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

Presented by:

Fiber Modeling and Fabrication Technical Group
Fiber Modeling and Fabrication Technical Group

Welcomes You for the webinar on

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

March 13 2020, 8 pm
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.

Find us:
https://www.osa.org/FF  
Join Us:
https://www.facebook.com/groups/OSAfibermodelingandfabrication/  
https://www.linkedin.com/groups/8302193/
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 !!!!
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 !!!!
How to join this 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
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.
OSA Webminiar
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

\[ \Delta E \cdot \Delta t \sim \hbar \]

Power in the time domain

By the uncertainty principle

\[ E = h\nu \]

Power in the frequency domain

![Diagram showing the relationship between time and frequency domains for long and short pulses.](image)
Various techniques are being developed but, the fundamental platform is “mode-locking” that enables pico~femtosecond pulse generation.

ELI (Extreme Light Infrastructure)
https://www.eli-beams.eu/
CPA (Chirped Pulse Amplification)
Fiber laser pulse generation? Mostly by Q-switching and Mode-locking
[Diagram of laser resonator and mode-locked lasers]

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 elaborate 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

- **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
• TMD
• BP

Appl. Sci. 2015, 5, 1440-1456
Biomedical Applications of Graphene and 2D Nanomaterials
Topological Insulators

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

$MX_2$ (M=Mo, W… : X=S, Se, Te)

Layered transition metal dichalcogenides

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

<table>
<thead>
<tr>
<th></th>
<th>Graphene</th>
<th>Carbon nanotube</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mode-locking</strong></td>
<td>0.8 µm 1 µm 1.5 µm 2 µm 2.5 µm</td>
<td>0.8 µm 1 µm 1.5 µm 2 µm 2.5 µm</td>
</tr>
<tr>
<td></td>
<td>63 fs (480 mW)</td>
<td>62 fs (600 mW)</td>
</tr>
<tr>
<td></td>
<td>160 fs (16 mW)</td>
<td>100 fs (230 mW)</td>
</tr>
<tr>
<td></td>
<td>91 fs (107 mW)</td>
<td>92 fs</td>
</tr>
<tr>
<td></td>
<td>410 fs (270 mW)</td>
<td>175 fs</td>
</tr>
<tr>
<td></td>
<td>226 fs (80 mW)</td>
<td>NA</td>
</tr>
<tr>
<td><strong>Q-switching</strong></td>
<td>0.8 µm 1 µm 1.5 µm 2 µm 2.5 µm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>56.2 ns (595.8 nJ)</td>
<td>1 µs, (1.74 µJ)</td>
</tr>
<tr>
<td></td>
<td>[37]</td>
<td>[38]</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Values</th>
<th>Other specifications of the lasers</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repetition rate</td>
<td>463 MHz (Fundamental ML)</td>
<td>Center wavelength 1556 nm, 3-dB bandwidth 6.1 nm, output power 5.9 mW, SA MoS$_2$ in polymer thin film</td>
<td>[57]</td>
</tr>
<tr>
<td></td>
<td>3.27 GHz (Harmonic ML)</td>
<td>Center wavelength 1556 nm, 3-dB bandwidth 5.1 nm, output power 22.8 mW, SA MoSe$_2$ deposited on side-polished fiber</td>
<td>[96]</td>
</tr>
<tr>
<td>3-dB bandwidth</td>
<td>63 nm</td>
<td>Center wavelength 1542 nm, repetition rate 95.4 MHz, output power 63 mW, SA Sb$_2$Te$_3$ deposited on tapered fiber</td>
<td>[61]</td>
</tr>
<tr>
<td>Pulse energy</td>
<td>25.5 nJ</td>
<td>Center wavelength 2783 nm, 3-dB bandwidth 2.8 nm, repetition rate 24.27 MHz, output power 613 mW, SA BP deposited on mirror</td>
<td>[115]</td>
</tr>
<tr>
<td>Shortest wavelength</td>
<td>1030 nm</td>
<td>3-dB bandwidth 1.1 nm, repetition rate 2.84 MHz, output power 8.02 mW, SA WS$_2$ in polymer thin film</td>
<td>[24]</td>
</tr>
<tr>
<td>Longest wavelength</td>
<td>2867 nm</td>
<td>3-dB bandwidth 4.35 nm, repetition rate 13.987 MHz, output power 87.8 mW, SA BP deposited on mirror</td>
<td>[116]</td>
</tr>
</tbody>
</table>

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

Graphene in HOF

Pulse duration 510fs
Fundamental repetition rate 15.36 MHz.
33rd harmonic pulse 506.9 MHz

“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)


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.
Soliton Pulses Based on MoS$_2$ Nano-sheets
CVD grown MoS\textsubscript{2}

Spin coating PMMA

Wet etching via KOH

Transfer on the SPF

Removing PMMA via Acetone


KOH
Dissipative Soliton Fiber laser

(a) M_{1}/PMMA
(b) MoS_{2} layer
(c) SMF
(d) Quartz block
(e) V-groove

(a) Intensity [dBm]
(b) Time [ns]
(c) RF frequency [MHz]
(d) RF frequency [MHz]
(e) Time [ps]
(f) Average output power [mW]

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.
Optical Deposition

1552nm laser
EDFA
Coupler
90%
Power Meter
10%
Circulator
MoS$_2$ in DMF Solution

Time (s)
Reflectivity (W)

On
Off

Optical Deposition

26/26
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

Tapered Optical Fiber

Interaction Length
Mode-locked Fiber Laser

<table>
<thead>
<tr>
<th></th>
<th>10 μm</th>
<th>15 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity length (m)</td>
<td>8.30</td>
<td>10.15</td>
</tr>
<tr>
<td>Dispersion (ps²)</td>
<td>-0.162</td>
<td>-0.205</td>
</tr>
<tr>
<td>Central wavelength (nm)</td>
<td>1561</td>
<td>1563</td>
</tr>
<tr>
<td>3dB Bandwidth (nm)</td>
<td>7.5</td>
<td>5.2</td>
</tr>
<tr>
<td>Pulse duration (fs)</td>
<td>369</td>
<td>563</td>
</tr>
<tr>
<td>Repetition rate (MHz)</td>
<td>24.93</td>
<td>20.39</td>
</tr>
<tr>
<td>Signal to noise ratio (dB)</td>
<td>69</td>
<td>58</td>
</tr>
</tbody>
</table>
Nonlinear Optical Characteristics of DNA (Deoxyribonucleic acid)

- DNA and DNA-CTMA
- Femtosecond fiber laser

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.
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)
My Heroes

Dr. Reza Khazaeinezhad
Alcon/Norvatis, USA
https://scholar.google.com/citations?user=sSO3rxAAAAAJ&hl=en

Dr. Sahar Hosseinzadeh
Kassani, Alcon/Norvatis, USA
https://scholar.google.com/citations?user=ZU9gPREAAAAAJ&hl=en

Dr. Seongjin Hong,
Center for Quantum Information, KIST, Korea
http://quantum.kist.re.kr/index.html