10 Mar. 2017, Why does the Universe accelerate? –Exhaustive study and challenge for the future- @KEK

An astro-comb developed by AIST (+YNU, UEC) and installed in OAO

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K. Hosaka[1,5], F.-L. Hong[1,2,5], A. Onae[1,5], K. Minoshima[4,5], H. Tsutsui[3,5],
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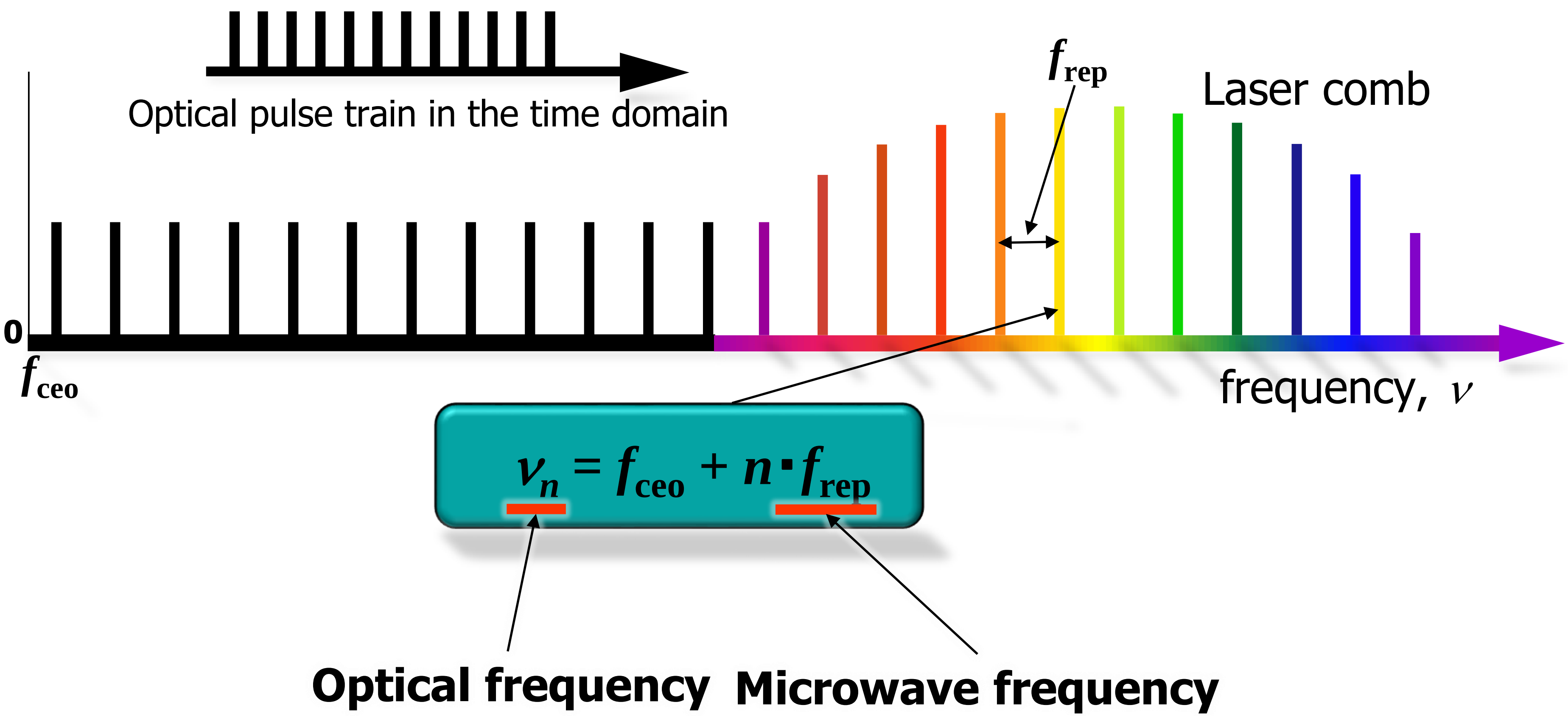
4. The university of Electro-Communications,
5. JST ERATO "Minoshima Intelligent Optical Synthesizer Project

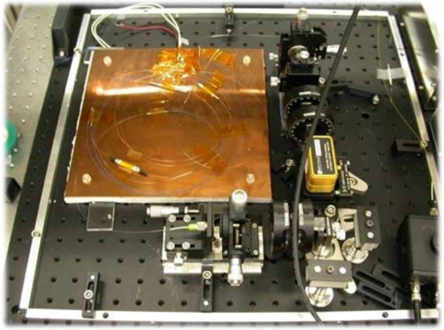
Outline

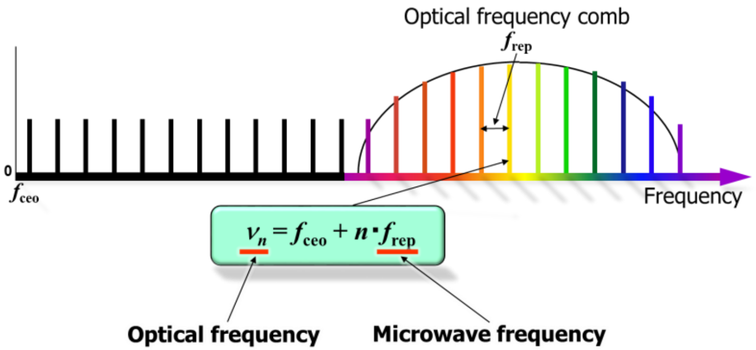
1. **Motivation**
   - Laser comb at AIST, NMIJ
   - High dispersion spectrograph at NAOJ, OAO
   - Global comb situation
2. **Overview of our astro-comb**
   - I_2-stabilized laser
   - Source comb
   - Visible comb generation
   - Mode-filtering cavity
3. **Current status**
4. **Future plans**

Laser comb at AIST, NMIJ

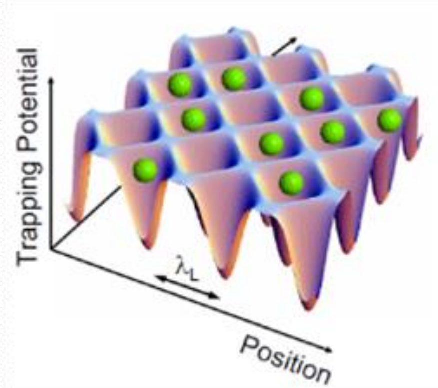


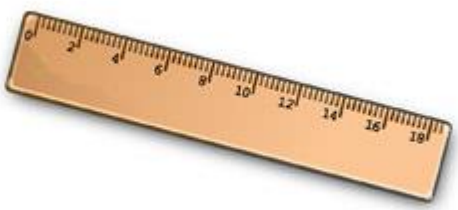
Laser comb at AIST, NMIJ





Fiber-based laser comb (Robust, low noise, compact)





Optical clocks **Length standard**

Astro comb

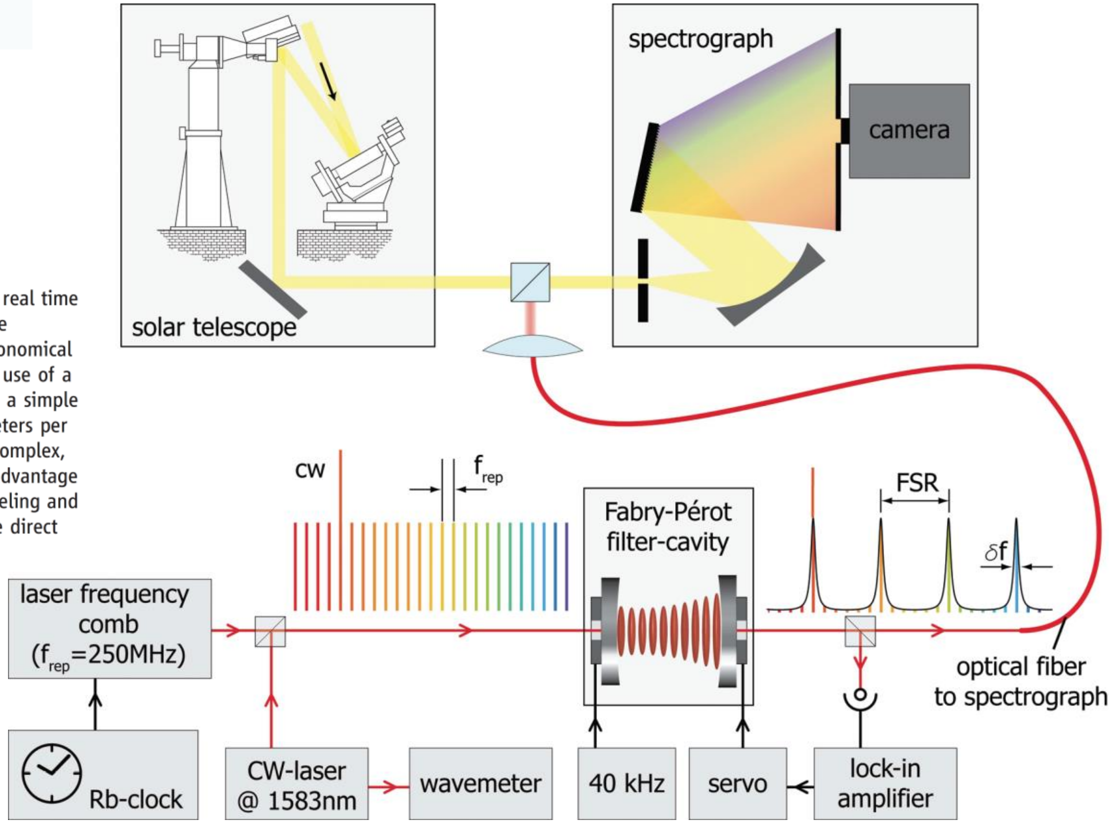
Optical frequency comb for calibration high-dispersion spectrograph

Steinmetz, *et. al.*, Science **321**, 1335 (2008)

