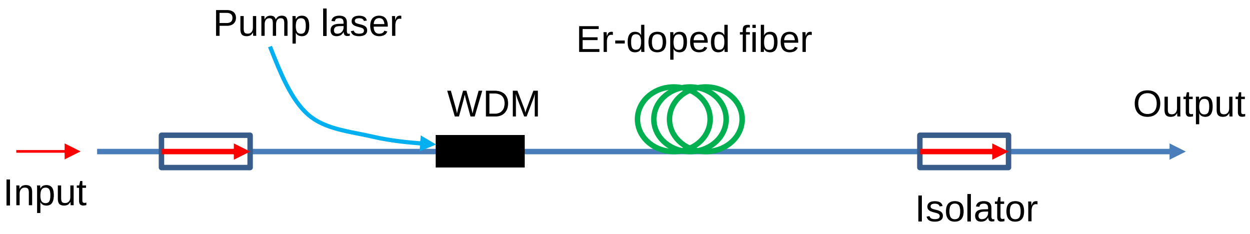
Fiber lasers and amplifiers

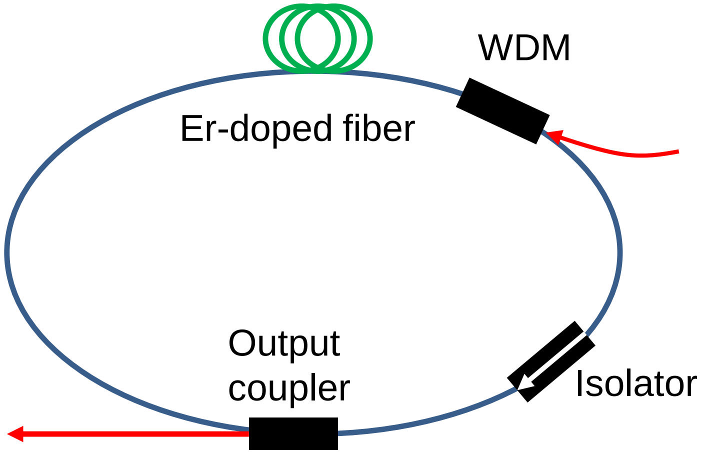
by: Khanh Kieu

Project #7: EDFA



Er-doped fiber amplifier

Amplifier construction
Gain,
ASE,
Output vs pump
Co- or counter pump?



Ring fiber laser

Laser construction
Lasing threshold
Spectral narrowing
Output vs pump power
Laser modes

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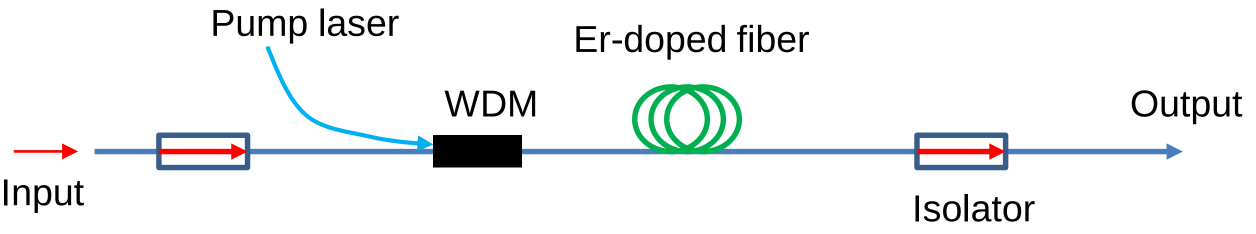
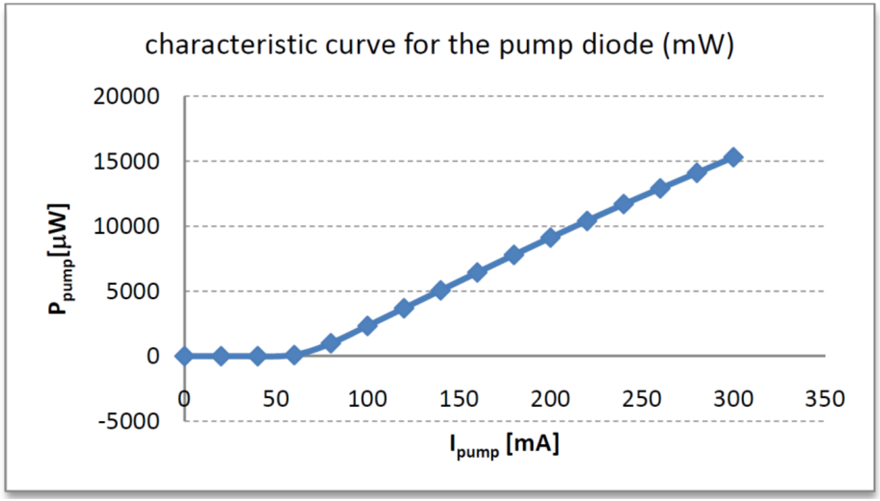


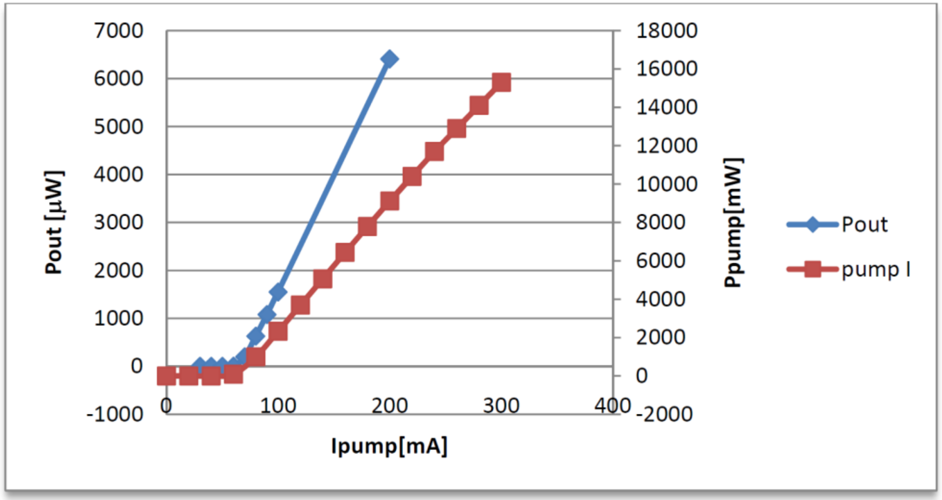
Er-doped fiber amplifier

Amplifier construction
Gain,
ASE,
Output vs pump
Co- or counter pump?

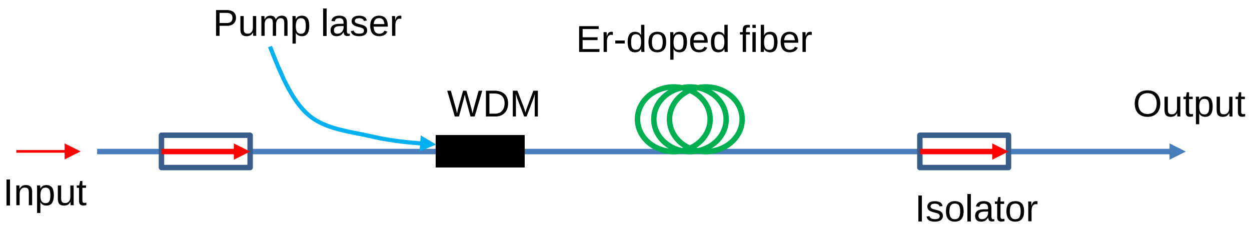
980 nmPump laser characterization



EDFA gain measurement



Project #7: EDFA


Pump laser

Er-doped fiber

WDM

Output

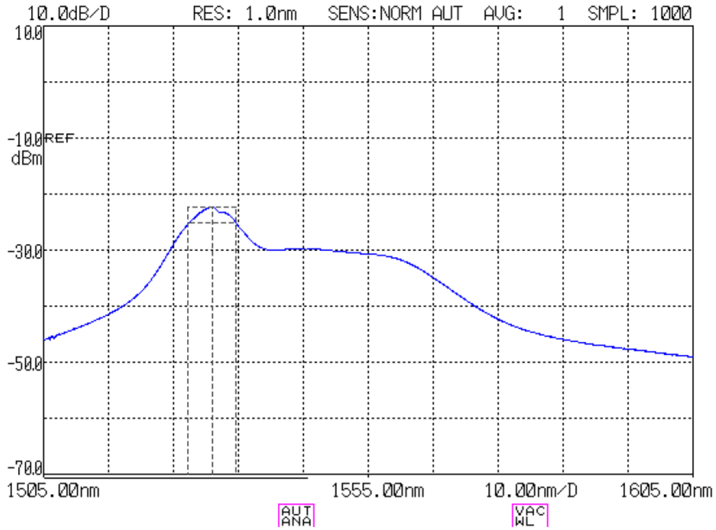
Input

Isolator

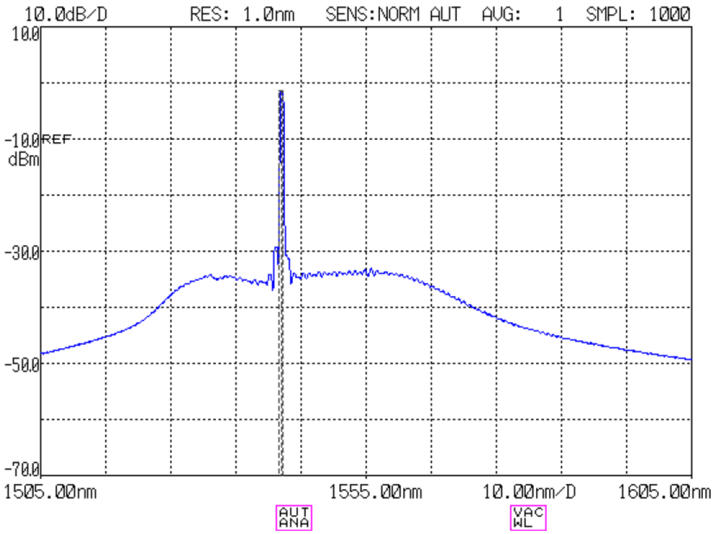
Amplifier construction
Gain,
ASE,
Output vs pump
Co- or counter pump?

Er-doped fiber amplifier

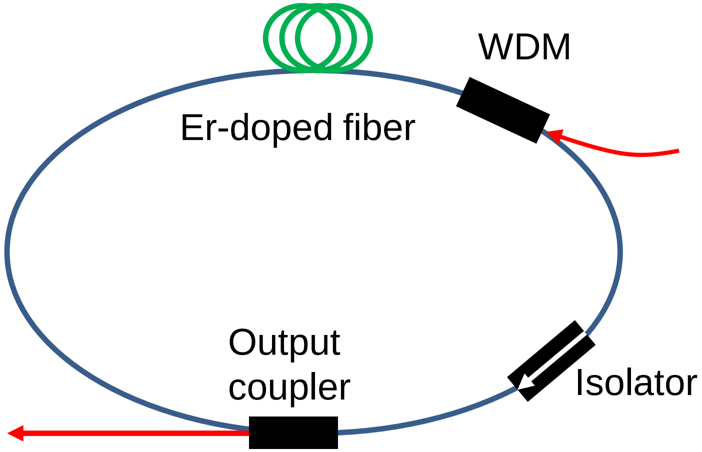
No seed signal



With seed signal

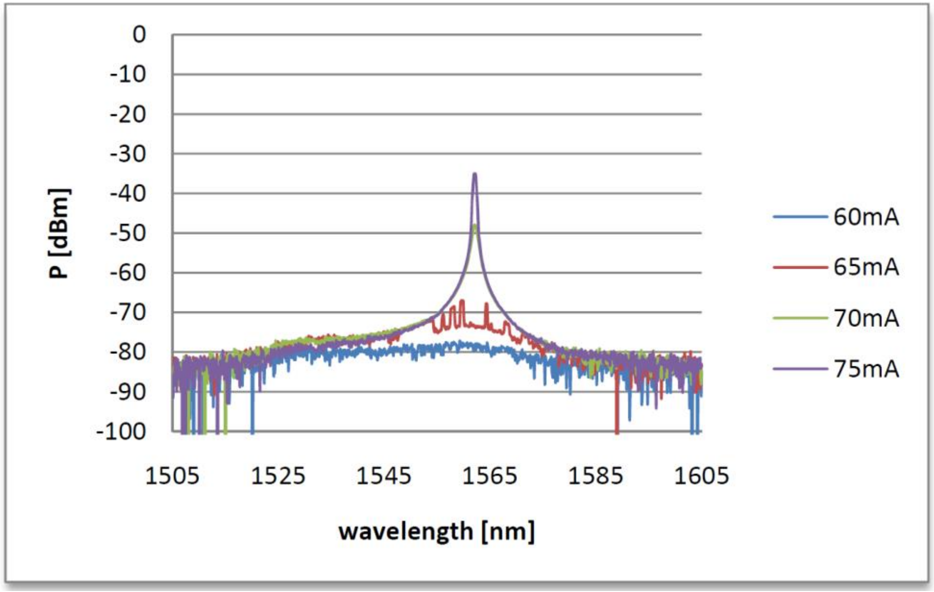


Project #7: Fiber laser



Laser construction
Lasing threshold
Spectral narrowing
Output vs pump power
Laser modes

Spectral domain measurements with an OSA



Outlines

- Introduction
- History
- Active fibers
- Laser performance
- Cladding pump technology
- Fiber laser research at the College of Optical Sciences
- Future directions

Introduction

Nobel Prize in Physics awarded for contribution related to laser

- 1964: Townes, Basov and Prokhorov
- 1971: Gabor
- 1981: Bloembergen and Schawlow
- 1997: Chu, Cohen-Tannoudji and Phillips
- 2000: Alferov and Kroemer
- 2005: Hänsch an Hall

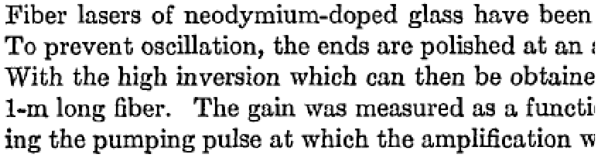
History

First laser was demonstrated in 1960 by T. Maiman

First fiber laser was demonstrated in 1963 E. Snitzer

Amplification in a Fiber Laser

Charles J. Koester and Elias Snitzer



Fiber lasers of neodymium-doped glass have been
To prevent oscillation, the ends are polished at an
With the high inversion which can then be obtaine
1-m long fiber. The gain was measured as a functi
ing the pumping pulse at which the amplification w

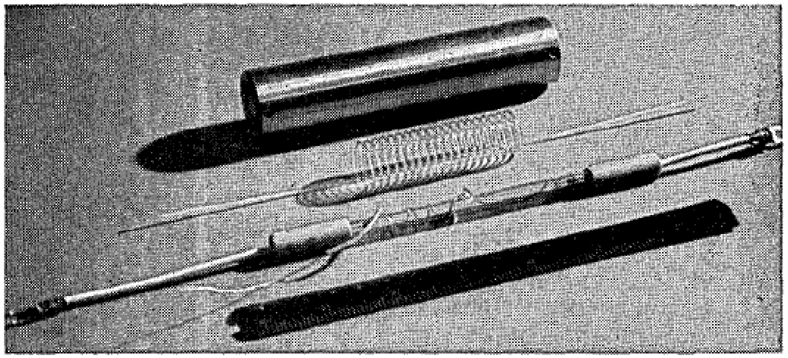
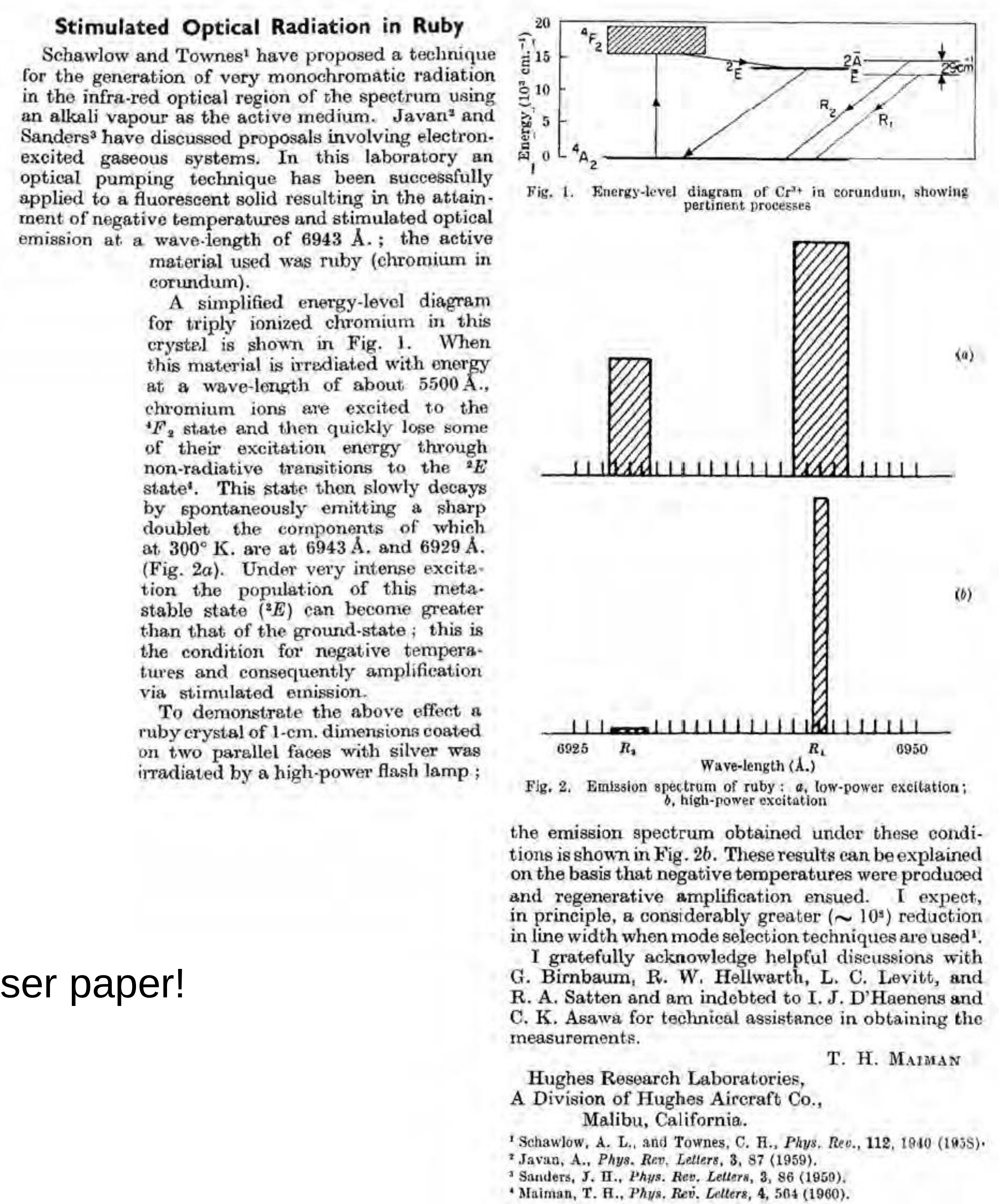


Fig. 1. Coiled fiber laser. From the top the components are: cavity, fiber laser, flashtube, and 18 cm scale



Stimulated Optical Radiation in Ruby

Schawlow and Townes[1] have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan[2] and Sanders[3] have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of 6943 Å.; the active material used was ruby (chromium in corundum).

A simplified energy-level diagram for triply ionized chromium in this crystal is shown in Fig. 1. When this material is irradiated with energy at a wave-length of about 5500 Å., chromium ions are excited to the $^4F_2$ state and then quickly lose some of their excitation energy through non-radiative transitions to the ^2E state[4]. This state then slowly decays by spontaneously emitting a sharp doublet the components of which at 300° K. are at 6943 Å. and 6929 Å. (Fig. 2*a*). Under very intense excitation the population of this metastable state (^2E) can become greater than that of the ground-state; this is the condition for negative temperatures and consequently amplification via stimulated emission.

To demonstrate the above effect a ruby crystal of 1-cm. dimensions coated on two parallel faces with silver was irradiated by a high-power flash lamp; the emission spectrum obtained under these conditions is shown in Fig. 2*b*. These results can be explained on the basis that negative temperatures were produced and regenerative amplification ensued. I expect, in principle, a considerably greater (~ 10^4) reduction in line width when mode selection techniques are used[1].

Fig. 1. Energy-level diagram of Cr^{3+} in corundum, showing pertinent processes

Fig. 2. Emission spectrum of ruby: *a*, low-power excitation; *b*, high-power excitation

I gratefully acknowledge helpful discussions with G. Birnbaum, R. W. Hellwarth, L. C. Levitt, and R. A. Satten and am indebted to I. J. D'Haenens and C. K. Asawa for technical assistance in obtaining the measurements.

T. H. MAIMAN

Hughes Research Laboratories,
A Division of Hughes Aircraft Co.,
Malibu, California.

[1] Schawlow, A. L., and Townes, C. H., *Phys. Rev.*, **112**, 1940 (1958).

[2] Javan, A., *Phys. Rev. Letters*, **3**, 87 (1959).

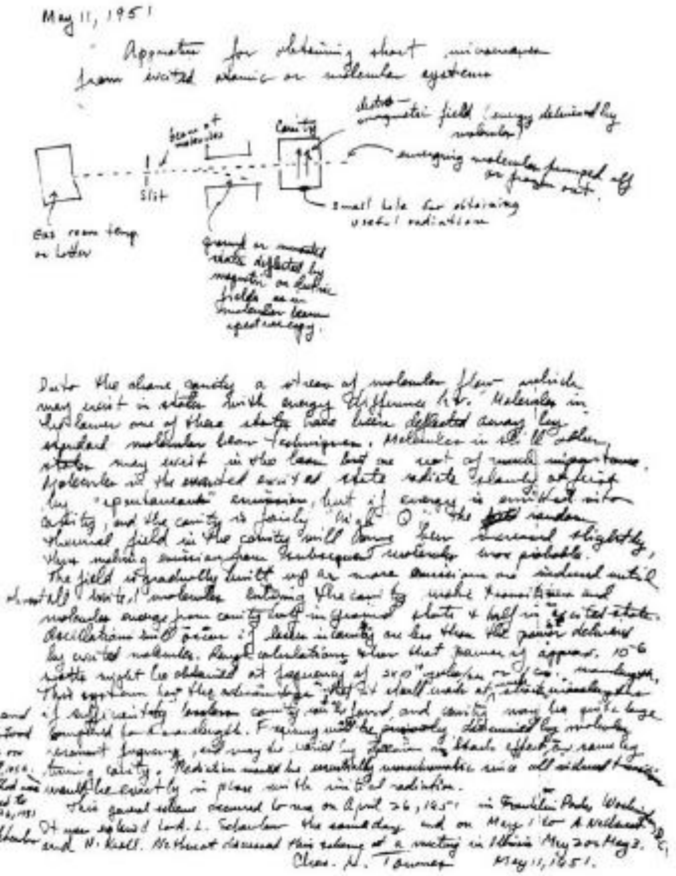
[3] Sanders, J. H., *Phys. Rev. Letters*, **3**, 86 (1959).

