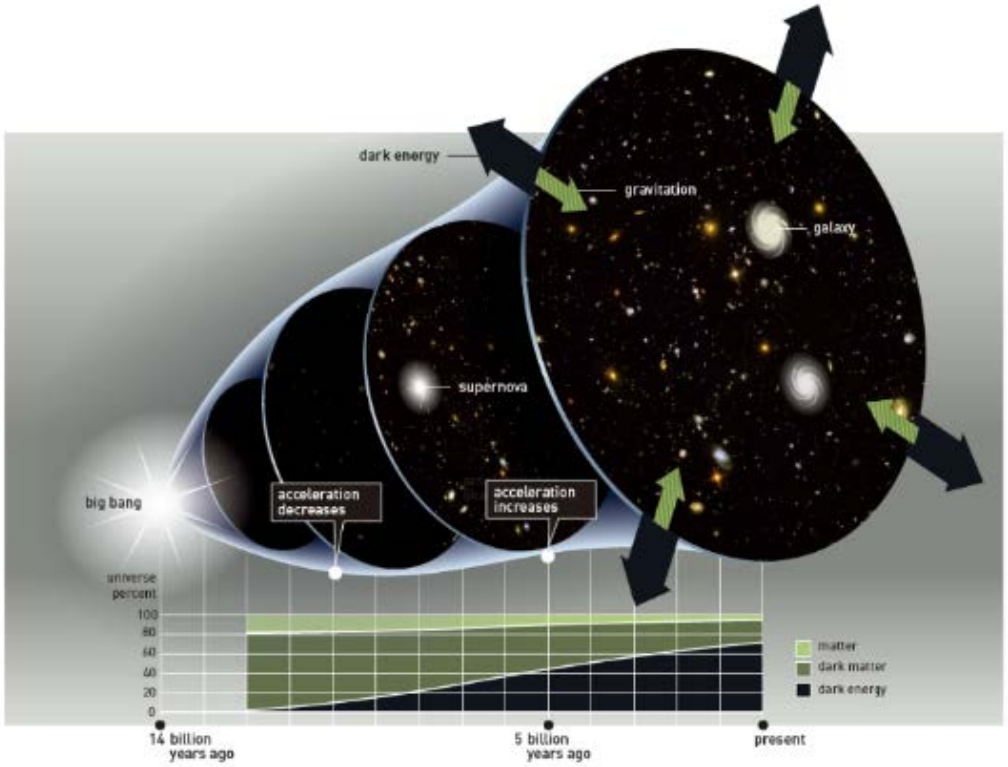
Development of laser comb to calibrate high dispersion spectrograph for radial velocity measurement

Hajime Inaba

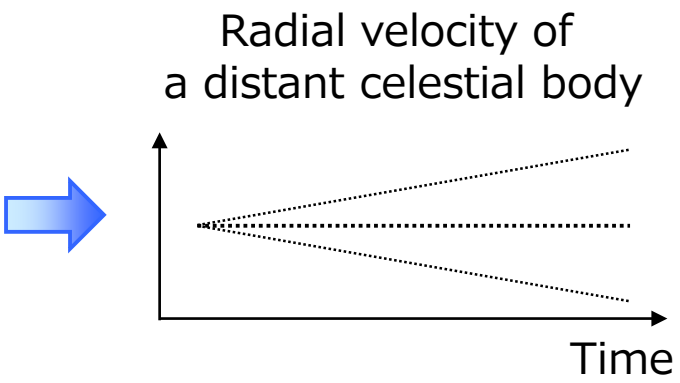
National Institute of Advanced Industrial Science and Technology

19 Feb. 2020, Cosmic Acceleration Symposium

Direct detection of cosmic acceleration of the universe



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



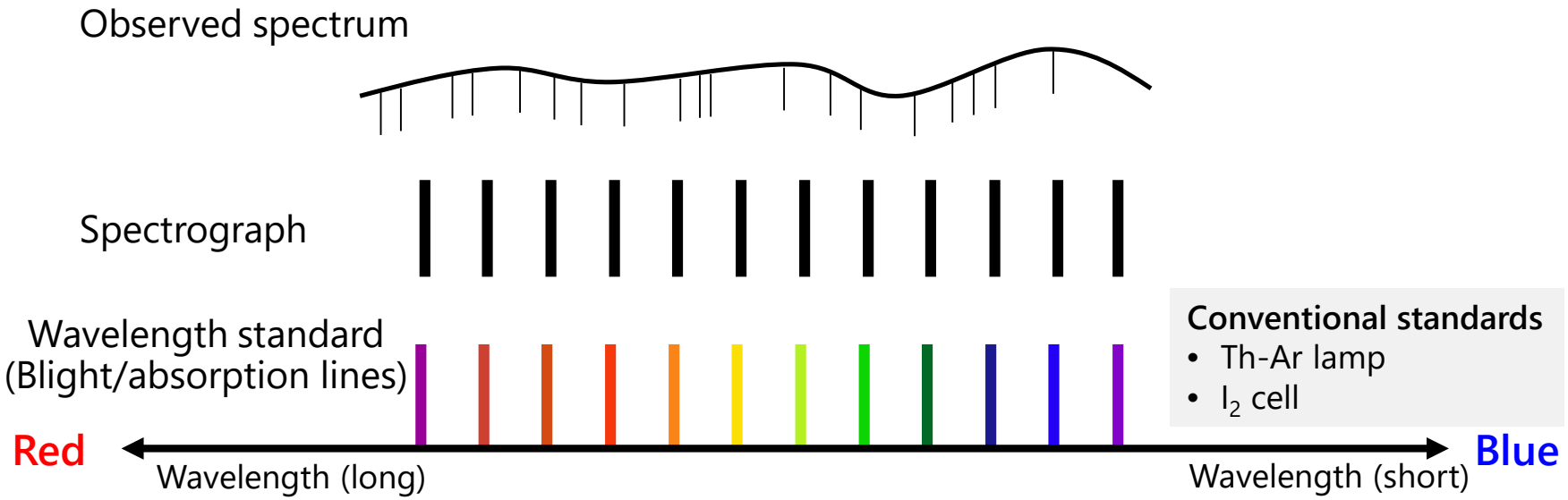
Which result do we obtain?

For the detection of cosmic acceleration,

We need a measurement precision of the radial velocity at the cm/s level.

Wavelength standard for spectrograph is a key for the precise measurement!

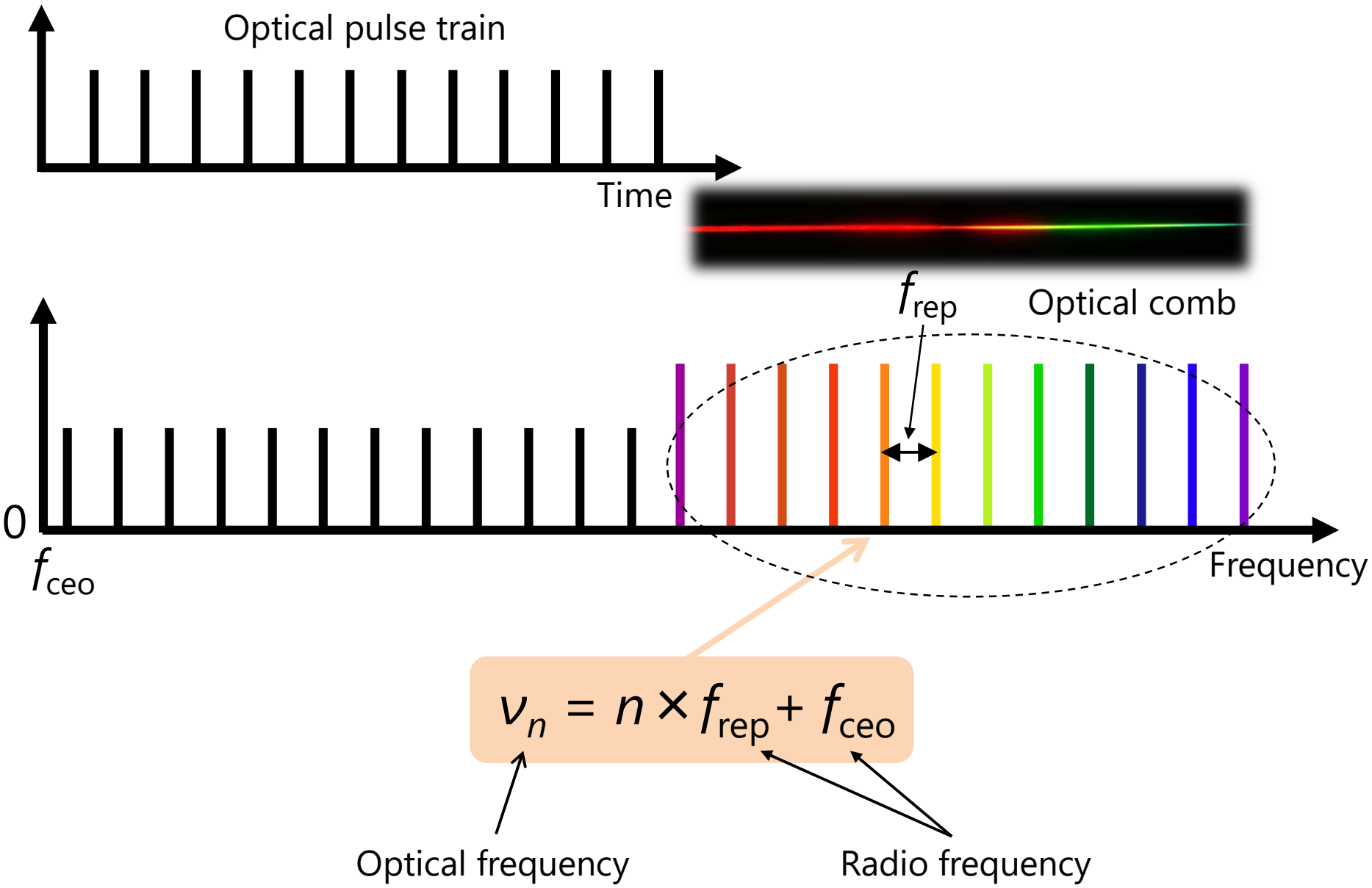
Wavelength standard for astronomical spectrographs



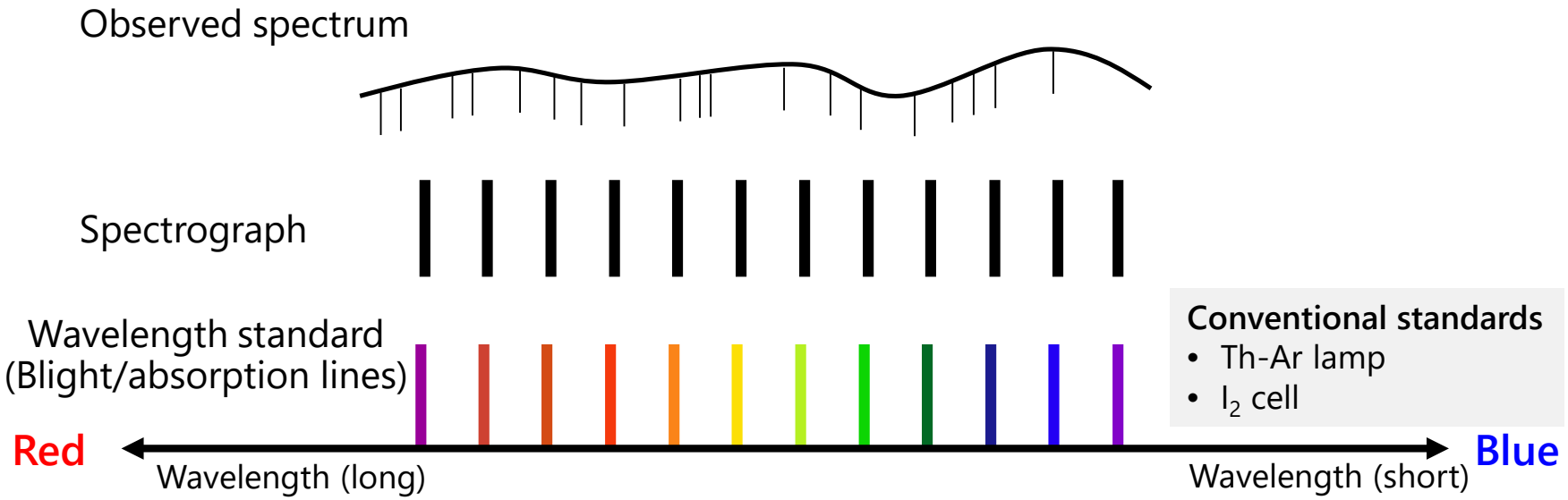
Requirements

1. Wavelength precision
2. Narrow spectral linewidths
3. Appropriate and uniform spectral density
4. High wavelength coverage
5. High and uniform spectral intensity

