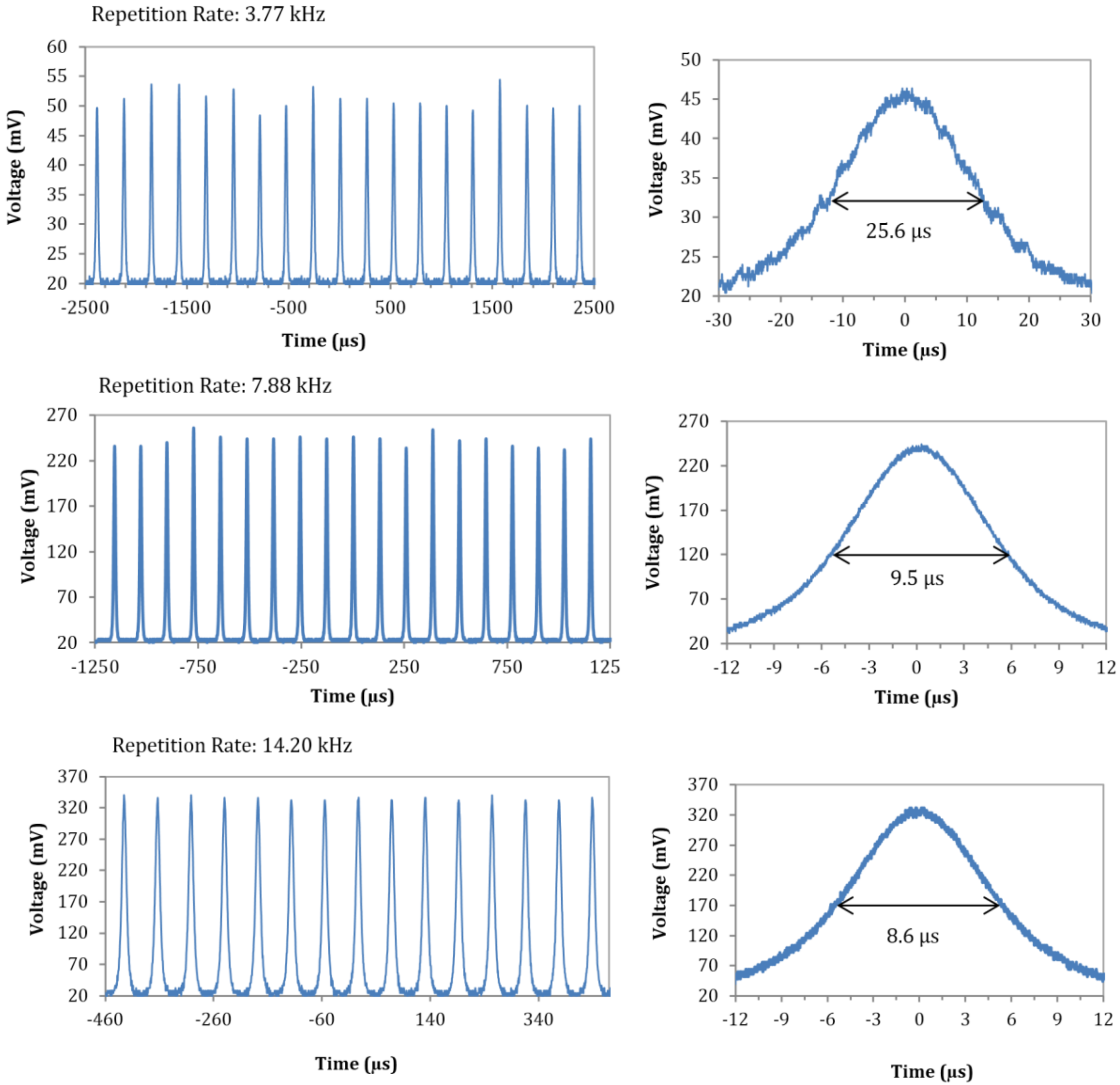


Schematic diagram for Q-switched fibre laser with SWCNT/PEO SA

- 3 m long of highly doped Zr-EDF at 3880 wt ppm as the gain medium, with an absorption coefficient of 22.0 dB/m at 980 nm.
- 980 nm pump laser diode as pump source, with 1550 nm FBG reflectivity of 98.9%) as wavelength locker. 3 dB bandwidth of the FBG is 0.24 nm. Maximum pump power is 141.80 mW
- 70% port connected to one end of the ferrule assembly containing the SWCNT/PEO composite saturable absorber
- Two measurement devices: Yokogawa AQ3230 OSA which has a resolution of 0.02 nm and LeCroy 352A oscilloscope together with an OE converter

The Zr-EDF as a Pulse Laser

Q-switched ZrEDF / SWCNT Fibre Laser

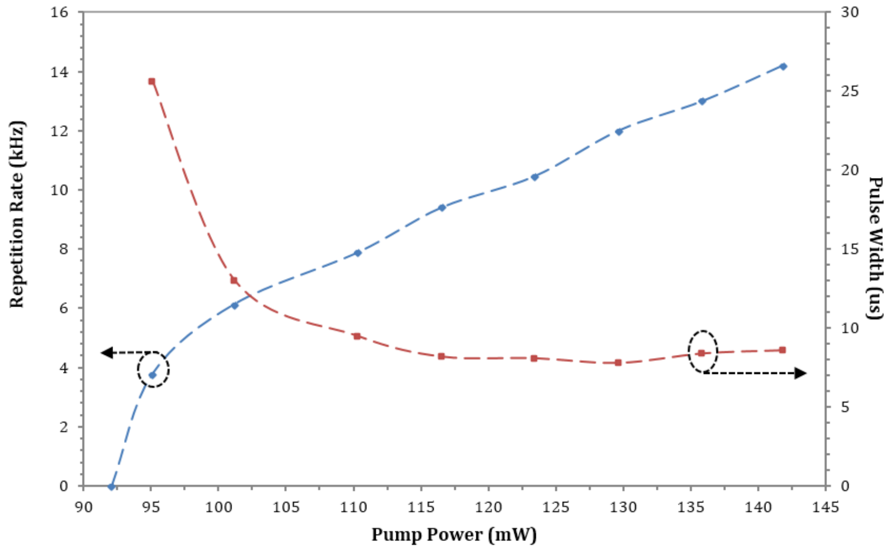


- Repetition rate and pulse width of the generated pulses as measured by the oscilloscope at pump powers of 95.1 mW, (rep. rate: 3.77 kHz, pulse width: 25.6 us) 110.3 mW (rep. rate: 7.88 kHz, pulse width: 9.5 us) and 141.8 mW (rep. rate: 14.20 kHz, pulse width: 8.6 us) (*from top to bottom*)

- Higher power gives more well defined pulses, with little fluctuations in peak power

The Zr-EDF as a Pulse Laser

Q-switched ZrEDF / SWCNT Fibre Laser

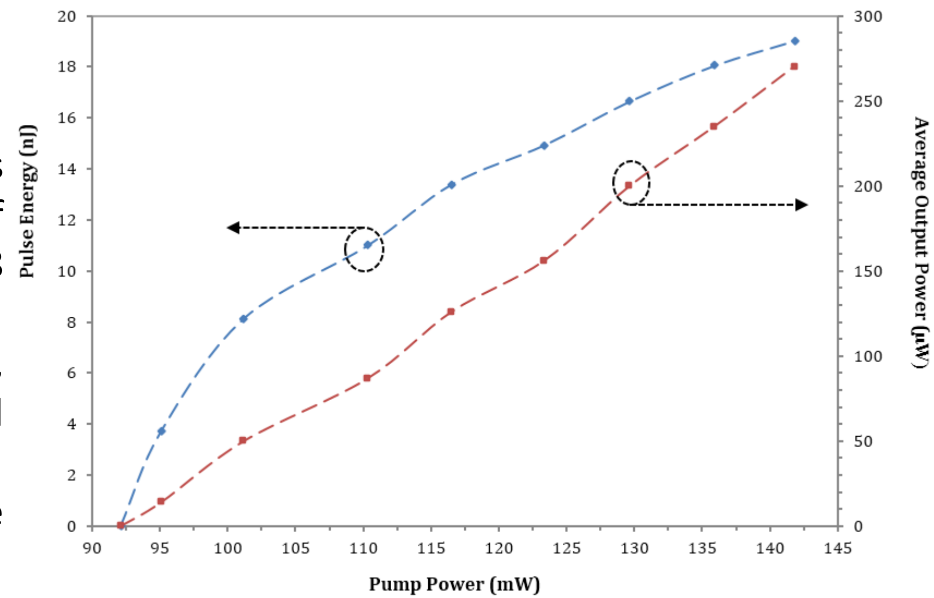


- The repetition rate grows predictably with a maximum repetition rate 14.20 kHz at a pump power of 141.8 mW
- The overall slope of the repetition rate plot is approximately 0.25 kHz/mW.
- The pulse width decreases exponentially from 25.6 us to 8.6 μs at the highest pump power.
- The minor changes at the higher pump powers indicate that the SA is nearing or at saturation.

Left: Pulse Repetition Rate (kHz) and Pulse Width (μs) for different pump powers.