[4] Maiman, T. H., *Phys. Rev. Letters*, **4**, 564 (1960).

The first laser paper!

Who invented the laser?

Concept for the MASER, May 11, 1951



May 11, 1951

Apparatus for obtaining short microwaves from excited atomic or molecular systems

beam of molecules

Slit

Cavity

electro-magnetic field (energy delivered by molecules)

emerging molecules pumped off or frozen out.

small hole for obtaining useful radiation

Gas room temp or hotter

ground or unwanted state deflected by magnetic or electric fields as in molecular beam spectroscopy.

Into the above cavity a stream of molecules flow which may exist in states with energy difference hν. Molecules in the lower one of these states have been deflected away by standard molecular beam techniques. Molecules in still other states may exist in the beam but are not of much importance. Molecules in the excited state radiate slowly at first by "spontaneous" emission, but if energy is emitted into cavity, and the cavity is fairly "high Q" the random thermal field in the cavity will have been increased slightly, thus making emission from subsequent molecules more probable. The field is gradually built up as more emissions are induced until [illegible] "excited" molecules entering the cavity make transitions and molecules emerge from cavity half in ground state & half in excited state. Oscillations will occur if losses in cavity are less than the power delivered by excited molecules. Rough calculations show that power of approx. 10^{-6} watts might be obtained at frequency of 3×10^{10} cycles or 1 cm. [illegible], This system has the advantage that it should work at [illegible] if sufficiently [illegible] cavity is found, and cavity may be quite large compared to a wavelength. Frequency will be primarily determined by molecular resonant frequency, and may be varied by [illegible] or Stark effects, or some by tuning cavity. Radiation would be essentially monochromatic since all induced [illegible] would be exactly in phase with the initial radiation.

This general scheme occurred to me on April 26, 1951 in Franklin Park, Washington, D.C. It was explained to A. L. Schawlow the same day and on May 1 to A. Nethercot and N. Kroll. Nethercot discussed this scheme at a meeting in Illinois May 2 or May 3.

Chas. H. Townes May 11, 1951.

Read and understood by me on Feb 28, 1956. The method was explained to me Apr. 26, 1951 A. L. Schawlow

Charles Townes & Jim Gordon

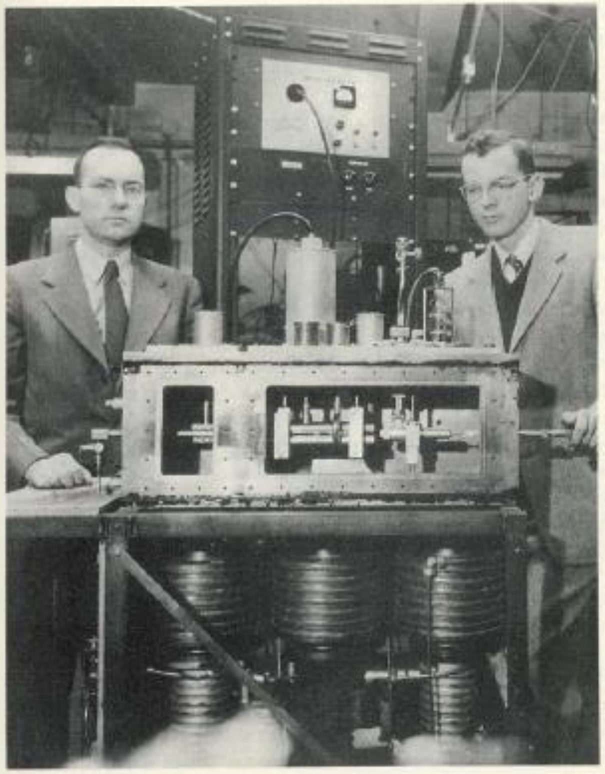
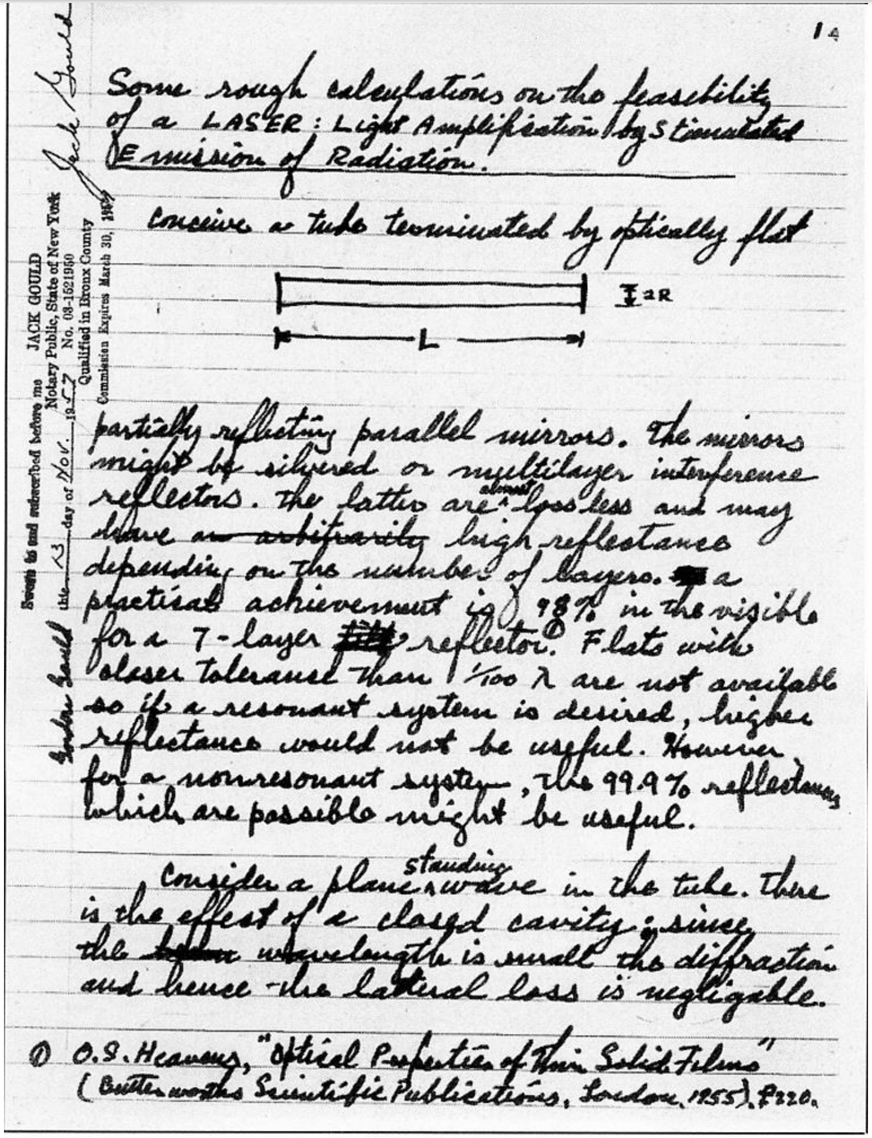


Figure 9. James Gordon (at right) and I were photographed with the second maser at Columbia University. The normally evacuated metal box where maser action occurred is opened up to show the four rods (quadrupole focuser) which sent excited molecules into a resonant cavity (the small cylinder to the right of the four rods). The microwaves that were generated emerged through the vertical copper waveguide near my hand. This second maser was essentially a duplicate of the first operating one, and it was built to examine the purity of maser signals, by allowing the two to beat together, thus producing

Who invented the laser?



1

Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation.

Conceive a tube terminated by optically flat

partially reflecting parallel mirrors. The mirrors might be silvered or multilayer interference reflectors. The latter are almost lossless and may have ~~an arbitrarily~~ high reflectance depending on the number of layers. a practical achievement is 98% in the visible for a 7-layer reflector.① Flats with closer tolerance than 1/100 λ are not available so if a resonant system is desired, higher reflectance would not be useful. However for a nonresonant system, the 99.9% reflectances which are possible might be useful.

Consider a plane standing wave in the tube. There is the effect of a closed cavity; since the wavelength is small the diffraction and hence the lateral loss is negligible.

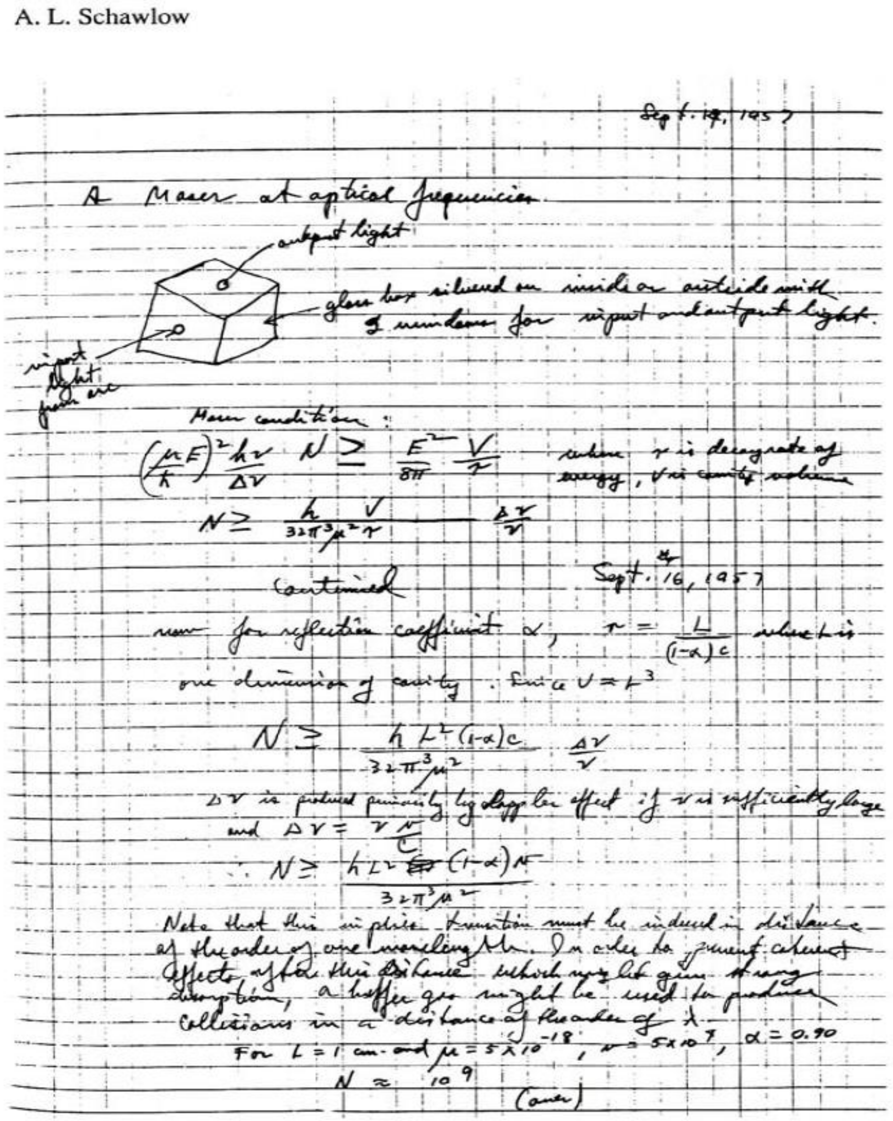
① O.S. Heavens, "Optical Properties of Thin Solid Films" (Butterworths Scientific Publications, London, 1955), p.220.

Sworn to and subscribed before me this 13 day of Nov. 1957
JACK GOULD
Notary Public, State of New York
No. 03-1521950
Qualified in Bronx County
Commission Expires March 30, 1959

Jack Gould

Gordon Gould

Who invented the laser?



A. L. Schawlow

Sept. 14, 1957

A Maser at optical frequencies

output light

glass box silvered on inside or outside with windows for input and output light.

input light from arc

Maser condition:

$$\left(\frac{\mu E}{h}\right)^2 \frac{h\nu}{\Delta\nu} N \geq \frac{E^2}{8\pi}\frac{V}{\tau}$$

where τ is decay rate of energy, V is cavity volume

$$N \geq \frac{h}{32\pi^3\mu^2}\frac{V}{\tau}\frac{\Delta\nu}{\nu}$$

continued Sept. $\overset{4}{16}$, 1957

now for reflection coefficient α, $\tau = \frac{L}{(1-\alpha)c}$ where L is one dimension of cavity. Since $V = L^3$

$$N \geq \frac{hL^2(1-\alpha)c}{32\pi^3\mu^2}\frac{\Delta\nu}{\nu}$$

Δν is produced primarily by doppler effect if ν is sufficiently large and $\Delta\nu = \nu\frac{v}{c}$

$$\therefore N \geq \frac{hL^2\cancel{c}(1-\alpha)v}{32\pi^3\mu^2}$$

Note that this implies transition must be induced in distance of the order of one wavelength. In order to prevent coherent effects after this distance which might give strong absorption, a buffer gas might be used to produce collisions in a distance of the order of λ.

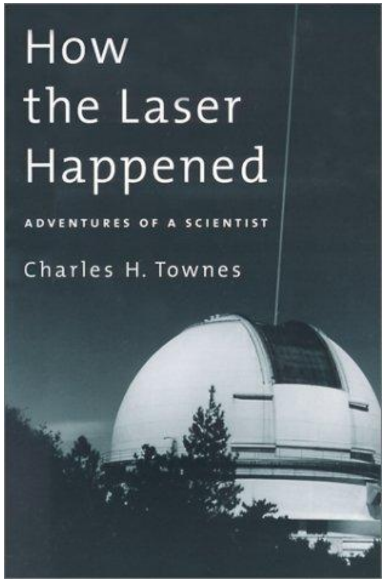
For $L = 1$ cm and $\mu = 5\times10^{-18}$, $v = 5\times10^{7}$, $\alpha = 0.90$

$N \approx 10^9$

(over)

Who invented the laser?

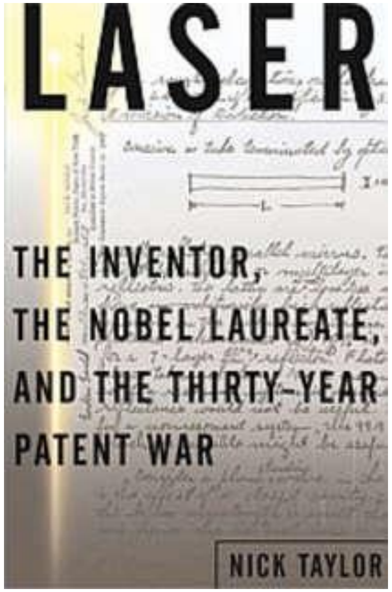
- Charles Hard Townes and Arthur Leonard Schawlow
- Gordon Gould
- N. Basov and A. Prokhorov
- Nico Blombergen



How
the Laser
Happened

ADVENTURES OF A SCIENTIST

Charles H. Townes

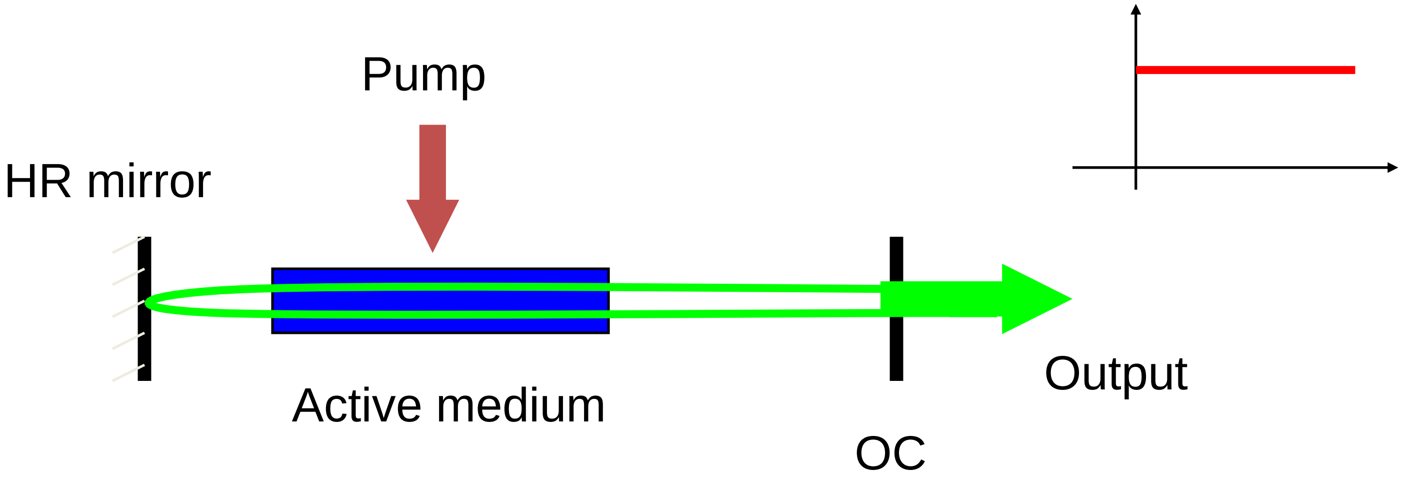


LASER

THE INVENTOR,
THE NOBEL LAUREATE,
AND THE THIRTY-YEAR
PATENT WAR

NICK TAYLOR

How does a laser work?



Pump

HR mirror

Active medium

Output

OC

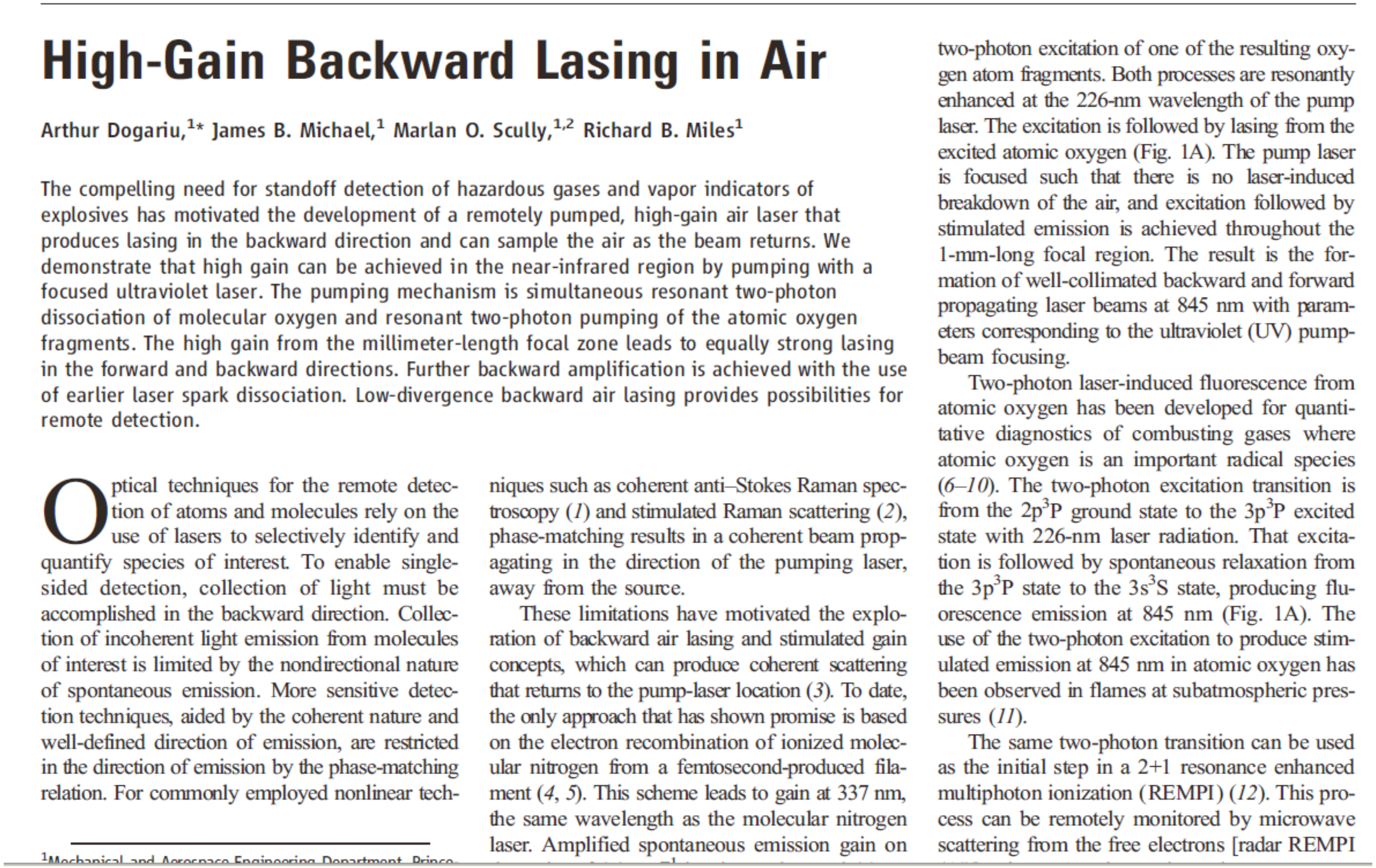
Lasers tend to operate in a mode so that the optical field in the cavity sees smallest loss per cavity round trip

How does a laser work?

We need to have 3 things put together in a certain way to make a laser:

1. Pump to create a population inversion
2. Gain medium where the population inversion occurs
3. Cavity to provide a positive feedback for the field to build up

Is this really a laser?