Optical frequency comb as a wavelength standard



Wavelength standard for astronomical spectrographs



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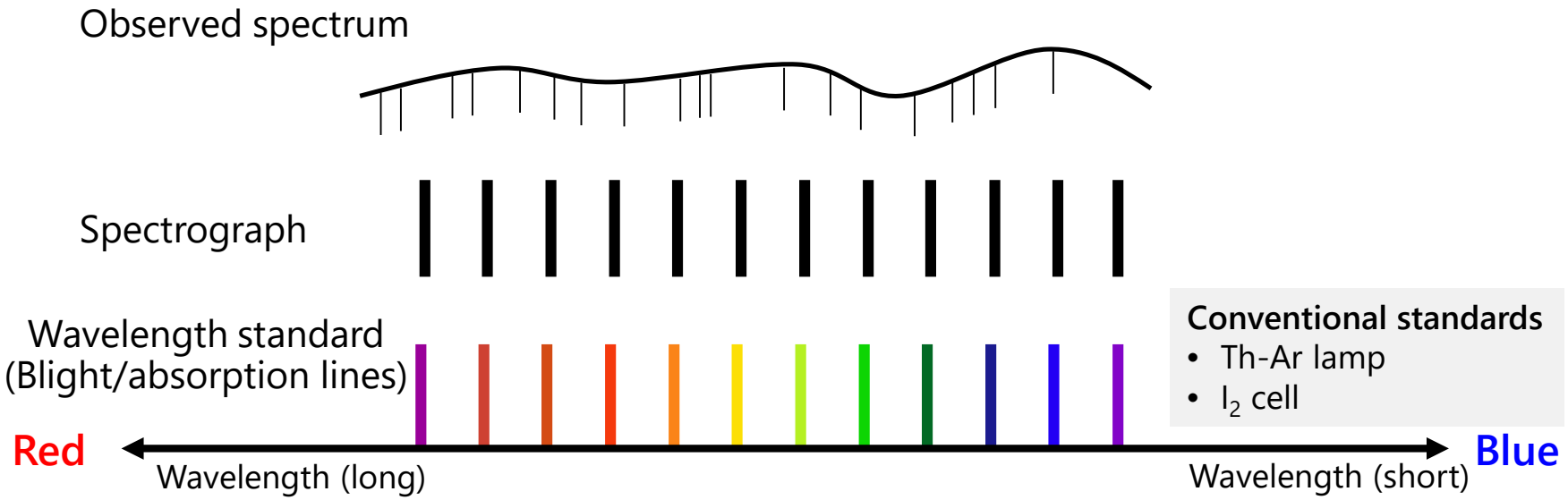

Requirements

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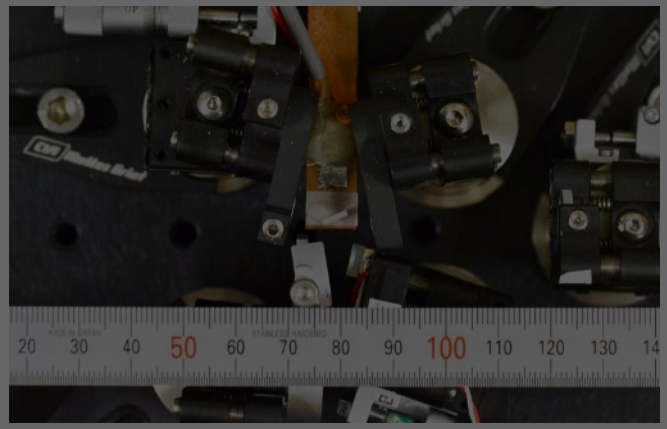
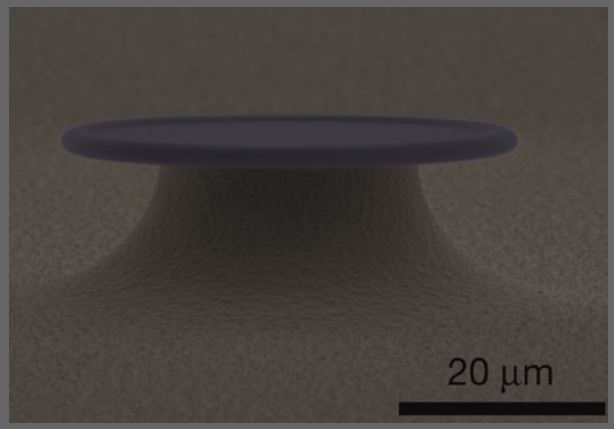
5. High and uniform spectral intensity

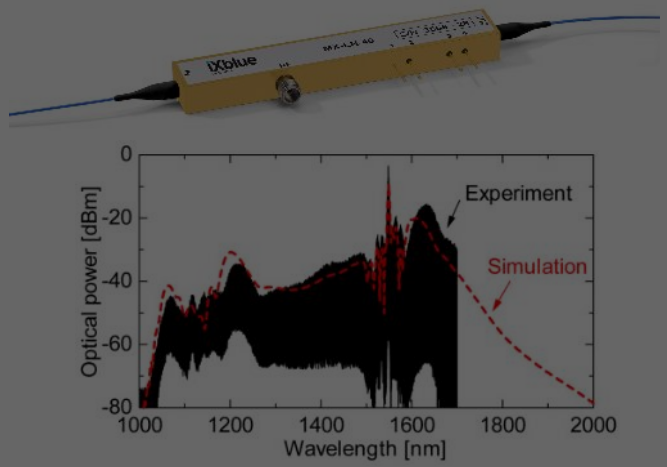
Comb sources for astronomical wavelength references



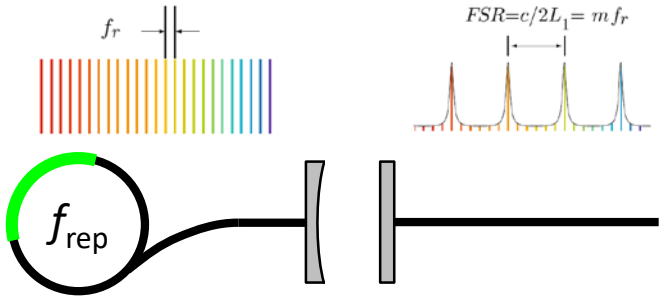
Compact mode-locked laser
Endo, et al. Opt. Express **23**, 1276 (2015)



Micro resonator comb
Del'Haye, et al. Nature **450**, 1214 (2007)

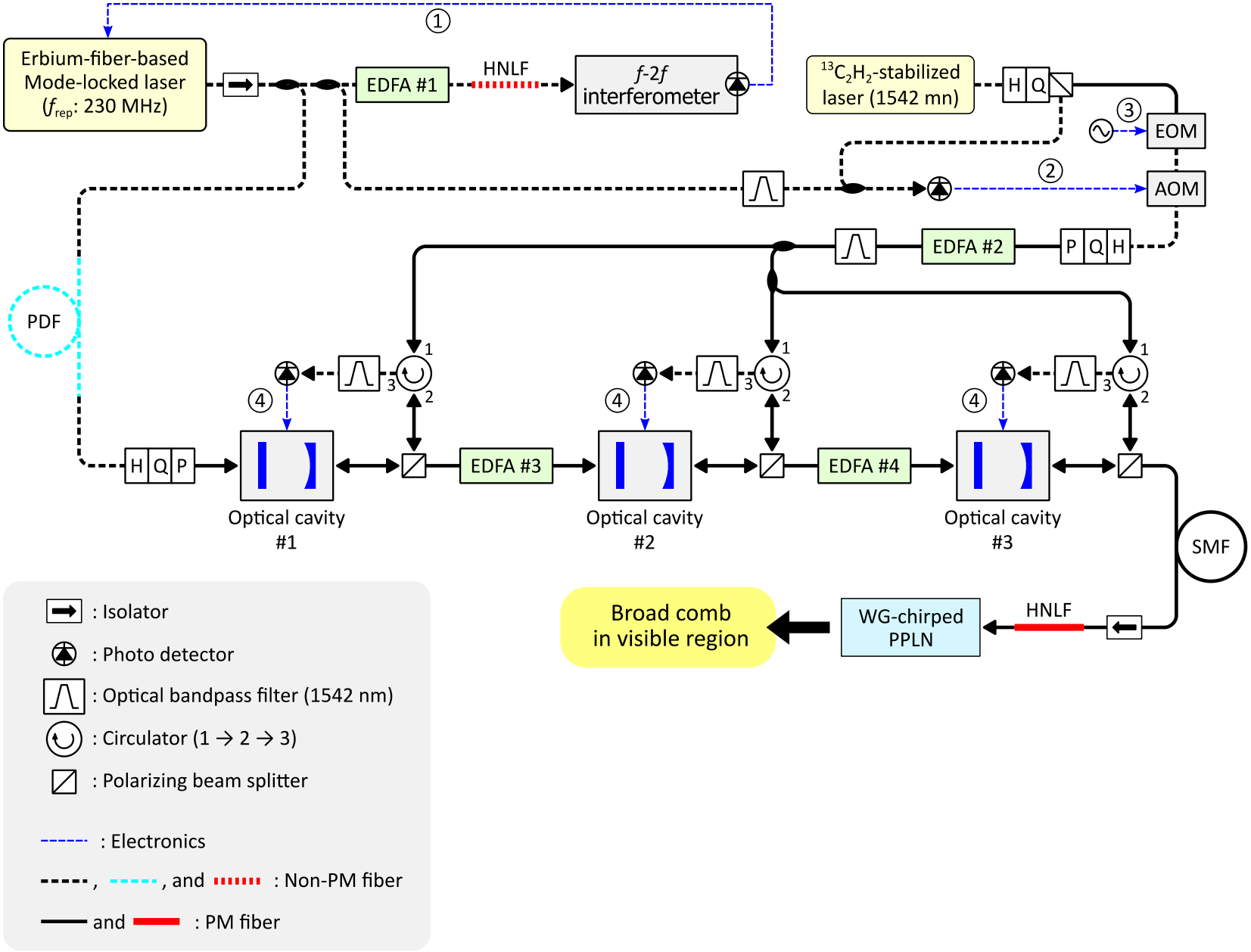


Modulator-based comb
Kashiwagi, et. al. Opt. Express **24**, 8120 (2016)