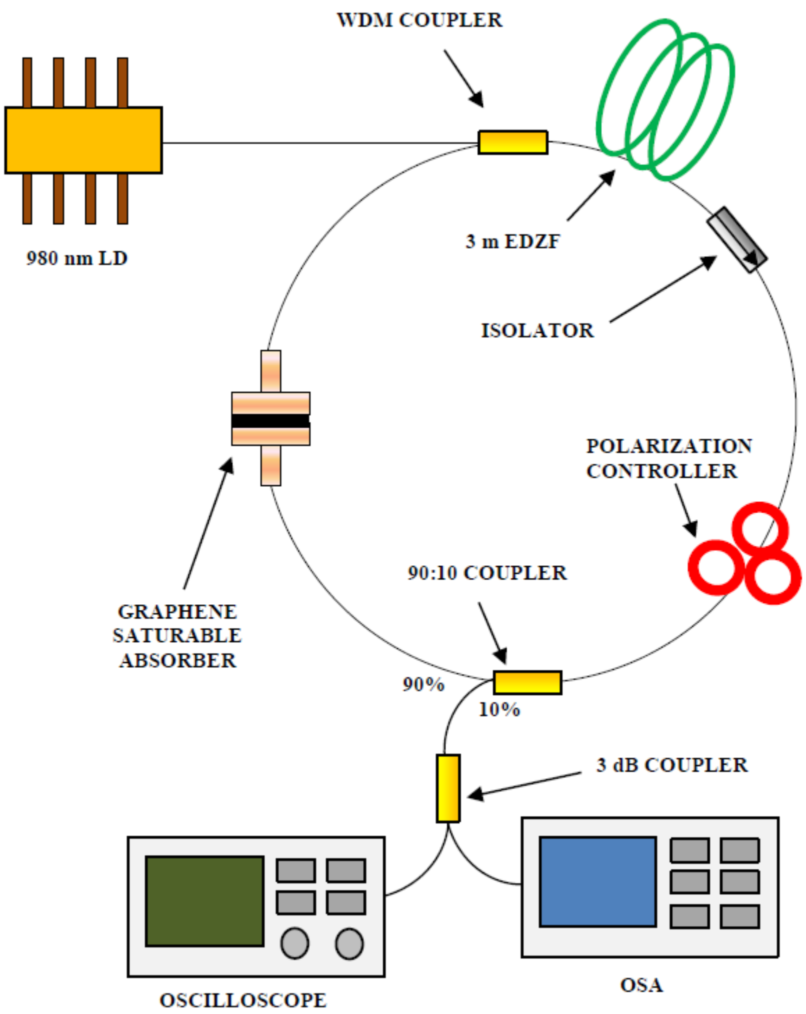
Right: Pulse energy (nJ) and average output power (μW) of the fiber laser as a function of the pump power.

- The average output power of the laser increases almost linearly giving an average output power of 270.0 μW at a maximum pump power of 141.8 mW. With an almost linear slope of 5.48 μW/mW.
- The pulse energy increases with the pump power, initially steeply at about 0.66 nJ/mW, and becoming shallower at 0.27 nJ/mW.
- At the highest pump power of 141.8 mW the maximum pulse energy of 19.02 nJ is obtained.



The Zr-EDF as a Pulse Laser

Q-switched ZrEDF / Graphene Fibre Laser

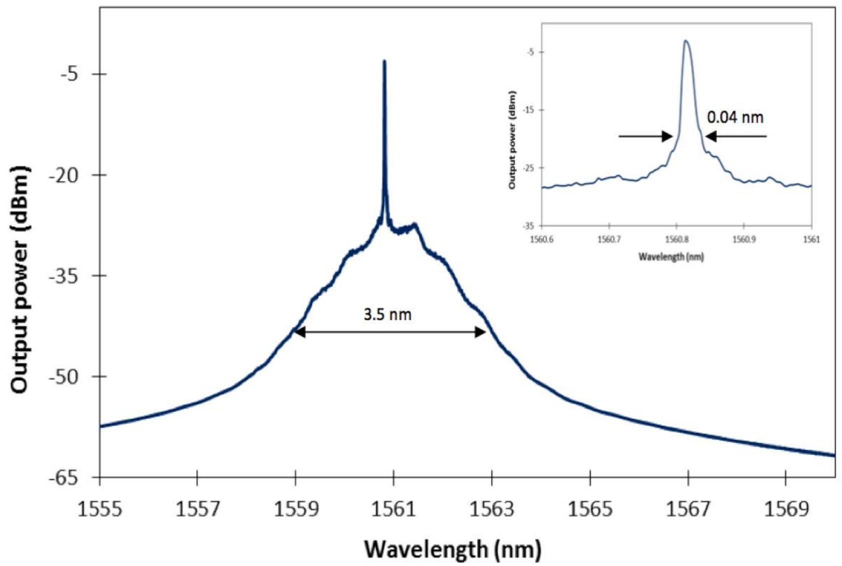


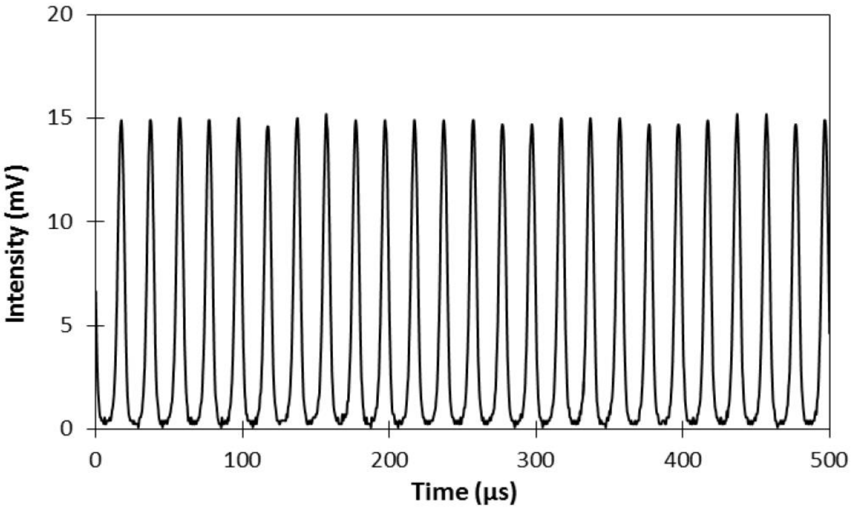
Schematic diagram for Q-switched fibre laser with graphene SA

- Uses the same configuration as before, with only minor changes to maintain experiment consistency
- SWCNT/PEO based SA is removed, and replaced with graphene based SA
- 1550 nm FBG also removed to take advantage of graphene's wide operating bandwidth
- Polarization controller is added to the setup
- All other operating conditions and parameters are maintained the same

The Zr-EDF as a Pulse Laser

Q-switched ZrEDF / Graphene Fibre Laser



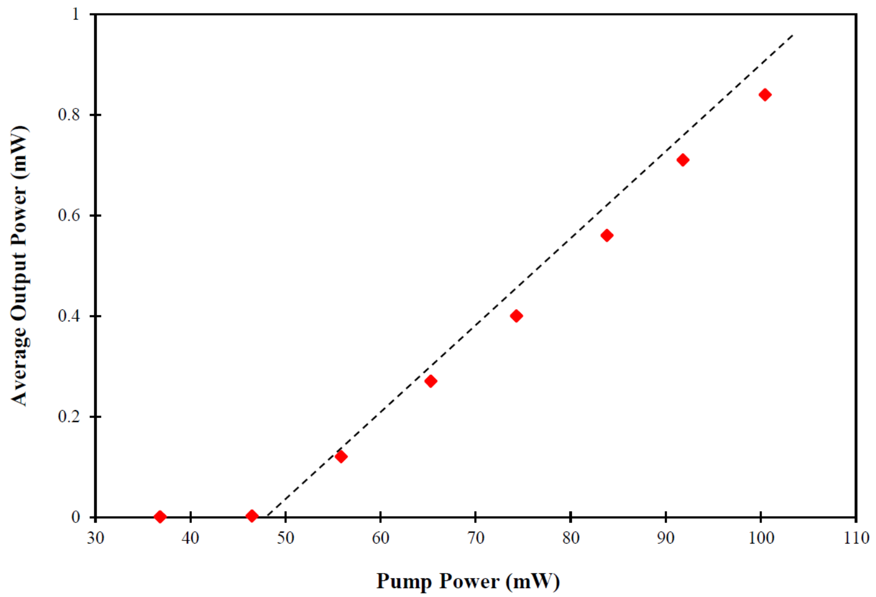


- At a pump power of about 100 mW the obtained pulse has a wide laser bandwidth, spanning from 1559.2 nm to 1562.7 nm at a power of -40 dBm.
- This gives apulse a bandwidth of approximately 3.5 nm
- The laser pulse peaks at 1560.8 nm, with a peak power of about -3.1 dBm and a linewidth of about 0.04 at -20 dBm.
- A pulse train with a repetition rate of 50.1 kHz is observed with the intensity of the peaks almost constant at 15 mV, indicating that the output of the laser is very stable.

Above left: Optical spectrum of Q-switched pulses from the ZrEDF laser incorporating a graphene based saturable absorber and below left: The output pulse train

The Zr-EDF as a Pulse Laser

Q-switched ZrEDF / Graphene Fibre Laser

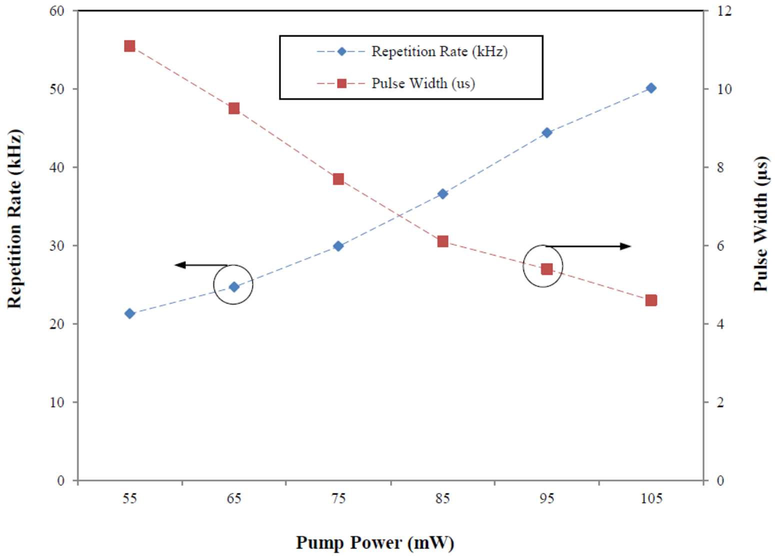


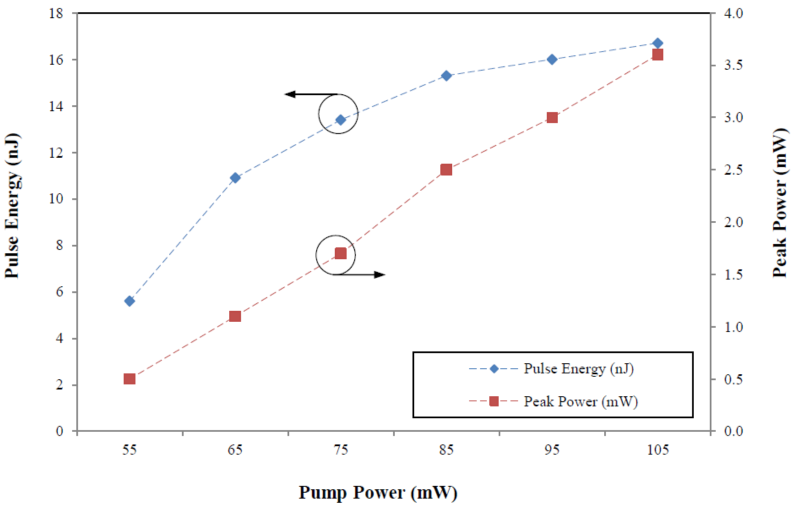
Average output power against pump power

- Change in the average output power amounts to an increment of about 0.15 mW for every 10 mW rise in the pump power
- Average output power that can be obtained in this setup is approximately 0.9 mW, which is obtained at a pump power of 100 mW
- Higher pump powers are not tested to prevent the graphene layer from being damaged, though projected power is about 1.4 mW at a pump power of 141.8 mW.
- Lasing threshold for is about 48 mW, Q-switching is about 56 mW