Laser Frequency Combs for Astronomical Observations

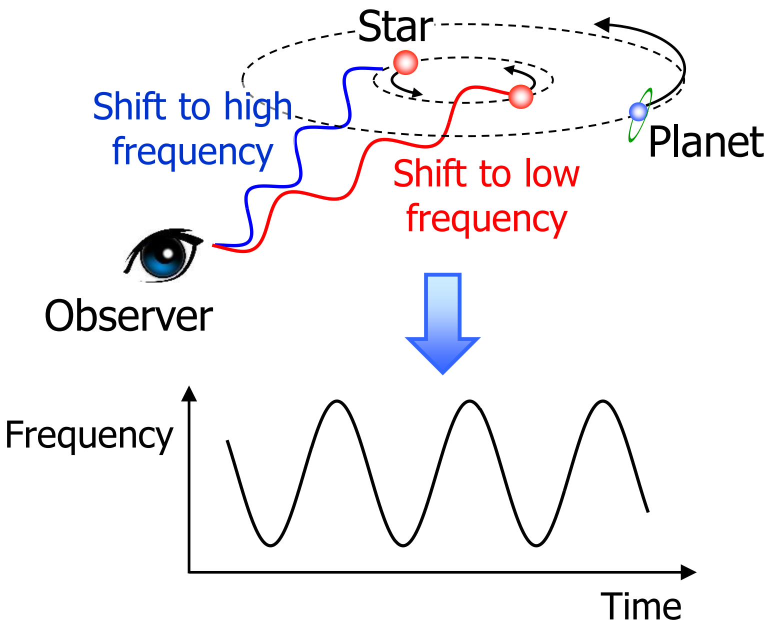
Tilo Steinmetz,[1,2] Tobias Wilken,[1] Constanza Araujo-Hauck,[3] Ronald Holzwarth,[1,2] Theodor W. Hänsch,[1] Luca Pasquini,[3] Antonio Manescau,[3] Sandro D'Odorico,[3] Michael T. Murphy,[4] Thomas Kentischer,[5] Wolfgang Schmidt,[5] Thomas Udem[1*]

A direct measurement of the universe's expansion history could be made by observing in real time the evolution of the cosmological redshift of distant objects. However, this would require measurements of Doppler velocity drifts of ~1 centimeter per second per year, and astronomical spectrographs have not yet been calibrated to this tolerance. We demonstrated the first use of a laser frequency comb for wavelength calibration of an astronomical telescope. Even with a simple analysis, absolute calibration is achieved with an equivalent Doppler precision of ~9 meters per second at ~1.5 micrometers—beyond state-of-the-art accuracy. We show that tracking complex, time-varying systematic effects in the spectrograph and detector system is a particular advantage of laser frequency comb calibration. This technique promises an effective means for modeling and removal of such systematic effects to the accuracy required by future experiments to see direct evidence of the universe's putative acceleration.

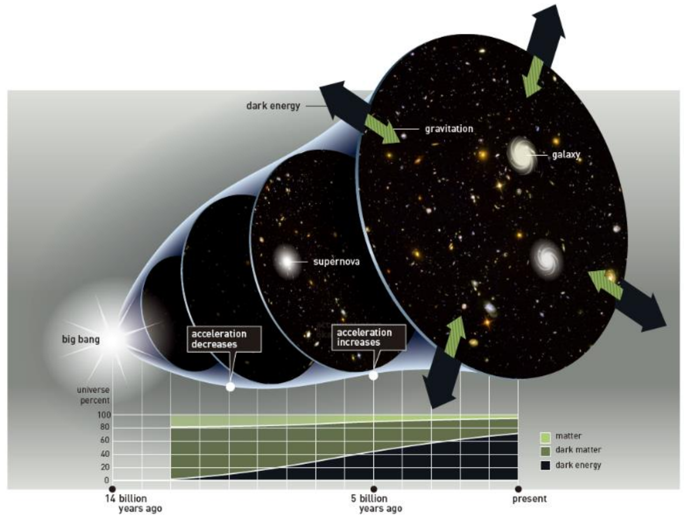


Astro comb

Application 1：Exoplanets exploration



Application 2：Study of Universe acceleration



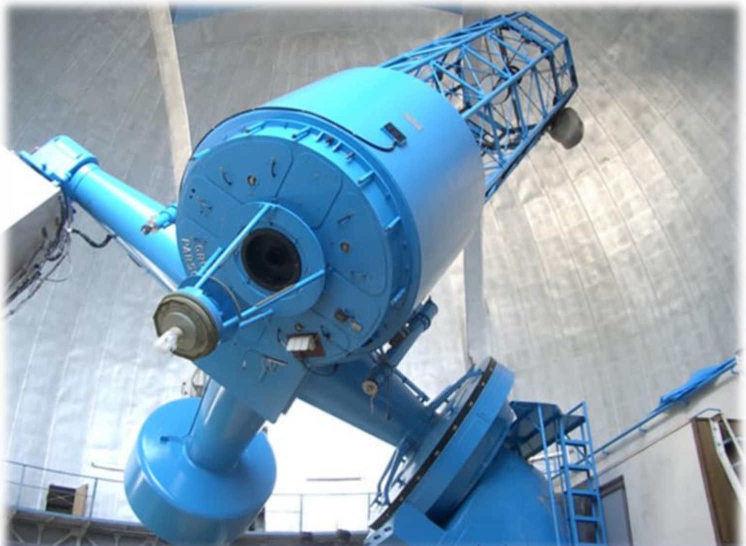
Novel prize HP
http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/popular.html

need ~cm/s precision to find earth-type planets

need 2~10 cm/s precision to study Universe acceleration

Recent astrophysics requires precise measurements of Doppler shift of atomic absorption lines. The precision of "Horizontal axis" of astronomical spectrograph has become important.

Collaboration with Okayama Astrophysics Observatory (OAO) of National Astronomical Observatory of Japan



2003 First discovery of exoplanet in Japan

From OAO website

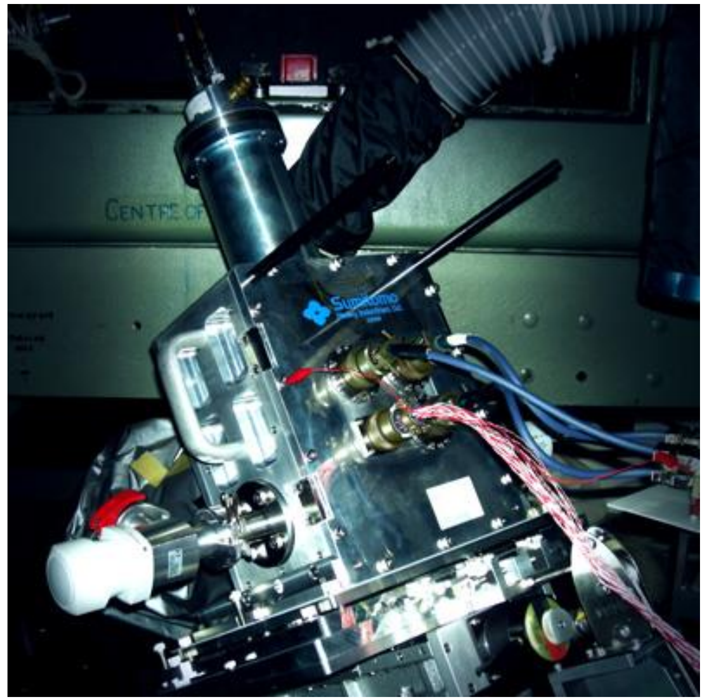
巨星のまわりの惑星を発見

★ 日本初の発見！

国立天文台、東京大学を中心とする研究グループは、国立天文台の岡山天体物理観測所188cm反射望遠鏡の高分散分光器HIDES(ハイデス)を用いた観測により、巨星の周りをまわる惑星を発見しました。これまでに、太陽以外の星をまわる惑星（太陽系外惑星）は約100個ほど発見されていますが、**日本における発見は今回が初めてです。**

図1：惑星の発見された巨星HD104985（Digitized Sky Survey Dataより）

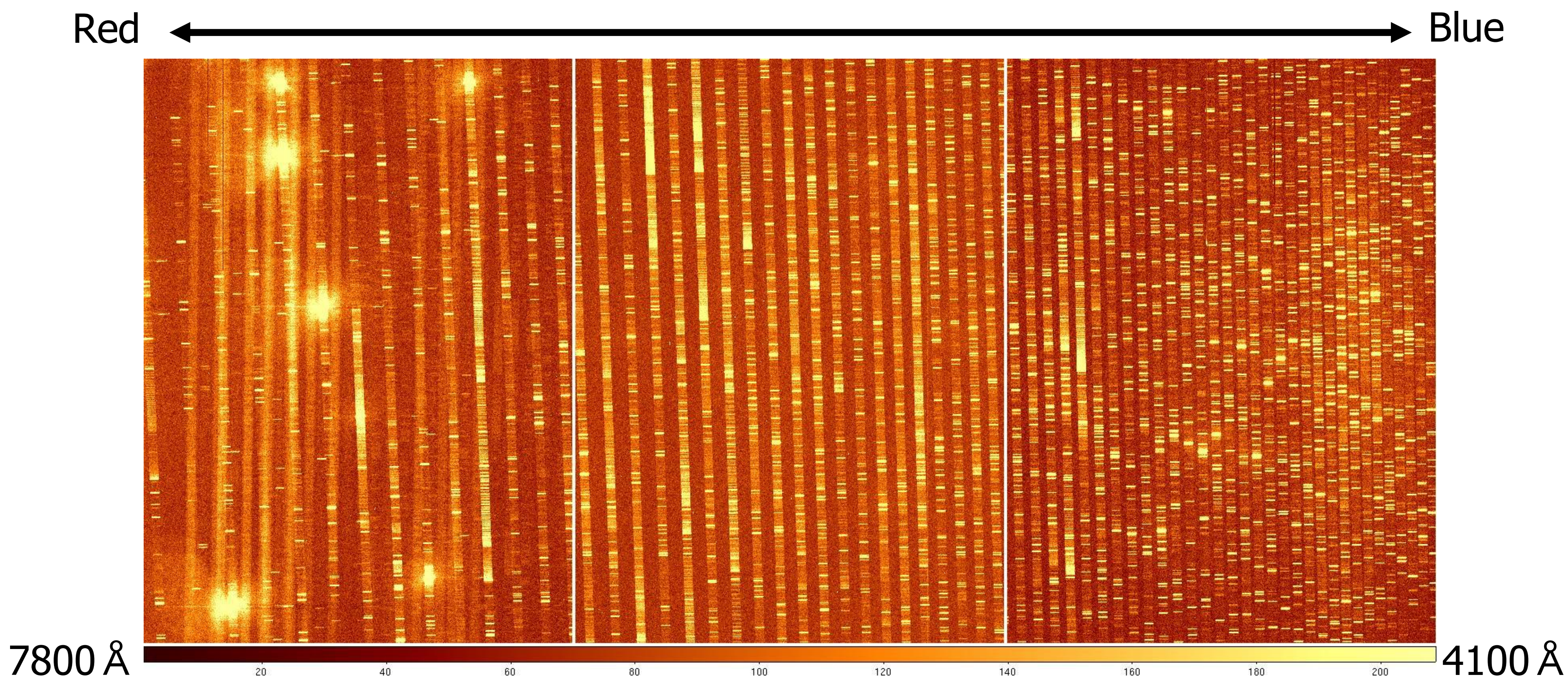
High-dispersion spectrograph at OAO "HIDES-F"



