Journal seminar (the first semester)

M1 Hiroto Kimura

①History of optical comb development

John L.Hall, and Theodor W. Hansch, FEMTOSECOND OPTICAL FREQUENCY COMB TECHNOLOGY, pp. 1-11(2004).

I explain the history and the foundation theory of the laser.

②Optical comb dynamics and stabilization

Gunter Steinmeyer, and Ursula Keller, FEMTOSECOND OPTICAL FREQUENCY COMB TECHNOLOGY,
pp. 112-132(2004).

I explain a concept of frequency comb and stabilization of f_{rep} and f_{CEO}.

③Carrier-Envelope Phase Control of Femtosecond Mode-Locked Lasers and Direct Optical Frequency Synthesis

David J. Jones, et al, Science 288, 635-639 (2000).

Using a setup, I explain the absolute optical frequency metrology.

History of optical comb development

John L.Hall, and Theodor W. Hansch,
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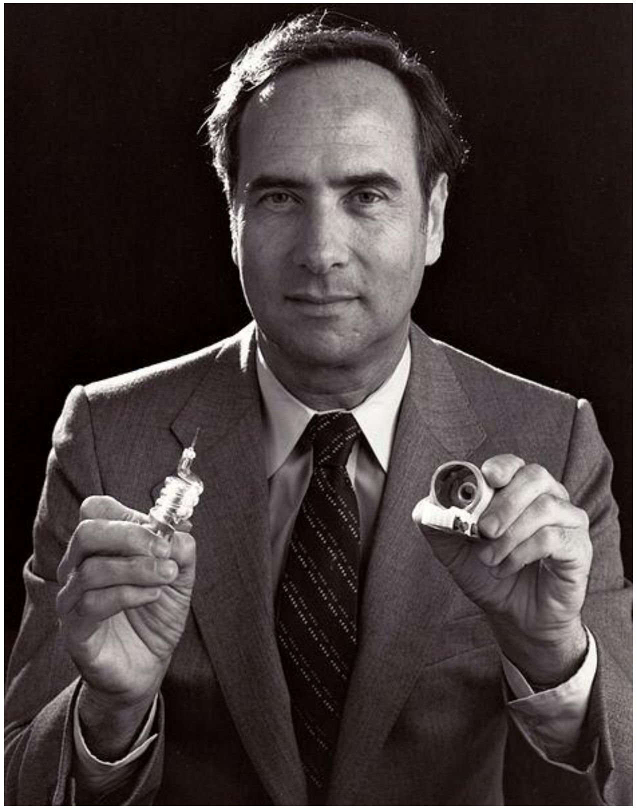
Chronological table of laser and optical comb development

1960 — Ted Maiman invented the first laser in the world.

1970 — Mode-locked gas lasers was developed to give nanosecond pulses at 100 MHz rates.

The mid -1970s — Mode-locked picosecond dye lasers were introduced.
The comb approach to frequency measurement was inevitable.

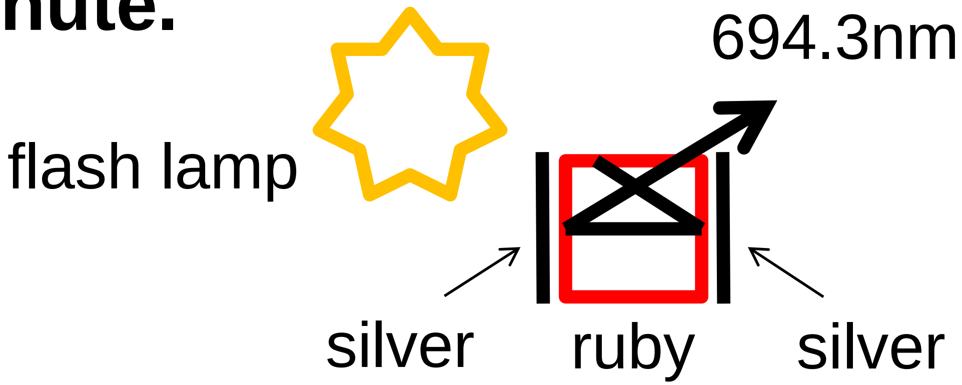
The first laser in the world



Theodore Harold Maiman

Ted Maiman was an American physicist who made the first laser.

His solid-state ruby laser involved kilojule discharges into flash lamps and repetition rates from zero up to once per minute.



Chronological table of laser and optical comb development

1960 — Ted Maiman invented the first laser in the world.

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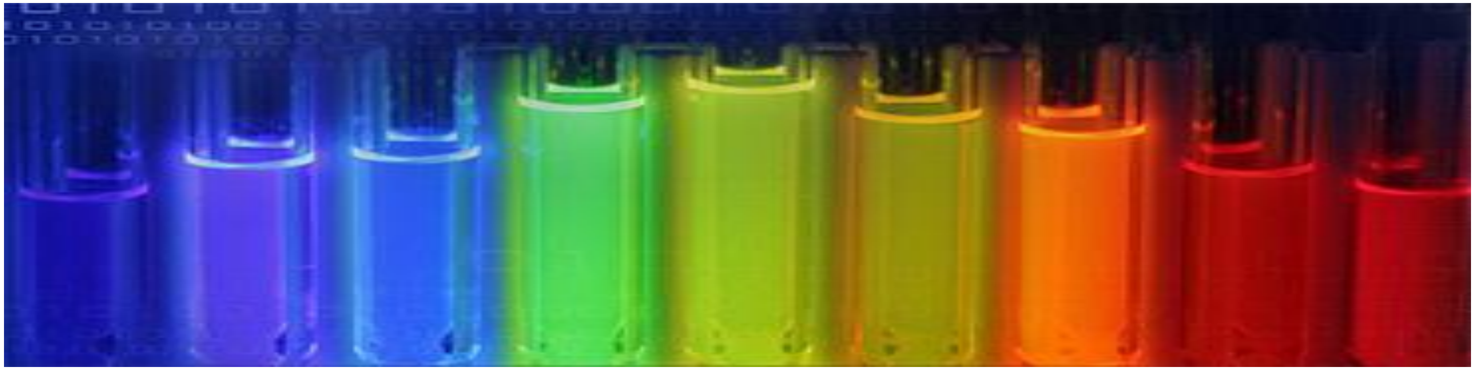
Dye lasers

It is the organic dye that dissolved dye molecules in an organic solvent (alcohol, ethylene glycol, ethyl, methyl) to be used in the medium of the liquid laser most.



Wavelength：320nm ～ 1200nm
Oscillation form：CW, pulsed
Pumping source：flash lamp

merits

- ●The oscillation wavelength area is large.
- ●The exchange of the medium is easy.

demerits

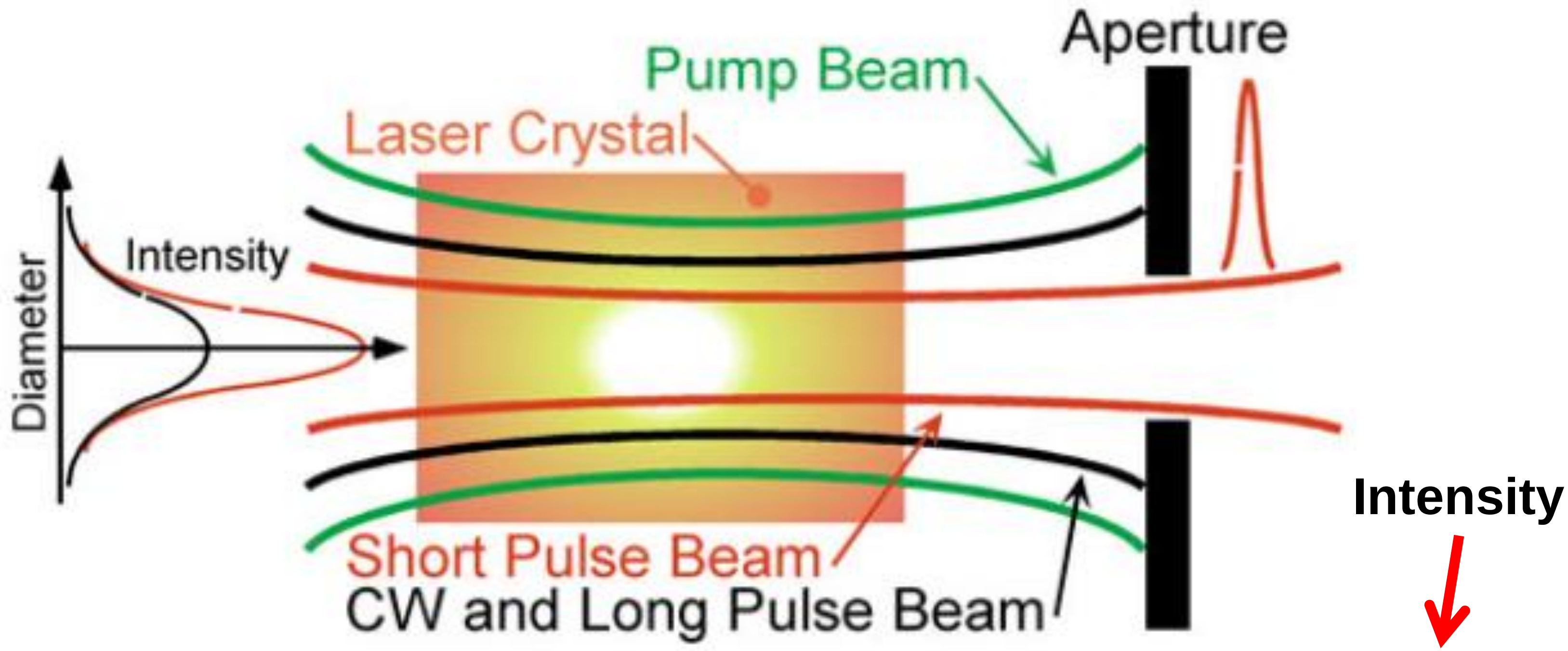
- ●The life of the medium is short.
- ●The solvent has venomousness.