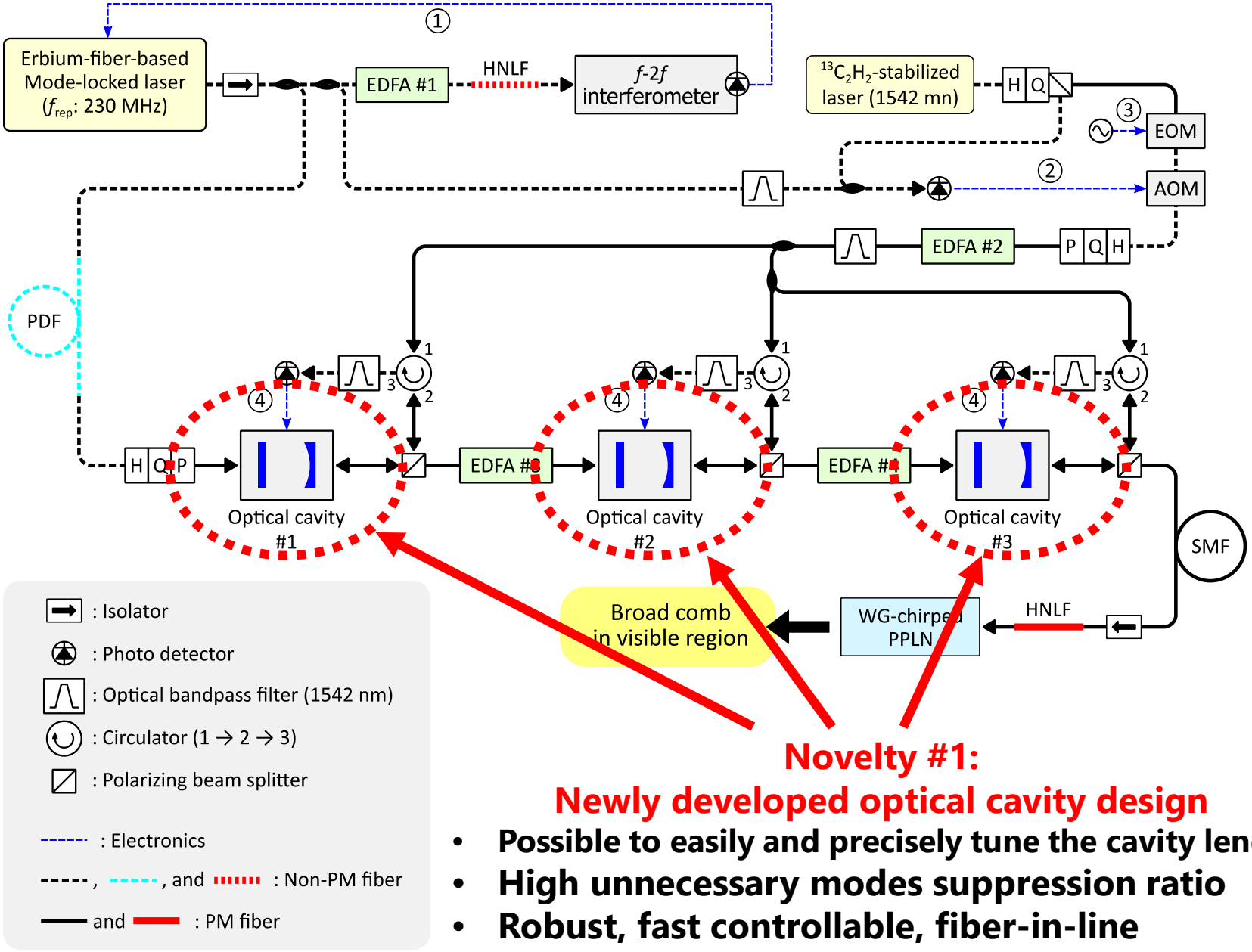


Mode-locked laser + Optical cavity
Steinmetz, et al. Appl. Phys. B **96**, 251 (2009)

Setup of our developed laser comb (2nd gen.)



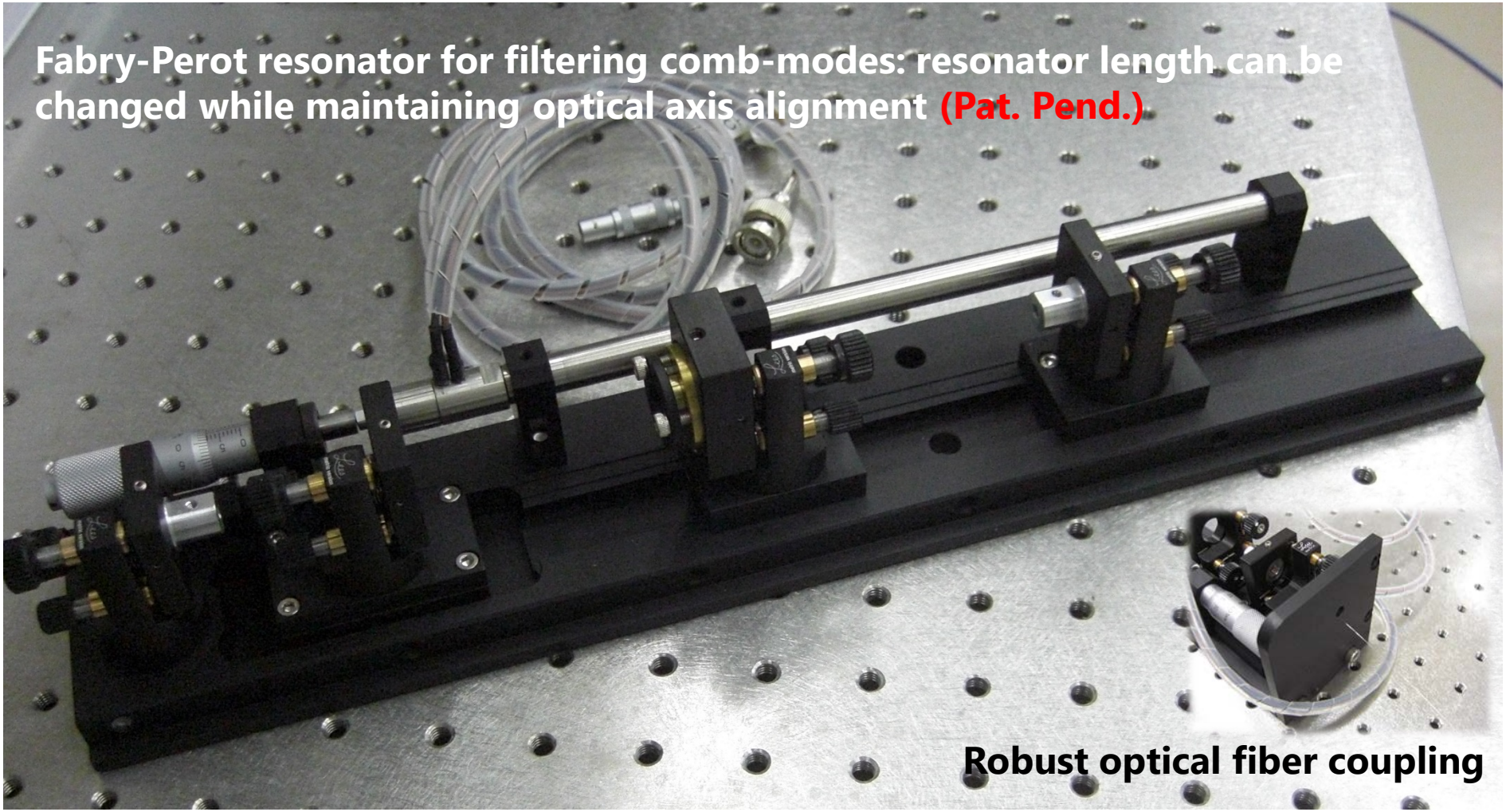
Novelty #1:Newly developed optical cavity design



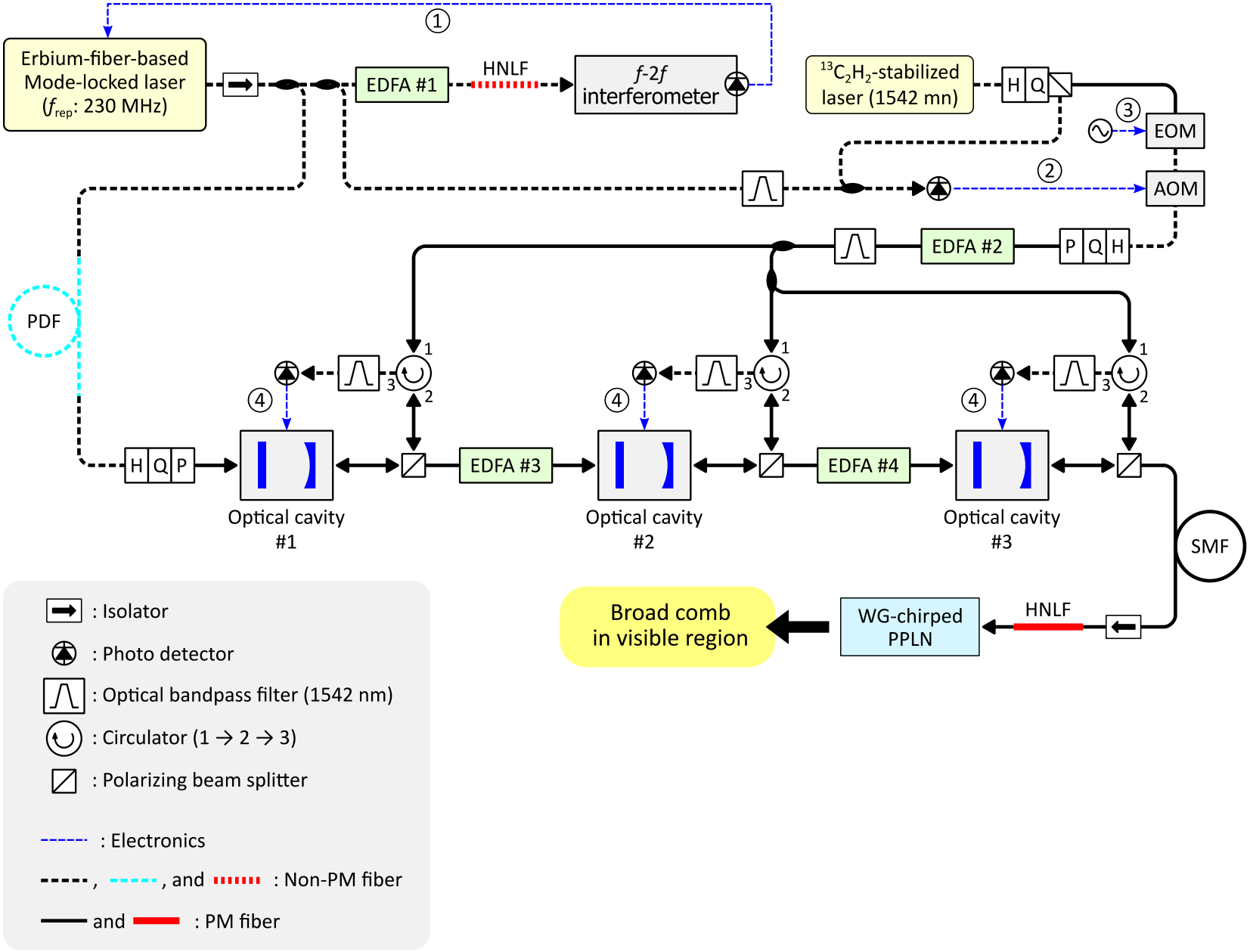
Novelty #1:
Newly developed optical cavity design

- **Possible to easily and precisely tune the cavity length**
- **High unnecessary modes suppression ratio**
- **Robust, fast controllable, fiber-in-line**