High dispersion spectrograph "HIDES-F (HIgh Dispersion Echelle Spectrograph)" settle in Coude's focus of 188 cm reflecting telescope

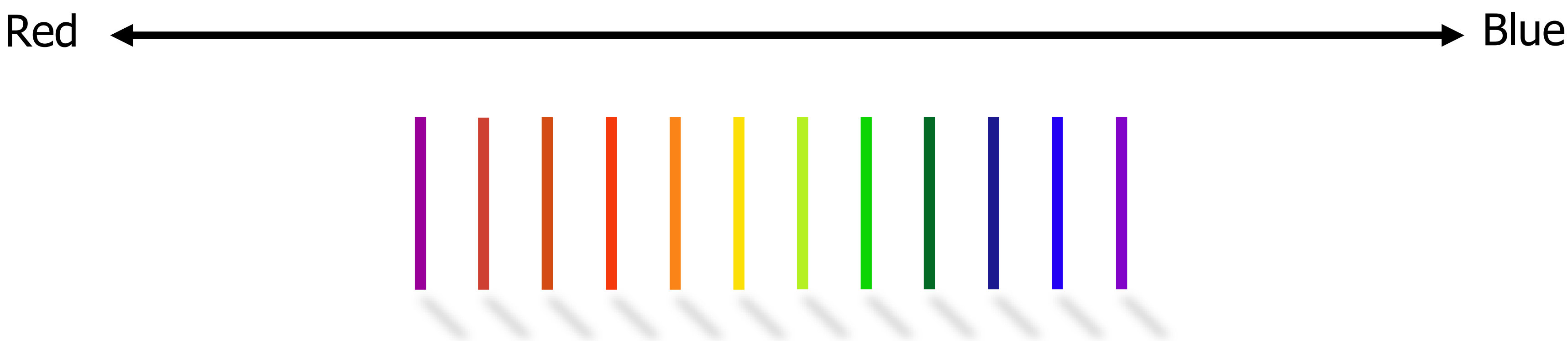
Resolution	$(\lambda/\Delta\lambda) \approx$ 50,000 (Practically)-120,000 (Max)
	$\Delta\nu \approx$ 12 GHz @ 500 nm
Wavelength	400-700 nm

An Th-Ar lamp spectrum observed by HIDES-F



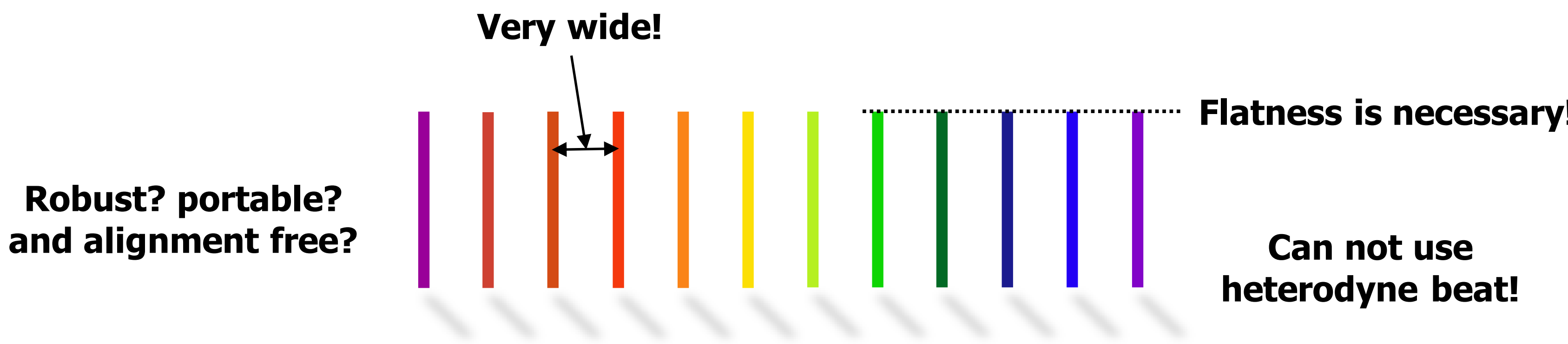
Spectrum of Th-Ar lamp in the range from 4100 Å to 7800 Å at a resolution (λ/Δλ) ~ 100,000 taken simultaneously with the HIDES mosaic CCD camera.

Laser comb spectrum and advantages



1. Precision $<10^{-11}$ (limited by RF reference), which corresponds to 3 mm/s of radial velocity!
2. Equal frequency interval
3. Broad spectrum and modes with high intensities

Difficulty of astro-comb



1. **Very high repetition rate (several tens GHz) is needed to calibrate spectrograph with even high resolution.**
2. **A flat spectrum is needed.**
3. **It must be robust, portable, and alignment free.**
4. **Beat frequency measurement based on heterodyne technique can NOT be used for spectrograph calibration. Therefore, directly reflecting comb's precision needs other devices.**

Astro-comb of the world

Target	λ	Group	Spectrometer	Telescope	Scheme
F/G/K type	Visible (optical)	Max-Planck	HARPS (R=115,000)	3.6 m ESO	Source comb (Yb) → 250 MHz → Mode filtering → 18 GHz → λ conversion, Broadening
		Harvard	HARPS-N (R=115,000)	TNG	Source comb (Ti:sapphire) → 1 GHz → λ conversion, Broadening → 16 GHz → Mode filtering
		AIST/NAOJ	HIDES Fiber-Feed (R=52,000/110,000)	1.88 m OAO	Source comb (Er) → 100 MHz → λ conversion, Broadening → 40 GHz → Mode filtering
M type	NIR	NIST	CSHLL (R=46,000) NIRSPEC (R=25,000)	3 m IRTF 10 m Keck-II	**Source comb with high f_{rep}** → 12 GHz → λ conversion, Broadening
		TAT/NAOJ	IRD (R=70,000)	Subaru	**Source comb with high f_{rep}** → 12.5 GHz → λ conversion, Broadening

Target of development

- "Practical astro-comb" has not yet been established on a global level. (Especially in short wavelength)
- Domestic comb-maker will be available for users.

- Develop a long-term operational, robust, and short-wavelength (380-540 nm) astro-comb.
- Develop an astro-comb for HIDES of OAO first, subsequently for HDS of SUBARU. **Then, towards TMT…**

Various approaches of astro-comb in the optical (visible) region

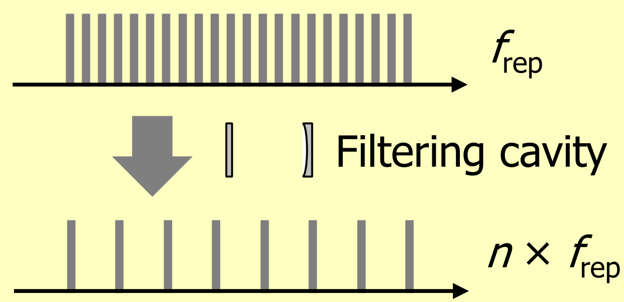
Source comb

Mode-locked laser
(f_{rep} = 100 MHz – 1 GHz)
- Er fiber
- Yb fiber
- Ti:Sapphire

Modulator-based comb
(f_{rep} = 10-20 GHz)
CW laser → EOM →

Kerr comb
(f_{rep} = 10-100 GHz)
CW laser → μ cavity →

Mode filtering



Wavelength conversion, Spectral broadening
- Nonlinear Crystal
- PCF
- HNLF

Various approaches of astro-comb in the optical (visible) region

Source comb

Mode-locked laser
(f_{rep} = 100 MHz – 1 GHz)
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Modulator-based comb
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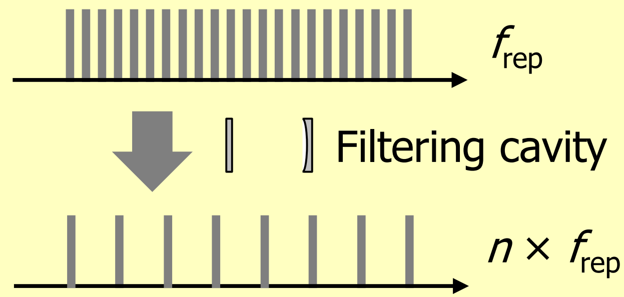
Kerr comb
(f_{rep} = 10-100 GHz)
CW laser — μ cavity