Chronological table of laser and optical comb development

1977 **Hansch's team demonstrated one of the first mode-locked "femtosecond" dye lasers (with a pulse length of less than one picosecond).**

1990 **The titanium-doped sapphire laser system with the important discovery of Kerr-lens mode locking was introduced and developed by Wilson Sibbett.**

Kerr-lens mode locking



Nonlinear refractive index change : $n = n_0 + n_2 I$

⇩

Only short pulse is affected

⇩

A laser crystal becomes the oversaturated absorber.

Chronological table of laser and optical comb development

1993 — **Kourogi demonstrated intracavity modulator-based spectral comb generators.**

1997 — **Hansch's proposed an octave-spannning self-referenced universal optical-frequency comb synthesizer.**

I illustrate by the next article in detail.

2005 — **Theodor W. Hansch and John L. Hall won the Nobel Prize.**

Summary

- Optical frequency combs have given us some comfortable metrological headroom for pushing ideas for new optical frequency standards and for measuring interesting physical constants.

Optical comb dynamics and stabilization

Gunter Steinmeyer, and Ursula Keller,

FEMTOSECOND OPTICAL FREQUENCY COMB TECHNOLOGY,

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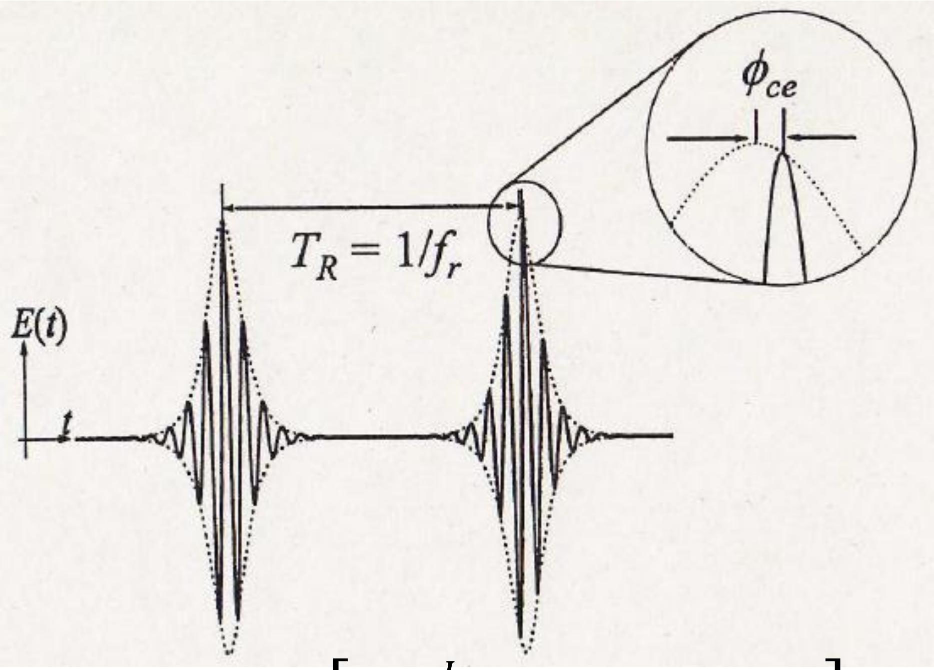
Time versus frequency



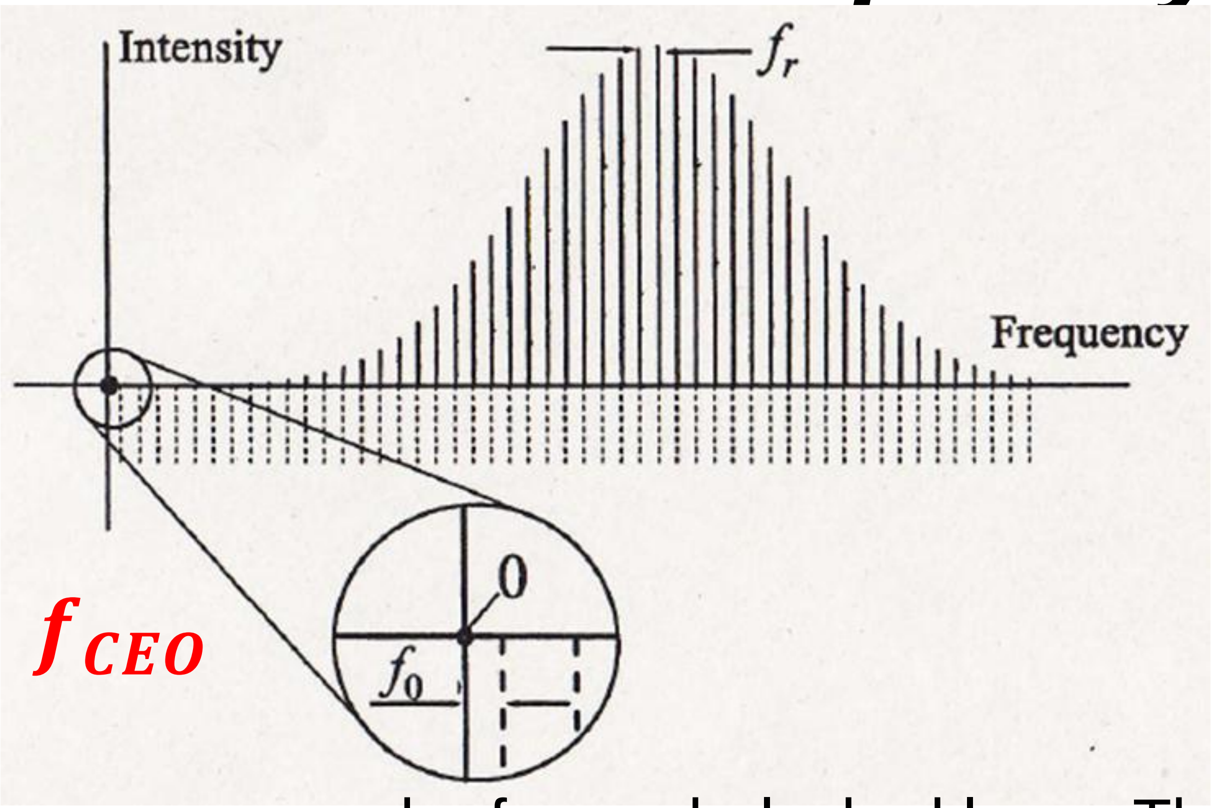
The electric field E(t) of two subsequent pulses from a mode-locked laser (solid line). The envelope ±A(t) is shown as dashed lines. The electric-field patterns of the pulses experience a pulse-to-pulse phase shift $\Delta\phi_{ce}$ according to Equation(1).

$$\Delta\phi_{ce} = \left[\frac{2\pi}{\lambda}\int_0^L n_g(z) - n(z)dz\right] mod 2\pi = \left[\frac{\omega^2}{c}\int_0^L \frac{dn(z)}{d\omega}dz\right] mod 2\pi \quad (1)$$

$$\Delta\phi_{ce}(t) = \phi_{ce}(t) - \phi_{ce}(t - T_R) \quad (2)$$

$$f_0 = \frac{\Delta\phi_{ce}}{2\pi} f_r \quad (3)$$

Time versus frequency



Equidistant frequency comb of a mode-locked laser. The comb lines are spaced by the repetition rate f_r and exhibit a nonvanishing offset frequency f_0 at zero frequency unless the electric-field pattern exactly reproduces from pulse to pulse (compare to th time domain picture in upper figure).

Self-referencing technique

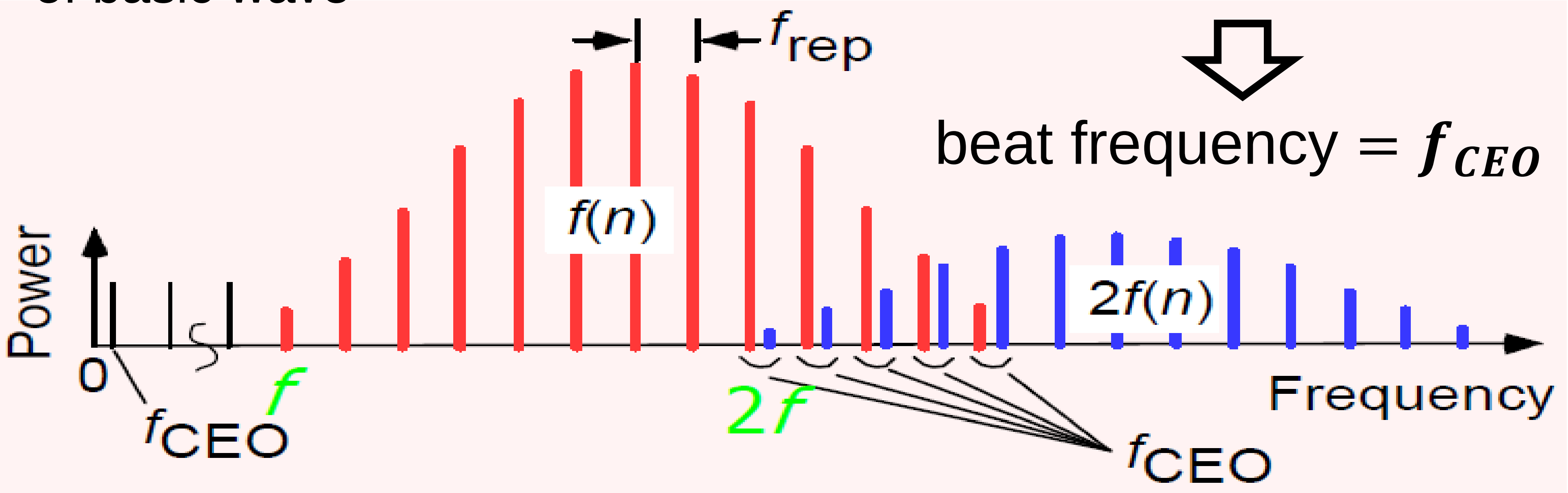
The second harmonics of the low frequency edge