The Zr-EDF as a Pulse Laser

Q-switched ZrEDF / Graphene Fibre Laser



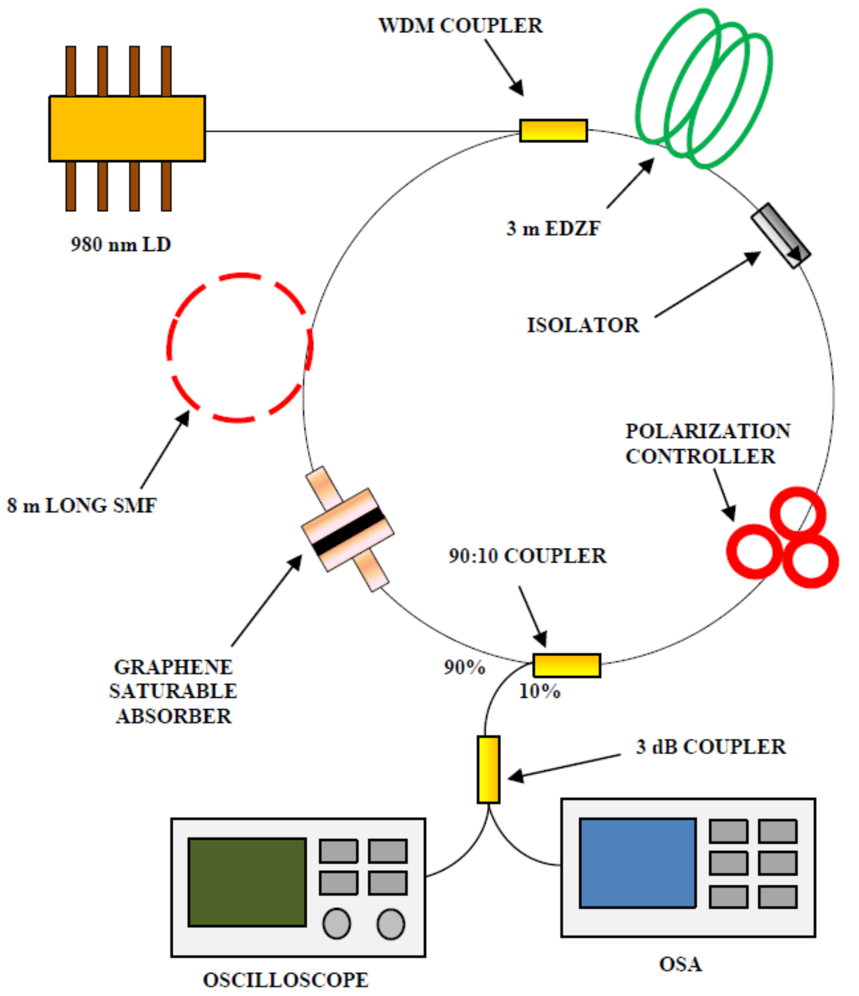


Above left: repetition rate and pulse width, below left: pulse energy and peak power

- Maximum repetition rate is 50.1 kHz at 100 mW. The average change in the repetition rate is between 3 to 7 kHz for every additional 10 mW of pump power.
- Pulse width decreases as the pump power increases, with an overall drop in the pulse width from 11.1 µs to 4.6 µs as the pump power changes from 56 mW to 100 mW
- Pulse energy rises steeply from 5.6 nJ to 13.4 nJ as the pump power increases from 56 mW to 74 mW, but this pump power, and then rising from 15.3 nJ at a pump power of 84 mW to only 16.8 nJ at the highest pump power of 100 mW.
- Peak power increases linearly with the pump power with a maximum value of 3.6 mW at pump power of100 mW, (0.6 mW in the peak power for every 10 mW increase in pump power)

The Zr-EDF as a Pulse Laser

Mode-Locked ZrEDF / Graphene Fibre Laser

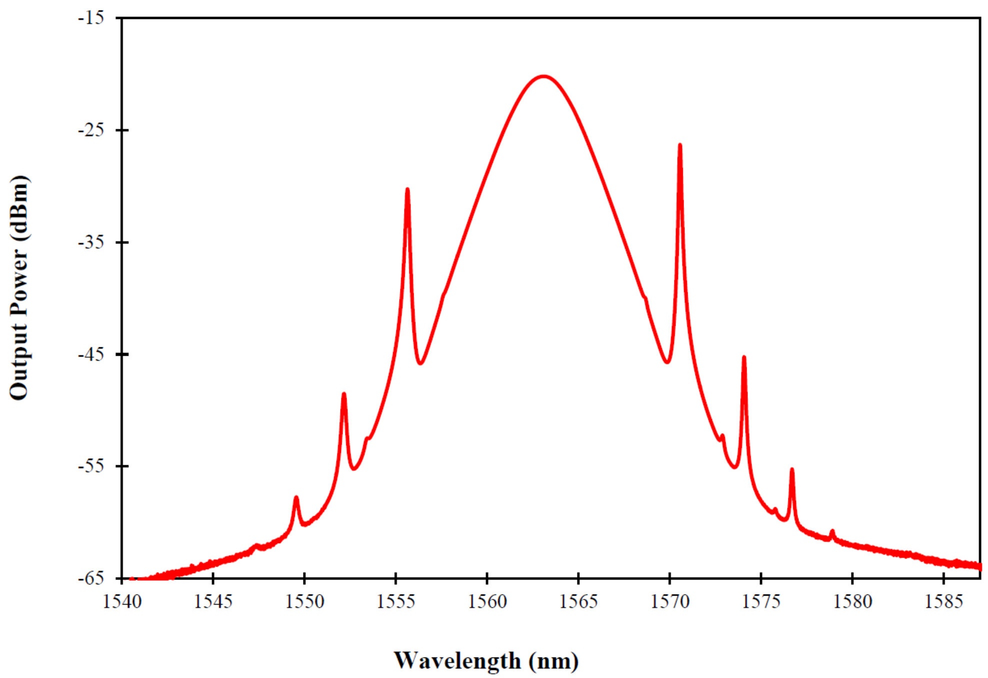


Schematic diagram for mode-locked fiber laser with ZrEDF and graphene based SA

- Same setup as the mode-locked fibre laser using a graphene based SA is used
- An 8 m long Single-Mode Fibre (SMF) is added to the setup to change the Group Velocity Dispersion (GVD)
- The ZrEDF has a dispersion coefficient of +28.45 $ps.nm^{-1}.km^{-1}$, The 8 m long SMF has a dispersion coefficient of +17 $ps.nm^{-1}.km^{-1}$. The GVD for the entire cavity now becomes -0.294 ps^2, taking into account the remaining SMF lengths in the cavity as well.
- This puts the cavity in the anomalous dispersion region, and allows the laser to operate in a soliton mode-locking regime. soliton mode-locking behaviour had been observed at a threshold pump power of 90 mW and all subsequent measurements are taken at a pump power of 100 mW.

The Zr-EDF as a Pulse Laser

Mode-Locked ZrEDF / Graphene Fibre Laser

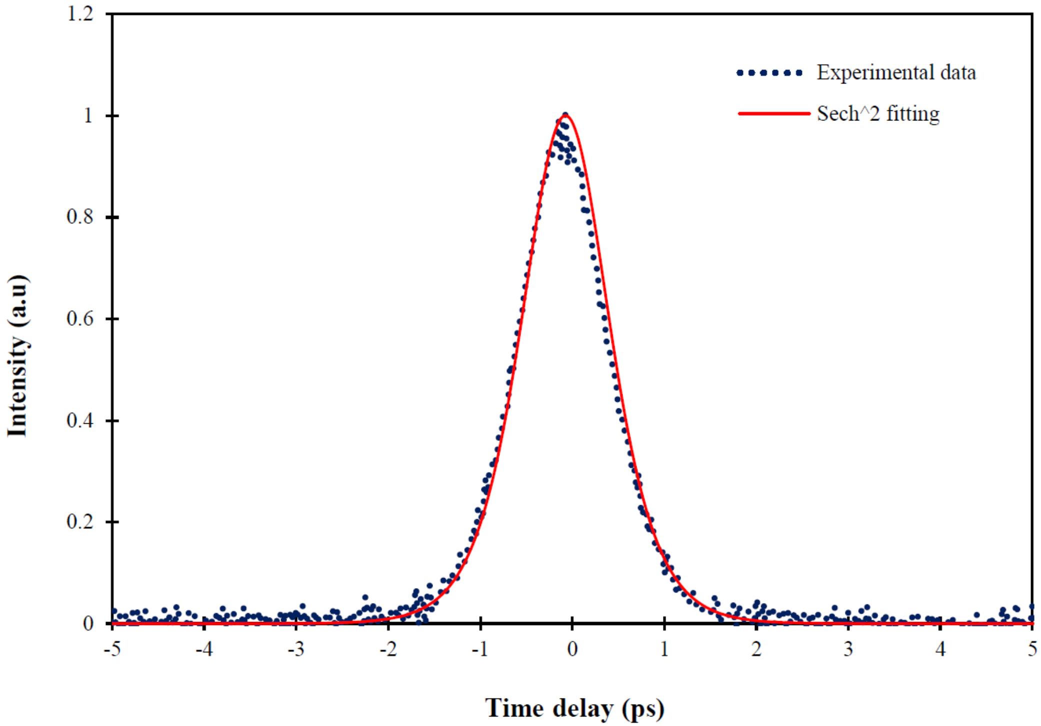


Optical spectrum of the ZrEDF mode-locked fibre laser at a pump power of 100 mW using the graphene based saturable absorber

