



Integrated disruptive components for 2 $\mu$ m fibre Lasers  
ISLA

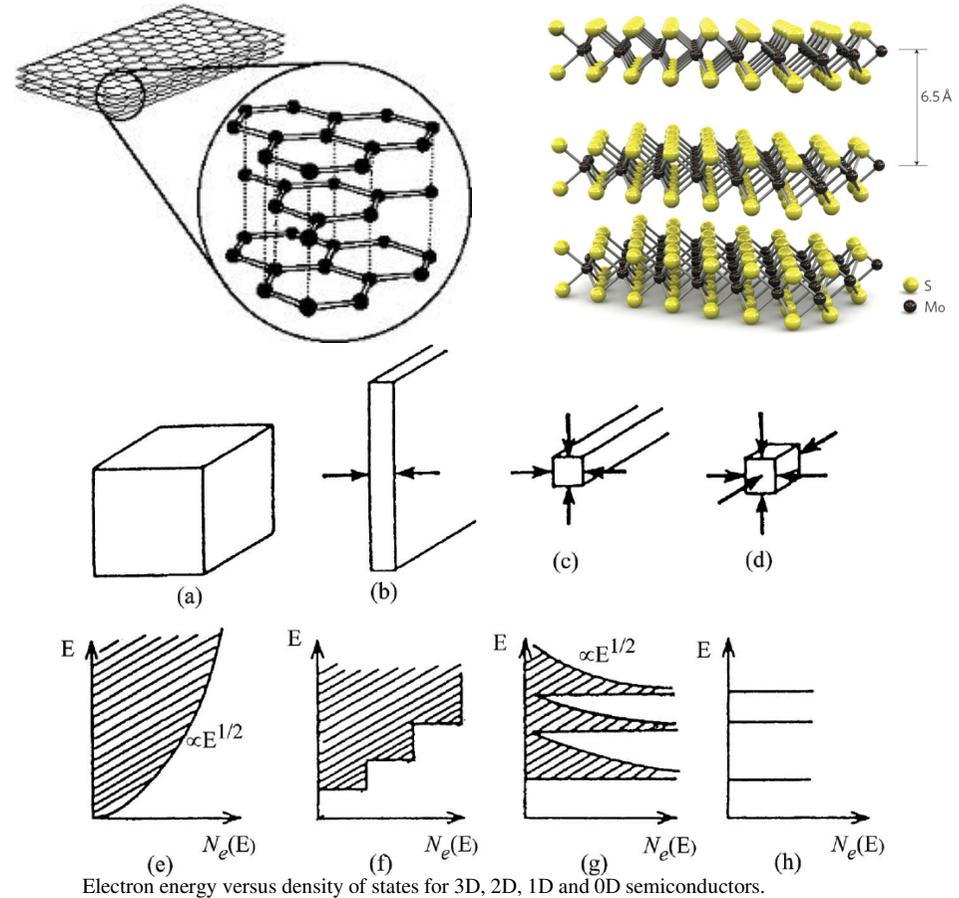
# Graphene Based Saturable Absorber Modelockers at 2 $\mu$ m

Prof. Werner Blau - Trinity College Dublin  
Friday, 26th of June 2015

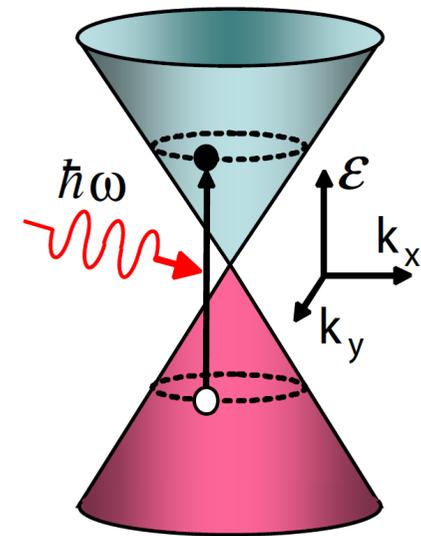
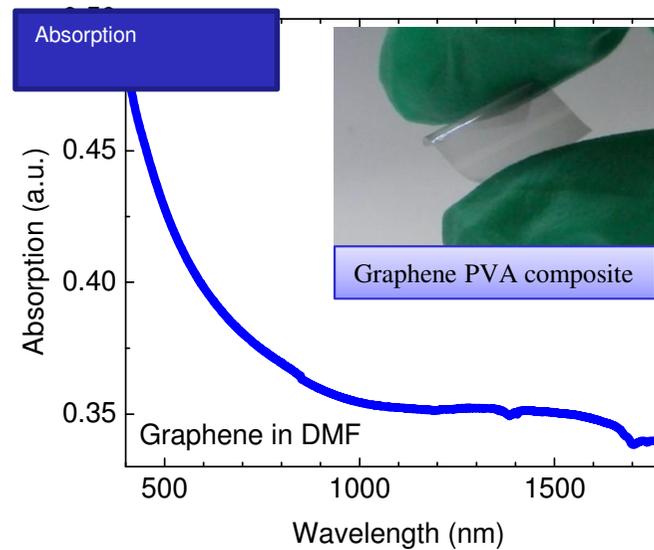
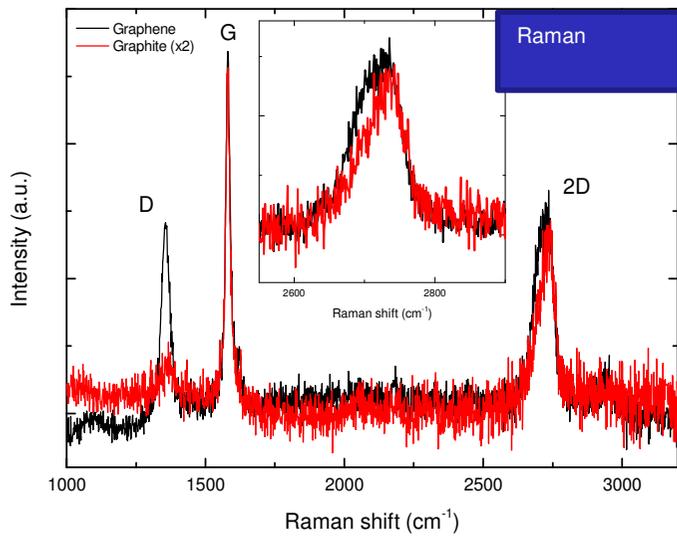
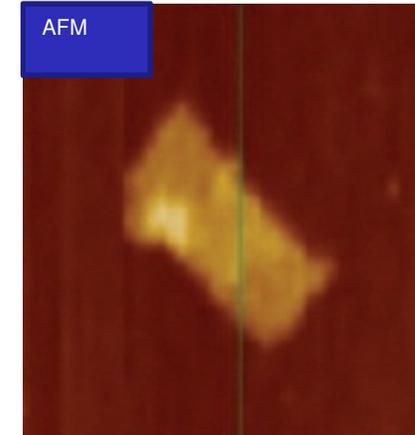
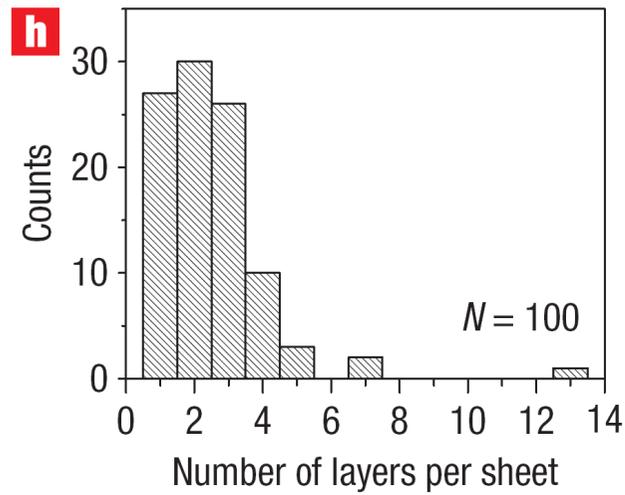
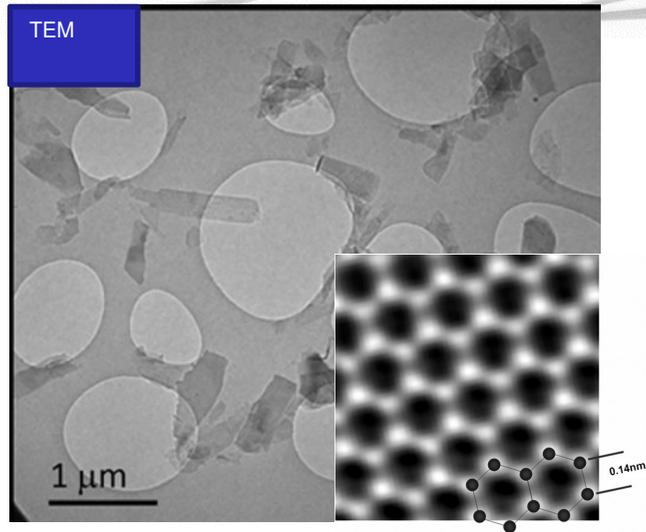
# 2D Nanosystems