High-Gain Backward Lasing in Air

Arthur Dogariu,[1]* James B. Michael,[1] Marlan O. Scully,[1,2] Richard B. Miles[1]

The compelling need for standoff detection of hazardous gases and vapor indicators of explosives has motivated the development of a remotely pumped, high-gain air laser that produces lasing in the backward direction and can sample the air as the beam returns. We demonstrate that high gain can be achieved in the near-infrared region by pumping with a focused ultraviolet laser. The pumping mechanism is simultaneous resonant two-photon dissociation of molecular oxygen and resonant two-photon pumping of the atomic oxygen fragments. The high gain from the millimeter-length focal zone leads to equally strong lasing in the forward and backward directions. Further backward amplification is achieved with the use of earlier laser spark dissociation. Low-divergence backward air lasing provides possibilities for remote detection.

Optical techniques for the remote detection of atoms and molecules rely on the use of lasers to selectively identify and quantify species of interest. To enable single-sided detection, collection of light must be accomplished in the backward direction. Collection of incoherent light emission from molecules of interest is limited by the nondirectional nature of spontaneous emission. More sensitive detection techniques, aided by the coherent nature and well-defined direction of emission, are restricted in the direction of emission by the phase-matching relation. For commonly employed nonlinear techniques such as coherent anti–Stokes Raman spectroscopy (*1*) and stimulated Raman scattering (*2*), phase-matching results in a coherent beam propagating in the direction of the pumping laser, away from the source.

These limitations have motivated the exploration of backward air lasing and stimulated gain concepts, which can produce coherent scattering that returns to the pump-laser location (*3*). To date, the only approach that has shown promise is based on the electron recombination of ionized molecular nitrogen from a femtosecond-produced filament (*4*, *5*). This scheme leads to gain at 337 nm, the same wavelength as the molecular nitrogen laser. Amplified spontaneous emission gain on

two-photon excitation of one of the resulting oxygen atom fragments. Both processes are resonantly enhanced at the 226-nm wavelength of the pump laser. The excitation is followed by lasing from the excited atomic oxygen (Fig. 1A). The pump laser is focused such that there is no laser-induced breakdown of the air, and excitation followed by stimulated emission is achieved throughout the 1-mm-long focal region. The result is the formation of well-collimated backward and forward propagating laser beams at 845 nm with parameters corresponding to the ultraviolet (UV) pump-beam focusing.

Two-photon laser-induced fluorescence from atomic oxygen has been developed for quantitative diagnostics of combusting gases where atomic oxygen is an important radical species (*6*–*10*). The two-photon excitation transition is from the $2p^3P$ ground state to the $3p^3P$ excited state with 226-nm laser radiation. That excitation is followed by spontaneous relaxation from the $3p^3P$ state to the $3s^3S$ state, producing fluorescence emission at 845 nm (Fig. 1A). The use of the two-photon excitation to produce stimulated emission at 845 nm in atomic oxygen has been observed in flames at subatmospheric pressures (*11*).

The same two-photon transition can be used as the initial step in a 2+1 resonance enhanced multiphoton ionization (REMPI) (*12*). This process can be remotely monitored by microwave scattering from the free electrons [radar REMPI

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[1]Mechanical and Aerospace Engineering Department, Prince-

Science, 28 January 2011

Laser characteristics

- Directional emission
- Clear lasing threshold
- Spectral narrowing

Required components:

- Gain medium
- Pump
- Cavity

Why are people still doing research in lasers?

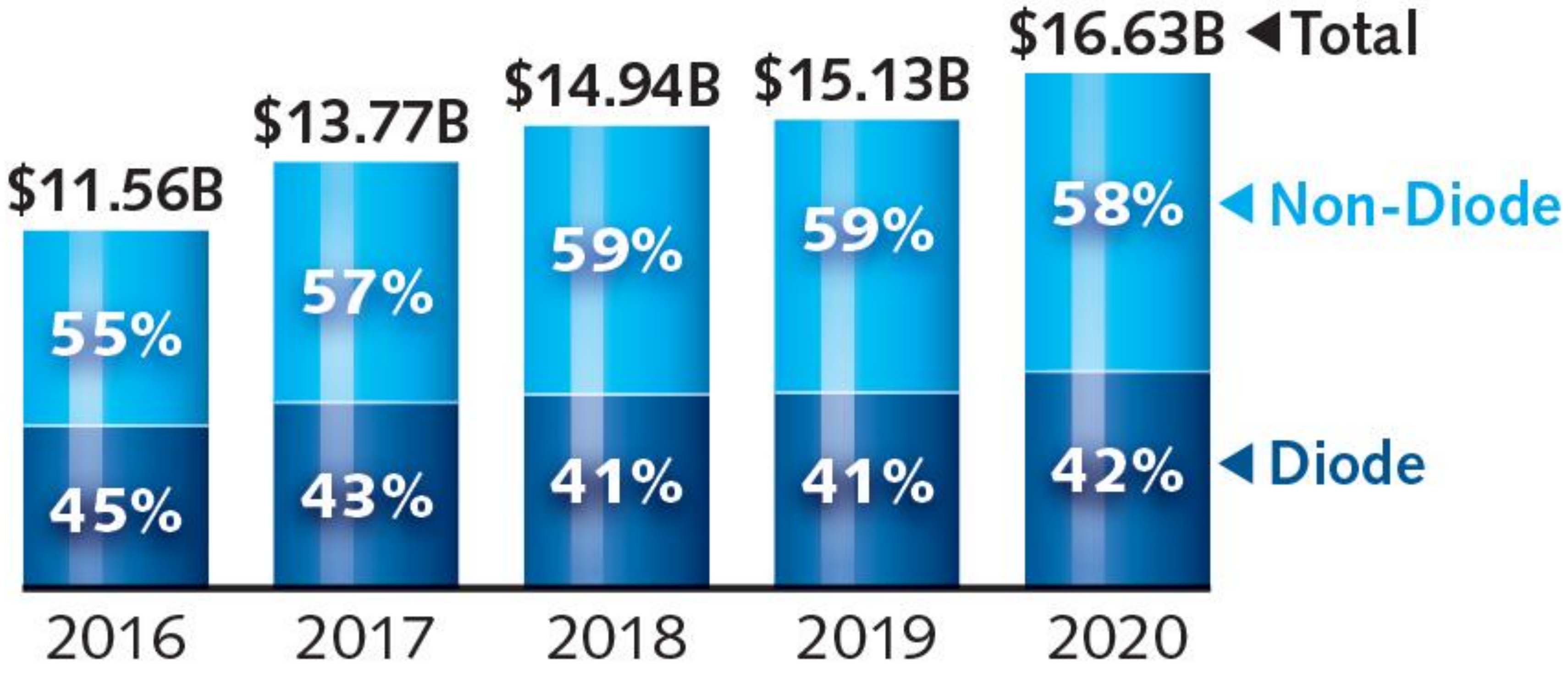
The physics of laser operation is well understood. But there is always need for better and cheaper lasers. Also, there are still a lot of applications' requirements that current technology can not satisfy.

Requirements:

- New wavelength bands
- Maximum average output power
- Maximum peak output power
- Minimum output pulse duration
- Maximum power efficiency
- Minimum cost

Laser market

Figure 1. **Past laser revenues and 2020 forecast**



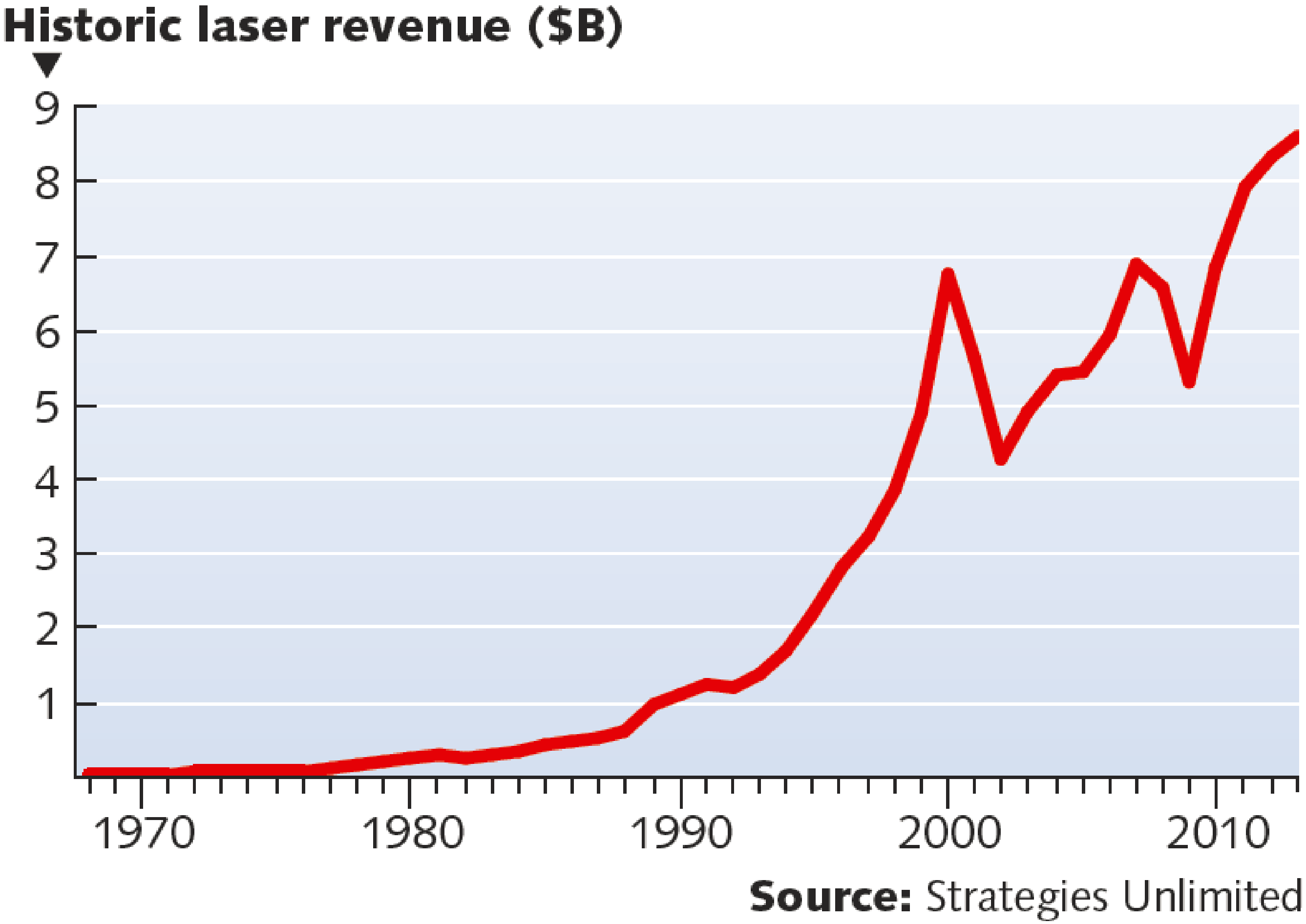
Source: Strategies Unlimited

Laserfocusworld.com

Laser market

Laserfocusworld.com

Laser market



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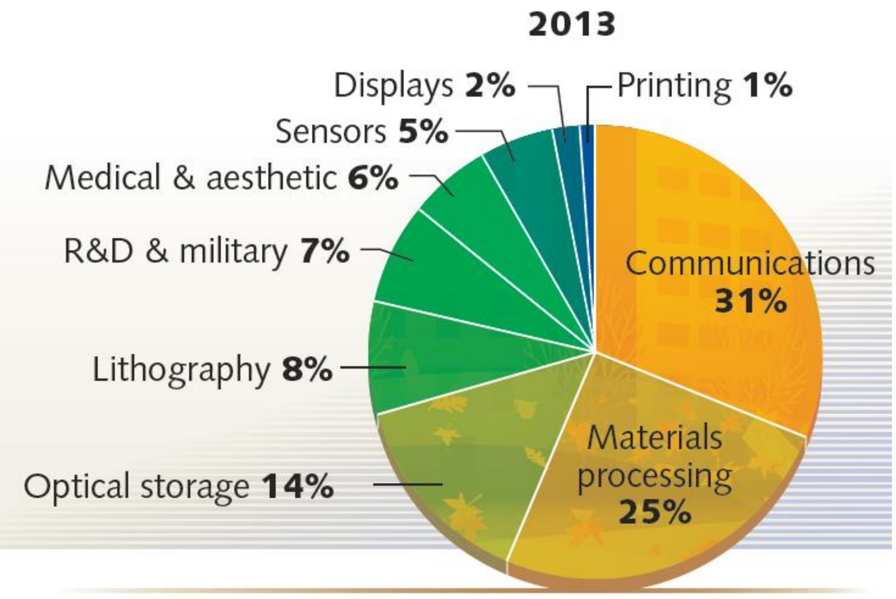
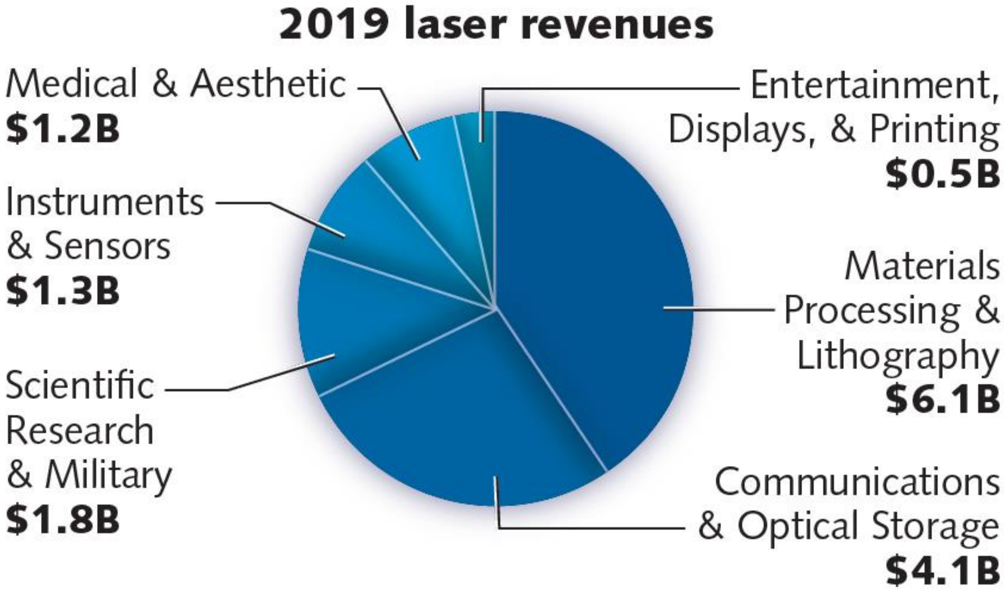
Laserfocusworld.com

Laser market





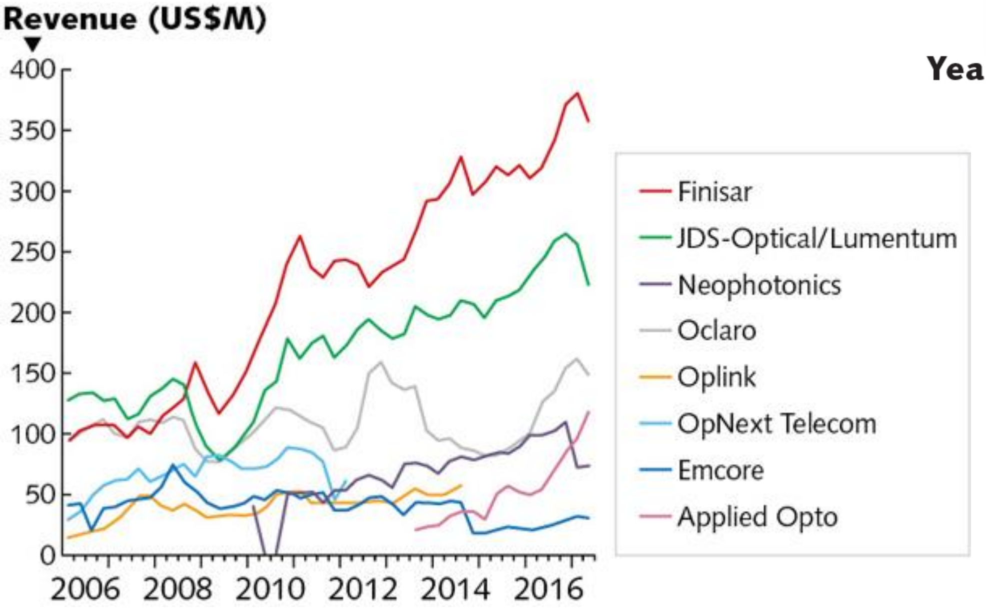
Laserfocusworld.com

Communications & optical storage

Includes all laser diodes used in telecommunications, data communications, and optical storage applications, including pumps for optical amplifiers.

Figure 3. **Communications and Optical Storage**

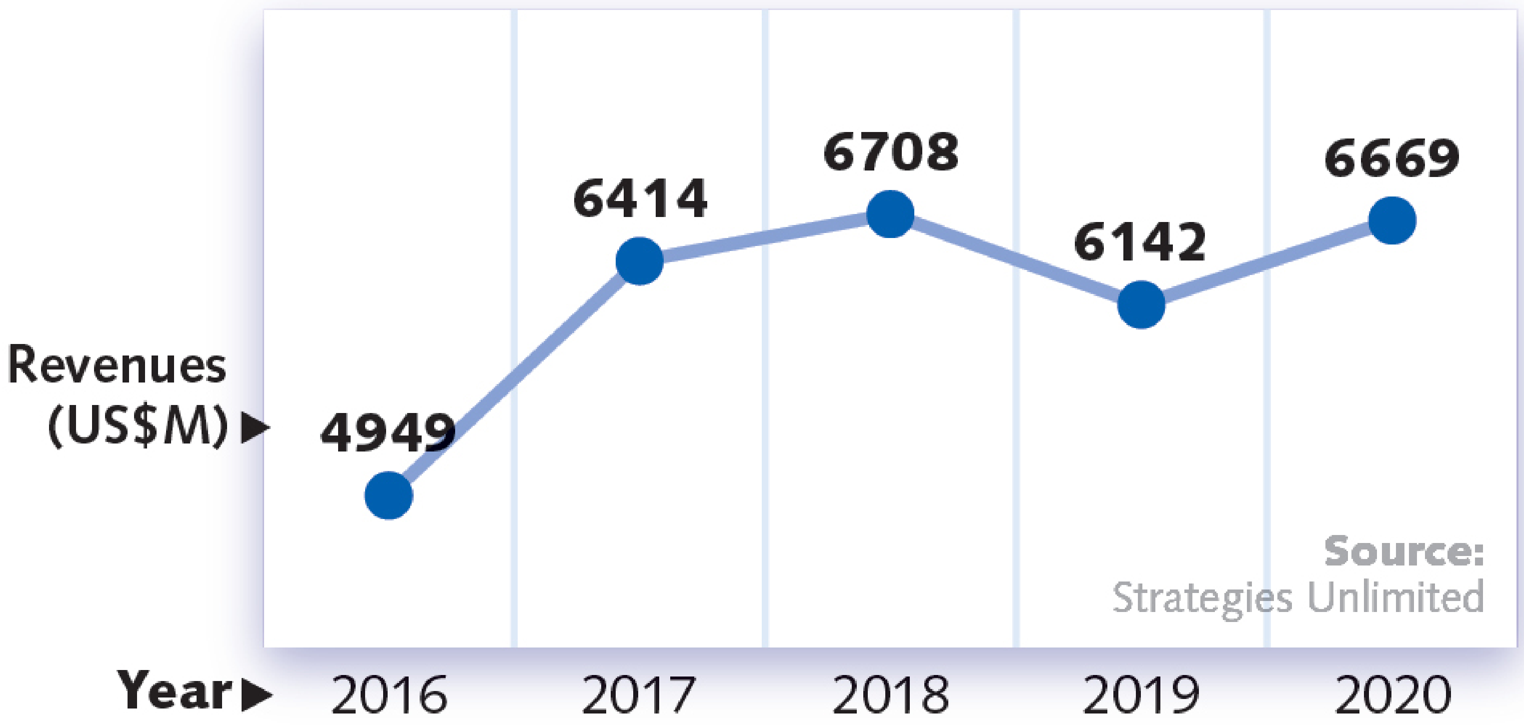
Source: Strategies Unlimited



Materials processing & lithography

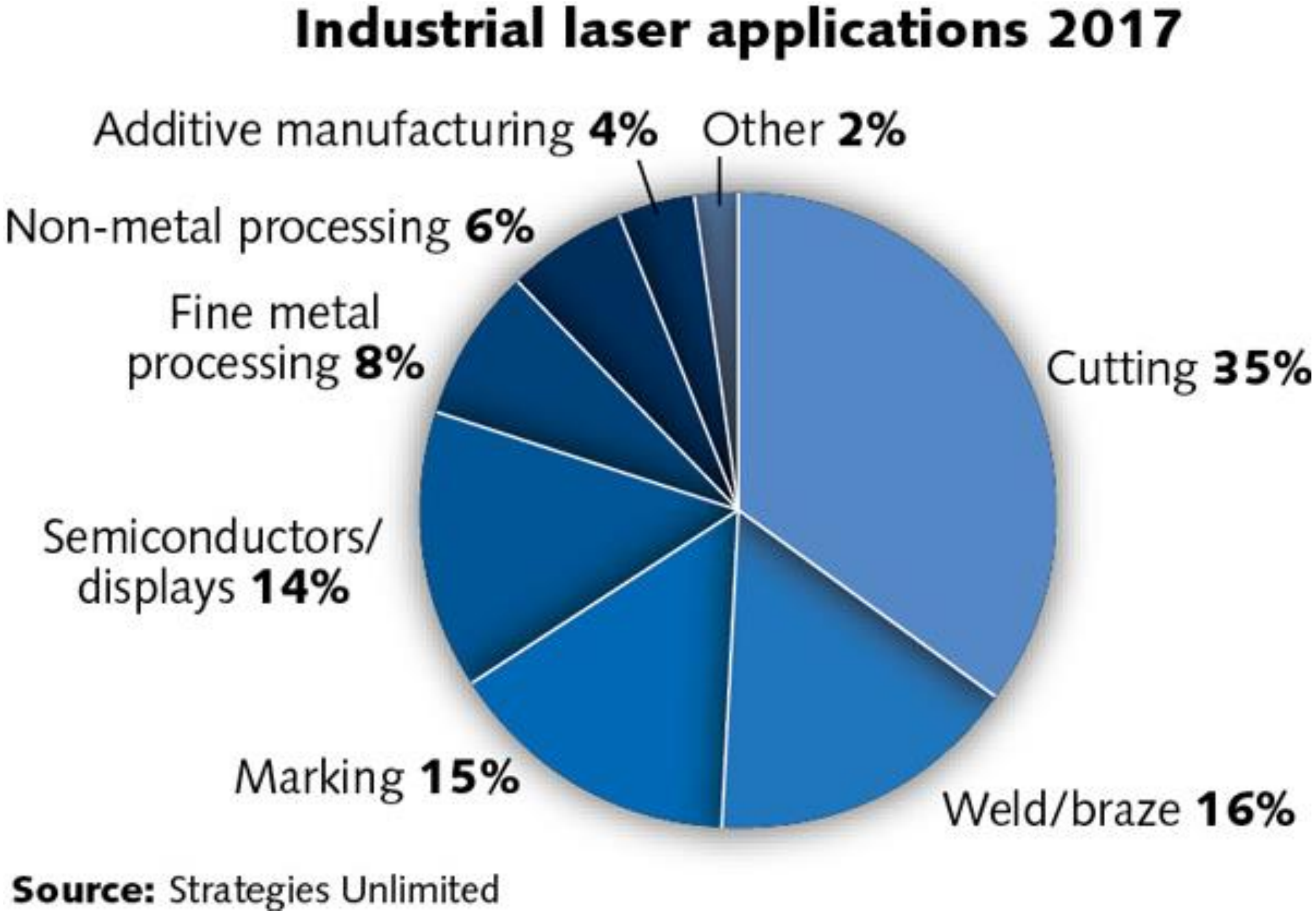
Includes lasers used for all types of metal processing (welding, cutting, annealing, drilling); semiconductor and microelectronics manufacturing (lithography, scribing, defect repair, via drilling); marking of all materials; and other materials processing (such as cutting and welding organics, rapid prototyping, micromachining, and grating manufacture). Also includes lasers for lithography.