- The central wavelength of the pulse lies at approximately 1563.0 nm with multiple Kelly's sidebands observed, thereby confirming that the system is operating in the soliton regime
- The mode-locked pulses have an average output power of 1.6 mW, with a pulse energy of 23.1 pJ and peak power of 31.6 W.
- The pulse repetition rate is 69.3 MHz, corresponding to a pulse spacing of approximately 14.5 ns in the pulse train

The Zr-EDF as a Pulse Laser

Mode-Locked ZrEDF / Graphene Fibre Laser

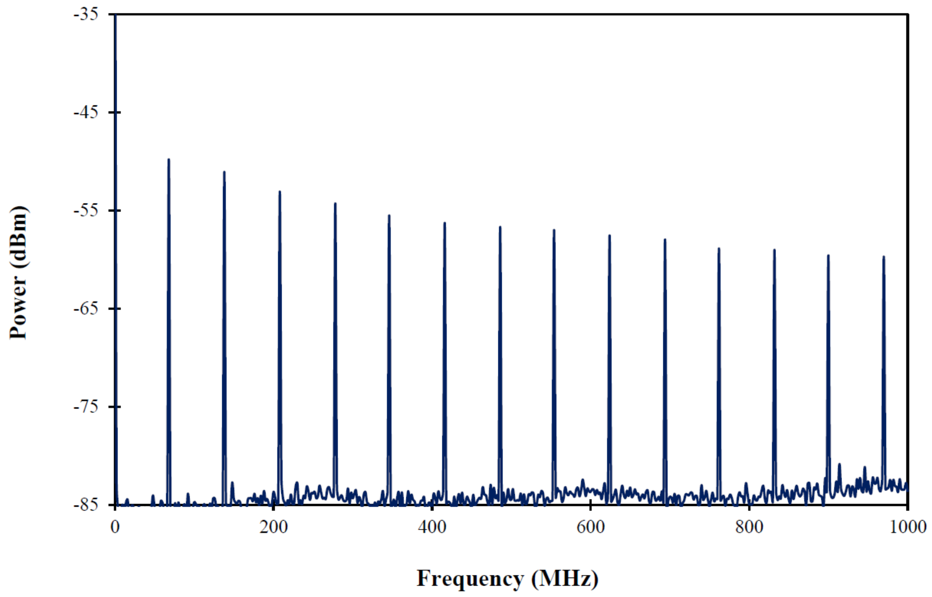


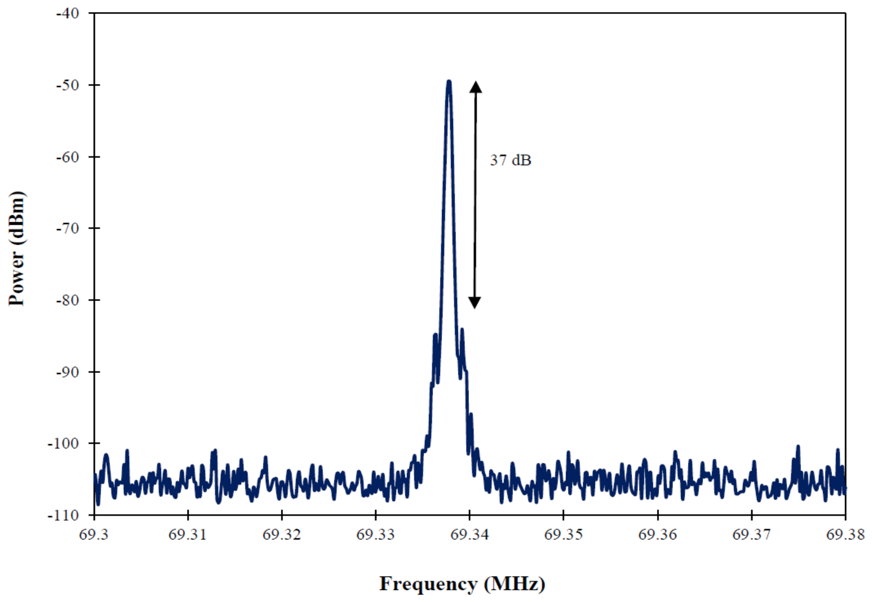
Autocorrelation trace of the mode-locked pulses

- The autocorrelation trace of the second harmonic generation, which has an estimated pulse duration of 730 fs at the FWHM point.
- The time-bandwidth product of 0.32 is obtained from the product of the 3 dB bandwidth, which amounts to 3.6 nm or 0.44 THz and the FWHM of the pulse.
- Although the obtained value is slightly higher than the transform limit of 0.315, this is to be expected.

The Zr-EDF as a Pulse Laser

Mode-Locked ZrEDF / Graphene Fibre Laser



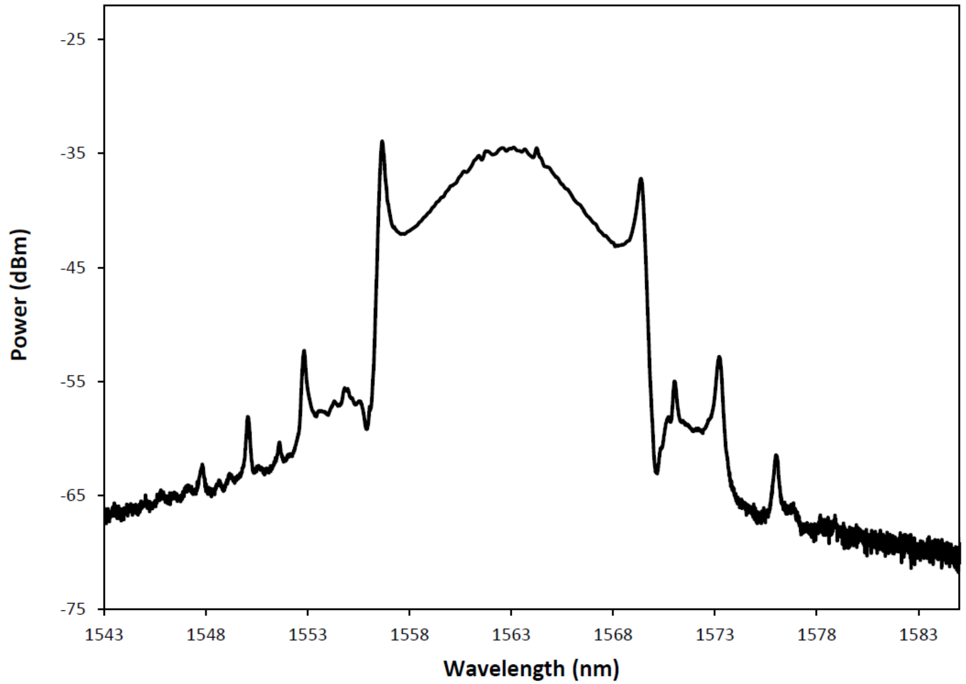


Above left: RF spectrum of the mode-locked pulse, above right: RF spectrum at the fundamental repetition rate of 69.3 MHz

- The RF repetition rate of the pulse is approximately 69.3 MHz
- A fundamental harmonic frequency of 69.3 MHz at an 80 kHz frequency span and resolution of 300 Hz is also observed , indicating the mode-locked laser works in its fundamental regime.
- The estimated peak-to-pedestal ratio being about 37 dB.

The Zr-EDF as a Pulse Laser

Mode-Locked ZrEDF / SWCNT/PEO Fibre Laser

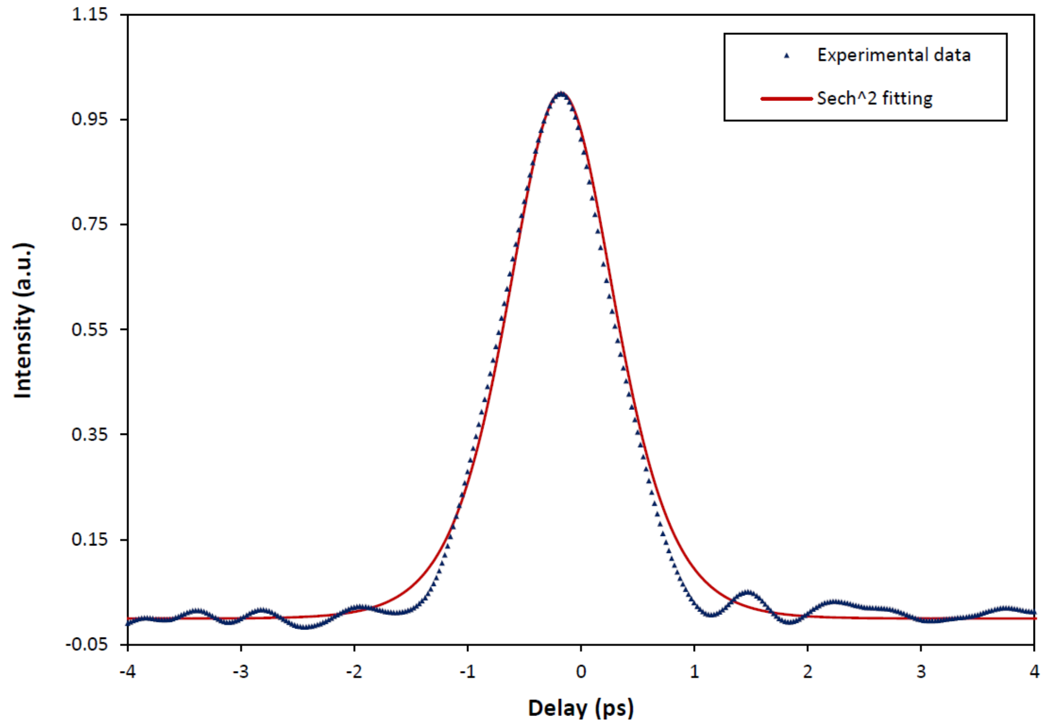


Optical spectrum of the ZrEDF mode-locked fibre laser at a pump power of 100 mW using the SWCNT/PEO based saturable absorber

