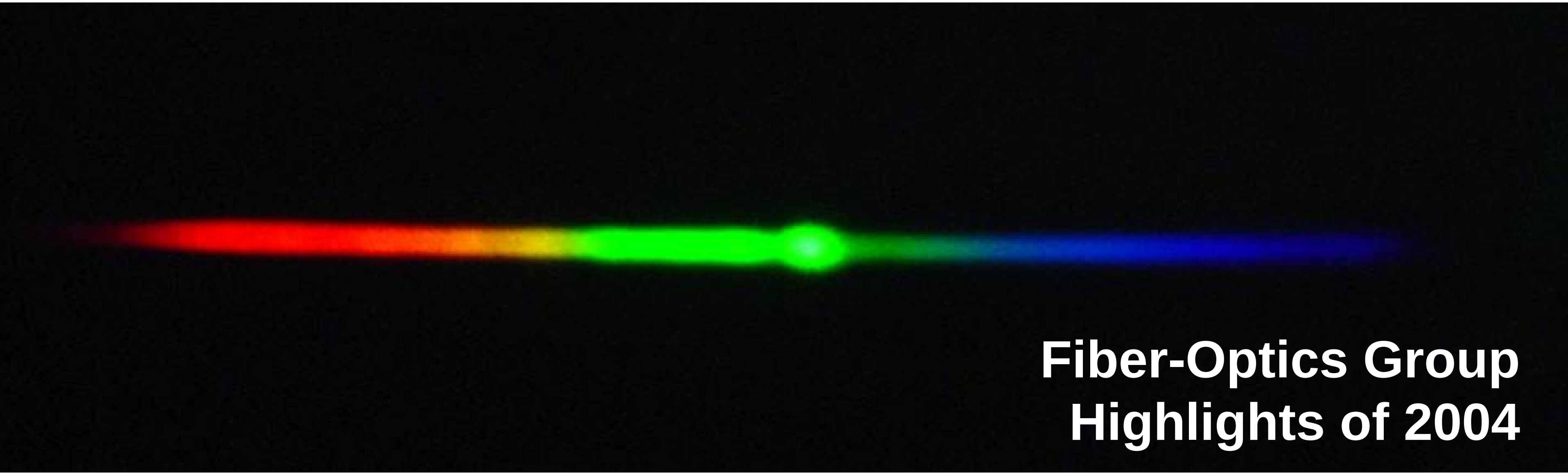
HELSINKI UNIVERSITY OF TECHNOLOGY



Fiber-Optics Group
Highlights of 2004

Micronova

Department of Electrical and Communications Engineering
Helsinki University of Technology

Fiber-Optics Group

Group Leader: Hanne Ludvigsen

Postdoctoral researcher: Goëry Genty

Postgraduate students:
Mikko Lehtonen (due 2005)
Tuomo Ritari (due 2006)
Jesse Tuominen (due 2006)
Tuomo von Lerber (due 2006)

http://metrology.hut.fi/fiberopticsgroup

Research topics

Photonic crystal fibers (PCFs)

- Supercontinuum generation in PCFs
- Sensing with PCFs
- Switching with PCFs
- Wavelength references based on PCFs for WDM communications systems
- Tapering of PCFs for efficient mode coupling to PC waveguides
- Characterization of dispersion and polarization-mode dispersion (PMD)
- Modeling of light propagation in PCFs

Other activities

- Fiber laser for C- and L-band
- Tapering of standard fibers
- Modeling of light propagation in tapered standard fibers

Collaborating partners

Crystal Fibre A/S, Denmark

Technical University of Denmark, Research Centre COM, Denmark

Group of Applied Physics, University of Geneva, Switzerland

COST Action P11 - Physics of linear, nonlinear and active photonic crystals

Funding

Academy of Finland

Academy Research Fellow, 1999-2005

Applications of photonic crystal fibers – appropriation to postdoctoral researcher, 2003-2005

Novel photonic components based on photonic crystal fibers and fiber tapering, 2003-2004

Photonic crystal based integrated optics, TULE programme, 2003-2006

Novel sensor applications based on photonic crystal fibers, 2005-2007

European Commission

Physics of linear, nonlinear and active photonic crystals - *COST* Action P11, 2003-2007

Graduate schools

Modern Optics and Photonics

Information Technology, TKK

Companies

NKT Research and Innovation A/S, Denmark, Compact supercontinuum source

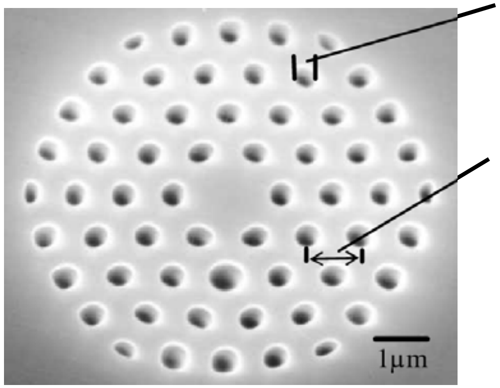
Asperation Oy, Multi-wavelength all-optical clock recovery

Scientific outcome 2004

In 2004, the group produced:

1	Doctoral thesis (G. Genty)
1	Licentiate thesis (M. Lehtonen)
8	Publications in refereed journals
1	International patent application
7	International conference papers (1 invited talk + 5 talks)
3	National conference papers (1 talk)