Figure 2. **Materials Processing and Lithography**



Source:
Strategies Unlimited

Laser materials processing



Source: Strategies Unlimited

Research and Military

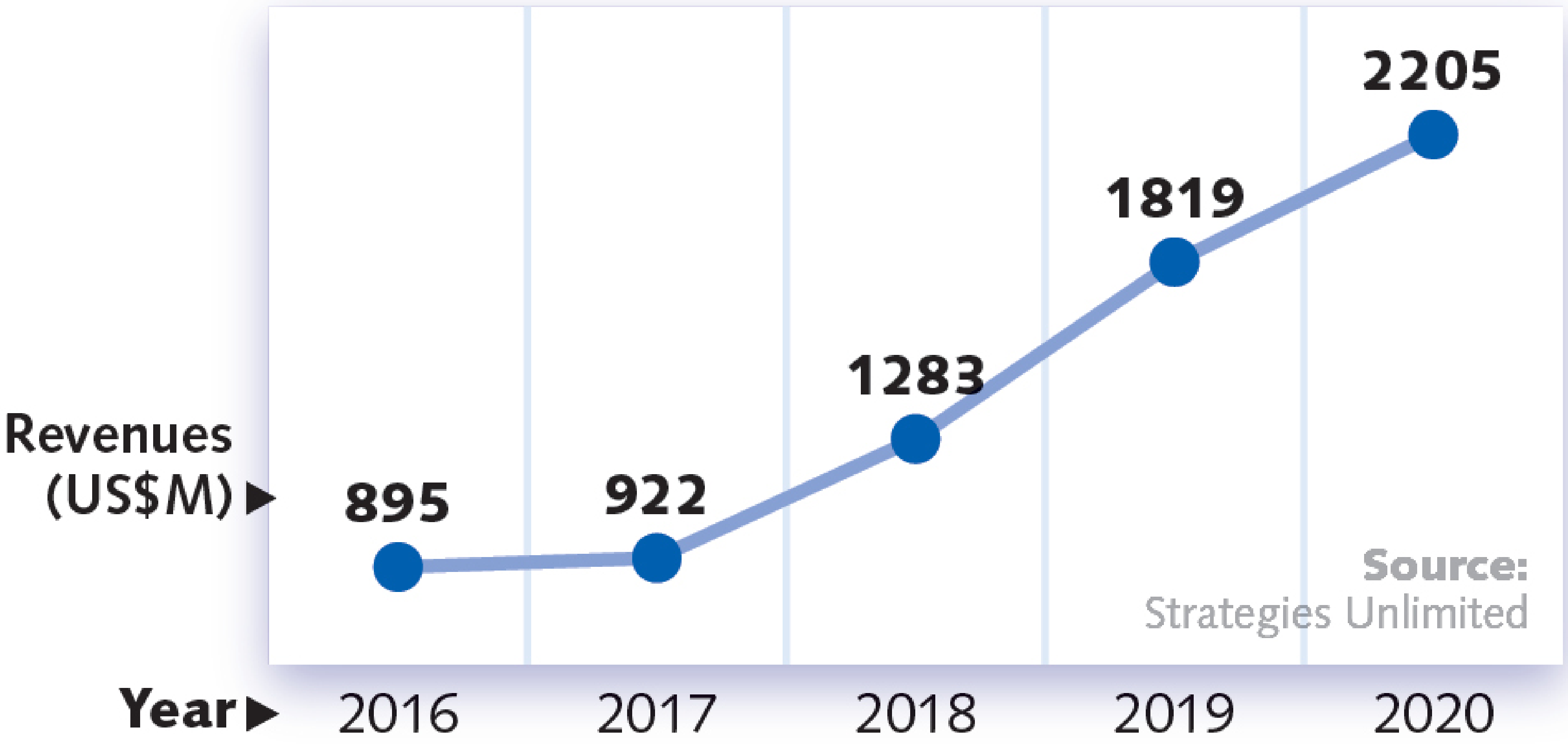
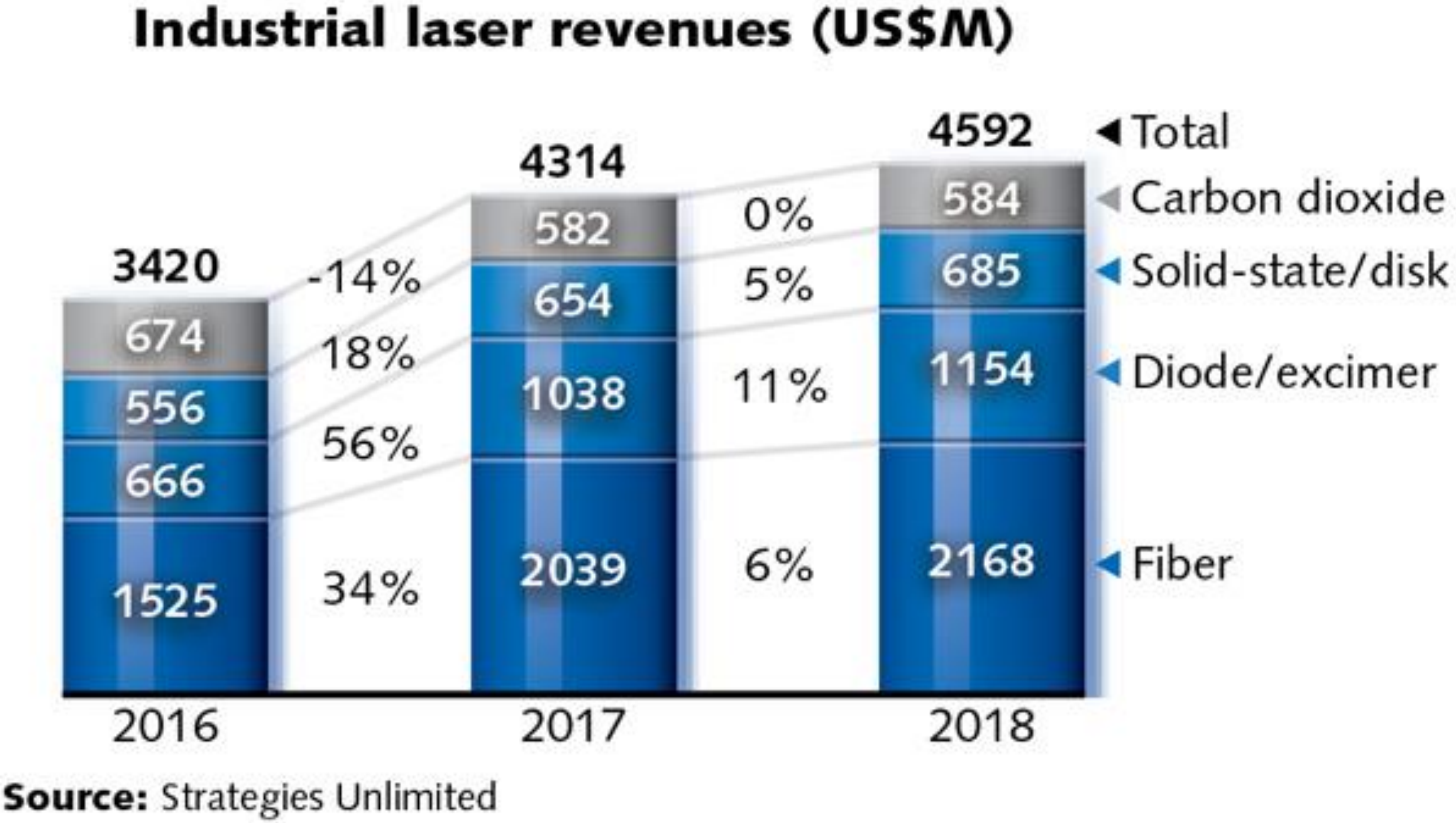


Figure 4. Scientifc Research and Military

Source:
Strategies Unlimited

Laser market



Source: Strategies Unlimited

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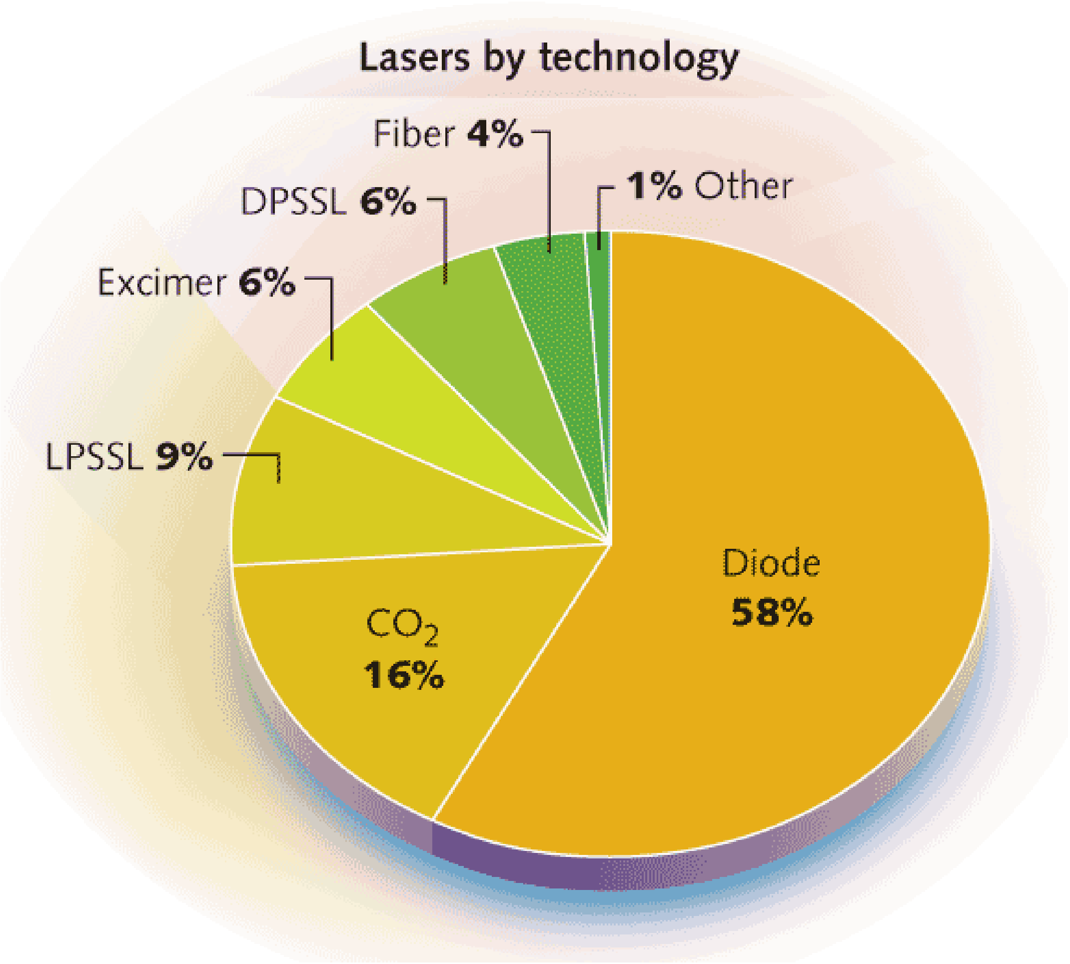
Laser market

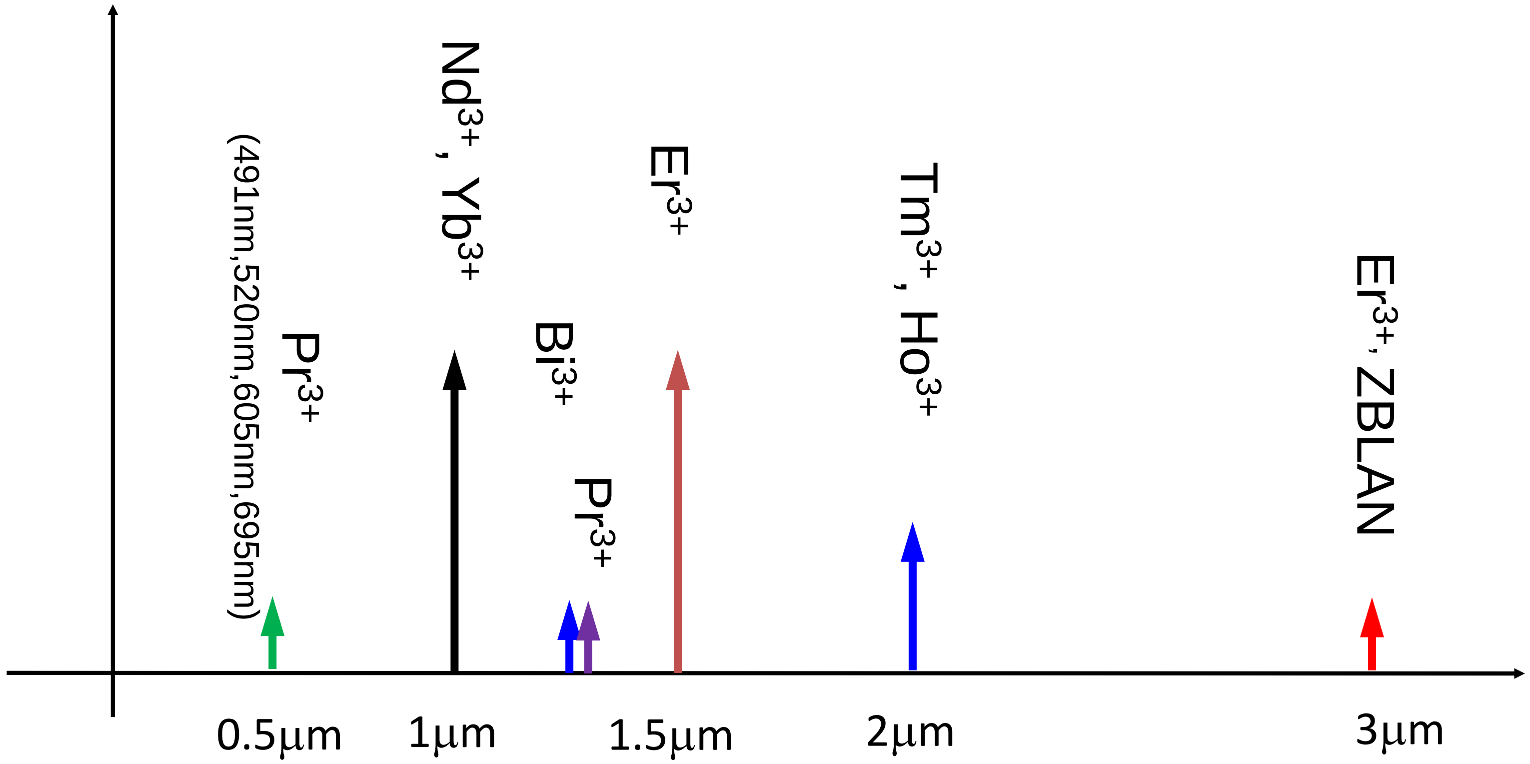


Current fiber lasers market share is ~ 25%

(2013 data)

Laserfocusworld.com

Active fibers



Advantages of fiber format

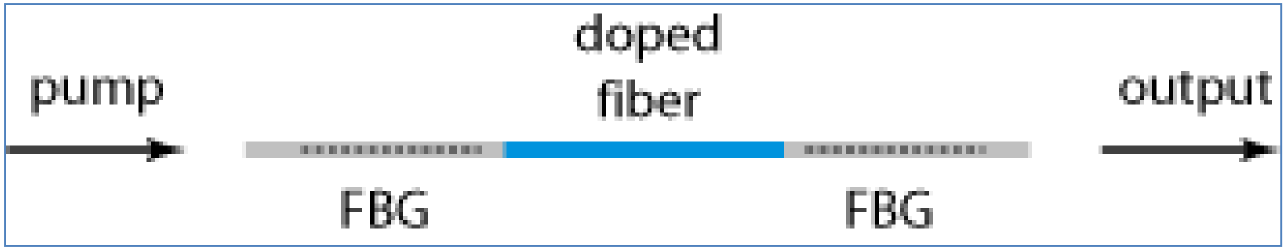
Fiber format removes the strict requirement of heat management which is normally very critical in solid-state lasers

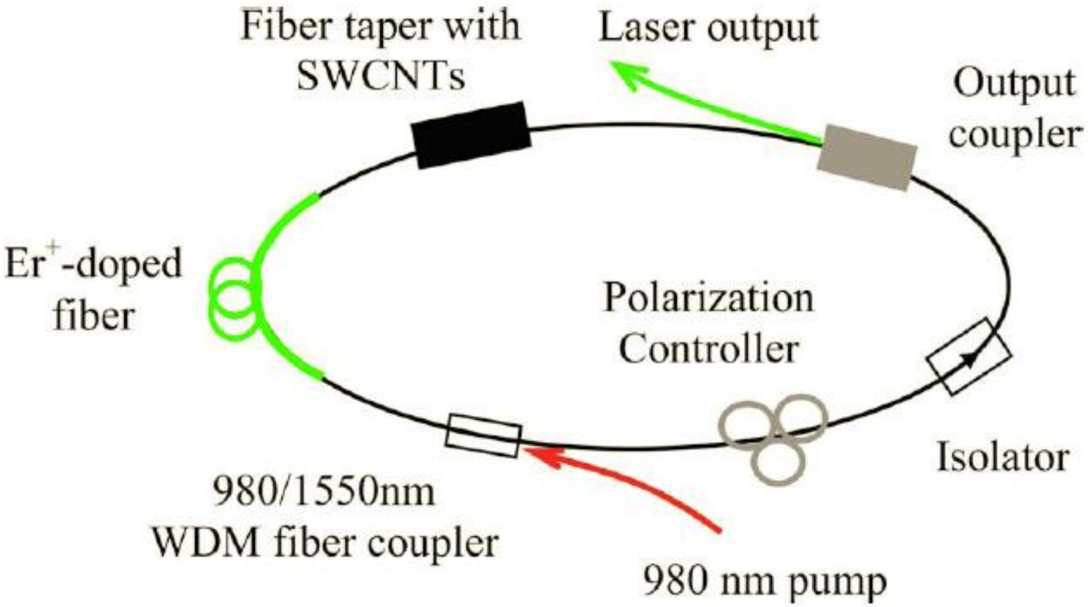
But there are also disadvantages:

- Long gain media
- High nonlinearity
- Polarization stability

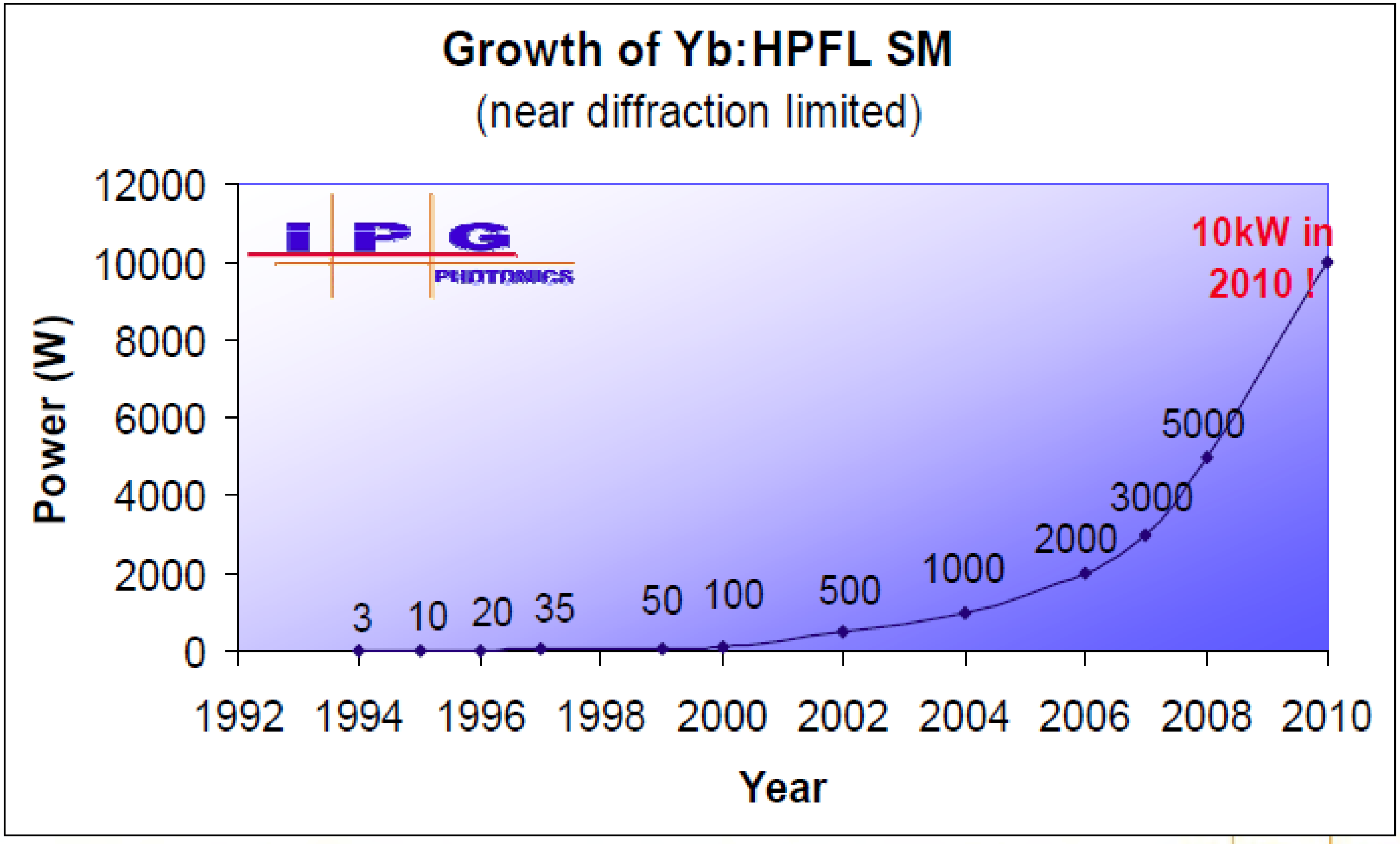
- High efficiency
- Air-cooled
- Direct diode pumping
- Compact
- Alignment free
- Reliable
- Low cost
- Performance

Laser design

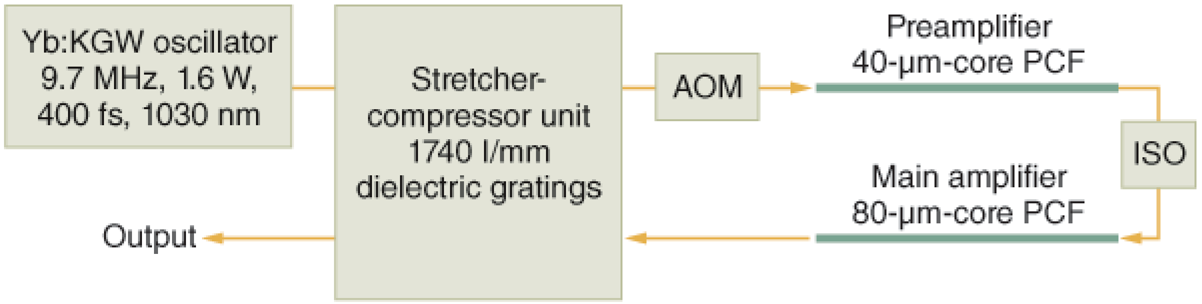




Fiber laser performance



mJ energy femtosecond fiber laser: > 1GW peak power!