- The SWCNT/PEO SA can also be used to obtain mode-locked pulses. This is done by replacing the grapheme SA of the previous setup with the SWCNT/PEO based SA.
- The central wavelength is 1562.67 nm, with minor perturbations at the side indicating the system is not as stable as with the grapheme based SA
- The average output power of the system is measured to be 180 µW, with a repetition rate of 17.74 MHz and a peak power of 14.09 W. The pulse energy of the system is 0.01 nJT
- The pulse repetition rate is 69.3 MHz, corresponding to a pulse spacing of approximately 14.5 ns in the pulse train

The Zr-EDF as a Pulse Laser

Mode-Locked ZrEDF / SWCNT/PEO Fibre Laser

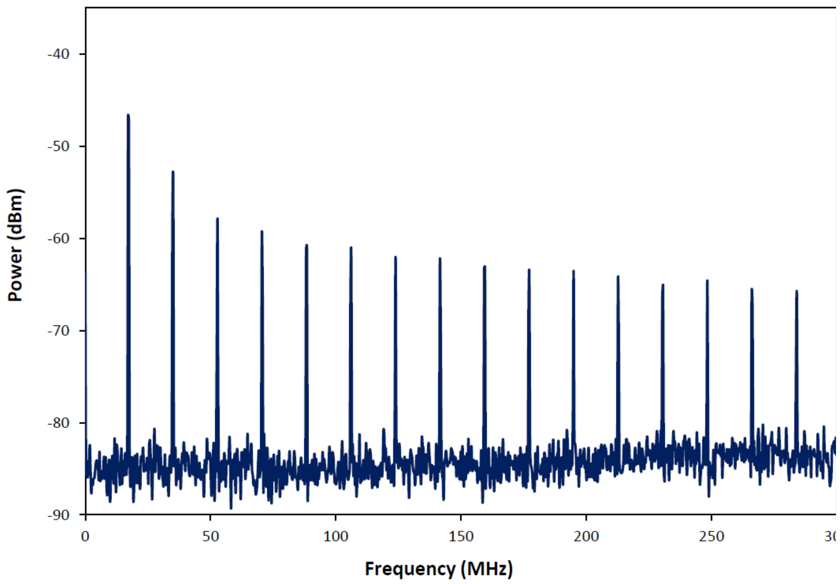


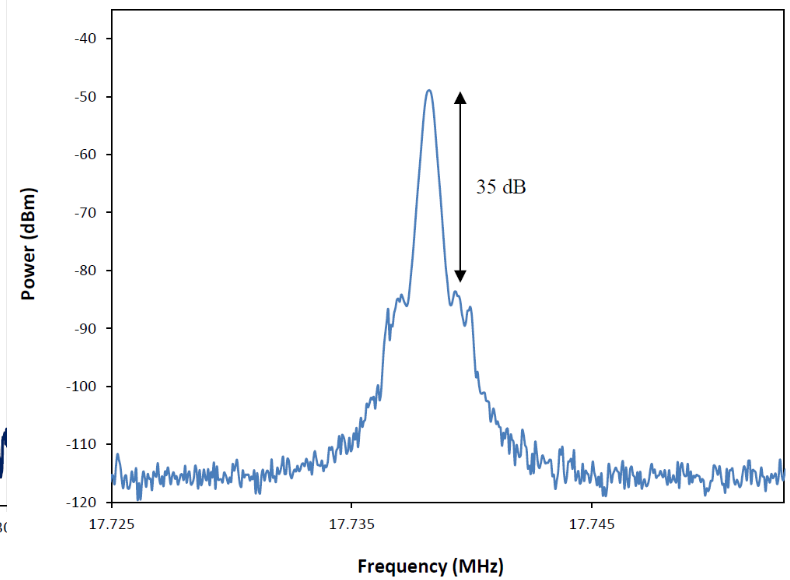
Autocorrelation trace of the mode-locked pulses

- The estimated pulse duration obtained by the system is approximately 720 fs at the FWHM point.
- The autocorrelation trace indicates that the experimentally obtained values augur well with the theoretical $sech^2$ fitting, and no pulse breaking or pulse pair generation is observed.
- A time-bandwidth product of 0.48 is obtained from the product of the 3 dB bandwidth, which is higher than the expected transform limit of 0.315

The Zr-EDF as a Pulse Laser

Mode-Locked ZrEDF / SWCNT/PEO Fibre Laser





Above left: RF spectrum of the mode-locked pulse, above right: RF spectrum at the fundamental repetition rate of 17.7 MHz

- The RF repetition rate of the pulse is approximately 17.7 MHz
- A fundamental harmonic frequency of 17.7 MHz at a 60 kHz frequency span and resolution of 300 Hz is also observed
- The estimated peak-to-pedestal ratio being about 35 dB.

Summary of Findings and Moving Forward

- The ZrEDF provides a unique opportunity to work with a conventional silica fiber that has a very high erbium dopant concentration
- The most common application would be in the development of compact, high powered fiber lasers and amplifiers
- A side-effect of the high-dopant concentration is the ability to amplify slightly further than the C-band region (defined as the extended C-band). This behavior is akin to an L-band EDF amplifier
- The ZrEDF shows good potential for use in SLM applications, as well as the exploitation of its non-linear phenomenon such as FWM
- The primary objective of the work is achieved, which is to used the ZrEDF together with SWCNT and Graphene based SAs to generate mode-locked and Q-switched pulses.

Summary of Findings and Moving Forward

- A number of potential research aspects have been identified during the course of this work for the ZrEDF
- Owing to the non-linear characteristics of the ZrEDF, new applications of the ZrEDF can be realized, such as the generation of Supercontinuum emissions. This will allow the ZrEDF to serve as a cheap and viable alternative towards the exotic fibers currently being used to generate these emissions. Another interesting area of study would be on the non-linear characteristics of the ZrEDF, which would provide the platform for the development of advanced and compact optical devices such as wavelength converters.

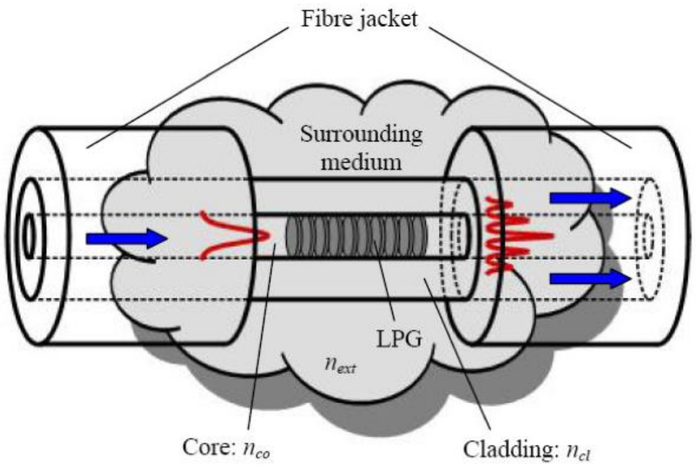
OPTICAL SENSING FOR BIOLOGICAL APPLICATIONS

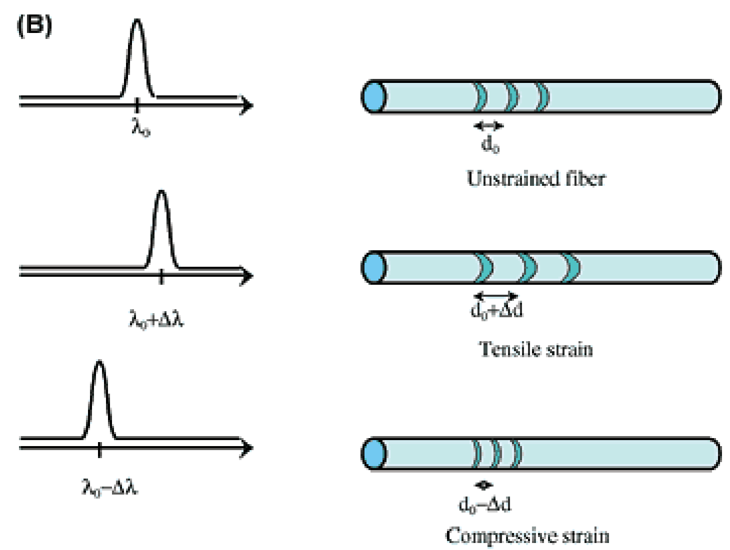
Introduction

- Optical fibre sensors are highly capable sensors, able to measure a wide range of parameters.

- Fiber sensors have significant advantages over conventional sensors, such as:
  - Being lighter and compact, allowing flexible operating conditions
  - Immune to electromagnetic interference
  - Being generally low cost and simple in design, which is especially useful when deployed in scale
  - They can be multiplexed, further reducing cost and making deployment easier

- Typically, they are used for measuring temperature, pressure, compression and strain





Top: LPG sensor, and above: Typical FBG sensor

Introduction

- The current interest in optical sensing - a non-invasive, or minimally invasive measurement system capable of undertaking real-time measurements of various biological or chemical constituents
- Current approaches to optical sensing for biological and chemical constituents:
  - interferometry based techniques
  - low coherence interferometry and wavelength-scanning interferometry with confocal microscopy for increased accuracy
- These systems have multiple drawbacks: optical alignment, high-resolution translation stages and are expensive, bulky and complex
- Our approach: fiber sensors based on Fresnel reflection. Advantages:
  - They are minimally invasive
  - Real-time measurements.
  - Significantly cheaper and easier to assemble and operate.