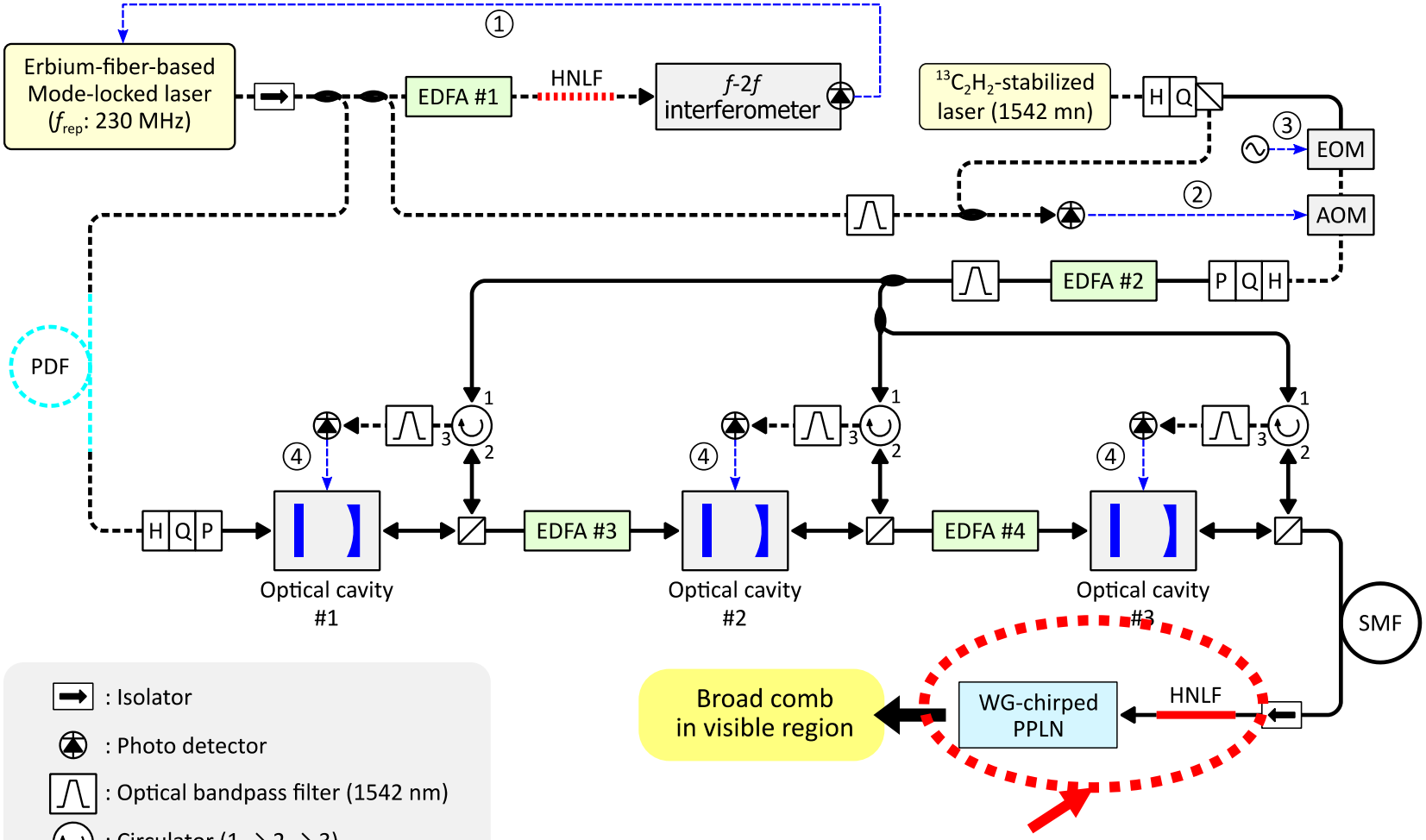
Novelty #1:Newly developed optical cavity design



Setup of our developed laser comb



Novelty #2: A novel wavelength conversion scheme



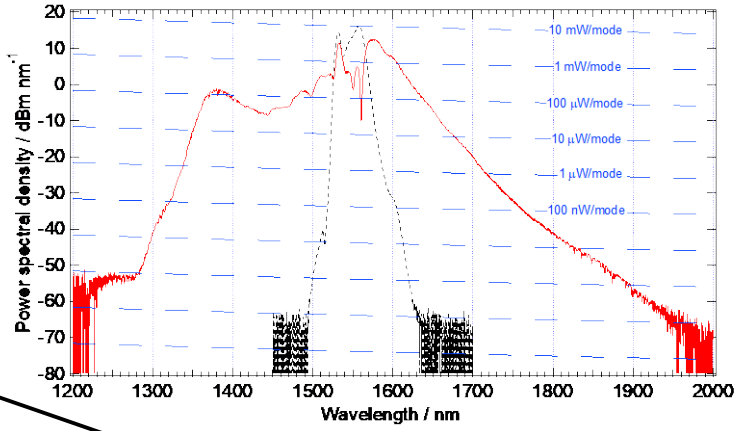
Novelty #2:

A wavelength conversion scheme for realizing a broad spectrum in the optical region

Highly nonlinear fiber + chirped PPLN waveguide

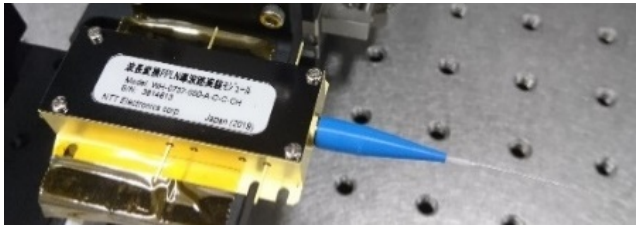
Novelty #2: Novel wavelength conversion scheme

Highly NonLinear Fiber (HNLF) for broaden the comb spectrum in the infrared region



Laser comb in the infrared region

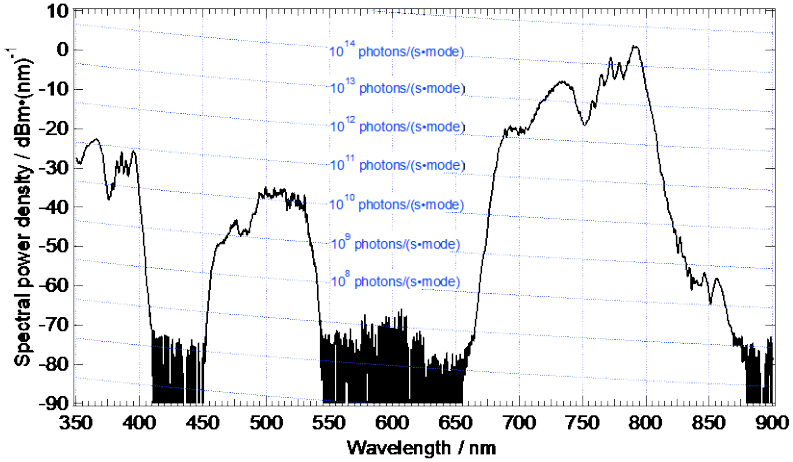
PPLN waveguide for wavelength conversion to the optical region while maintaining broad spectrum



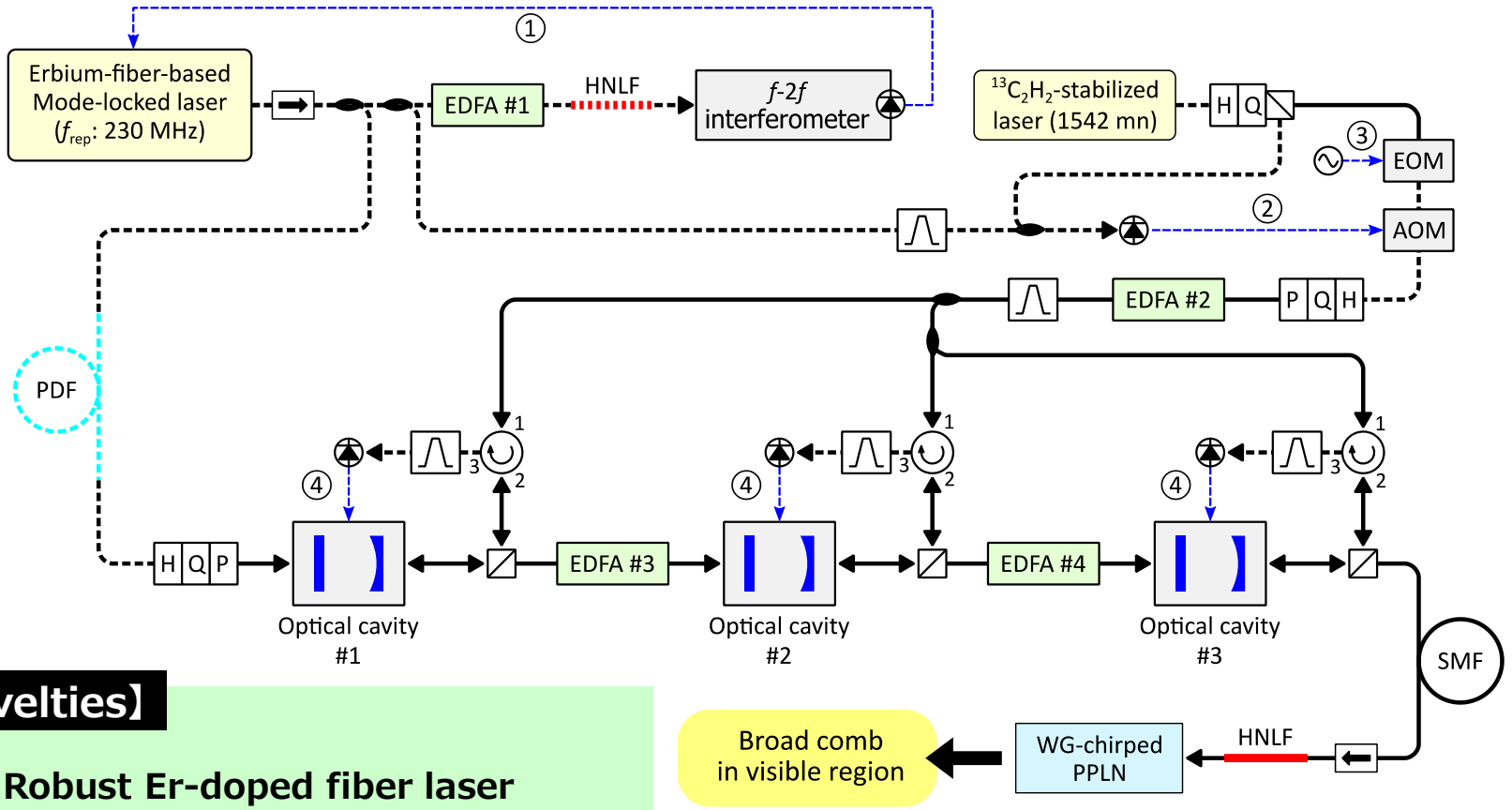
Generate **2nd**, **3rd**, and **4th** harmonics

(Pat. Pend.)