Yb:KGW oscillator
9.7 MHz, 1.6 W,
400 fs, 1030 nm

Stretcher-compressor unit
1740 l/mm
dielectric gratings

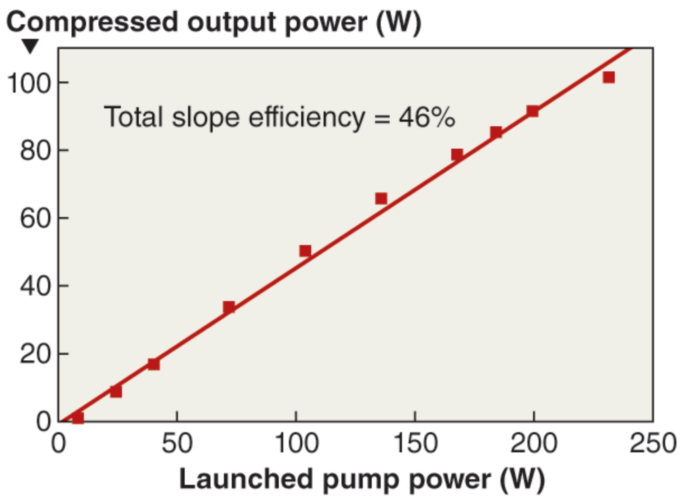
AOM

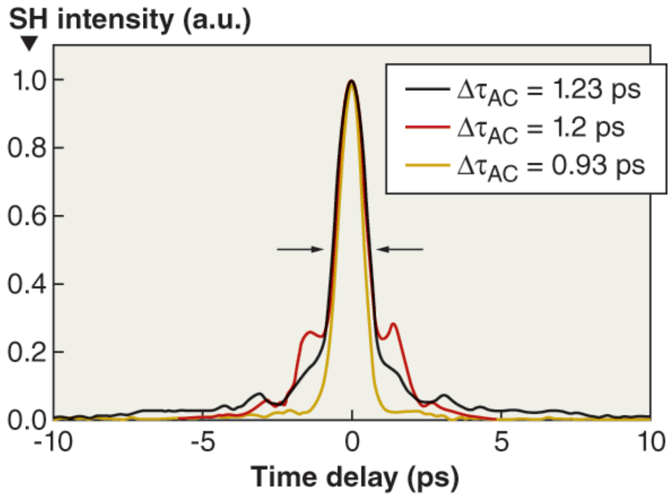
Preamplifier
40-µm-core PCF

ISO

Main amplifier
80-µm-core PCF

Output

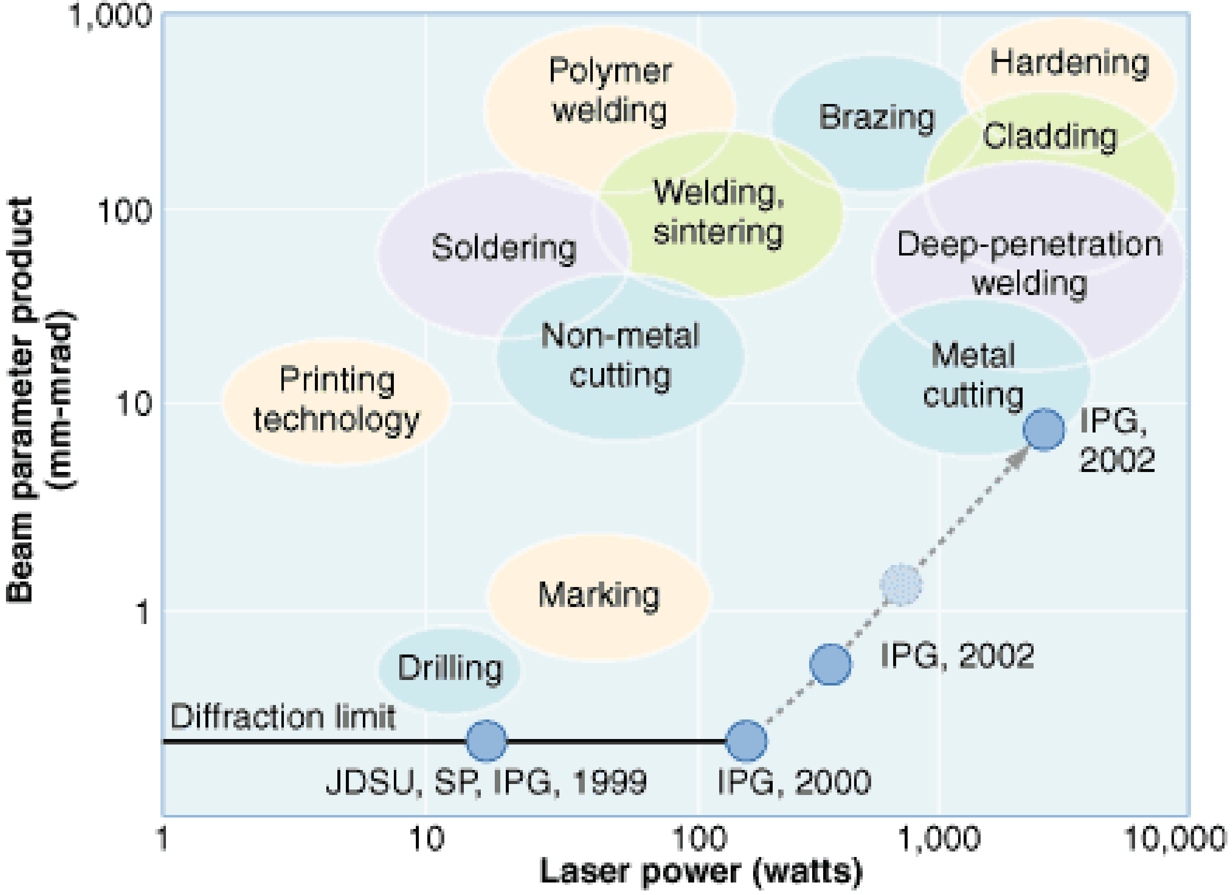




Tünnermann’s group

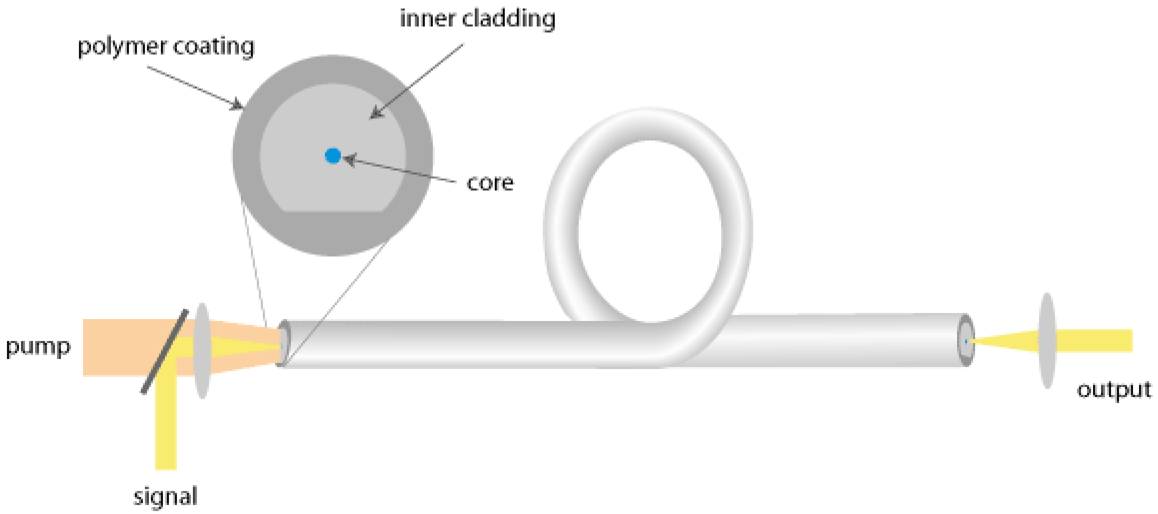
What can fiber laser do?

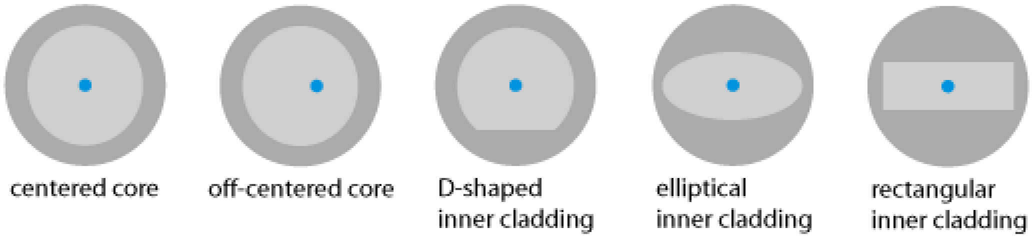
Overlay locus of high-power fiber lasers



Source: P. Loosen, Fraunhofer Inst., Fuer Lasertechnik, Aachen, Germany

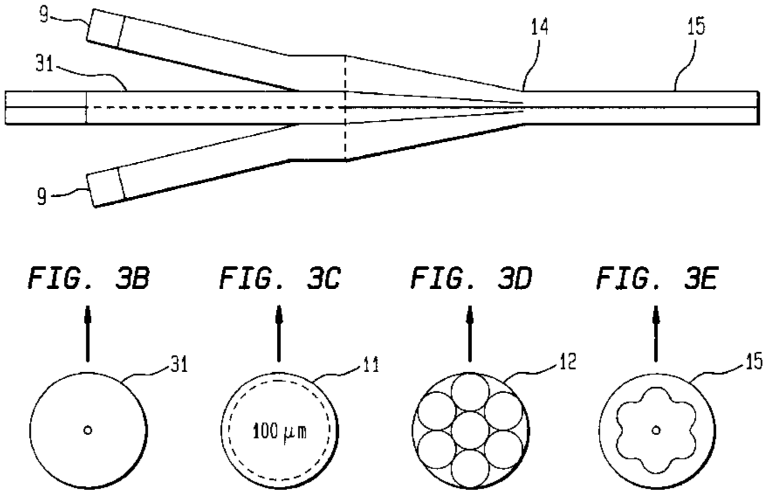
Cladding pump technology





http://www.rp-photonics.com/double_clad_fibers.html

Cladding pump technology



(US patent # 5,864,644)

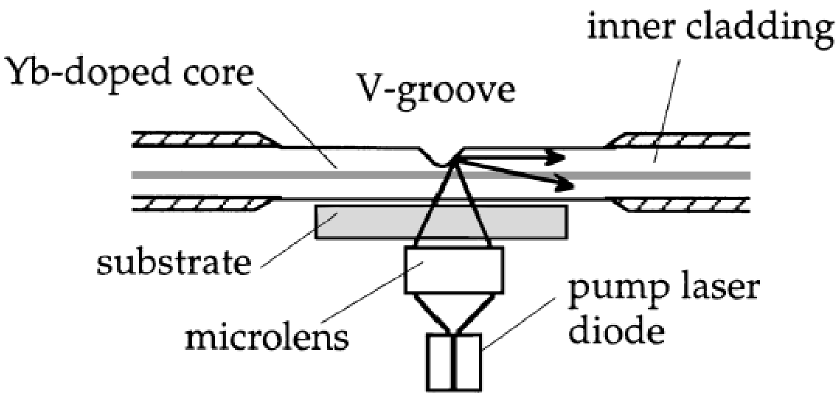
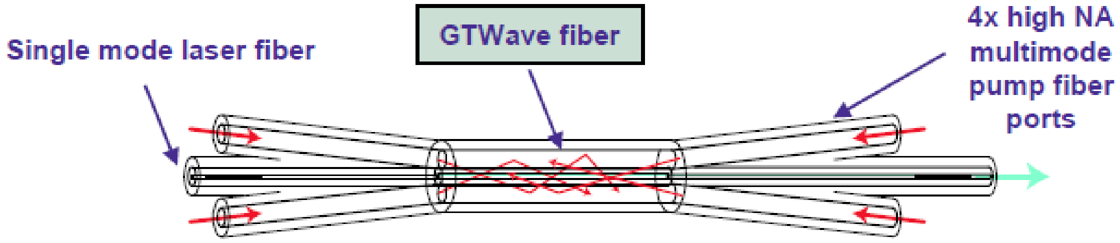
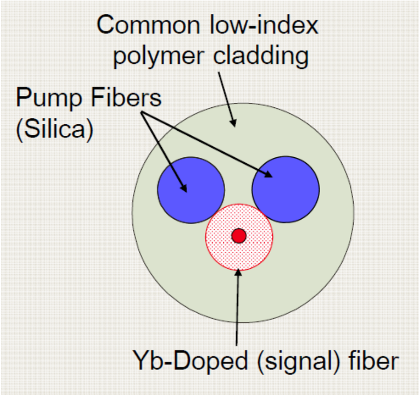


Fig. 1. V-groove side-pumping arrangement.

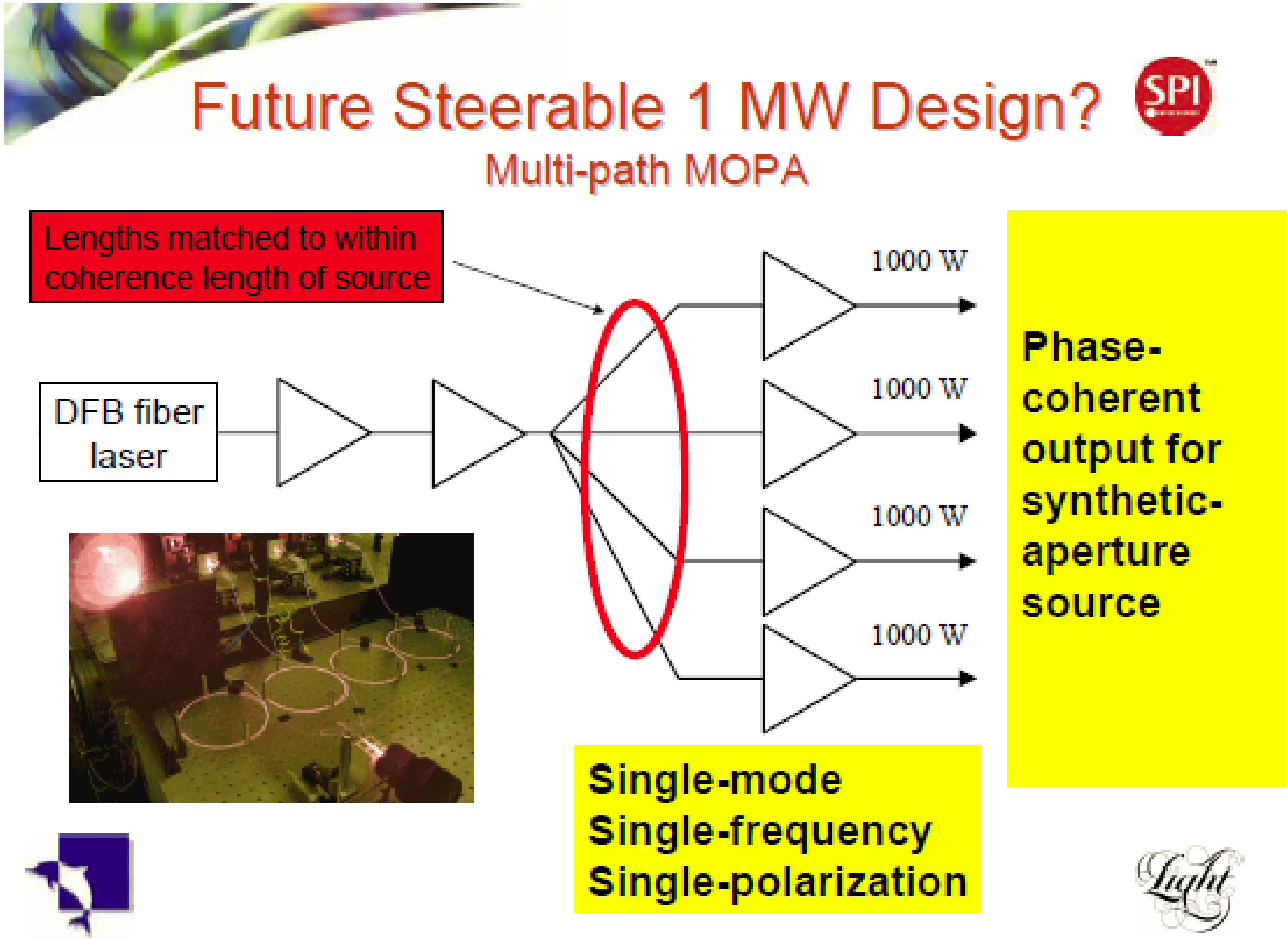
(Goldberg, Opt. Lett. 1999)



GTWave technology (credit: D. Payne)



Beam combination



Future Steerable 1 MW Design?