Sample Preparation

- Sound intact deciduous stem cells (SCDs) were extracted from individual patients (age 6-11, n=3) who were undergoing planned serial extraction for at the Department of Children's Dentistry and Orthodontics, Faculty of Dentistry, University of Malaya.

- Human umbilical cords were collected from full-term births after either cesarean section or normal vaginal delivery (age=28-35, n=3) with informed written consent as per the approved guidelines by the Ministry of Health, Malaysia. Wharton's Jelly mesenchymal stem cells (WJSCs) were extracted/obtained from the umbilical cords as previously described (Nekanti, U., et al, 2010)

- Samples were obtained and stored under a protocol that is approved by the Medical Ethics Committee, Faculty of Dentistry, University of Malaya. (Medical Ethics Approval Number DFCD0907/0042(L)).

- Dental root surfaces were sterilized externally with povidone iodine and the pulps were extirpated within 2 hours after extraction and processed.

Sample Preparation

- The pulp tissue was minced into small fragments before digestion in a solution of 3 mg/mL collagenase type I (Gibco, Grand Island, NY) for 40 minutes at 370^{o}C.

- Similarly, the WJSC tissue samples were minced into small fragments before digestion in a 3mg/mL solution of collagenase type I for 40 minutes at 370^{o}C.

- All samples were then neutralized with 10% of fetal bovine serum (FBS) (Hyclone; ThermoFisher Scientific Inc, Waltham, MA), centrifuged and were seeded in T25 culture flasks with conditioned media containing DMEM-KO Basal media (Invitrogen, Carlsbad, CA, USA),0.5%10,000mg/mL penicillin/ streptomycin (Invitrogen); 1% 1x Glutamax (Invitrogen) and 10% FBS, with humidified atmosphere of 95% of air and 5% of CO_2at 37^{0}C. The cells were typsinized prior to 80% confluence and processed for subsequent subcultures. (SC1, SC2, SC3, SC4 etc.).

Sample Preparation

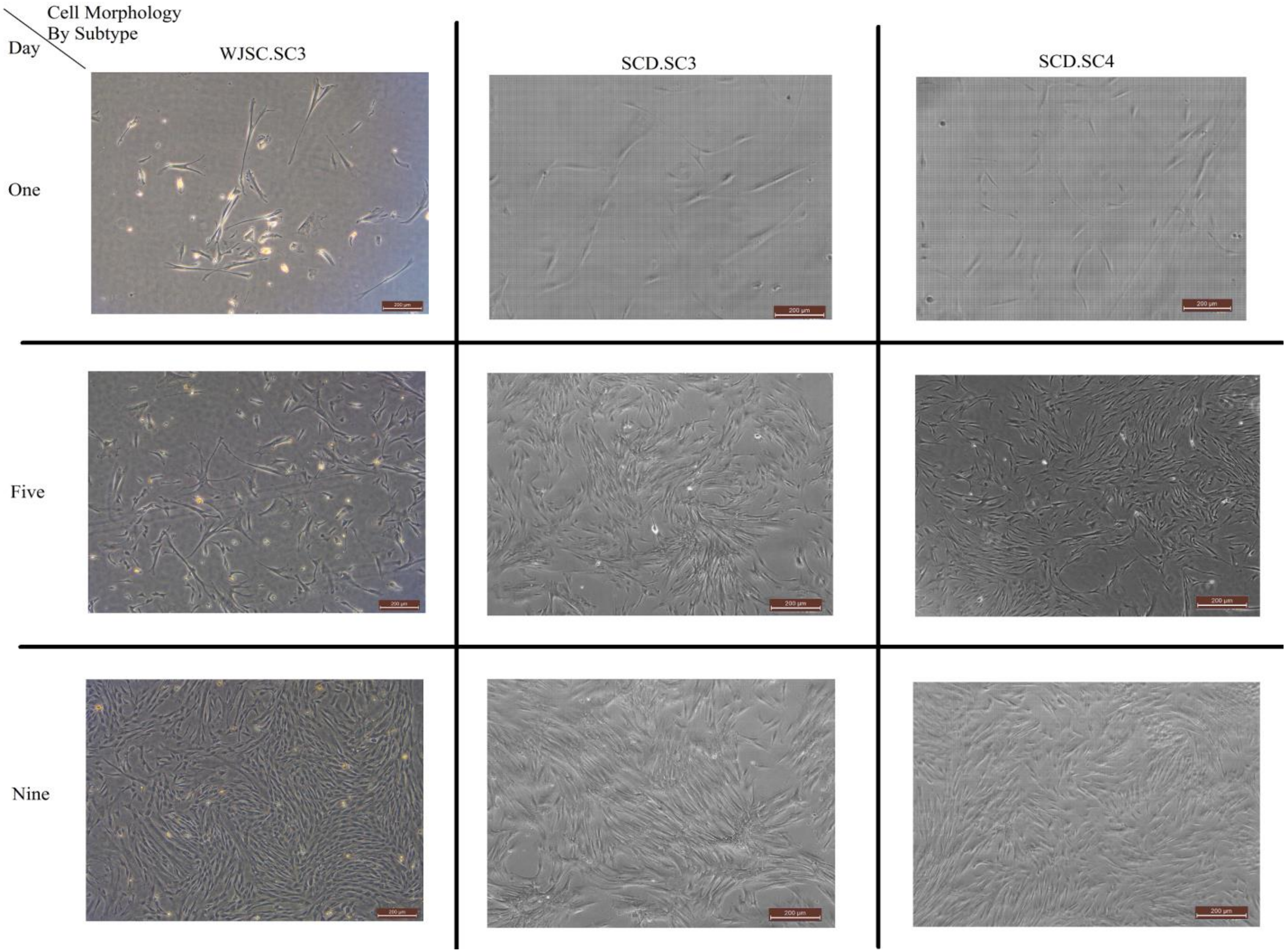
- Three sub-cultures, Deciduous Dental Stem Cell Subculture 3 (SCD.SC3), Deciduous Dental Stem Cell Subculture 4 (SCD.SC4) and Wharton's Jelly Stem Cell Subculture 3 (WJSC.SC3were plated at a seeding density of 1000 cells/cm^2.

- Cultures were allowed to grow in standard growth conditions during the experiment duration of 9 days, and each day viable cell counts were performed using a haemocytometer and 0.4% tryphan blue dye, with each sample undergoing repeat counts to reduce error. Simultaneously, on Day 1 through Day 9, conditioned media (CM1 through to CM9) was collected from each subculture in triplicate fashion (Day 1 = [R1, R2, R3], Day 2 = [R4, R5, R6], Day 3 = [R7, R8, R9], etc.) placed into vials before being stored at -80^{o}C, resulting in a total of 27 samples for each subculture and an overall total 81 samples for testing.

Stem cell count obtained over 9 days for all three cell lines, with standard deviations (SDs)

Day	WJSC.SC3	SD	SCD.SC3	SD	SCD.SC4	SD
1	3333	2886.751	33333	5773.502	5000	0.000
2	3333	2886.751	41667	5773.502	23333	2886.751
3	6667	2886.751	48333	10408.33	16666	2886.751
4	11667	5773.502	151667	40414.520	138333	18930.000
5	75000	10000.000	160000	10000.000	148333	34034.000
6	28333	2886.751	210000	65000.000	176667	32532.035
7	50000	10000.000	156667	52041.650	208333	28431.200
8	40000	15000.000	141667	27537.850	128333	20207.260
9	21667	10408.000	143333	12583.060	241667	32532.035

Sample Preparation



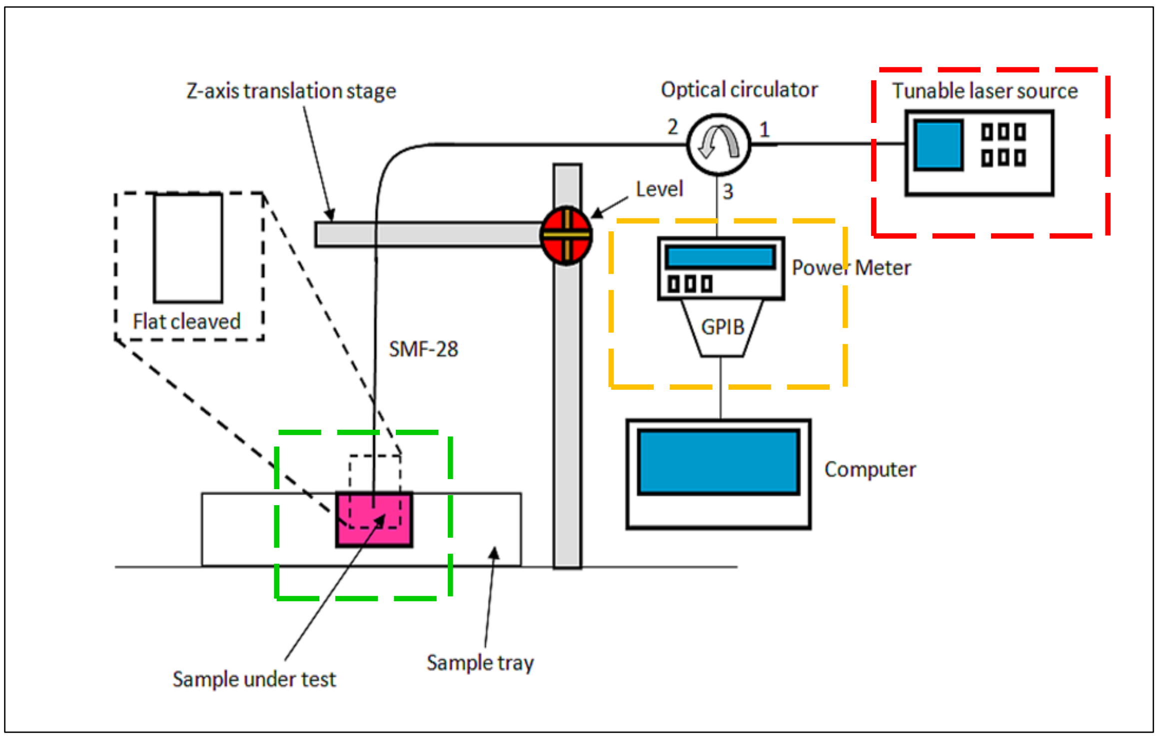
Morphology and the growth of the different MSCs obtained at different days of the experiment. The captured images provide a visual validation of the cell counts obtained in the table of the previous slide.

