Integration of 2-Dimensional Materials in Fiber Optics for Ultra-Short Pulse Lasers

Presented by:

OSA Fiber Modeling and Fabrication Technical Group

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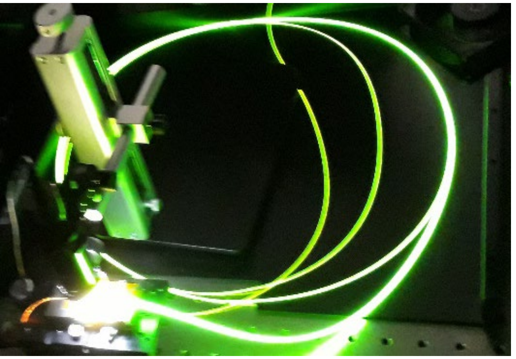
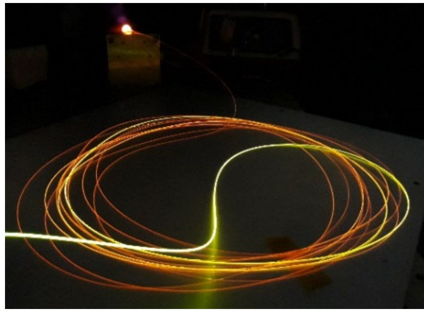
Welcomes You for the webinar on

"Integration of 2-Dimensional Materials in Fiber Optics for Ultra-Short Pulse Lasers"



March *13 2020, 8 pm*



OSA Fiber Modeling and Fabrication Technical Group

About us: A unique group of more than 900 researchers from 70+ countries from North America, South America, Europe, Asia, Africa, and Oceania.

Goals:

To benefit **OSA members** having interest in Fiber Design, Modeling, Fabrication, and Applications of fibers.

To Provide a platform to Fiber Community for connecting, Engaging and Exciting with others.

To Organize Webinars, Technical and Networking Events, and Special Journal Issues.

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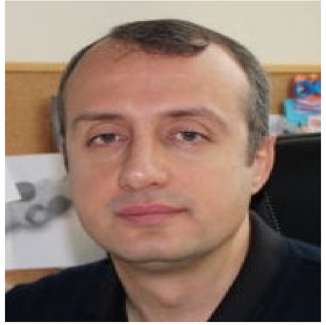

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Fiber Modeling and Fabrication Technical Group

Past Events:

1. Networking Event: Date: Tuesday, 16 Jul 2019 17:00-18:00
Location: Naupaka III, Waikoloa Beach Marriott Resort & Spa, Waikoloa Beach, Hawaii

2. Webinar 1: Everything you always wanted to know about supercontinuum modelling in optical fibers (but were afraid to ask) Date: 26th August 2019, at Swiss time 2pm/ EDT 8am
A/Prof. Alexander Heidt, University of Bern, Switzerland.

3. Webinar 2: The development of thulium and holmium fiber sources
Date: 30th September, 2019 at 1pm (UK time)/ EDT 7am
Dr. Nikita Simakov, DSTO, Australia.

4. Webinar 3: Recent development in hollow-core optical fiber
Date: 14 November, 2019, 8 am Beijing Time
A/Prof. Y Wang, Beijing University of Technology, China.

Many More to come shortly !!!!

OSA Fiber Modeling and Fabrication Technical Group

Current/Future Webinars:

Webinar 1: Integration of 2-dimensional materials in fiber optics for ultra-short pulse lasers
Date: 13th March 2020, 8 pm EDT.
Prof. Kyunghwan Oh, Yonsei University, South Korea.

Webinar 2: Novel Optical Materials for optical Fibers
Date: 24th April 2020, 11 am EDT.
Prof. John Ballato, Clemson University, USA.

Webinar 3: Mid-Infrared Supercontinuum Generation in Optical Fibers
Date: 20 May 2020, 10 am EDT.
Dr. Christian Petersen, Technical University of Denmark, Fotonik.

Events at CLEO San Jose, CLEO Pacific-Rim, and FIO USA !!!!

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Fiber Modeling and Fabrication Technical Group

If you are OSA member: Log-in to your OSA Account and chose FF group in Technical Groups Category.

You can join the Facebook Group even if you are not member of OSA:
https://www.facebook.com/groups/OSAfibermodelingandfabrication/

You can contact me if you are interested in giving a Webinar/Talk/Panel Discussion, on **deepakjain9060@gmail.com**

Today's Webinar

Fiber Modeling and Fabrication Technical Group

Integration of 2-Dimensional Materials in Fiber Optics for Ultra-Short Pulse Lasers

Prof. Kyunghwan Oh, Yonsei University, South Korea

Speaker's Short Bio: Kyunghwan Oh is a professor in the Department of Physics at Yonsei University, Seoul, Korea. He is also a director of High-Efficiency Laser Research Laboratory and Photonics Device Physics Laboratory. Prof. Oh has earned his MS in Engineering in 1991 and Ph. D. in Optics in 1994 from Brown University, Providence, RI, USA. Prof. Oh's research has been focused on fiber optics, optical materials, and lasers. He has been affiliated with world-leading photonics research institutes such as Lucent Bell Labs, Murray Hill in the USA, Leibniz Institute for Photonic Technology in Germany, Optoelectronics Research Centre in the University of Southampton UK, EPFL in Switzerland, The University of Tokyo in Japan, to name a few. He has authored and co-authored more than 300 SCI journal papers, 7 US patents, 1 book "Silica Optical Fiber Technology, Wiley" and 5 book chapters. He is a Fellow of The Optical Society of America (OSA), and has been serving the photonics community as a Topical Editor of Optics Letters, Associate Editor of IEEE Photonics Technology Letters, Associate Editor of Optical Fiber Technology-Elsevier, International Advisory Board Member of Optics Communications-Elsevier, and Editor in Chief, Journal of The Optical Society of Korea.

연세대학교 YONSEI UNIVERSITY

Photonic Device Physics Laboratory

OSA Webminar
Integration of 2-Dimensional Materials in Fiber Optics for Ultra-Short Pulse Lasers

Kyunghwan Oh

Reza Khazaeinezhad*, Sahar Hosseinzadeh Kassani**, Seongjin Hong***

Photonic Device Physics Laboratory,

Institute of Physics and Applied Physics, Yonsei University

*Beckman Laser Institute, **Alcon,

* * * Korean Institute of Science and Technology

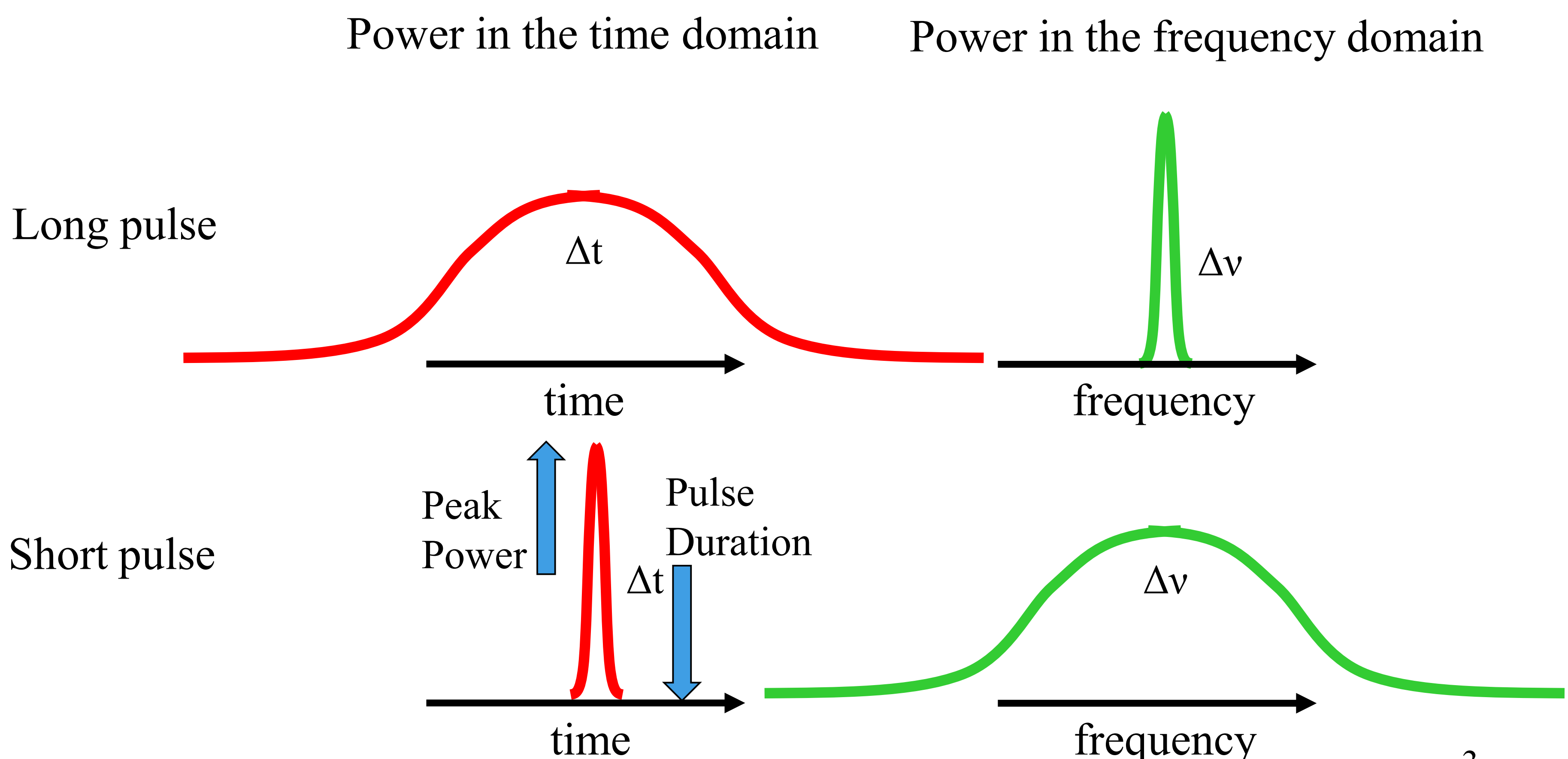
Contents

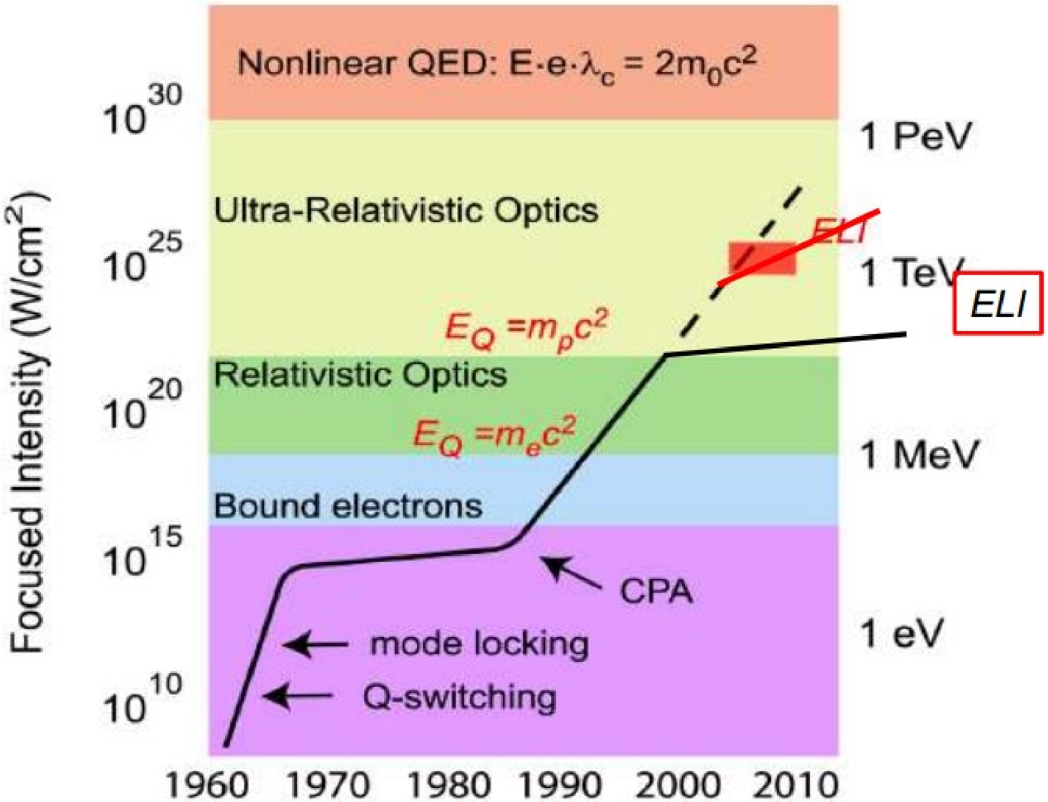
- Laser mode locking using a saturable absorber
- 2D material review
- 2D material as a saturable absorber
- Integration of 2D material in fiber optics
- Examples
- Question and answers

