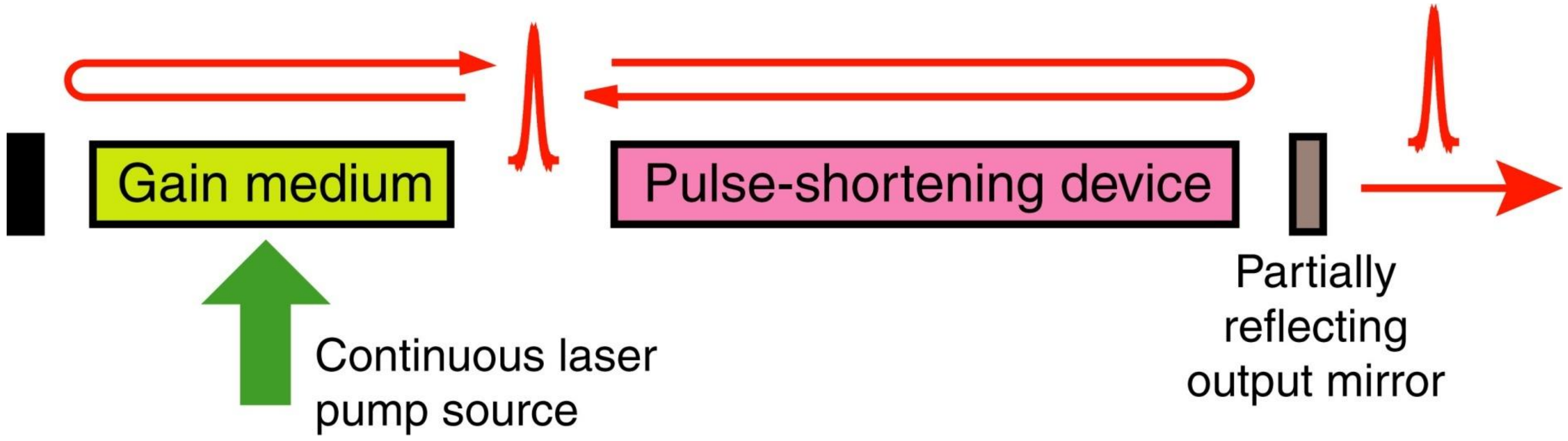
A generic ultrashort-pulse laser

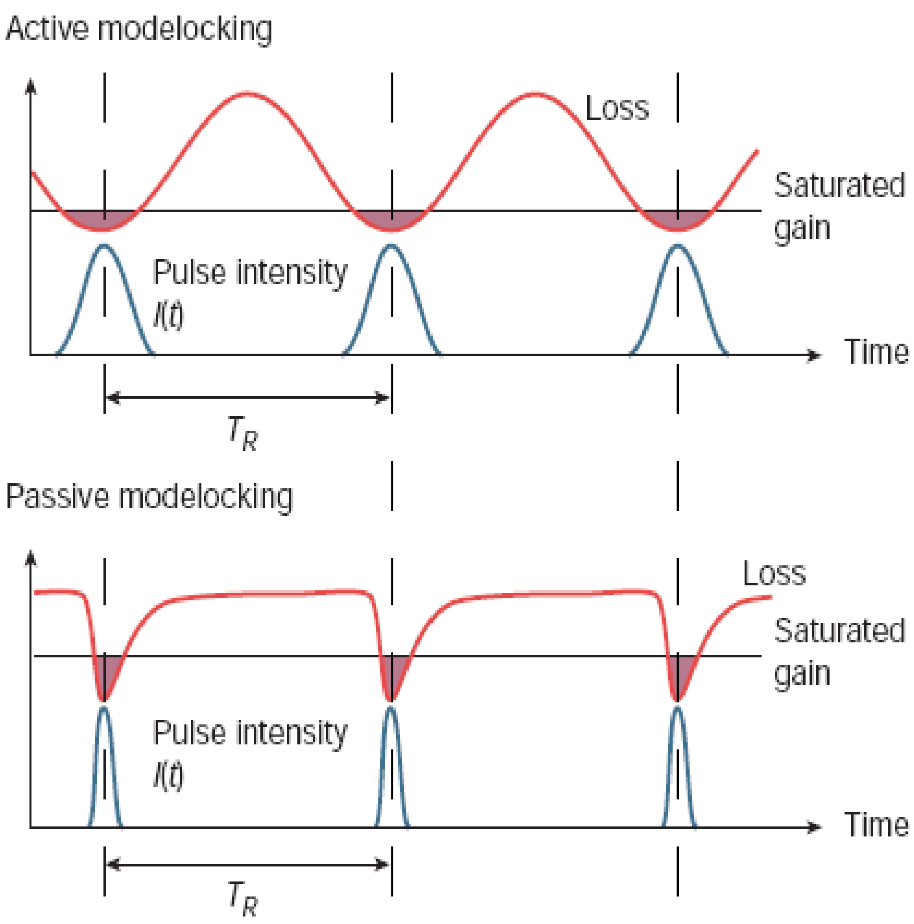
- A generic ultrafast laser has a broadband gain medium, a pulse-shortening device, and two or more mirrors:



Many pulse-shortening devices have been proposed and used.

Active and Passive Mode Locking

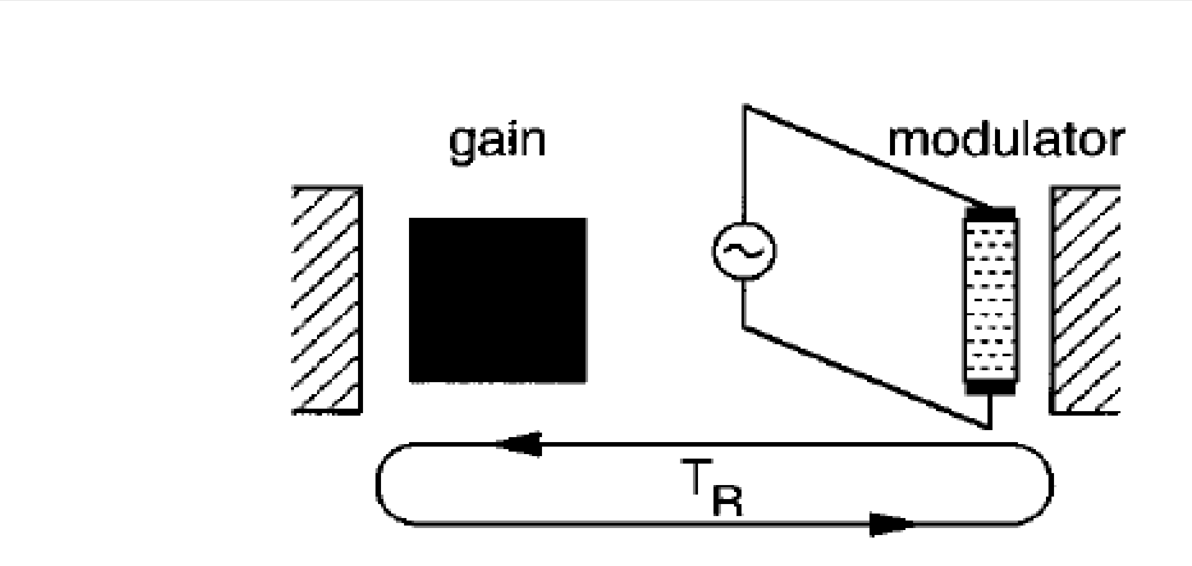
- The **acoustic-optical** or **electro-optical modulator** => periodic sinusoidal loss modulation => equal the **cavity round trip time**
- A saturable absorber => to obtain a **self-amplitude modulation** of the light inside the laser cavity.
- **Loss modulation** => Relatively large for **low intensities** but significantly smaller for a short pulse with high intensity.
- The **high intensity** @ the peak of pulse => saturates the absorber more strongly than its low intensity wings => **pulse shaping effect**



Active mode-locking

➢Any amplitude modulator can preferentially induce losses for times other than that of the intended pulse peak. This produces short pulses.

➢It can be used to start a Ti:Sapphire laser mode-locking.



Schematic of actively mode-locked laser

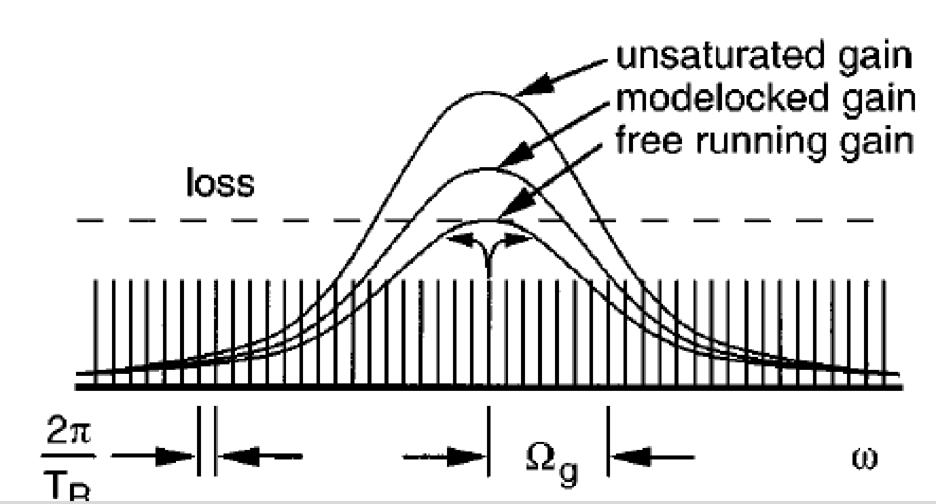
Schematic of actively mode-locked laser, the spectrum in the time domain and the time dependence of net gain.

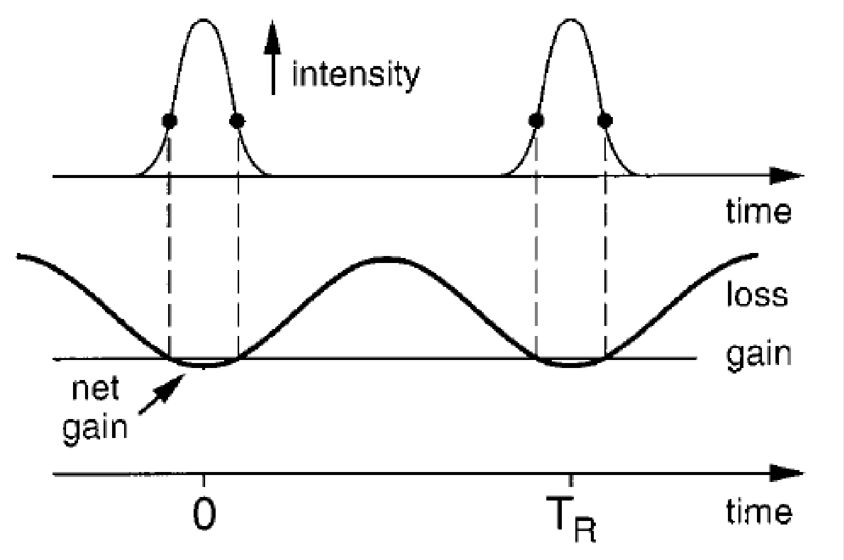
- An optical Fabry–Pérot resonator formed of two mirrors has axial modes separated in frequency by
,

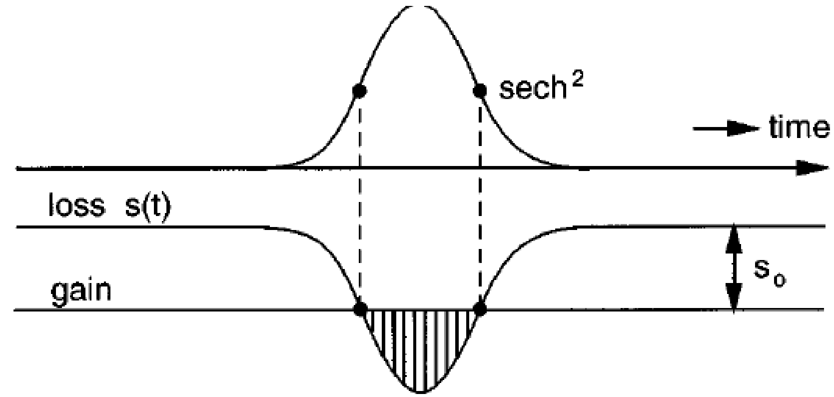
$\Delta\Omega = 2\pi / T_R$

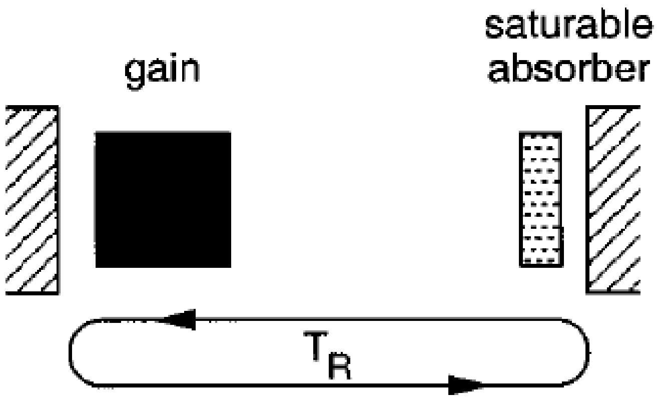
Where T_R is the roundtrip time.

Active mode-locking does not lead to ultrashort pulses

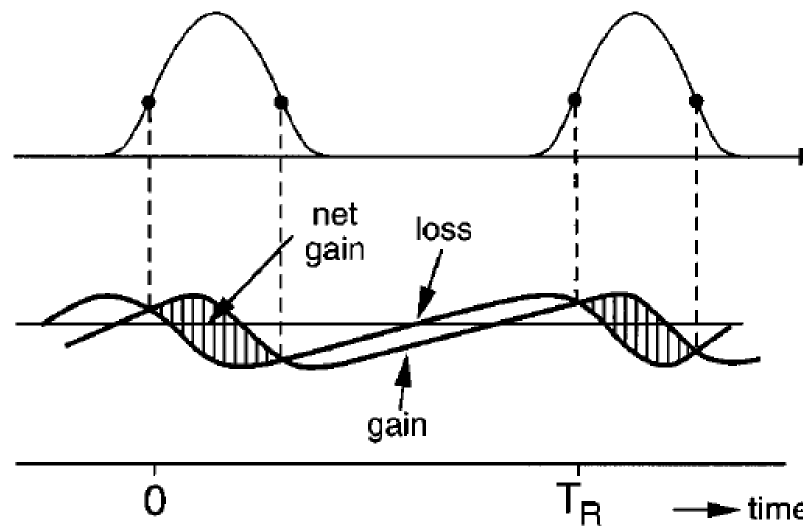






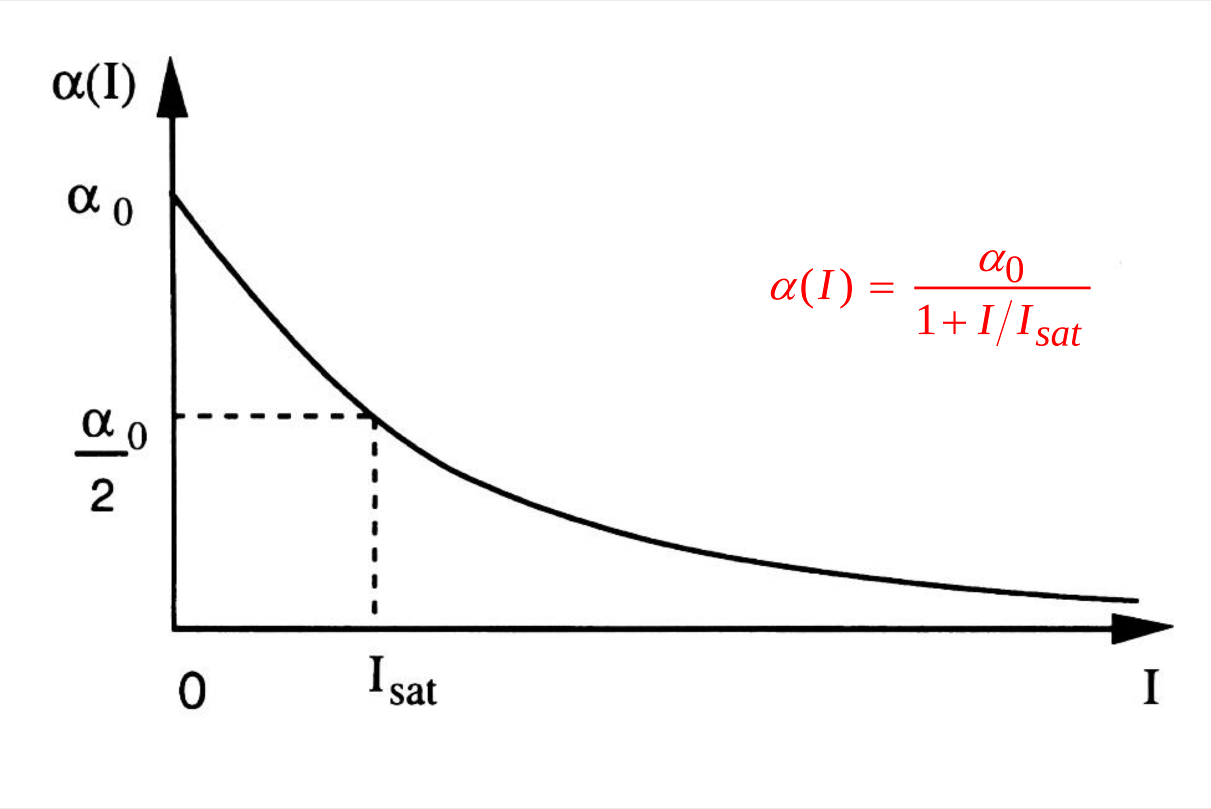


Schematic of laser passively mode-locked with fast saturable absorberand the time dependence of pulse, and net gain



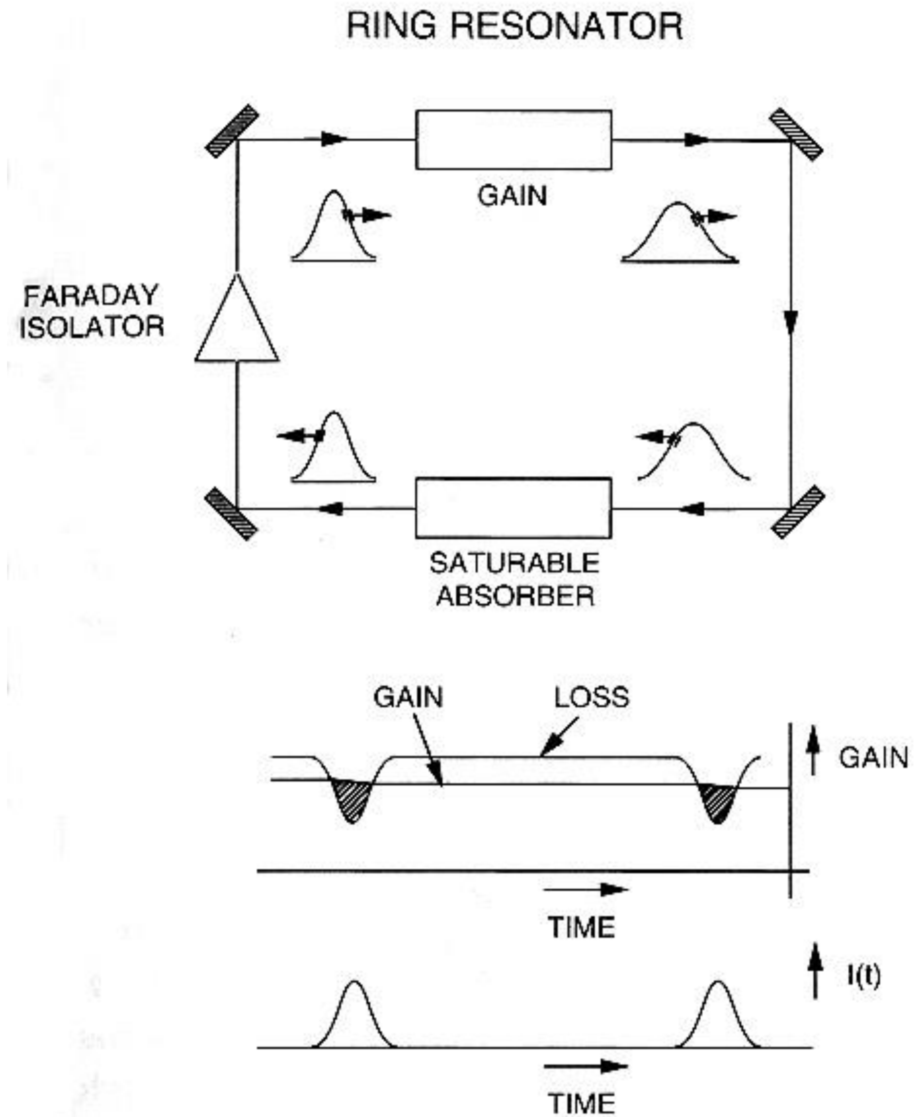
Passive mode-locking: the saturable absorber

- Like a sponge, an absorbing medium can only absorb so much.
- High-intensity spikes burn through; low-intensity light is absorbed.