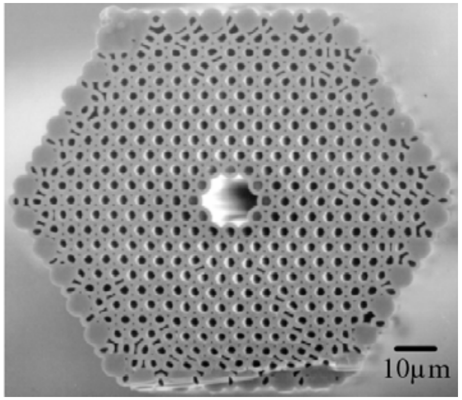
Photonic crystal fiber



Hole diameter > 0.01 µm

Hole-to-hole pitch 0.5 - 10 µm

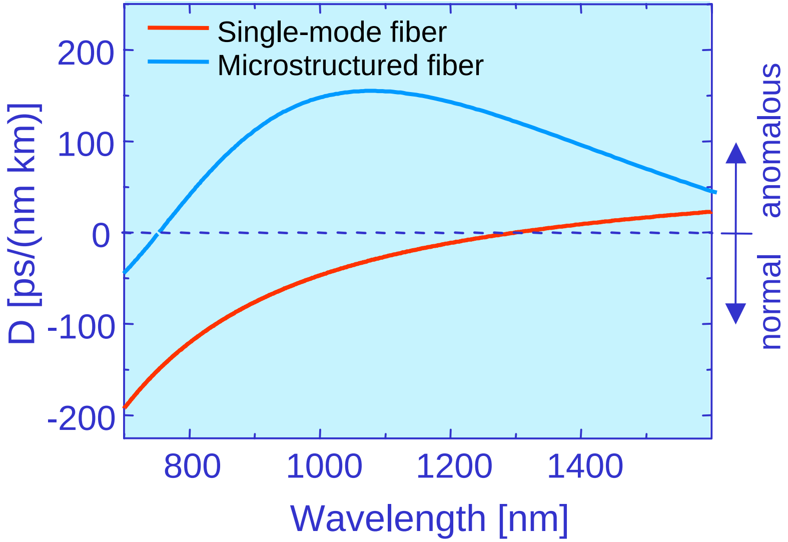
Micro-structured fiber
(Holey fiber)



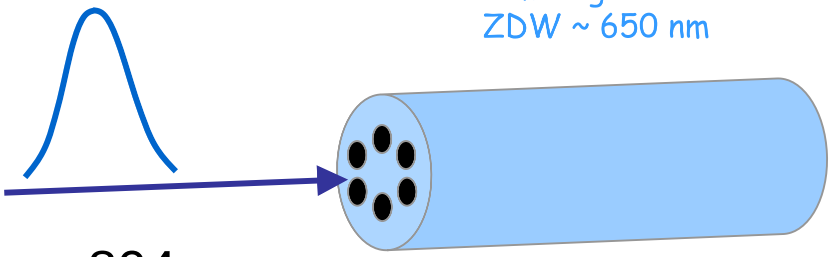
Photonic band-gap fiber

- Made of pure silica
- Micro-structure on the scale of λ
- Holes run along the whole length of the fiber
- Light guided in
  a) the filled-in central hole
  b) the central air hole !

Supercontinuum



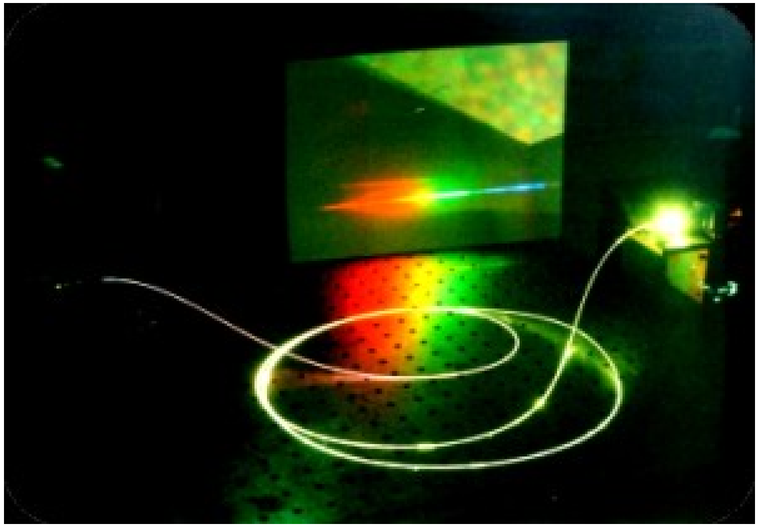
- Unique dispersion properties
- Enhanced nonlinear effects
  - small core



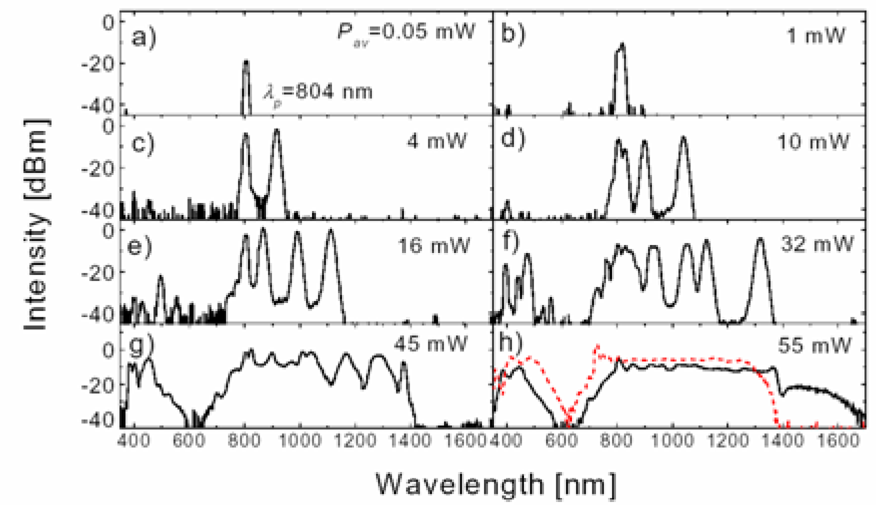
$\Delta\tau \sim 100$ fs

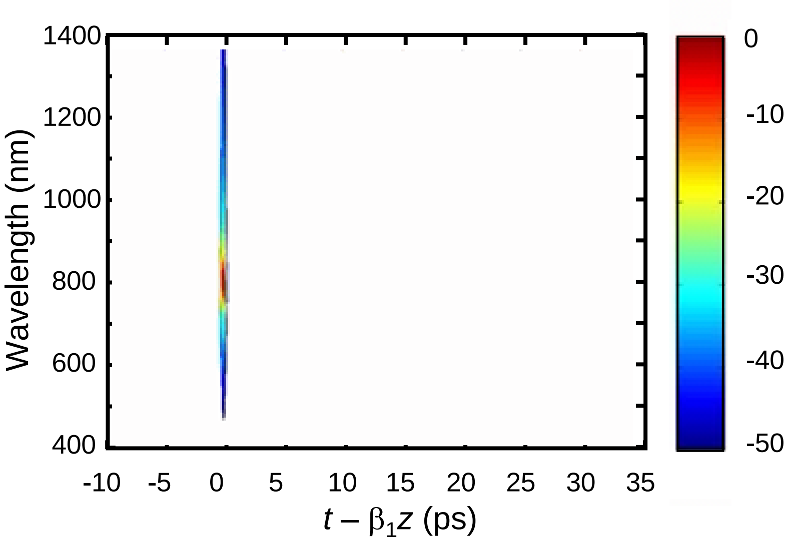
1.5 x 2.4 μm^2 core
5 m long
ZDW ~ 650 nm