Broad spectrum in the optical wavelength region



Other novelties



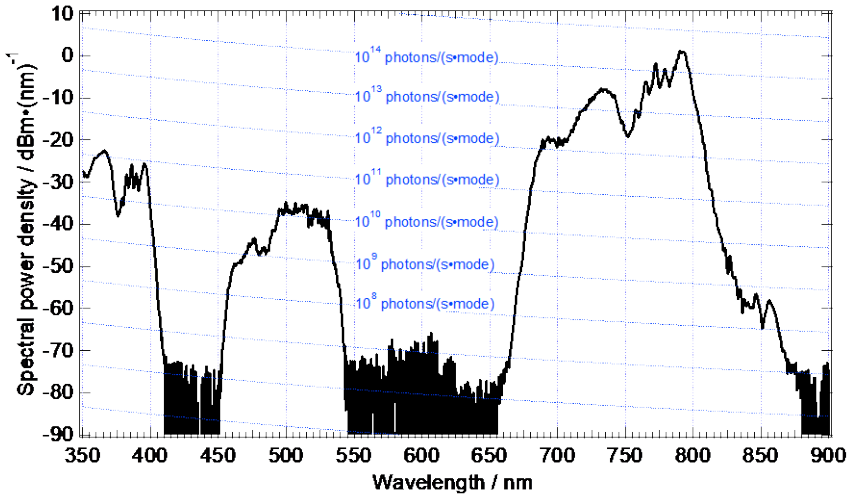
【Novelties】

- ✓ **Robust Er-doped fiber laser**
- ✓ **Optical cavities for comb-mode filtering（特願2019-147825）**
- ✓ **Mirrors with a low reflectivity for stable mode-filtering**
- ✓ **Optical cavity stabilization using a CW laser**
- ✓ **Putting the final-stage cavity after the boost amplifier for high contrast**

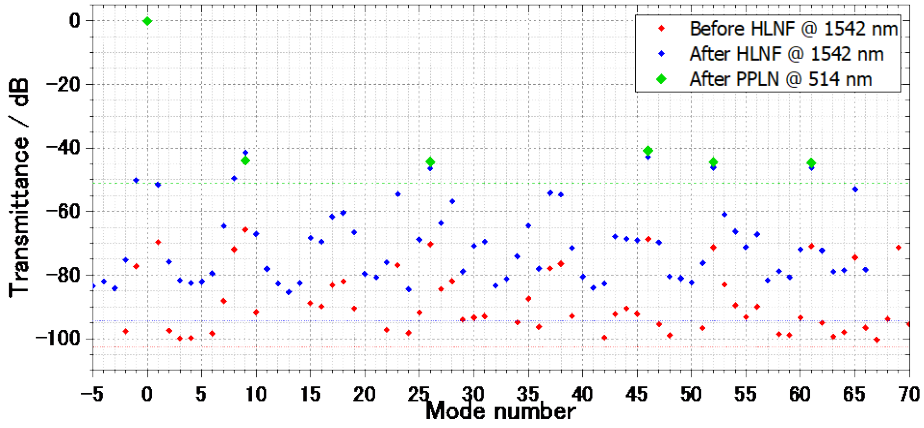
- ✓ **Broadband comb generation in the optical wavelength（特願2019-034525）**
- ✓ **Self-referencing comb referencing microwave frequency reference**
- ✓ **Realized 200 fs optical pulse by chirped pulse amplification etc…**

Strong points

1. **Broad spectrum with 30 GHz frequency interval (Wavelength coverage > 50 % in the optical region)**



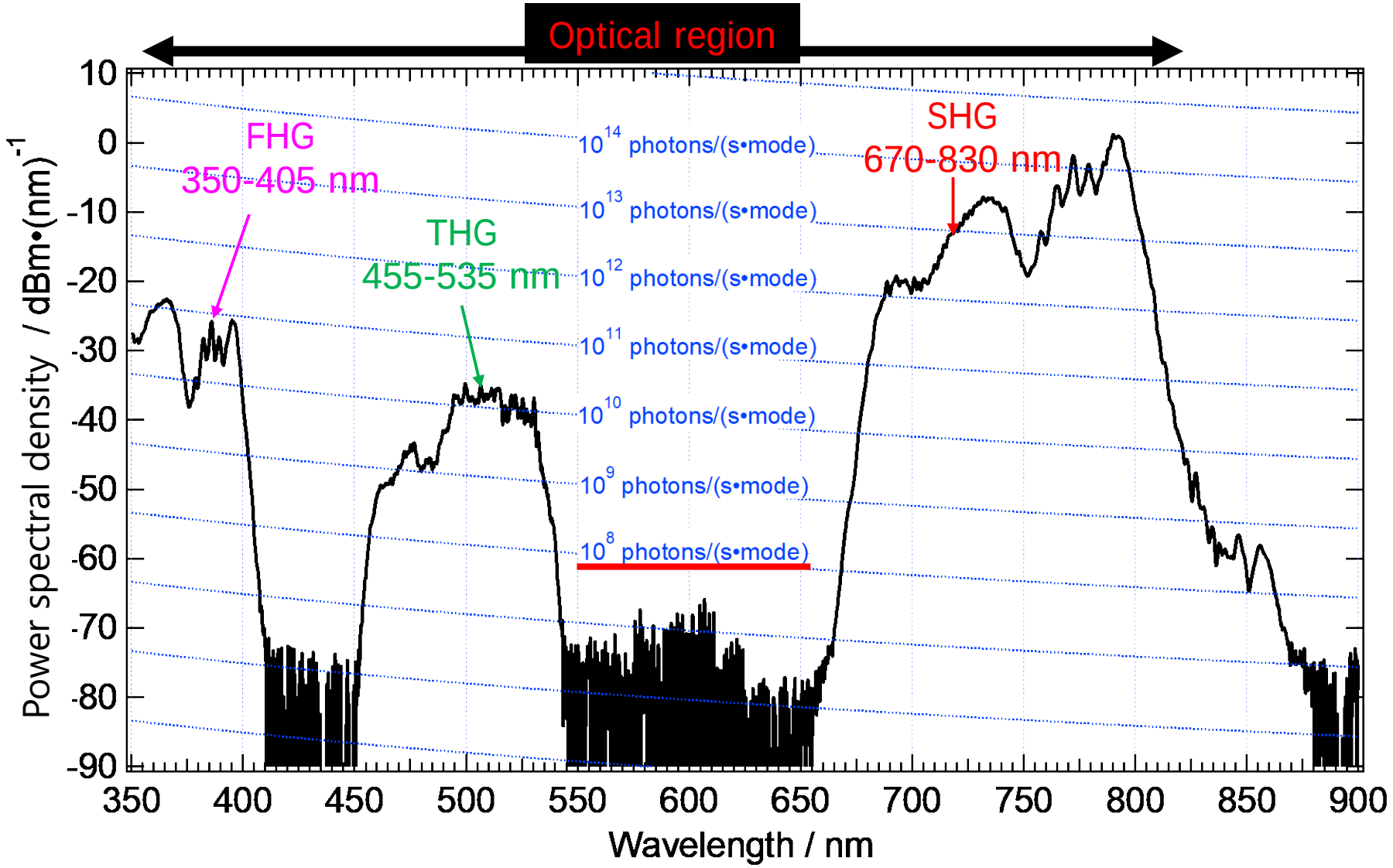
2. **High contrast > 40 dB in the optical region**



3. **Practicality**

Robust, reliable, use neither super-high-power amplifier nor short lifetime item

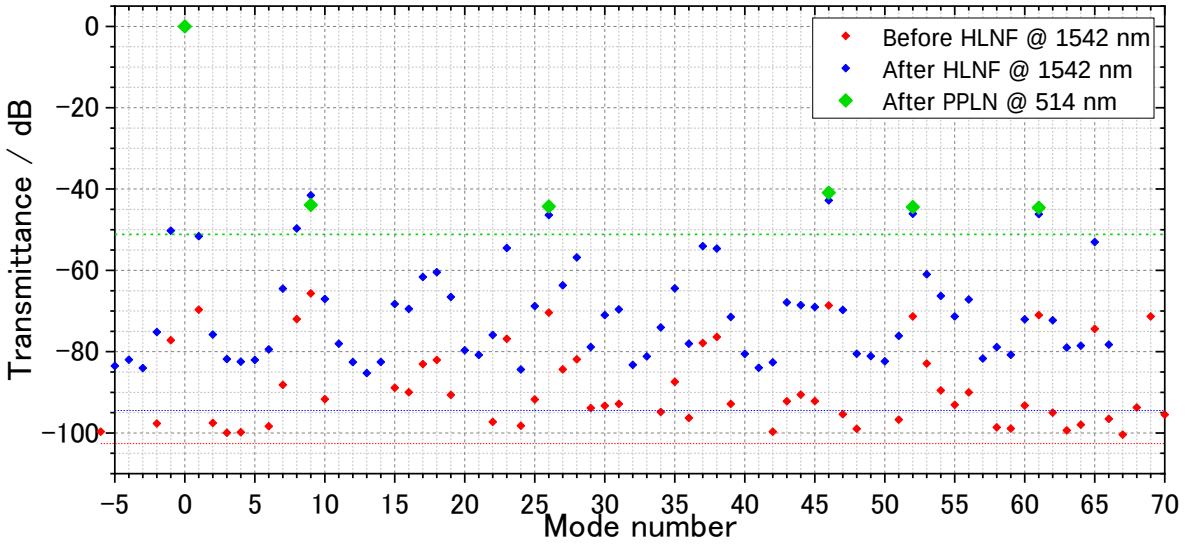
Strong point #1: Broad spectrum with 30 GHz frequency interval



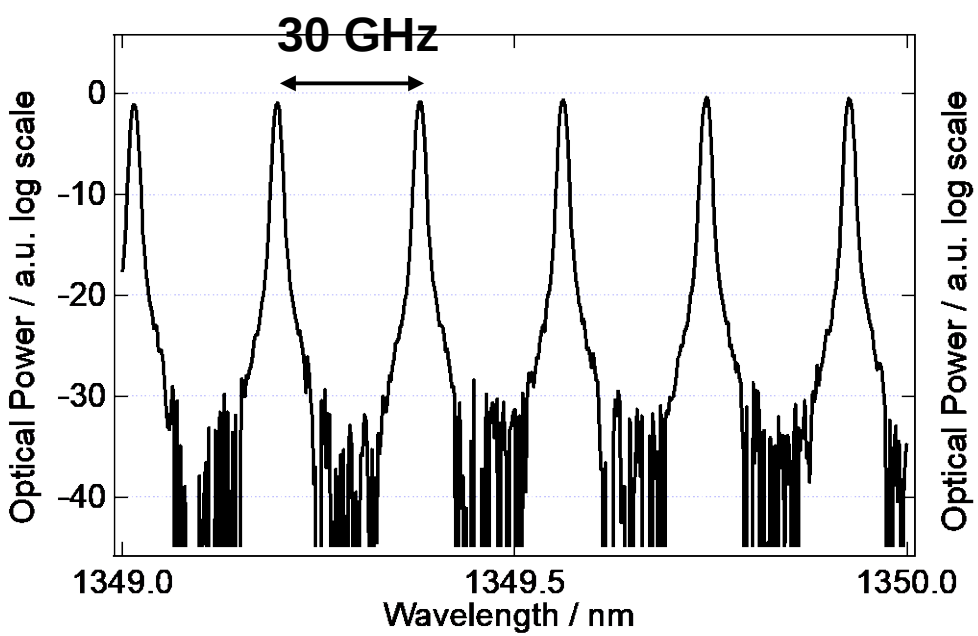
Wavelength coverage : 57 % in the optical region (360 ~ 830 nm)