Mode filtering



Wavelength conversion,
Spectral broadening
- Nonlinear Crystal
- PCF
- HNLF

Overview of our astro comb

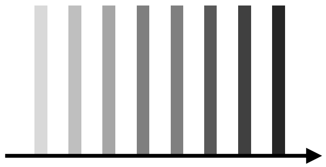
System overview

Reference for
comb & cavities

① I_2-stabilized CW laser

Phase lock

② Source comb



f_{ceo} = 0 Hz

f_{rep} = 100 MHz, 1560 nm

1063 nm

SHG

③ Visible comb generation

f_{rep} = 100 MHz, **380-540 nm**

532 nm

Reference for cavities

④ Mode filtering using triple cavity

f'_{rep} = **40 GHz** (f_{rep} x 400), 380-540 nm

To HIDES-F

System overview

Reference for
comb & cavities

① I_2-stabilized CW laser

Phase lock

② Source comb

f_{ceo} = 0 Hz
f_{rep} = 100 MHz, 1560 nm

1063 nm

SHG

Frequency-stabilized laser

generation

f_{rep} = 100 MHz, **380-540 nm**

532 nm

④ Mode filtering using triple cavity

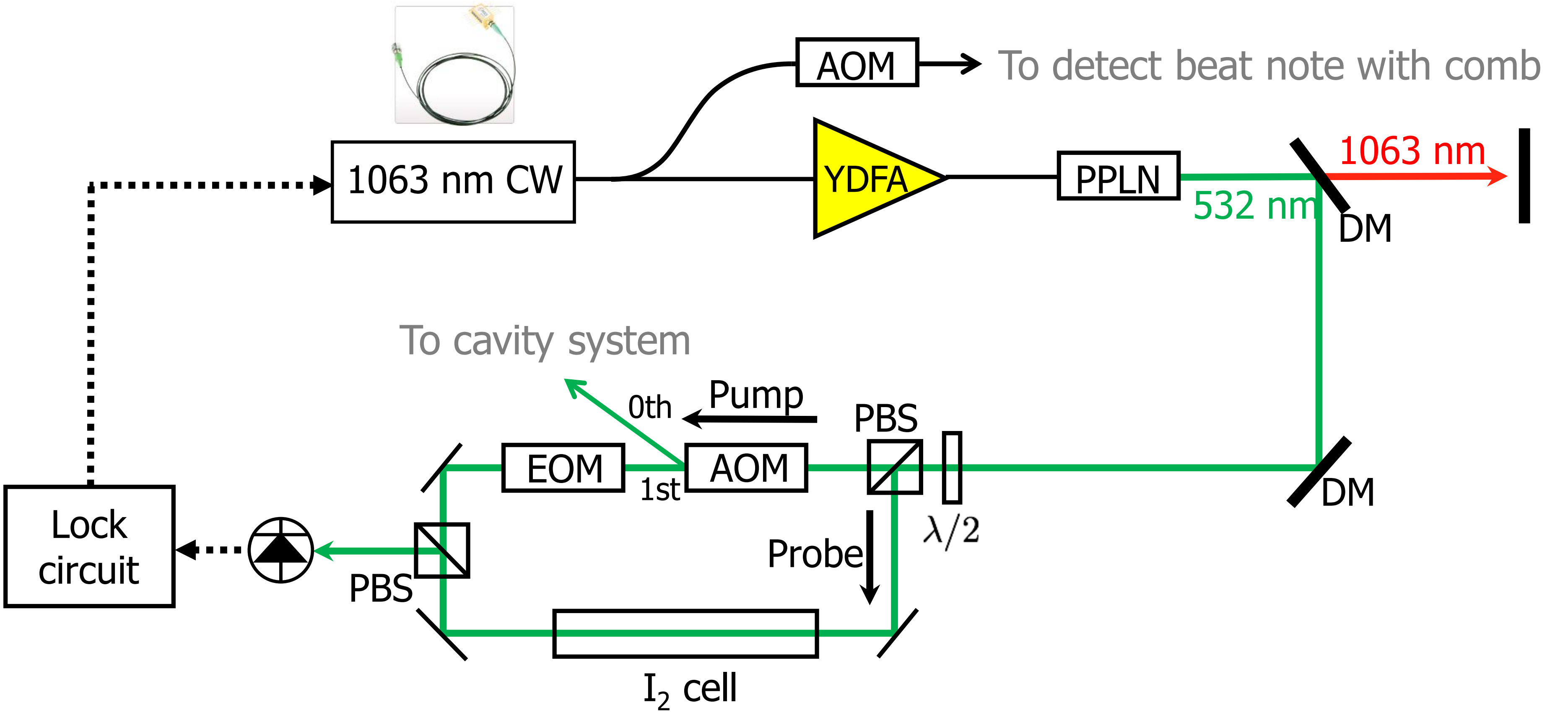
Reference for cavities

f'_{rep} = **40 GHz** (f_{rep} x 400), 380-540 nm

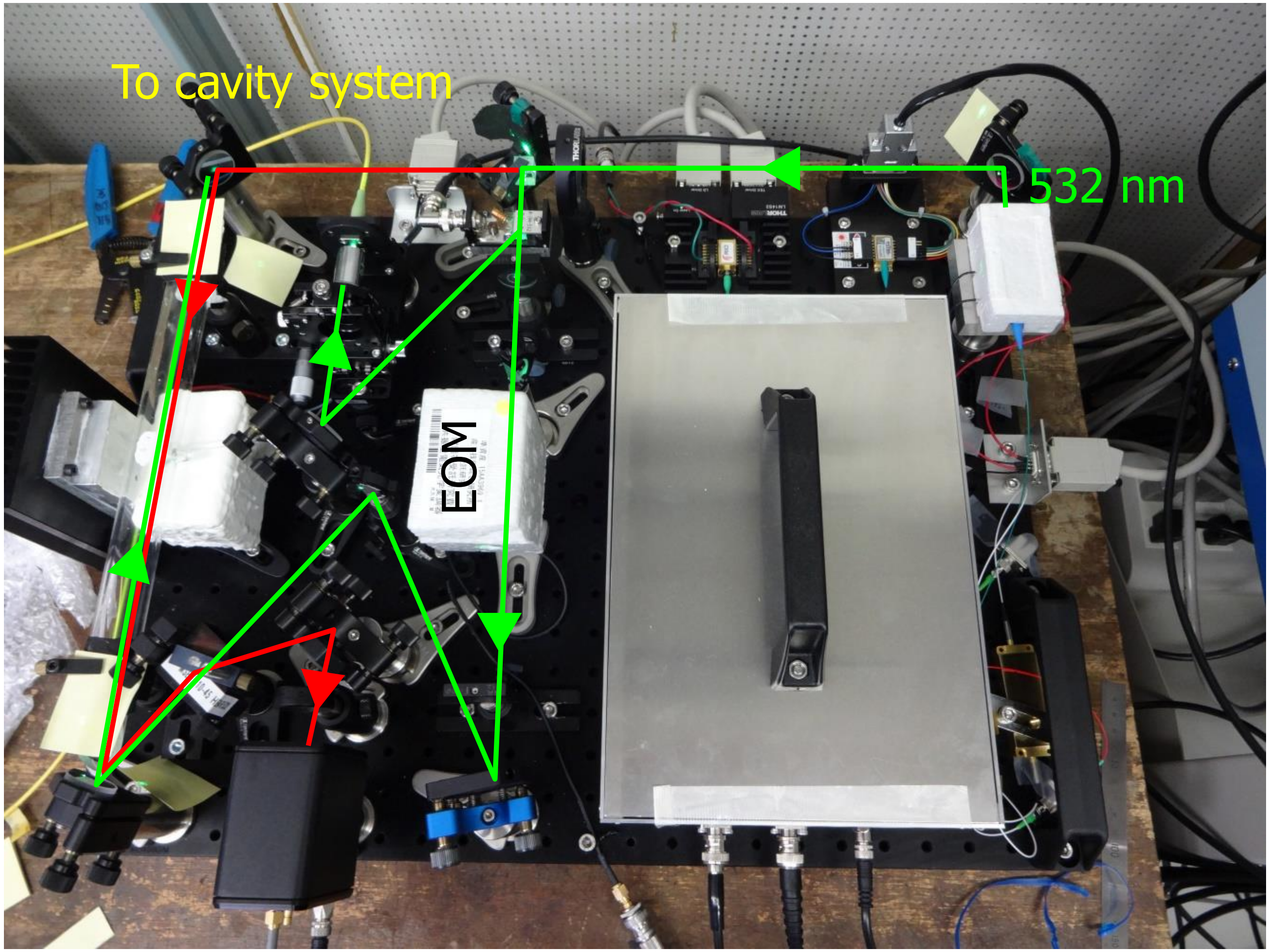
To HIDES-F

I_2-stabilized 1063 nm CW laser

Modulation transfer technique



I_2-stabilized 1063 nm CW laser



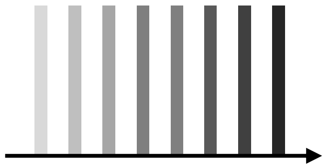
System overview

Reference for
comb & cavities

① I_2-stabilized CW laser

Phase lock

② Source comb



f_{ceo} = 0 Hz

f_{rep} = 100 MHz, 1560 nm

1063 nm

SHG

Optical frequency comb
(Source comb)