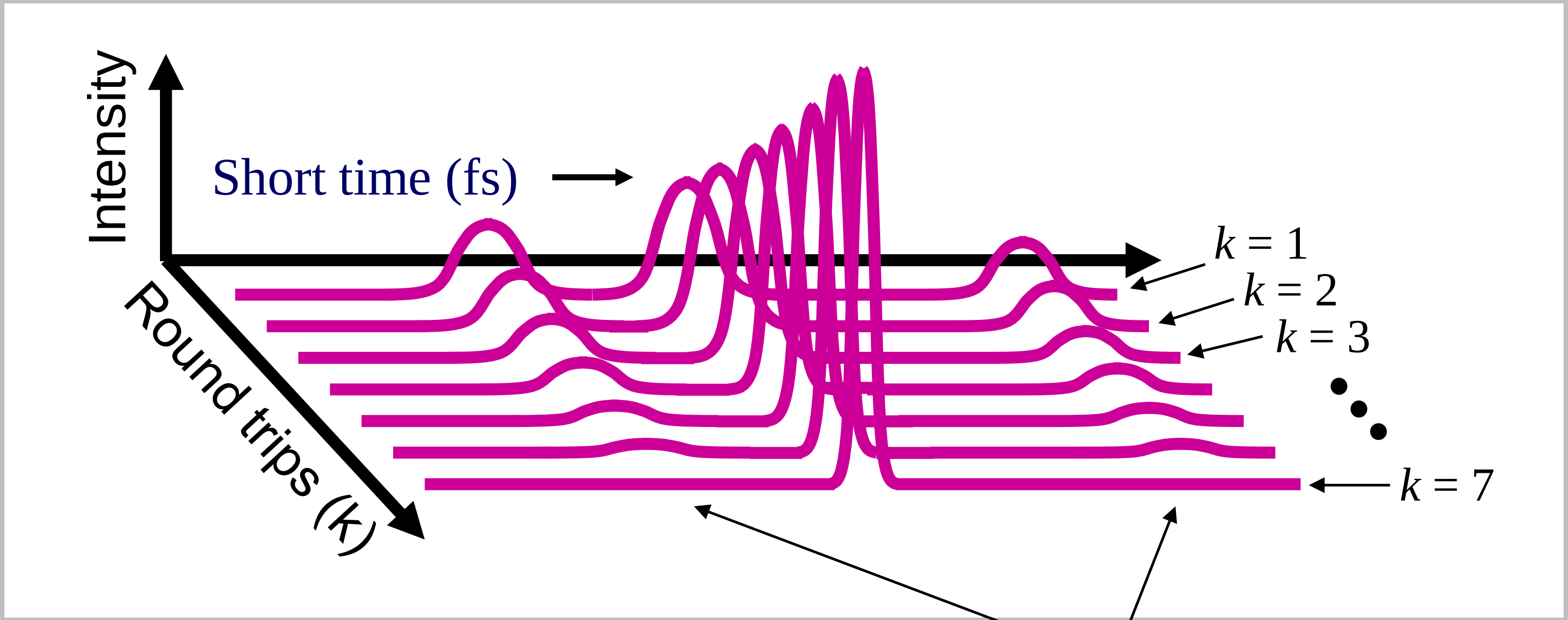
Passive mode-locking: the saturable absorber

- High-intensity spikes (i.e., short pulses) see less loss and hence can lase while low-intensity backgrounds (i.e., long pulses) won’t.



The effect of a saturable absorber

First, imagine raster-scanning the pulse vs. time like this:

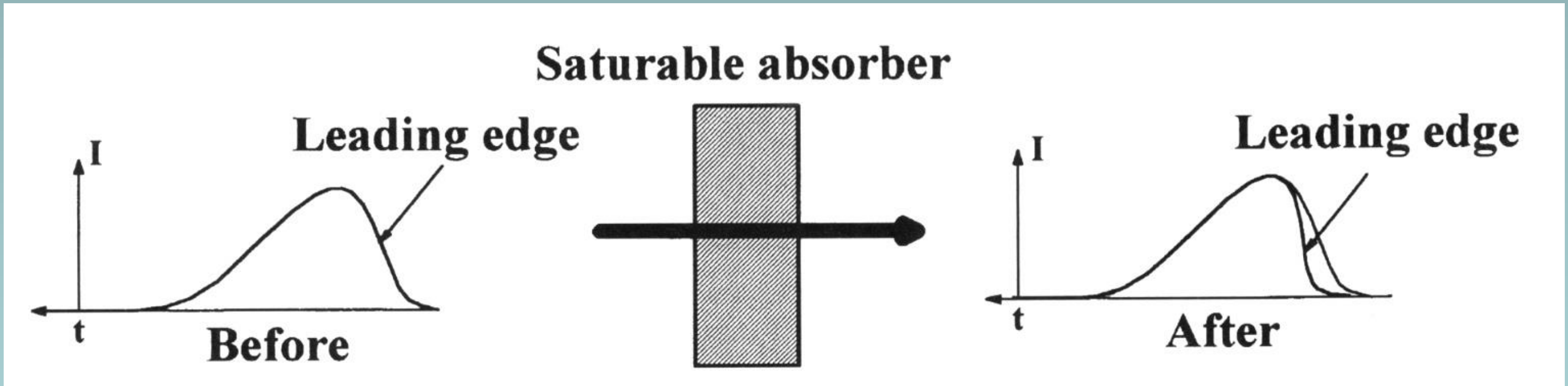


Notice that the weak pulses are suppressed, and the strong pulse shortens and is amplified.

After many round trips, even a slightly saturable absorber can yield a very short pulse.

Passive Mode-locking with a Slow Saturable Absorber

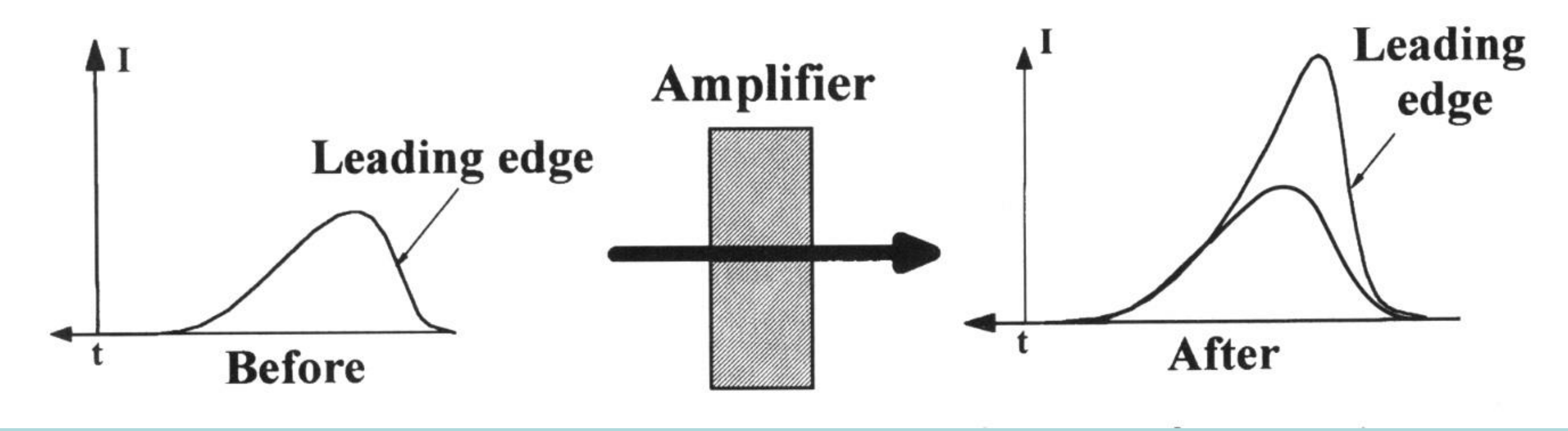
- What if the **absorber** responds **slowly** (more slowly than the pulse)?
- Then only the **leading edge** will experience pulse shortening.



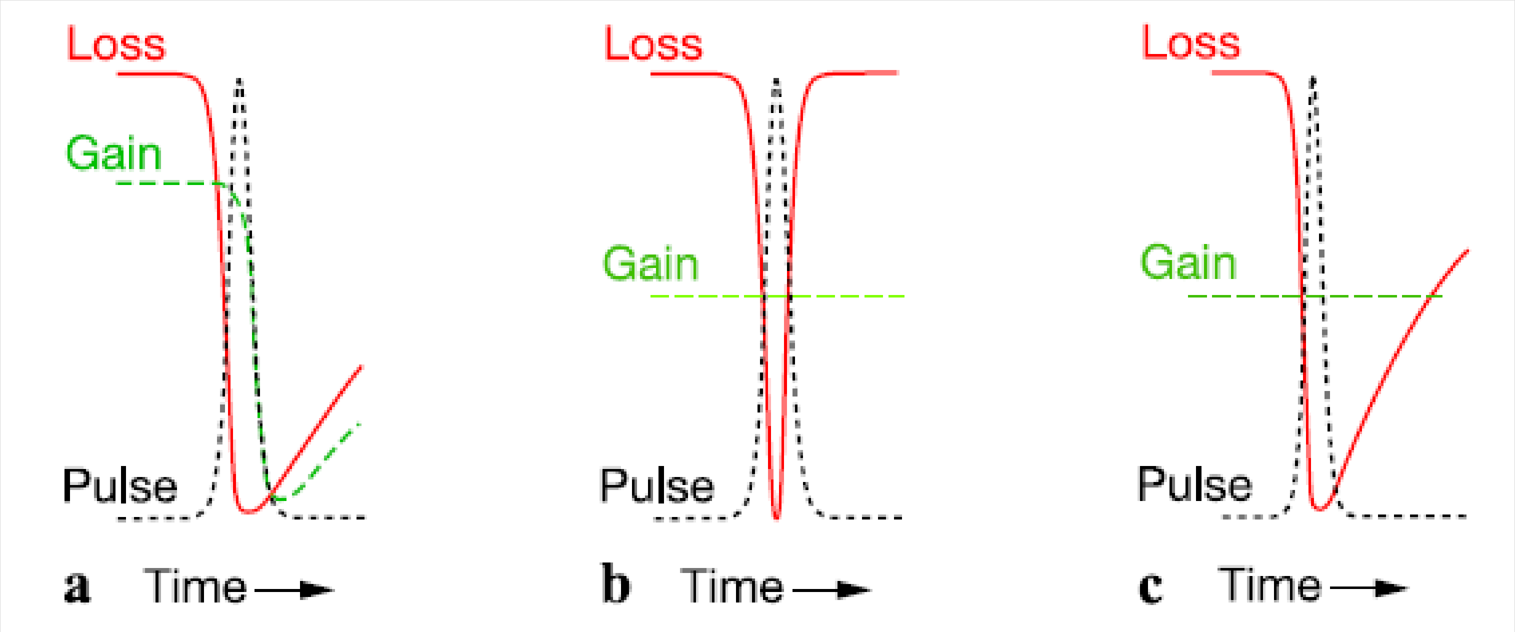
This is the most common situation, unless the pulse is many ps long.

Gain Saturation shortens the pulse trailing edge.

- The **intense spike uses up** the **laser gain-medium energy**, reducing the **gain available** for the **trailing edge** of the pulse (and for later pulses).



Summary of the different mode locking techniques:



(a) **Passive mode-locking** with a **slow saturable absorber** and **dynamic gain saturation**

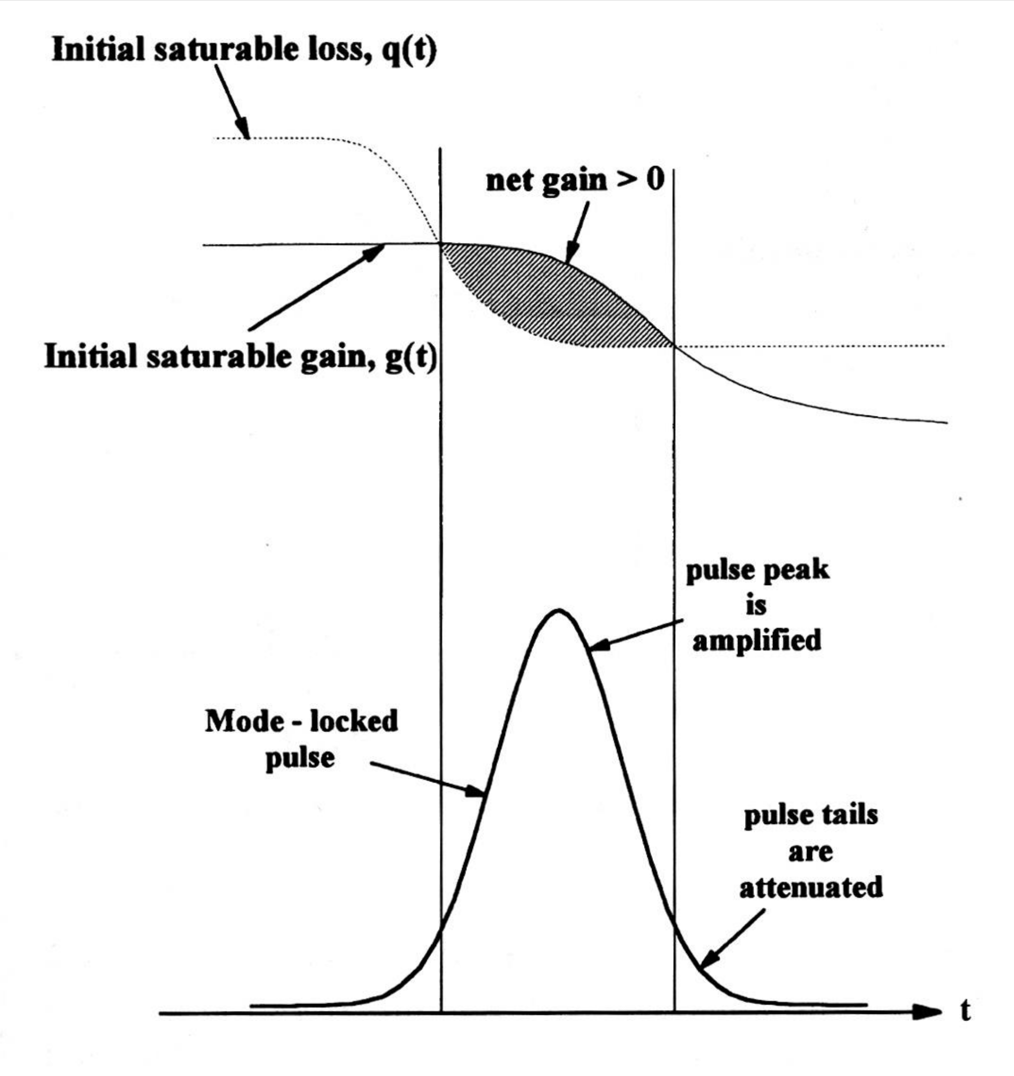
(b) Passive mode-locking with a **fast saturable absorber**

(c) Passive mode-locking with a **slow saturable absorber without dynamic gain saturation** in the **picosecond regime** and in the **femtosecond** regime (referred to as **soliton mode-locking**)

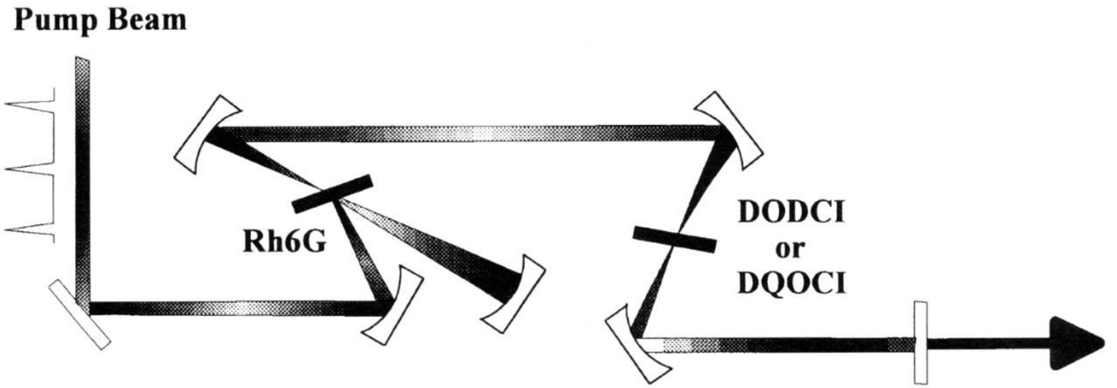
Saturable gain and loss

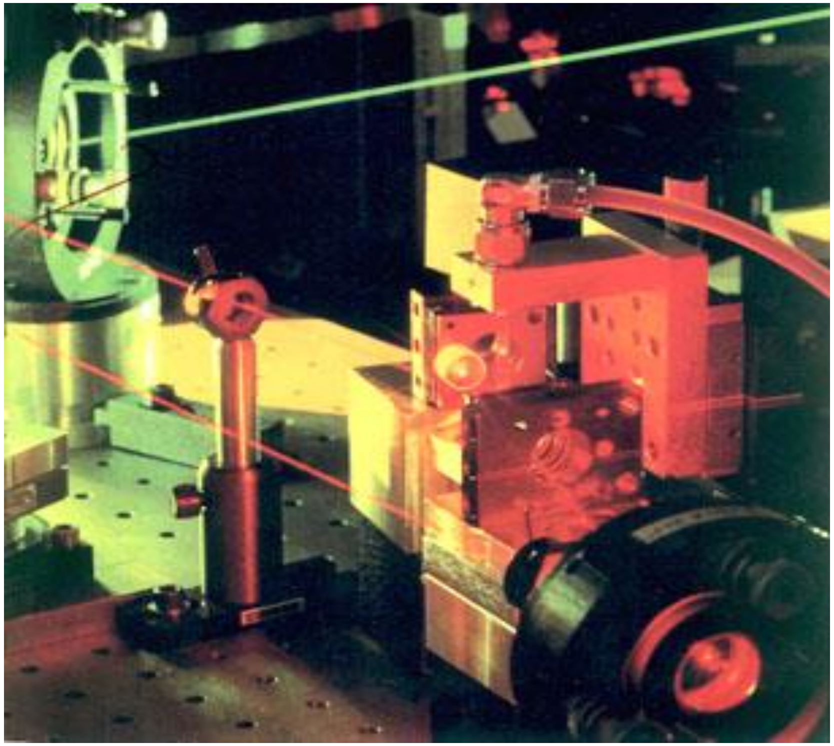
Lasers lase when the **gain** exceeds the **loss**.