$$2f(n) = 2 \times (nf_{rep}) + 2f_{CEO}$$

The high frequency edge of basic wave

$$f(2n) = 2nf_{rep} + f_{CEO}$$

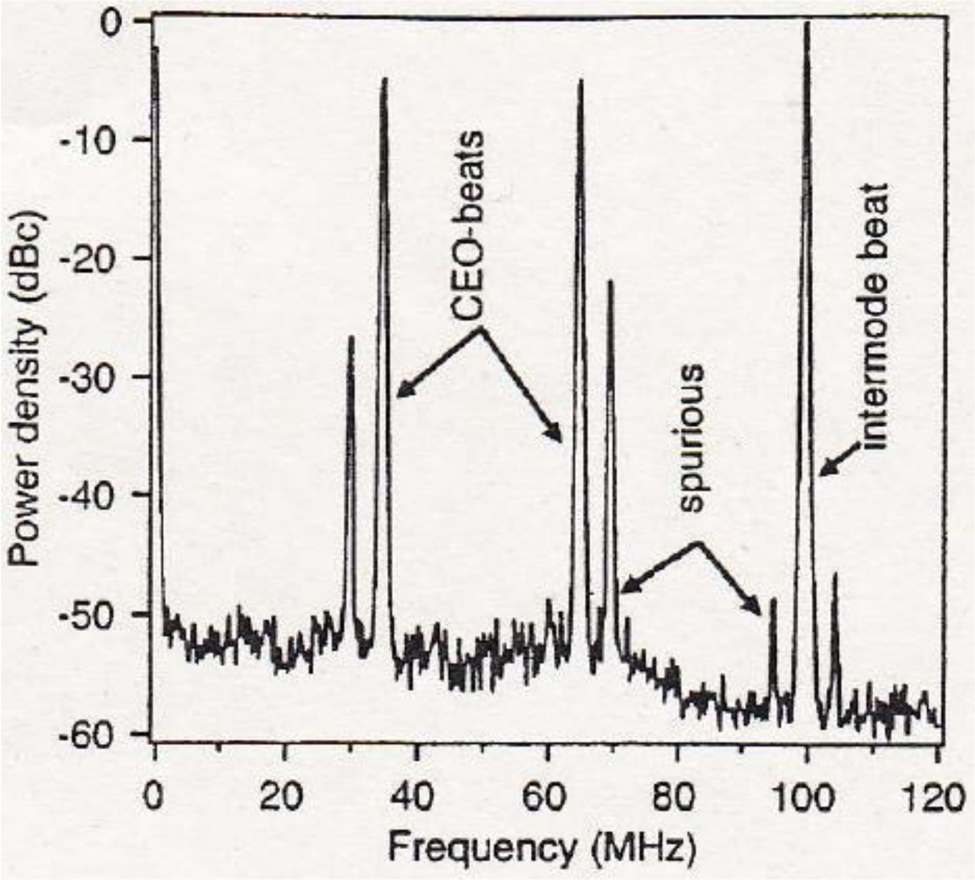
beat frequency $= f_{CEO}$



We can measure the laser frequency of a wide wavelength range continually.

CEO beat note signal

This signal was measured at a Ti:sapphire laser heterodyning the fundamental and the second-harmonic-generation (SHG) signal from a continuum generated in a microstructure fiber.



RF spectrum of the CEO beat note signal

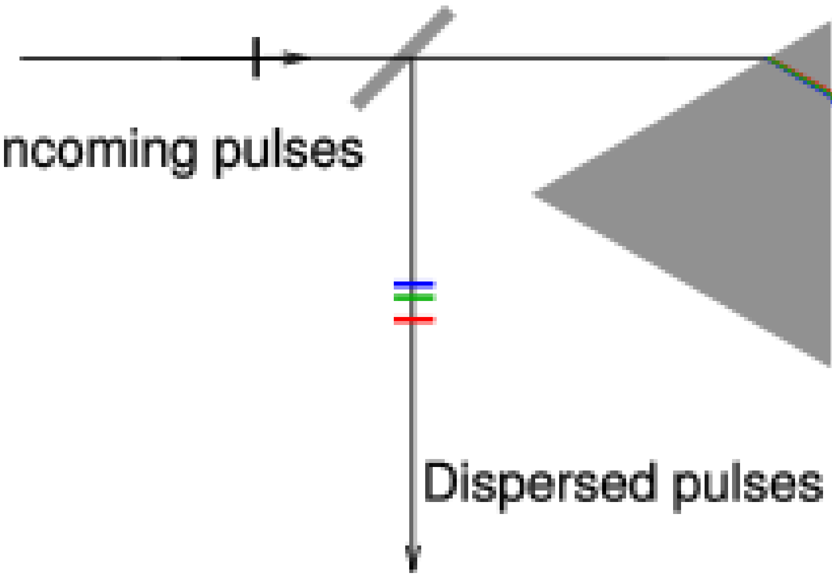
The laser has a **100 MHz** repetition rate.

The CEO beat is located at **35 MHz**.
Its mirror frequency is also visible at **65 MHz**.

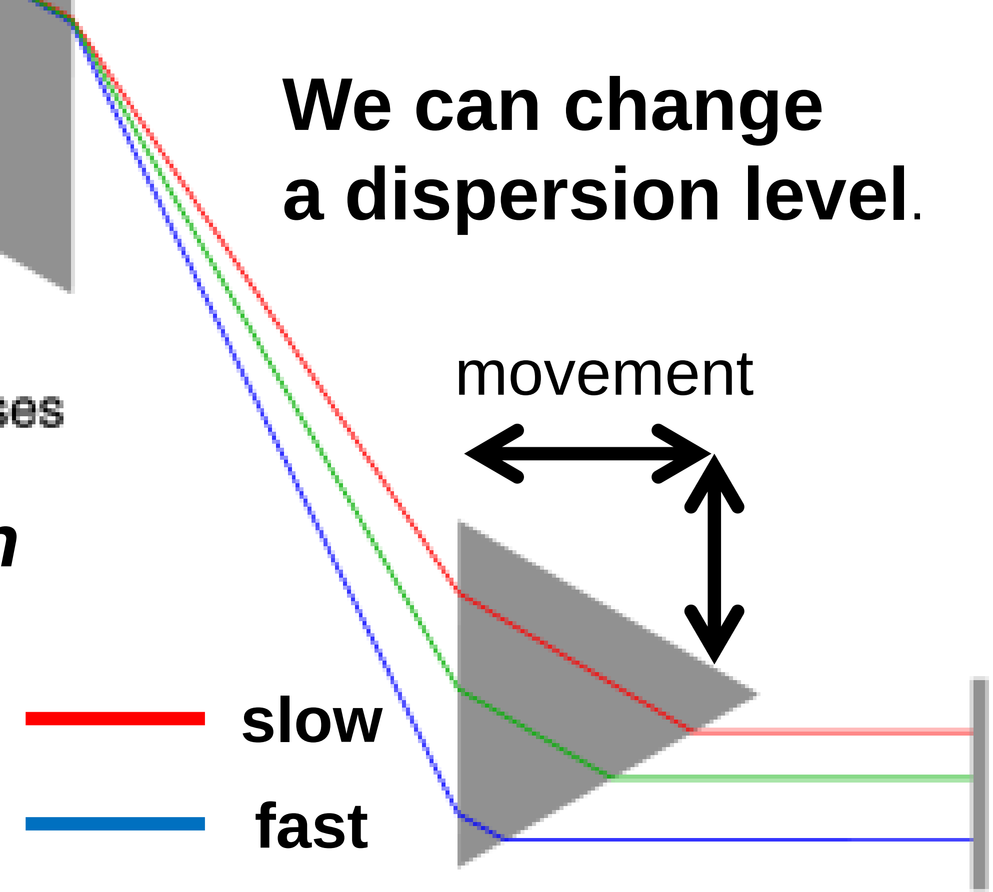
Some spurious contributions have been generated by nonlinear electronic mixing process in the detector circuitry.

Controlling the CEO frequency

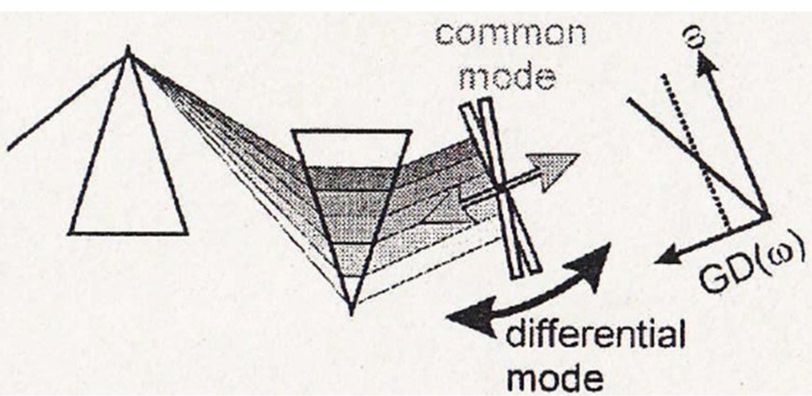
with normal dispersion



We can change a dispersion level.



Negative dispersion



Summary

- The CEO phase turns out to be a very sensitive parameter that is easily shielded by enclosing the laser.