③ Visible comb generation

f_{rep} = 100 MHz, **380-540 nm**

532 nm

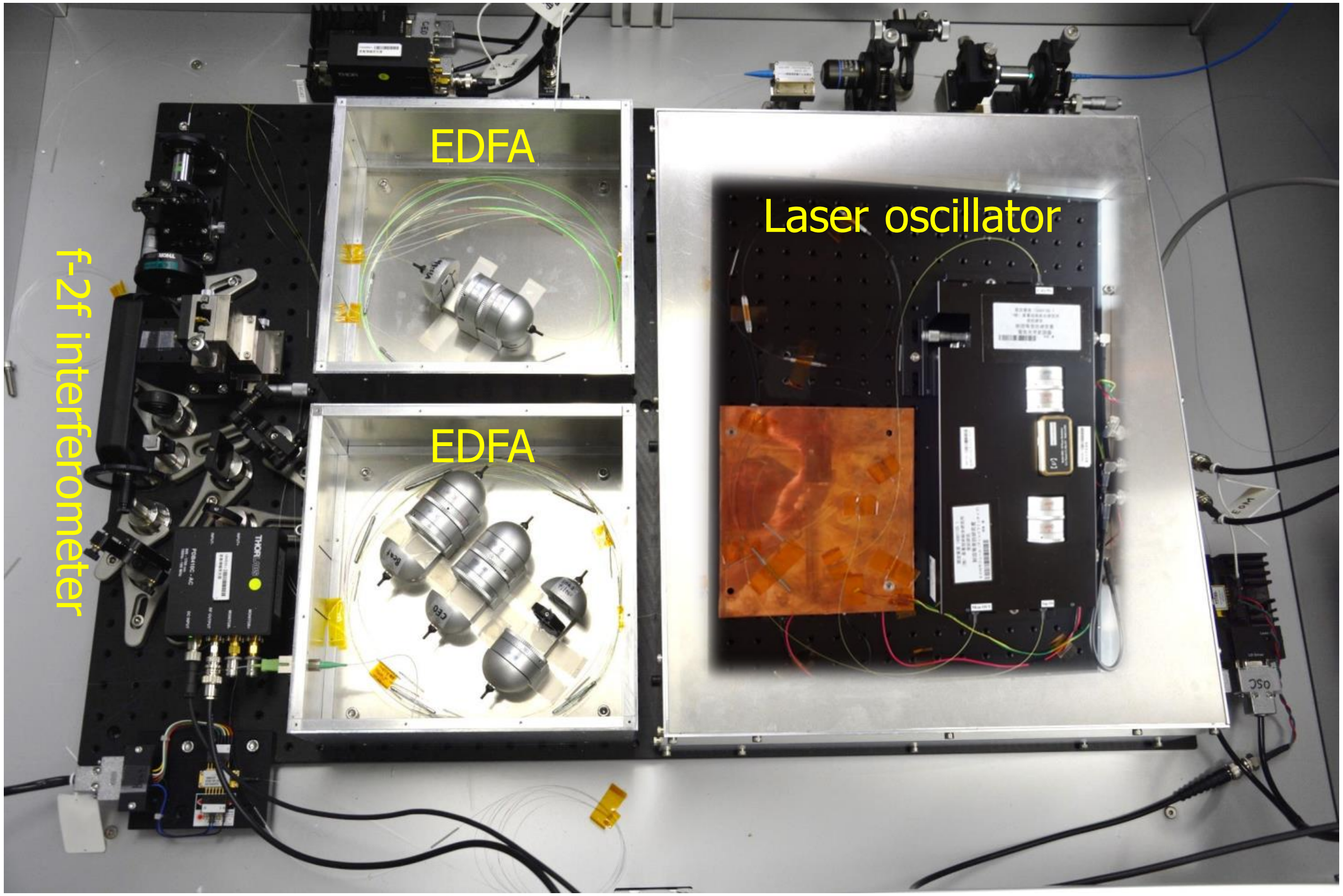
Reference for cavities

④ Mode filtering using triple cavity

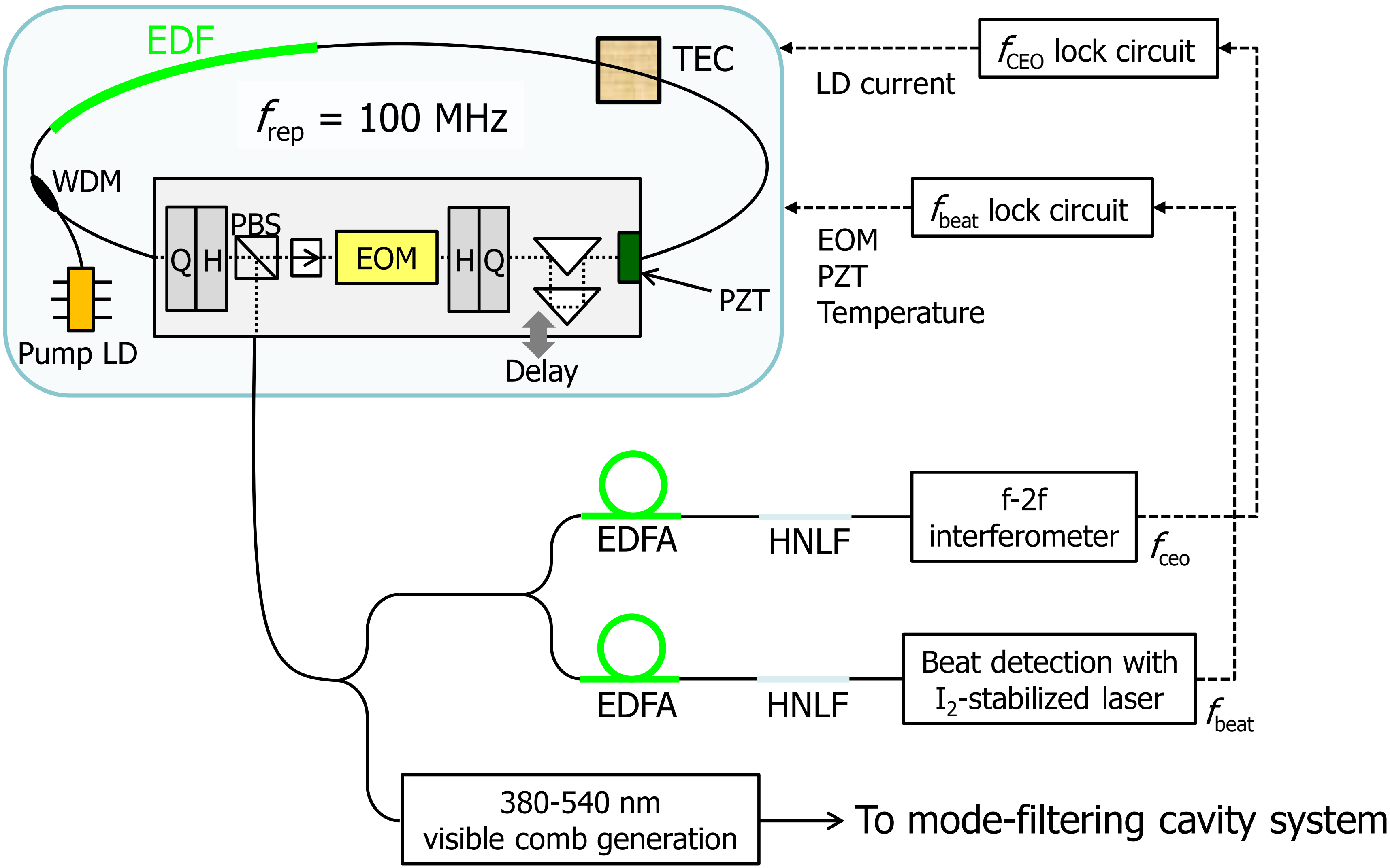
f'_{rep} = **40 GHz** (f_{rep} x 400), 380-540 nm

To HIDES-F

Source comb



Source comb stabilization



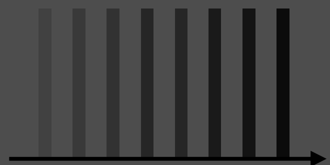
System overview

Reference for
comb & cavities

① I_2-stabilized CW laser

Phase lock

② Source comb



f_{ceo} = 0 Hz

f_{rep} = 100 MHz, 1560 nm

1063 nm

SHG

③ Visible comb generation

f_{rep} = 100 MHz, **380-540 nm**

532 nm

Broadband comb generation in the visible (optical) region

Reference for cavities

using triple cavity

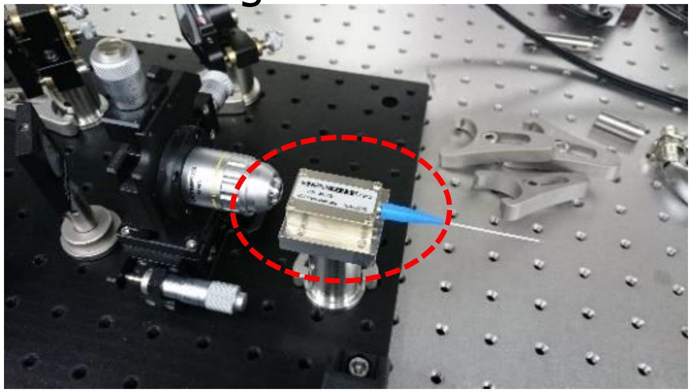
f'_{rep} = **40 GHz** (f_{rep} x 400), 380-540 nm

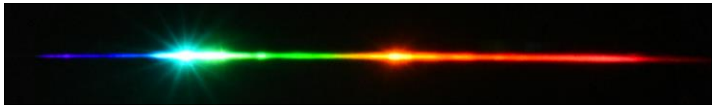
To HIDES-F

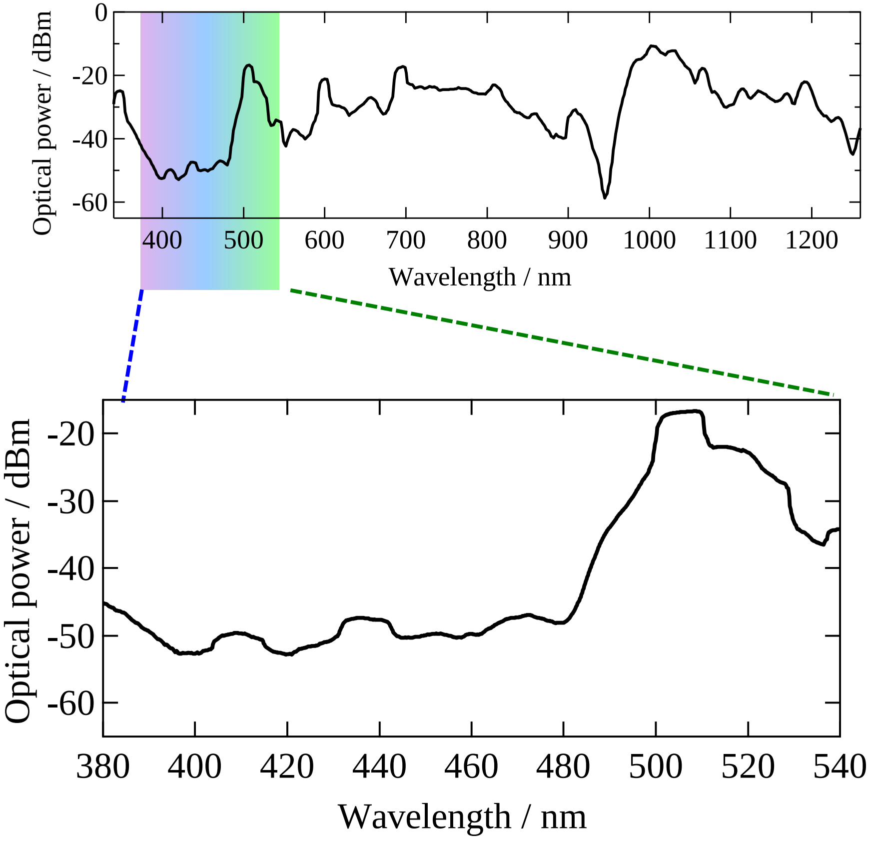
Visible comb generation

Scheme

PPLN waveguide







K. Iwakuni, *et. al.*, Opt. Lett. **41**, 3980 (2016)
"Generation of a frequency comb spanning more than 3.6 octaves from ultraviolet to mid infrared"