Multi-path MOPA

Lengths matched to within coherence length of source

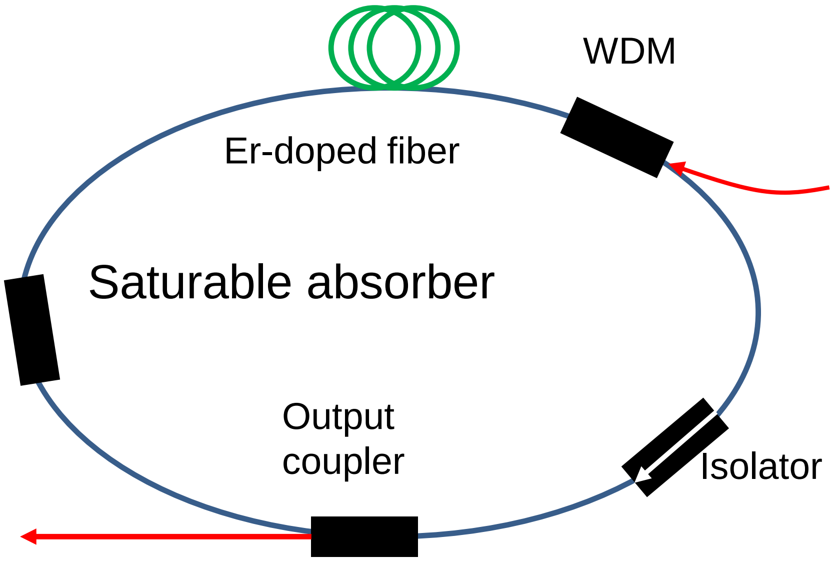
Phase-coherent output for synthetic-aperture source

Single-mode
Single-frequency
Single-polarization

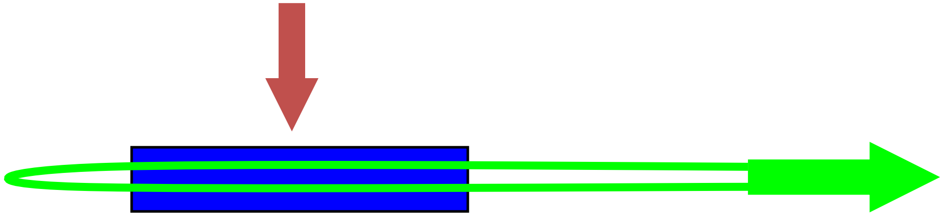
(credit: D. Payne)

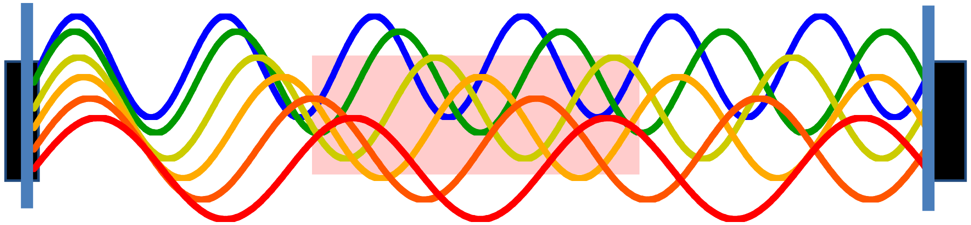
Project #8: Mode-locked fiber laser

- Measure laser pulse train
- Measure output spectrum
- Measure laser pulse duration
- Observe phase-locked of laser modes

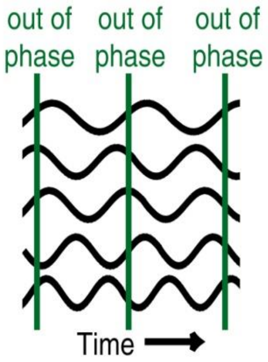


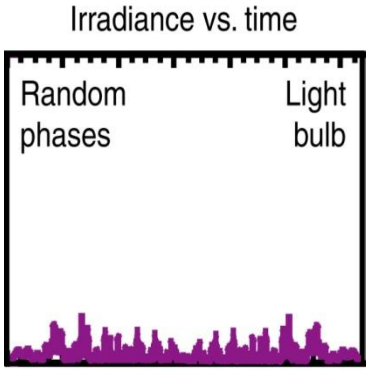
Mode-locked ring fiber laser

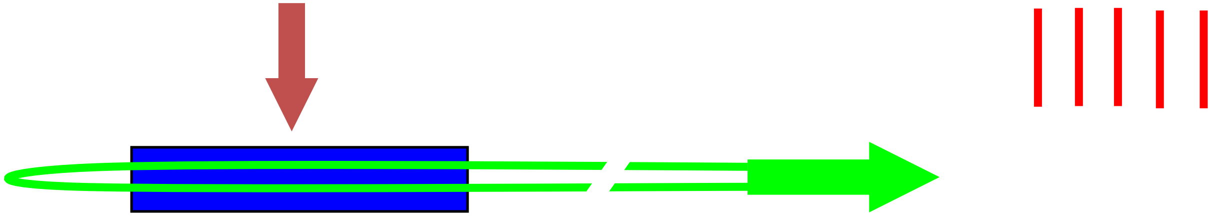


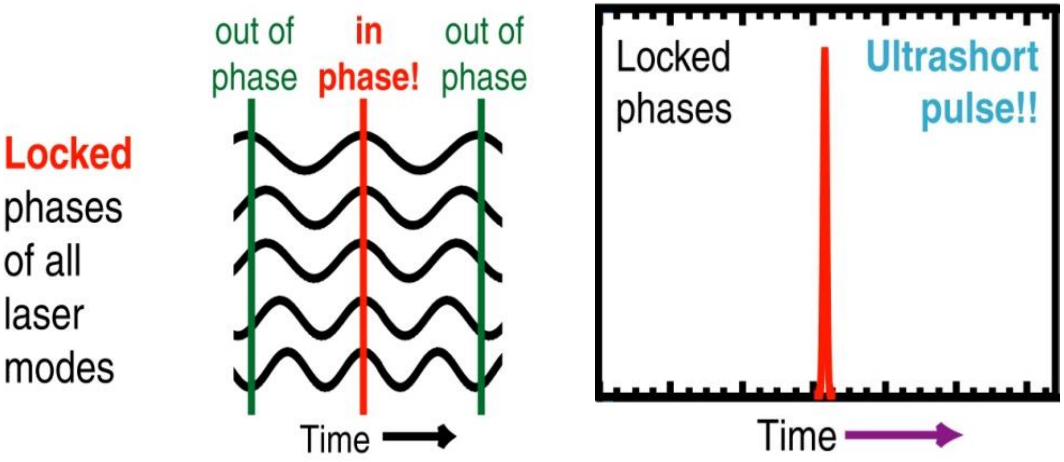


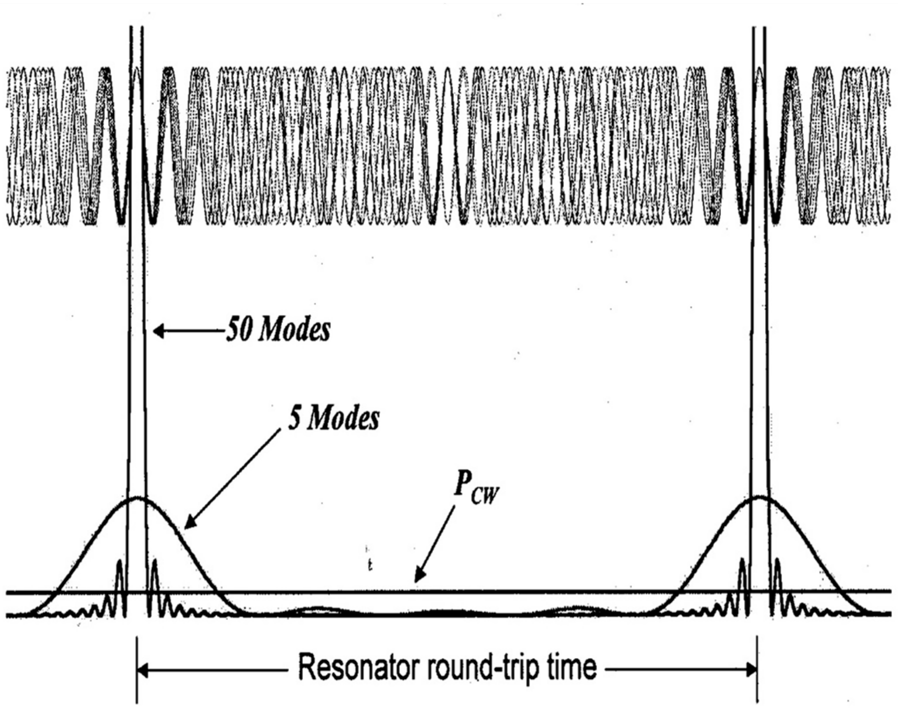
Random phases of all laser modes

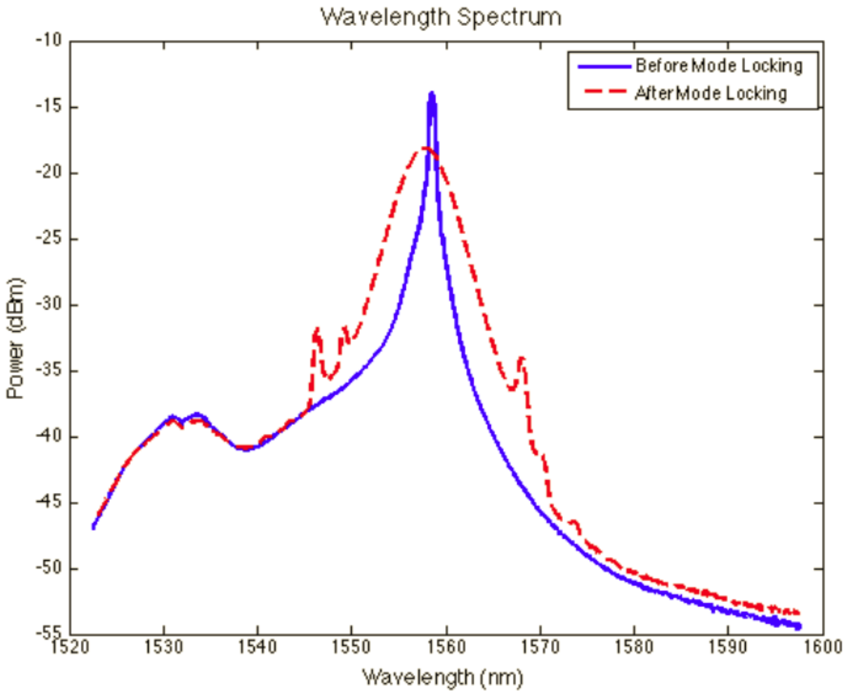


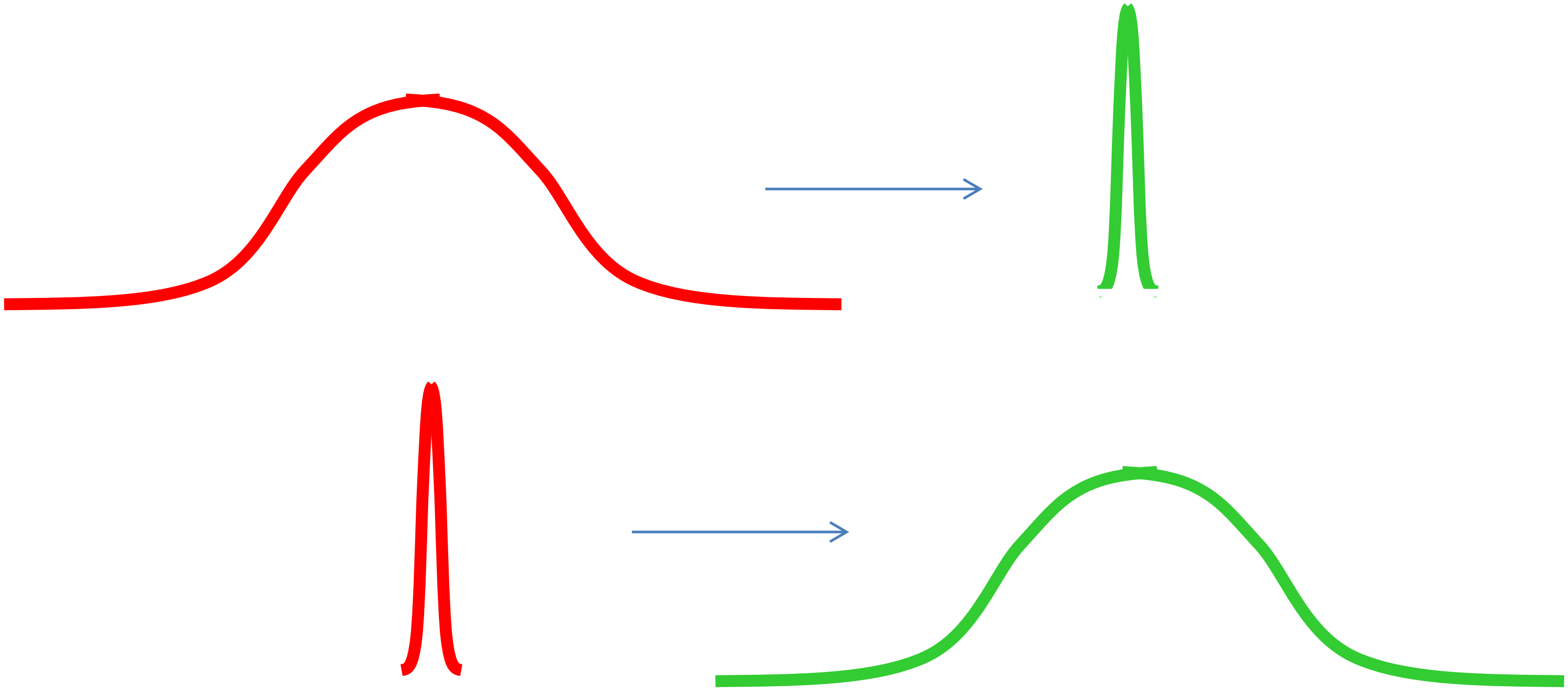


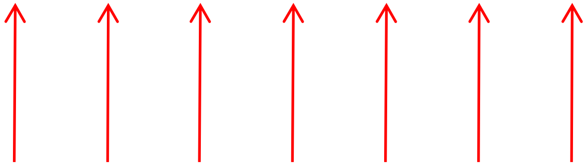



Locked
phases
of all
laser
modes
out of
phase
in
phase!
out of
phase
Time
Locked
phases
Ultrashort
pulse!!
Time

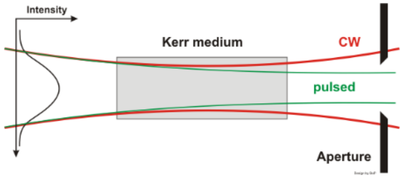

50 Modes
5 Modes
P_{CW}
Resonator round-trip time

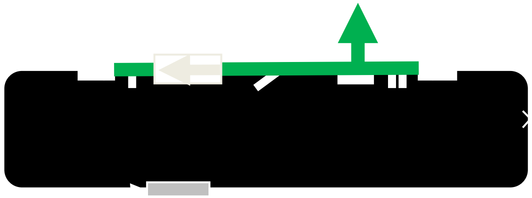

Wavelength Spectrum
Before Mode Locking
After Mode Locking
Power (dBm)
-10
-15
-20
-25
-30
-35
-40
-45
-50
-55
1520
1530
1540
1550
1560
1570
1580
1590
1600
Wavelength (nm)

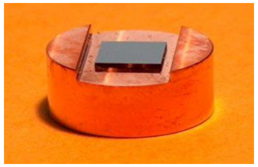


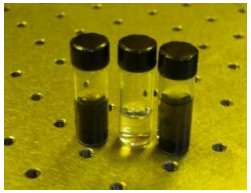


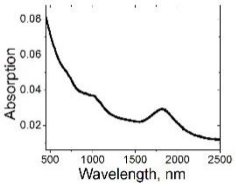
- Carbon nanotubes (CNT) and graphene

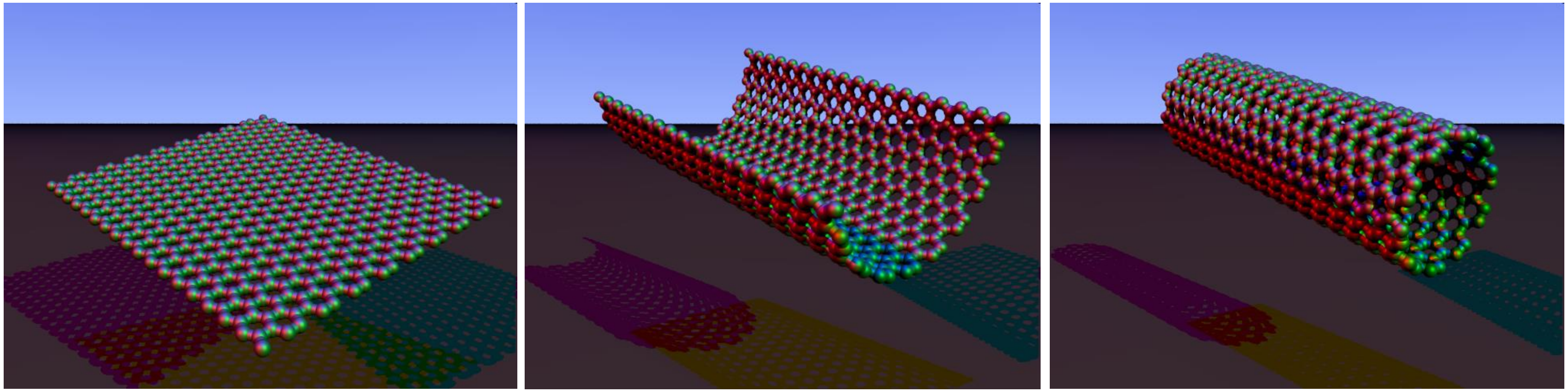


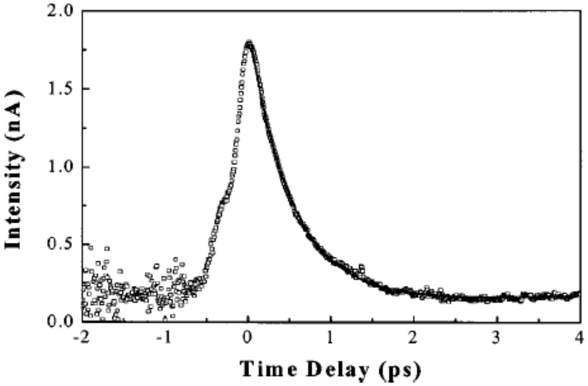


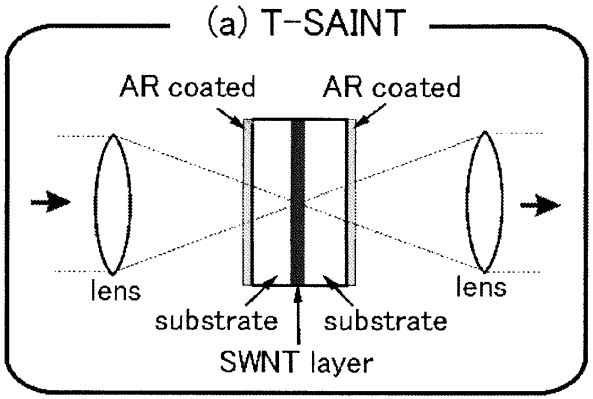


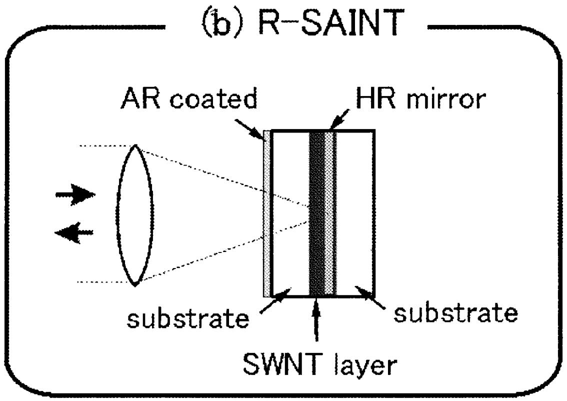


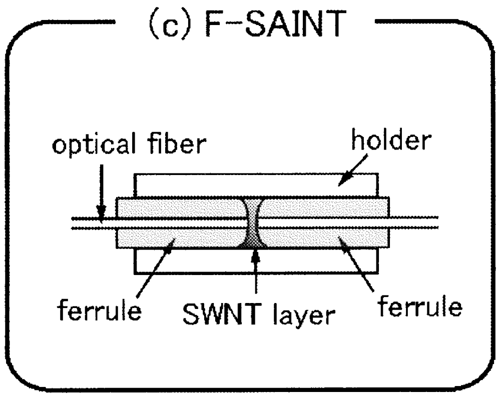


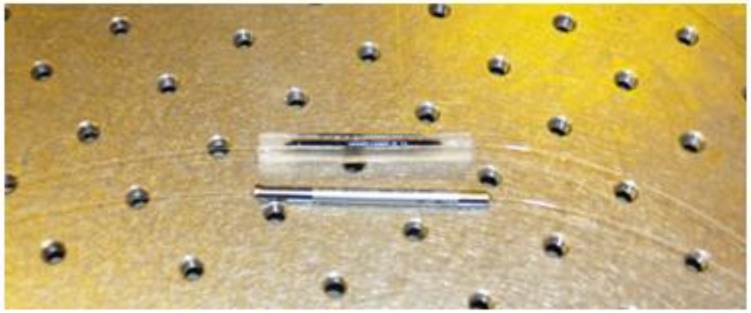


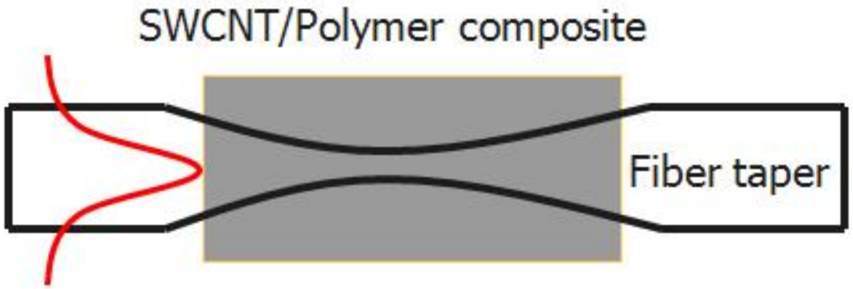

Intensity (nA)
2.0
1.5
1.0
0.5
0.0
-2
-1
0
1
2
3
4
Time Delay (ps)


(a) T-SAINT

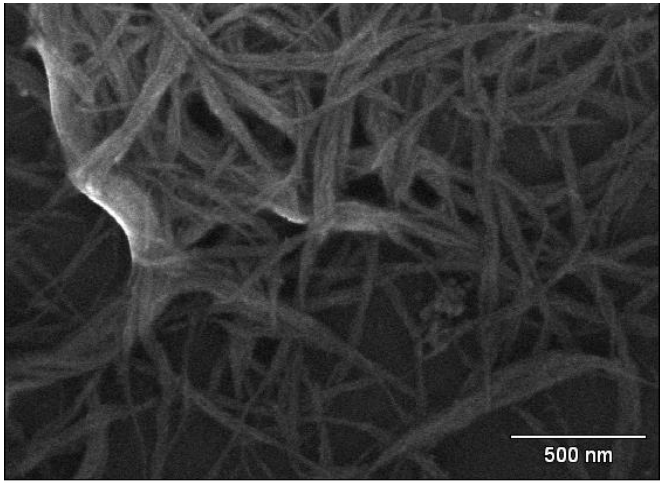

(b) R-SAINT

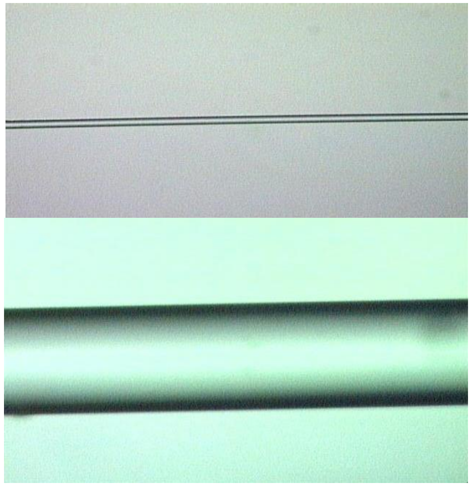

(c) F-SAINT

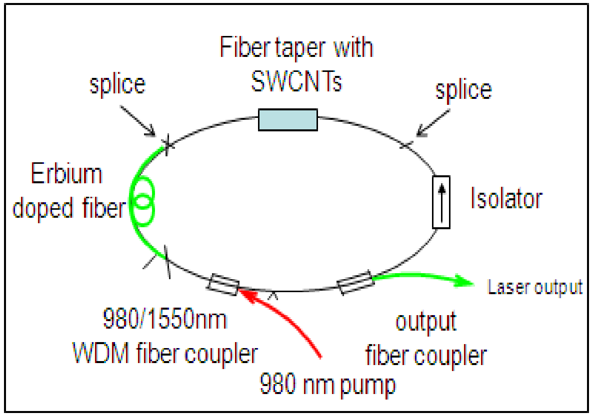


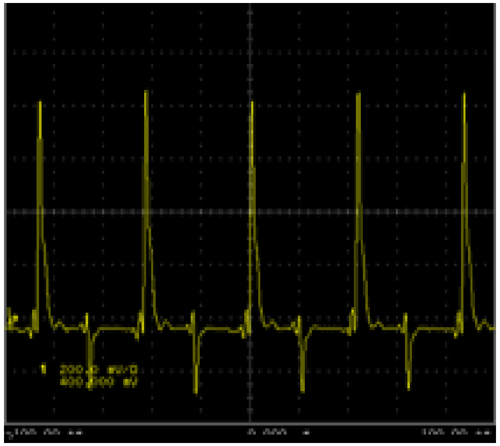


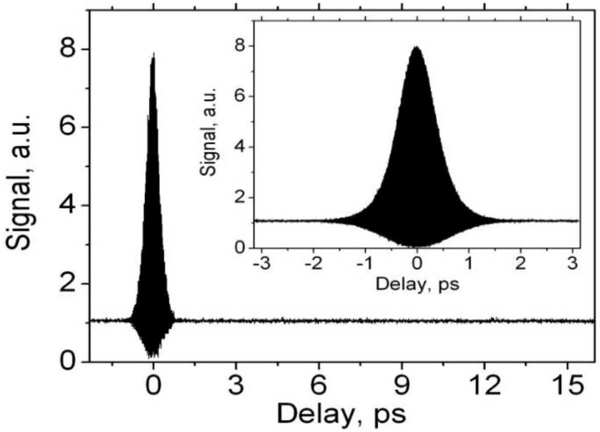
(K. Kieu and M. Mansuripur, Opt. Lett, 2007)