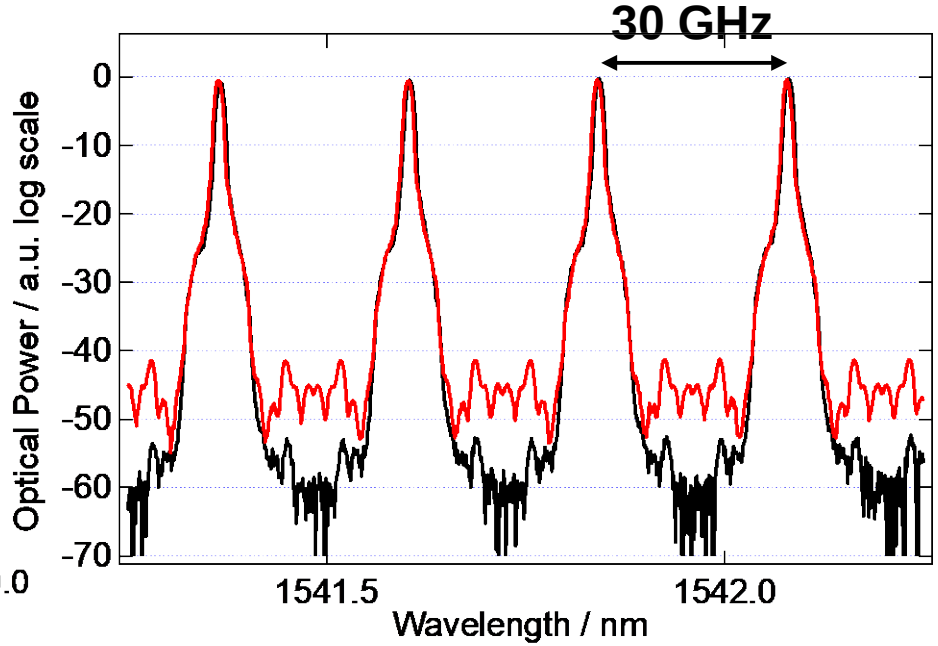
・・・ World's best

Strong point #2: High contrast



RBW:0.01 nm





Background noise = Unnecessary modes + Amplified Spontaneous Emission

Strong point #3: Practicality

1. **Durability**

   Do NOT use short-life device (Tapered fiber, super-high-power amplifier, special mode-locker such as SESAM)

2. **Robustness**

   Use an erbium-doped fiber-based mode-locked fiber laser as the comb source, Almost-all-polarization-maintain fiber optics

3. **User-friendliness**

   Easy to alignment (for specialist), auto-relock system, remote controllable,

Laser combs for astronomical observation in the world

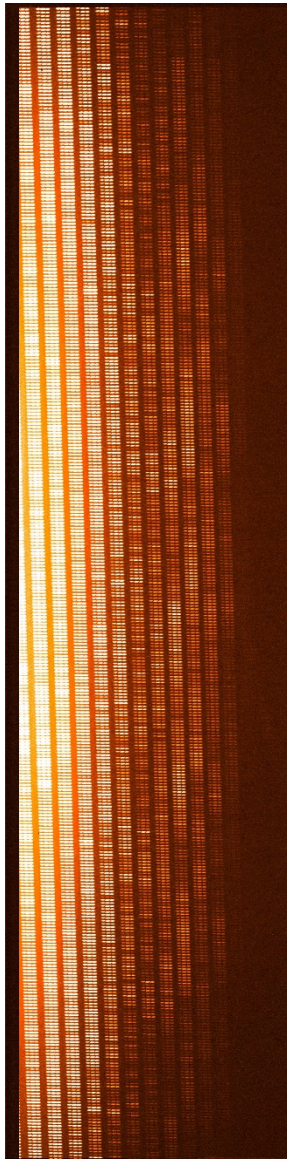
Increasing the comb mode interval → Spectral broadening / wavelength conversion of the comb

Blue：Optical
Red ：Infrared

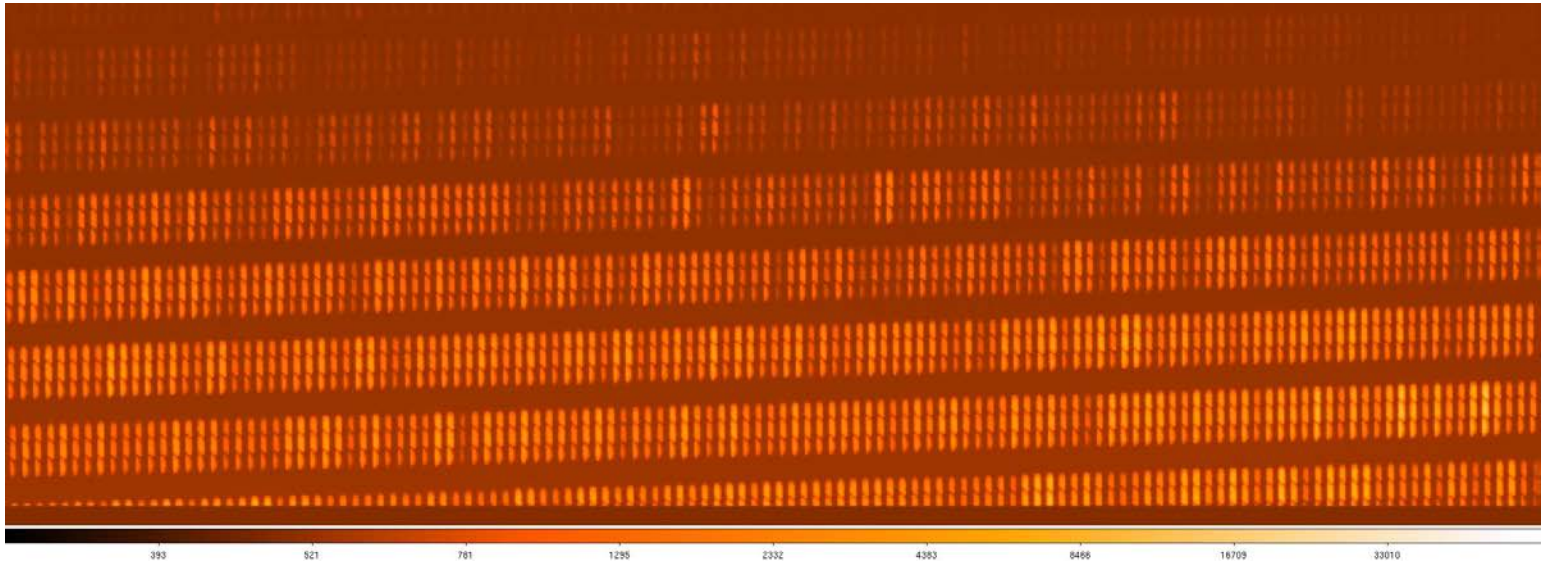
Group	Spectrometer	Comb source	Scheme	Spacing	Coverage
Menlo Systems	HARPS (R = 115,000)	Yb fiber (~1030 nm)	Mode filtering → SHG/PCF	18 GHz	450-600 nm (35 %)
Harvard	HARPS-N (R = 115,000)	Ti:Sapphire (~945 nm)	PCF → Mode filtering	16 GHz	500-620 nm (25 %)
	TRES		BBO → Mode filtering	50 GHz	400-420 nm 780-880 nm (13 %)
AIST #2	**HIDES-F (R = 50,000)**	**Er fiber (~1560 nm)**	**Mode filtering → HNLF, WG-PPLN**	**30 GHz**	**350-405 nm 455-535 nm (57%) 670-830 nm**
NIST	Pathfinder (R = 50000)	Er fiber (~1560 nm)	Mode filtering → HNLF	25 GHz	1450-1700 nm
	GIANO-B (R = 50,000)	Microresonator-based comb with a wide mode-spacing		23.7 GHz	1480-1550 nm 1570-1650 nm
	HPF (R = 50,000)	EOM-based comb with a wide mode-spacing	λ conversion, Broadening	30 GHz	680-1650 nm (17 %)
TAT	IRD (R = 70,000)		λ conversion, Broadening	12.5 GHz	1040-1750 nm

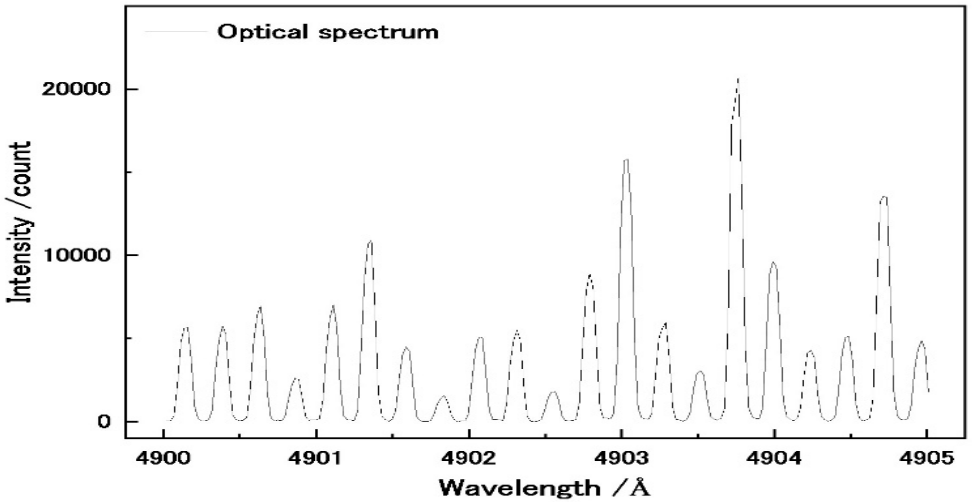
The second-generation laser comb @Okayama

A laser comb spectrum observed with HIDES-F

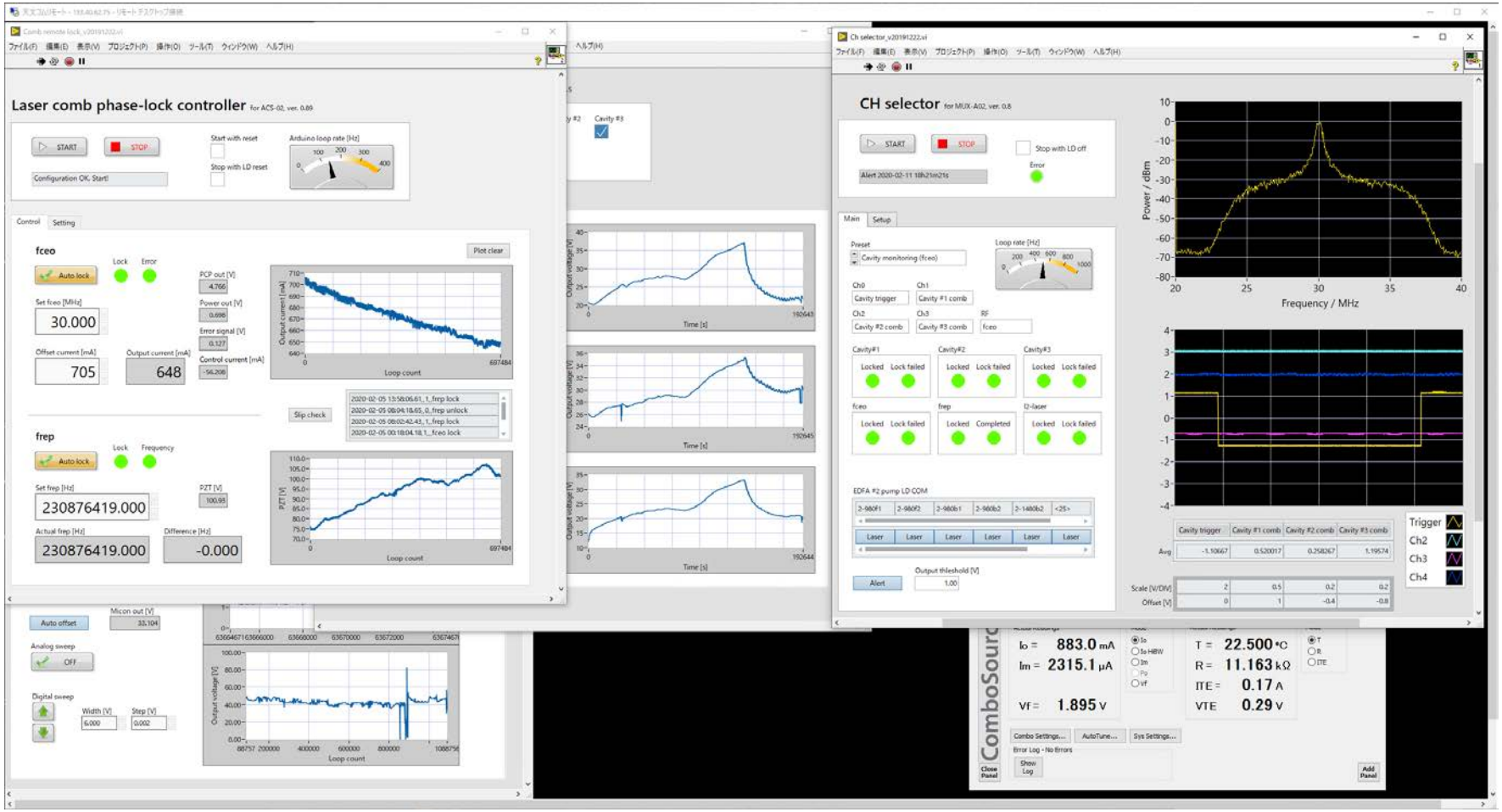


Appropriate wavelength interval: 30 GHz
High contrast: 40 dB
High wavelength coverage: 57 % of the optical region