The combination of **saturable absorption** and **saturable gain** yields short pulses even when the **absorber** is **slower** than the pulse.



The Passively Mode-locked Dye Laser

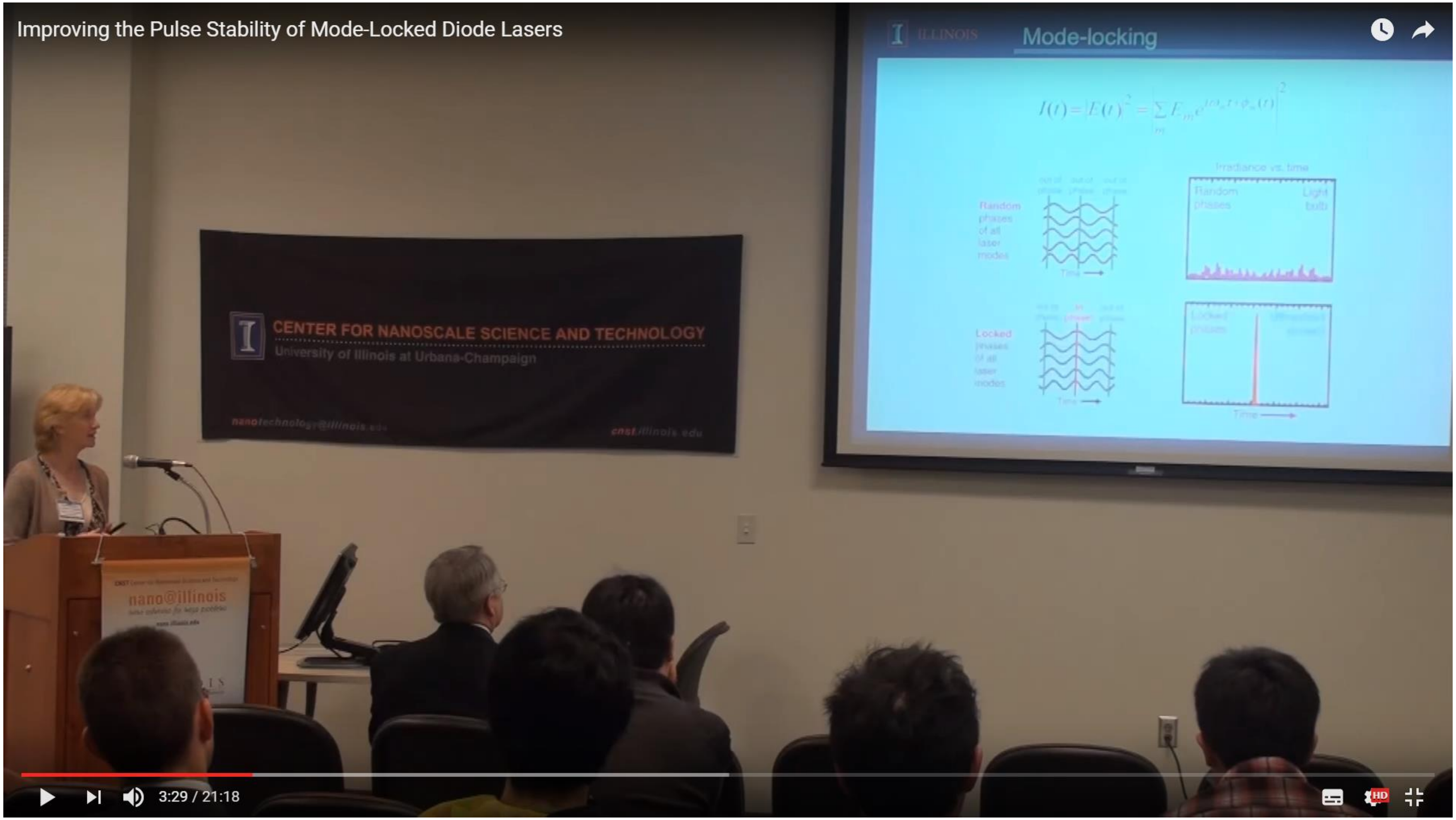




Passively mode-locked dye lasers yield pulses as short as a few hundred fs.

Mode locking by the saturable absorber

- https://www.youtube.com/watch?v=CVVDnx_EhhU

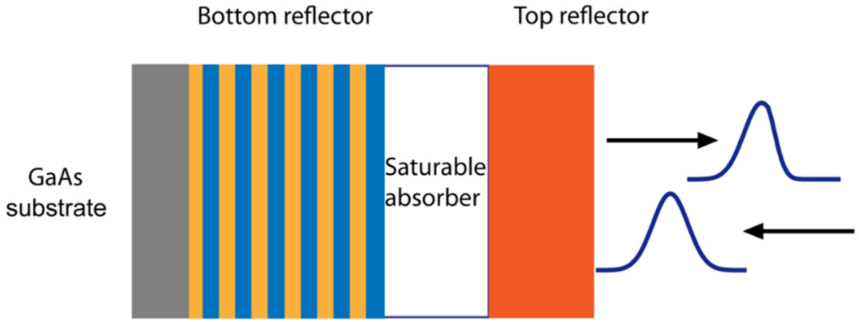


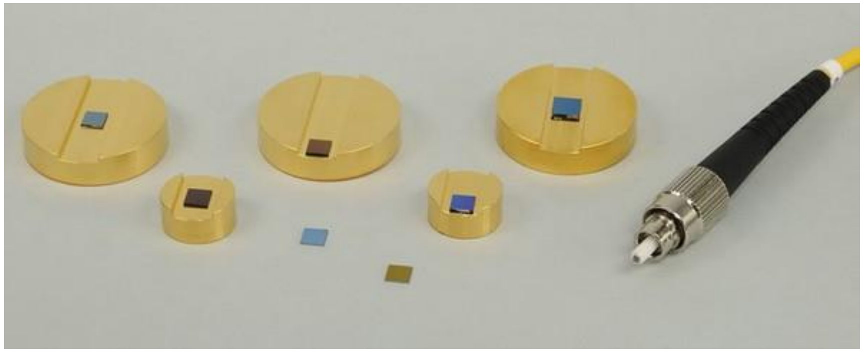
Some common dyes and their corresponding saturable absorbers

Gain dye	Saturable absorber	Wavelength in nm
Rh6G	DODCI, DDI	575–620
Kiton Red	DQOCI	600–655
DCM	DODCI, DTDCI	620–660
Pyridine 1	DTDCI, DDI	670–740
LD 700	DTDCI, DDI, IR 140	700–800
Pyridine 2	IR 140, HITC	690–770
Styryl 9M	DDI, IR 140	780–860

Passive mode locked fiber lasers in use of saturable absorber

Saturable absorber (SA)	Disadvantage
Semiconductor saturable absorber mirror (SESAM) [1]	1.Complicated fabrication and packaging technique 2.Limited operation bandwidth

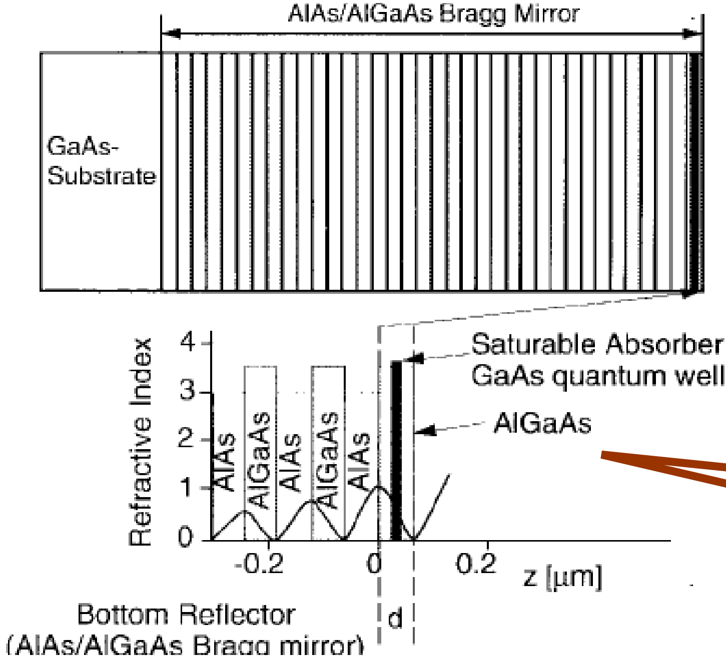


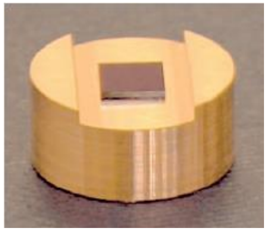


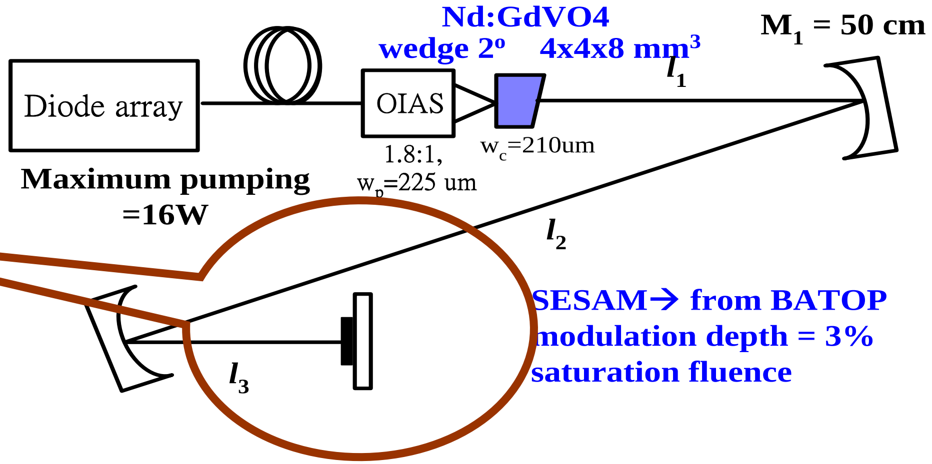
- SAs demand less stringent fabrication method, fast recovery time, low saturation intensity and low cost.

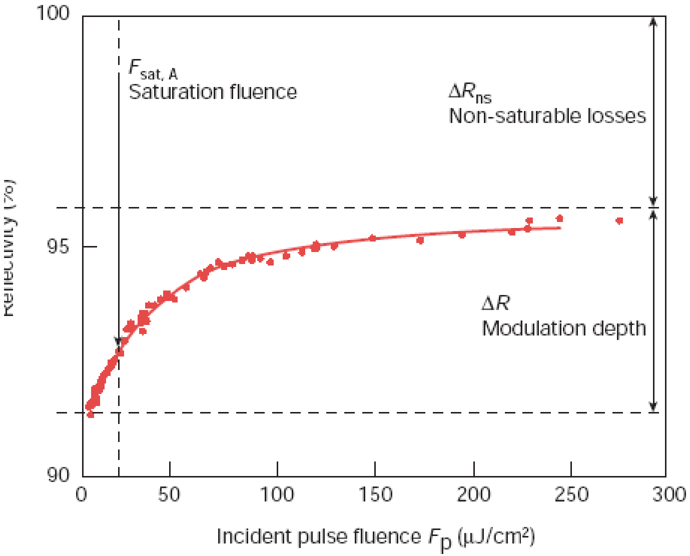
[1] O. Okhotnikov, et al. New journal of physics 6(1) (2004), 177.

Semiconductor Saturable Mirror (SESAM)



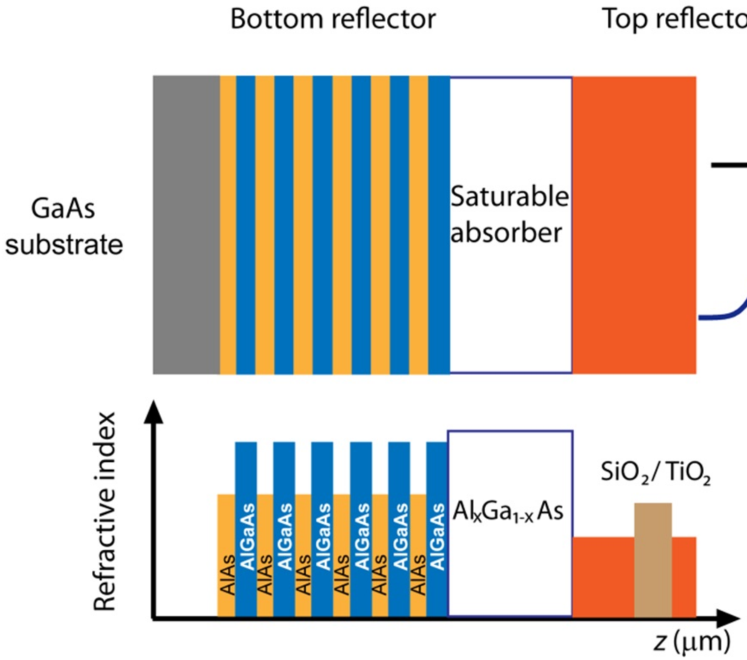


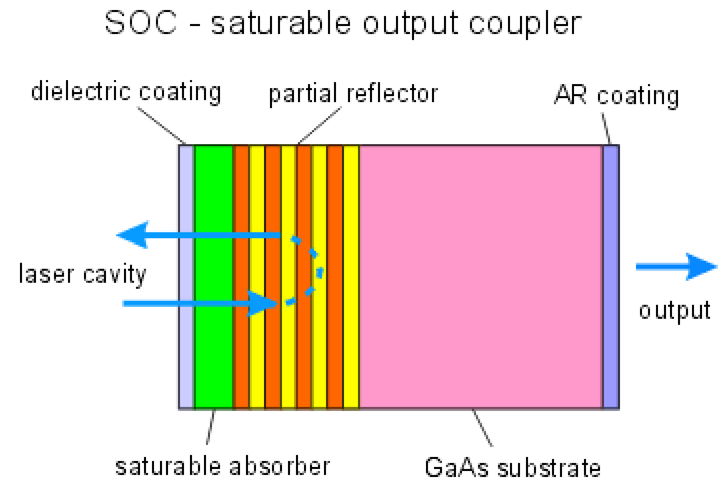


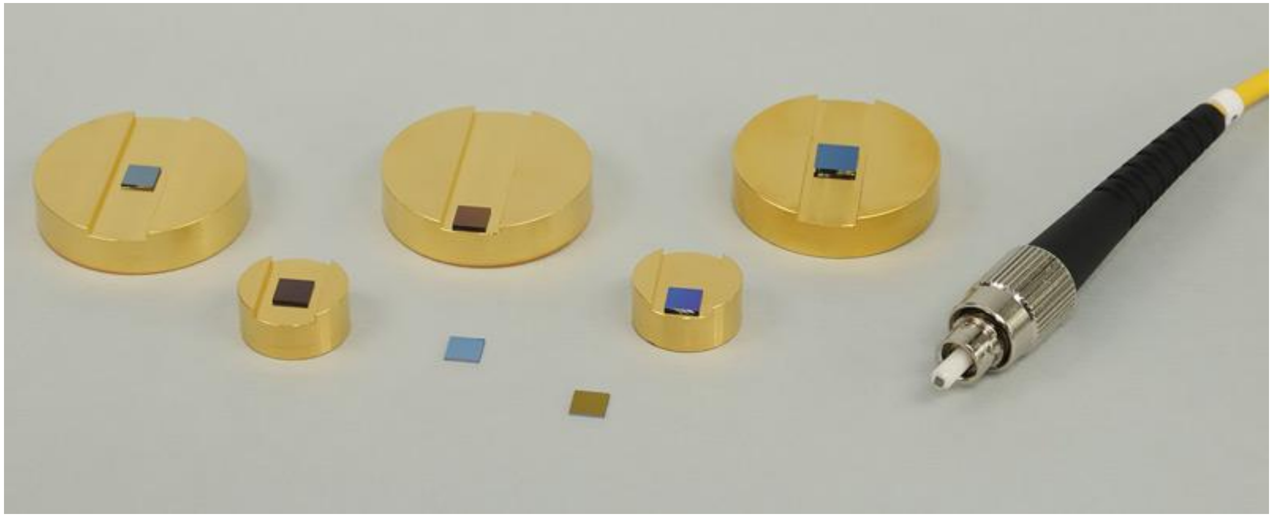


- A **saturable absorber** in conjunction with the **Bragg mirror** that is formed by the quarter-wave layer of two dielectric media
- **Reflectivity** of the mirror increase @ the peak of the pulse

Semiconductor saturable absorber mirror



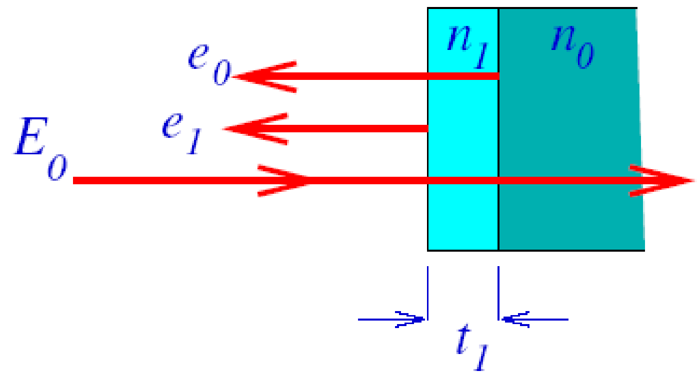




Single layer Anti-reflection Coating

- At **normal incidence**, the amplitude reflectance of the interface interface between dielectric materials of refractive index n_1 and n_2,

$$r = \frac{n_1 - n_2}{n_1 + n_2}$$



- The **intensity reflectance** is

$$R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$$

- For an air/glass interface with n_1 = 1.0 and n_2 = 1.5, we get R 4%, which is a very significant loss.
- If we illuminate the surface with a normal incident beam of amplitude E_0 and wavelength λ, *T*hen we will get reflections from both the **air/n_1** and the **n_1/n_0** interface of e_1 and e_0,

$$e_1 = E_0 r_1 \quad \text{and} \quad e_0 = E_0 r_0 \exp(-i g_1)$$

- Where $r_1 = \frac{1-n_1}{1+n_1}$ and $r_0 = \frac{n_1 - n_0}{n_1 + n_0}$ and $g_1 = 2\frac{2\pi}{\lambda} t_1 n_1$

- To get **anti-reflection condition,** we want e_1 and e_0 to cancel, so $e_1 + e_0 = 0$

- We want e_1 and e_0 be of opposite sign, so $\boldsymbol{g_1 = \pi}$, giving that

$$n_1 t_1 = \frac{\lambda}{4} \quad \text{so that} \quad t_1 = \frac{\lambda}{4 n_1}$$

$$g_1 = (2m+1)\pi \Rightarrow t_1 = (2m+1)\frac{\lambda}{4n_1}$$

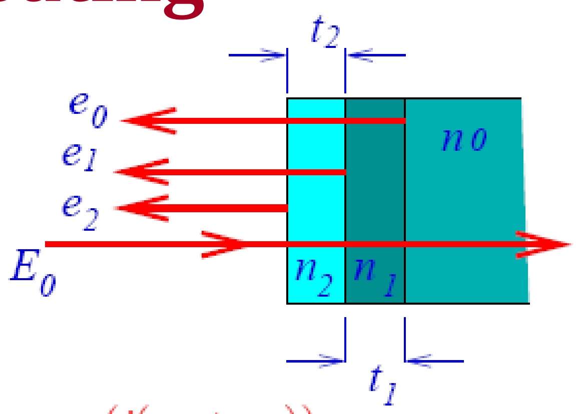
- The coating must have a optical path-length of quarter of a wavelength, and also we must have that

$$r_1 = r_0 \quad \text{to that} \quad \frac{1-n_1}{1+n_1} = \frac{n_1 - n_0}{n_1 + n_0}$$

- It has the solution

$$\boxed{n_1 = \sqrt{n_0}}$$

Double layer Anti-reflection Coating



The solution is to use *two* layers coating.