- **Strong** covalent bonds in layer;
- **Weak** van der Waals interaction between layers;
- **Specific** 2D confinement of electron motion;
- **Absence** of interlayer perturbation;
- **Unique** electronic, optical, mechanical and thermal properties.



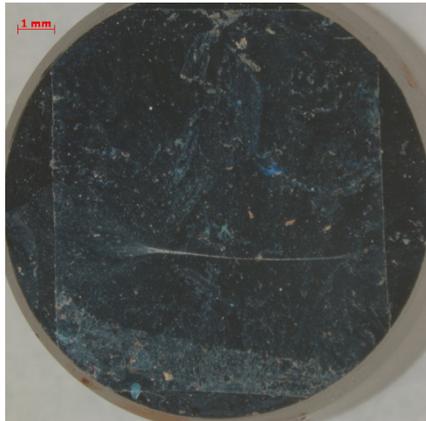
# Graphene - Characterisation



# Graphene SAM

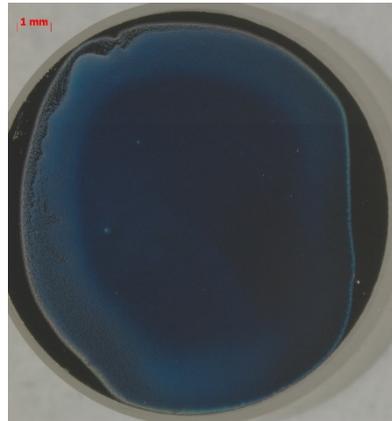


Chemical Vapour  
Deposition

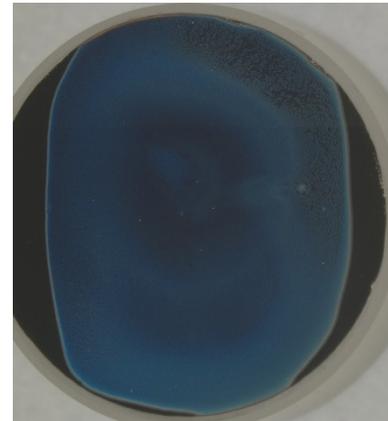


PMMA Prepared  
Grown on Cu

Liquid Phase Exfoliation

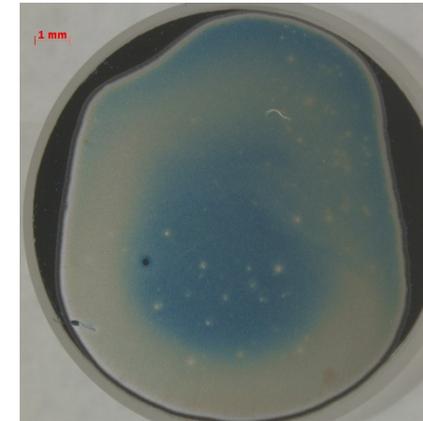


Oven Prepared  
5% Solution



Oven Prepared  
10% Solution

Drop Casting

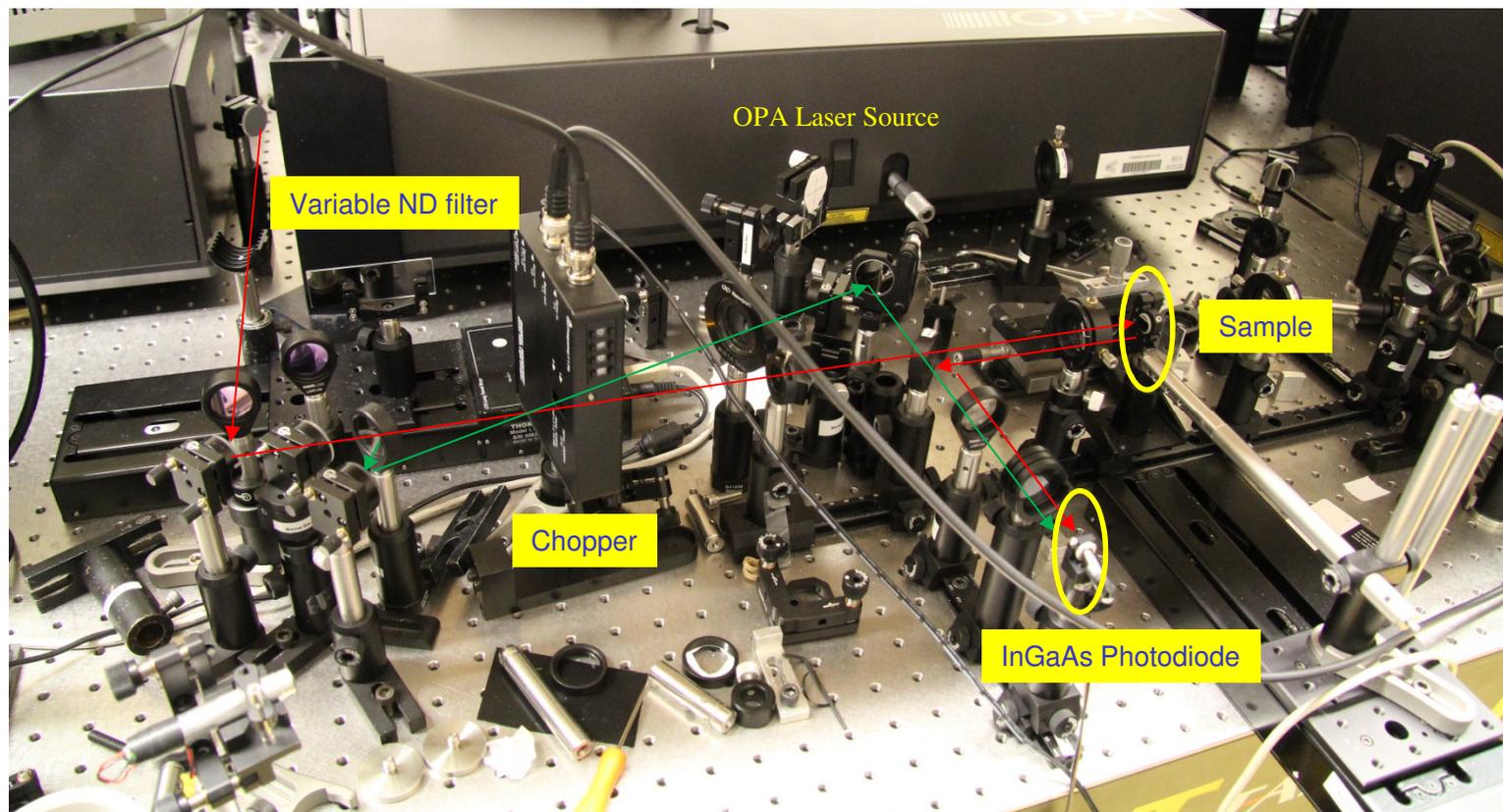


Vacuum Prepared  
5% Solution

**Thickness**



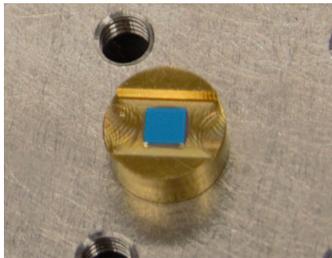
# I-scan Setup



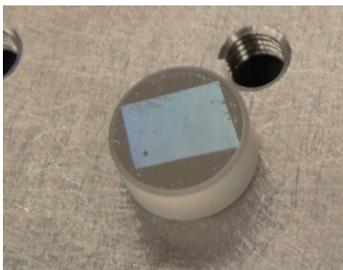
# I-scan of Graphene on Mirror and SESAM