Remote operation is available

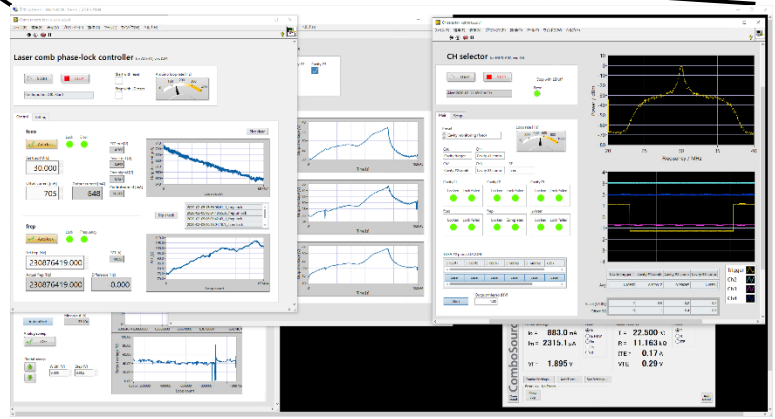


The laser comb is almost continuously operating for about 2-month so far.

Current operation status

OBO@Asakuchi

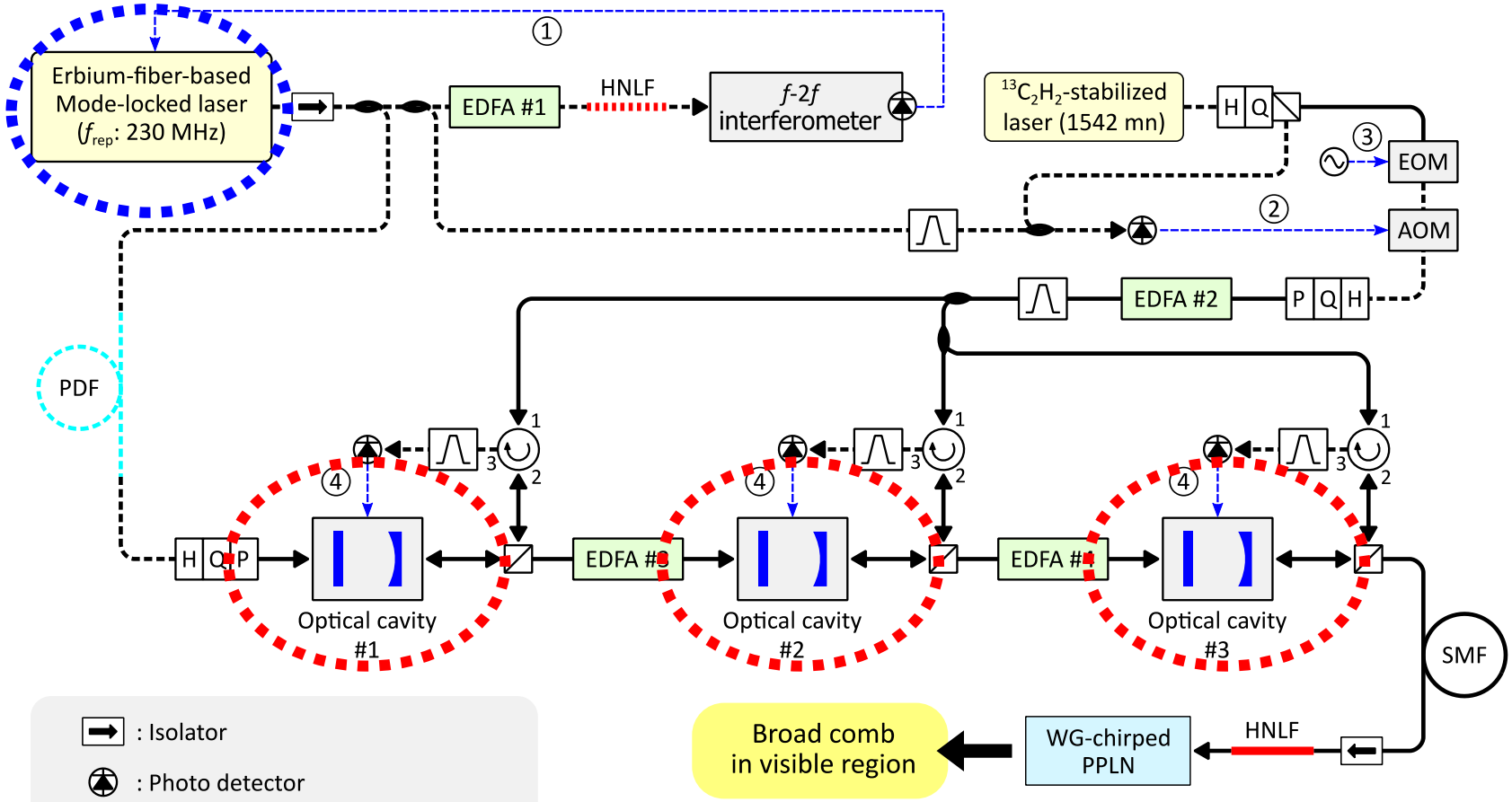
AIST@Tsukuba



The laser comb is available as a wavelength reference of HIDES-F!

Outcomes from Minoshima-group@UEC

Setup of AIST laser comb



Outcomes from Minoshima-group are for…

Higher rep-rate laser for wider mode spacing

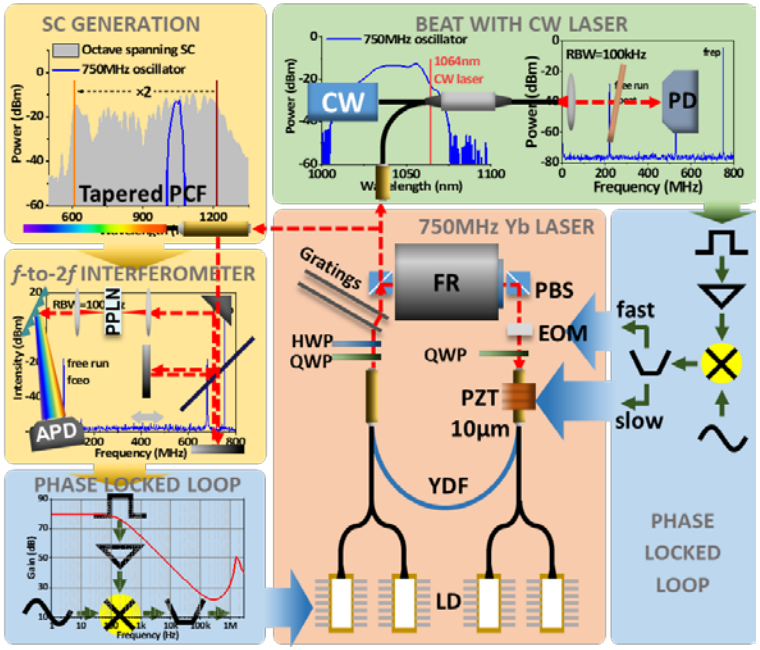
More robust optical cavity

B. Xu, et al., Opt. Express **25** (2017): Y. Ma, et al., Opt. Lett. **43** (2018)

Low noise 750-MHz Yb:fiber frequency comb

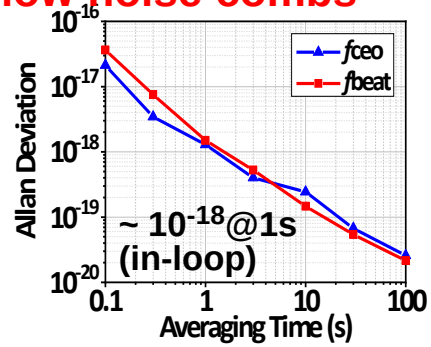
➢ Why 750-MHz Yb: fiber frequency comb ?

- *Large mode spacing*
- *Higher output power scalability*
- *High power for every comb mode*
- *Visible region SC generation*



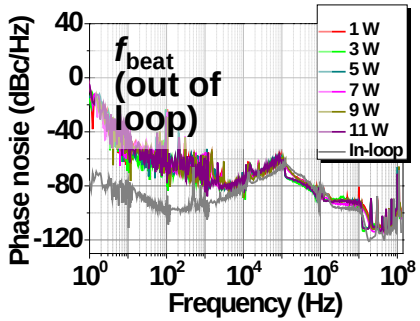
Oscillator, mode-locked Yb:fiber laser

- **Repetition rate: 750 MHz**
  - ✓ **Highest in fiber based low noise combs**
- **Mode Locking: NPR**
- **Output power: >600 mW**
- **Pulse duration: ~70 fs**
- **Direct detection of f_{ceo} (SNR >40dB)**



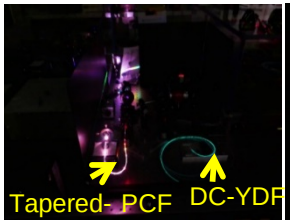
Low noise amplifier

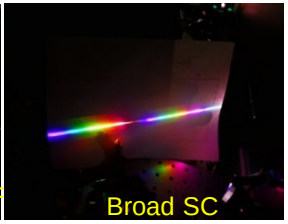
- **Output power: 10 W**
- **Pulse duration: ~90fs**

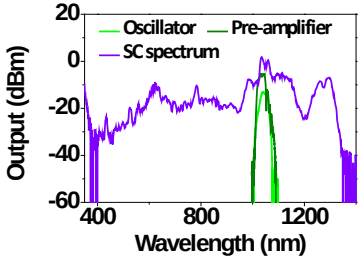


- **Broad SC generation**

Launched power into the tapered-PCF : ~ 2 W





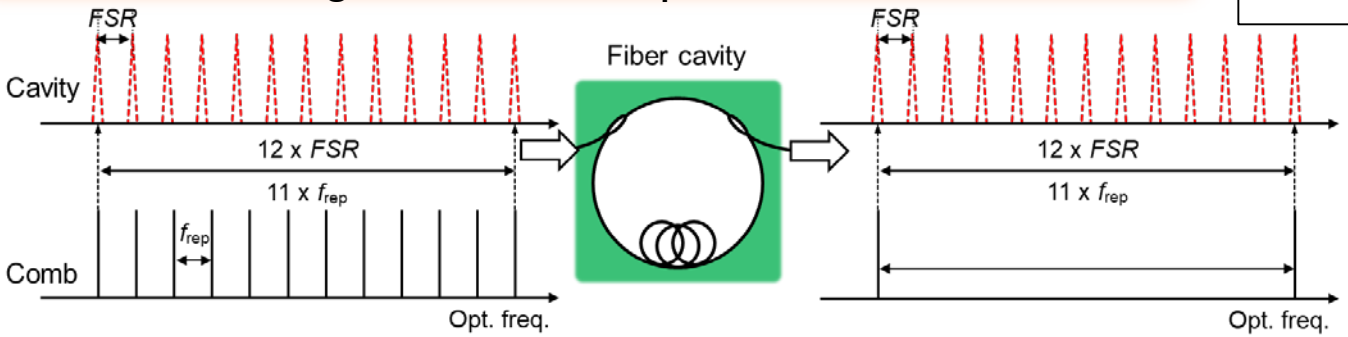


Y. Nakajima, A. Nishiyama, K. Minoshima, Opt. Express **26** (2018)

All-fiber-based mode-filtering technique

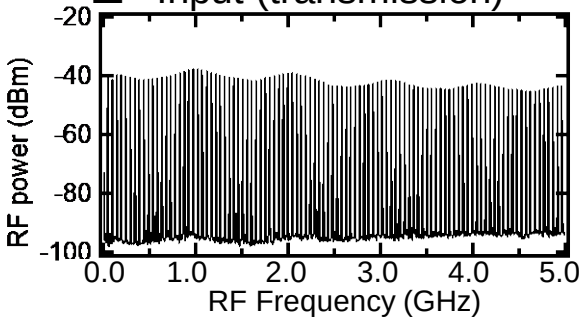
- No physical limitation for shortening the cavity length
- All-fiber configuration can improve robustness

$$nL = \frac{21-10}{21}\frac{c}{f_{\mathrm{rep}}} = \frac{11}{21}\frac{c}{f_{\mathrm{rep}}}$$