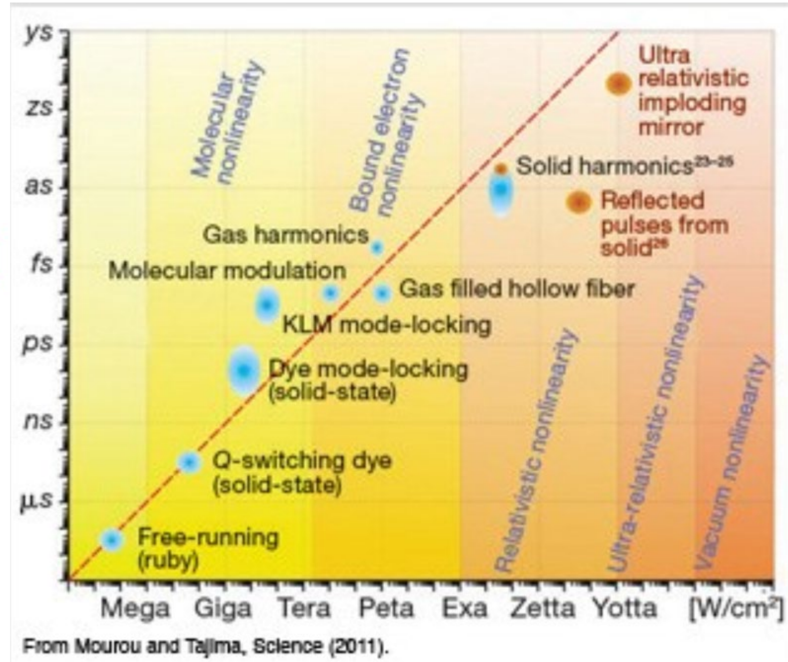
CW versus Pulsed Laser

- By the uncertainty principle

$$\Delta E \cdot \Delta t \sim \hbar \qquad E = h\nu$$



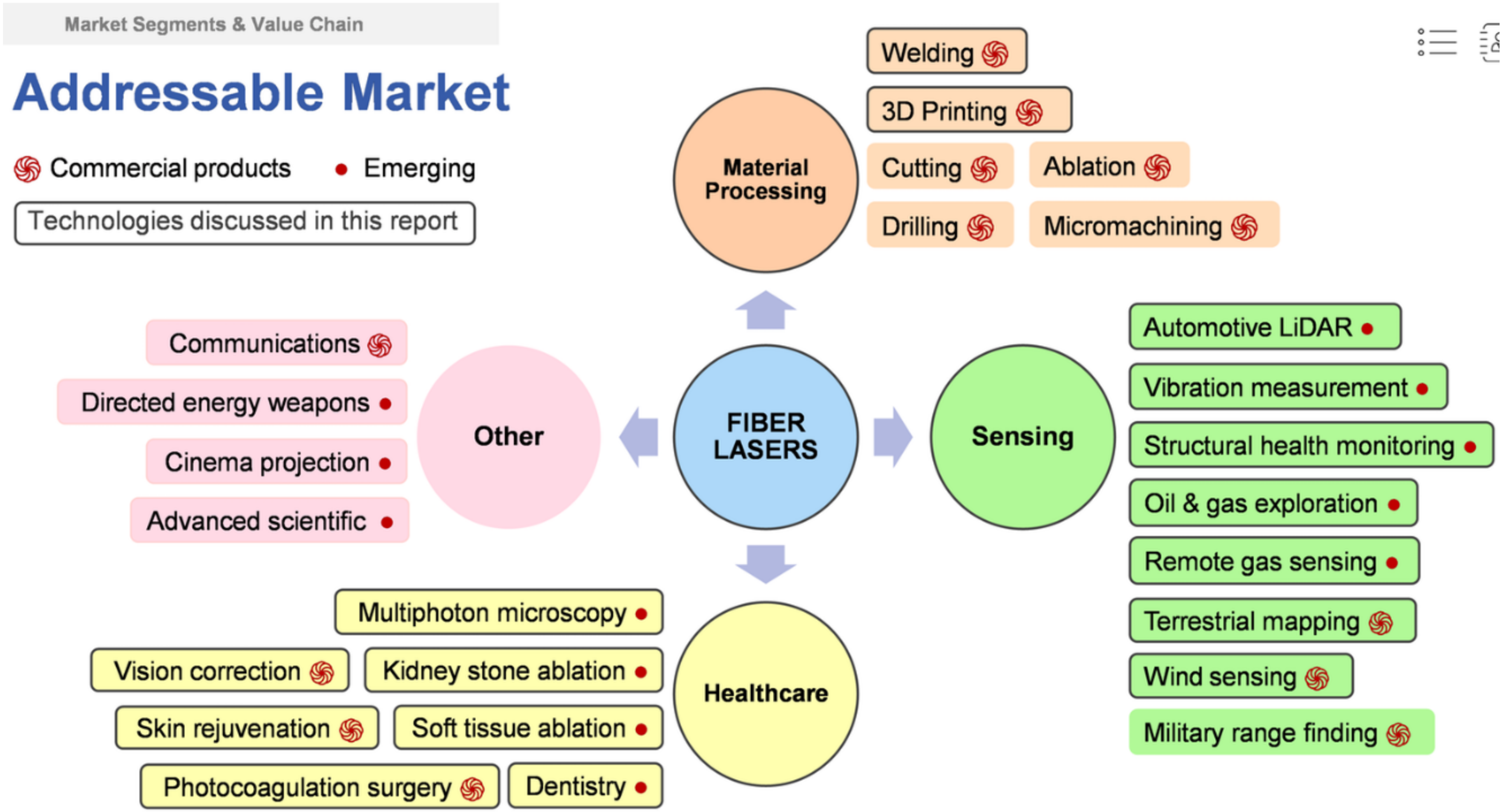




G. Mourou *et al.* Rev. Mod. Phys . **78**, p. 309 (2006)

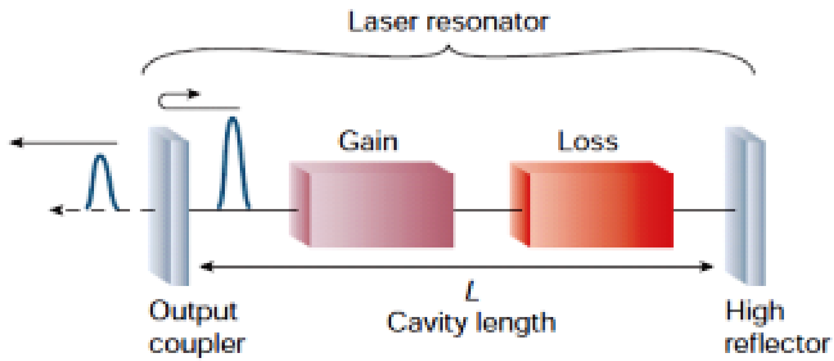
ELI(Extreme Light Infrastructure)
https://www.eli-beams.eu/
CPA(Chirped Pulse Amplification)

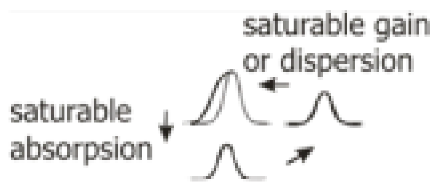
Various techniques are being developed but, the fundamental platform is "mode-locking" that enables pico~femtosecond pulse generation.

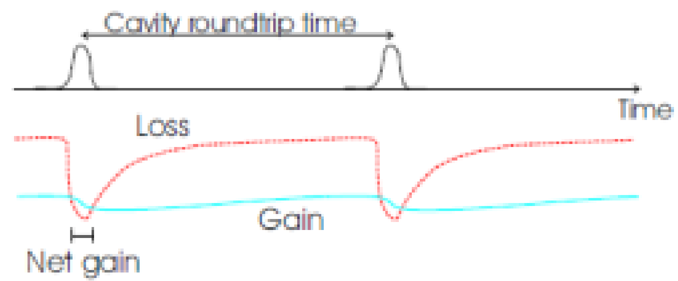


IDTechEx Fiber Lasers 2018-2028: Technologies, Opportunities, Markets & Forecasts

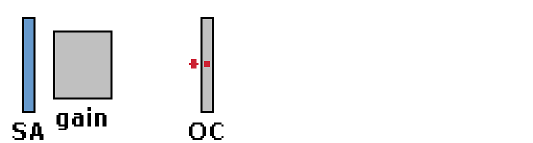
Fiber laser pulse generation? Mostly by Q-switching and Mode-locking





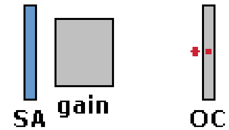


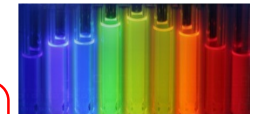
https://www.fotonik.dtu.dk/english/research/nanophotonics/nanodev/research/lasers/mode-locked-lasers



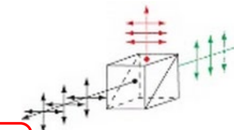
https://www.rp-photonics.com/mode_locking.html

Saturable Absorbers

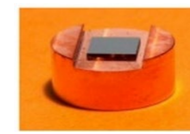




- Dye SA
  - -Short lifetimes
  - -High toxicity and complicated handling procedures



- Nonlinear Polarization Evolution (NPE)
  - -Highly sensitive to environmental fluctuations

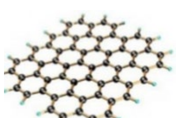


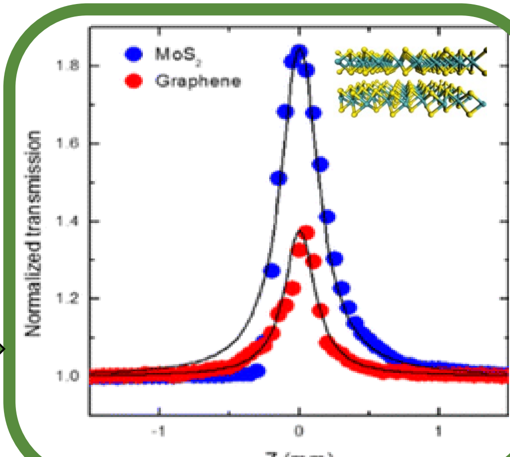
- Semiconductor Saturable Absorber Mirrors (SESAMs)
  - -Complex and elaborative fabrication process
  - -Narrow bandwidths operation

- Carbon Nanotubes (CNTs)
  - -Band-gaps depend on their diameter and chirality
  - -Colloidal suspension in toxic solvent
  - -Polymer composites for homogeneous dispersion

OSA/IEEE JLT, **22**, 51–56 9267 (2013)

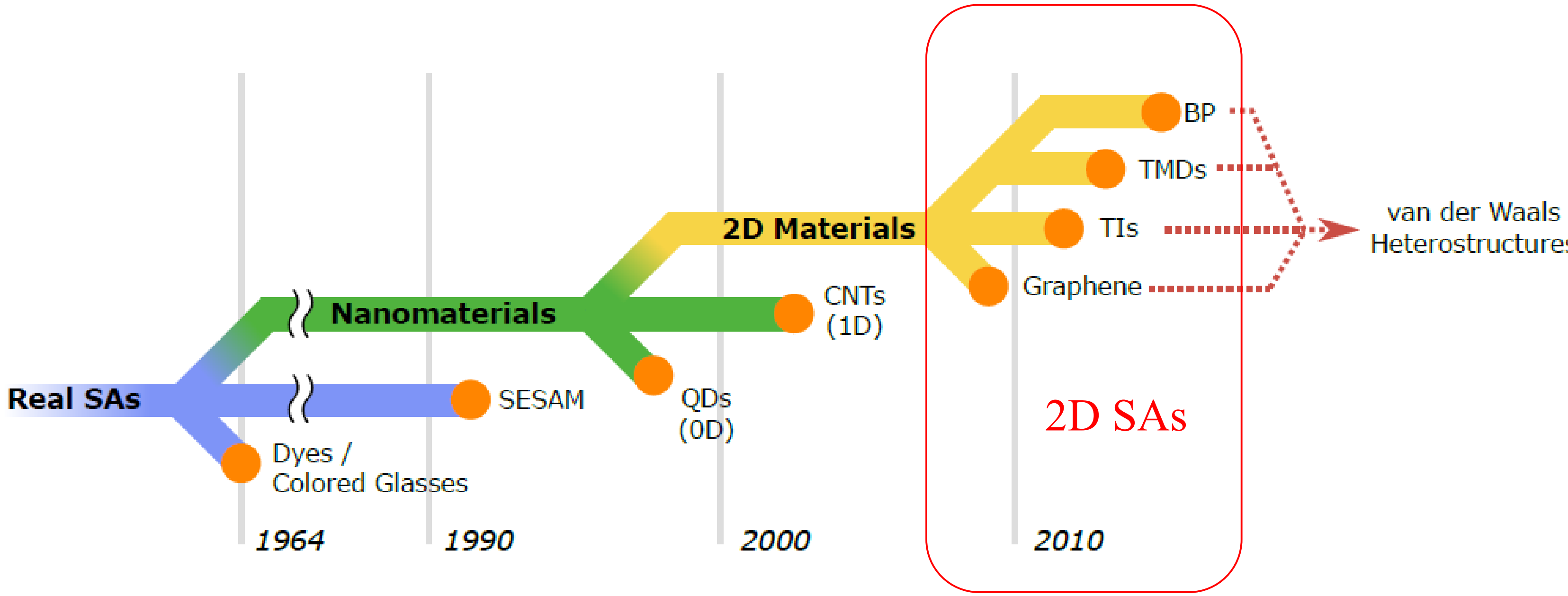
- Graphene
  - $-MoS_2$ demonstrated stronger nonlinear optical response than graphene.





ACS Nano, **7**, 9260–9267 (2013)

Fast two decades in nonlinear optics with Nano, 2D material



semiconductor saturable absorber mirror (SESAM)
quantum dots (QDs), carbon nanotubes (CNTs),
topological insulators (TIs), transition metal dichalcogenides (TMDs)
black phosphorous (BP)

R. I. Woodward et al., Appl. Sci. 2015, 5, 1440-1456

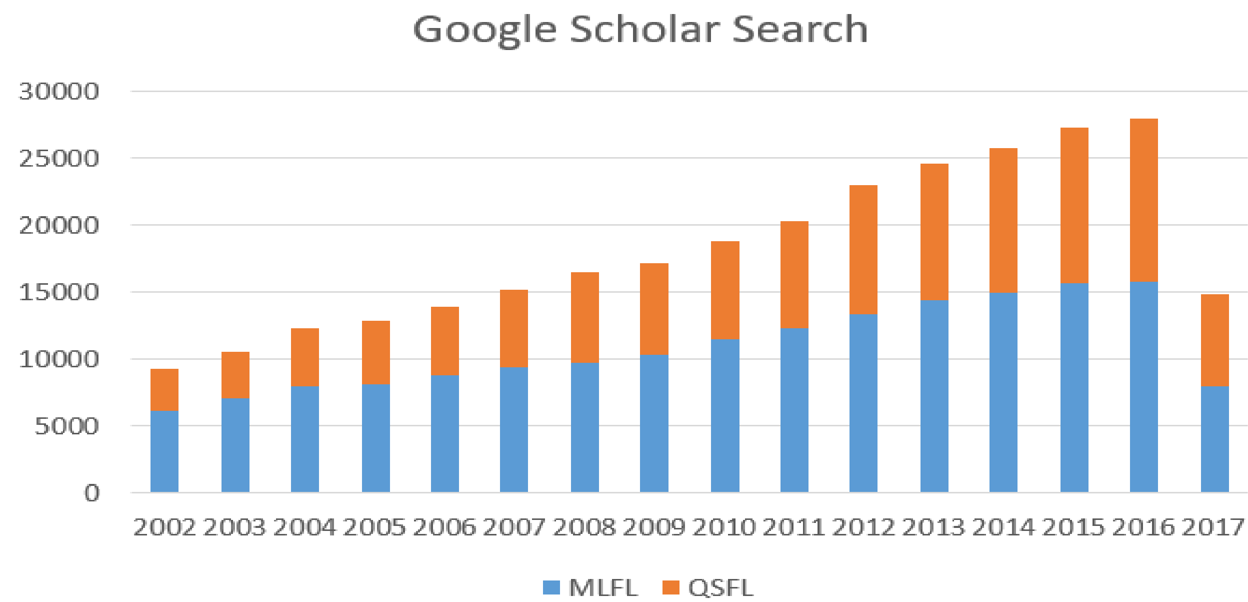
Annual research trends (2002~2016)