$\lambda_{Pump} = 804$ nm



Route to supercontinuum generation





Femtosecond pulses

Key processes:

- pulse breakup into multiple Raman-shifted solitons
- blue-shifted radiated waves

G. Genty et al., Opt. Express 10, 1083 (2002)

M. Lehtonen et al., APL 82, 2197 (2003)

- Pumping at two ZDWs

G. Genty et al., Opt. Express 12, 3471 (2004)

- Pumping with sub-30fs

G. Genty et al., Opt. Express 12, 929 (2004)

Miniature supercontinuum sources

Nanosecond pulses (S. Buchter, Optics and Molecular Materials)

January 2004

Patent licensing agreement with Koheras A/S

Engineering prototype shown at Photonics West

May 2004

Product released at CLEO

Visible+infrared: 430-1800 nm

Pump wavelength = 1064+532 nm
Frequency doubled
Passively Q-switched Nd:YAG laser

S. Buchter et al., International patent application

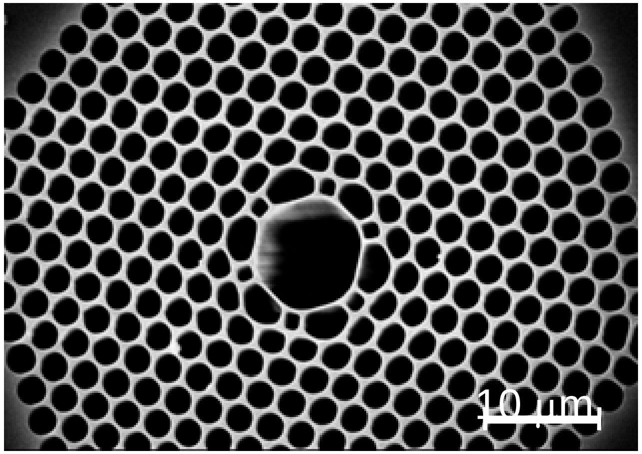
Infrared: 1064-1800 nm

Pump wavelength = 1064 nm
Passively Q-switched Nd:YAG laser

Applications of air-core PCFs

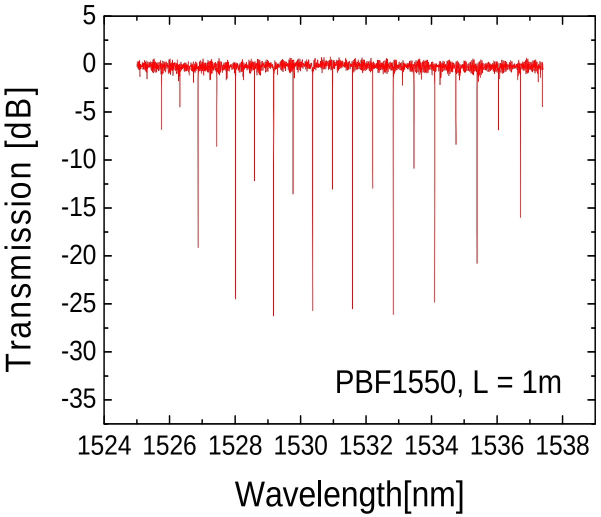
- Gas sensor
  - long optical path with good field overlap
  - only a tiny amount of gas needed