Ignoring multiple reflections, we then want $e_2 + e_1 + e_0 = 0$

where $e_2 = E_0 r_2$ and $e_1 = E_0 r_1 \exp(i g_2)$ and $e_0 = E_0 r_0 \exp(i(g_2 + g_1))$

Simplest case *quarter wave*, $g_1 = g_2 = \pi$, so, $t_2 = \dfrac{\lambda}{4 n_2}$ and $t_1 = \dfrac{\lambda}{4 n_1}$

For an *anti-reflection* coating we require that $r_2 - r_1 + r_0 = 0$

where we have that $r_2 = \dfrac{1 - n_2}{1 + n_2}$ and $r_1 = \dfrac{n_2 - n_1}{n_2 + n_1}$ and $r_0 = \dfrac{n_1 - n_0}{n_1 + n_0}$

which if you expand, and collect terms, give the required solution that

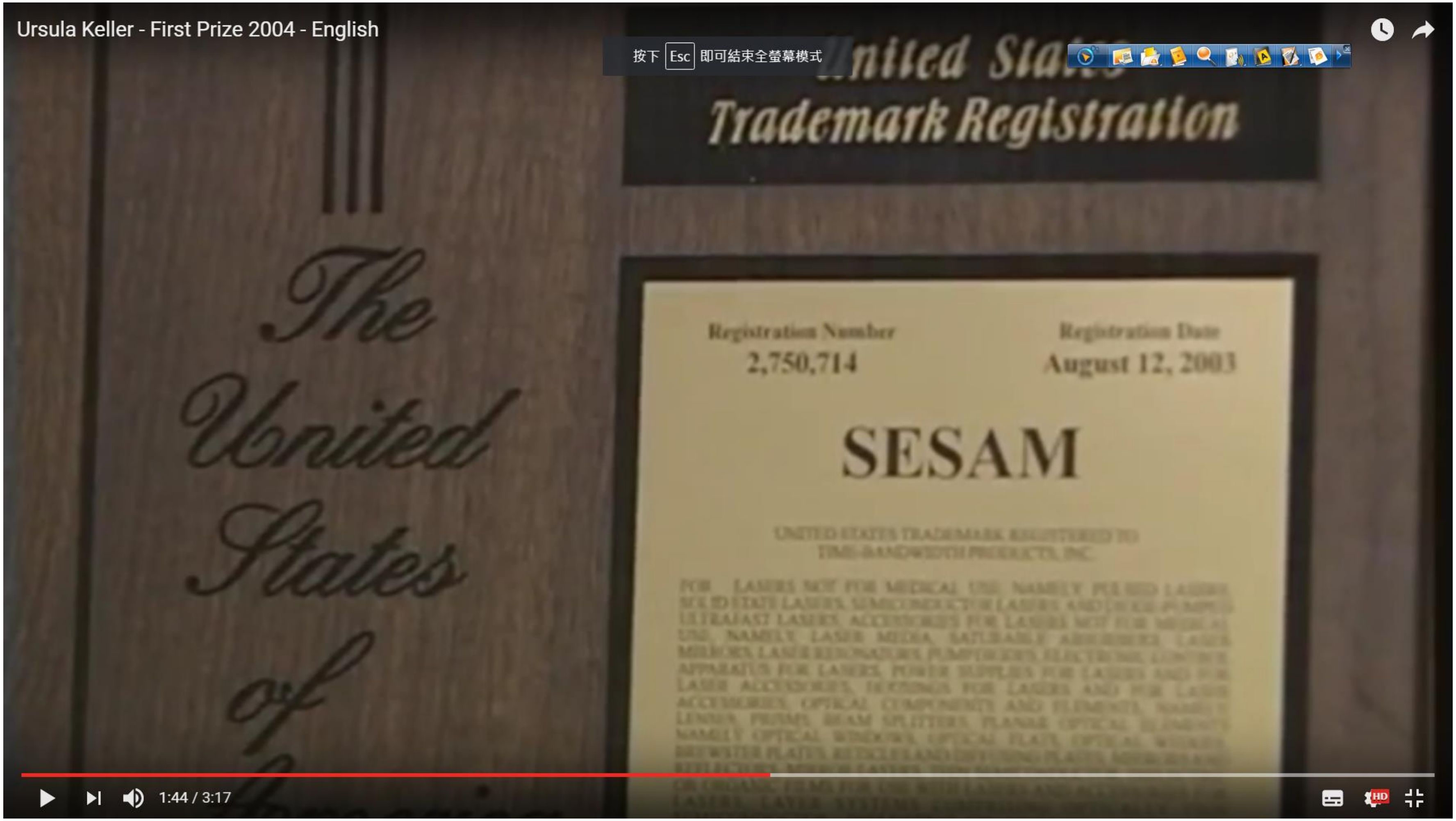
$$\frac{n_1}{n_2} = \sqrt{n_0}$$

so for any glass, we get a range of possible combinations to give an *anti-reflection* coating.

For $n_0 = 1.51$ then MgF_2, $n_2 = 1.38$ and Al_2O_3 $n_1 = 1.63$ *almost* work!

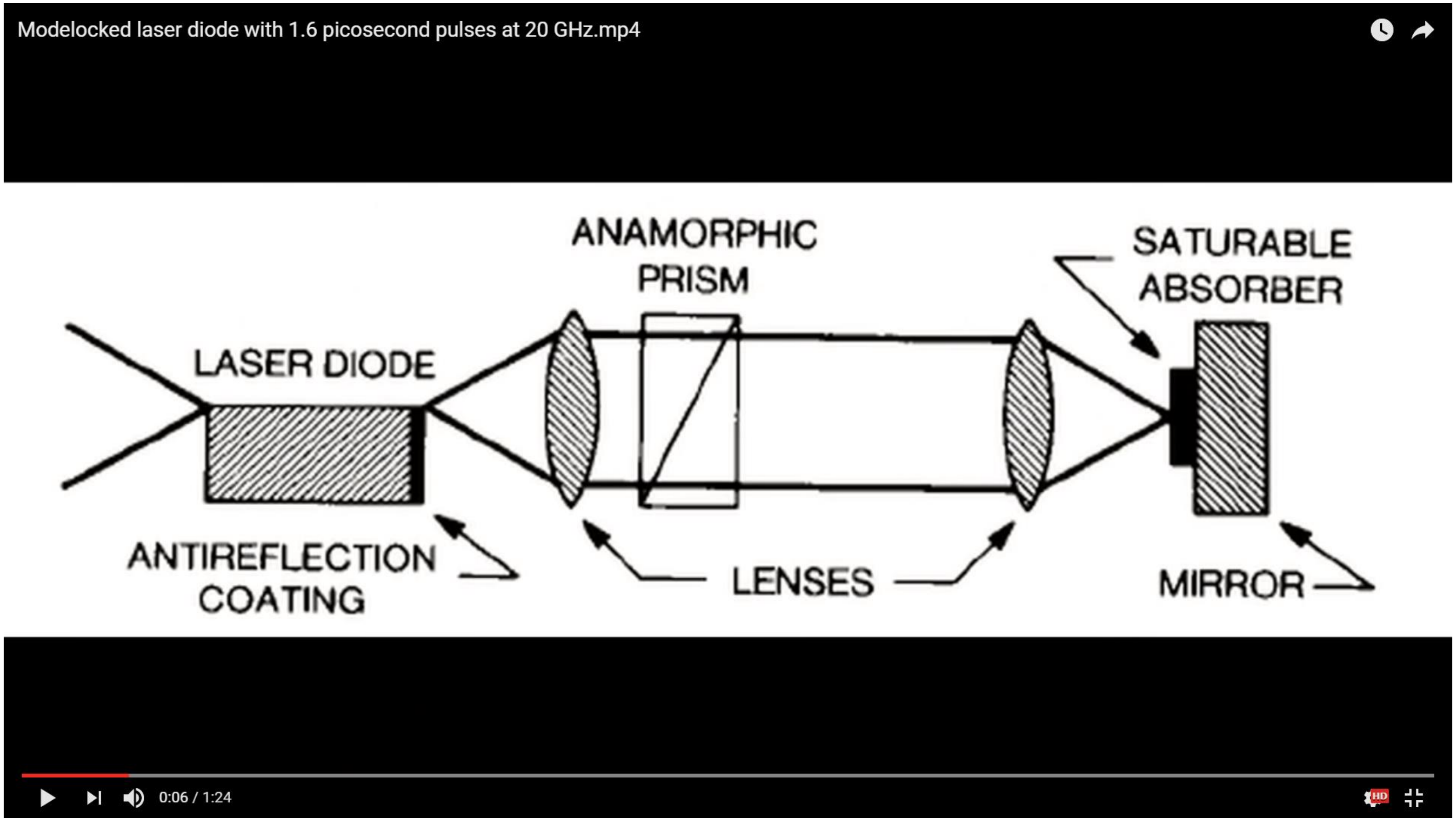
Keller - First Prize 2004

https://www.youtube.com/watch?v=QbaqNoxPNcQ

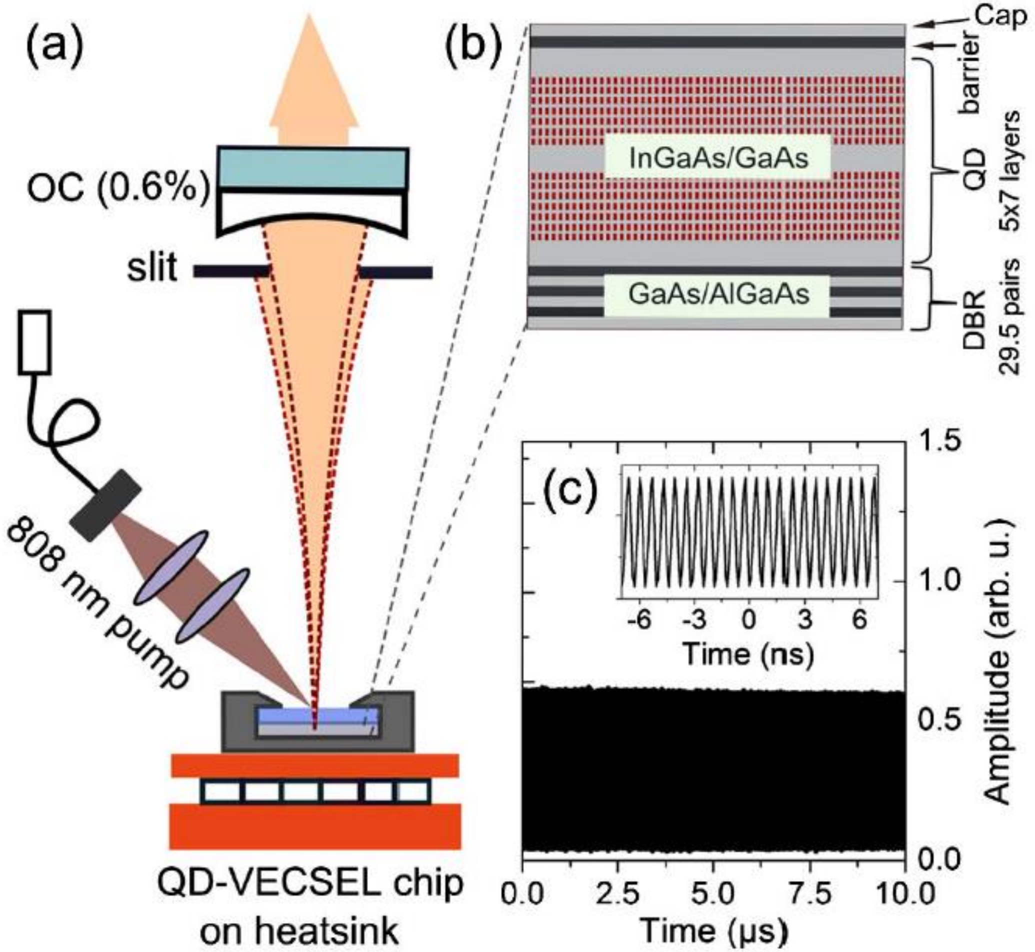


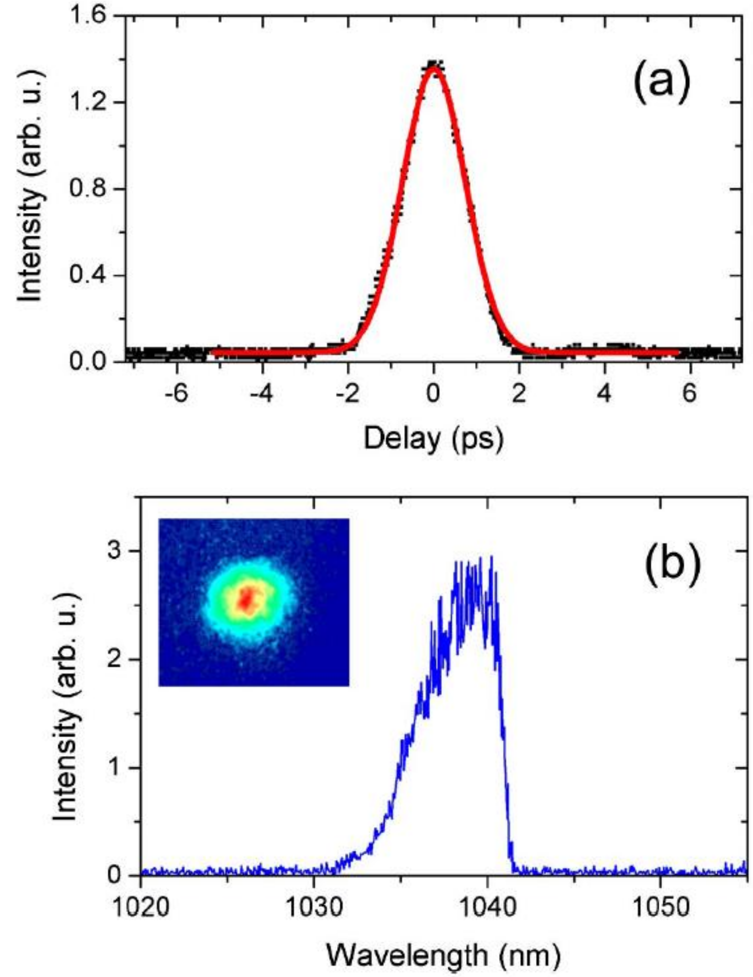
Mode-locked diode with 20 GHz

- https://www.youtube.com/watch?v=aOTLhk6GuB4



Self-mode-locked quantum-dot vertical-external-cavity surface-emitting laser

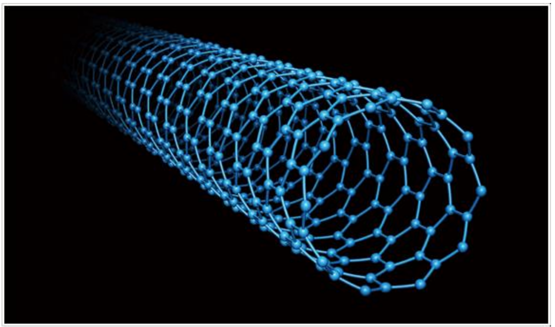




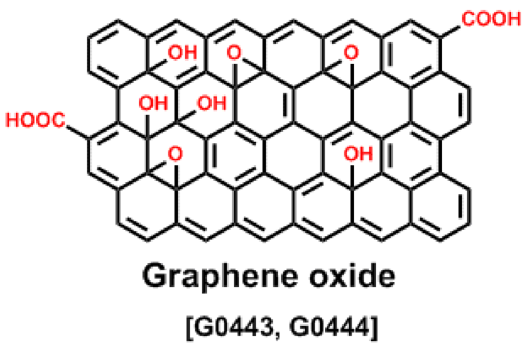
Passive mode locked fiber lasers in use of saturable absorber

Saturable absorber (SA)	Disadvantage
Carbon nanotubes [1]	1.Working wavelengths related to the diameter of the nanotubes 2.Relatively expensive
Graphene or Graphene oxide [2-3]	1.Small absorption 2.Low modulation depth

Carbon nanotubes



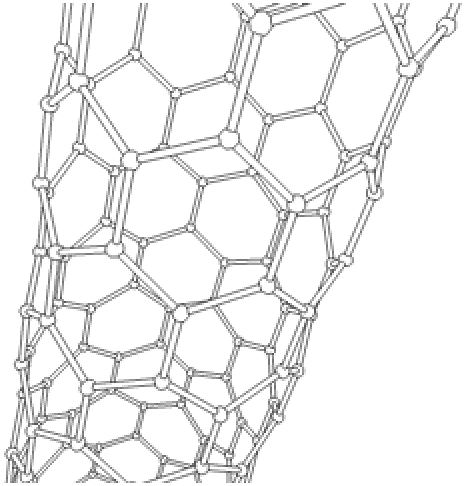
Molecular structure



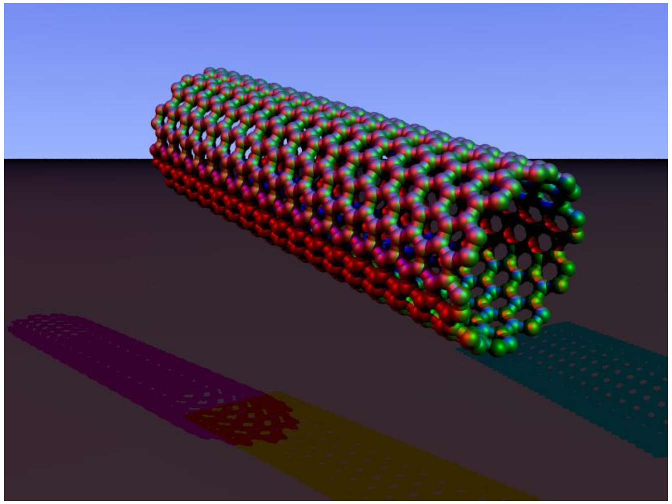
[1] F. Wang, et al. Nature nanotechnology 3(12) (2008), 738-742.
[2] G. Sobon, et al. Laser Physics Letters 9(8) (2012), 581.
[3] J. Lee, et al. Laser Physics Letters 10(3) (2013), 035103.

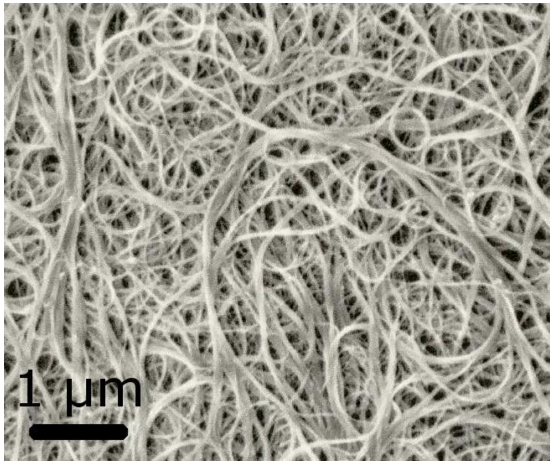
Carbon nanotubes (CNTs)

- **Carbon nanotubes** (**CNTs**) are **allotrope of carbon** with **cylindrical nanostructure**.
- **Nanotubes** have been constructed with **length-to-diameter ratio** of up to 132,000,000:1, significantly larger than for any other material.
- These **cylindrical carbon molecules** have unusual properties, which are valuable for **nanotechnology**, **electronics**, **optics** and other fields **of materials science** and **technology**.
- In particular, owing to their **extraordinary thermal conductivity** and **mechanical** and **electric properties, carbon nanotubes** find applications as additives to various structural materials.
- For instance, nanotubes form a tiny portion of the material(s) in some (primarily **carbon fiber**) **baseball bats**, **golf clubs**, car parts or **damascus steel**.