## at 2 $\mu\text{m}$

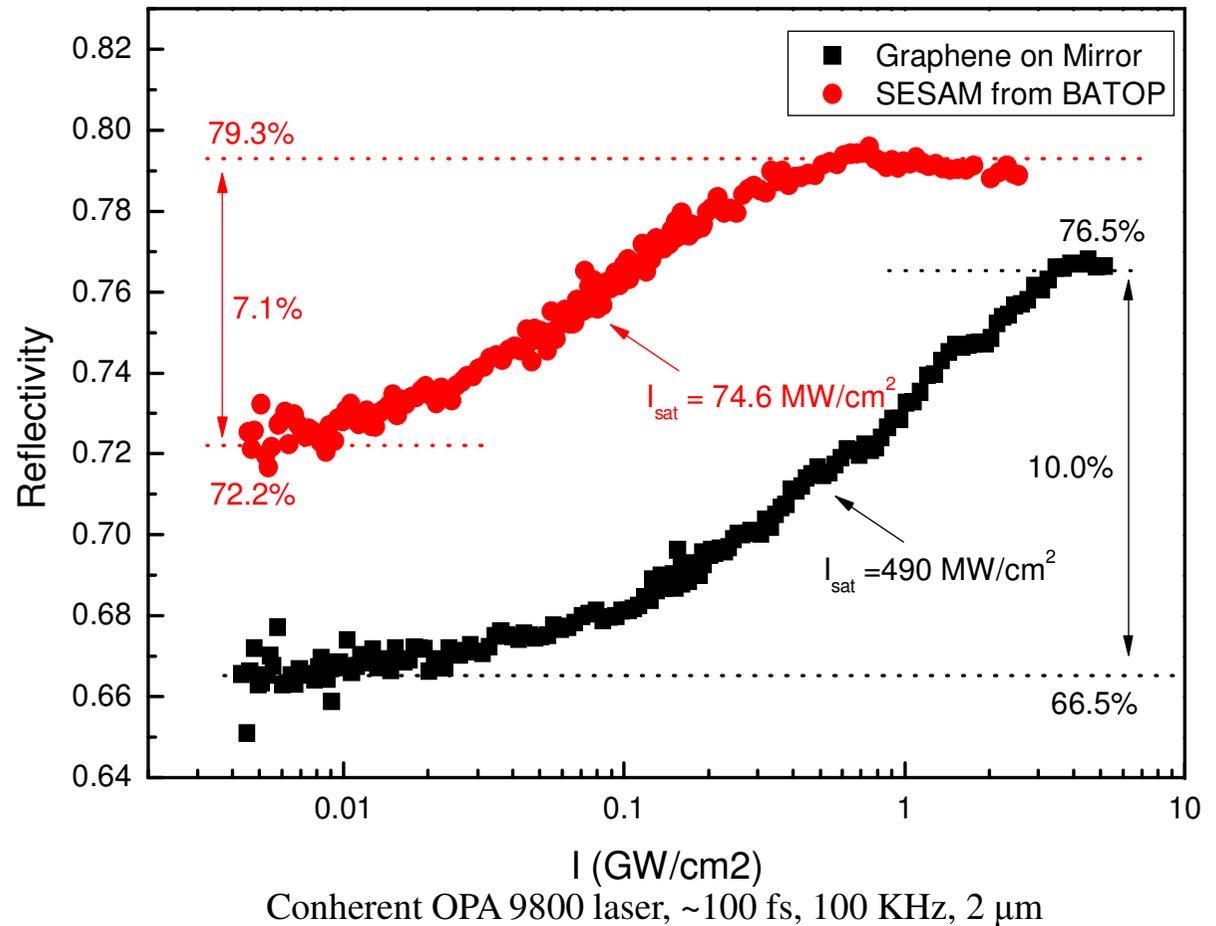
- Very clear saturable absorption of graphene coat Mirror at 2  $\mu\text{m}$
- SESAM from BATOP (SAM-2000-44-10ps-x)



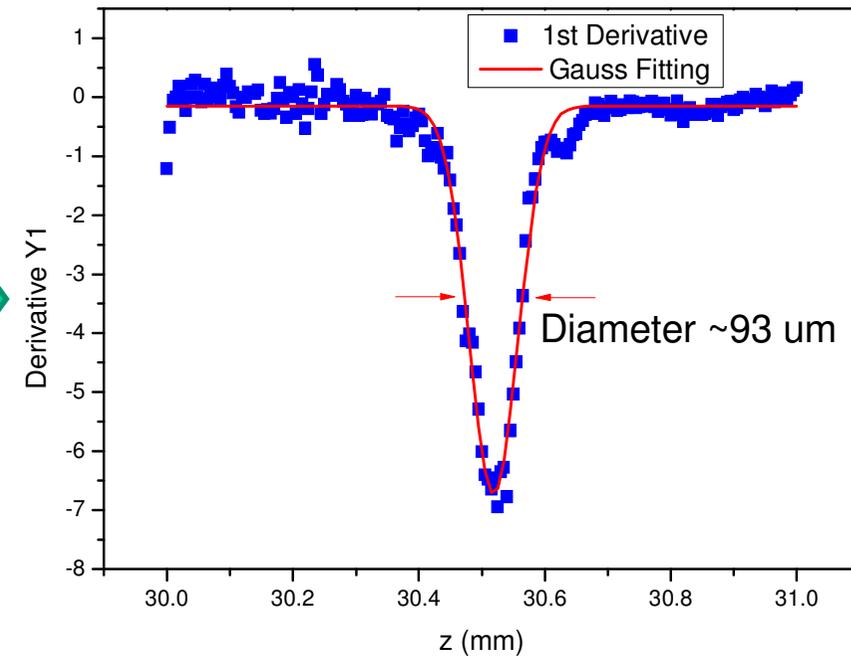
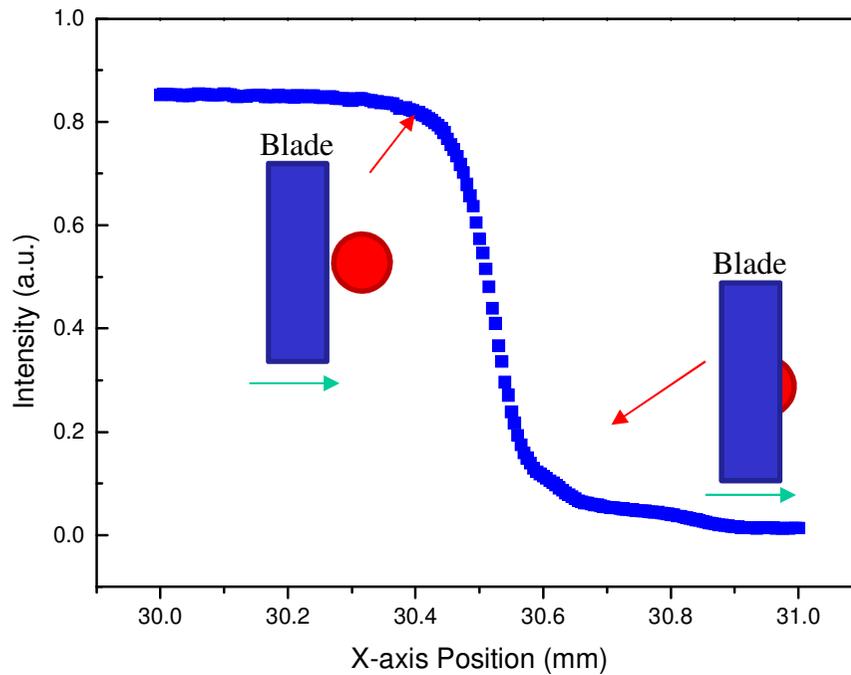
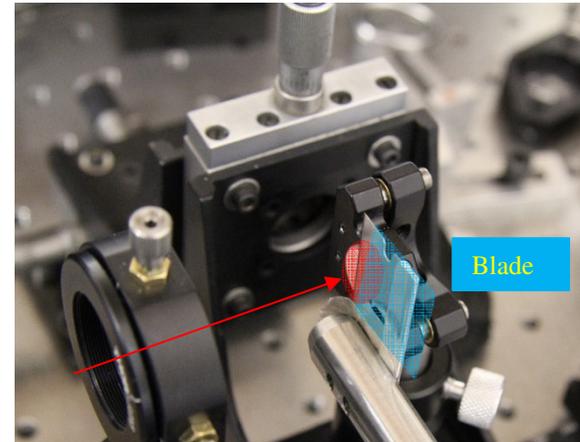
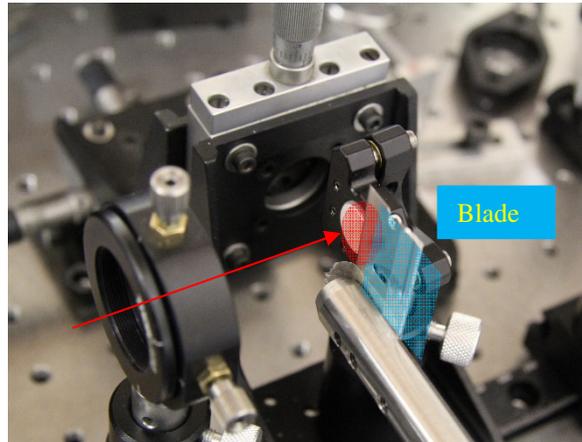
- Graphene Mirror prepared by vacuum filtration