T. Ritari et al., Opt. Express 12, 4080 (2004)

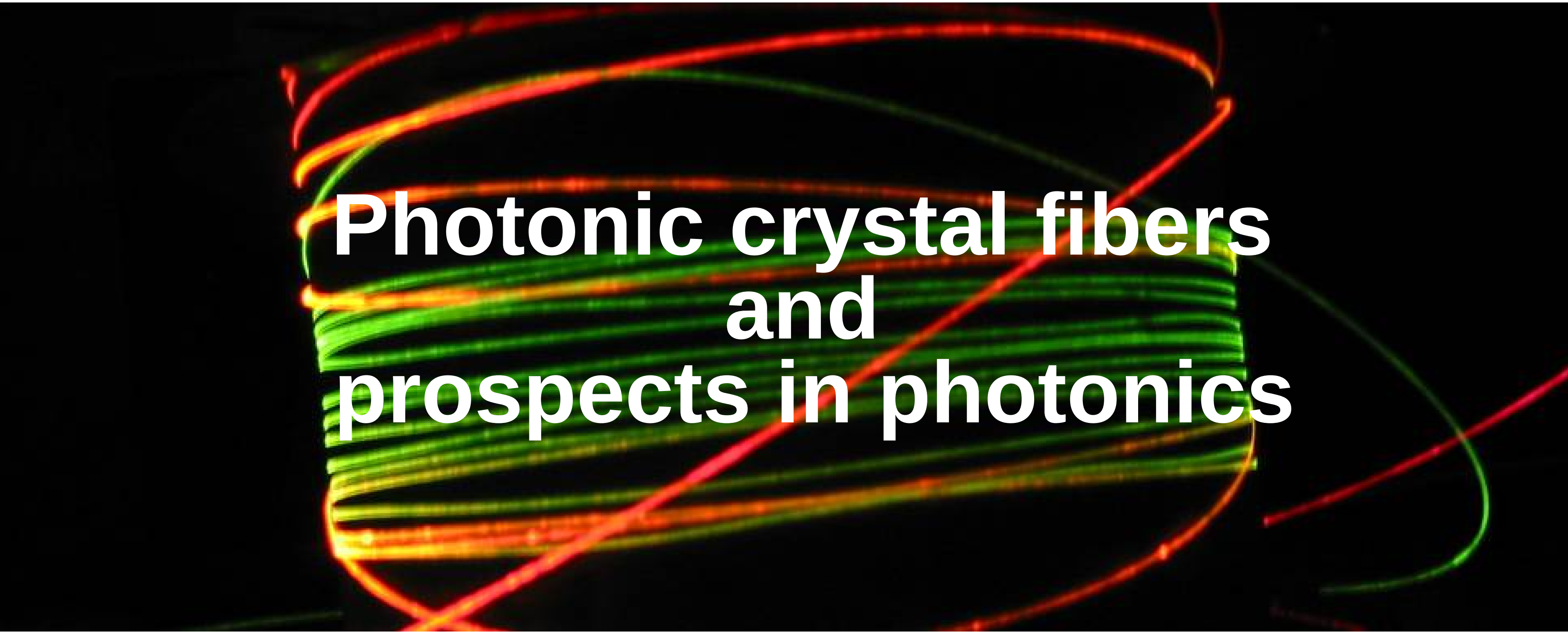


- Wavelength reference
  - wavelength range: 1300 and 1500 nm

T. Ritari et al., ECOC 2004, paper Mo3.2.2



MICRONOVA
CENTRE FOR MICRO- AND NANOTECHNOLOGY



Photonic crystal fibers and prospects in photonics

Goëry Genty

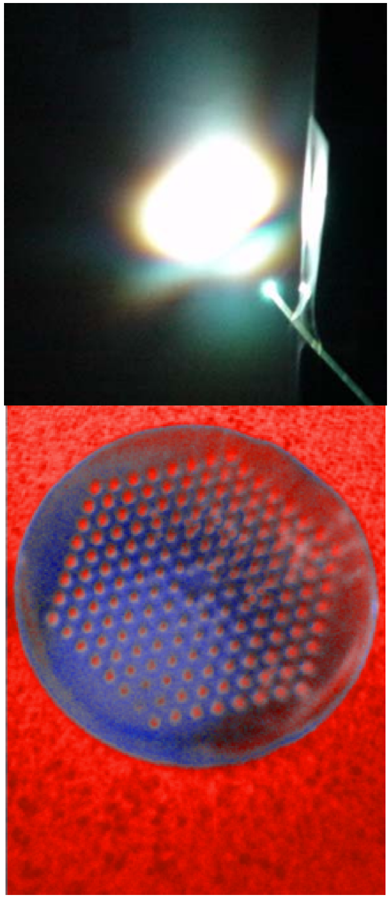
Fiber-Optics Group
Helsinki University of Technology

Micronova Seminar 3 December 2004

Outline

- Introduction to supercontinuum
- Dispersion properties
- Nonlinear effects
- Supercontinuum sources and their applications
- Summary

Introduction

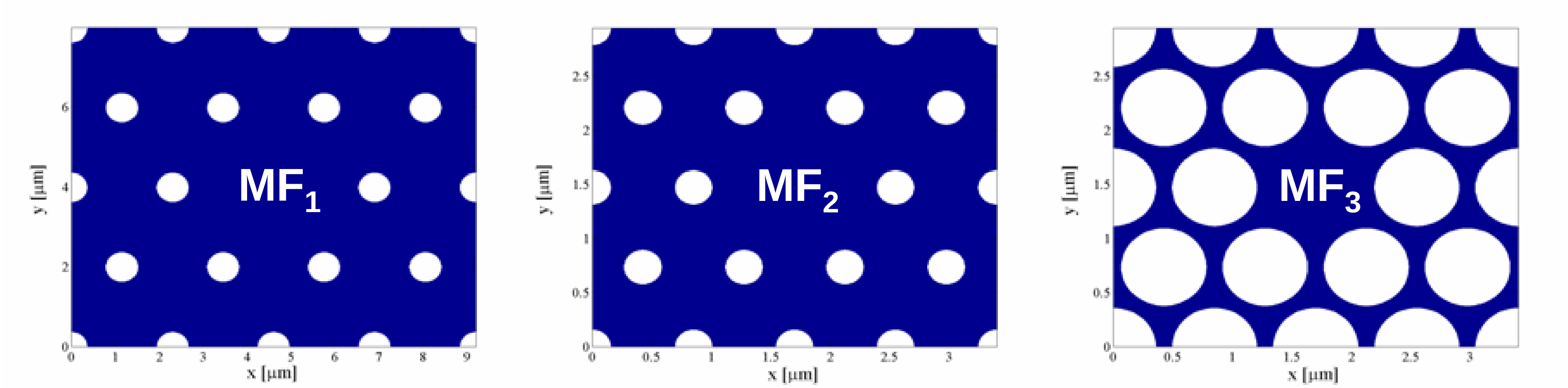


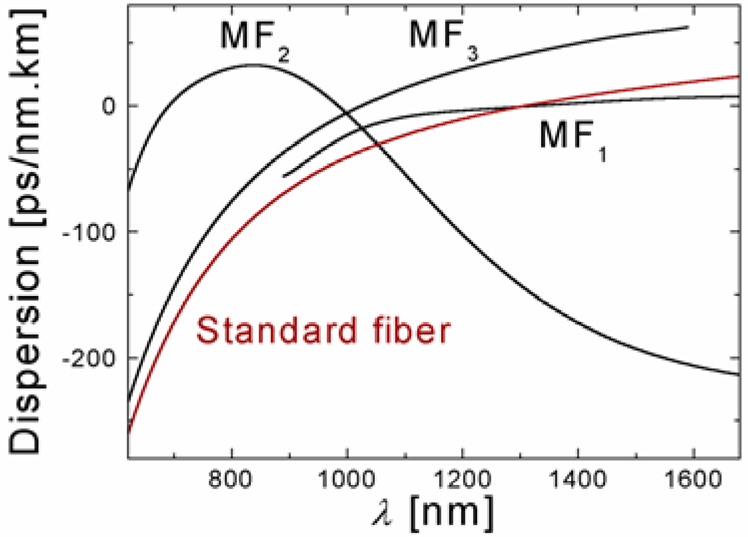
Supercontinuum (SC) =

spectral broadening of pump pulses
in a nonlinear medium

- SC generation in microstructured fibers (MFs) more efficient than in other nonlinear media
- MFs allow for efficient SC generation using short laser pulses
- The physical mechanisms leading to SC drastically depends on the pulse width (ns, ps or fs)

Dispersion properties



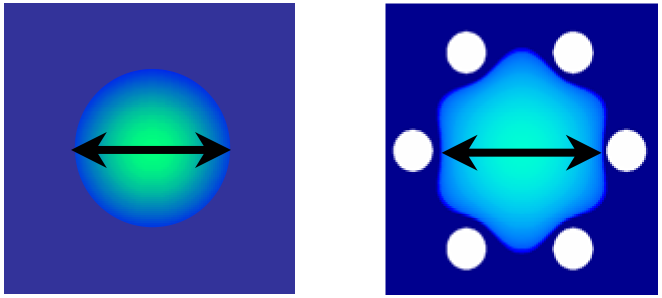


- **Dispersion can be tailored by varying the microstructure**
- **e.g., λ_{ZD} can be pushed to visible**