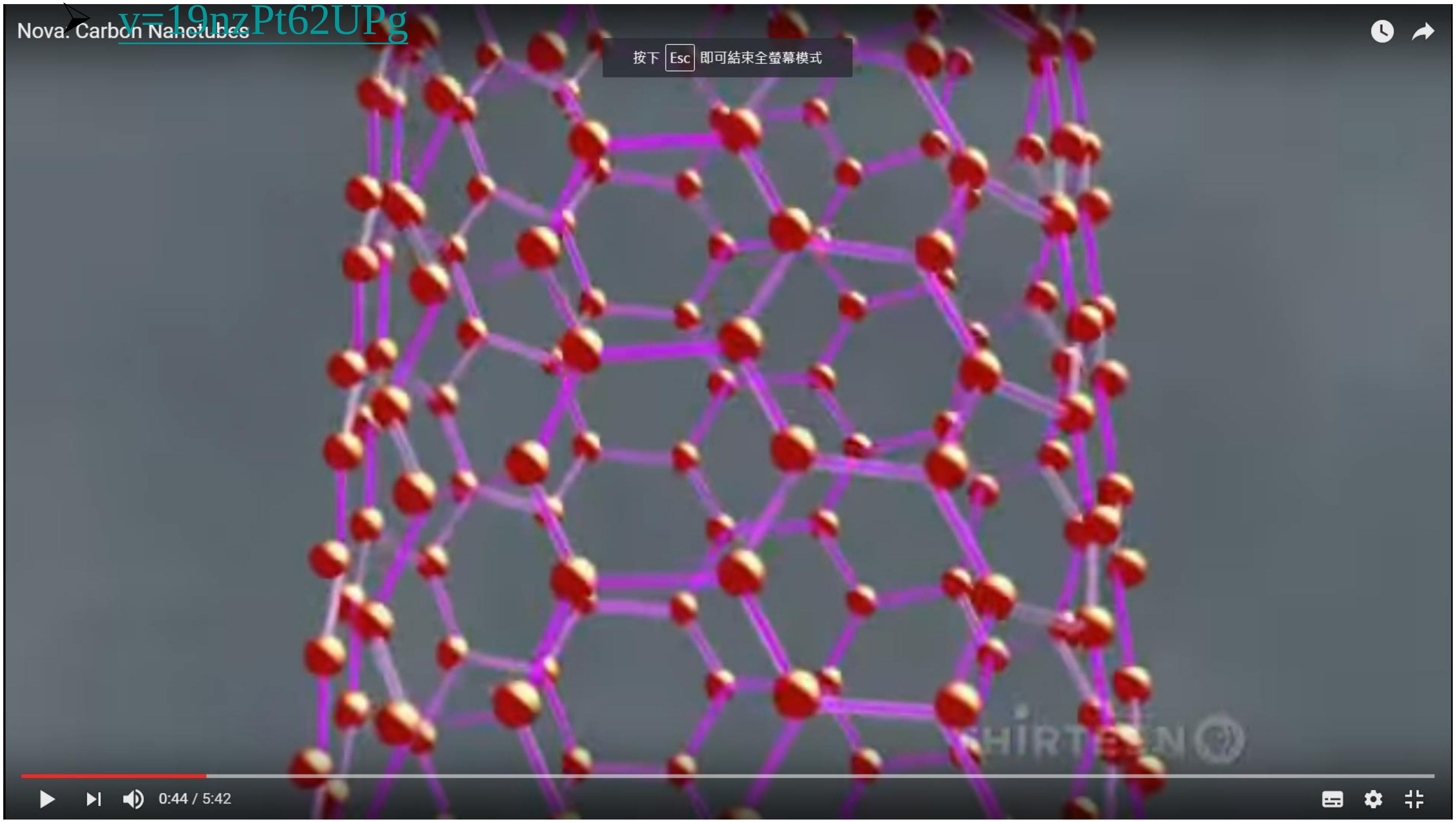
- The name of **nanotubes** is derived from their long, **hollow structure** with the **walls** formed by **one-atom-thick sheets** of **carbon**, called **graphene**.
- These sheets are rolled at **specific** and **discrete** ("**chiral**") angles, and the combination of the **rolling angle** and **radius** decides the nanotube properties.
- Nanotubes are categorized as **single-walled nanotubes** (SWNTs) and **multi-walled nanotubes** (MWNTs)

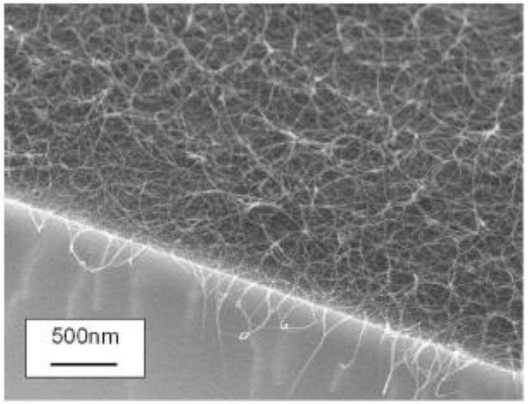


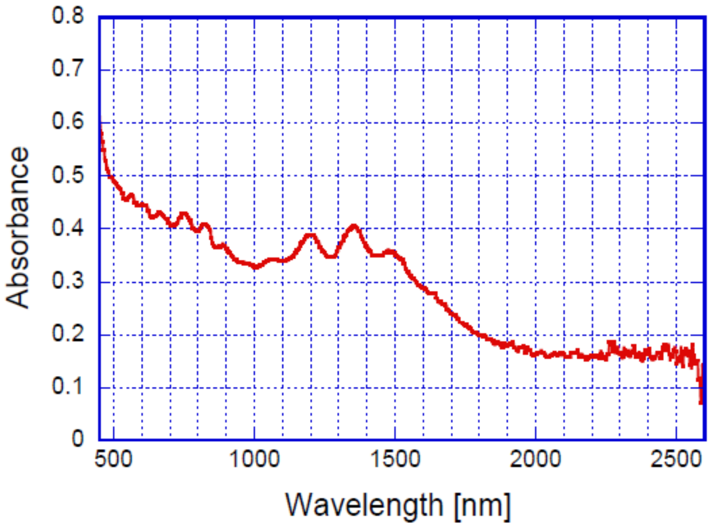


Carbon nanotube

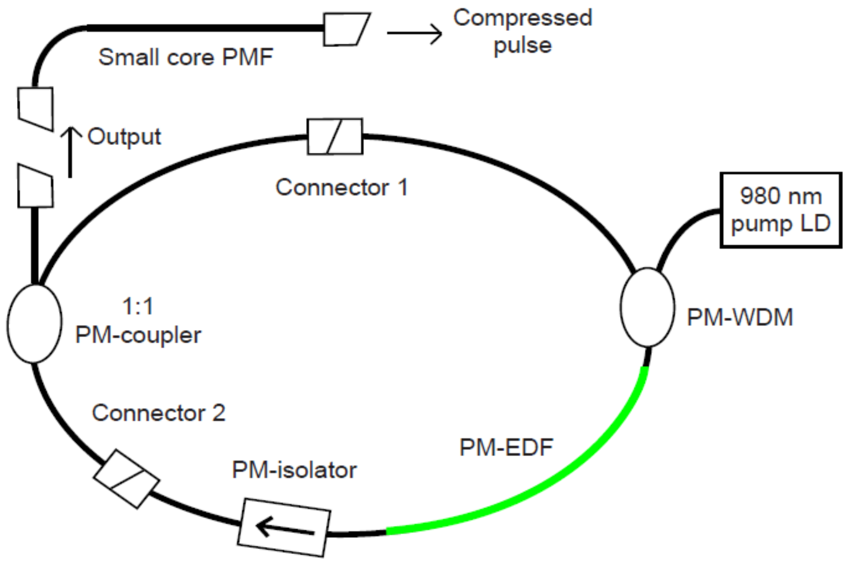
- https://www.youtube.com/watch?
- v=19nzPt62UPg







SWNT synthesized directly onto a **quartz substrate**: (a) field-emission scanning electron microscopeimage, (b) absorption.



Configuration of all polarization-maintaining (PM) passively mode-locked Er-doped ultrashort-pulse fiber laser using **SWNT–polyimide film**.

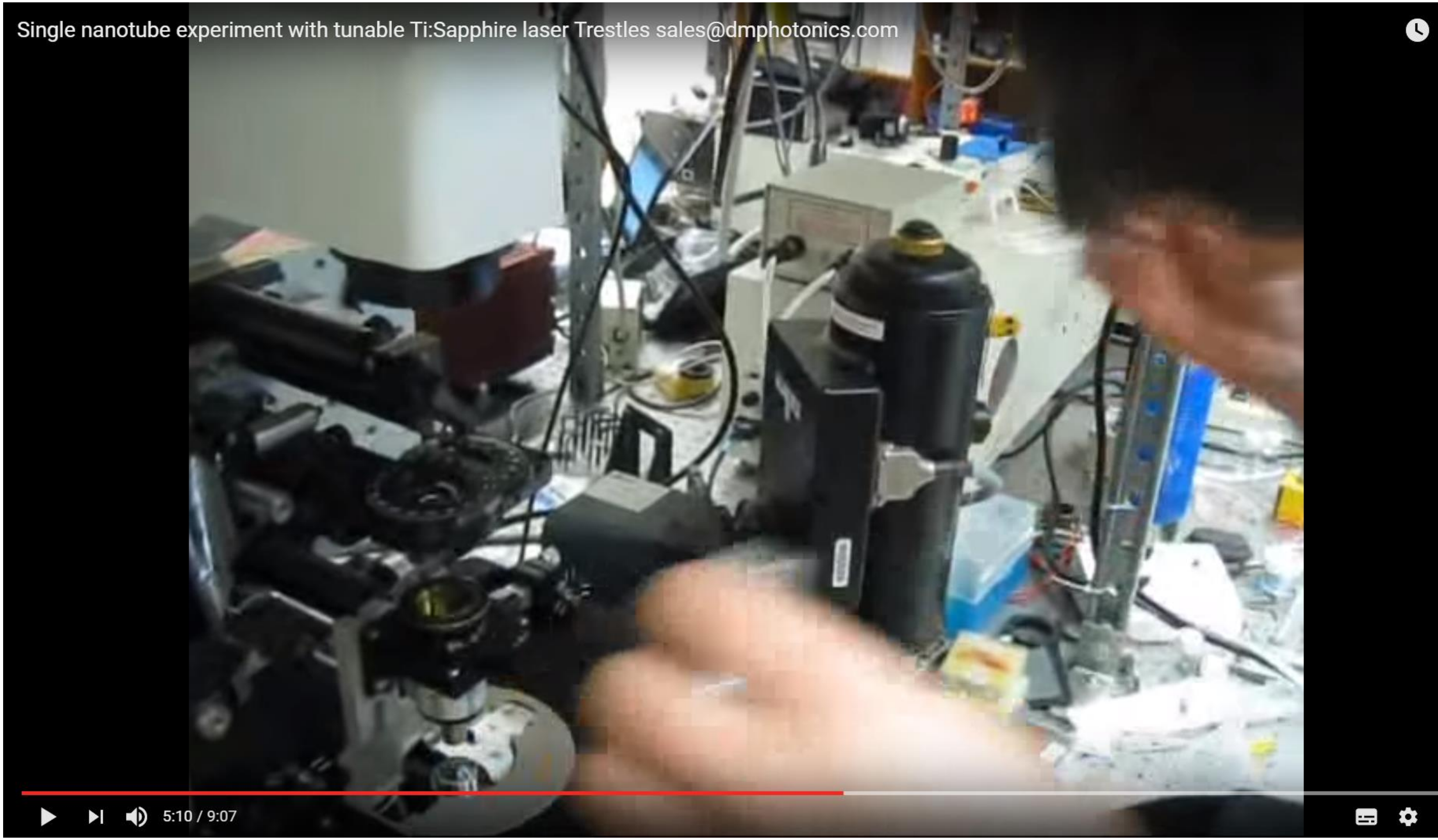
23 2008 Vol. 16, No. 13 OPTICS EXPRESS 9429

Polymer-carbon nanotube films

- https://www.youtube.com/watch?v=ATv8lDcwS2s

Study carbon nanotube by tunable laser

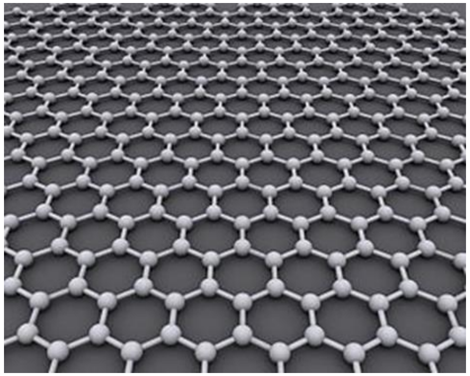
- https://www.youtube.com/watch?v=1PbWyPjD788



Graphane from wiki

graphit
e

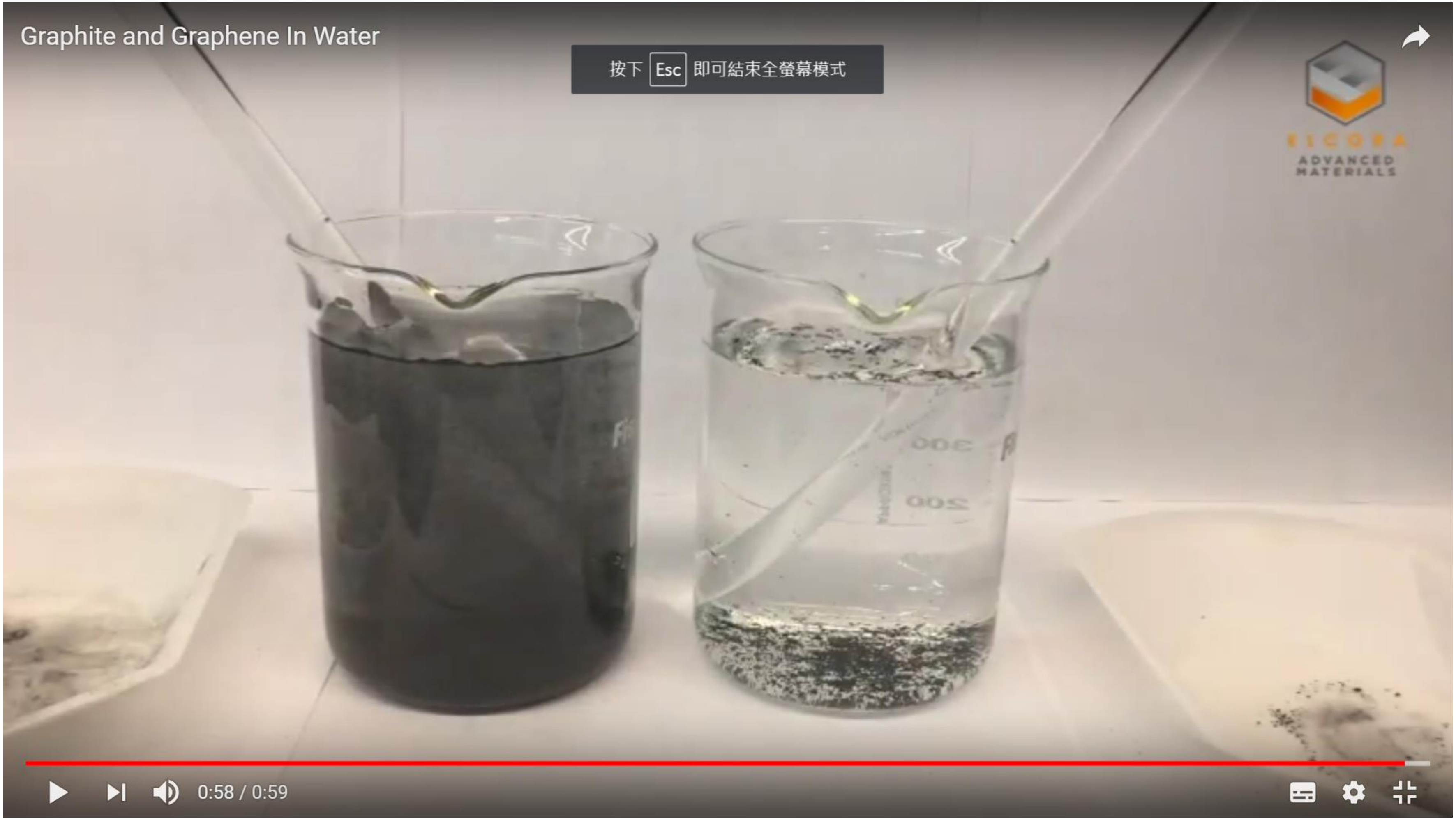
- Graphane is an **allotrope (同素異形體)** of **carbon** in the form of **two dimensional**, **atomic-scale**, **honey-comb lattice** in which one atom form each vertex.
- It is the **basic structureal element** of other allotrope including
  - graphite (石墨)
  - charcoal (木炭)
  - carbon nanotube
  - fullerenes (富勒烯)



- It can also be considered as indefinitely large **aromatic molecule (芳香族分子)**，the ultimate case of the family of **flat polycyclic aromatic hydrocarbons (聚環狀芳香族碳氫物 or 多環芳香烴)**. https://zh.wikipedia.org/wiki/%E5%A4%9A%E7%92%B0%E8%8A%B3%E9%A6%99%E7%83%B4

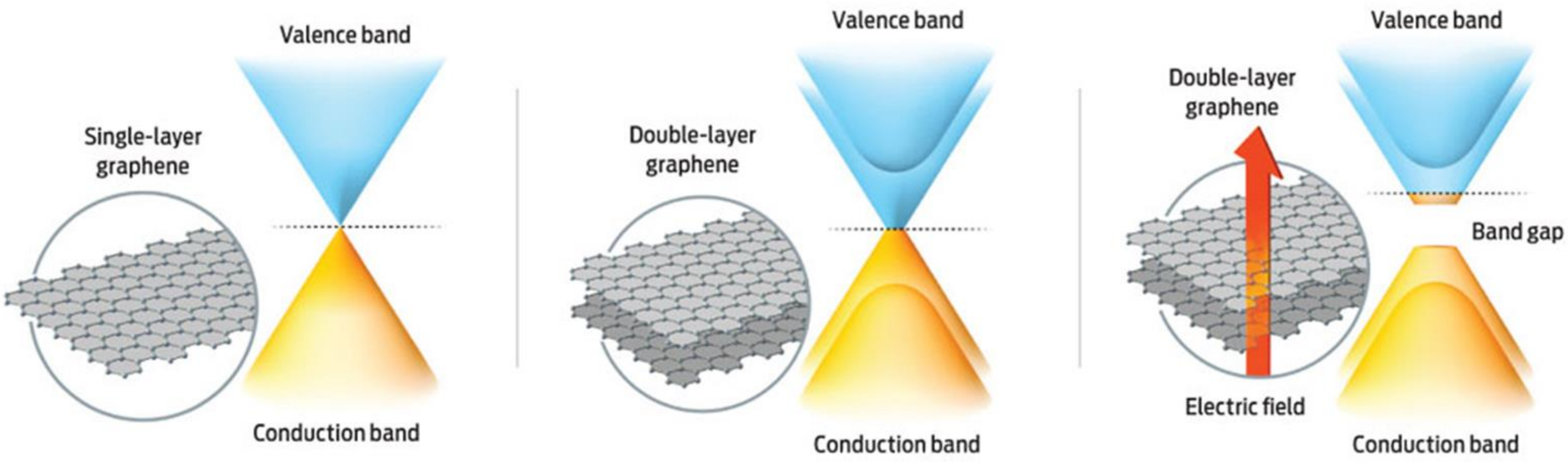
Graphite and Graphene In Water

- https://www.youtube.com/watch?v=V_aduFC-Ybk



Extraordinary properties of Graphene

- It is about **100 times stronger** than the **strongest steel**.
- It conducts **heat** and **electricity efficiently** and is nearly **transparent**.[3]
- Researchers have identified the **bipolar transistor effect (雙極型電晶體)**, **ballistic transport** (彈道傳輸) **of charges** and **large quantum oscillations** in the material.
- Scientists have theorized about **graphene** for decades.
- It has likely been unknowingly produced in small quantities for centuries, through the use of **pencils** and other similar applications of graphite.
- It was originally observed in **electron microscopes** in 1962, but only studied while supported on **metal surfaces**.