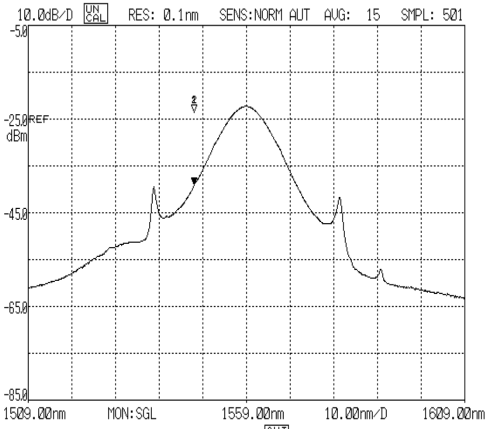


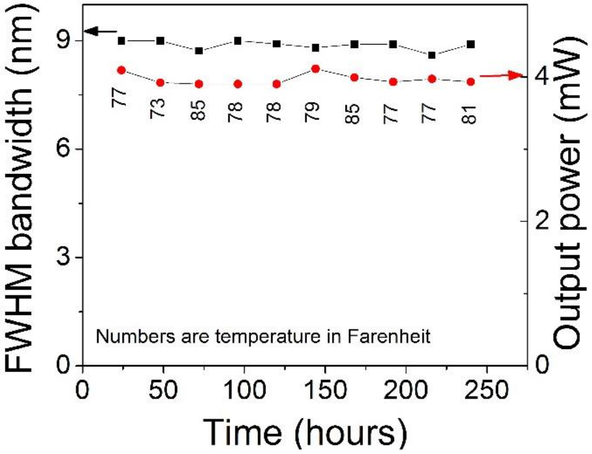


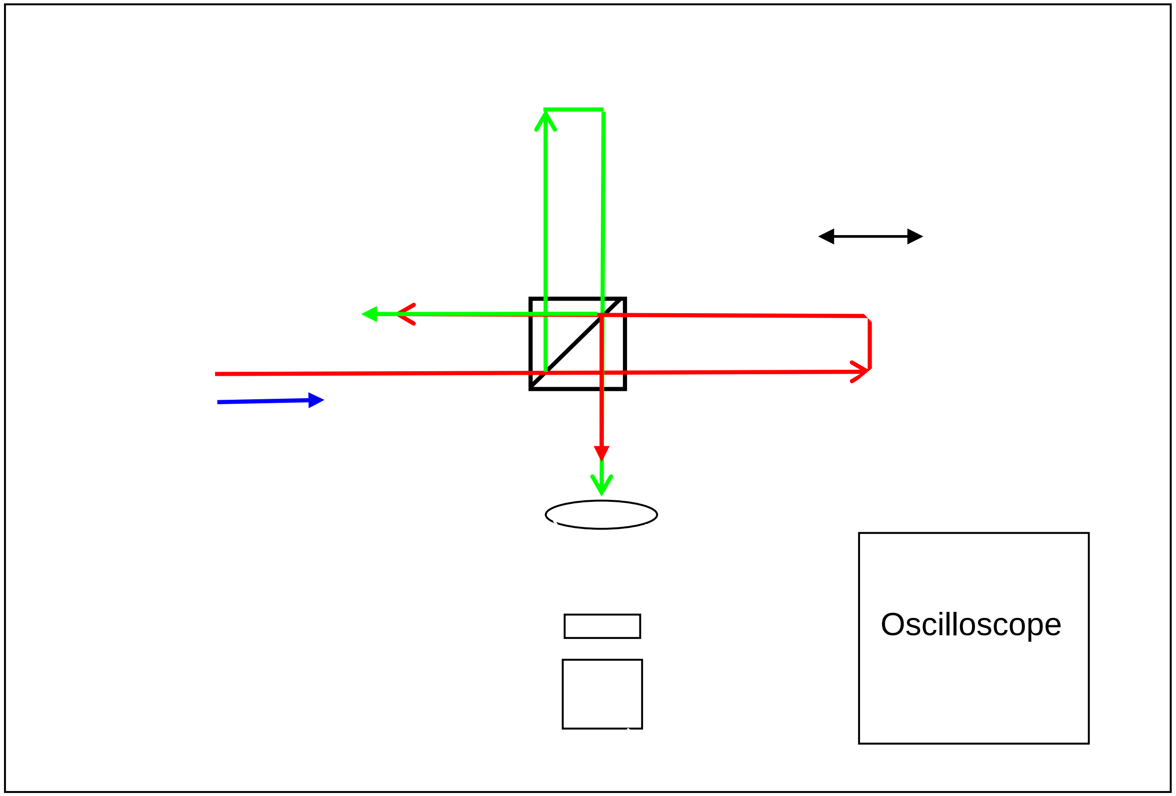

Fiber taper with SWCNTs
splice
splice
Erbium doped fiber
Isolator
Laser output
980/1550nm WDM fiber coupler
output fiber coupler
980 nm pump

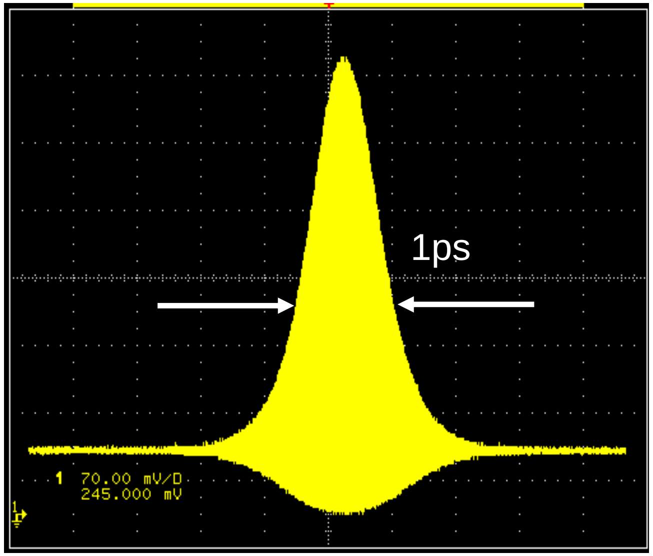


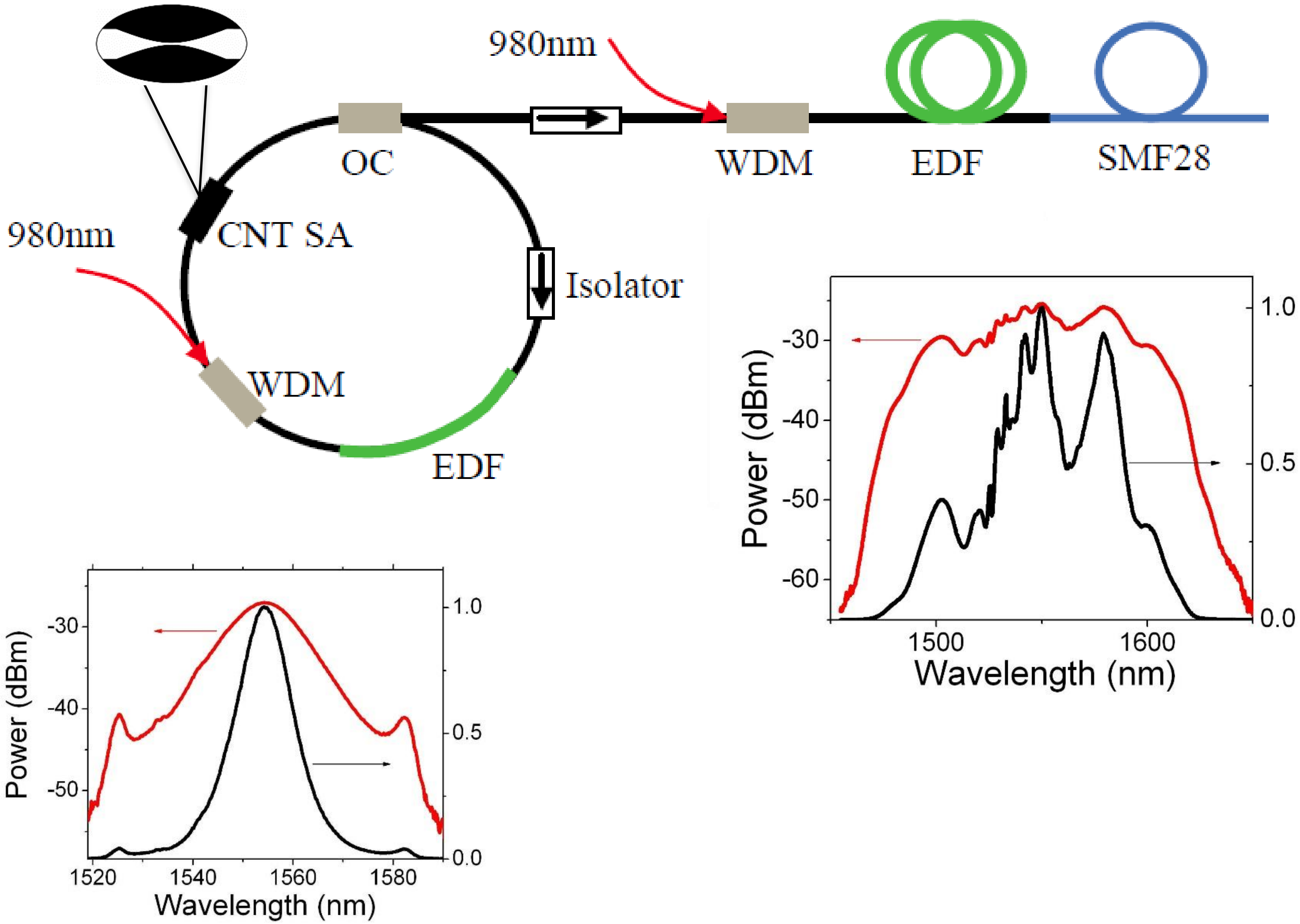

Signal, a.u.
8
6
4
2
0
0
3
6
9
12
15
Delay, ps
Signal, a.u.
8
6
4
2
0
-3
-2
-1
0
1
2
3
Delay, ps

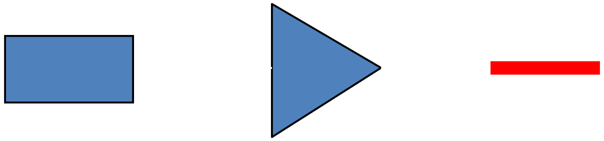

10.0dB/D
UN CAL
RES: 0.1nm
SENS:NORM AUT
AVG: 15
SMPL: 501
-5.0
-25.0 REF dBm
-45.0
-65.0
-85.0
1509.00nm
MON:SGL
1559.00nm
10.00nm/D
1609.00nm

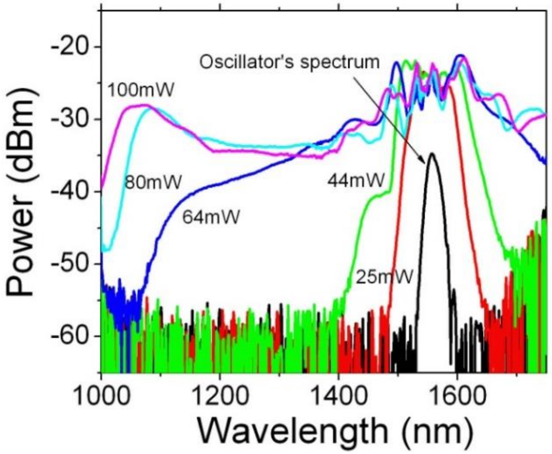

FWHM bandwidth (nm)
9
6
3
0
Output power (mW)
4
2
0
77
73
85
78
78
79
85
77
77
81
Numbers are temperature in Farenheit
0
50
100
150
200
250
Time (hours)

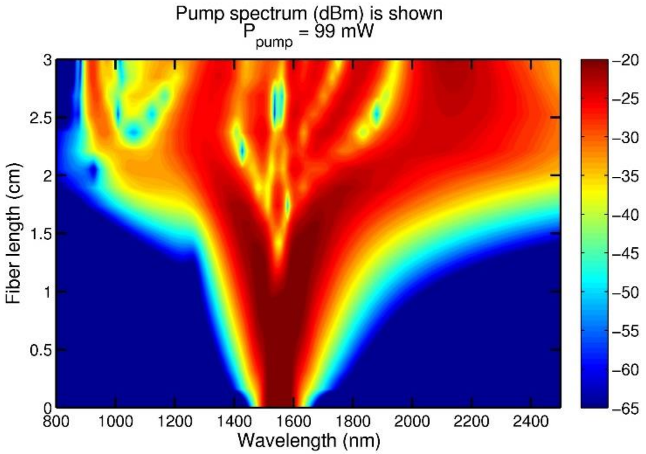

Oscilloscope

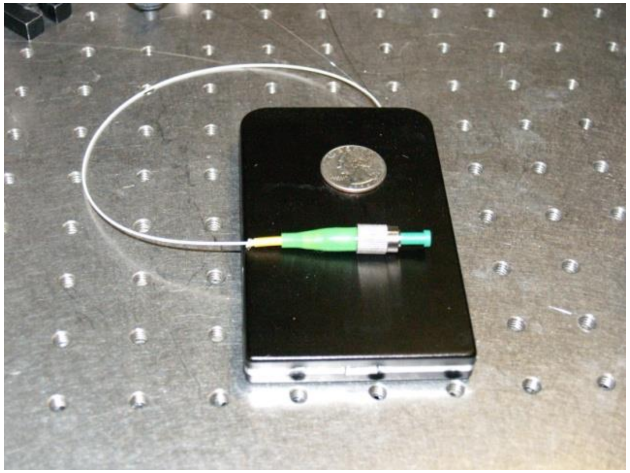

1ps
1 70.00 mV/D
245.000 mV

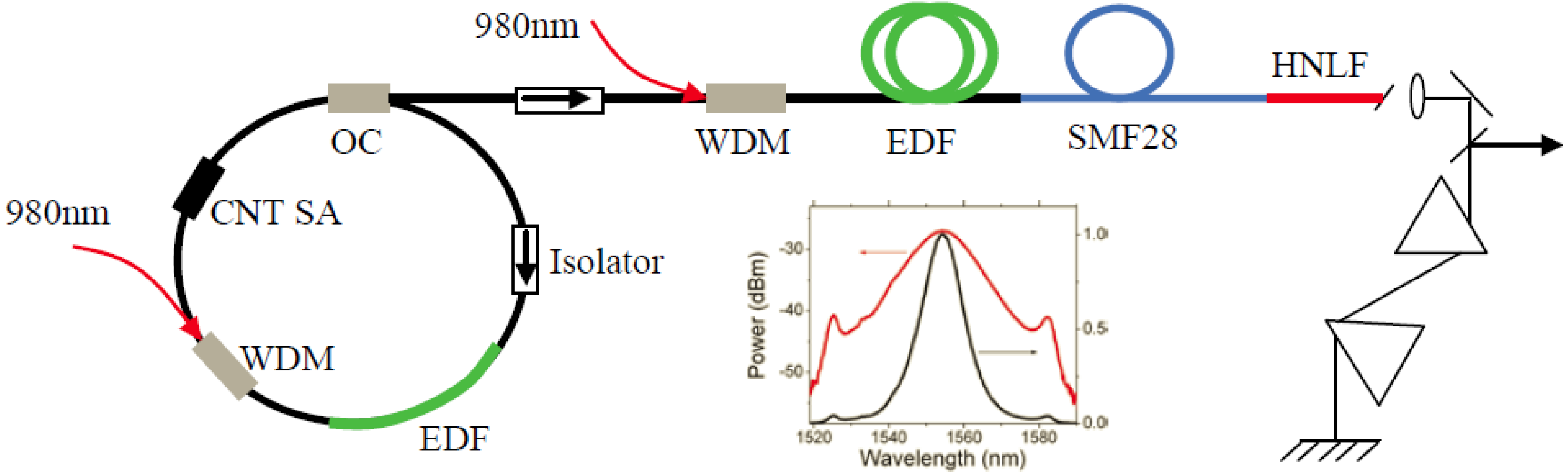

980nm
980nm
OC
CNT SA
Isolator
WDM
EDF
WDM
EDF
SMF28
Power (dBm)
-30
-40
-50
-60
1.0
0.5
0.0
1500
1600
Wavelength (nm)
Power (dBm)
-30
-40
-50
1.0
0.5
0.0
1520
1540
1560
1580
Wavelength (nm)

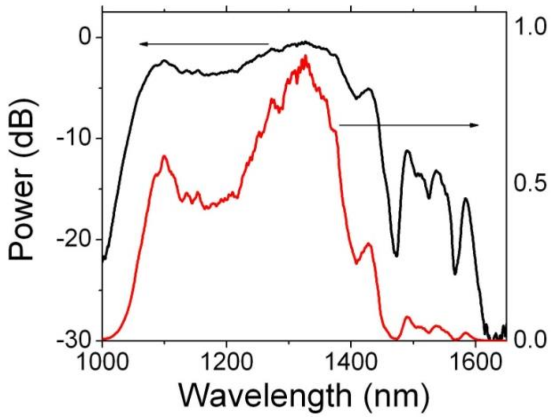


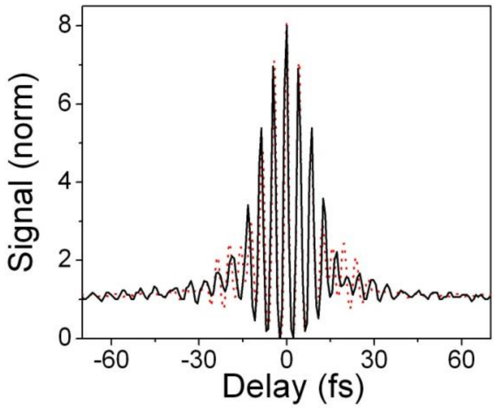

Power (dBm)
-20
-30
-40
-50
-60
Oscillator's spectrum
100mW
80mW
64mW
44mW
25mW
1000
1200
1400
1600
Wavelength (nm)

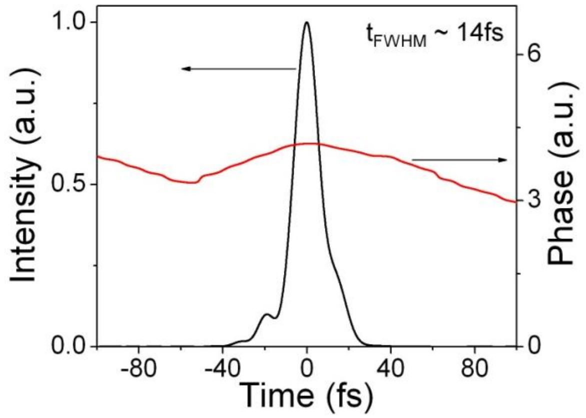

Pump spectrum (dBm) is shown
P_{pump} = 99 mW
Fiber length (cm)
0
0.5
1
1.5
2
2.5
3
800
1000
1200
1400
1600
1800
2000
2200
2400
Wavelength (nm)
−20
−25
−30
−35
−40
−45
−50
−55
−60
−65

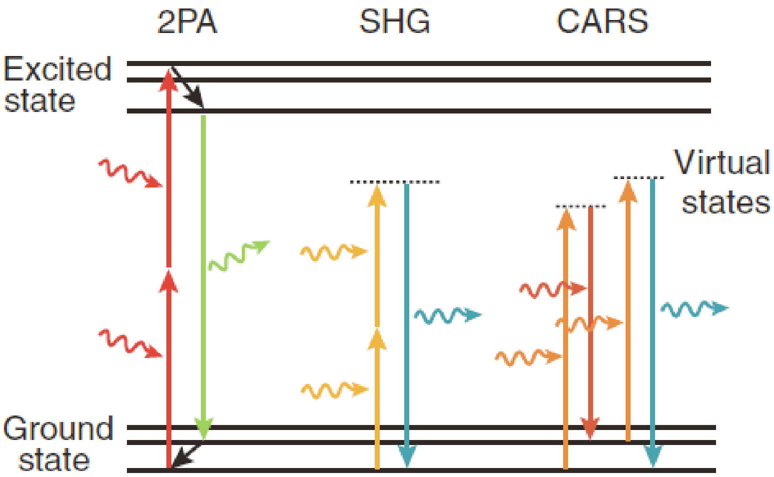


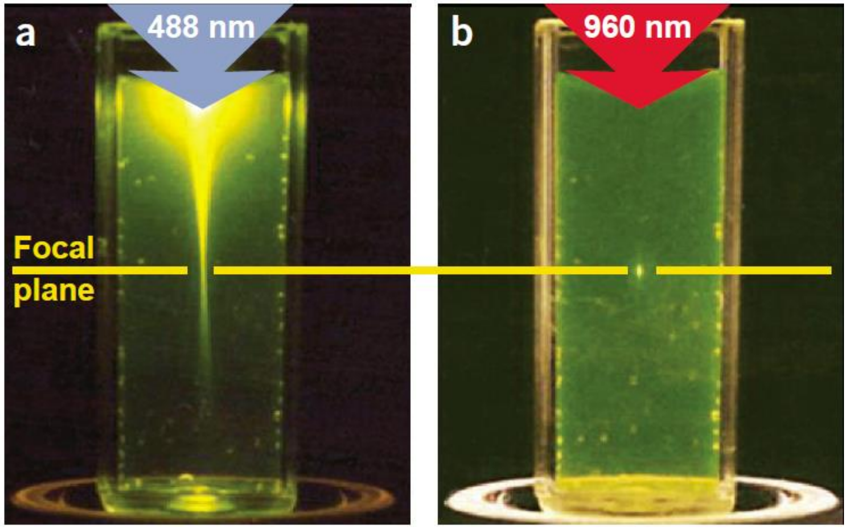

980nm
980nm
OC
CNT SA
Isolator
WDM
EDF
WDM
EDF
SMF28
HNLF
Power (dBm)
-30
-40
-50
1.0
0.5
0.0
1520
1540
1560
1580
Wavelength (nm)