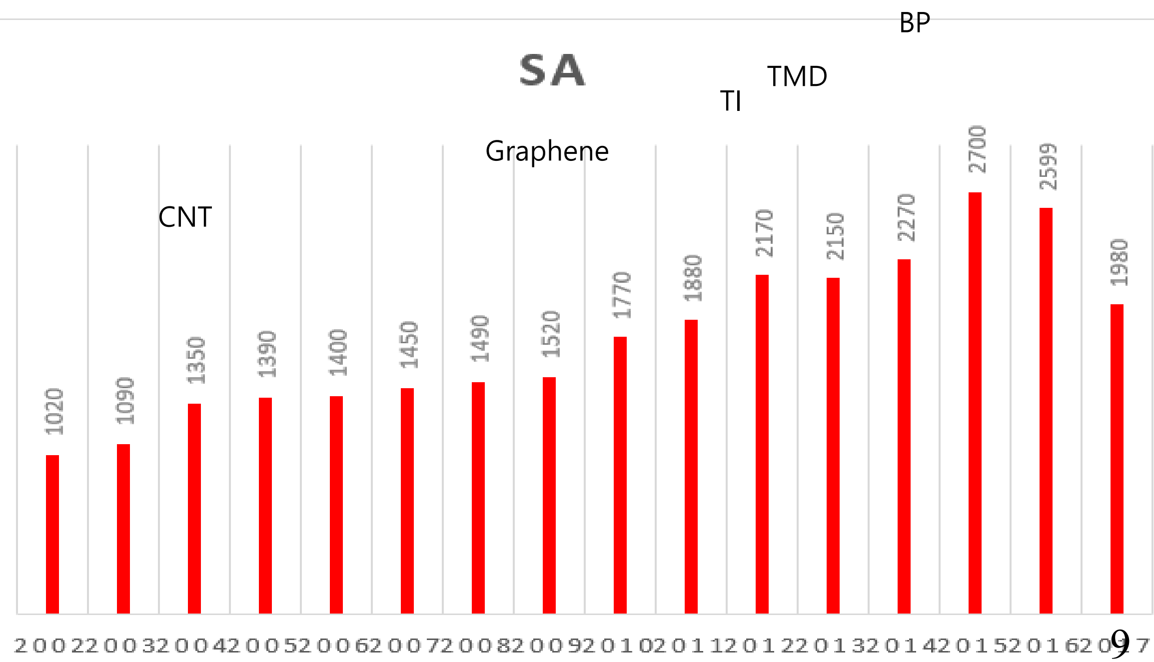
Mode Locke Fiber Laser (M.L.F.L.)
~6,000->~16,000
Q-Switched Fiber Laser (Q.S.F.L)
~2,500->11,000
Saturable Absorber
~1,000->~2,600

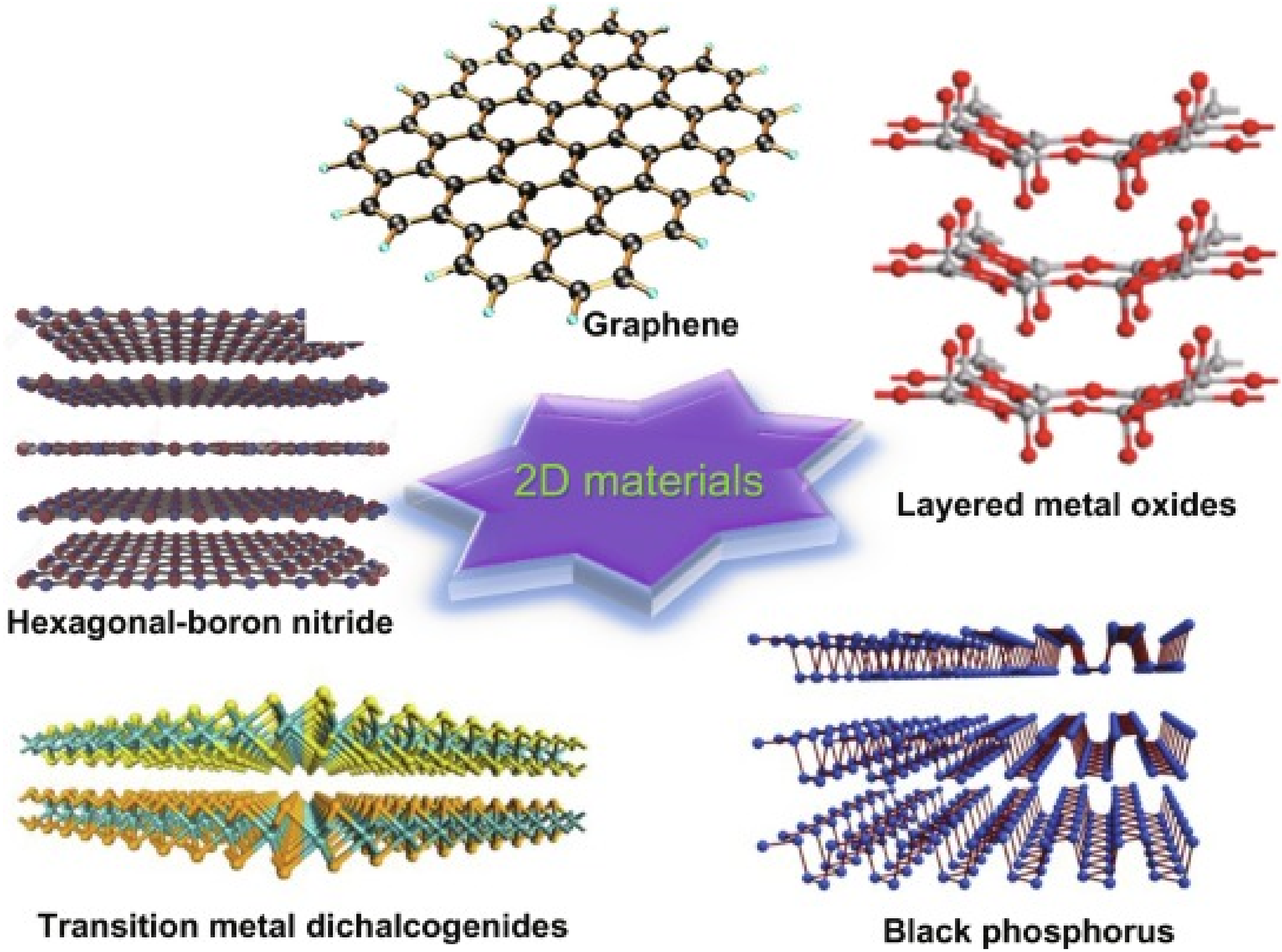
Drivers:

- CNT
- Graphene
- TI
- TMO
- BP

Appl. Sci. 2015, 5, 1440-1456

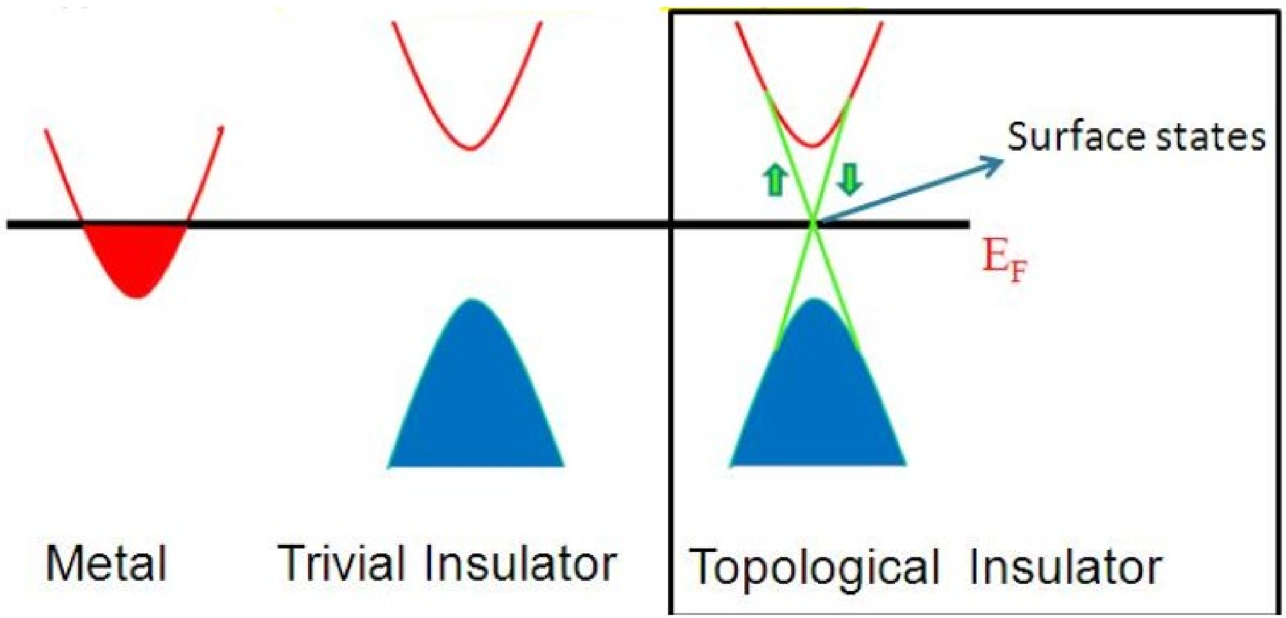






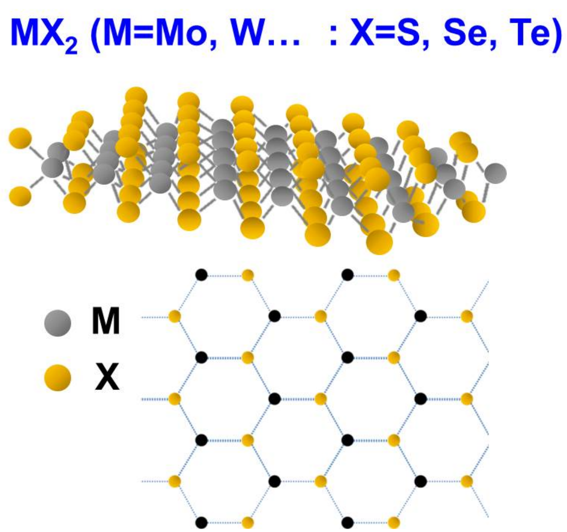
Biomedical Applications of Graphene and 2D Nanomaterials
Micro and Nano Technologies, 165-186 (2019)

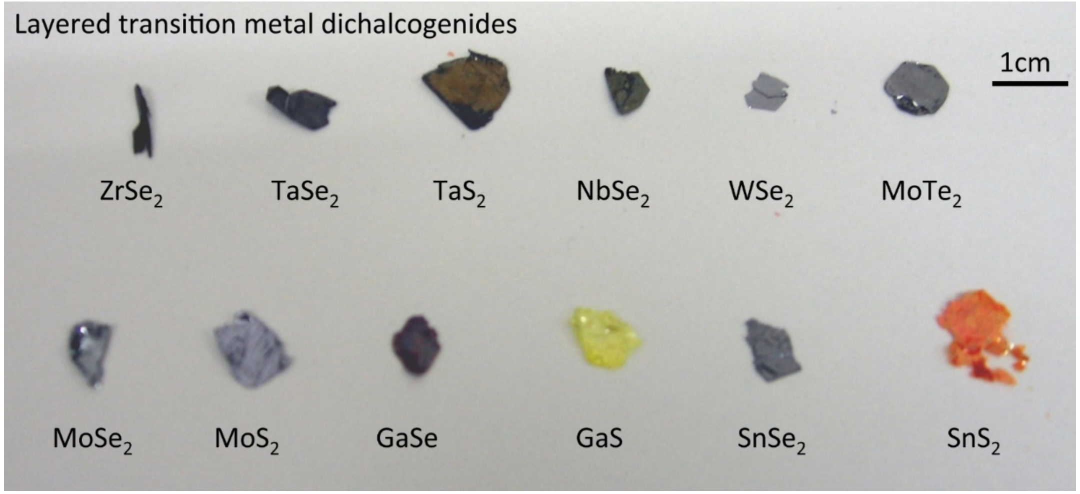
Topological Insulators



Reviews of Modern Physics, Volume 88, Issue 2, id.021004, 2016,

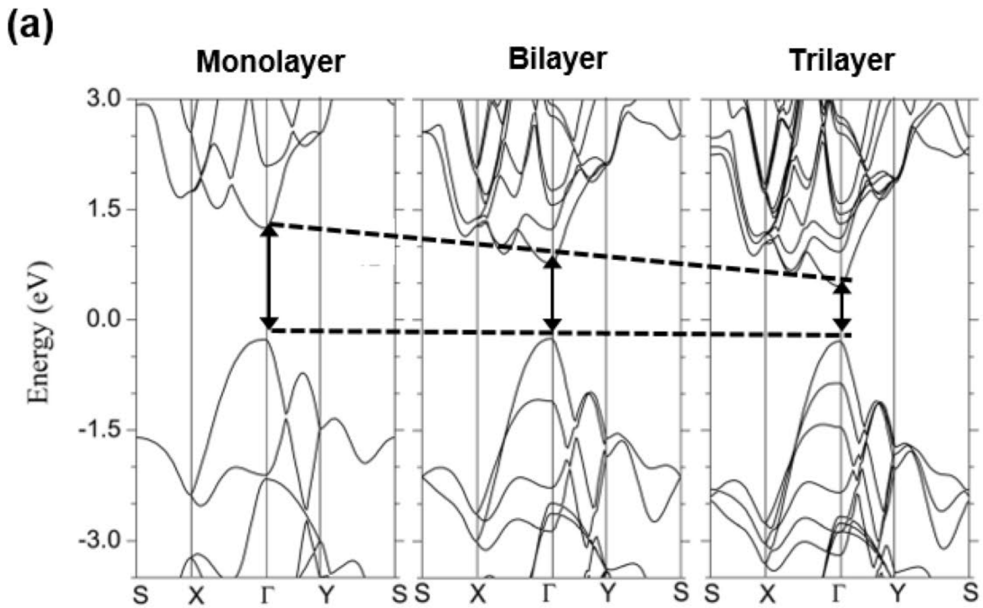
Transition Metal Dichalcogenides

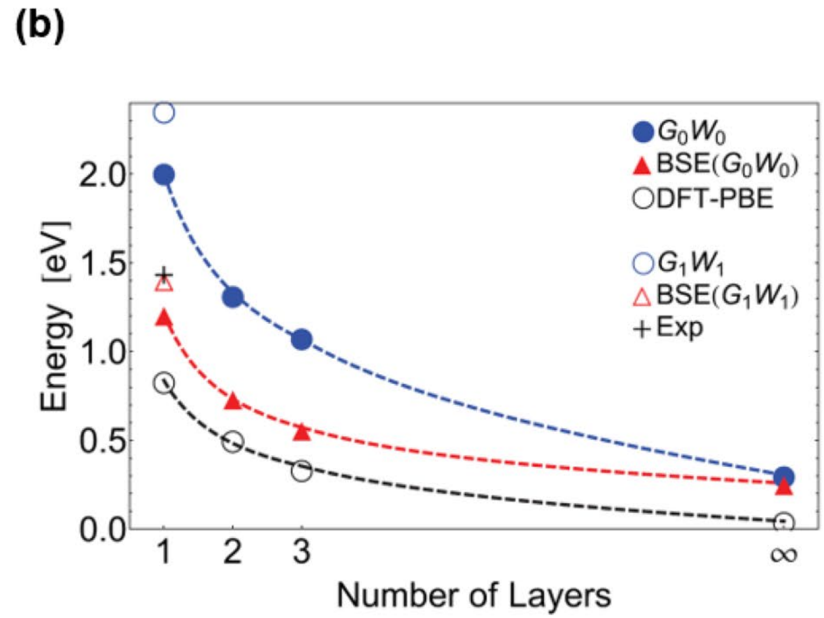


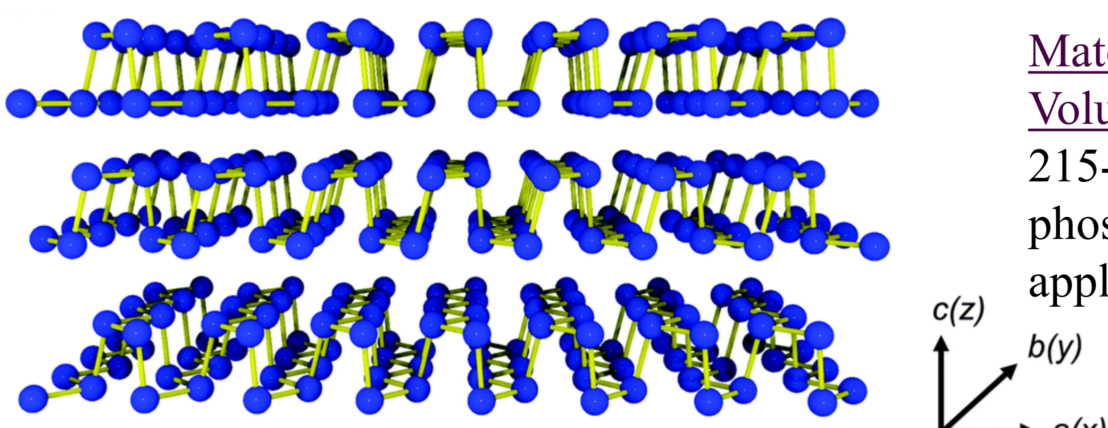


Nature Reviews Materials **2**, Article number: 17033 (2017)
doi:10.1038/natrevmats.2017.33, 2D transition metal dichalcogenides
Sajedeh Manzeli, Dmitry Ovchinnikov, Diego Pasquier, Oleg V. Yazyev & Andras Kis