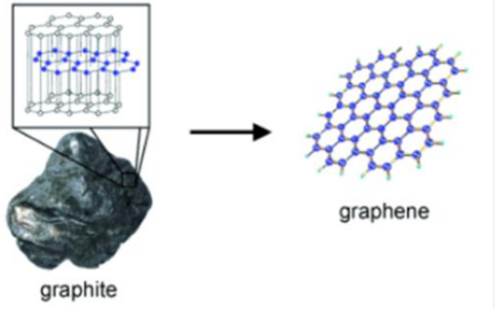


Breaking Symmetry: The existence of an energy gap between the **conduction** and **valence electron bands** of a semiconductor is what makes it possible for the material to act as a semiconductor. In both single-layer and double-layer graphene [left and middle], the valence and conduction bands are in effect **conical** and meet at a point, with no band gap. The introduction of an **electric field** perpendicular to the layers [right] creates an asymmetry, which generates a **band gap**. Though small, the gap is tunable, creating possibilities for new devices.

- https://spectrum.ieee.org/semiconductors/materials/graphene-makes-transistors-tunable

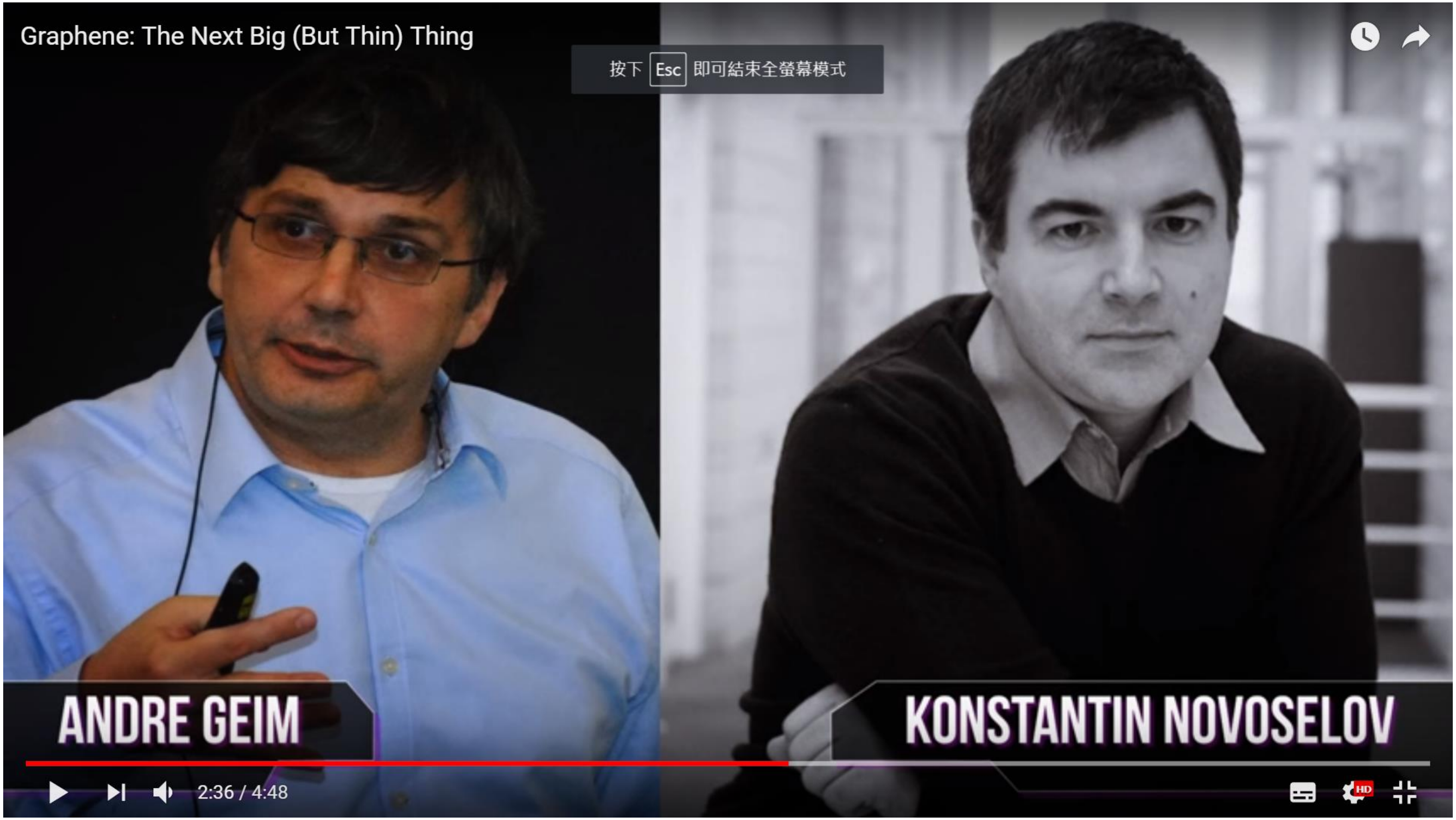
Novbel Prize of Physics

- The material was later rediscovered, isolated and characterized in 2004 by **Andre Geim** (安德烈·海姆) and **Konstantin Novoselov** (康斯坦丁·諾沃肖洛夫) at the **University of Manchester** (英國曼徹斯特大學).
- Research was informed by existing theoretical descriptions of its **composition**, **structure** and **properties**.
- High-quality graphene proved to be surprisingly easy to isolate, making more research possible.
- This work resulted in the two winning the **Nobel Prize in Physics** in 2010 "for **groundbreaking experiments regarding the two-dimensional material graphene**."



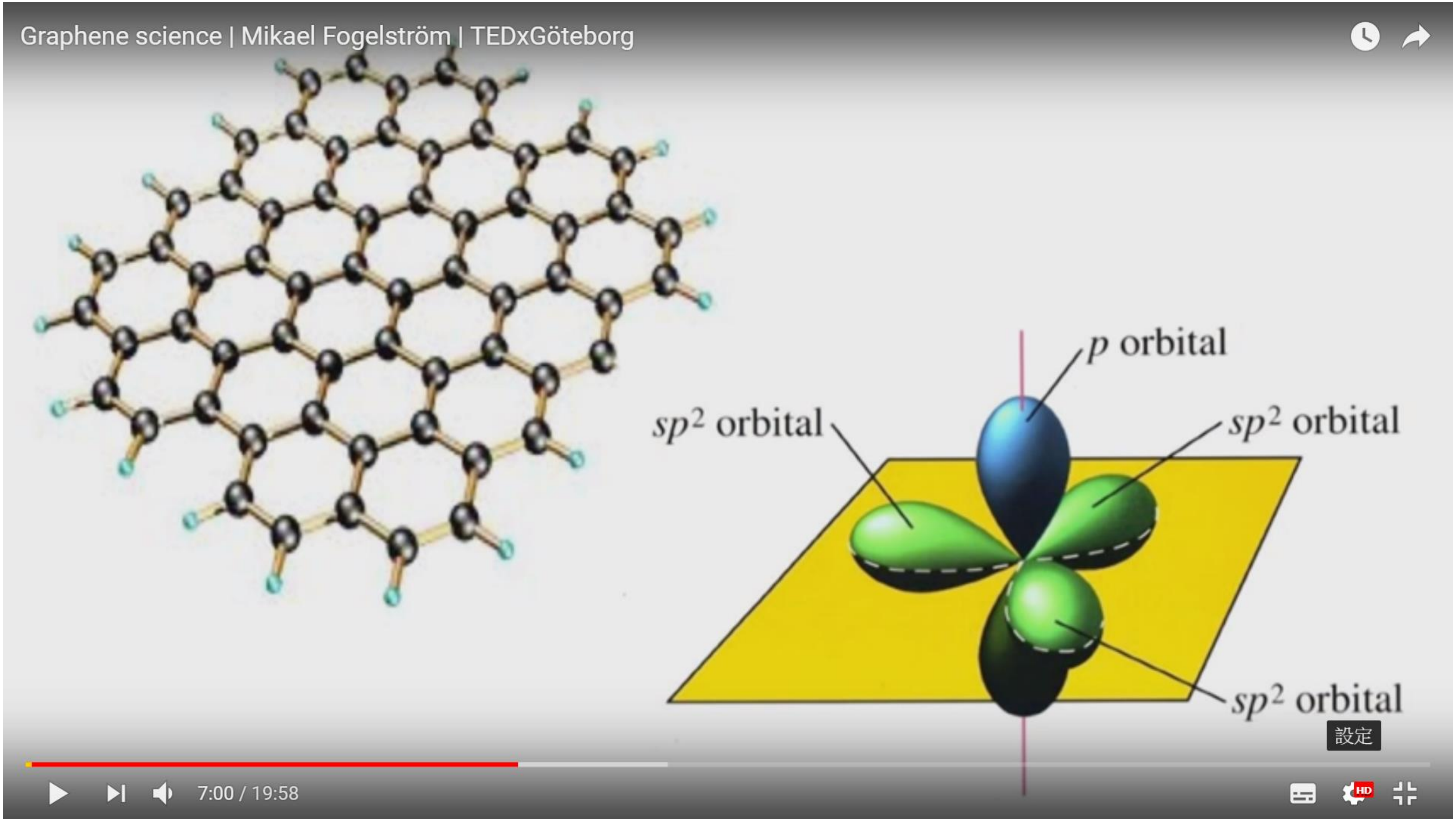
Graphene: The Next Big (But Thin) Thing

➢ https://www.youtube.com/watch?v=Mcg9_ML2mXY



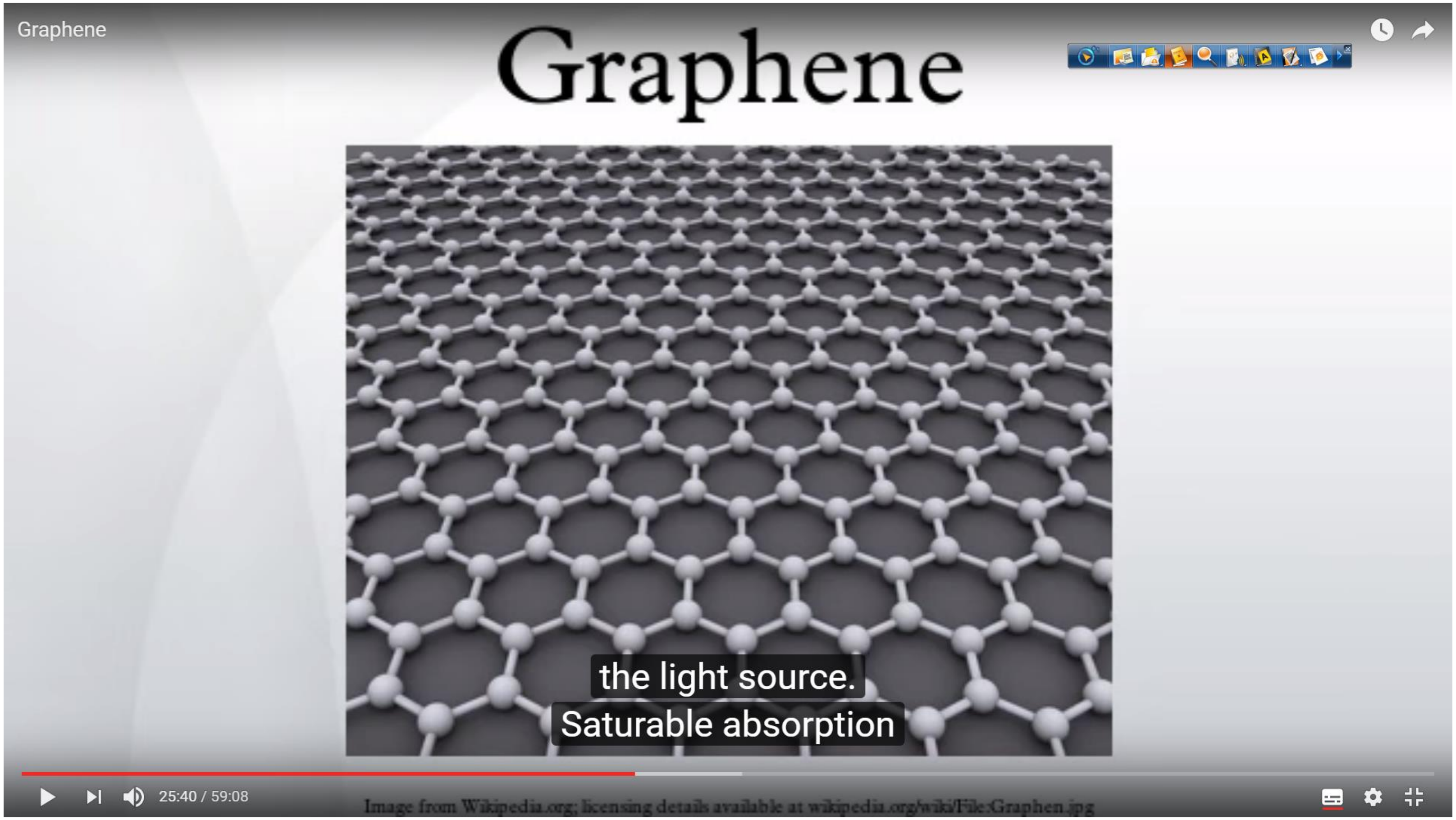
Graphene science

- https://www.youtube.com/watch?v=eh3dA8xnZ4Y



Graphene and Graphene oxide (SA 25:40)

https://www.youtube.com/watch?v=p5pXzOHhOZE

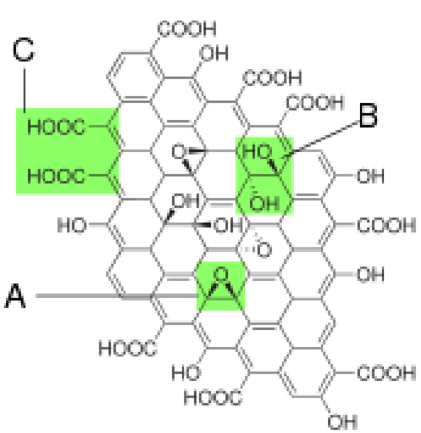


Production of Carbon Nanotubes and Graphene at the MpNL

- https://www.youtube.com/watch?v=CuqS8GSpC-4

Graphite oxide (from wiki)

- **Graphite oxide**, formerly called graphitic oxide (**石墨氧化物**) or graphitic acid (**石墨酸**), is a compound of **carbon**, **oxygen**, and **hydrogen** in variable ratios, obtained by treating graphite with strong oxidizers.
- The **maximally oxidized bulk product** is a **yellow solid** with **C:O ratio** between **2.1 and 2.9**, that retains the layer structure of graphite but with a much larger and irregular spacing

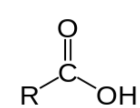


Structure proposed in 1998[1] with functional groups.

A: Epoxy bridges, (環氧化合物)

B: Hydroxyl groups, (羥ㄑㄧㄤˇ基又稱**氫氧基**，化學式為**–OH**)

C: Pairwise carboxyl groups. (羧ㄙㄨㄛ基，通式是R-COOH)

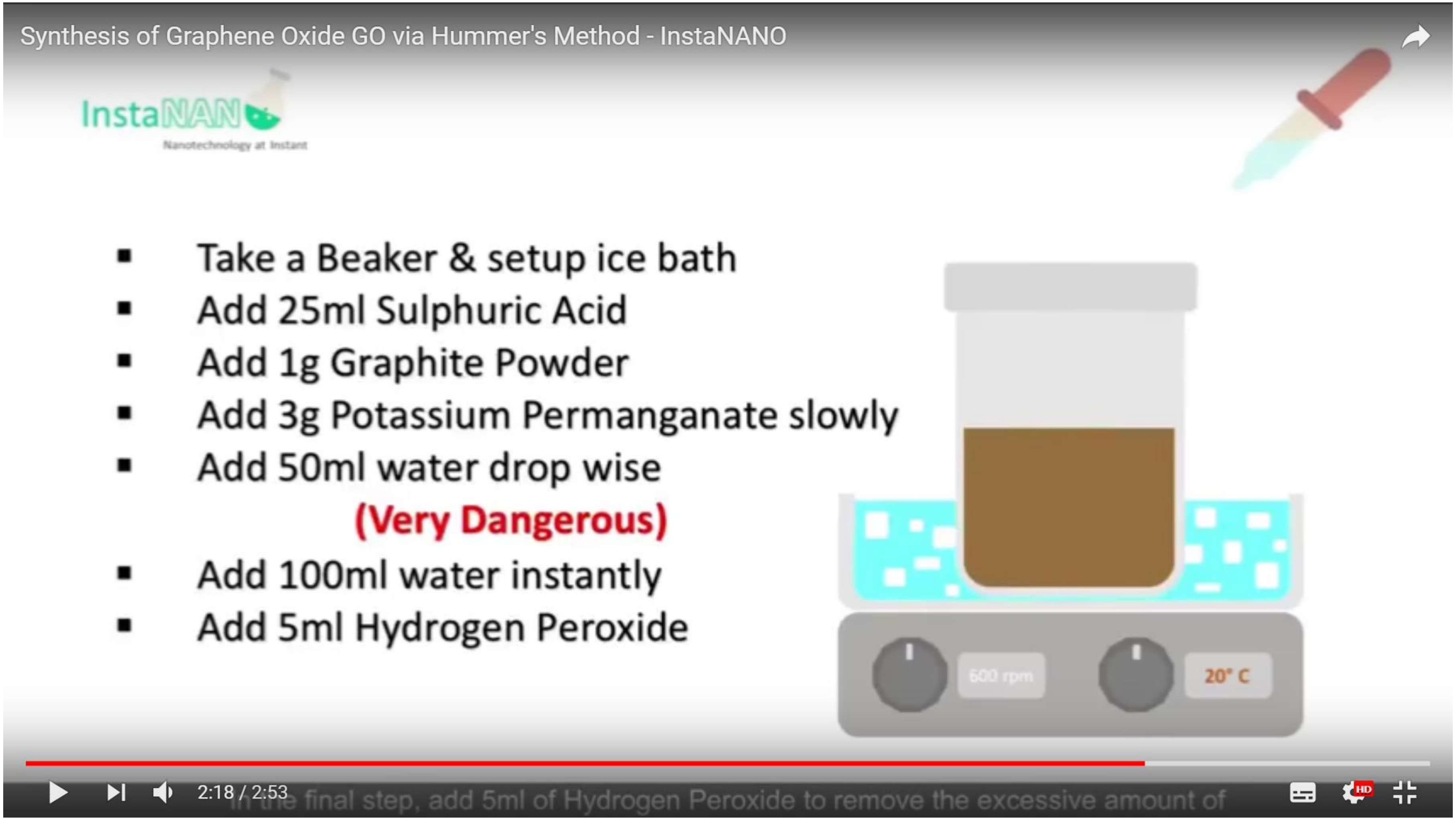


- The **bulk material** disperses in basic solutions to yield **monomolecular sheets**, known as **graphene oxide** by analogy to graphene, the **single-layer** form of graphite.[3]
- Graphene oxide sheets have been used to prepare strong paper-like materials, **membranes**, **thin films**, and **composite materials**.
- Initially **graphene oxide** attracted substantial interest as a possible **intermediate** for the manufacture of **graphene**.
- The graphene obtained by **reduction** of **graphene oxide** still has many chemical and structural defects which is a problem for some applications but an advantage for some others.[4]
- **Graphite oxide** typically preserves the layer structure of the parent **graphite**, but the layers are buckled and the **interlayer spacing** is about **two times larger** (~0.7 nm) than that of graphite.