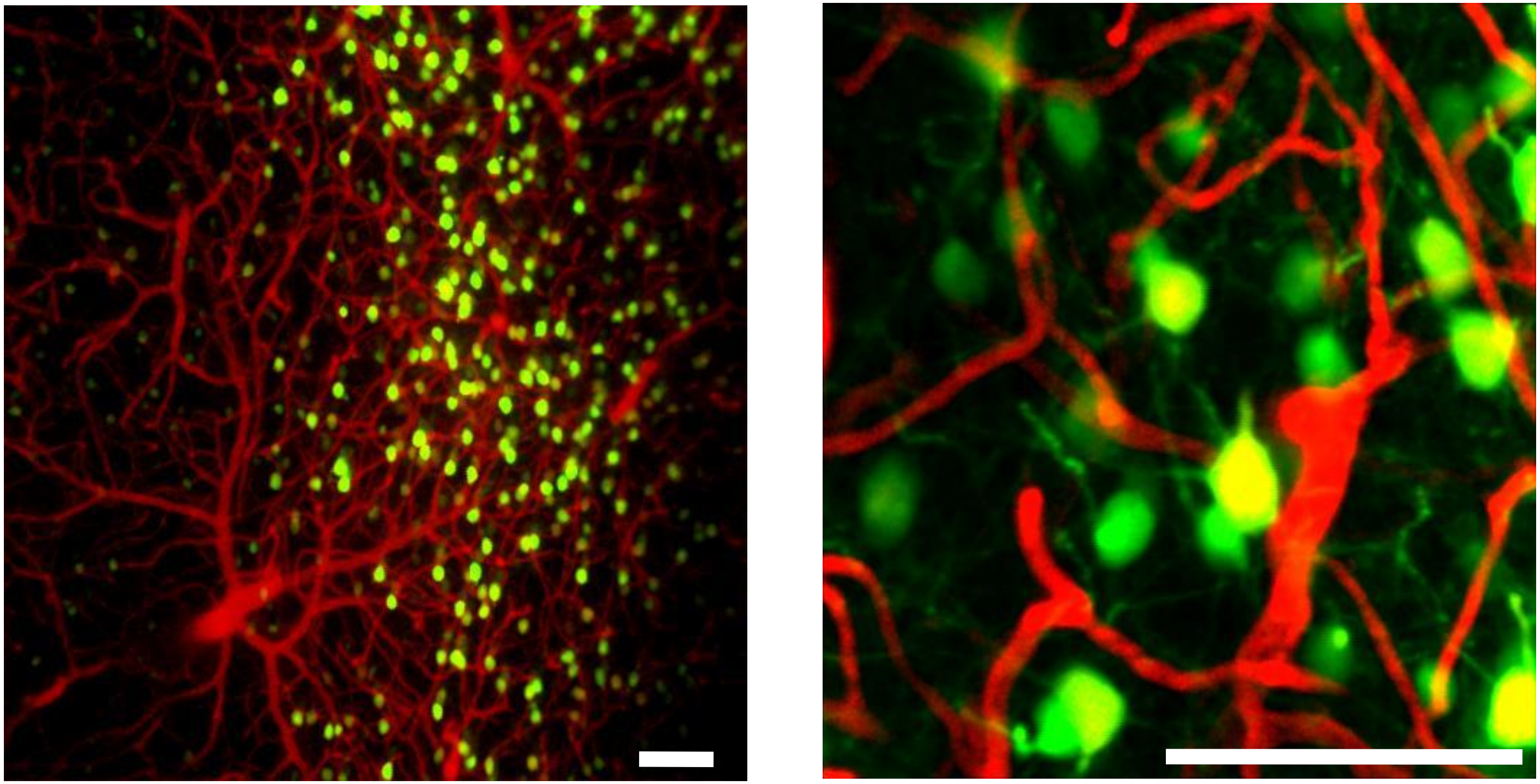

Power (dB)
0
-10
-20
-30
1.0
0.5
0.0
1000
1200
1400
1600
Wavelength (nm)

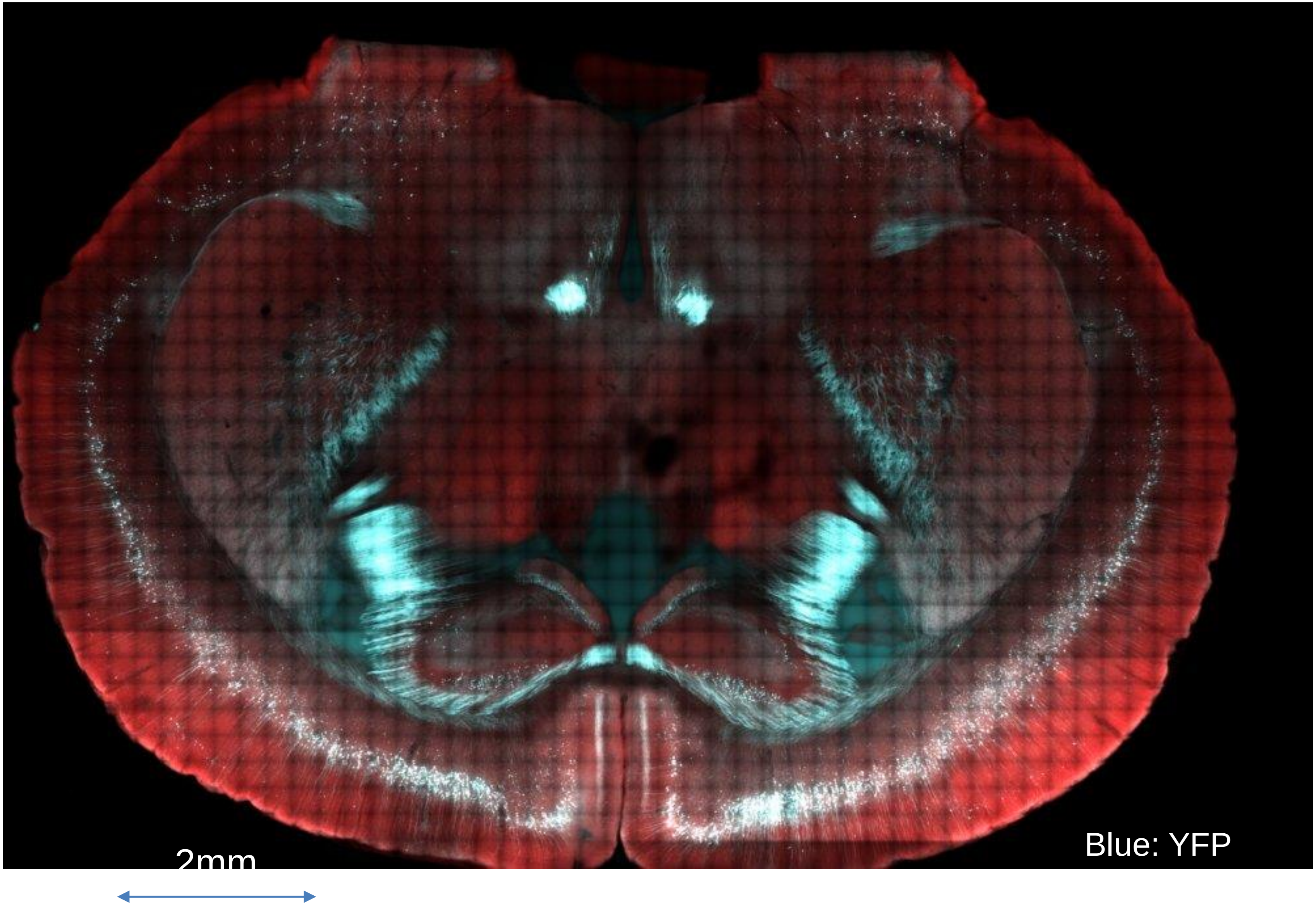

Signal (norm)
8
6
4
2
0
-60
-30
0
30
60
Delay (fs)

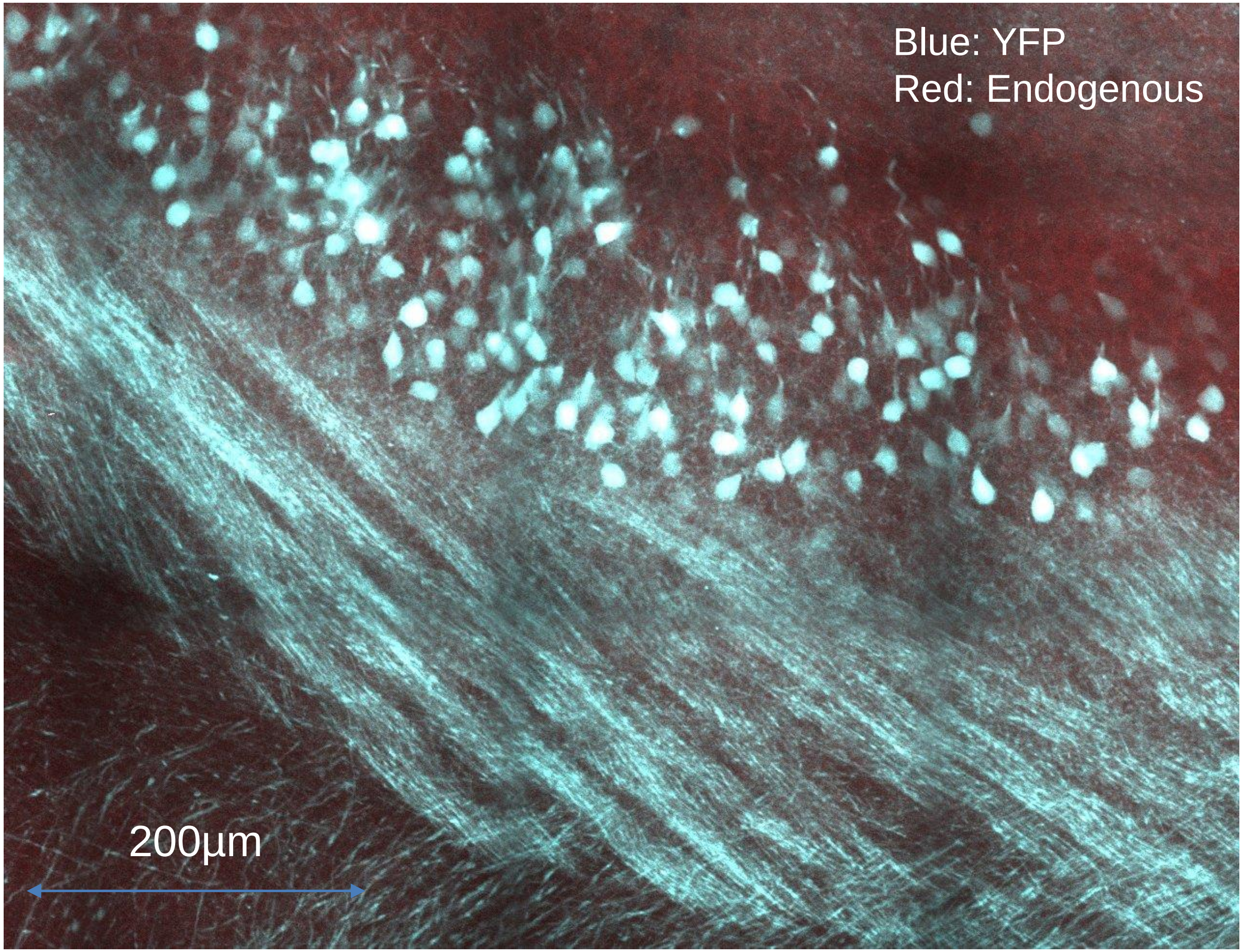

t_{FWHM} ~ 14fs
Intensity (a.u.)
1.0
0.5
0.0
Phase (a.u.)
6
3
0
-80
-40
0
40
80
Time (fs)

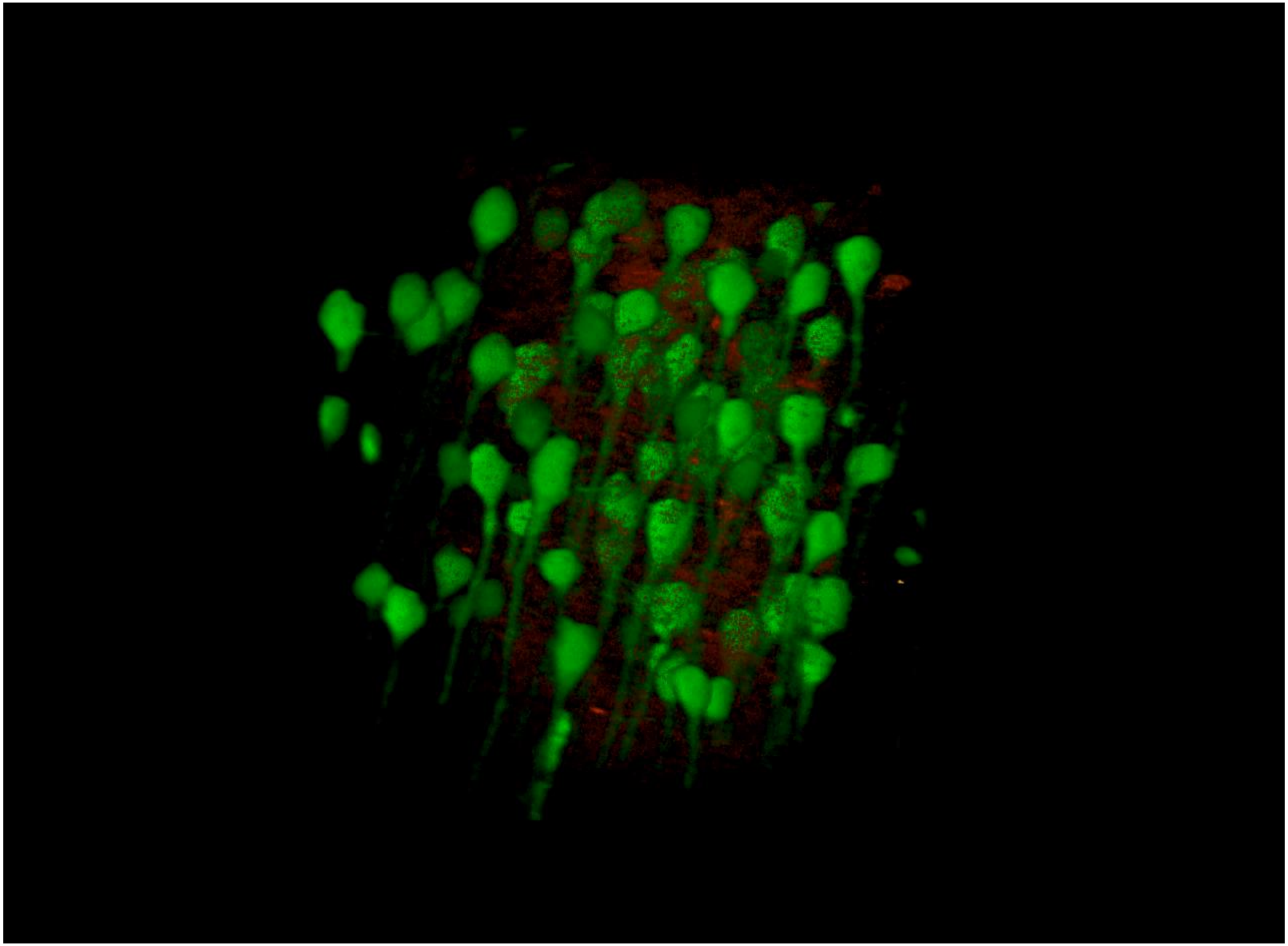

2PA
SHG
CARS
Excited state
Virtual states
Ground state

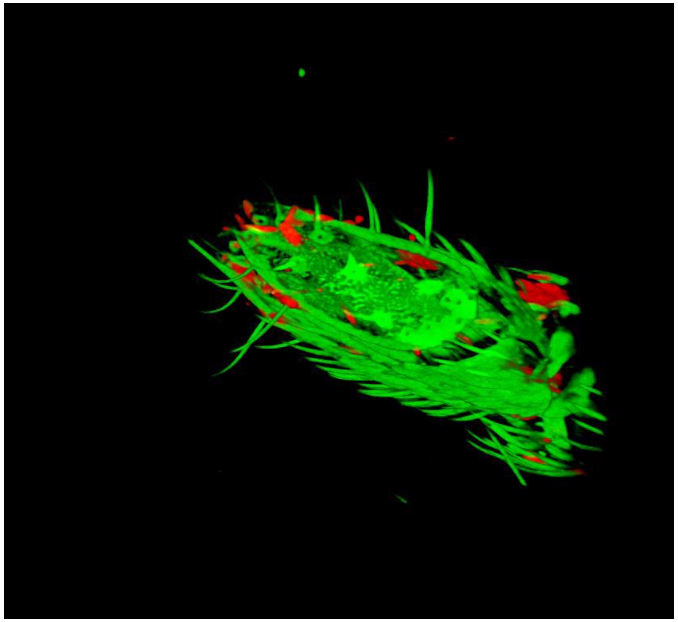

a
488 nm
b
960 nm
Focal plane

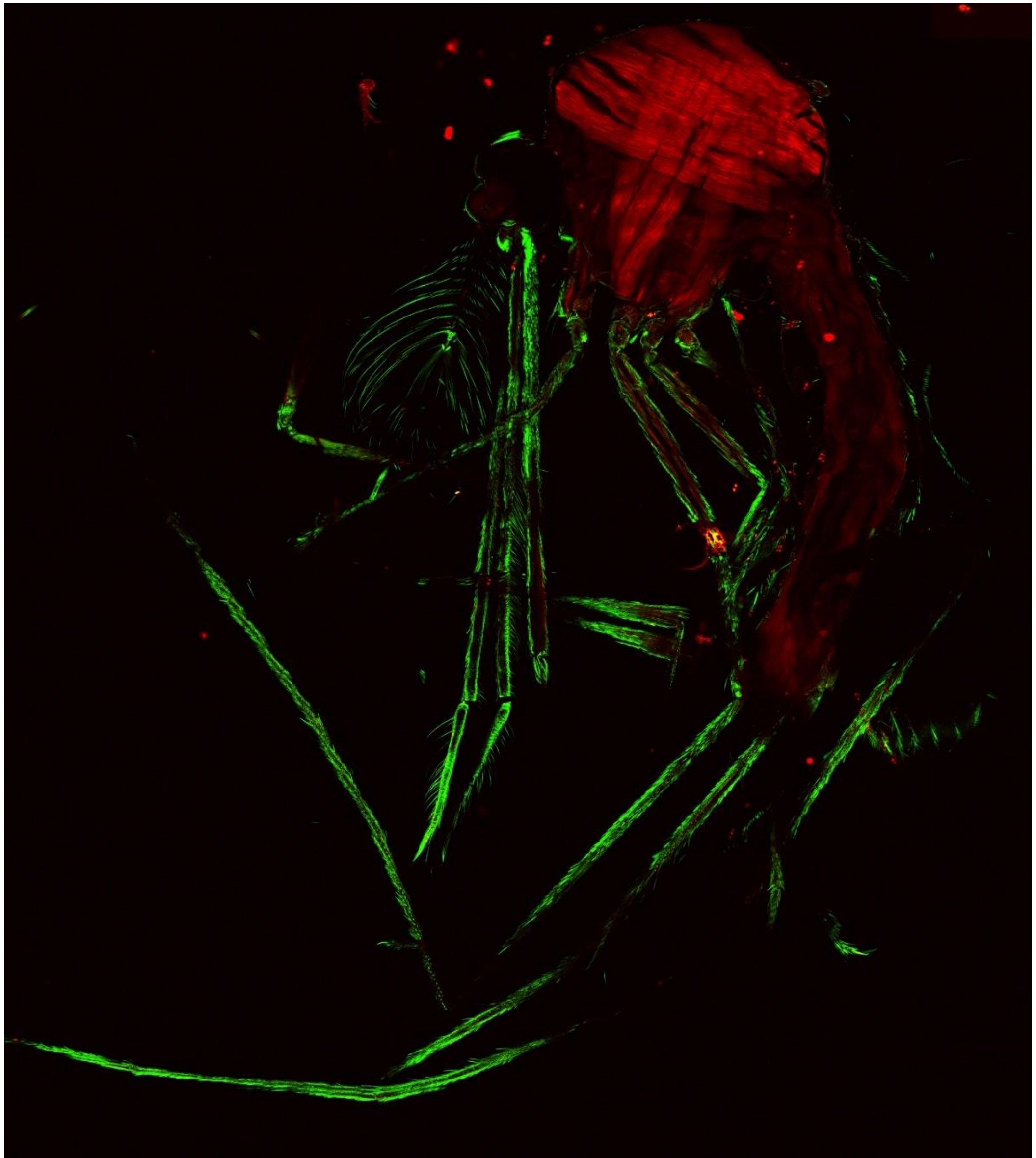



Blue: YFP
2mm


Blue: YFP
Red: Endogenous
200µm







Questions for thoughts

- Can fiber lasers be used for all applications?

(Think of a application that current fiber lasers can not be used)

- What is the power limit of fiber lasers?
- Is that important to know exactly who invented the laser?
- How many more years are we going to do research on laser?
- Can we use lasers to predict earthquakes?