Typical I-scan curves of SESAM and Graphene Mirror at 2  $\mu\text{m}$



# Beam Size Measure for I-scan

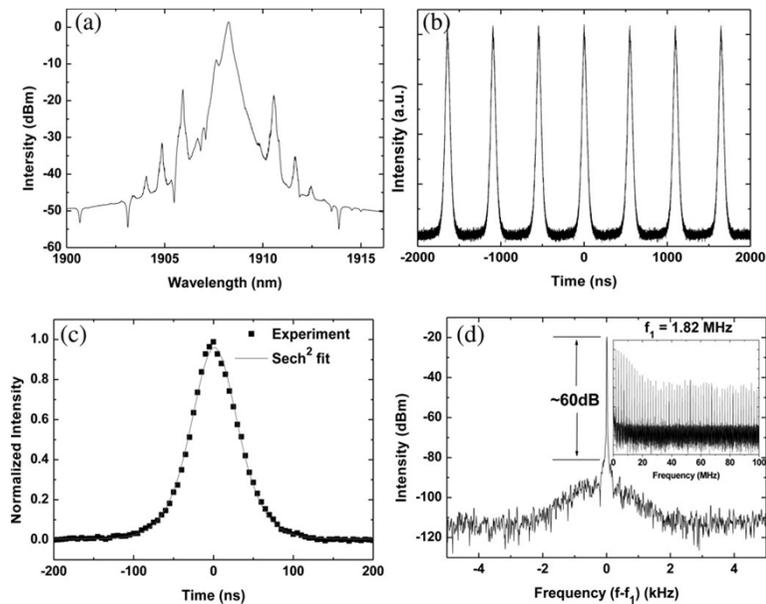


# Graphene Mode-locked Laser Development



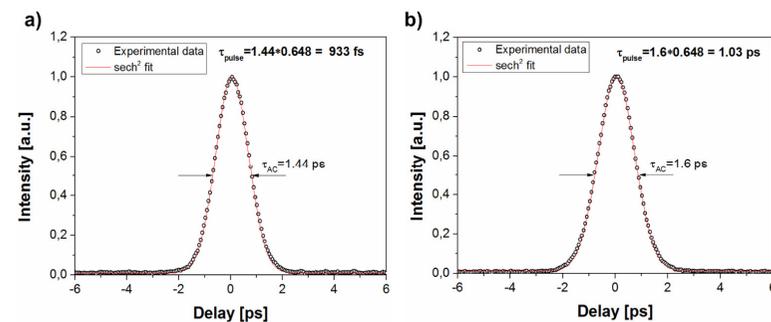
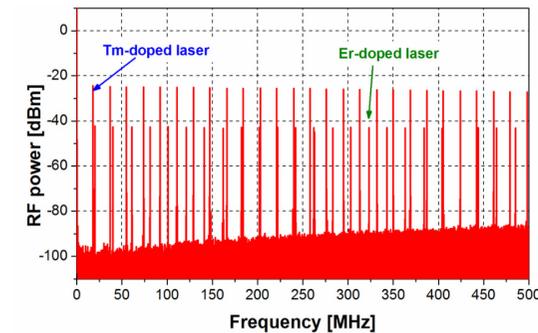
- 2  $\mu\text{m}$  mode-locked lasers were achieved by several groups using graphene absorbers

1. Wavelength: 1908 nm;  
Rep. Rate: 1.82 MHz; Pulse Energy: 16.2 nJ;  
Pulse Duration:  $\sim 65$  ns



Fu, Bo, et al. "Broadband graphene saturable absorber for pulsed fiber lasers at 1, 1.5, and 2  $\mu\text{m}$ ." Selected Topics in Quantum Electronics, IEEE Journal of 20.5 (2014): 411-415.

2. Wavelength: 1944 nm;  
Rep. Rate: 18.43 MHz; Power: 1.3 mW;  
Mode-locked Pulse Duration:  $\sim 1.6$  ps

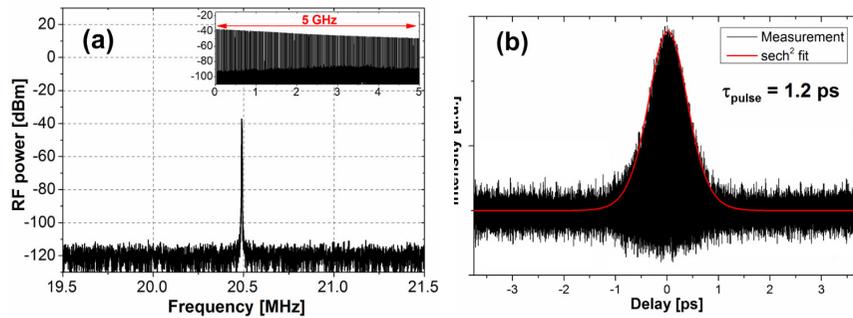
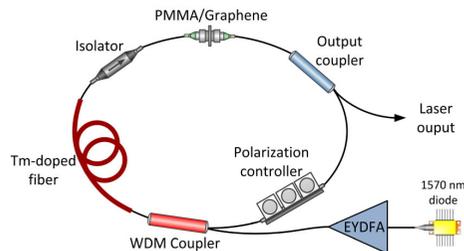


Sotor, Jaroslaw, et al. "Simultaneous mode-locking at 1565 nm and 1944 nm in fiber laser based on common graphene saturable absorber." Optics Express 21.16 (2013): 18994-19002.