- Graphite oxide was first prepared by Oxford (牛津大學) chemist Benjamin C. Brodie (班傑明 布羅迪) in 1859, by treating graphite with a mixture of potassium chlorate (氯酸鉀) and fuming nitric acid.[5] (濃硝酸)
- He reported synthesis of "paper-like foils" with 0.05 mm thickness.
- In 1957 Hummers (赫爾摩斯) and Offeman (奧佛曼) developed a safer, quicker, and more efficient process called Hummers‘ method, using a mixture of sulfuric acid H_2SO_4 (濃硫酸), sodium nitrate $NaNO_3$ (硝酸鈉), and potassium permanganate $KMnO_4$, (高錳酸鉀) which is still widely used, often with some modifications.[2][6][7]
- Largest monolayer GO with highly intact carbon framework and minimal residual impurity concentrations can be synthesized in inert containers using highly pure reactants and solvents.[8]

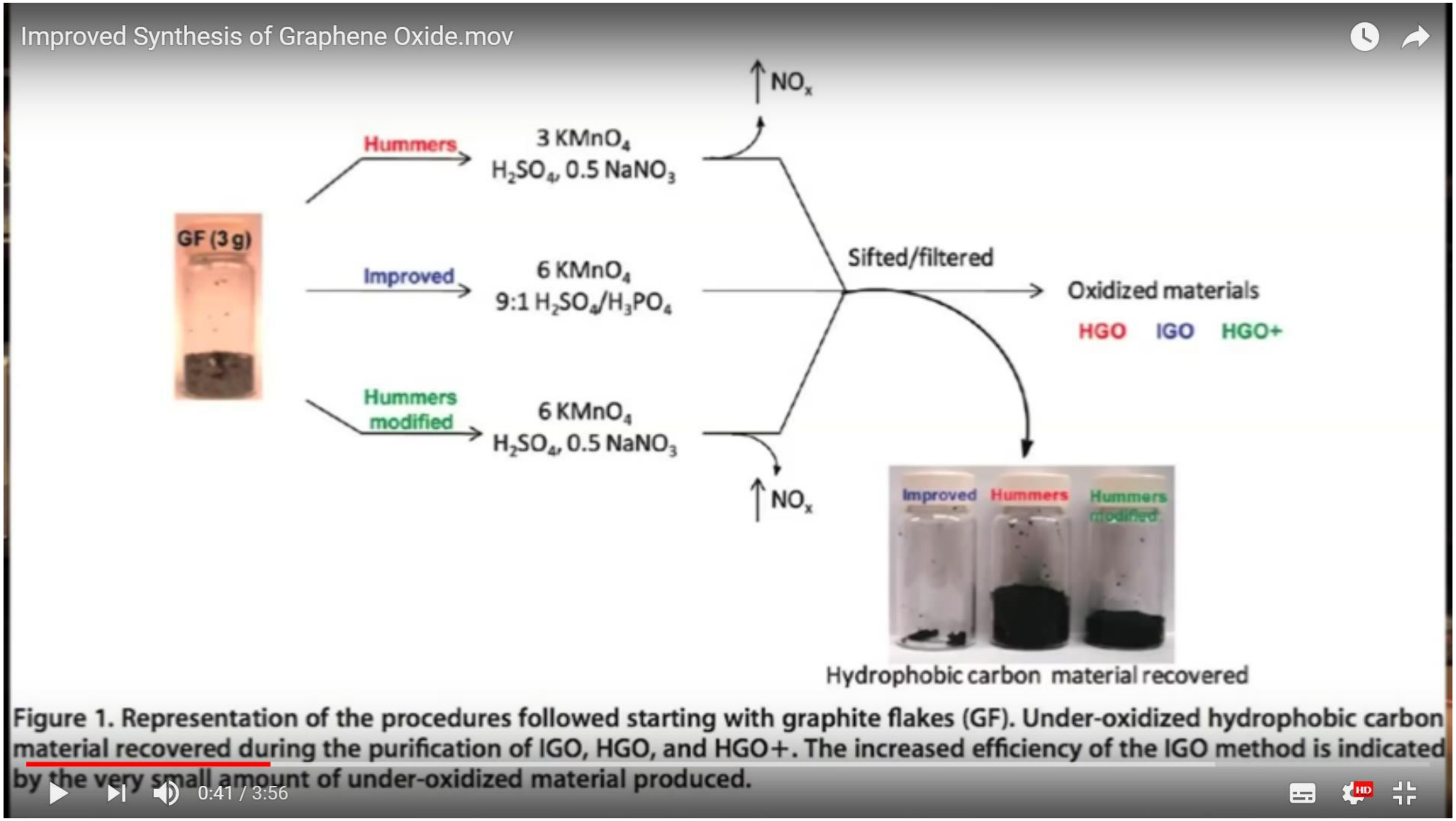
Synthesis of Graphene Oxide GO via Hummer's Method

➢ https://www.youtube.com/watch?v=RFKBP1pQXes



Improved Synthesis of Graphene Oxide

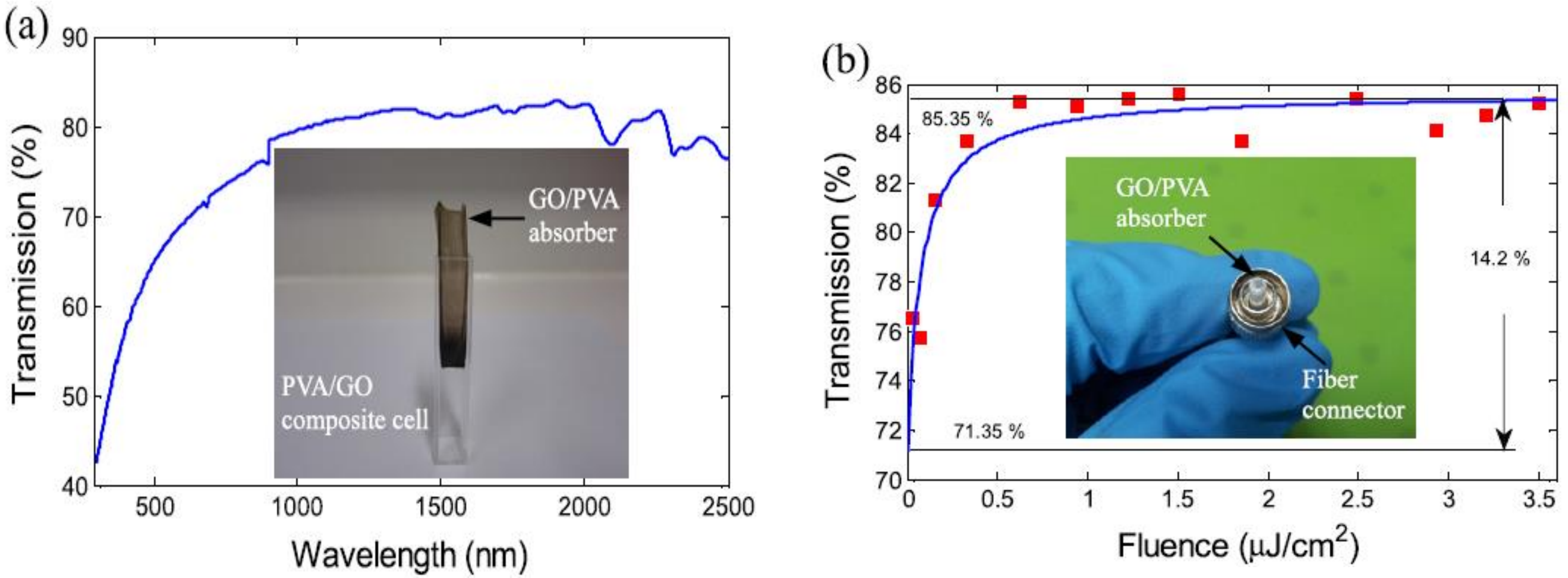
➤ https://www.youtube.com/watch?v=sTooYDp1KD4



Synthesis of graphene oxide using Modified Hummers Method

- https://www.youtube.com/watch?v=DdPBihsCSQ0

All-normal-dispersion passively mode-locked Yb-doped fiber ring laser based on a graphene oxide saturable absorber

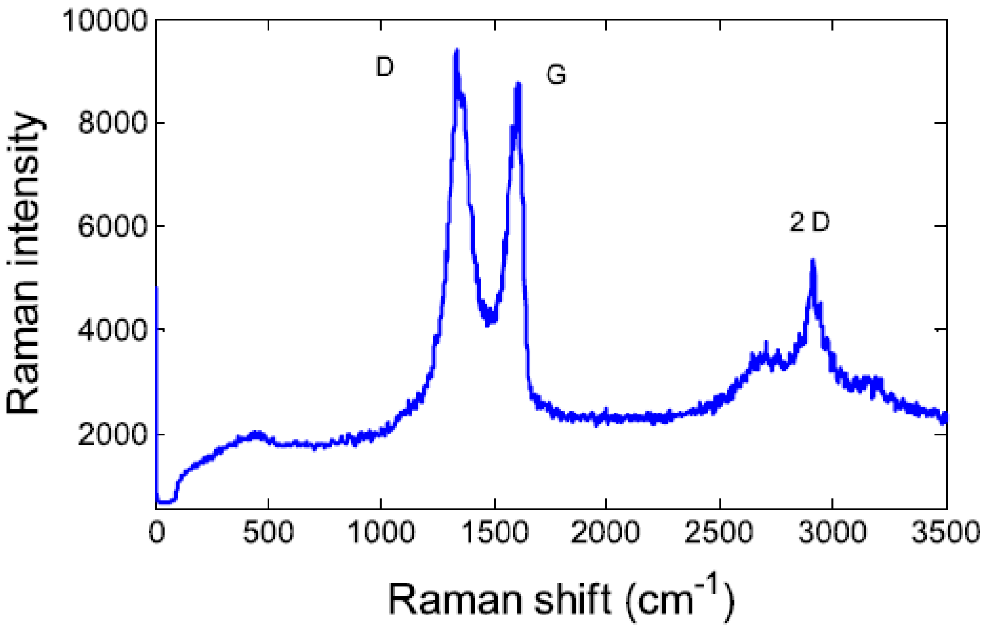


(a) Linear transmission curve of the fabricated GO–PVA absorber.

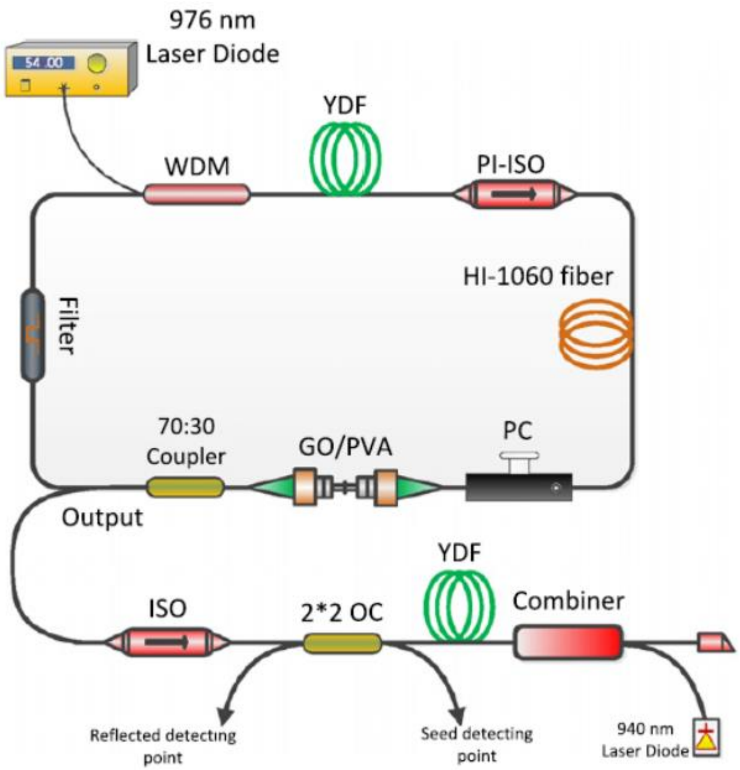
(b) Measured transmission curve with an increase of the probe laser power in the 1 μm regime.

- The D peak is due to the **defect-induced breathing mode** of sp2 rings. It is from the **structural imperfections** created by the attachment of **hydroxyl** (氫氧根) and **epoxide (環氧化物) groups** on the carbon basal plane.
- The G peak corresponds to **optical photons E_2g** at the **Brillouin zone center** and is due to **bond stretching** of sp2 carbon pairs in both rings and chains.
- The **2D band** represents the existence of **graphene material**

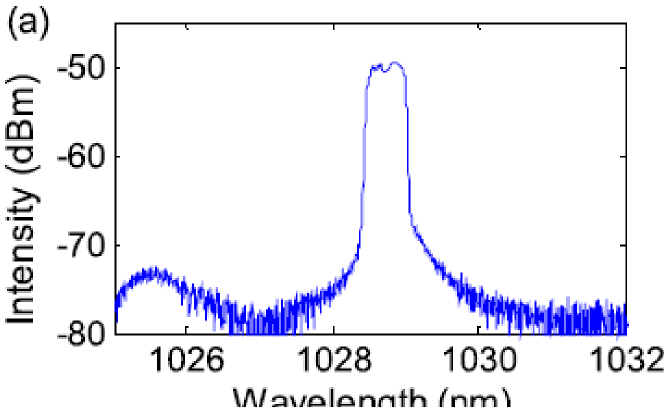
Raman spectrum of Graphene oxide



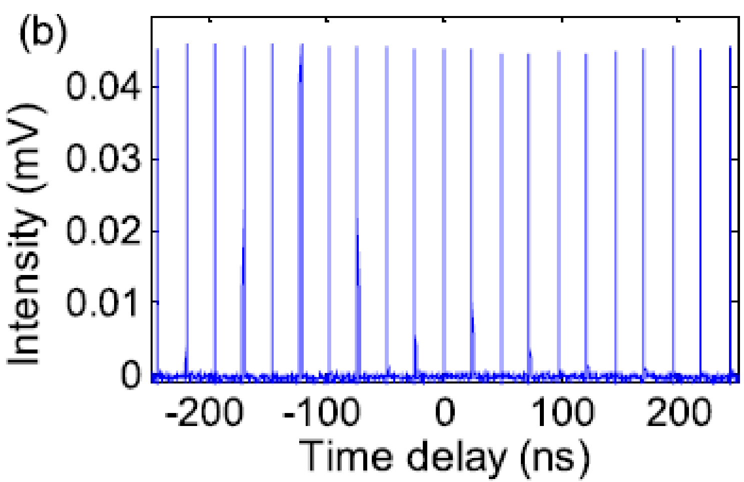
Experimental Setup



Optical spectrum



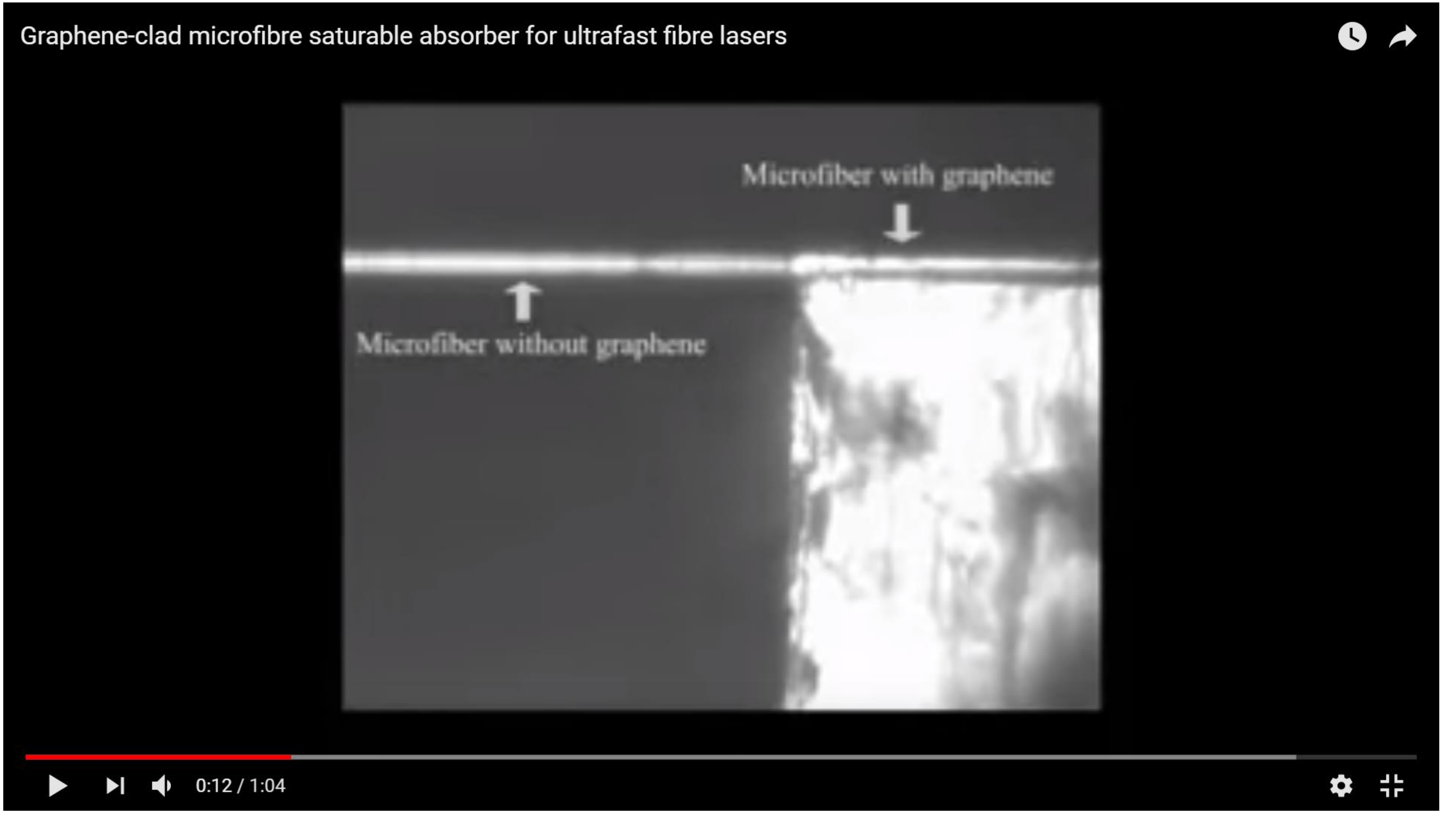
Time Trace from OS



Laser Phys. Lett. 10 (2013) 075108 (5pp)

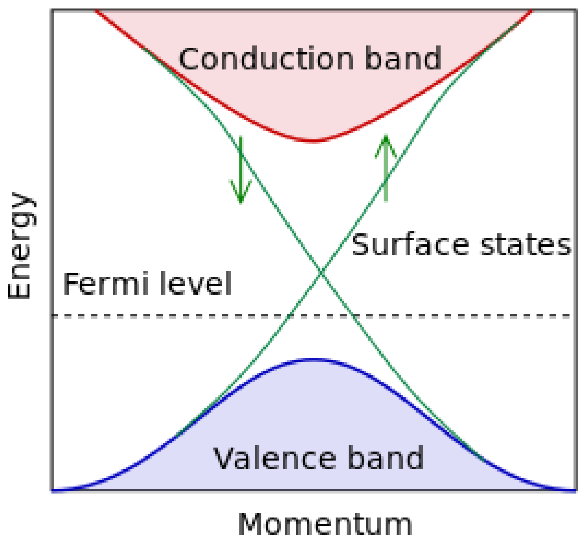
Graphene-clad microfibre saturable absorber for ultrafast fibre lasers

- https://www.youtube.com/watch?v=dIoeqQAyrHY



Topological insulators

- **Topological insulators** such as **Bi_2Se_3, Bi_2Te_3** and **Sb_2Te_3** have attracted much attention for their promising applications in fiber lasers .
- Topological insulator is a **nove**l kind of **quantum electronic matter** which behaves **metallic states** in **surface** but **insulator states** in interior, meaning that electrons can only move along the surface of material.