Nonlinear effects

- Results from $n(\mathrm{I})$
- Inversely proportional to A_{eff}

- Self-phase modulation (SPM)
- Cross-phase modulation (XPM)
- Four-wave mixing (FWM)
- Stimulated Raman scattering (SRS)
- Soliton self-frequency shift (SSFS)
- Dispersive wave generation (DW)



Nonlinearity × 25

Enhanced NL effects
unique dispersion properties

→ **Supercontinuum**

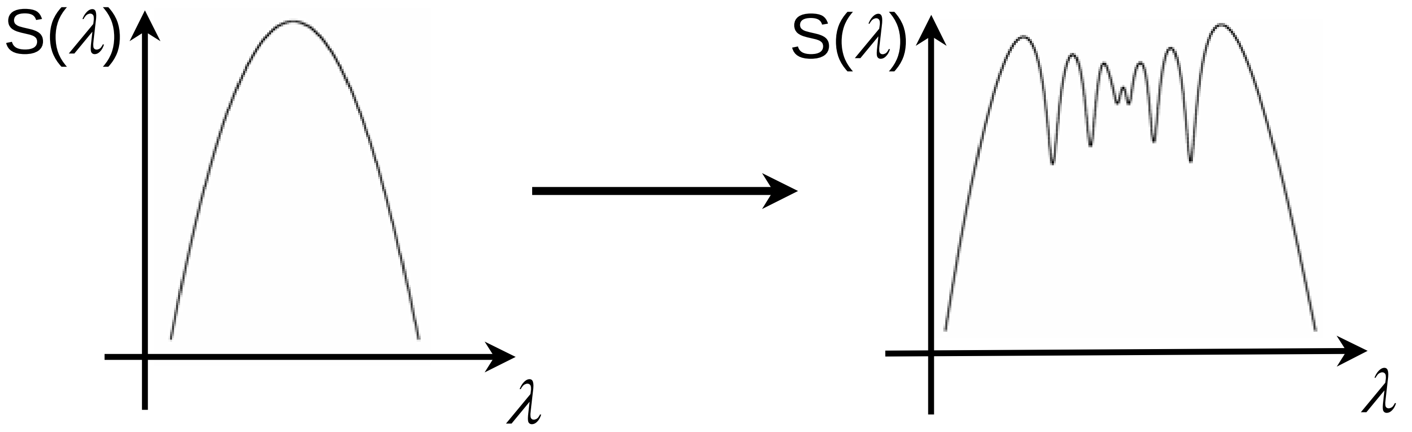
Self-phase/cross-phase modulation

Intensity dependence of the refractive index

$$n = n_L + n_2 \mathrm{I}$$

SPM: $\phi(t)=\phi_0+\phi_{NL}(t)$, $\phi_{NL}(t) = [2\pi n_2 l(\lambda A_{eff})]\times \mathrm{I}(t)$

XPM: $\phi_1(t)=\phi_{01}+\phi_{NL2}(t)$, $\phi_{NL2}(t) = [4\pi n_2 l(\lambda_1 A_{eff})]\times \mathrm{I}_2(t)$

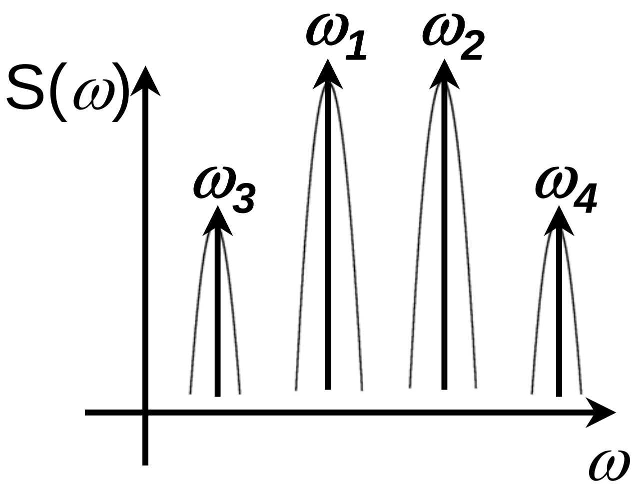


Four-wave mixing and Raman scattering

FWM:

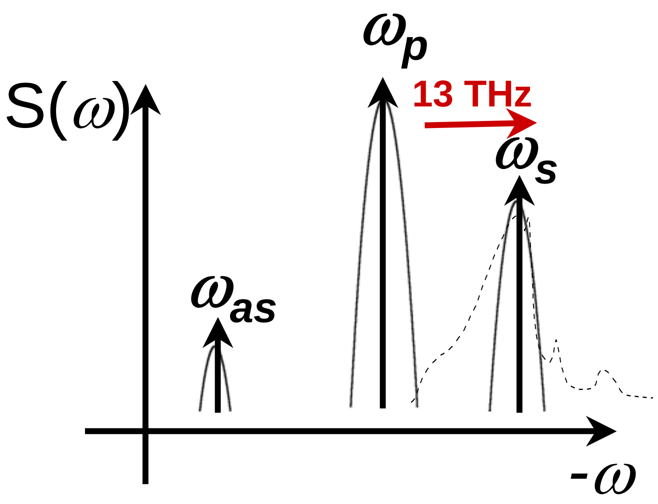
$$\omega_1+\omega_2 \longrightarrow \omega_3+\omega_4$$

$$\phi(\omega_1) + \phi(\omega_2) \longrightarrow \phi(\omega_3)+\phi(\omega_4)$$