# Graphene Mode-locked Fibre Laser Development

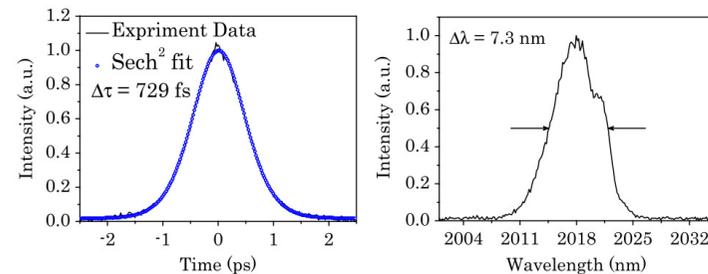
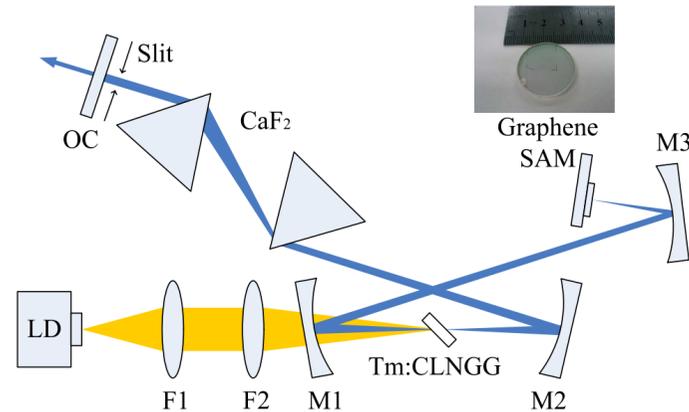


3. Wavelength: 1884 nm;  
Rep. Rate: 20.5 MHz;  
Mode-locked Pulse Duration: 1.2ps



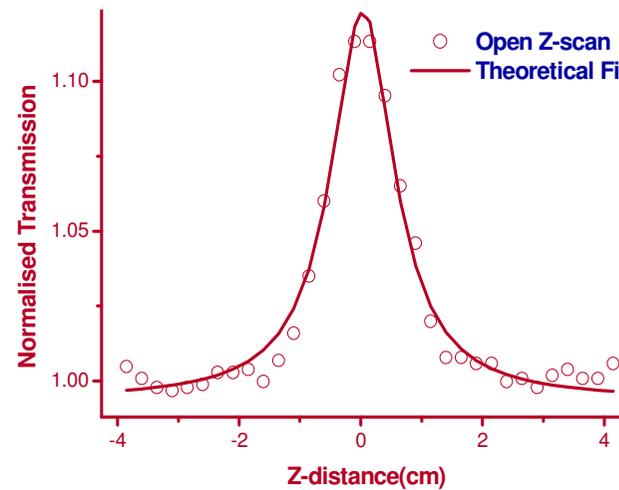
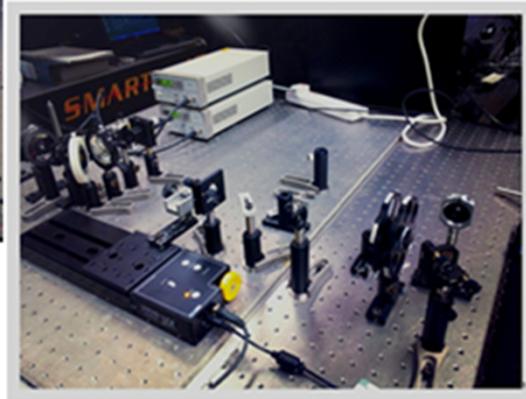
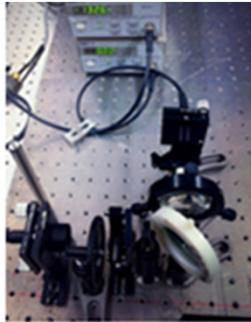
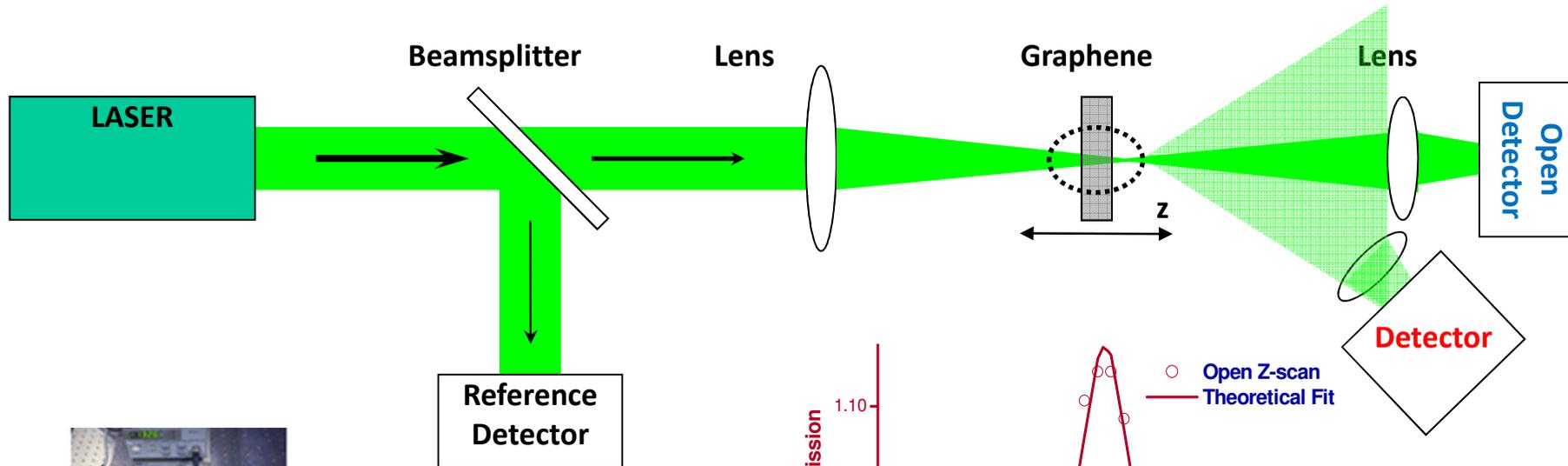
Sobon, Grzegorz, et al. "Thulium-doped all-fiber laser mode-locked by CVD-graphene/PMMA saturable absorber." Optics express 21.10 (2013): 12797-12802.

4. Wavelength: 2018 nm;  
Rep. Rate: 99 MHz; Power: 60.2 mW  
Mode-locked Pulse Duration: 729 fs



Ma, J., et al. "Graphene mode-locked femtosecond laser at 2 μm wavelength." Optics letters 37.11 (2012): 2085-2087.

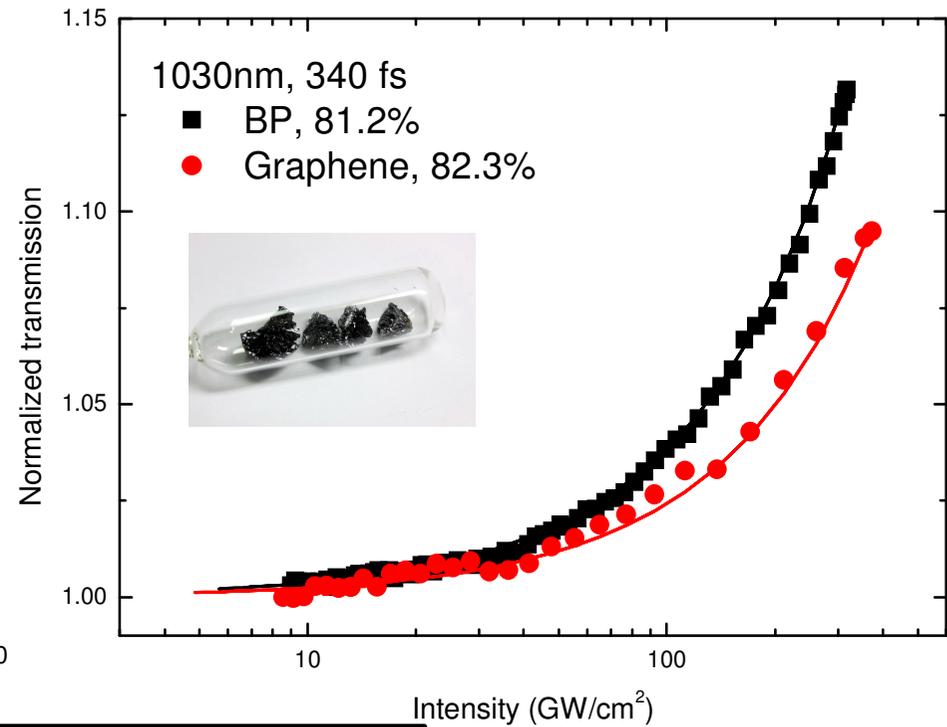
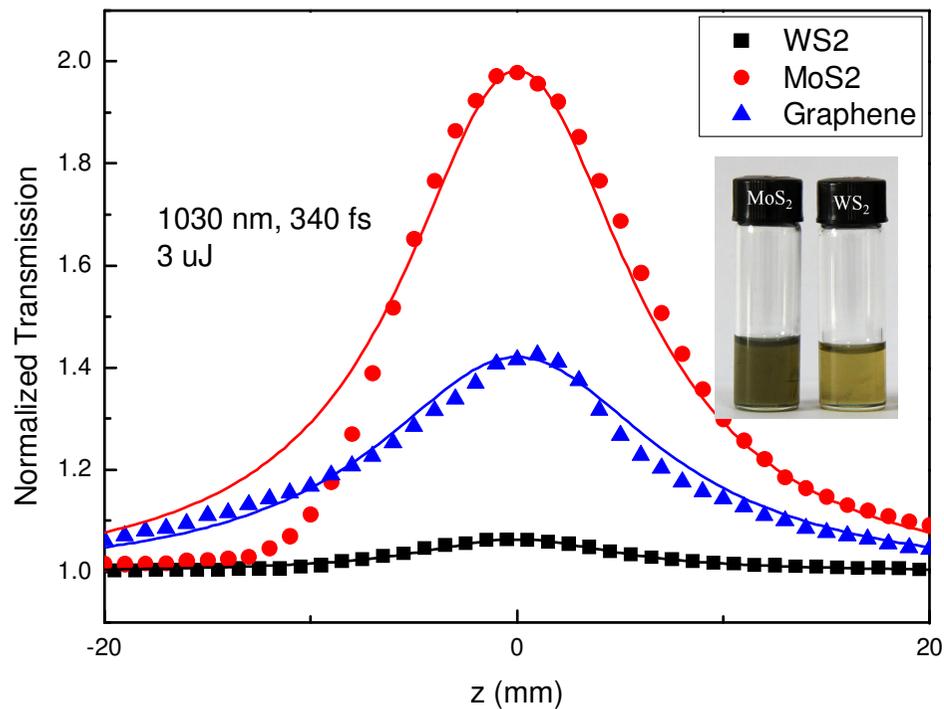
# Rapid Material Characterisation Z-scan