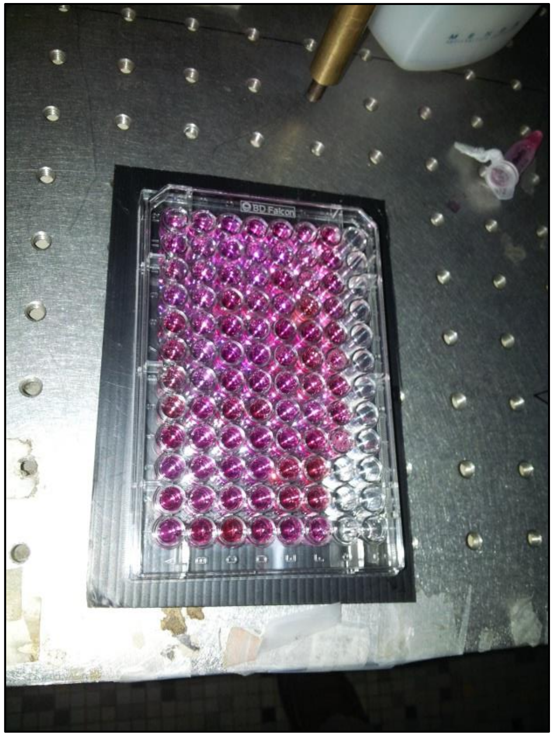
Experimental Setup

The sensor consists of three main parts:

- Transmitter (Tunable Laser Source)
- Sensor (Fresnel Fibre Probe)
- Receiver (Receiver and Computation Unit)

Other components serve to direct the light signal to and from the sample to the necessary equipment

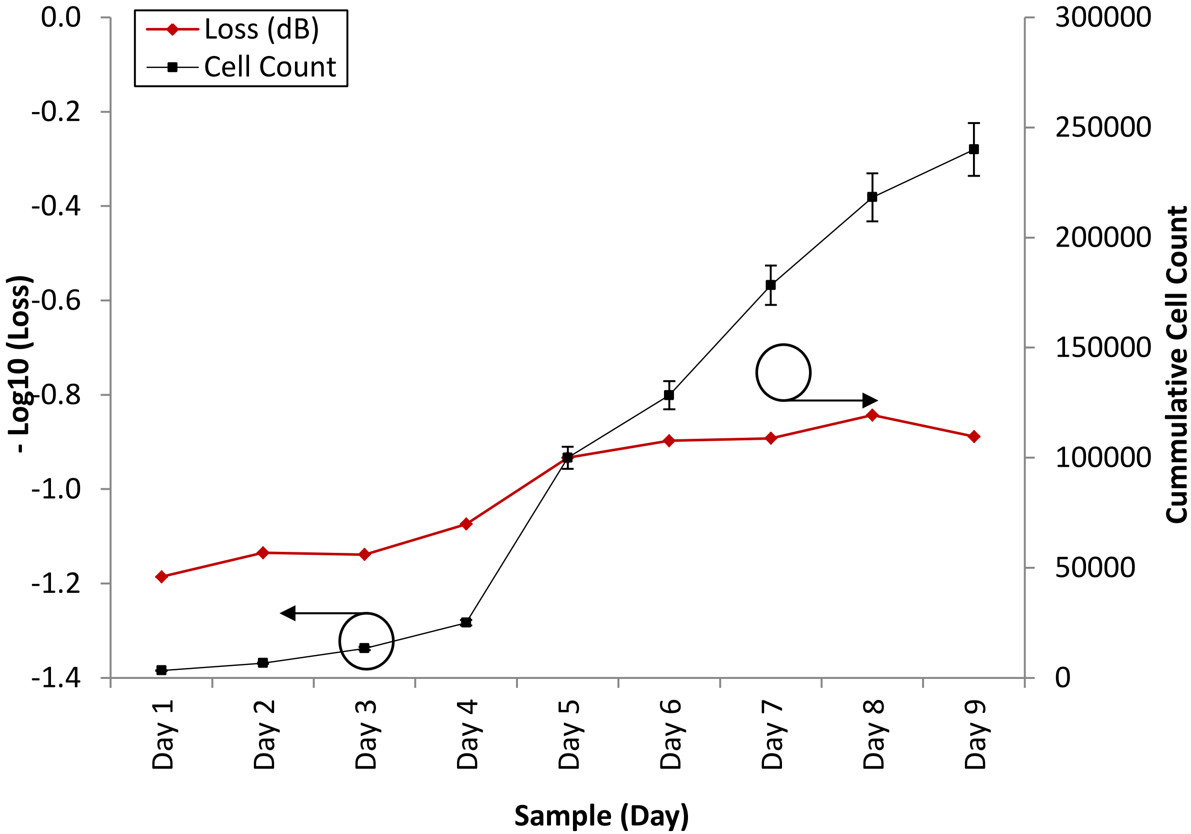




Above left: the experimental setup, consisting of the transmitter, sensor and receiver modules, and above right: samples as they have been prepared on the sample tray.

Sensor Results

Sensor Responses to WJSC.SC3 Samples



-Log 10 (Power Loss) (dB) and cumulative cell count against different culture samples for the WJSC.SC3 cell line. The power loss is represented by the line graph, with the corresponding X-axis on the left, while the cell count is represented by the bar chart, with the corresponding X-axis on the right side of the graph

- Power loss decreases by 0.4 dB in the conditioned media for an average increase of 1000 mesenchymal stem cells
- The power returning from the face of the fiber can be given as:

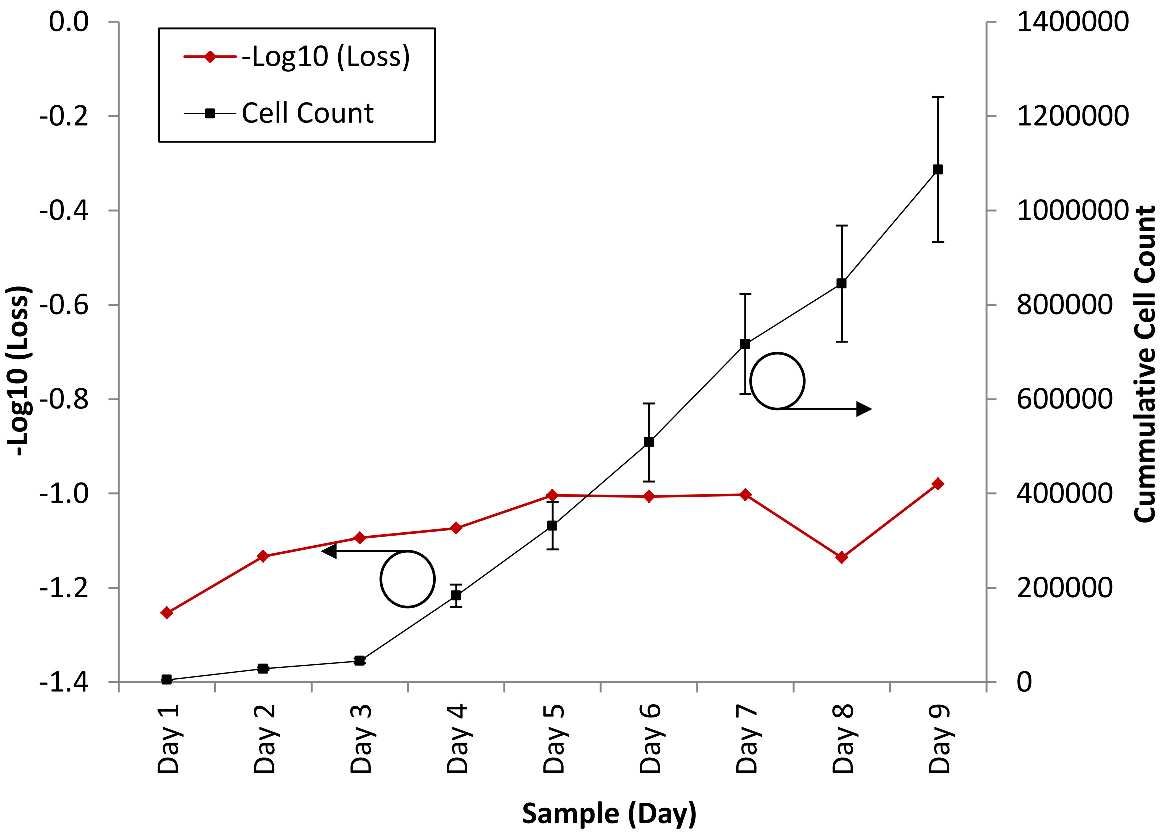
$$R = \left(\frac{n_1 - n_o}{n_1 + n_o}\right)^2$$

where R is the fraction of incident light reflected by the face of the fiber, n_1 is the refractive index of the fiber core (1.45 for most commercially available fibers) and n_o is the refractive index of the culture medium.