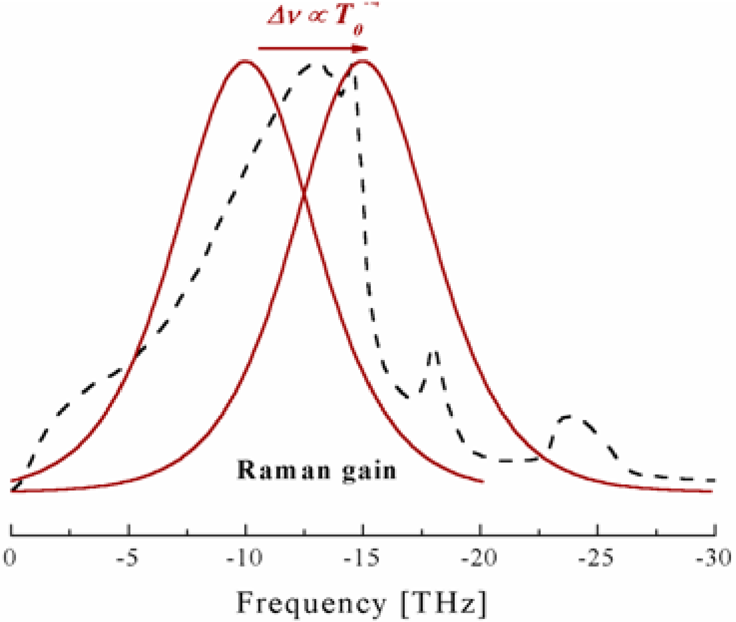
SRS:

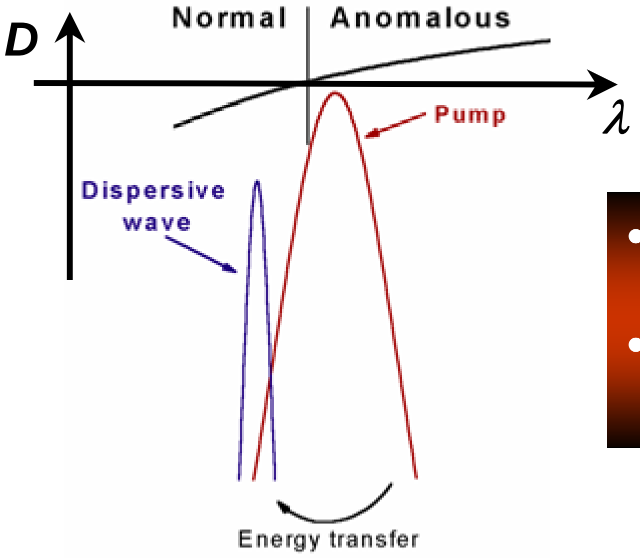
$$\omega_p+\omega_p \longrightarrow \omega_{as}+\omega_s$$



Soliton self-frequency shift and dispersive wave generation

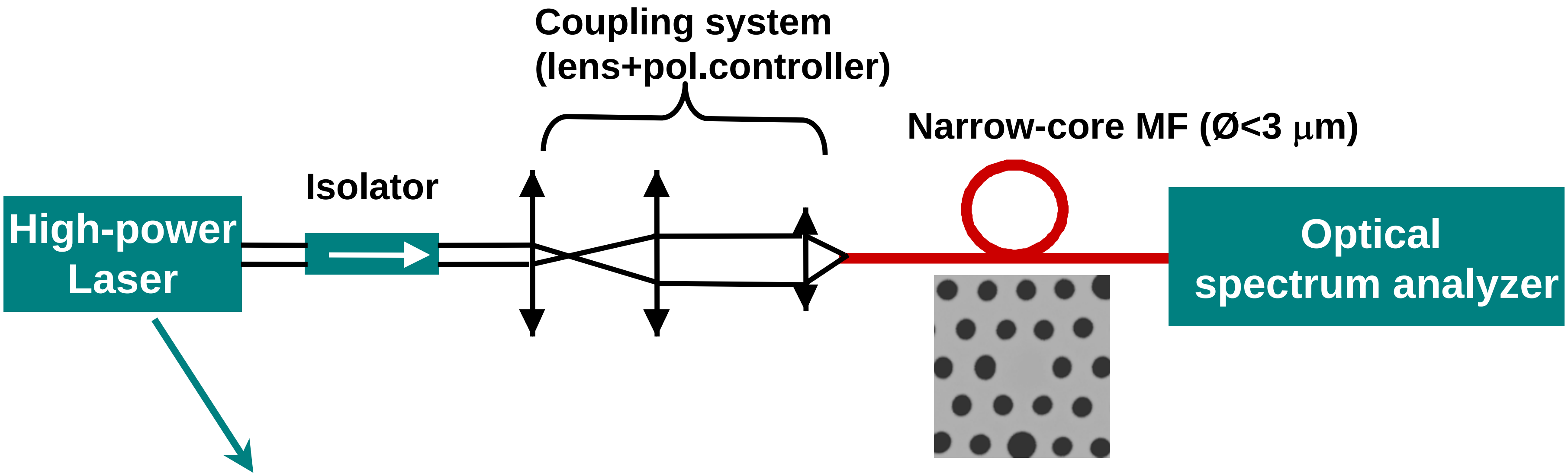
- **Physical origin: Raman scattering**
- **Pulses<1 ps:**
  spectrum overlaps with Raman gain
- **f_R amplified at the expense of f_B**
- **$\lambda_{soliton}$ shifts with propagation**





- **Pulse in D_A with spectrum extending in D_N**
- **Dispersive wave generation in D_N such that**
  $k_p=2\pi/\lambda_p\times(n_p+n_2\lambda_p)=k_{DW}=2\pi/\lambda_{DW}\times n_{DW}$

Experimental setup



Coupling system (lens+pol.controller)

Narrow-core MF ($Ø<3\ \mu m$)