# Other 2D Materials

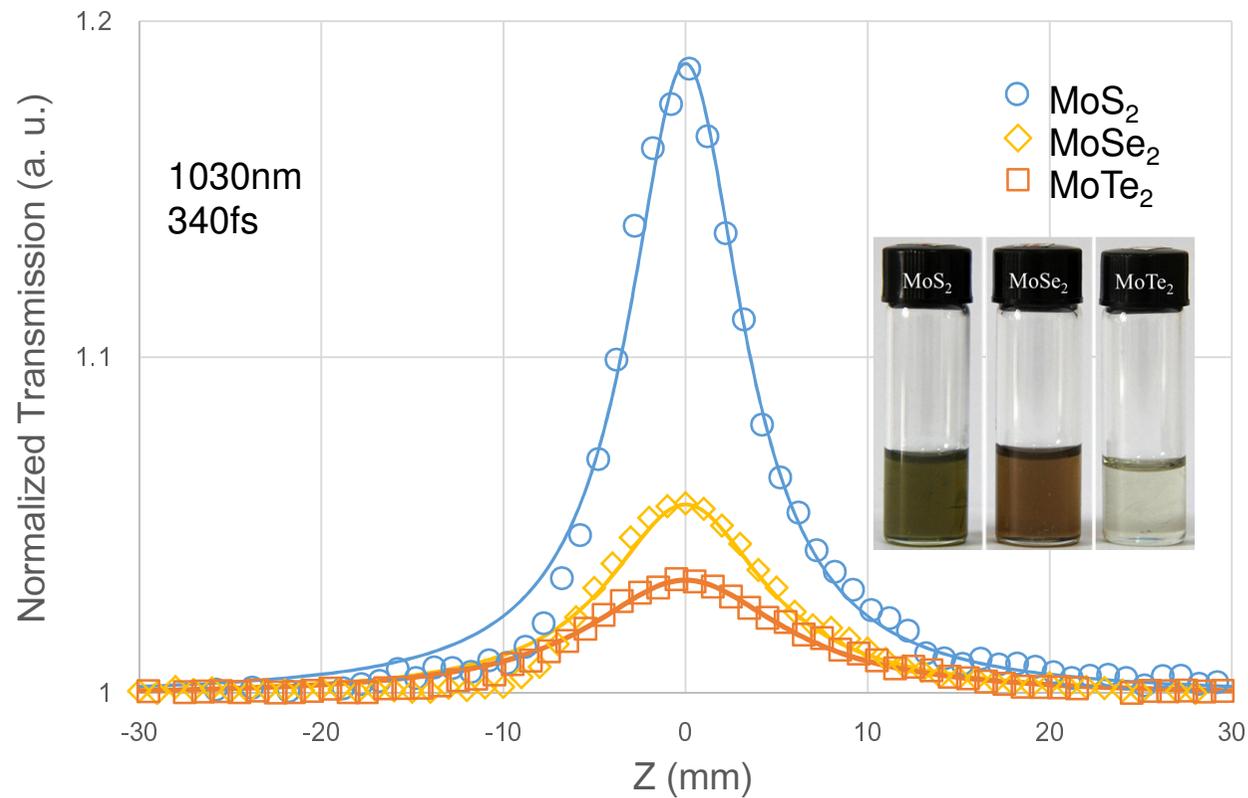


- Other layered materials, such as transition metal dichalcogenides (TMDs) and black phosphorus, also have prominent saturable absorption in infrared region.



Z-scan Result of Several 2D materials

# Other 2D Materials



Z-scan Result of Several 2D materials

# CNT/Graphene Based Saturable Absorber Modelockers at 2 $\mu$ m



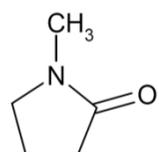
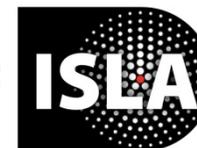
- **WP leaders**

- Prof. Werner Blau
- Dr. Yong Zhang
- Dr. Kanpeng Wang
- Aidan A. Murray
- John J. Magan

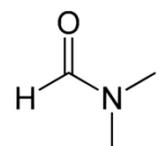
- **Objectives**

- Investigating SWNT/Graphene saturable absorption and potential for mode-locking in 2 $\mu$ m region
- Implementation and testing of mode-locker devices in fibre laser setup