In the bulk of a non-interacting topological insulator, the electron band structure resembles an ordinary **band insulator**, with **the Fermi level** falling between the conduction and valence bands.

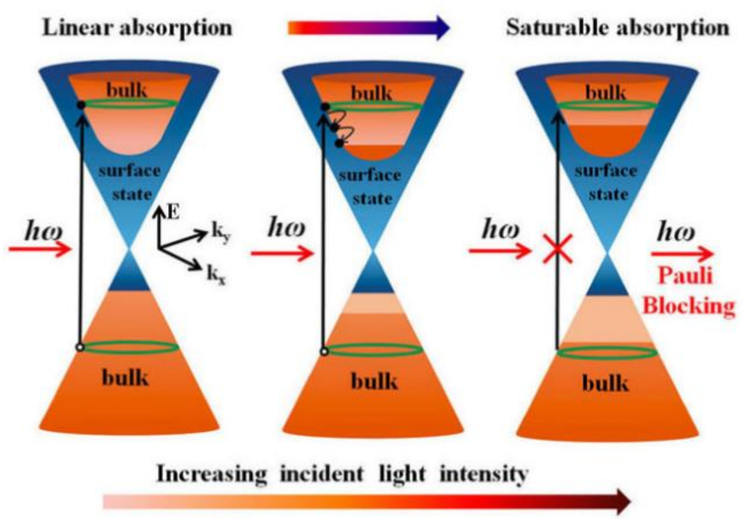
On the **surface** of a topological insulator there are special states that fall within the **bulk energy gap** and allow surface

Introduction of Topological insulator

Characteristic of TI

1. Dirac-like electronic band structure
2. Widely studied in the condensed-matter physics
3. Wavelength independent,
   low saturable optical intensity,
   high damage threshold,
   large modulation depth,
4. The used TI in PM-FLs
   1. Bi_2Te_3
   2. Bi_2Se_3
   3. Sb_2Te_3
   4. ....

[1]



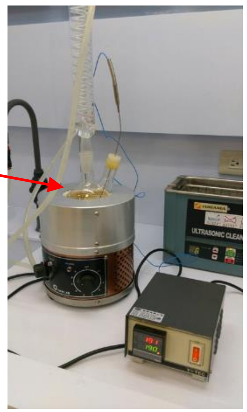
- Bi_2Se_3 has a relatively larger bulk band gap (0.3 eV), and it is considered as a promising optical material for the room-temperature applications

[1] Zhang et al, Opt. Express, 23, 13380 2015

Preparation of TI:Bi_2Se_3 nanoplates

Polyol method

two-neck flask



- $Bi(NO_3)_3 \cdot 5H_2O$ 0.6 g
- sodium selenite 0.3 g
- polyvinyl pyrrolidone 1.32 g
- ethylene glycol 60 mL

Heating and stirring
At 190 °C for 3 ~ 6 hr

Centrifugation Clearing
6000 RPM 10min

Drying
Put in Oven 50 °C 4 hrs

Powder

Microbalancer

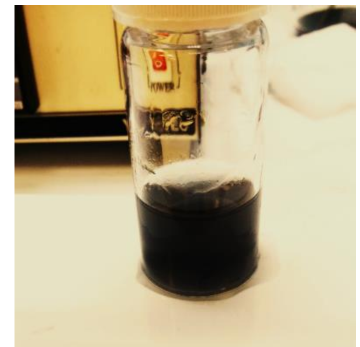
Three **reagent** and ethylene glycol (EG) is solvent

Preparation of Bi_2Se_3 PVA/film

Ultrasonication agitation
4.5 hr

↓

Adding PVA
(0.02 g/ml)

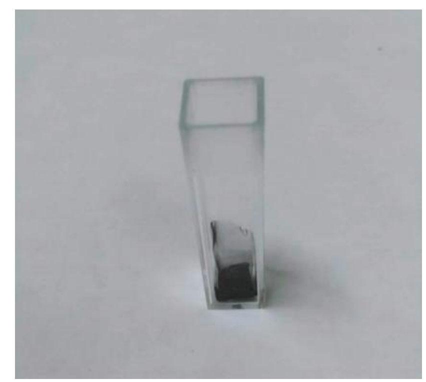


↓

Heating and stirring
At 90 °C for 3 ~ 4 hr

↓

Drying
3 Days



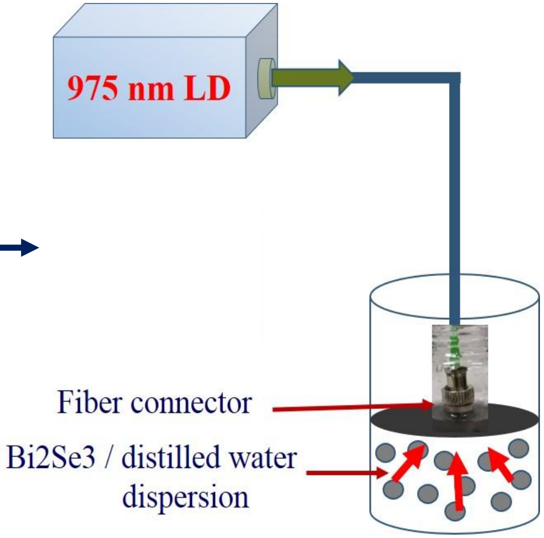
End facet deposition of Bi_2Se_3

Ultrasonication agitation

3 hr

Illumination

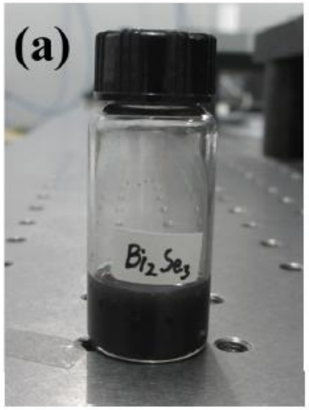
976 nm, 40 mW for 3 hr

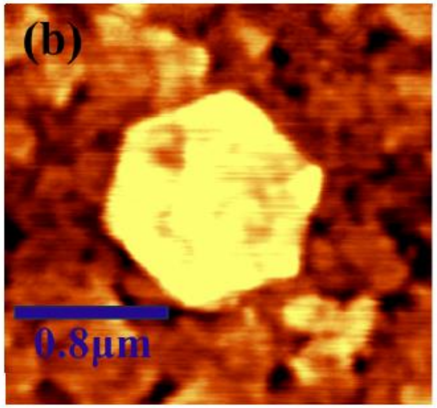


Drying

50˚C for 3 hr

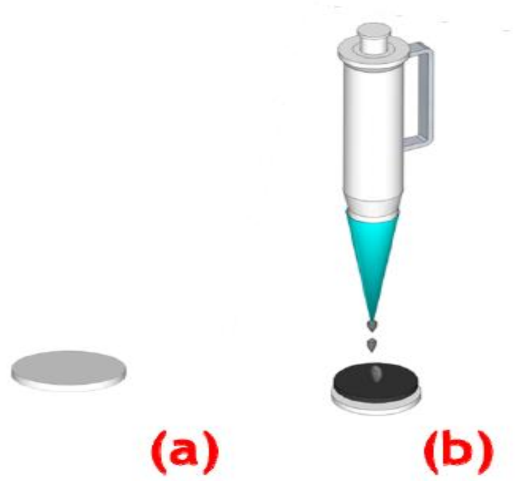
- In order to remove the impurity, the Bi_2Se_3 solution was washed with **isopropyl alcohol (IPA 異丙醇)** and centrifuged several times.
- Dispersion suspensions of Bi_2Se_3 in **deionized water solution (DI water)** were prepared by **centrifugation** and **ultrasonication agitation** for 1 hour, as shown in Fig.1(a).
- The Bi_2Se_3 solution was observed by **atomic force microscope** (AFM), as shown in Fig.1(b).
- The thickness of the TI: Bi_2Se_3 NPs was about 10-15 nm.
- The thickness of the **single layer** Bi_2Se_3 was **0.96 nm**, so the TI: Bi_2Se_3 we obtained were estimated to be 10-16 layers.



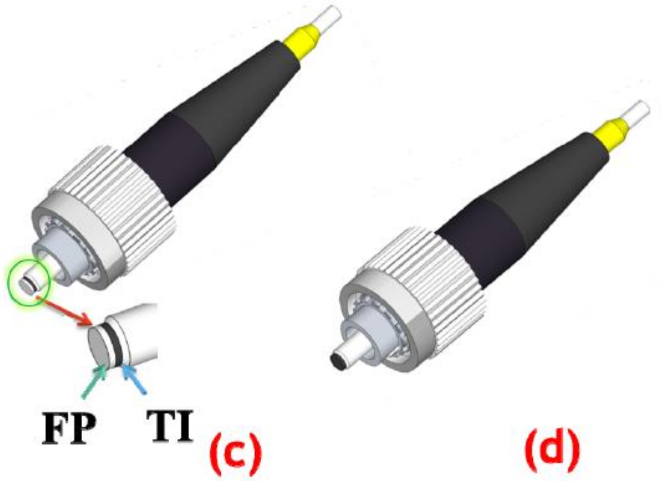


The procedures of the preparation of pure Bi_2Se_3-SA (BS-SA) film.

- Firstly, **filter paper (FP)** (GVWP02500 Millipore) with the pore size of 0.22 μm was immersed in **deionized water** until it **soaked** completely, as shown in Fig. (a).
- Then **Bi_2Se_3 water solution** was drop wise added on the filter paper slowly, as displayed in Fig. (b).
- The pure Bi_2Se_3 remained on the surface of filter paper due to the diameter of Bi_2Se_3 morphologies (1.2 μm) was larger than the **pore size** of the filter paper.

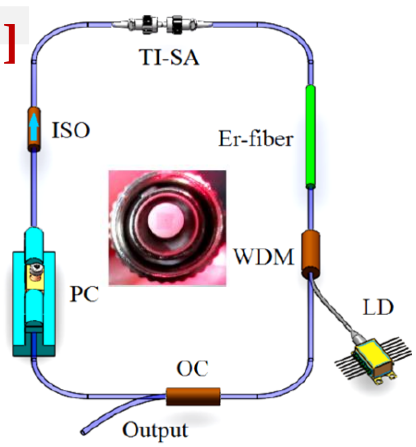


- Put the filter paper with Bi_2Se_3 in drying oven until filter paper dried thoroughly, as displayed in Fig. 1(c).
- Thirdly, shear a small piece from the prepared Bi_2Se_3 filter paper and put it on the face of a fiber end-facet, as shown in Fig.(c).
- At last, put the **fiber end-facet** with the Bi_2Se3 filter paper into **acetone solution** (丙酮) to remove the filter paper (Fig. 2(d)).
- The filter paper needed washing quite a few times.

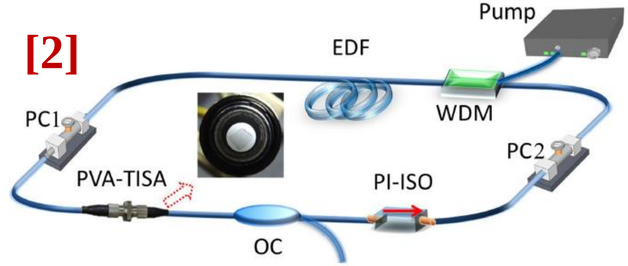


PML or Q-switched pulse generation in EDFL by using Bi_2Se_3 as a SA

[1]

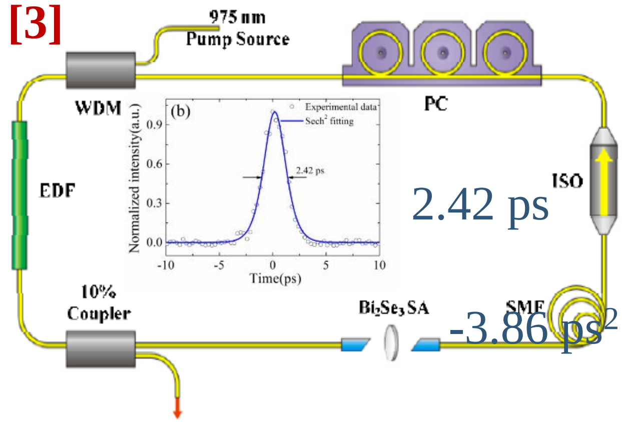


[2]



RR: 1.21 MHz

[3]

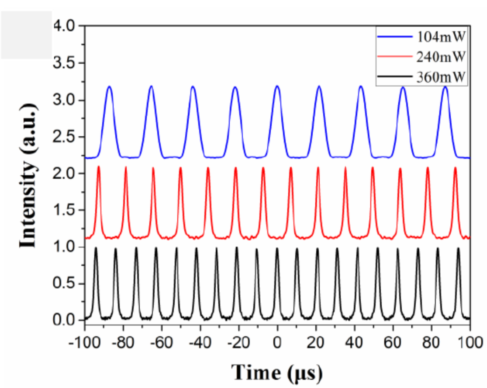


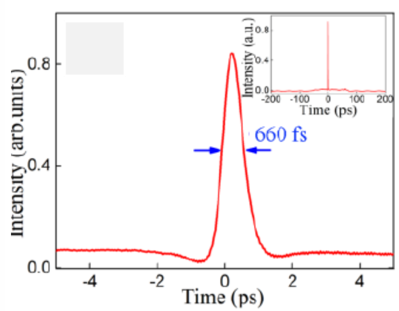
2.42 ps

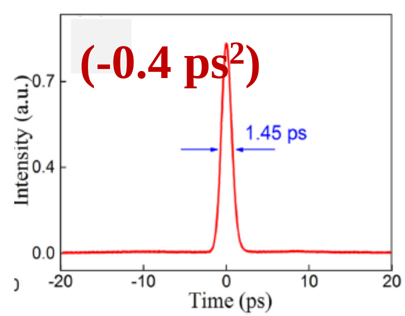
$-3.86\ ps^2$

The influence of cavity dispersion on the pulse duration

Q-switched fiber laser

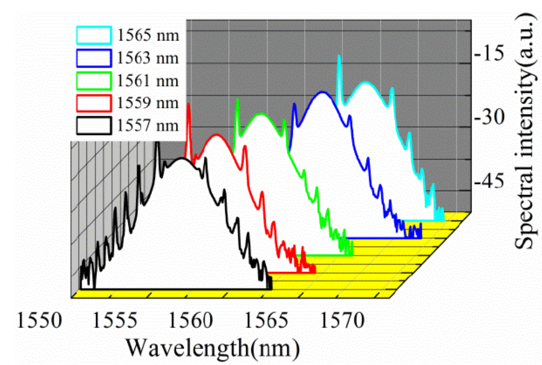






($-0.4\ ps^2$)

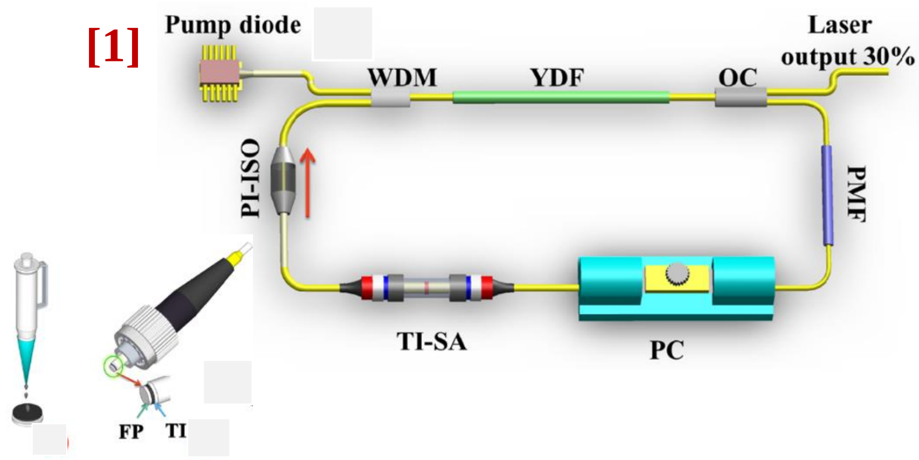
Wavelength tunable PML EDFL



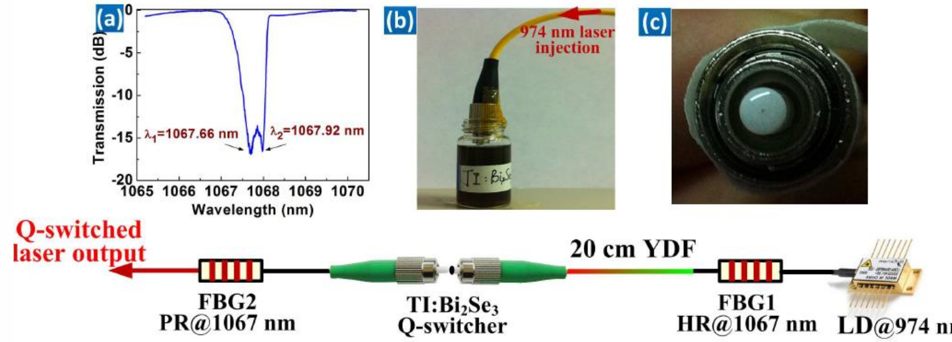
[1] Yu et al, Opt. Express, 22, 11512 2014; [2] Liu et al, Opt. Express, 22, 6868 2014;[3] Zhao et al, Opt. Express, 20, 27888 2012

PML or Q-switched pulse generation in YDFL by using Bi_2Se_3 as a SA

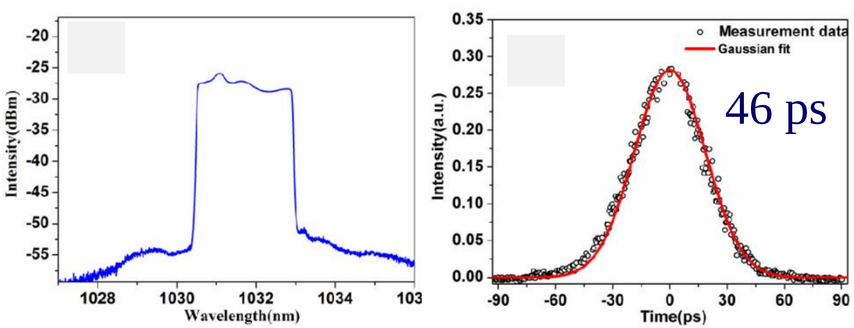
[1]



[2]

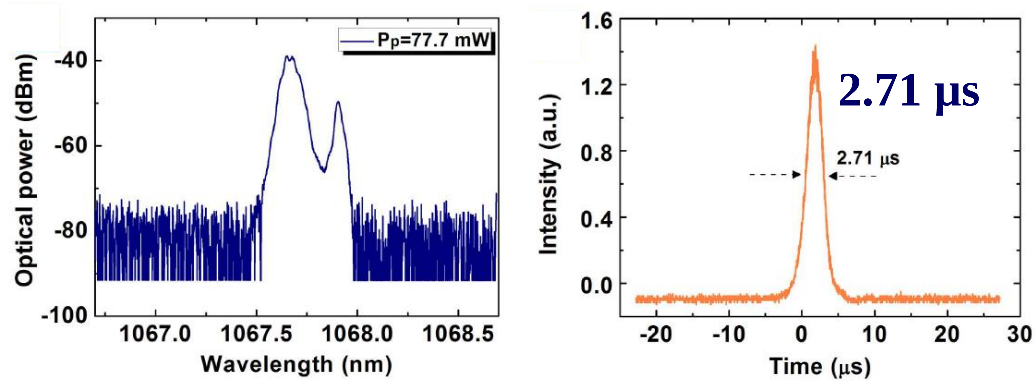


Mode-locked fiber laser with PMF



Q-switched fiber

RR:19.5 kHz



[1] Dou et al, Opt. Express, 22, 24055 2014;[2] Luo et al, Opt. Express, 21, 29518 2013