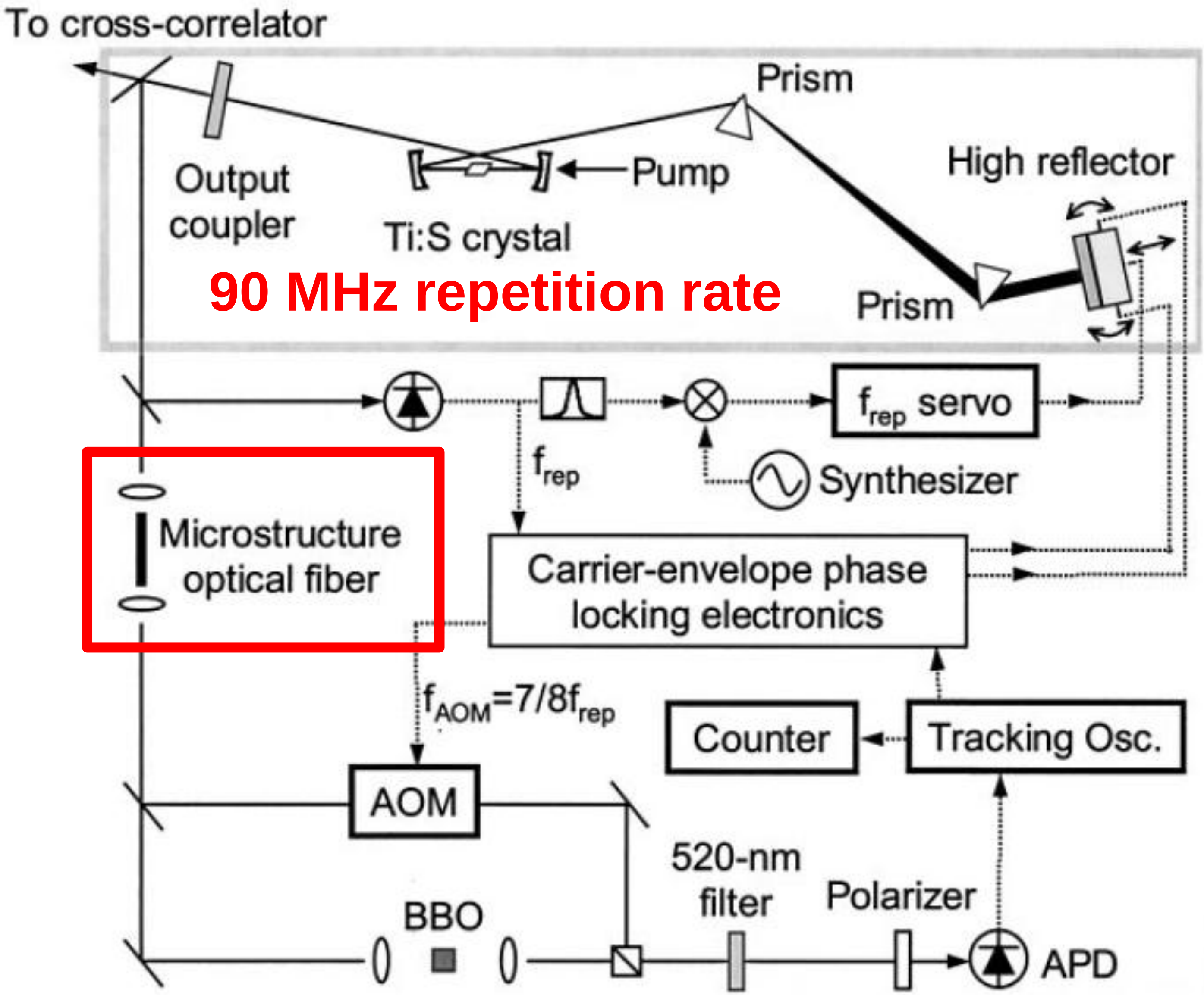
- An improved control of frequency comb parameters offers even higher precision in metrology applications and opens up novel applications in extreme nonlinear optics.

Carrier-Envelope Phase Control of Femtosecond Mode-Locked Lasers and Direct Optical Frequency Synthesis

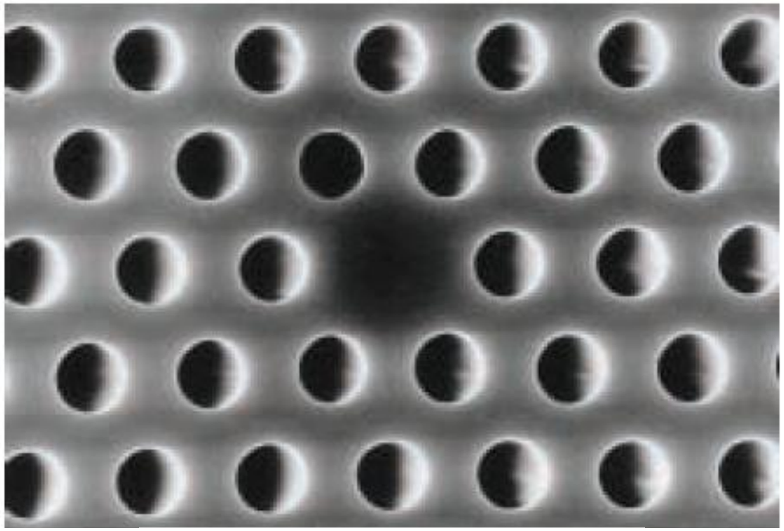
David J. Jones, et al,

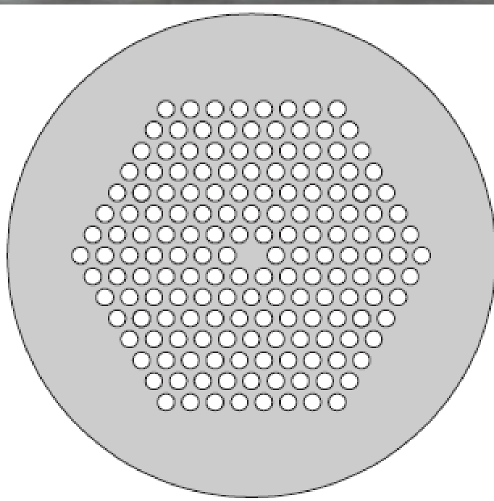
Science 288, 635-639 (2000)

Experimental setup for locking



Microstructure optical fiber





Refractive index

core>>>>>>>clad

- The effectiveness core cross section (A_{eff}) is small.
- The enclosure effect of the light is big.

increase

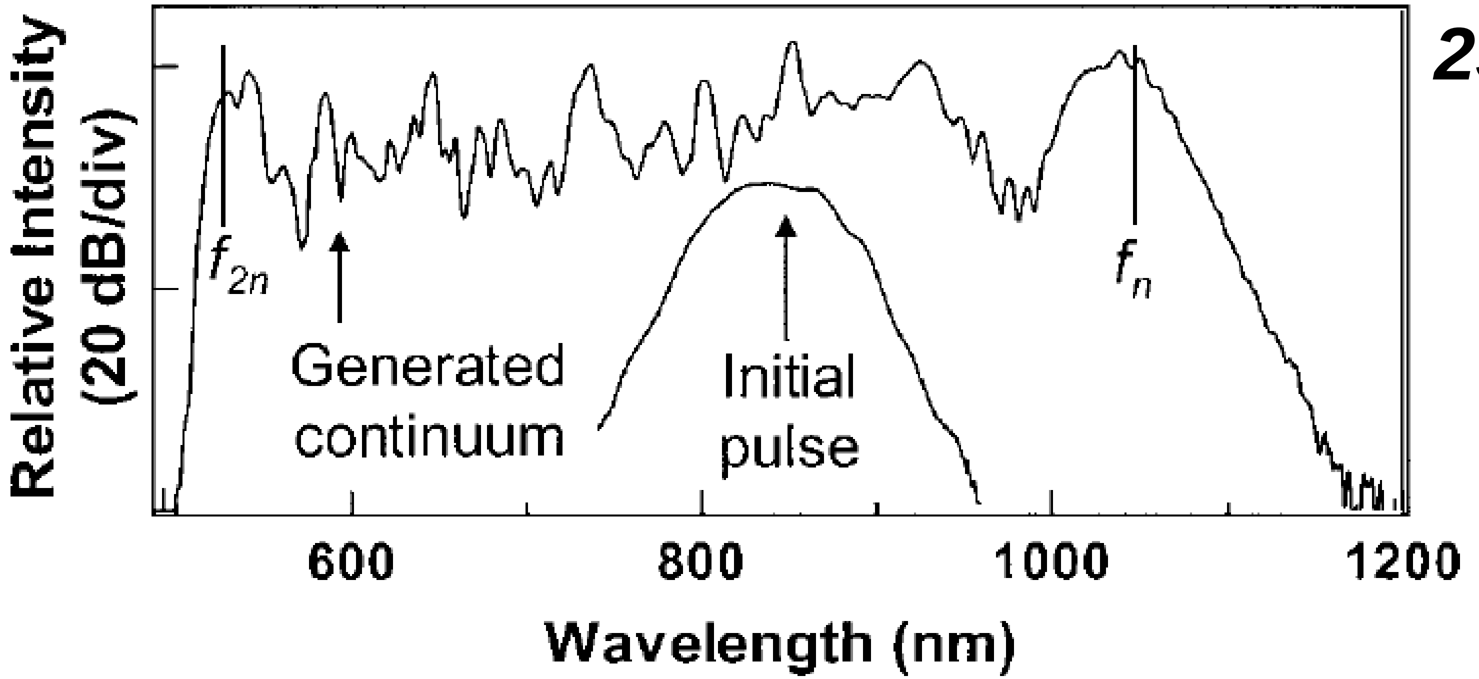
$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{eff}}$$

λ is nonlinear fixed number.
n_2 is nonlinear refractive index of the core.

- It has a zero dispersion wavelength.

We can get an octave-spanning spectrum without changing pulse width.