# Graphene - Liquid Phase Exfoliation



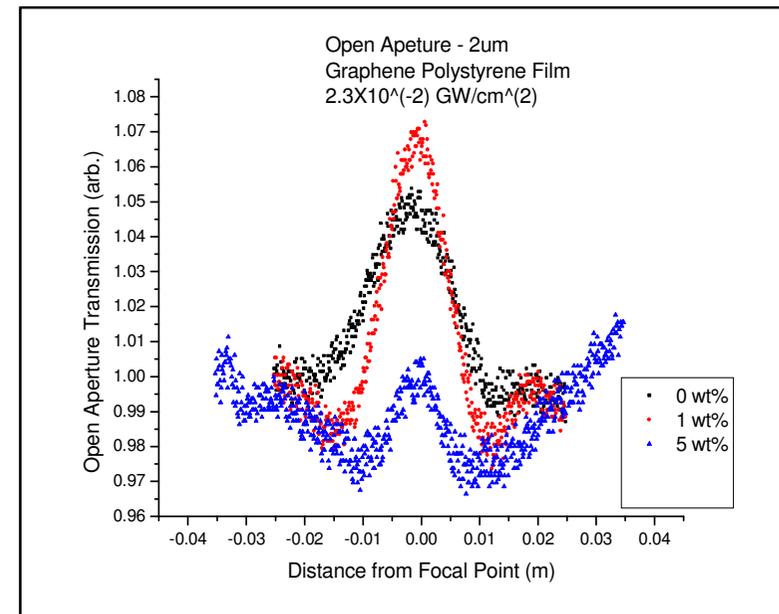
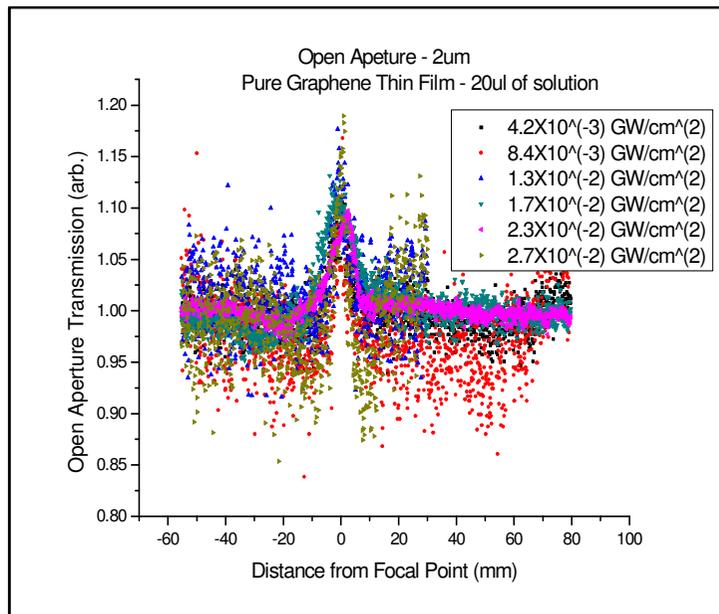
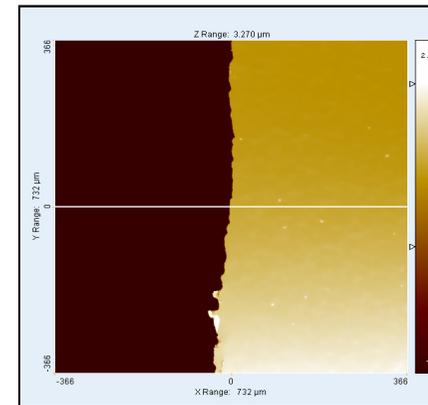
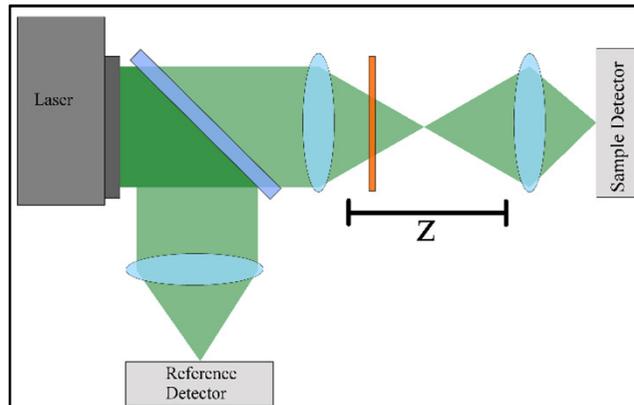
*N*-methyl-2-pyrrolidone (NMP)



*N,N*-dimethylformamide (DMF)



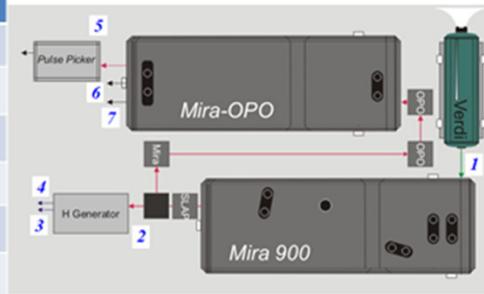
# 2 micron Z-scan - Graphene



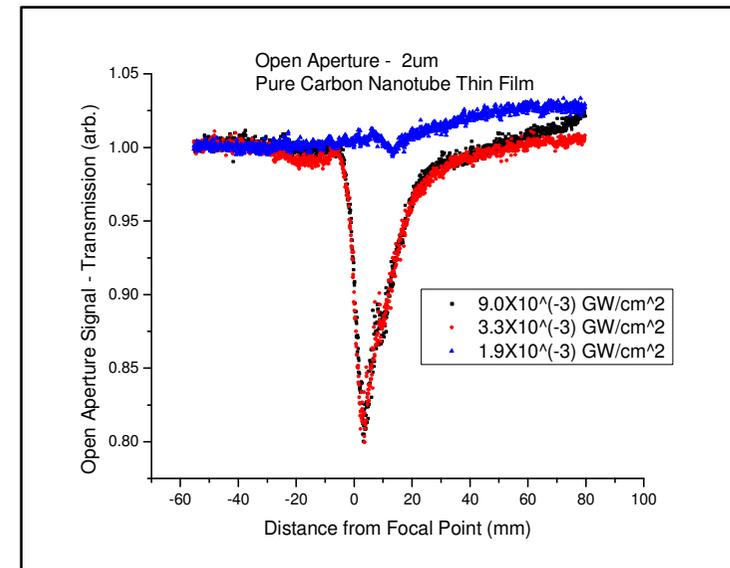
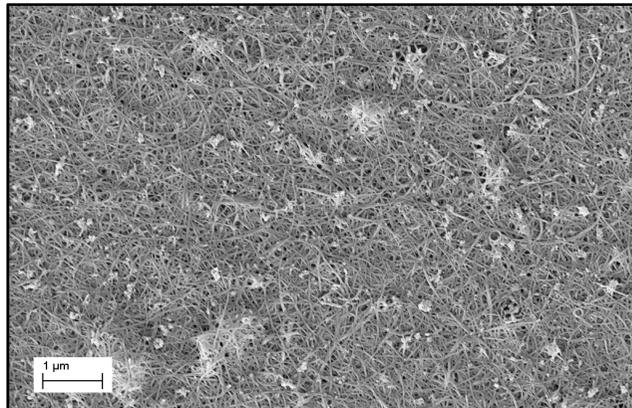
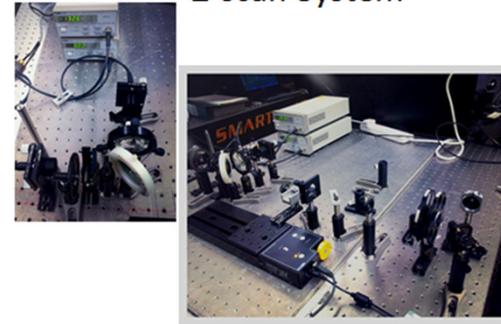
# 2 micron z-scan – Carbon Nanotubes



Specifications	
1	CW 532nm, 10W
2	80MHz, <130fs, 700nm-980nm
3	Pumped 500mW@ 832nm, SHG: 416nm
4	THG: 277nm
5	80MHz, <130fs, 550nm-750nm
6	80 MHz, <130fs, 1050nm-1600nm(Signal)
7	80 MHz, <130fs, 1600nm-2600nm(Idle)



Z-scan System



# Nanocarbon Modelocker

## Graphene Thin Films on Glass



Parameter	Symbol	Unit	Target Values for fiber lasers			Target Values for solid-state lasers			Values Achieved to-date
			min	max	target	min	max	target	
Modulation depth	DR	%	2	20	5	0.5	5	1-2	>5 *
Saturation fluence	Fsat	$\mu\text{J}/\text{cm}^2$			???	1	200	50	3 *
Non-saturable loss	Rns	%	0	???	1-2%	0	1	0.1	neglegible from z-scan
Recovery time	t1/e	ps	-		1	-		10	< 3
Induced absorption parameter	F2	$\text{J}/\text{cm}^2$			???			3000	
Damage fluence	Fd	$\text{mJ}/\text{cm}^2$			10-100			10-100	> 1***
Saturation Parameter	S	--			???	3	10		**

### References:

1. Maas et. al., "High precision optical characterization of semiconductor saturable absorber mirrors", Vol. 16, No. 10, Optics Express 12 May 2008, pp 7571-7579
2. Saraceno et. al., "SESAMs for High-Power Oscillators: Design Guidelines and Damage Thresholds", Vol. 18, NO. 1, IEEE J. OF Sel. Top. Quant. El., Jan/Feb 2012, pp. 29-41

\* measured in transmission by z-scan technique and then calculated for reflection from experimental data, at 2.0 micron with 100 fs pulses