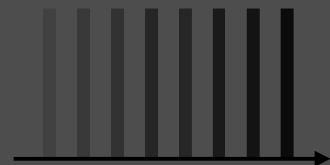
System overview

Reference for
comb & cavities

① **I_2-stabilized CW laser**

Phase lock

② Source comb



f_{ceo} = 0 Hz
f_{rep} = 100 MHz, 1560 nm

1063 nm

SHG

Optical cavity for mode filtering

generation

f_{rep} = 100 MHz, **380-540 nm**

532 nm

Reference for cavities

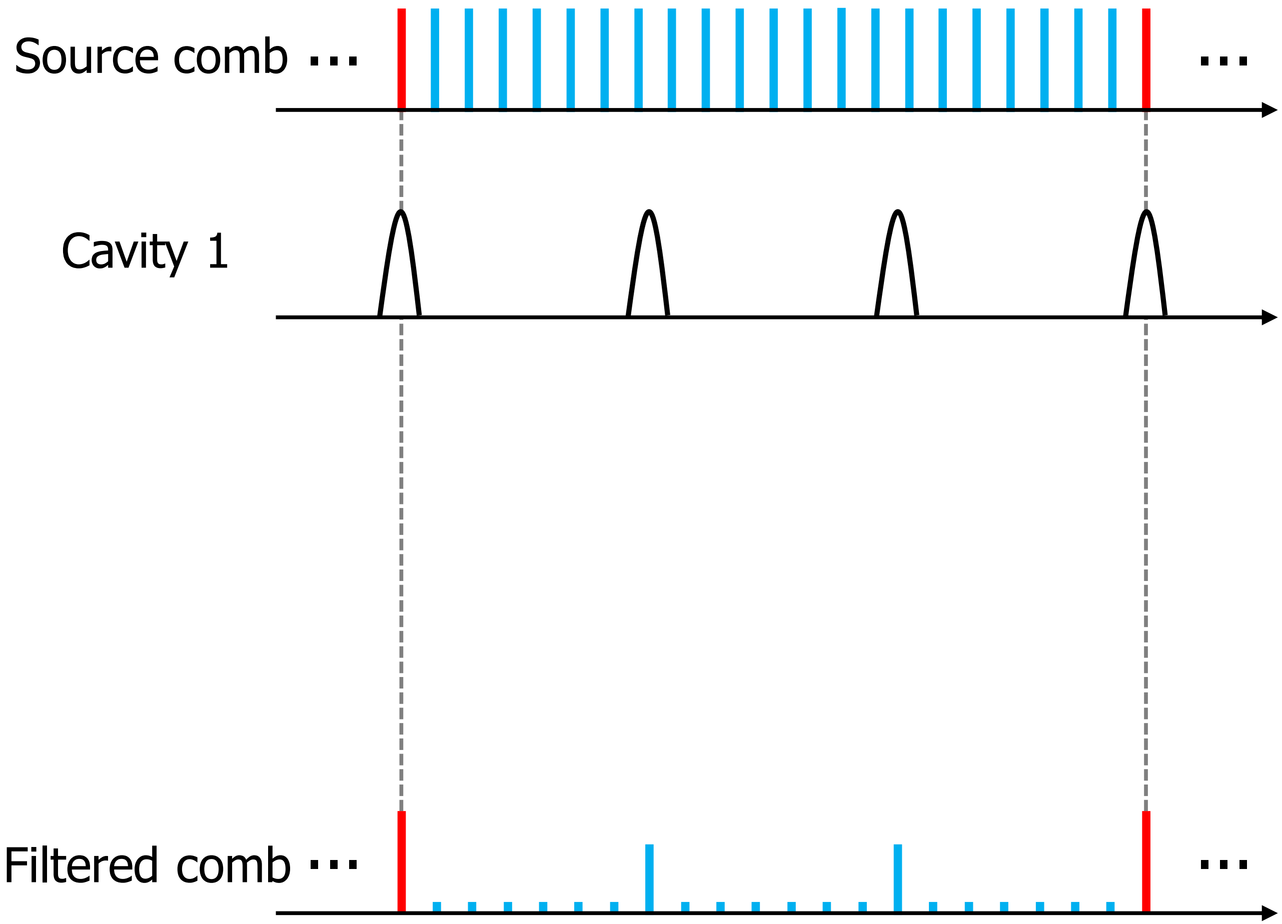
④ Mode filtering using triple cavity

f'_{rep} = **40 GHz** (f_{rep} x 400), 380-540 nm

To HIDES-F

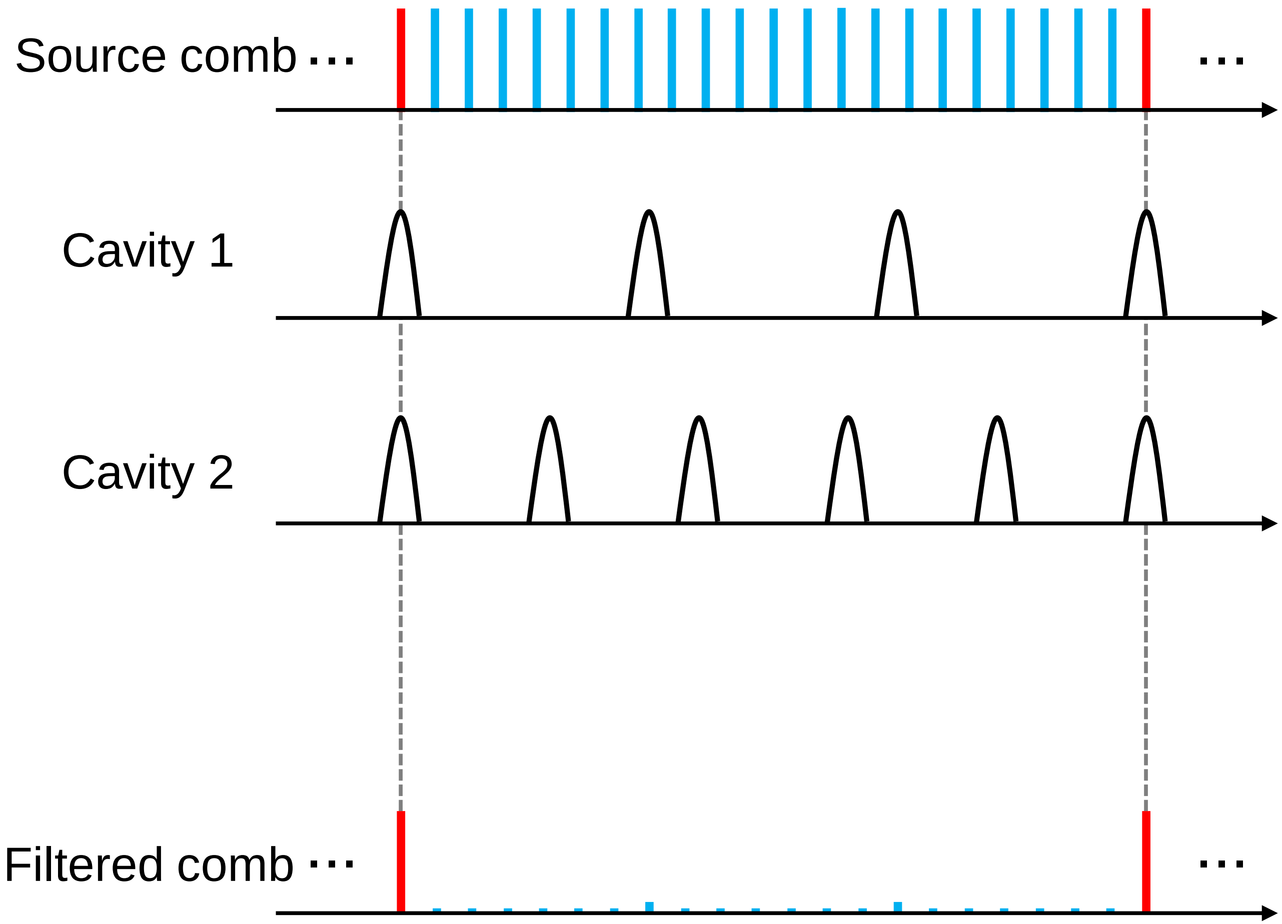
Mode filtering using three optical cavities