Black Phosphorous







Materials Chemistry and Physics Volume 189, 1 March 2017, Pages 215-229, Recent advance in black phosphorus: Properties and applications

Carbon Based Nano material SA

	Graphene					Carbon nanotube				
	Wavelength					Wavelength				
Mode-locking	0.8 µm	1 µm	1.5 µm	2 µm	2.5 µm	0.8 µm	1 µm	1.5 µm	2 µm	2.5 µm
	63 fs (480 mW) [28]	160 fs (16 mW) [29]	91 fs (107 mW) [30]	410 fs (270 mW) [31]	226 fs (80 mW) [32]	62 fs (600 mW) [33]	100 fs (230 mW) [34]	92 fs [35]	175 fs (35 mW) [36]	NA
	Wavelength									
Q-switching	0.8 µm	1 µm	1.5 µm	2µm	2.5 µm			NA		
	NA	56.2 ns (595.8 nJ) [37]	NA	1 µs, (1.74 µJ) [38]	NA					

H. Yu et al., Laser Photonics Rev. **7,** No. 6, L77–L83 (2013)
Carbon-nanotube-based passively Q-switched fiber laser for high energy pulse generation, Optics & Laser Technology, 45, 713-716 (2013)

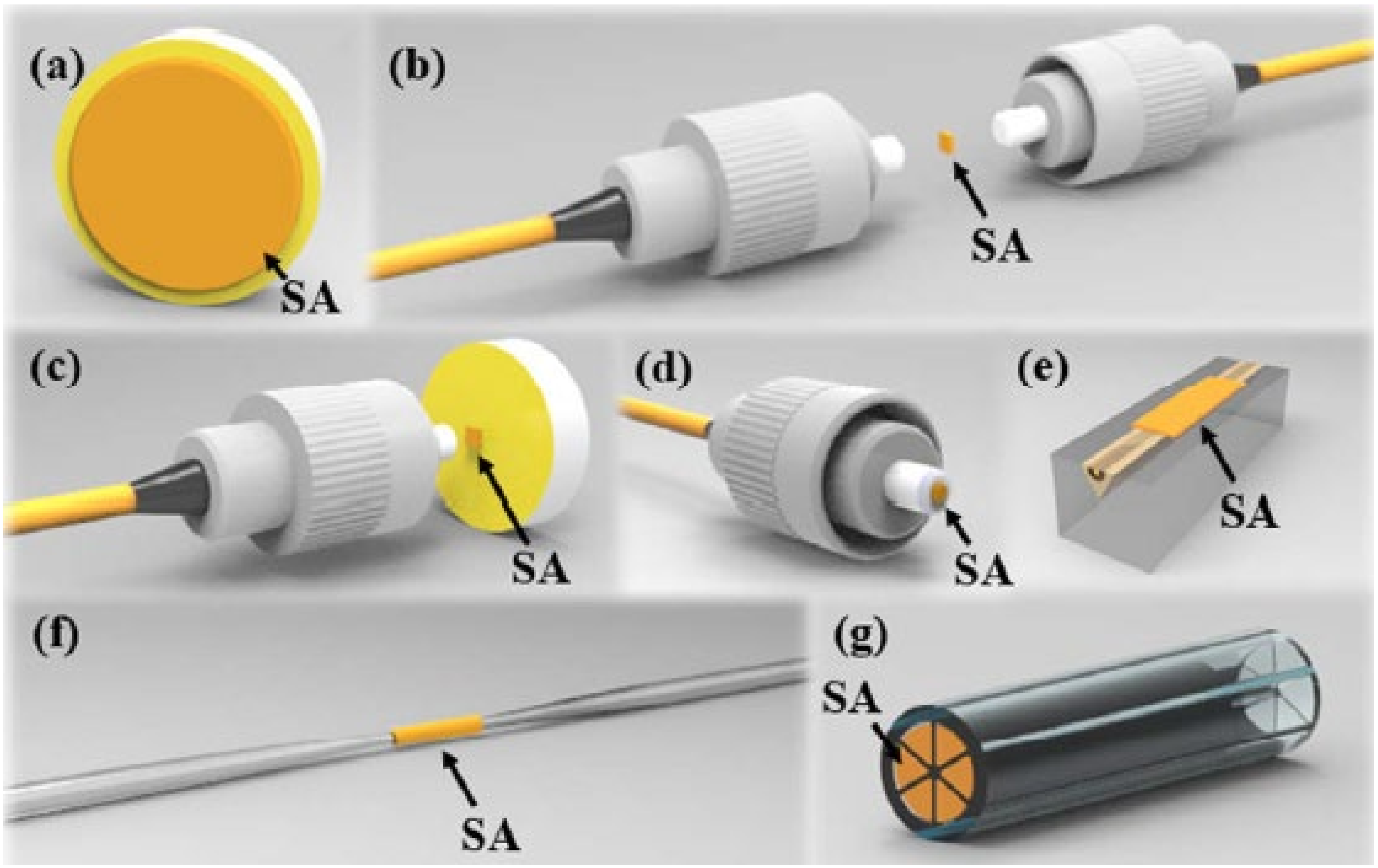
TI, TMD, BP based SA for MLFL

Specifications	Values	Other specifications of the lasers	Ref.
Repetition rate	463 MHz (Fundamental ML)	Center wavelength 1556 nm, 3-dB bandwidth 6.1 nm, output power 5.9 mW, SA MoS_2 in polymer thin film	[57]
	3.27 GHz (Harmonic ML)	Center wavelength 1556 nm, 3-dB bandwidth 5.1 nm, output power 22.8 mW, SA $MoSe_2$ deposited on side-polished fiber	[96]
3-dB bandwidth	63 nm	Center wavelength 1542 nm, repetition rate 95.4 MHz, output power 63 mW, SA Sb_2Te_3 deposited on tapered fiber	[61]
Pulse energy	25.5 nJ	Center wavelength 2783 nm, 3-dB bandwidth 2.8 nm, repetition rate 24.27 MHz, output power 613 mW, SA BP deposited on mirror	[115]
Shortest wavelength	1030 nm	3-dB bandwidth 1.1 nm, repetition rate 2.84 MHz, output power 8.02 mW, SA WS_2 in polymer thin film	[24]
Longest wavelength	2867 nm	3-dB bandwidth 4.35 nm, repetition rate 13.987 MHz, output power 87.8 mW, SA BP deposited on mirror	[116]

Wu, K., Optics Communications (2017), http://dx.doi.org/10.1016/j.optcom.2017.02.024

Plus many more!!

Adopting functional materials in Fiber Optics

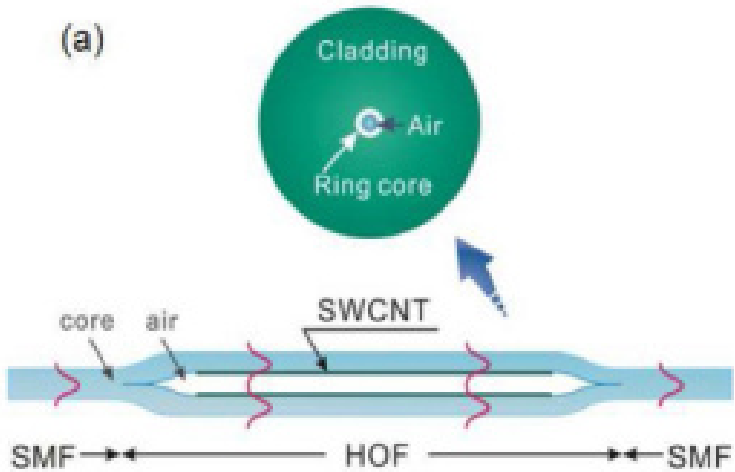


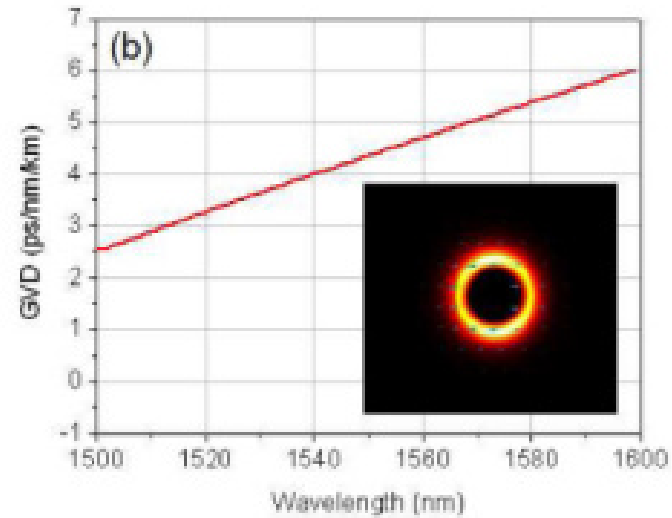
Wu, K., Optics Communications (2017), http://dx.doi.org/10.1016/j.optcom.2017.02.024

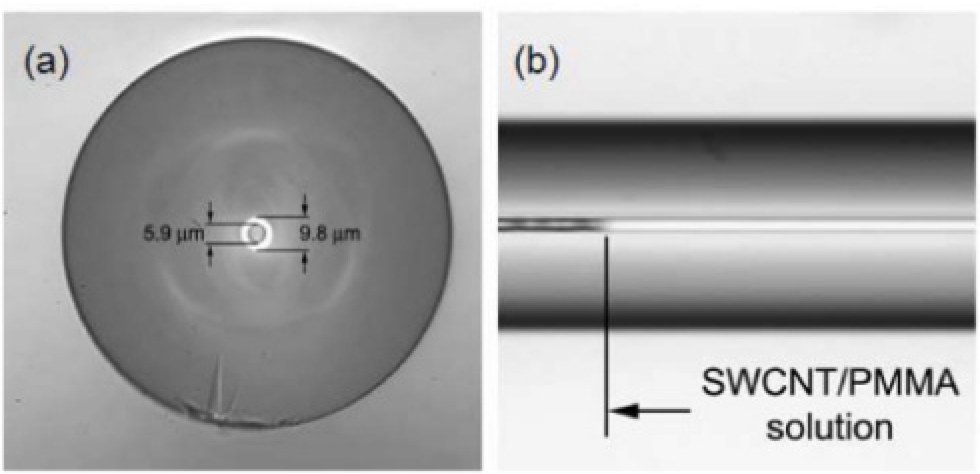
Key Technical Issues for New SAs in Fiber Laser Cavity

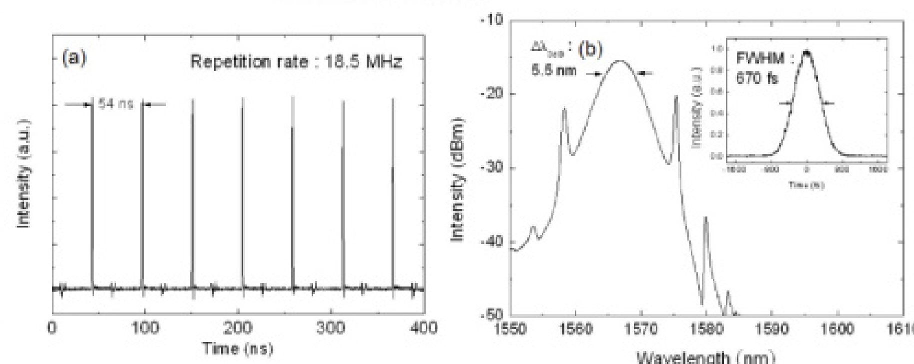
- Integrate the functional materials into fiber optics (flakes, nanosheets, nanofiber, etc)
- Keep the insertion loss low
- Maximize the light-matter interaction
- Compact and protective packaging
- All-fiber configuration