- Thus, the loss of power can be seen as being caused by a refractive in the refractive index of the culture

Sensor Results

Sensor Responses to SCD.SC4 Samples

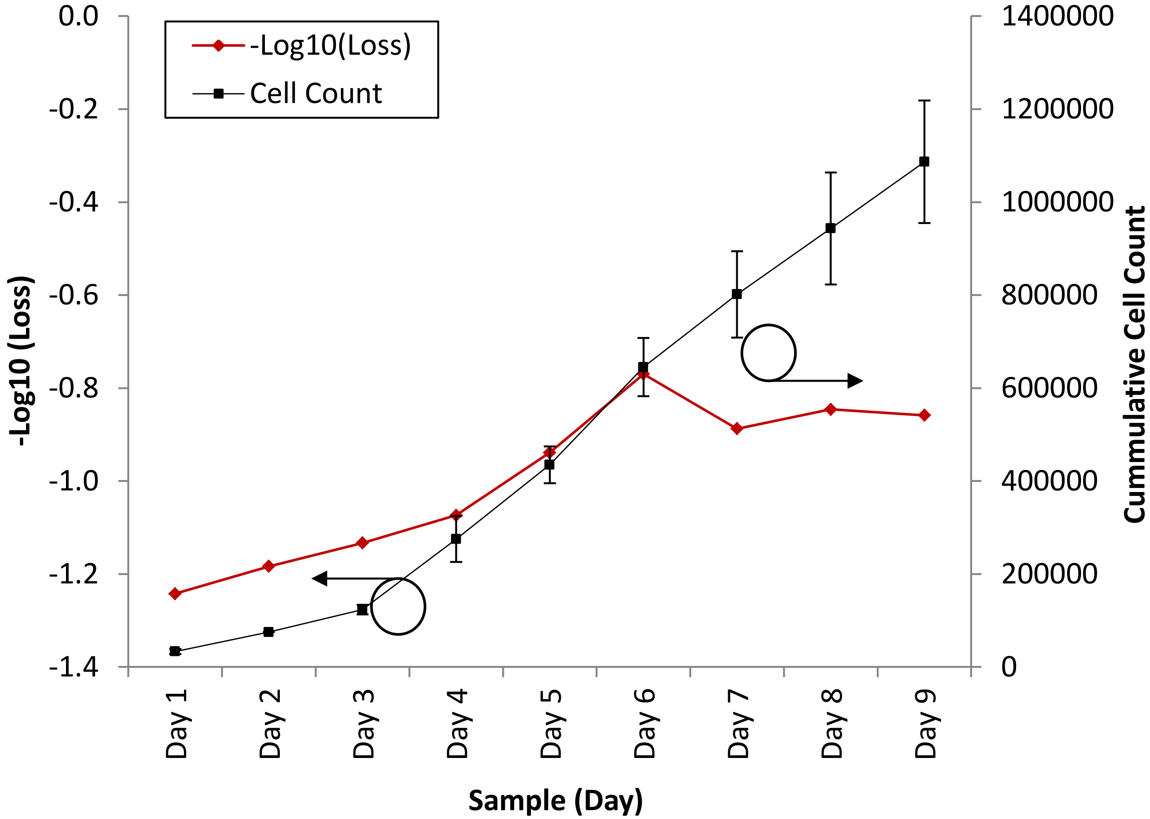


-Log 10 (Power Loss) (dB) and cumulative cell count against different culture samples for the SCD.SC4 cell line. The power loss is represented by the line graph, with the corresponding X-axis on the left, while the cell count is represented by the bar chart, with the corresponding X-axis on the right side of the graph.

- Sensor also tested with SCD cells from SCD.SC4 stem cell line.
- Done to gauge performance of sensor when used to measure samples from different stem cell types
- Similar behavior observed, with inverse power loss relationship to secretory and excretory biomolecules within conditioned media to the cell count
- Power loss value decreases by approximately 0.4 dB as well, indicating consistent performance for different cell samples.

Sensor Results

Sensor Responses to SCD.SC3 Samples

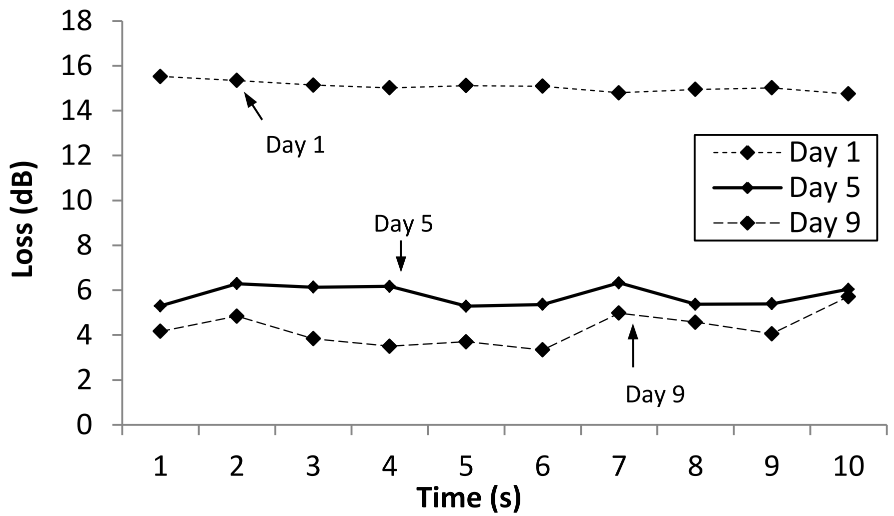


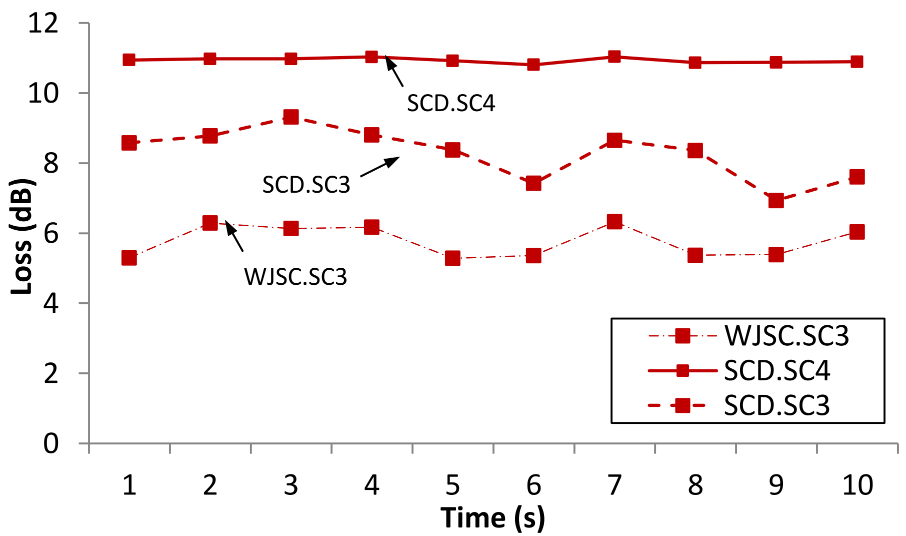
-Log 10 (Power Loss) (dB) and cumulative cell count against different culture samples for the SCD.SC3 cell line. The power loss is represented by the line graph, with the corresponding X-axis on the left, while the cell count is represented by the bar chart, with the corresponding X-axis on the right side of the graph.

- Sensor also tested with SCD cells from SCD.SC3 stem cell line.
- Done to gauge performance of sensor when used to measure samples from different stem cell cultures but of the same stem cell type.
- Similar behavior observed, with relatively inverse power loss relationship to secretory and excretory biomolecules within conditioned media to the cell count
- Power loss value decreases by approximately 0.3 dB, indicating consistent performance for different cell samples.

Sensor Results

Performance of Sensor over Time





- Analysis of sensor performance shows system is relatively stable.
- Measurement of samples from WJSC.SC3 line shows stable power loss readings for different days
- Measurement of samples taken from different cell lines in Day 1 also show low fluctuations over time, thus indicating reliability of results.

Above left: Power loss (dB) against time for selected samples for the WJSC.SC3 cell line (samples taken from Day 1, Day 5 and Day 9). Below left: Power loss (dB) against time for selected samples for the three different cell line (all samples taken from Day 1).

Publications

- H. Ahmad, K. Thambiratnam, N. A. Awang, M. H. Jemangin, and S. W. Harun, "Stable Zirconia–Erbium Doped Multiwavelength Fibre Laser by Precise Control of Polarization States," ***Las. Phys. Lett***., vol. 22, pp. 982-985, 2012.
- H. Ahmad, M. C. Paul, N. A. Awang, S. W. Harun, M. Pal and K. Thambiratnam, "Four-Wave-Mixing in Zirconia-Yttria-Aluminum Erbium," ***J. Europ. Opt. Soc. Rap. Public***., vol. 7, pp. 12011-1 - 12011-8, 2012.
- H. Ahmad, N. A. Awang, M. Z. Zulkifli, K. Thambiratnam, M.C. Paul, S. Das, and S.W. Harun, "Supercontinuum from Zr-EDF using Zr-EDF mode-locked fibre laser," ***Las. Phys. Lett***., vol. 9, pp. 44-49, 2012.
- H. Ahmad, K. Thambiratnam, N. A. Awang, Z. A. Ghani and S.W. Harun, "Four-wave mixing in zirconia-erbium doped fibre – a comparison between ring and linear cavities," ***Las. Phys. Lett***., vol. 9, pp. 819-825, 2012.

Publications

- H. Ahmad, K. Thambiratnam, M. C. Paul, A. Z. Zulkifli, Z. A. Ghani, and S. W. Harun, "Fabrication and application of zirconia-erbium doped fibres," ***Opt. Mat. Expr***., vol. 2, pp. 1690-1701, 2012.
- H. Ahmad, A.Z. Zulkifli, K. Thambiratnam and S.W. Harun "Q-switched Zr-EDF laser using single-walled CNT/PEO polymer composite as a saturable absorber," ***Opt. Mater***., vol. 35, pp. 347-352, 2013.
- K. Thambiratnam, H. Ahmad, , F. D. Muhammad, M. Z. Zulkifli, A. Z. Zulkifli, M. C. Paul and S. W. Harun, "Q-Switching and Mode-Locking in Highly-Doped Zr2O3-Al2O3-Er2O3 Doped Fibre Lasers using Graphene as a Saturable Absorber," ***IEEE J. Select. Topics in Quant. Electron***., vol. 20, pp. 1100108, 2014.
- Ahmad, H.; Thambiratnam, K.; Zulkifli, A.Z.; Lawrence, A.; Jasim, A.A.; Kunasekaran, W.; Musa, S.; Gnanasegaran, N.; Vasanthan, P.; Jayaraman, P.; Kasim, N.H.A.; Govindasamy, V.; Shahrir, M.S.; Harun, S.W. Quantification of Mesenchymal Stem Cell Growth Rates through Secretory and Excretory Biomolecules in Conditioned Media via Fresnel Reflection. *Sensors* **2013**, *13*, 13276-13288.

Thank You

We would like to acknowledge and thank all copyright holders for any and all materials used in this presentation