Mode filtering using three optical cavities



Extract comb modes with an integer times of FSR

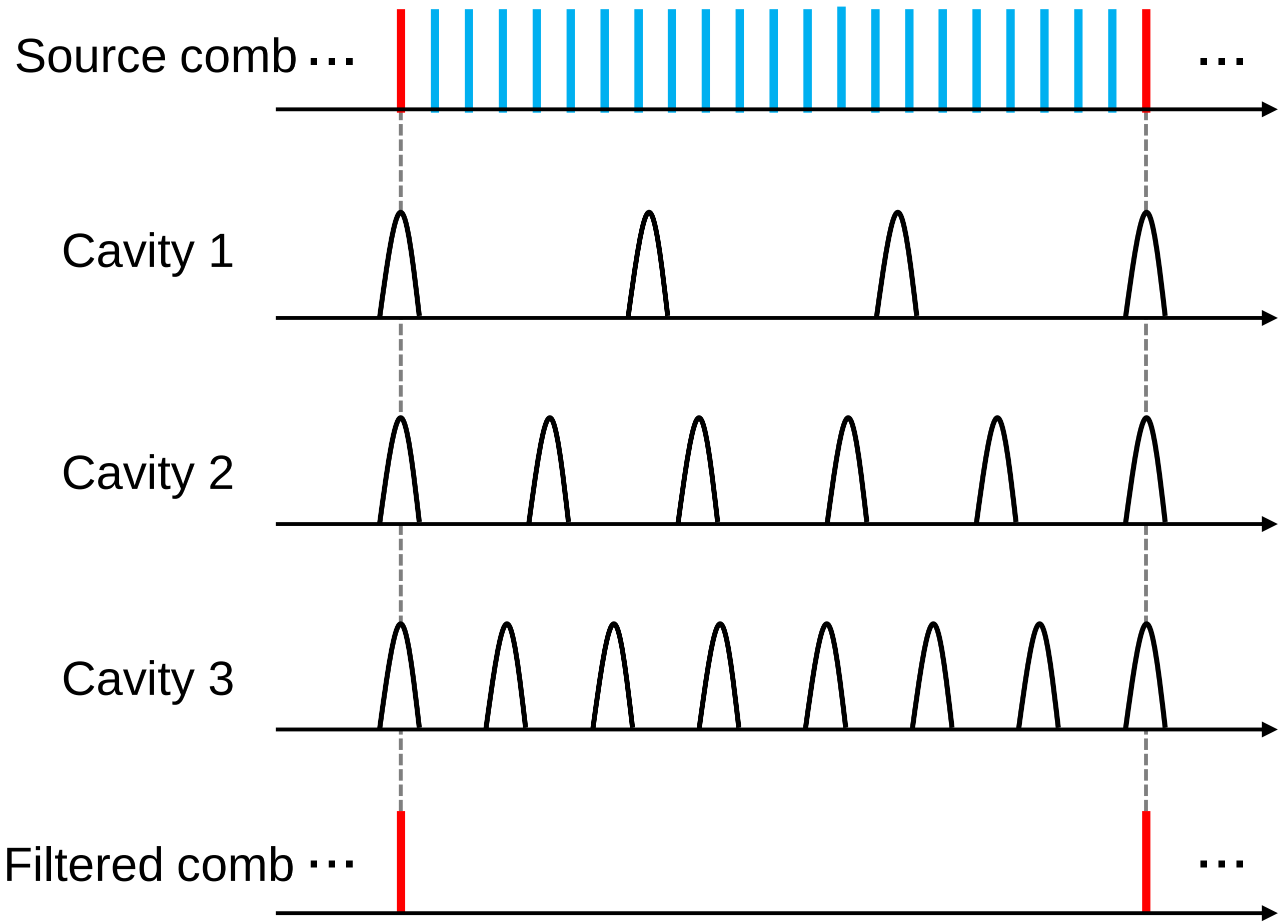
Mode filtering using three optical cavities



Extract comb modes with an integer times of FSR

Extract comb modes with another integer times of FSR

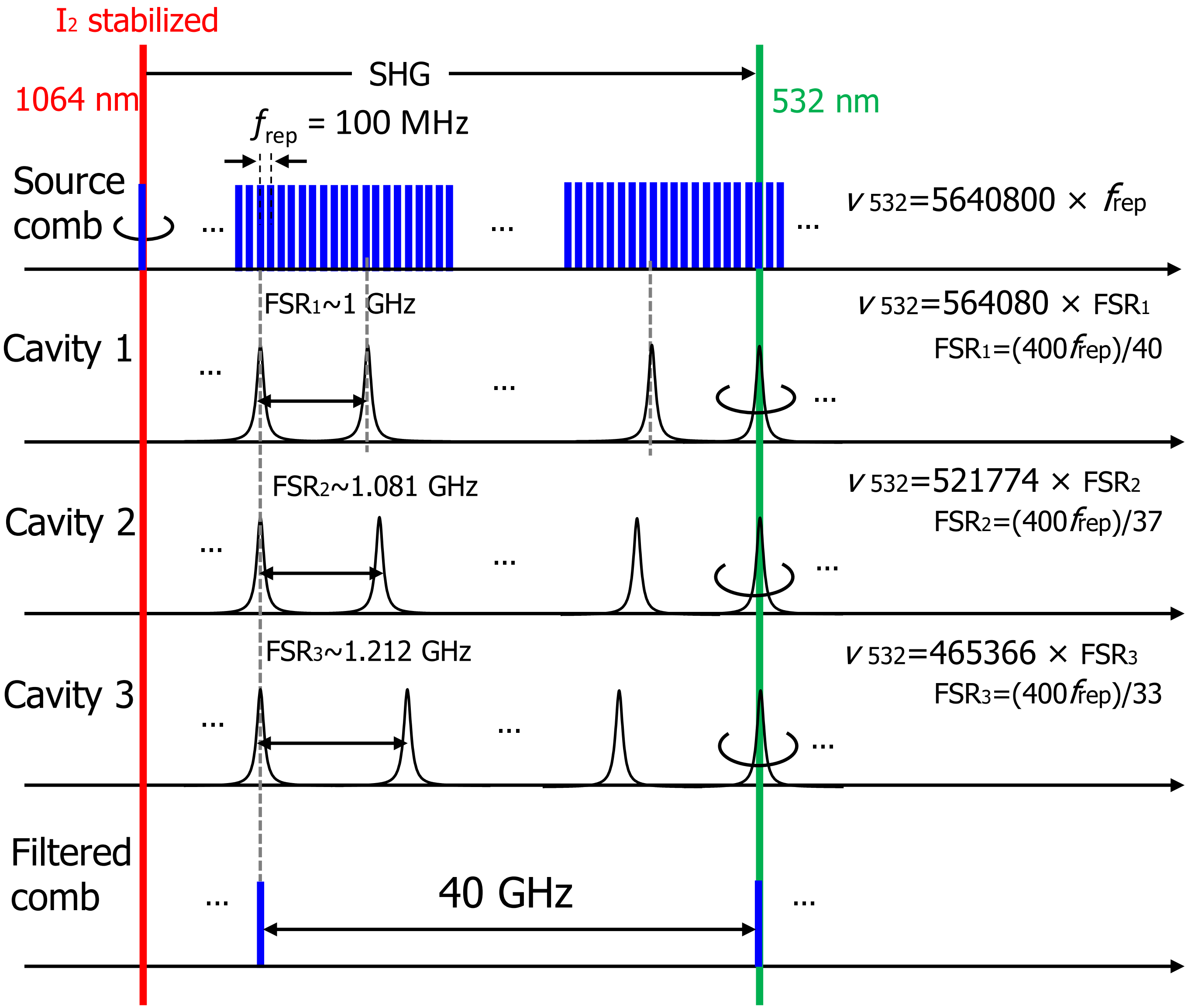
Mode filtering using three optical cavities

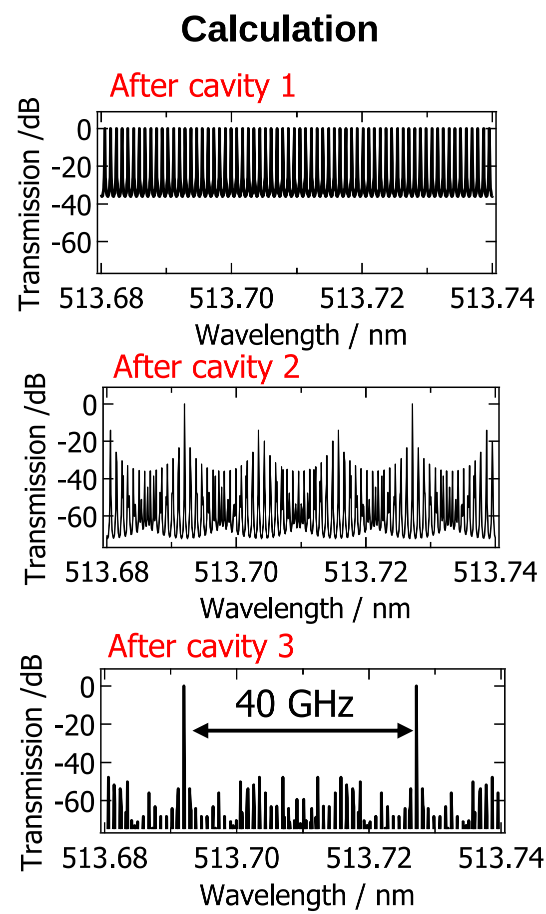


Extract comb modes with an integer times of FSR

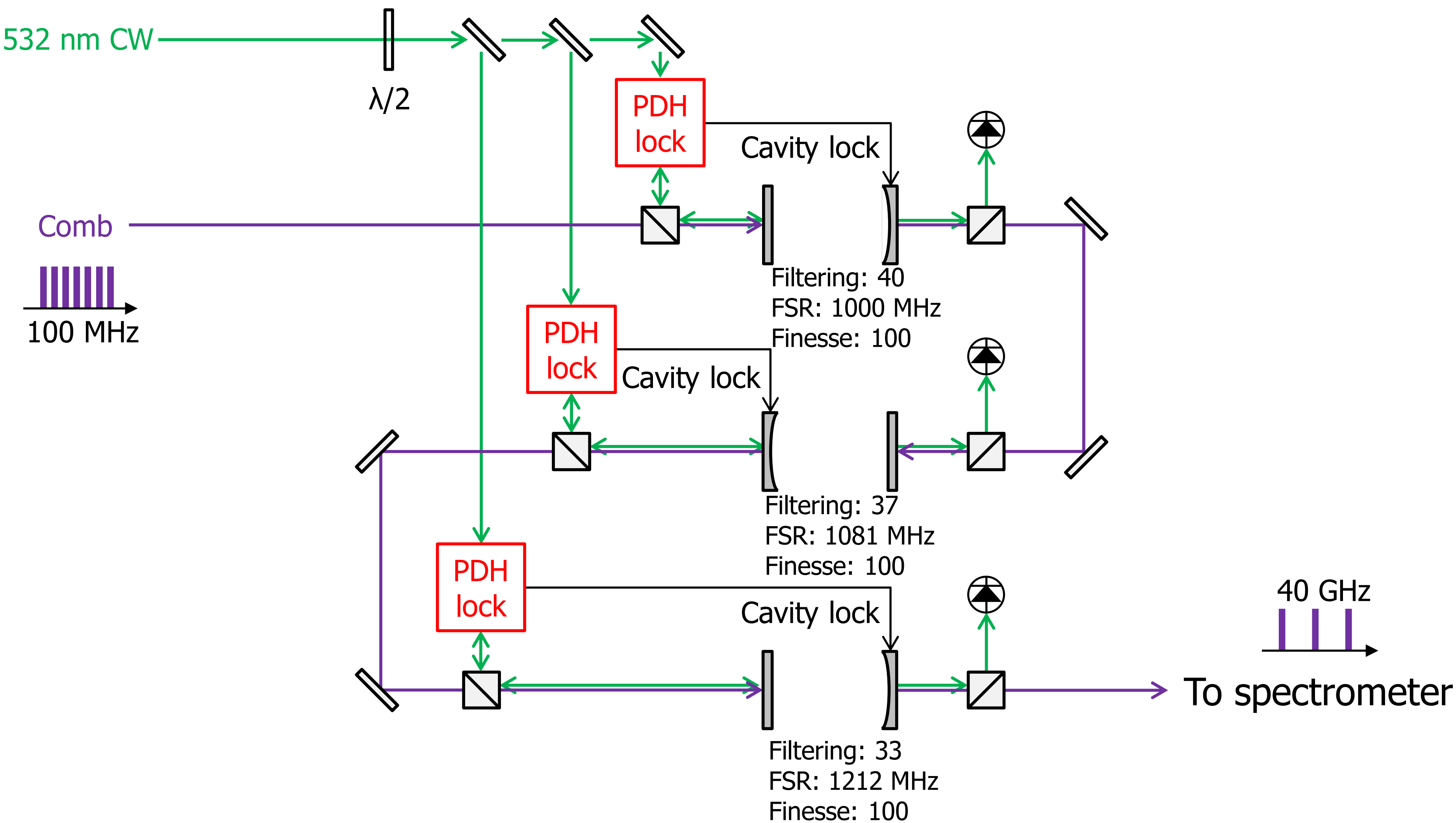
Extract comb modes with another integer times of FSR