CNT in HOF





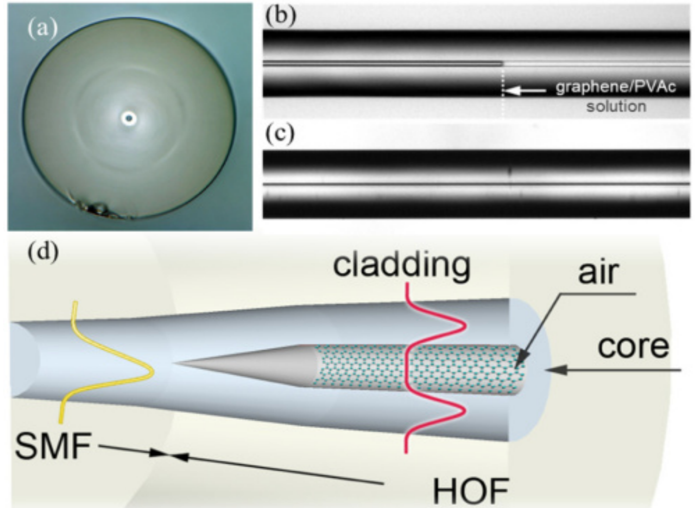


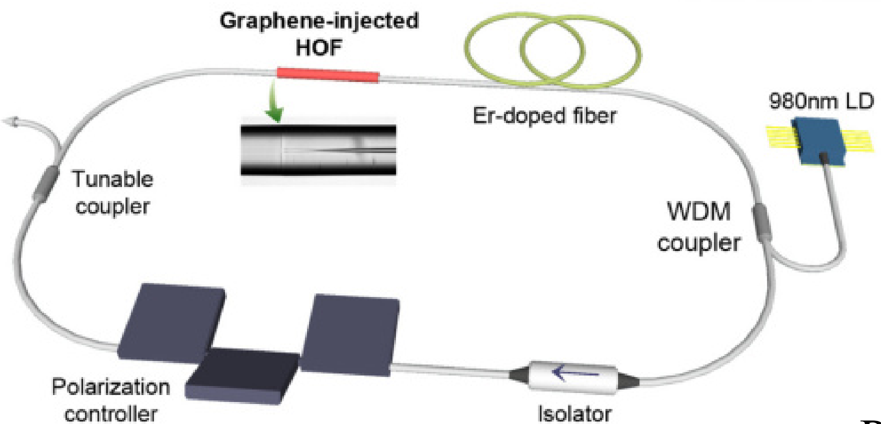


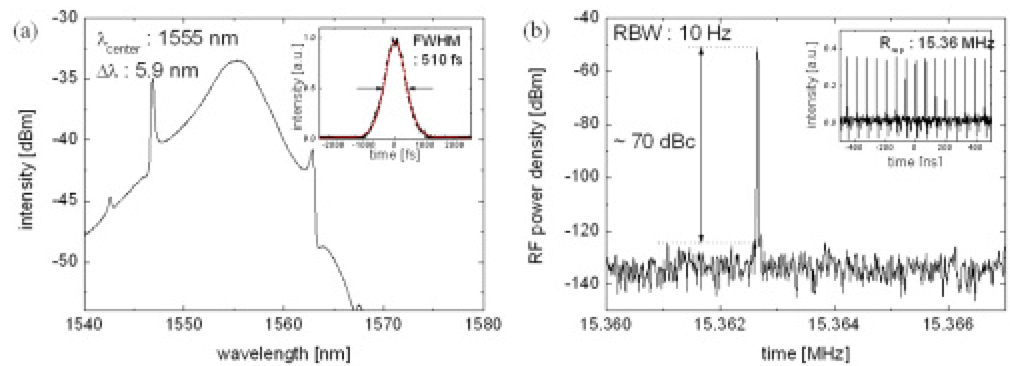
Spectral bandwidth 5.5 nm
Pulse duration 490 fs
Pulse repetition rate of 18.5 MHz

"Femtosecond mode-locked fiber laser employing a hollow optical fiber filled with carbon nanotube dispersion as saturable absorber," Opt. Express17, 21788-21793 (2009)

Graphene in HOF







Pulse duration 510fs

Fundamental repetition rate 15.36 MHz.

33rd harmonic pulse 506.9 MHz

"Graphene-filled hollow optical fiber saturable absorber for efficient soliton fiber laser mode-locking," Opt. Express 20, 5652-5657 (2012)

2D nanosheet on Fiber (PDPL at Yonsei Univ.)

“Mode-locking of Er-doped fiber laser using a multilayer MoS_2 thin film as a saturable absorber in both anomalous and normal dispersion regimes,” OSA Optics express 22, 23732-23742 (2014)

“Mode-Locked All-Fiber Lasers at Both Anomalous and Normal Dispersion Regimes Based on Spin-Coated Nano-Sheets on a Side-Polished Fiber,” IEEE Photonics Journal, 7, 1-9 (2014)

"All-fiber Er-doped Q-Switched laser based on Tungsten Disulfide WS_2 saturable absorber," OSA Opt. Mater. Express 5, 373-379 (2015)

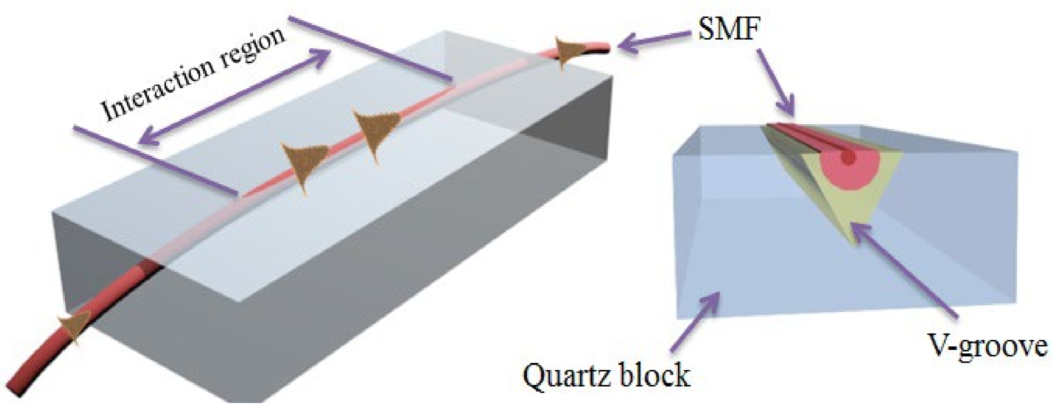
“Saturable optical absorption in MoS_2 nano-sheet optically deposited on the optical fiber facet,” Optics Communications 335, 224-230 (2015)

“Passive Q-Switching of an All-Fiber Laser Using WS_2-Deposited Optical Fiber Taper,” IEEE Photonics Journal, 7, 1-7 (2015)

“Femtosecond Soliton Pulse Generation Using Evanescent Field Interaction Through Tungsten Disulfide(WS_2) Film, Journal of Lightwave Technology 33, 3550-355 (2015)

Ultrafast Mode-locked Fiber Laser at Anomalous and Normal Dispersion

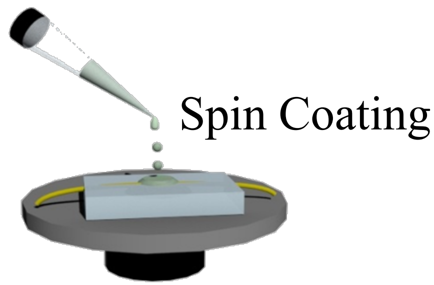
- Side Polished Fiber (SPF)
- Chemical Vapor Deposition (CVD) monolayer of MoS_2
- Soliton and dissipative soliton fiber laser

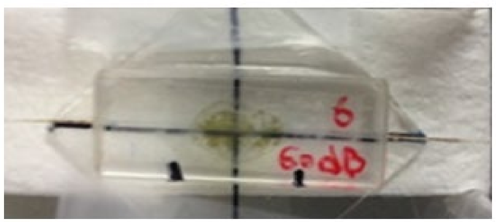


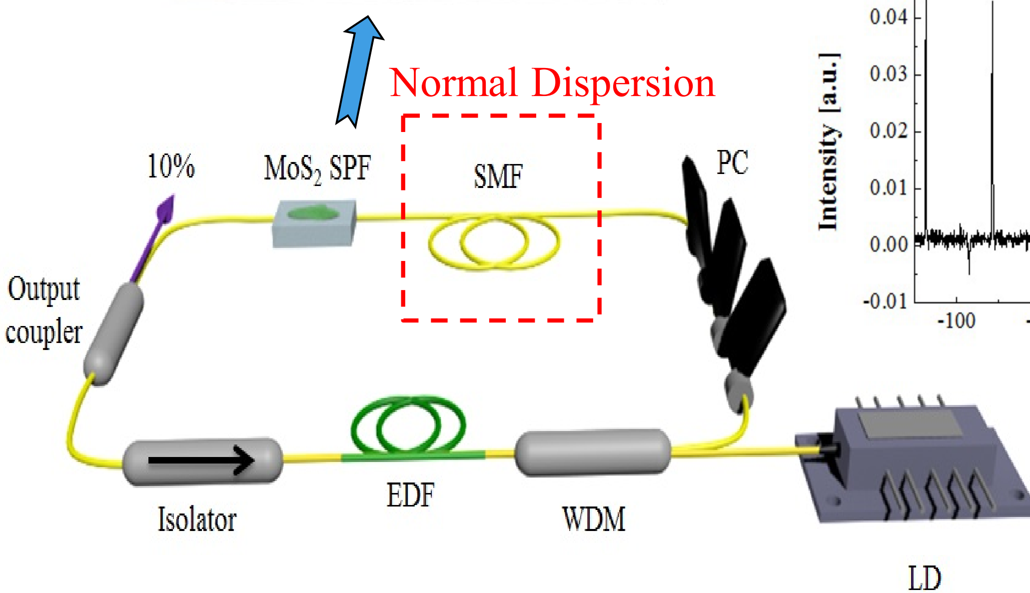
Ref: Reza, et al., Optics Express, 22, 23732-23742, 2014.

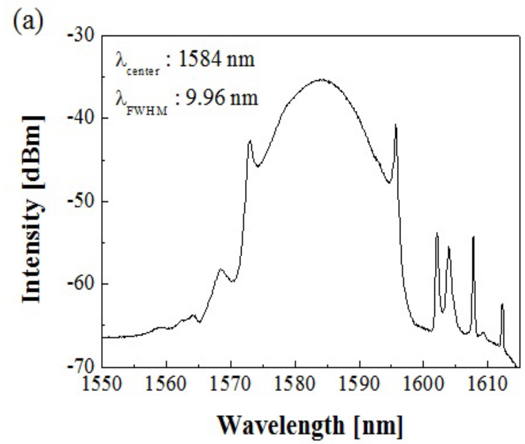
Ref: Reza, et al., IEEE Photonics Journal, 7, 1500109, 2015.

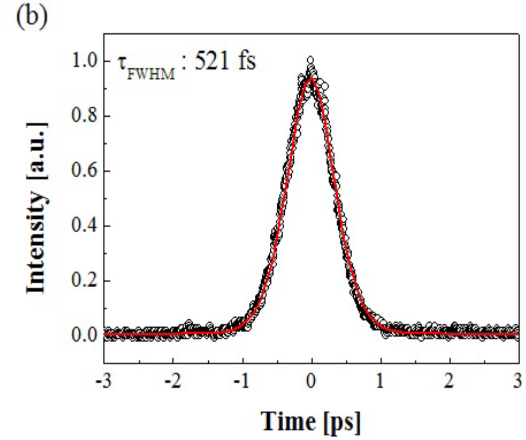
Soliton Pulses Based on MoS_2 Nano-sheets

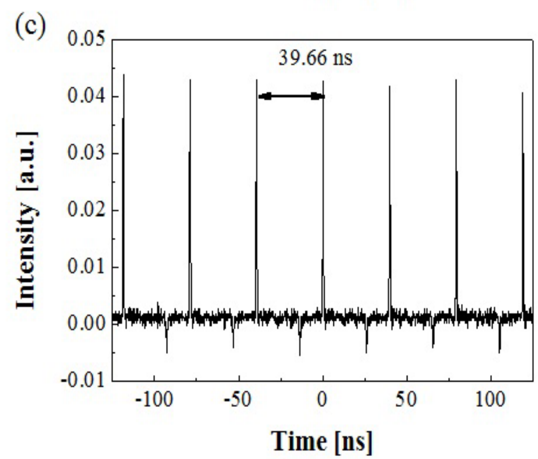


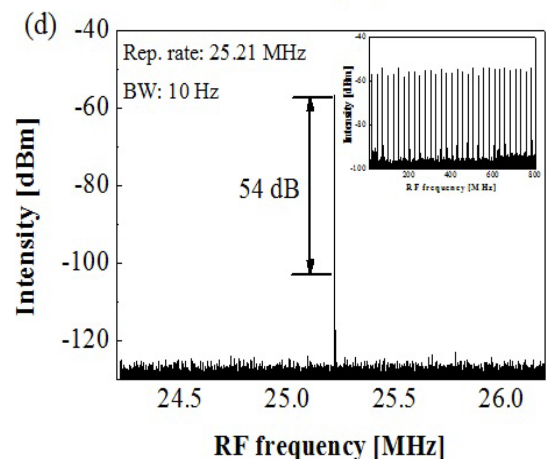




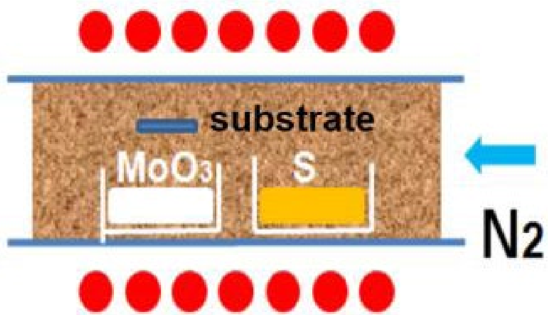




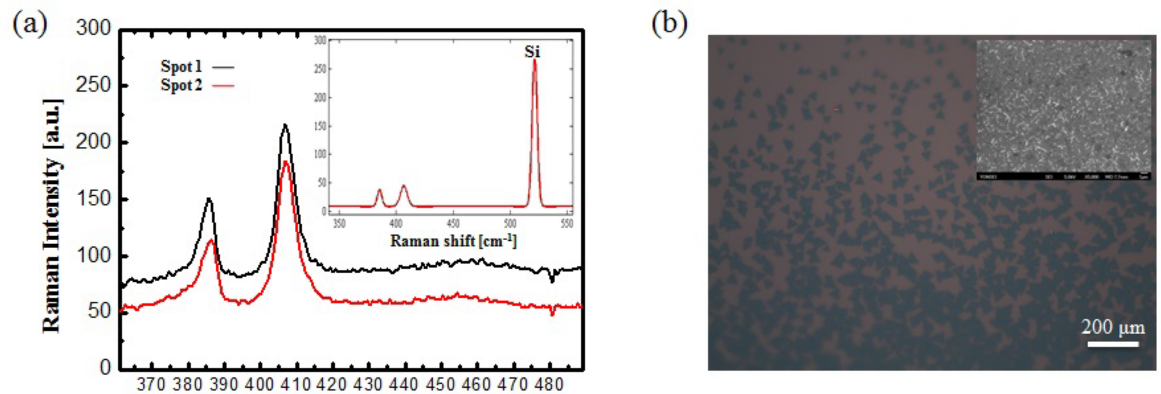




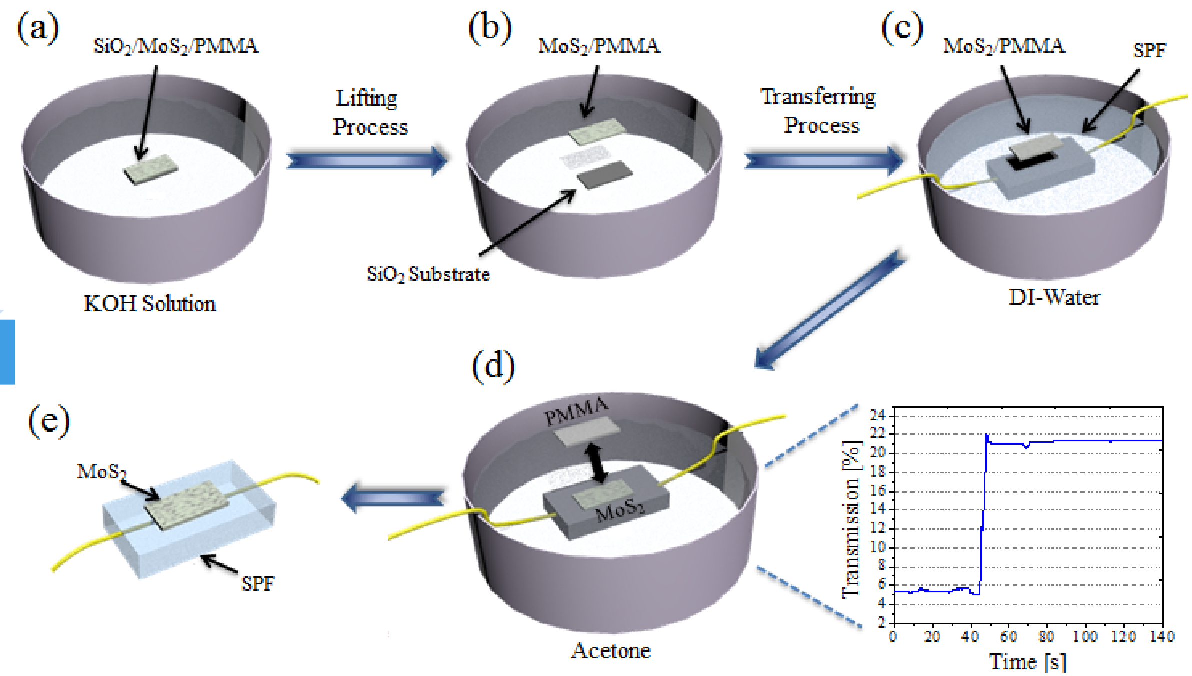
CVD grown MoS_2



Ref: Advanced Materials, **24**, 2320–2325, 2012.