Isolator

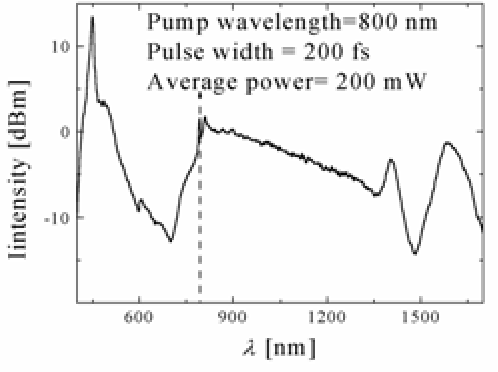
High-power Laser

Optical spectrum analyzer

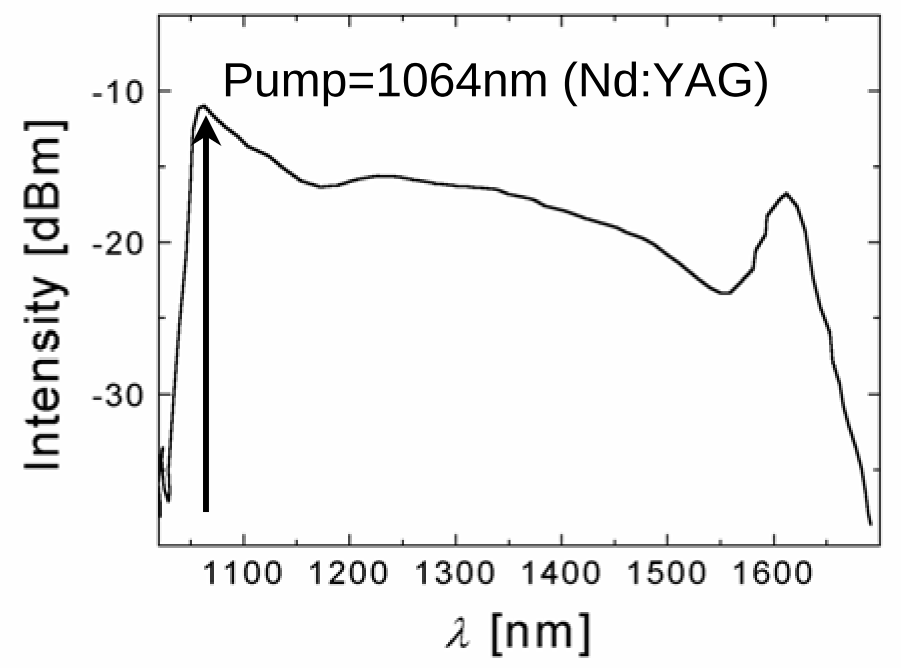
ns pulses: Q-switched Nd-YAG (1064 nm)

ps pulses: Kr (650 nm), Er^{3+} lasers (1550 nm)

fs pulses: Ti:Sapphire (800 nm), Cr:F (1250 nm)



SC generation with nanosecond pulses



SC formation dominated by SRS and FWM

- Requires longer fibers (typically L>10m)
- Pump pulses: E=3 μJ (P_{av}=10 mW)

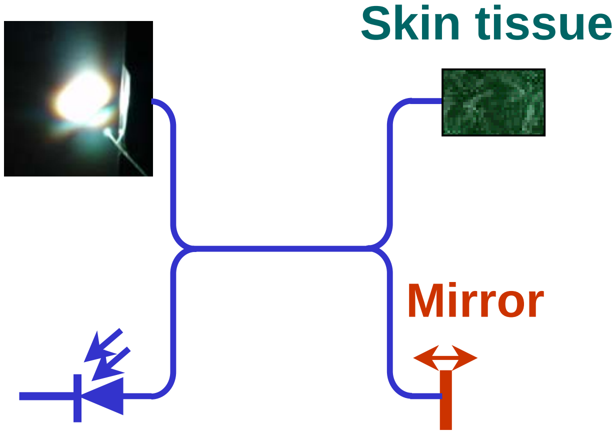
Application of ns SC

Optical coherence tomography

In situ imaging of tissue microstructure

Main considerations

- λ
- bandwidth
- power
- stability (coherence)