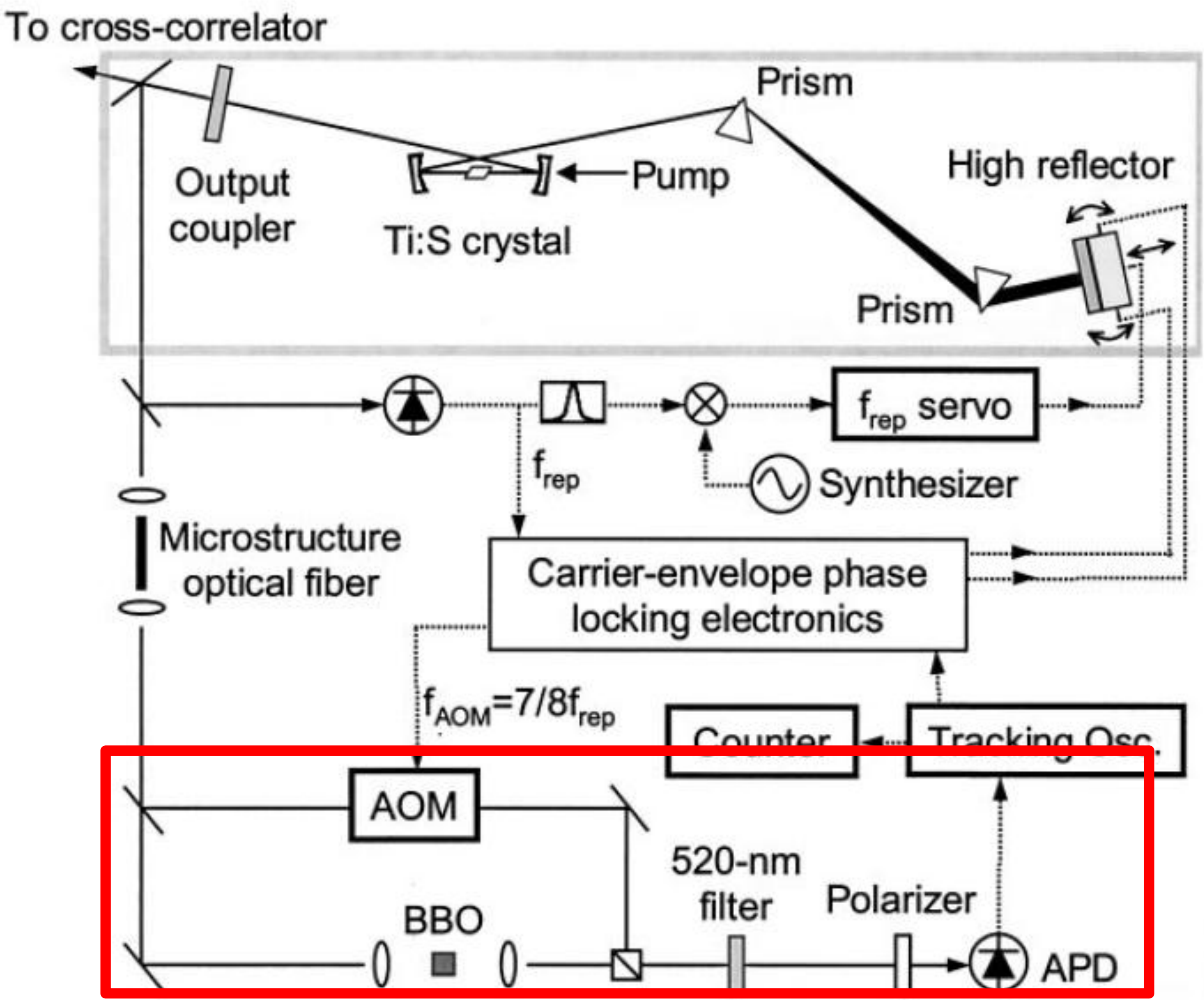
The spectra after optical fiber



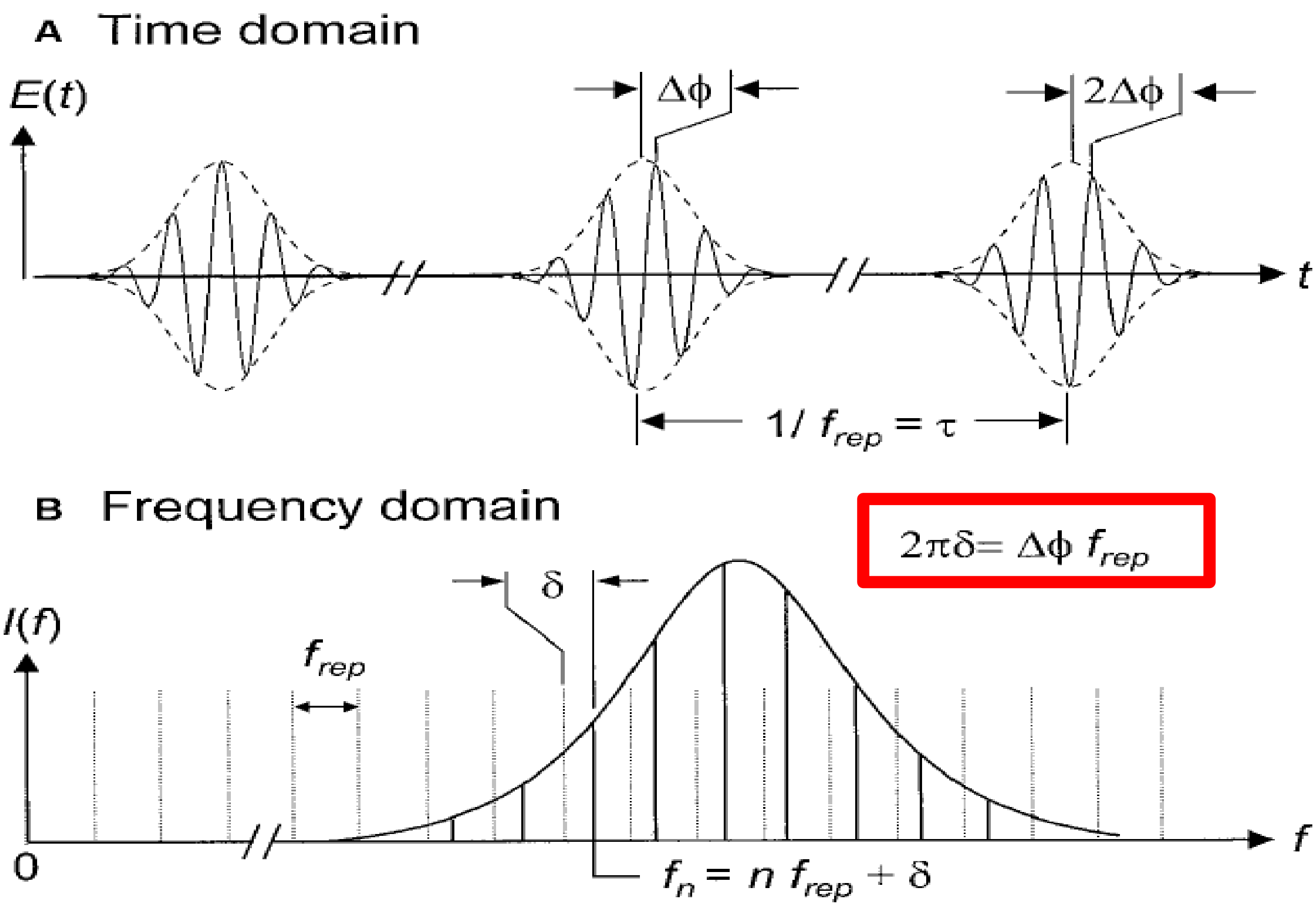
Continuum generated by microstructure fiber.

Self-phase modulation in the microstructured fiber ⇨ **The spectra spans more than one octave.**