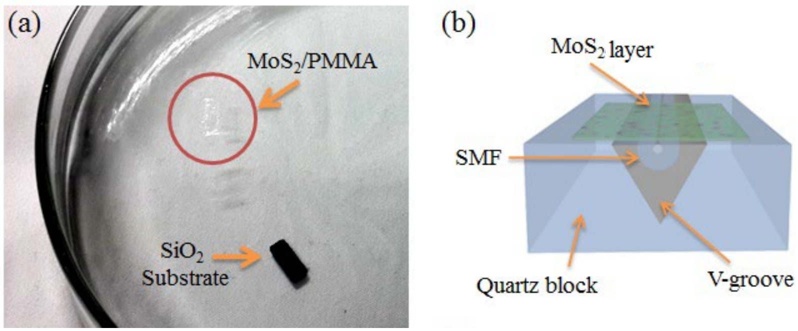


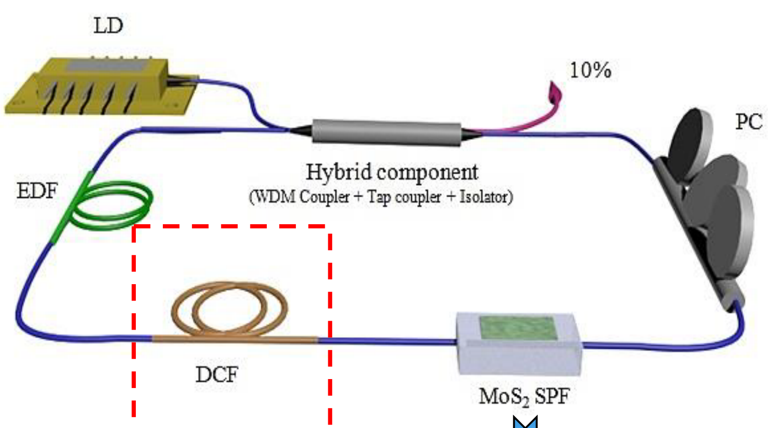
- Spin coating PMMA
- Wet etching via KOH
- Transfer on the SPF
- Removing PMMA via Acetone



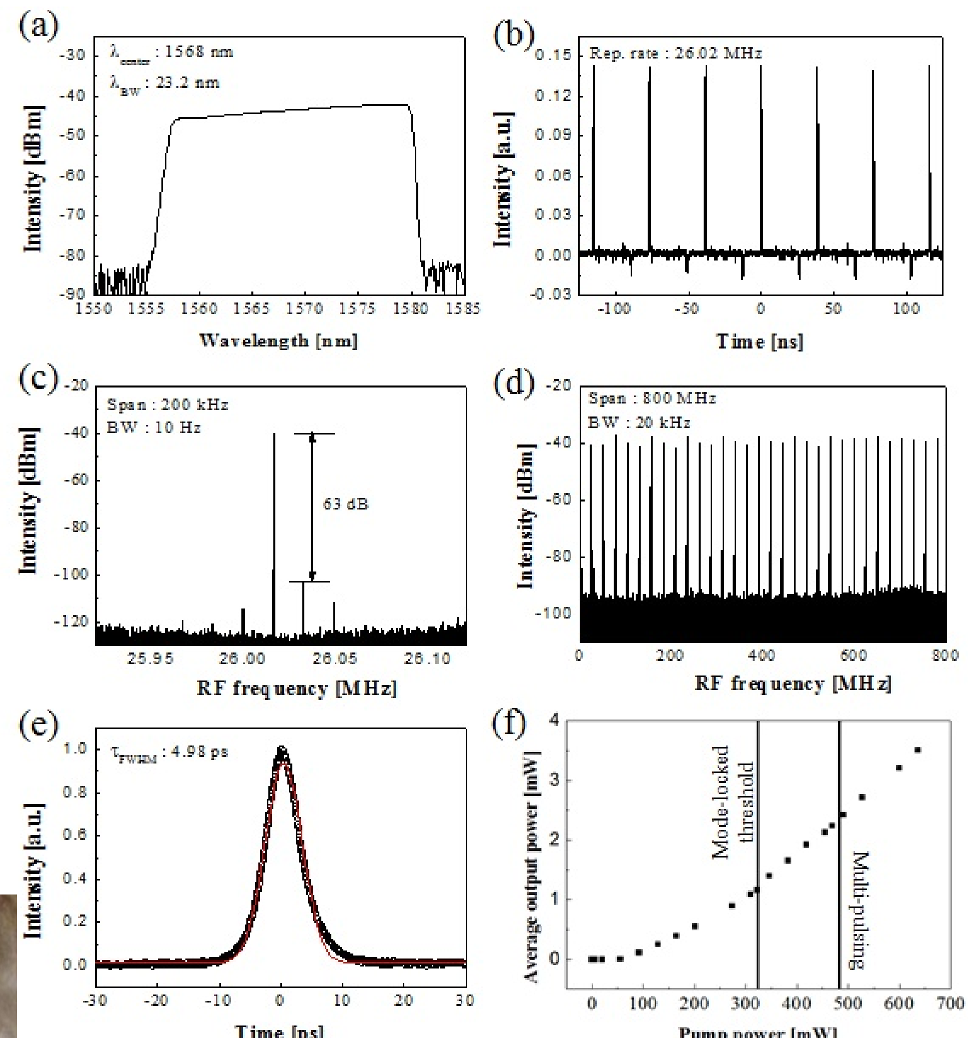
KOH

Dissipative Soliton Fiber laser



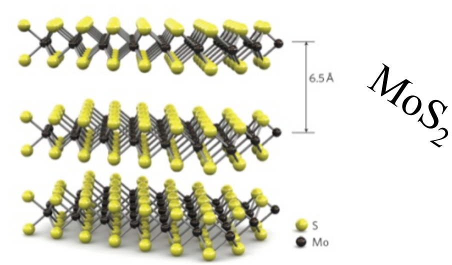


Anomalous Dispersion

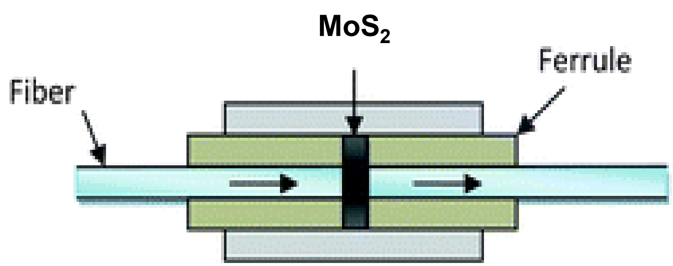


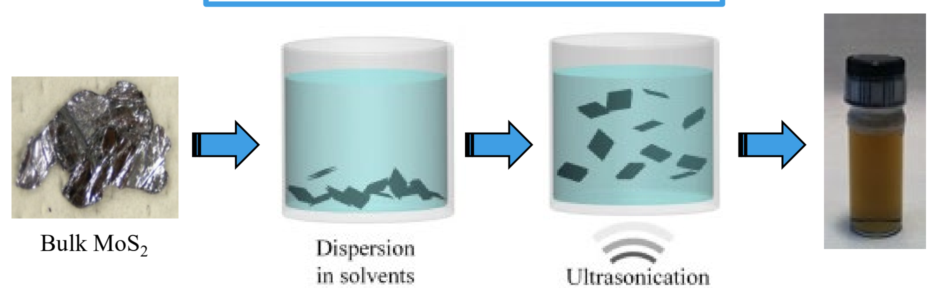
Q-switched Fiber Laser based on MoS_2 Nano-sheets

- Optical deposition and reflectometry
- Nonlinear optical properties of MoS_2
- Q-switched fiber laser



Liquid Phase Exfoliation (LPE)

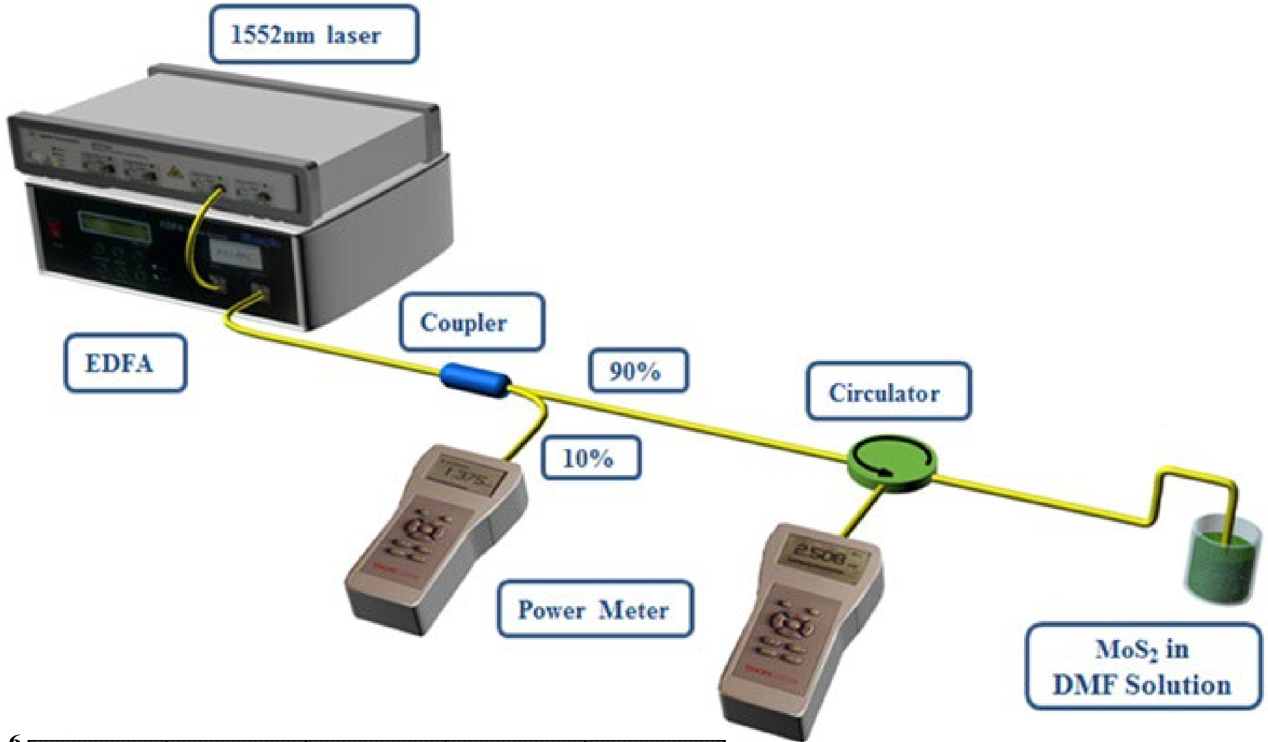


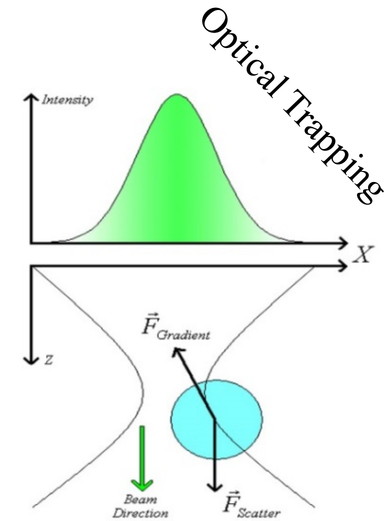


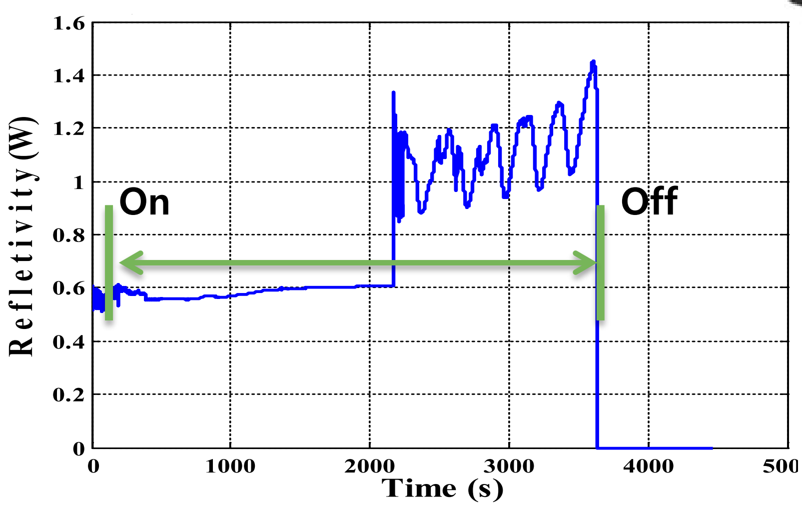
Ref: Science, **331**, 568-571, 2011.