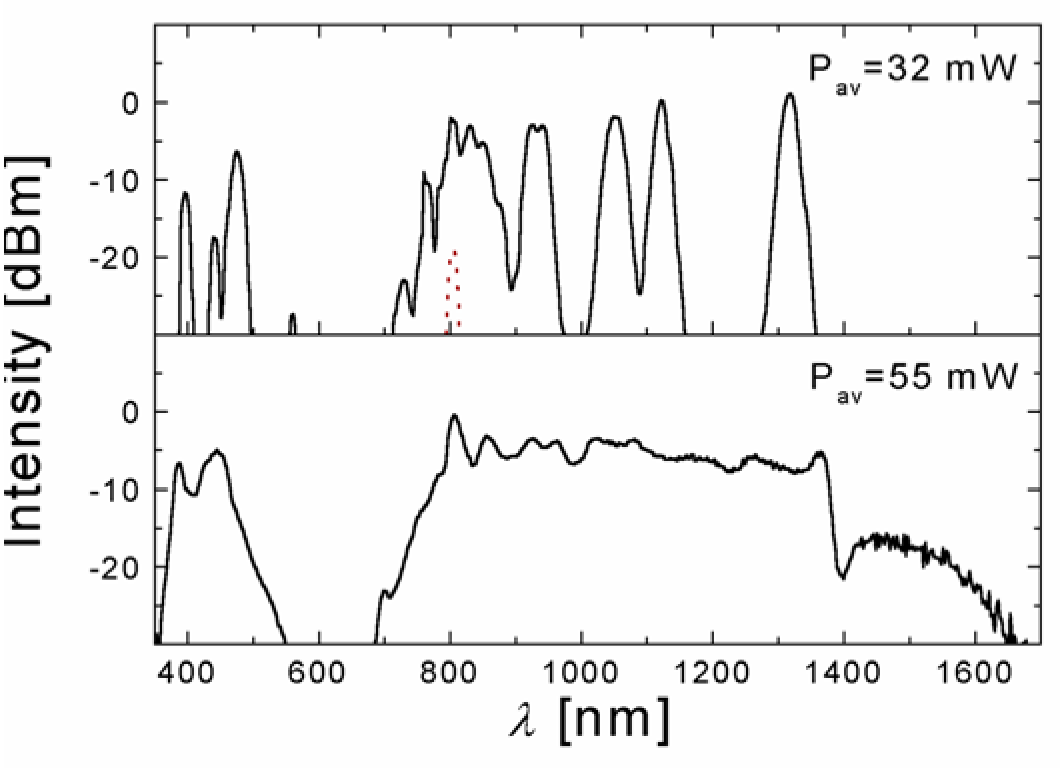


Broadband compact source

⬇

high resolution portable system

SC generation with femtosecond pulses

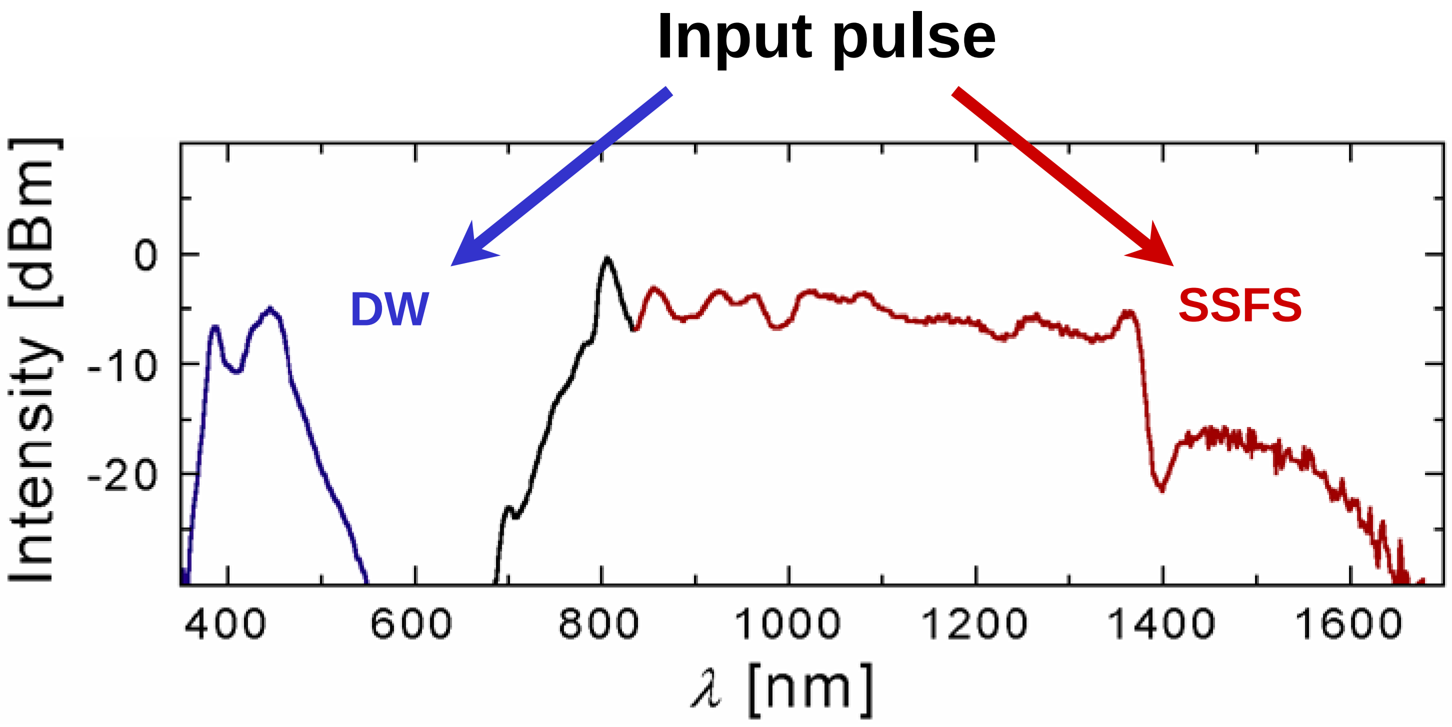


- **Ti:Sapphire laser**
- **rep. rate=80 MHz**
- **$\Delta\tau$=100 fs**
- **λ_{pump}=804 nm**

- **L=5 m**
- **core ∅=1.5×2.4 μm^2**
- **λ_{ZD}=670 nm**

- Requires shorter fibers (typically L<1m)
- Pump pulses: E=0.5 nJ (P$_{av}$=100 mW)

Pumping in anomalous dispersion region



Input pulse

DW

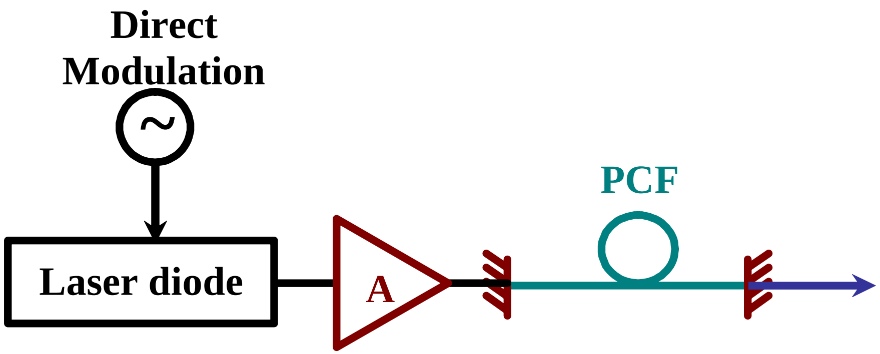
SSFS

Application of fs SC

- Frequency metrology (frequency standards/optical clock)
- Optical source for WDM communication links
- Broadband tunable source (spectroscopy, component characterization…)

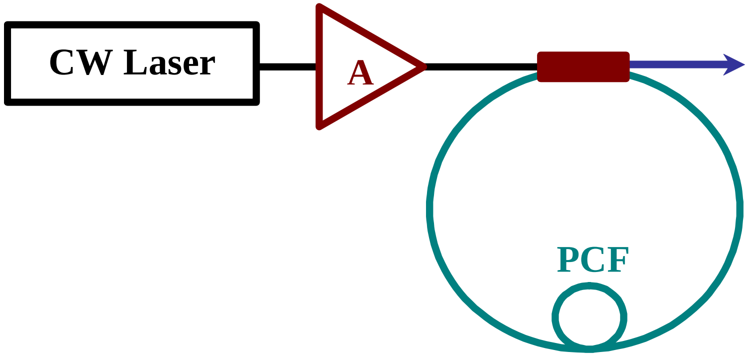
Photonic applications

Optical signal processing



Optical switch
Signal regeneration

Lasers

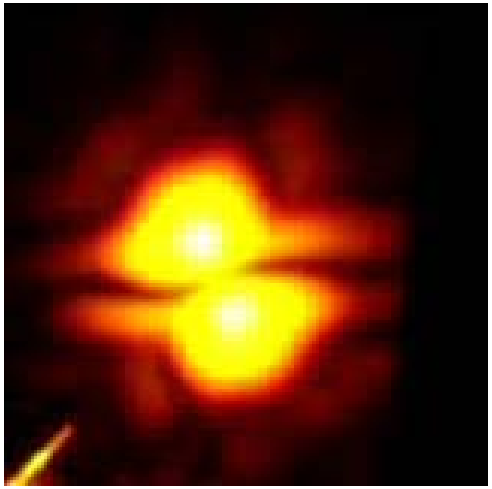


CW-seeded Optical Parametric Oscillator
Raman laser

Summary

Microstructured fibers:

- unique optical properties
- ideal medium for SC generation
- improvement in many applications



And that's all