Experimental setup for locking



The phase and group velocity



Phase velocity

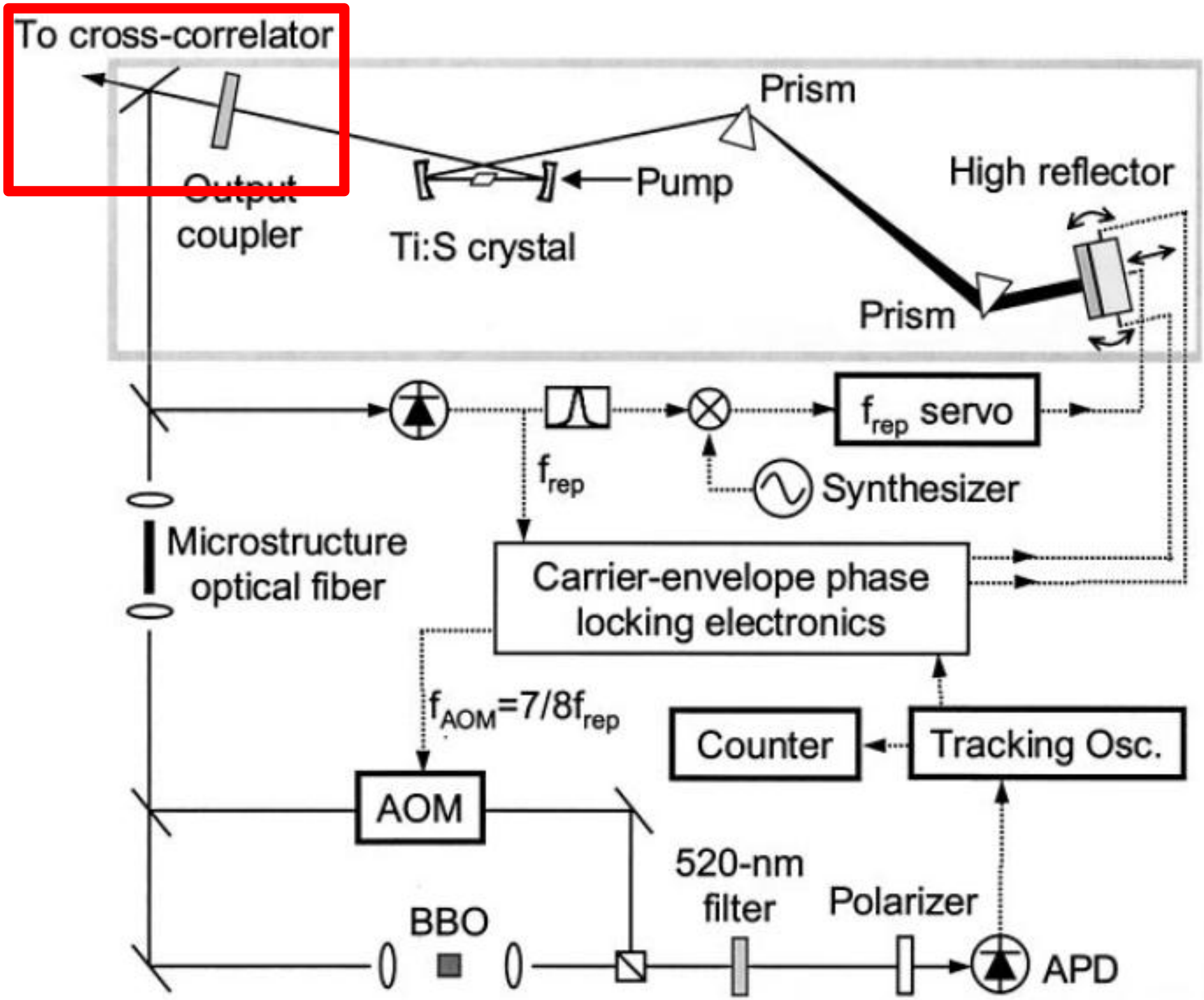
$$v_p = \frac{c}{n}$$

Group velocity

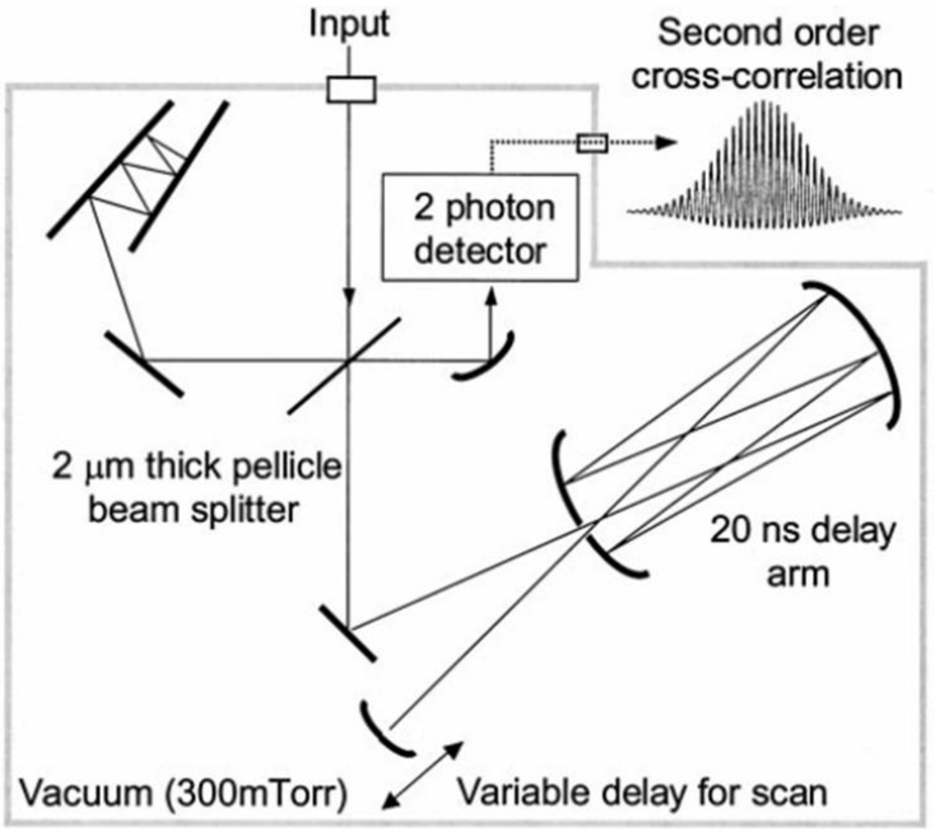
$$v_g = \frac{c}{n + \lambda \frac{dn}{d\lambda}}$$

If the pulse-to-pulse phase shift is 2π/8, then every eighth pulse will have the same phase, and the frequency offset will be f_{rep}/8.

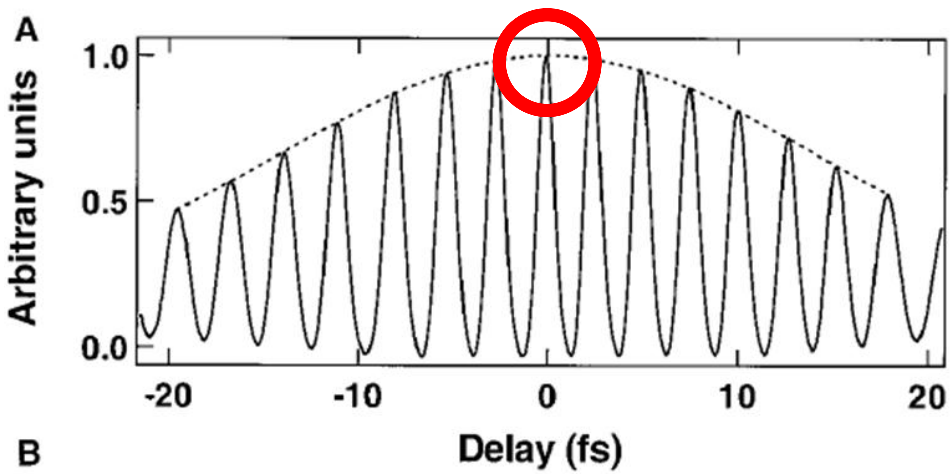
Experimental setup for locking



Temporal cross correlation



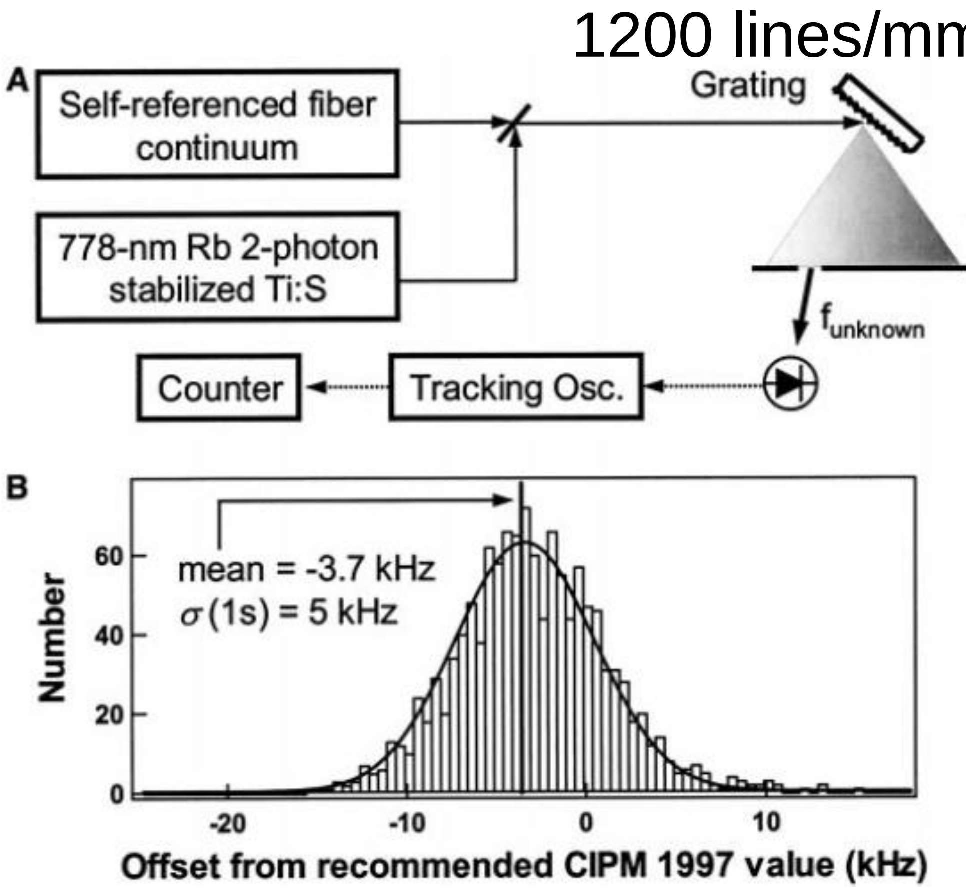
It keeps a peak and a peak.



With a 5% uncertainty

The second-order cross correlation between pulse i and pulse i+2 is measured to determine the pulse-to-pulse carrier-envelope phase shift.

Absolute optical frequency metrology



By counting both the offset frequency δ and the heterodyne beat signal between the CW Ti:S and the comb(f_{beat}).

$$f_{unknown} = \pm\delta + nf_{rep} \pm f_{beat}$$

Histogram of one set of measurements in relation to the recommended CIPM(1997) value of 385,285,142,378$\pm$5kHz for the rubidium transition.

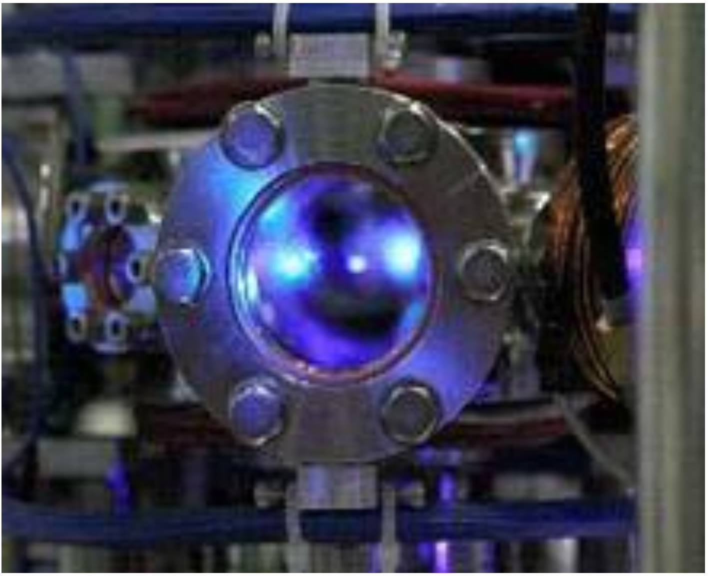
The standard deviation at the 5kHz, which is an absolute uncertainty of 1 part in 10^{11}.

Summary

●The self-referencing method represents a dramatic advance in optical frequency metrology, making measurement of absolute optical frequencies possible with a single laser.