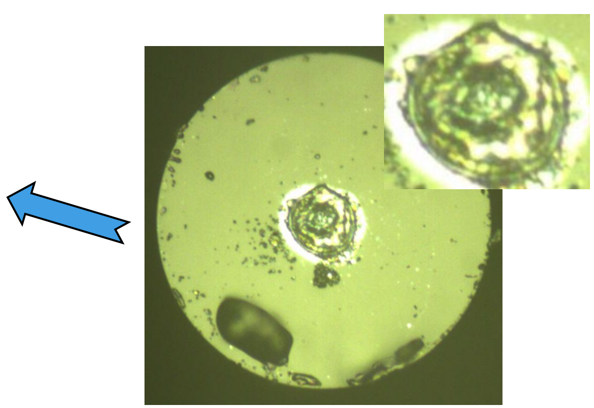
Ref: Reza, et al., Optics Communications, 335, 224–230, 2015.

Optical Deposition

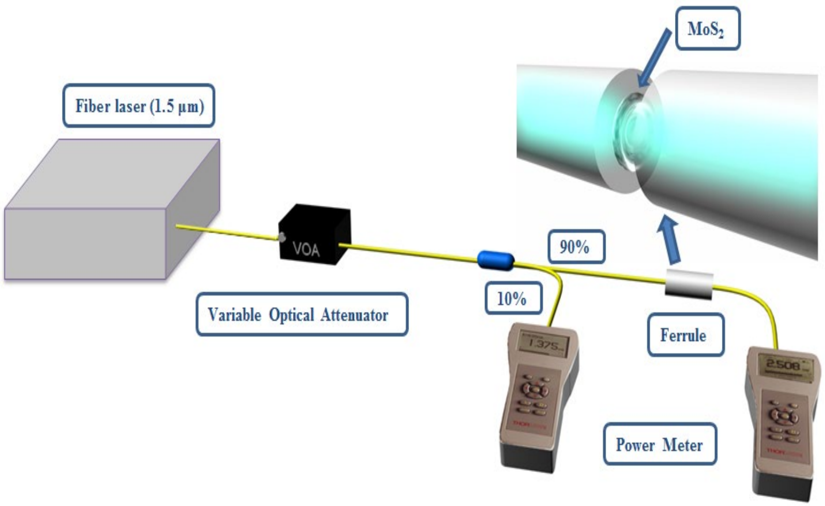


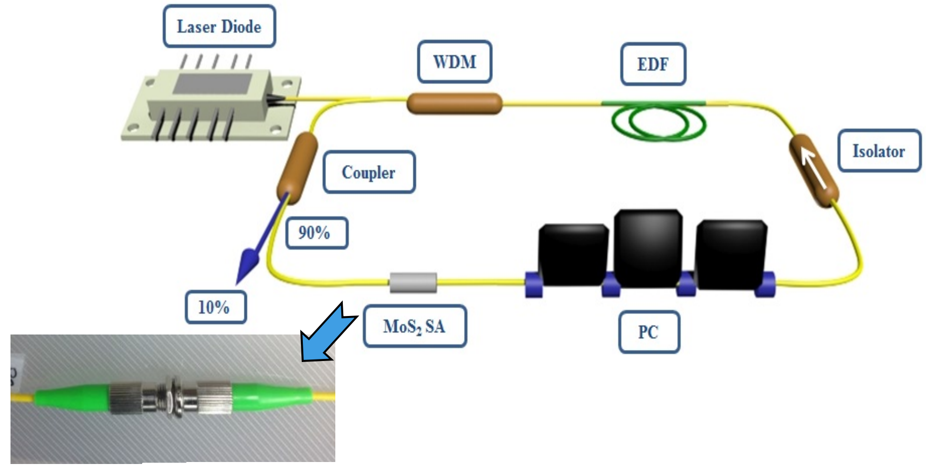


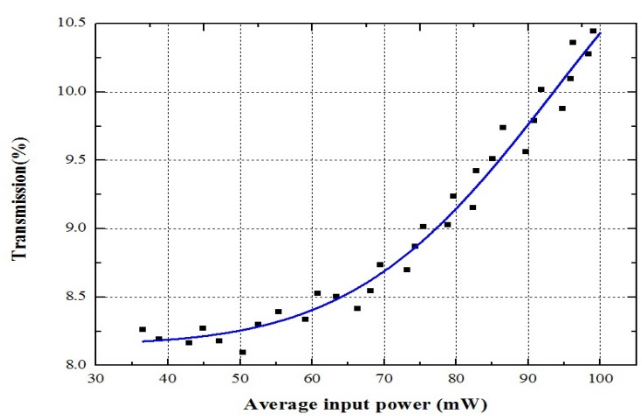




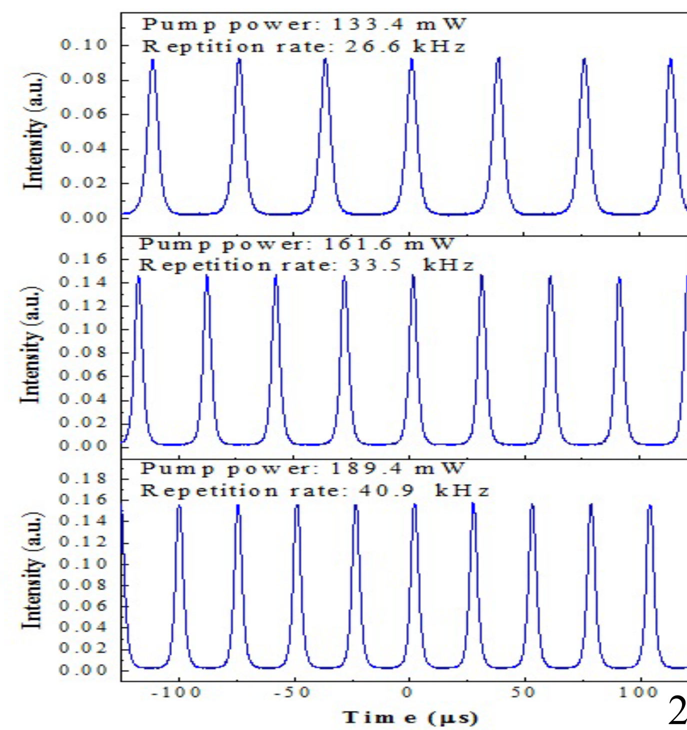
Q-switched Fiber Laser





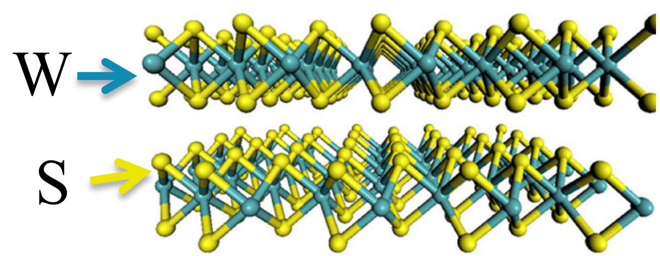


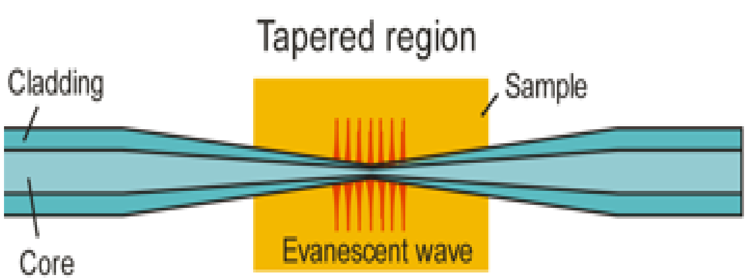
Intensity-dependent Transmission

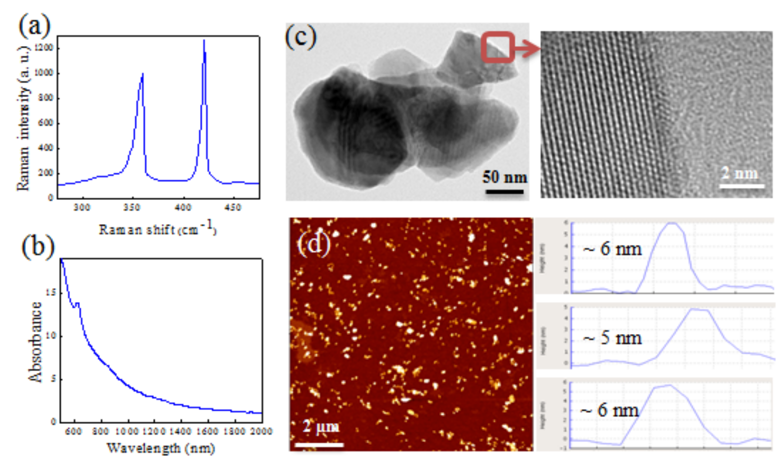


Mode-locked Fiber Laser based on WS_2 Nano-sheets

- Tapered optical fiber
- Optical deposition of WS_2 flakes
- Mode-locked fiber laser

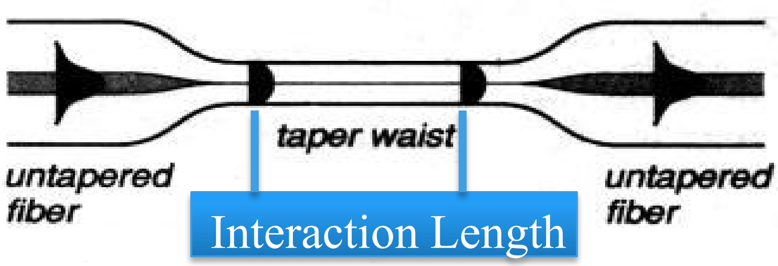


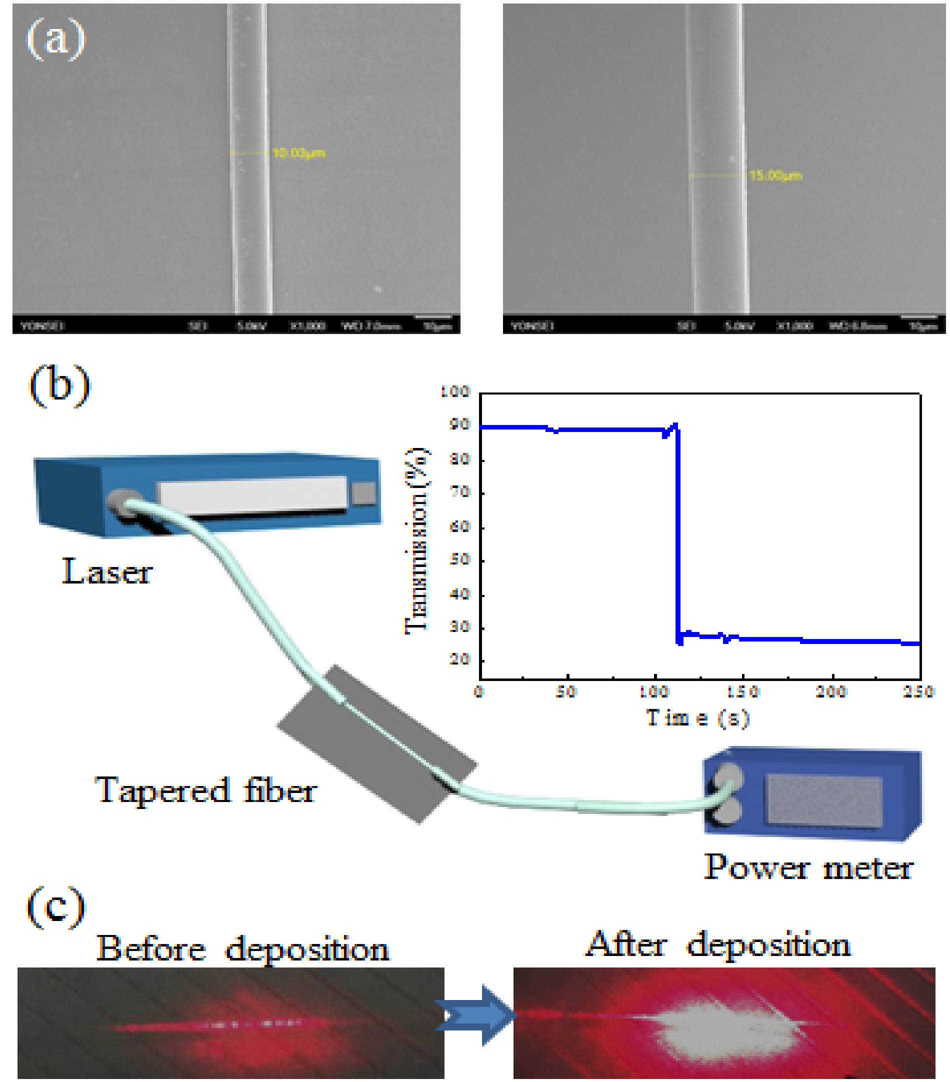




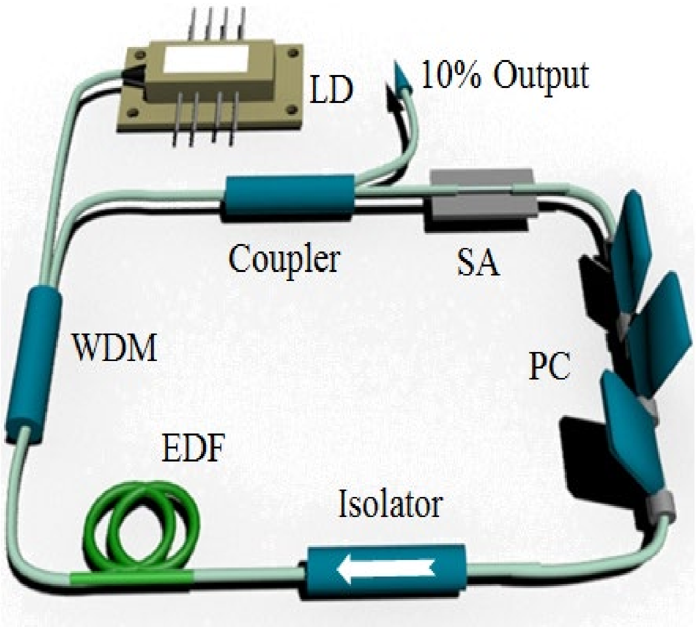
Ref: Reza, et al., OSA/IEEE Journal of Lightwave Technology 33, 3550-3557 (2015).