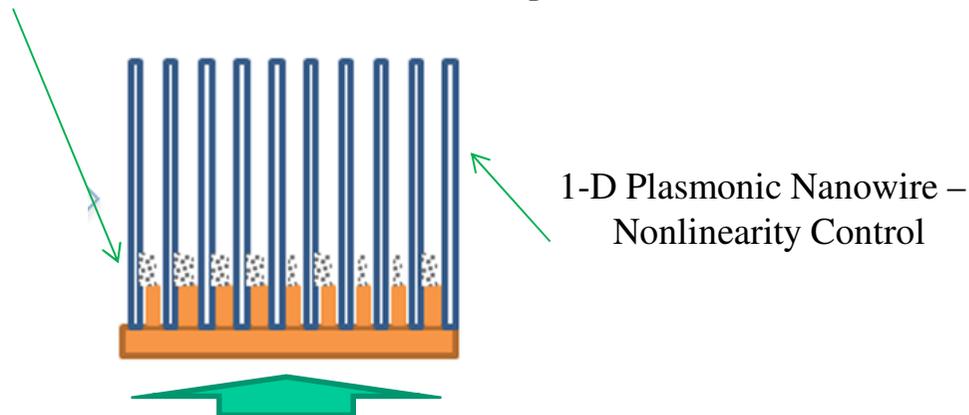
\*\* can only ve determined in actual testbed laser

\*\*\* No visibly observable damage seen, can only be determined quantitatively on testbed laser

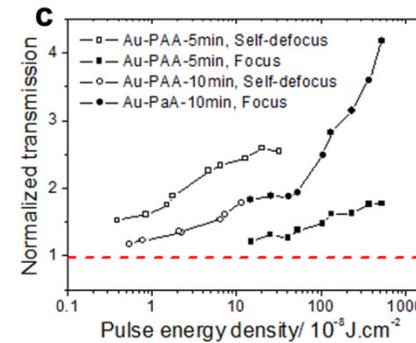
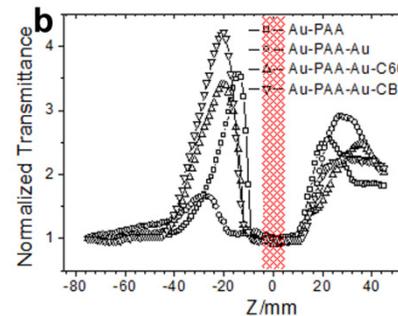
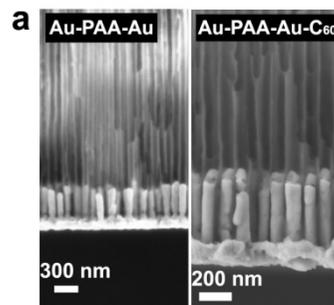
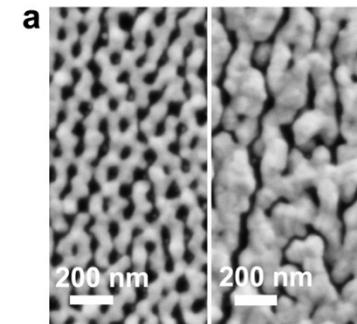
# Controlling Nanocarbon Nonlinearity



Nanocarbon –  
Broadband Ultrafast Nonlinear Response

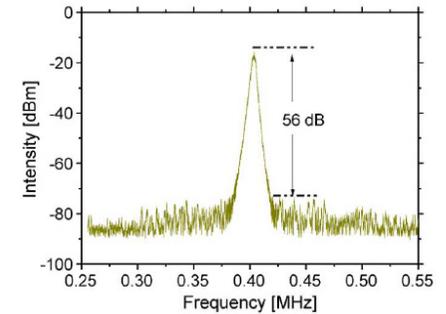
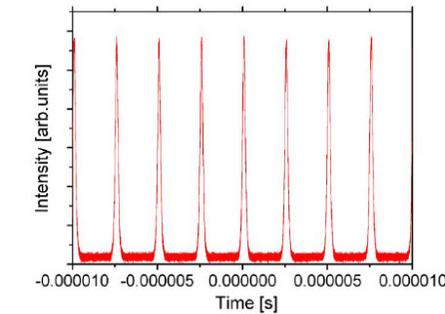
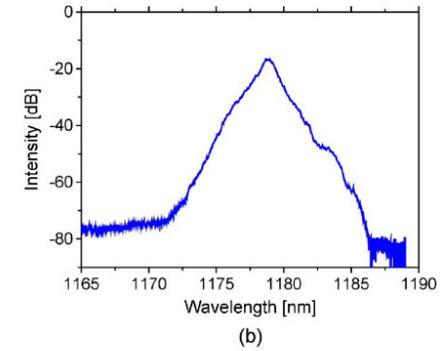
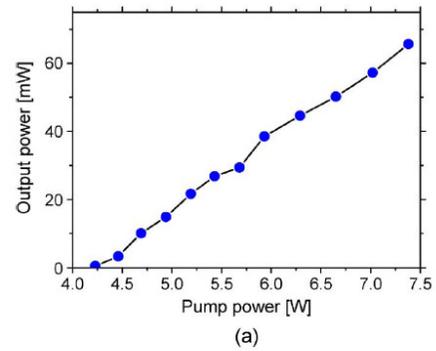
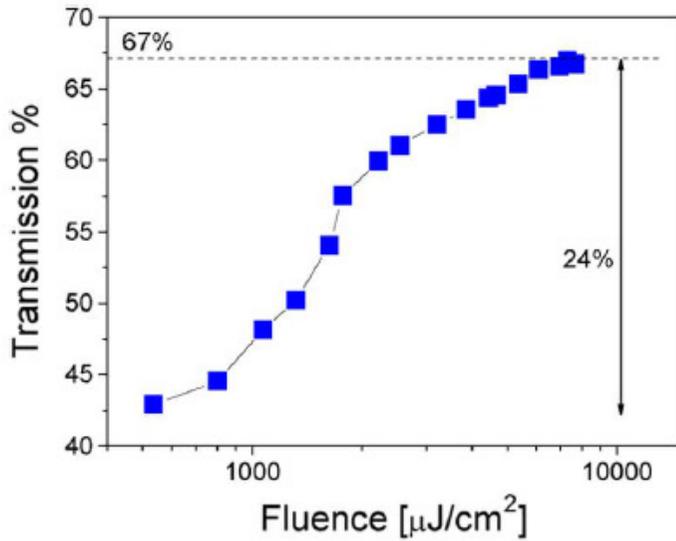
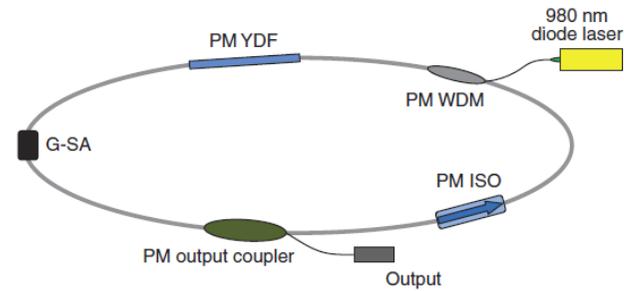
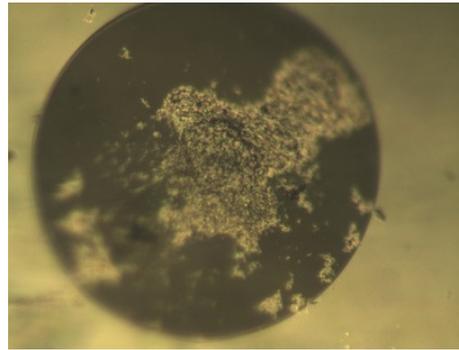
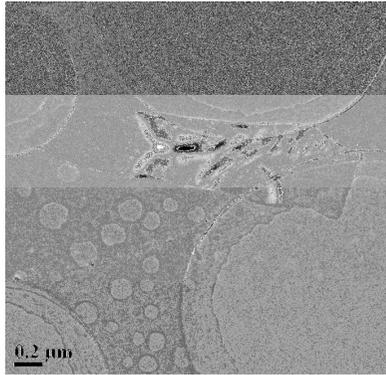


2-D Periodic Structure – Wavelength Control



Y Zhang,, JJ Wand & W Blau Nature Photonics 2013 under review

# Graphene – Mode-locked 1053 nm Fibre Laser



# Graphene – Saturable Absorption