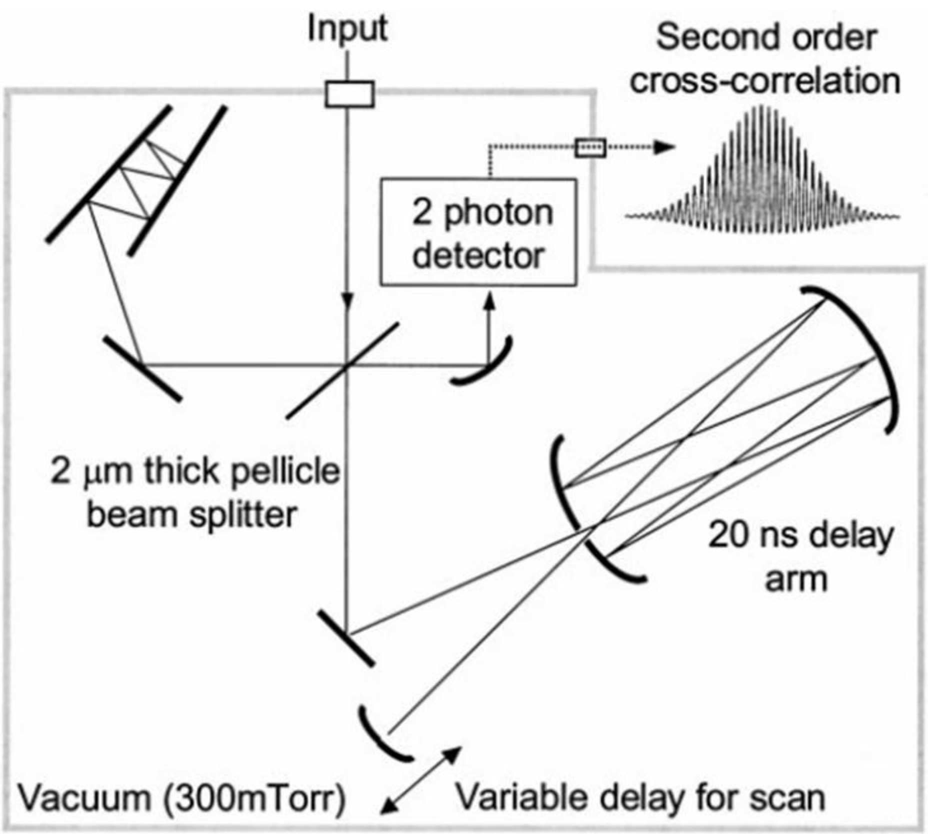
Summary

In the past 15 years, progress in laser stabilization, optical frequency measurement, femtosecond laser development and stabilization, nonlinear optics, and related topics has been stunning and unexpected.

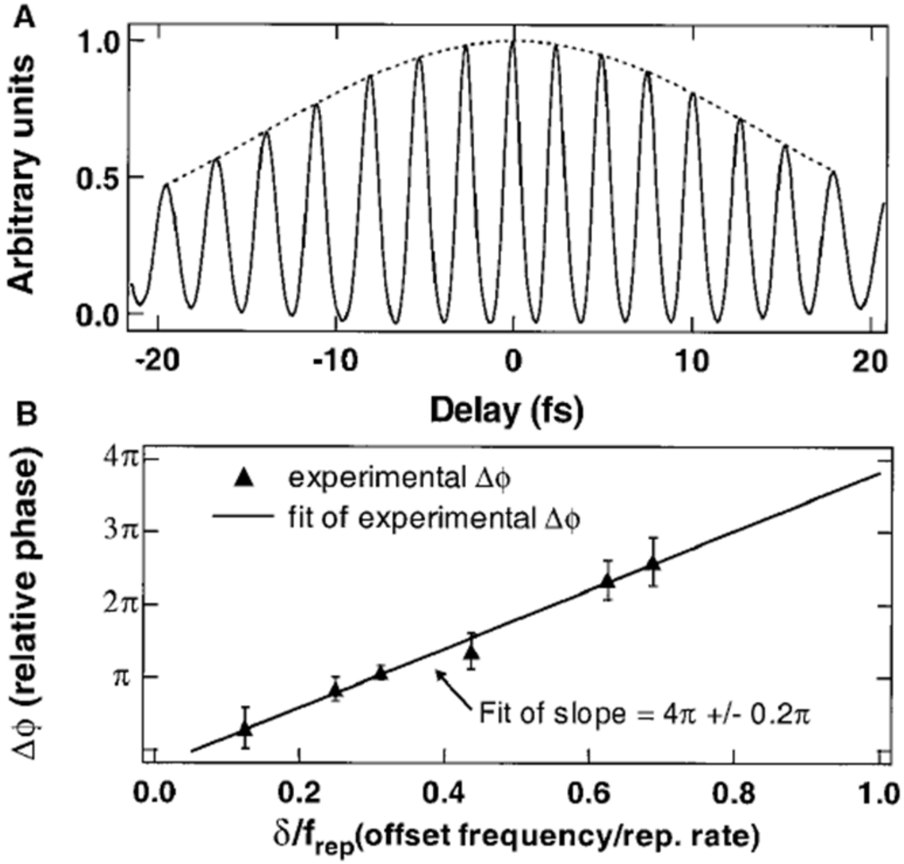


The self-referencing method represents a dramatic advance in optical frequency metrology, making measurement of absolute optical frequencies possible with a single laser.

Temporal cross correlation



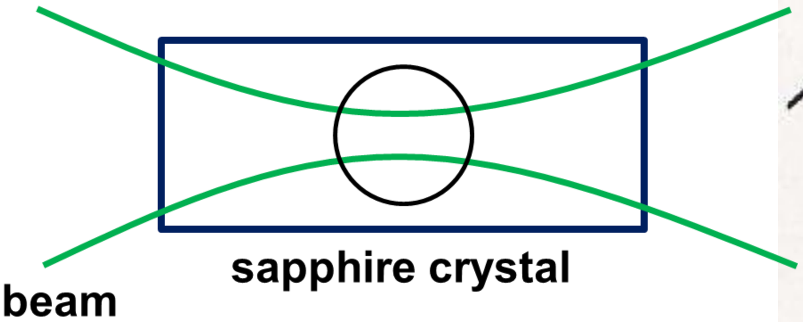
With a 5% uncertainty

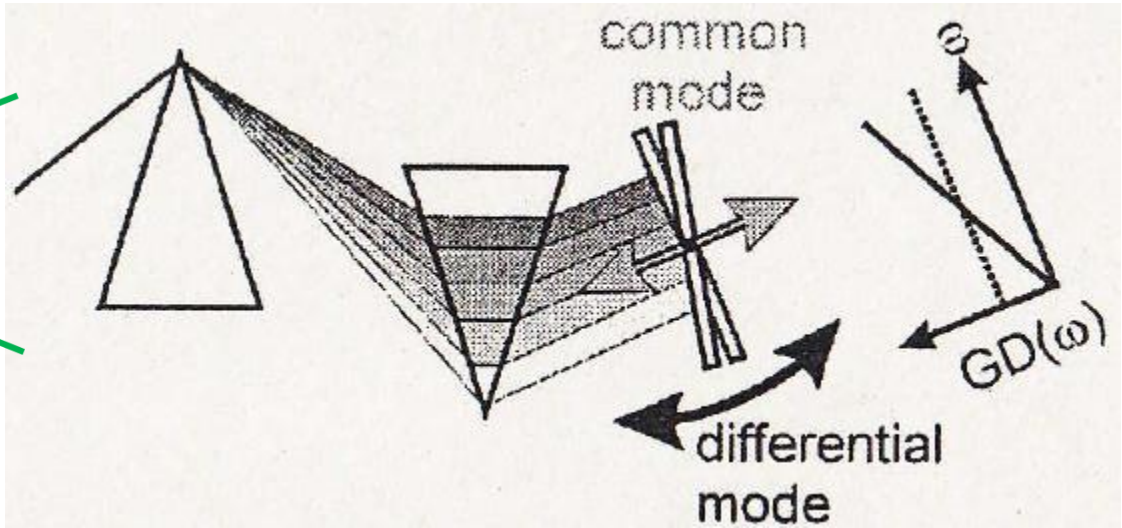


The second-order cross correlation between pulse i and pulse i+2 is measured to determine the pulse-to-pulse carrier-envelope phase shift.

Controlling the CEO frequency

f_{CEO} originates in the difference between the group and phase velocity.





The high-reflector mirror is mounted on PZT.
Change of the tilting and excursion.