Tapered Optical Fiber

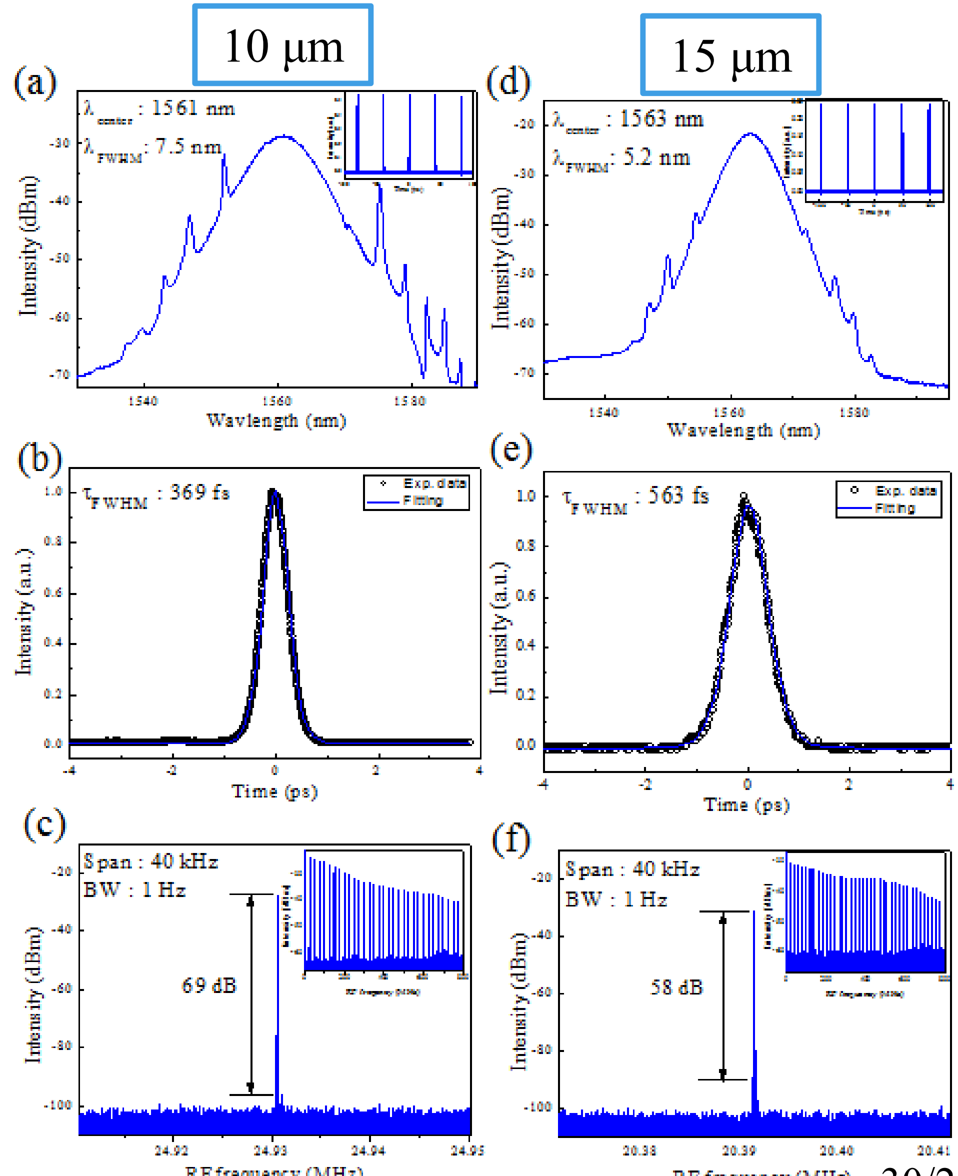




Mode-locked Fiber Laser

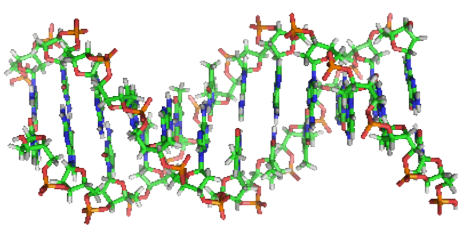


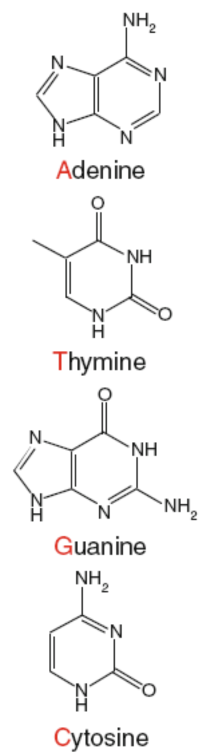
	10 µm	15 µm
Cavity length (m)	8.30	10.15
Dispersion (ps²)	-0.162	-0.205
Central wavelength (nm)	1561	1563
3dB Bandwidth (nm)	7.5	5.2
Pulse duration (fs)	369	563
Repetition rate (MHz)	24.93	20.39
Signal to noise ratio (dB)	69	58

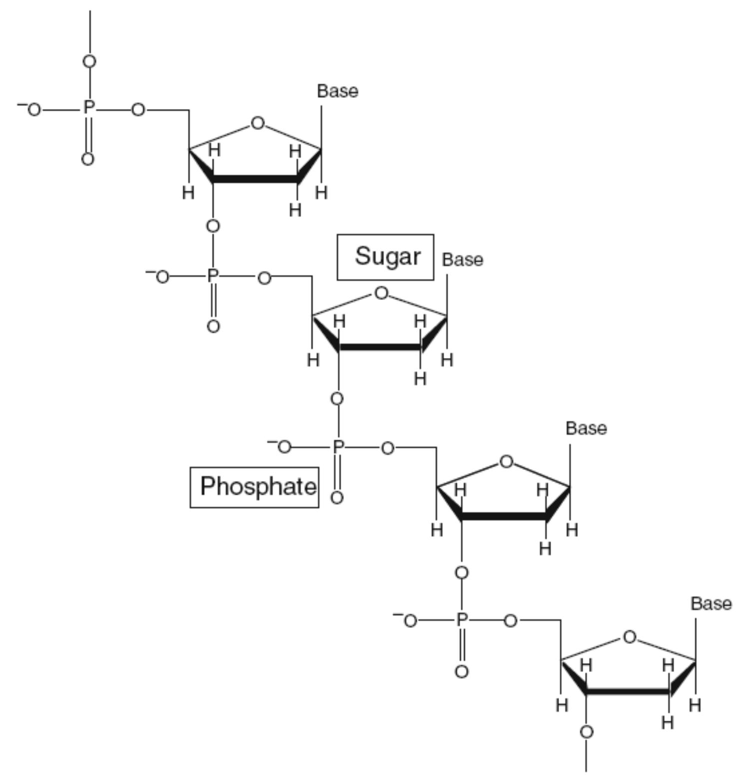


Nonlinear Optical Characteristics of DNA (Deoxyribonucleic acid)

- DNA and DNA-CTMA
- Femtosecond fiber laser





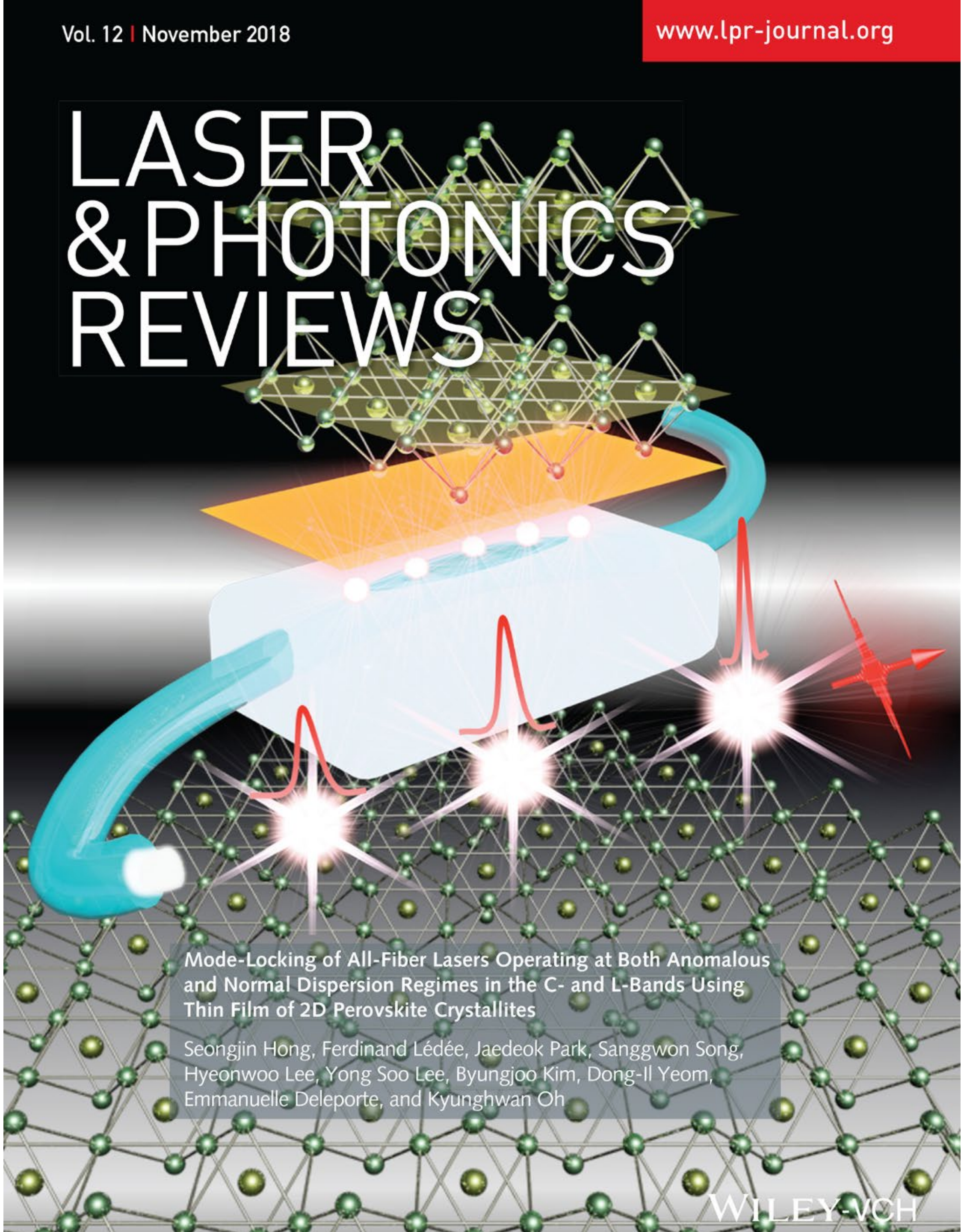


Ref: Reza, et al., **Scientific Reports 2017**.

Recent progress of pulsed fiber lasers based on transition-metal dichalcogenides and black phosphorus saturable absorbers

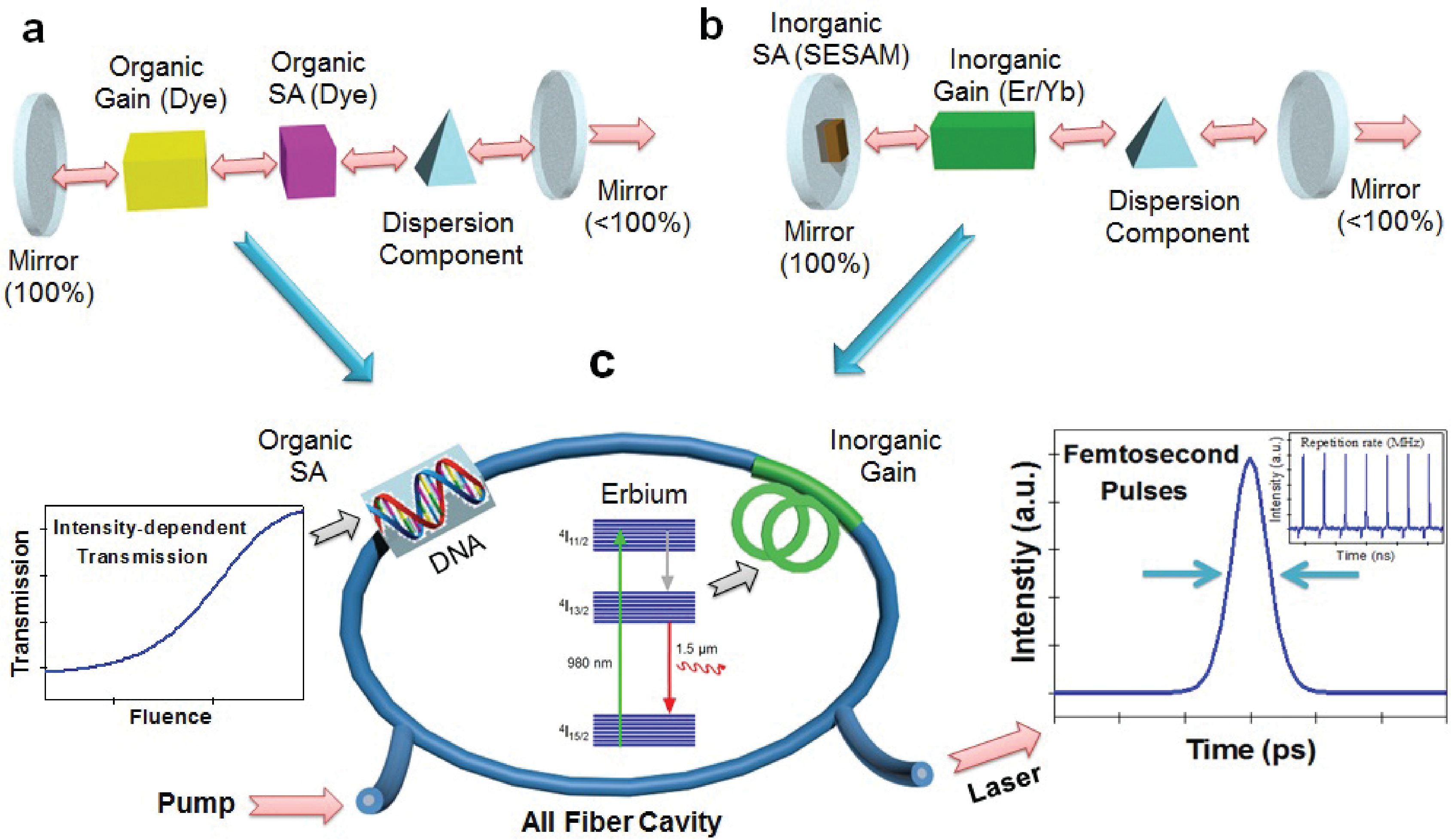
Xing Liu / Qun Gao / Yang Zheng / Dong Mao_ / Jianlin Zhao
Published Online: 2020-03-09 | DOI: https://doi.org/10.1515/nanoph-2019-0566

In recent years, some 2D monoelemental materials such as phosphorene [61], arsenene [62], antimonene [63], and bismuthene [64] have also attracted great interest owing to their extraordinary physical properties. Especially, black phosphorus (BP) [65], [66], [67], [68], [69], the most thermodynamically stable allotrope of the element phosphorus, has a layer-dependent bandgap from 0.3 eV (bulk) to 2.0 eV (monolayer) [70], [71], which covers the vacancy between zero-bandgap graphene and large-bandgap TMDCs (e.g. 1.29~1.8 eV for MoS_2) [72]. Thus, BP is a promising nonlinear optical material at the mid-infrared range that is beyond the absorption wavelength of TMDCs [66], [73], [74], [75], [76], [77], [78]. In addition to these famous 2D materials, several new materials such as tin sulfide [79], [80] and perovskite [81], [82], [83], were also found to exhibit a saturable absorption property.



https://onlinelibrary.wiley.com/doi/abs/10.1002/lpor.201870050

Organic-Inorganic Ultrafast Fiber Laser



Ultrafast nonlinear optical properties of thin-solid **DNA film** and their application as a saturable absorber in femtosecond mode-locked fiber laser, Scientific Reports 7, 41480 (2017)

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