Actual setting



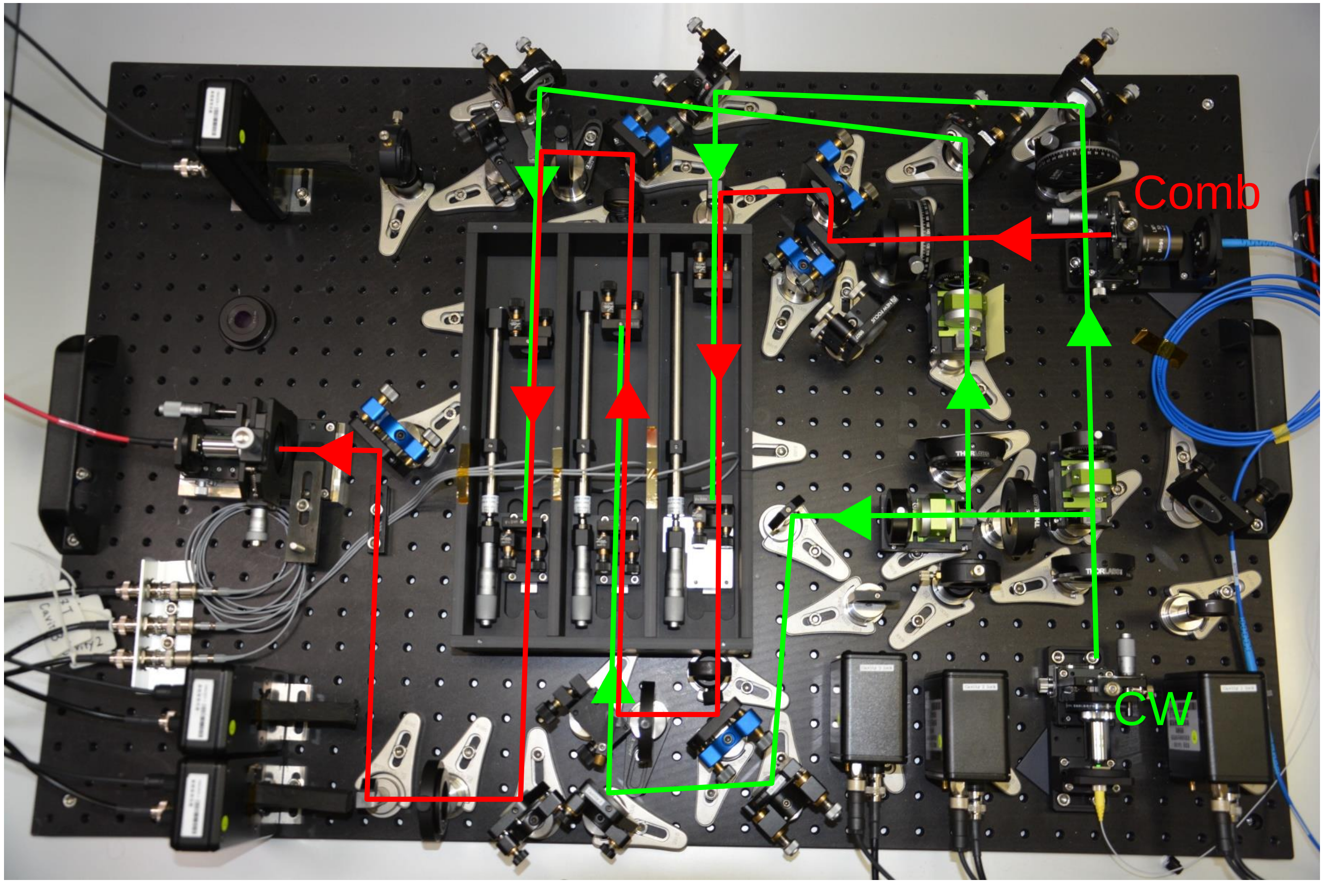


Stabilization of the three cavities



Cavity system overview

To HIDES-F



532 nm CW laser for cavity locking

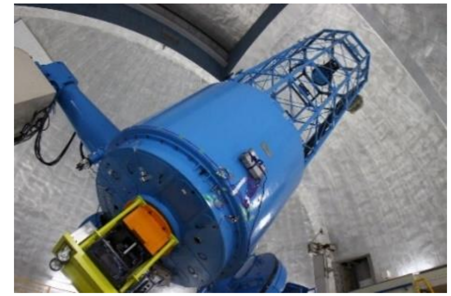
Comb

Current status

Current status

partly supported by ERATO Minoshima IOS project

OAO, NAOJ

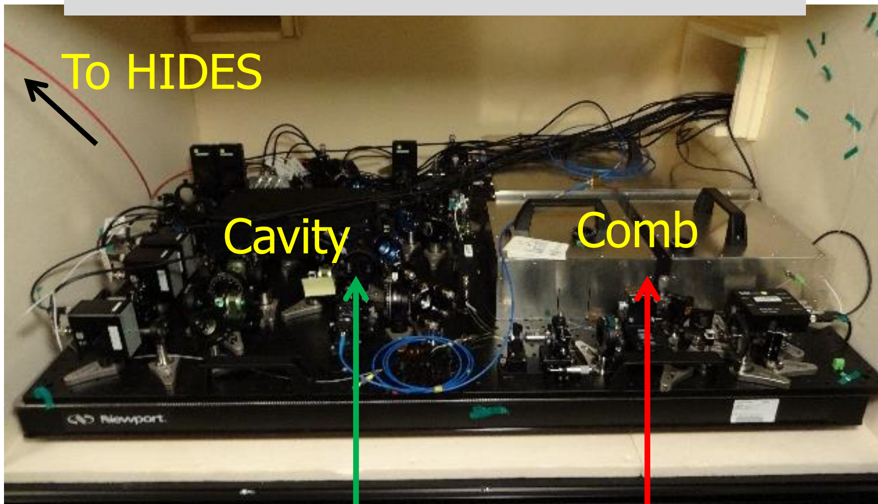


188 cm telescope

2015FY~June 2016	Develop an astro-comb system at AIST (collaborating with OAO, YNU, and UEC)
July 4~8, 2016	The astro-comb was transported from AIST and set at OAO
~Present	Improve and align the comb

Astro-comb system in OAO

Coudé room (temperature controlled for HIDES-F

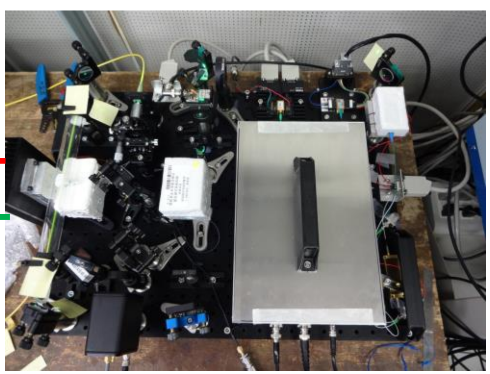


Control room

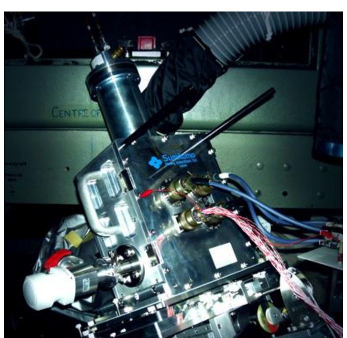
Electronics

Cable length
~10 m

For stabilization



I_2-stabilized
1063 nm CW laser



HIDES-F
is in this room

Summary of current status

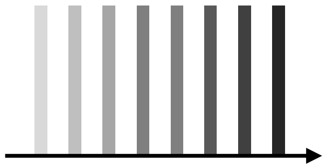
Reference for comb & cavities

☑OK

① I_2-stabilized CW laser

Phase lock

② Source comb



☑OK… should start from higher f_{rep}

f_{ceo} = 0 Hz

f_{rep} = 100 MHz, 1560 nm

1063 nm

SHG

③ Visible comb generation

☑OK… can improve more

f_{rep} = 100 MHz, **380-540 nm**

532 nm

Reference for cavities

④ Mode filtering using triple cavity

☐**Under development**

Need to reduce mirror's dispersion

f'_{rep} = **40 GHz** (f_{rep} x 400), 380-540 nm

To HIDES-F

Future plans

Software development

1. Develop a software to analyze the Doppler shift data using HIDES and the current astro-comb
2. Comparison with Th-Ar lamp and/or iodine absorption

Hardware improvement

1. Reduce Group Delay Dispersion (GDD) of the cavity mirrors

Improvement for stationary operation

1. Automatic or Remote control
2. Easy search of optimal points for mode-filtering cavity
3. More robust system

Development of the 2nd astro-comb

1. Higher f_{rep} of Source comb
2. Improve spatial mode in the short wavelength region of the broad comb

Thank you for your attention!!

This work is partly supported by
JST, ERATO “MINOSHIMA Intelligent Optical Synthesizer”