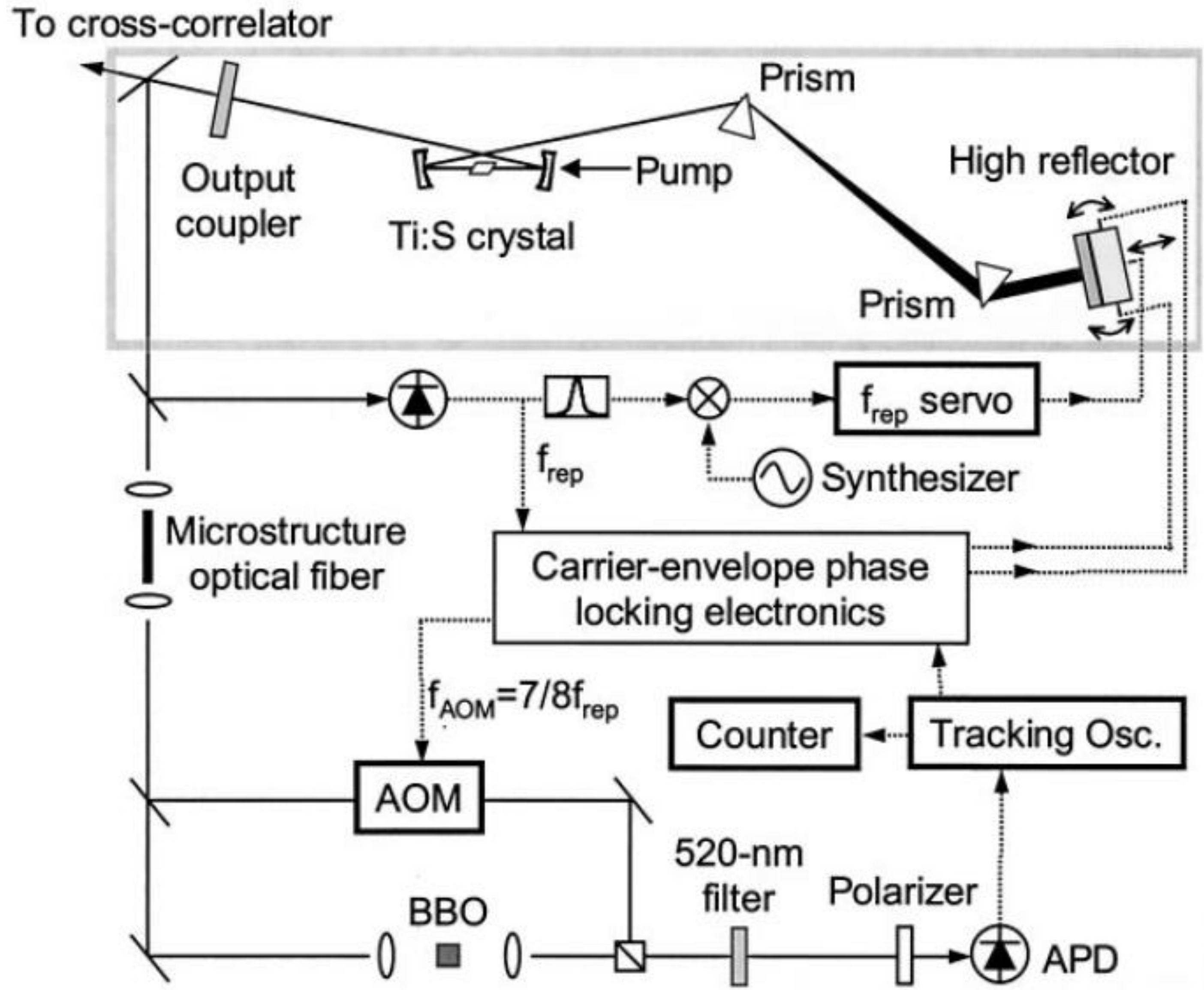
⇩

Change of the pulse intensity.

⇩

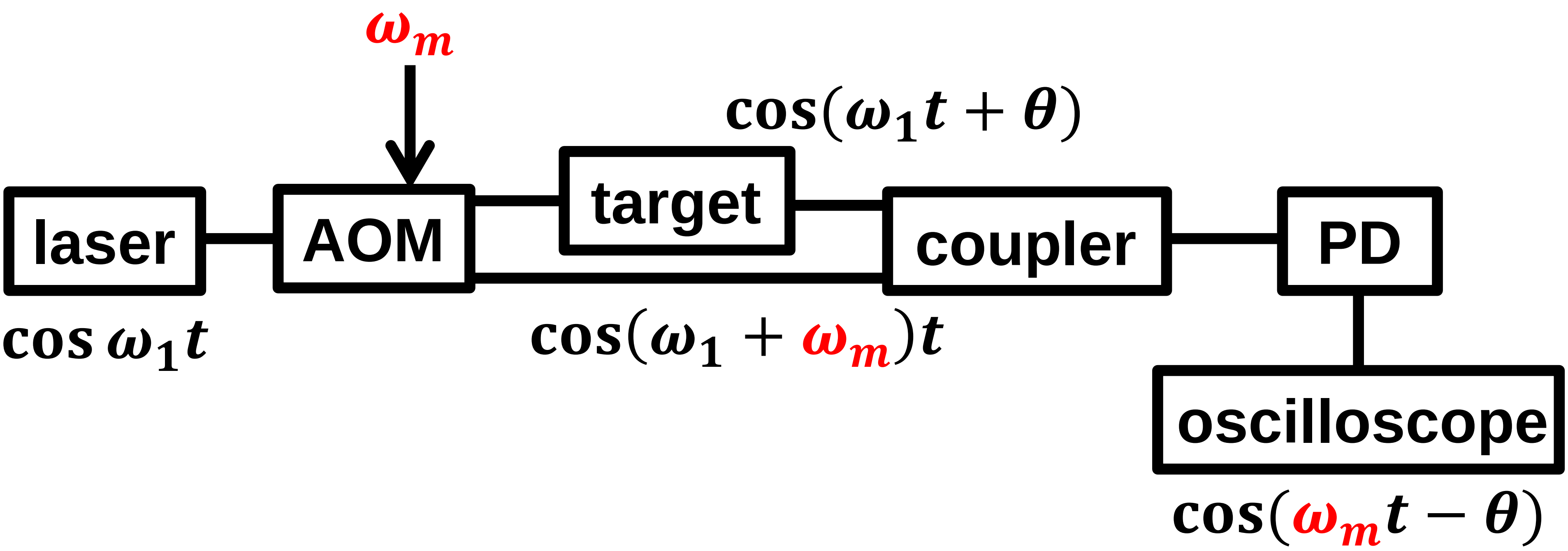
Change of the nonlinear refractive index.

Experimental setup for locking



Acousto-Optic Modulator

The AOM lets frequency shift.



The phase measurement by two wavelength heterodynes

⇨ **Continuous phase measurement is enabled.**

Microstructure optical fiber

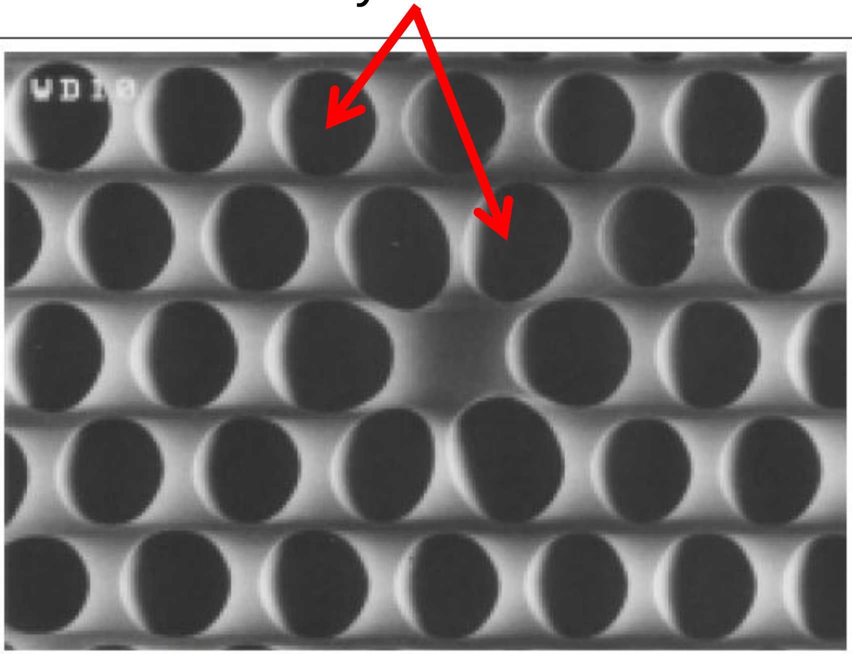


Fig. 2 零分散波長：800 nm をもつ高非線形 PCF
Cross sectional view of highly nonlinear PCFs with zero GVD wavelength of 800 nm

URL：http://www.mitsubishi-cable.co.jp/jihou/pdf/102/gi07.pdf

Refractive index
core>>>>>>>clad

- The effectiveness core cross section (A_{eff}) is small.
- The enclosure effect of the light is big.

⇩

increase

$$\gamma = \frac{2\pi}{\lambda} \frac{n_2}{A_{eff}}$$

λ is nonlinear fixed number.
n_2 is nonlinear refractive index of the core.

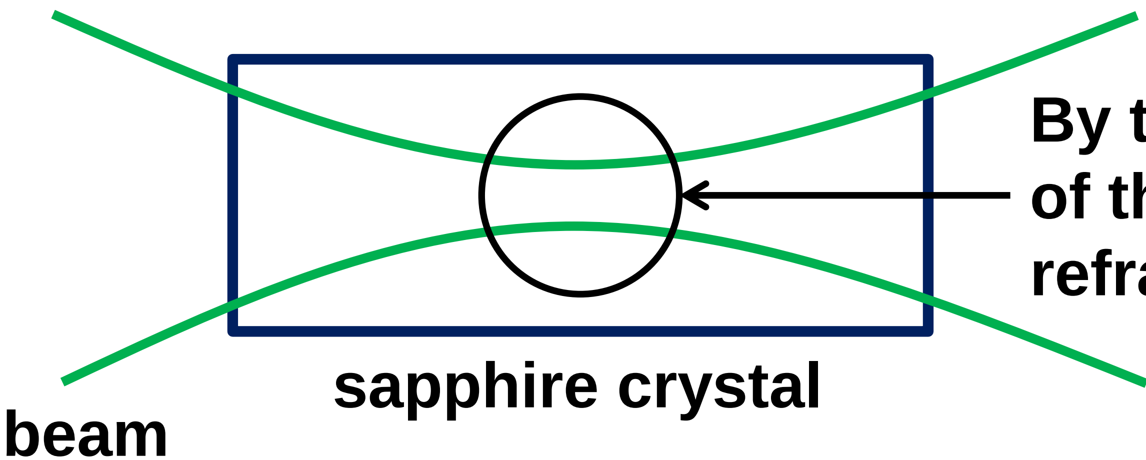
- It has a zero dispersion wavelength.

We can get an octave-spanning spectrum without changing pulse width.

Kerr-lens mode locking

●Kerr-lens mode(KLM) locking

KLM is one form of the passive mode locking. Sapphire crystal in itself acts as a mode locker and raises self-phase modulation in that. We perform passive mode locking by amplitude modulating it.



By the condensing strength of the beam, this sectional refractive index changes.

⇩

The pulsed light of the femtosecond occurs.