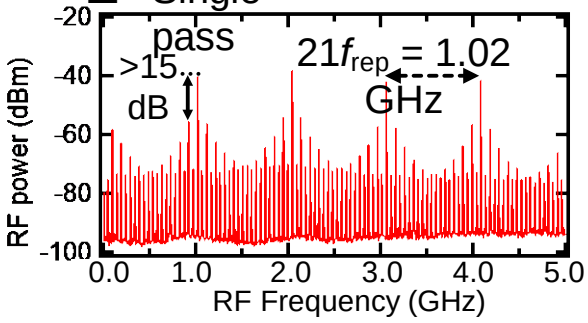


(21 - 10) x
FSR = 21 x f_{rep}
= 1.02 GHz

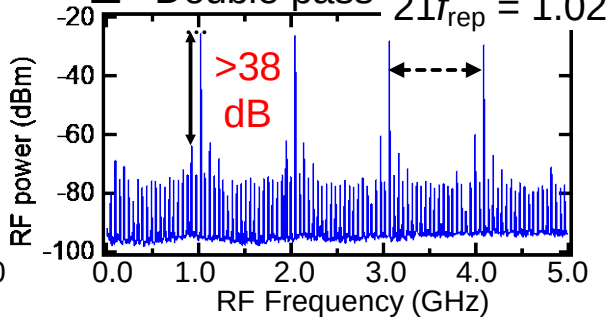
Input (transmission)



Single pass



Double pass



Mode-locked Er:fiber laser

Central wavelength	1560 nm
Repetition rate (f_{rep})	48.7 MHz
Tuning range of f_{rep} (Δf_{rep})	0.5 MHz
Pulse separation (c/f_{rep})	6.2 m

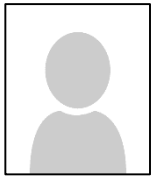
Fiber ring cavity

Multiplication factor (*M*)	21
Integer (*m*)	-10
Cavity length (optical)	3.2 m
FSR	92.9 MHz

Conclusion

1. We have developed the world's best comb.
2. The comb is now available in Okayama.
3. The comb is still evolving.

Thanks



Usuda
Aoki

Schramm

Kashiwagi

Minoshima

Hong

Tsutsui

Thank you for your attention !!

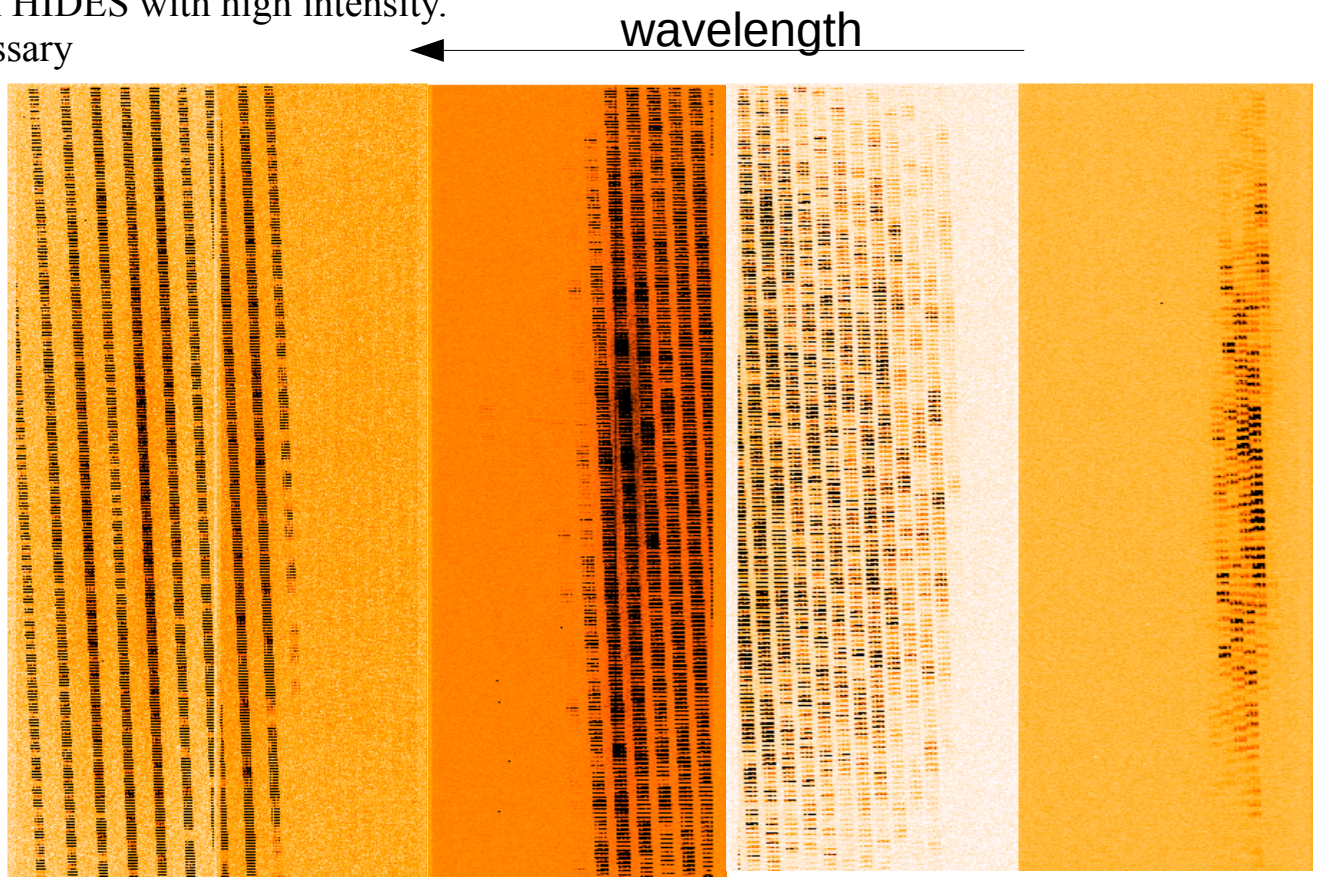
Astro-Comb First Performance Tests

✱ Comb was observed right from the start with HIDES with high intensity. Intensity was so strong that ND-filter was necessary

✱ Due to the setup of the HIDES spectrograph at the time of commissioning and the use of additional band-pass filters, we could not observe the entire comb spectrum at the blue and red end

✱ Wavelength coverage for the green region is essentially as expected. We observe the comb spectrum as low as 437nm

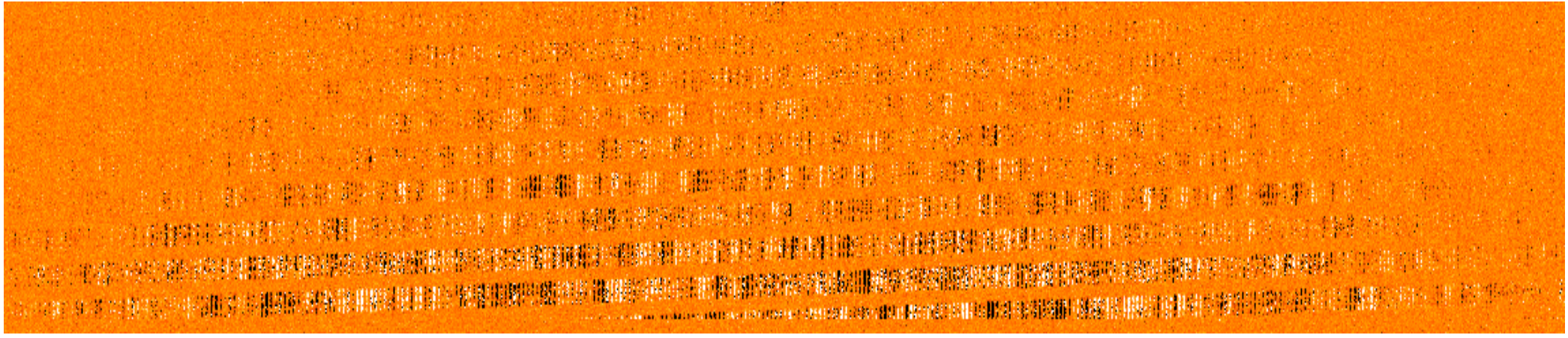
✱ Only few seconds exposure time needed compared to several minutes for the 1st Gen Comb



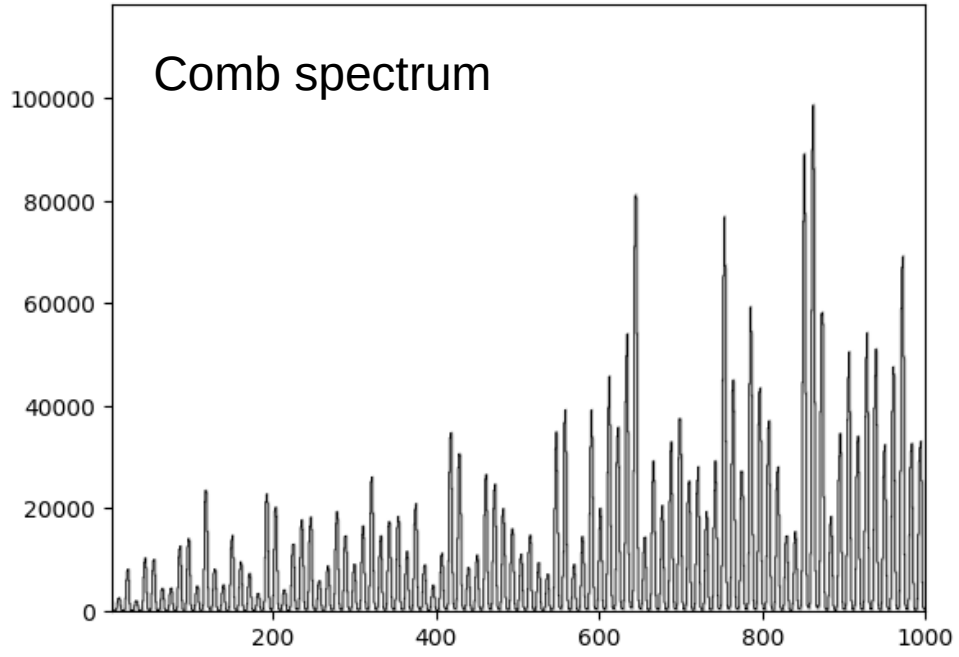
First Performance Tests

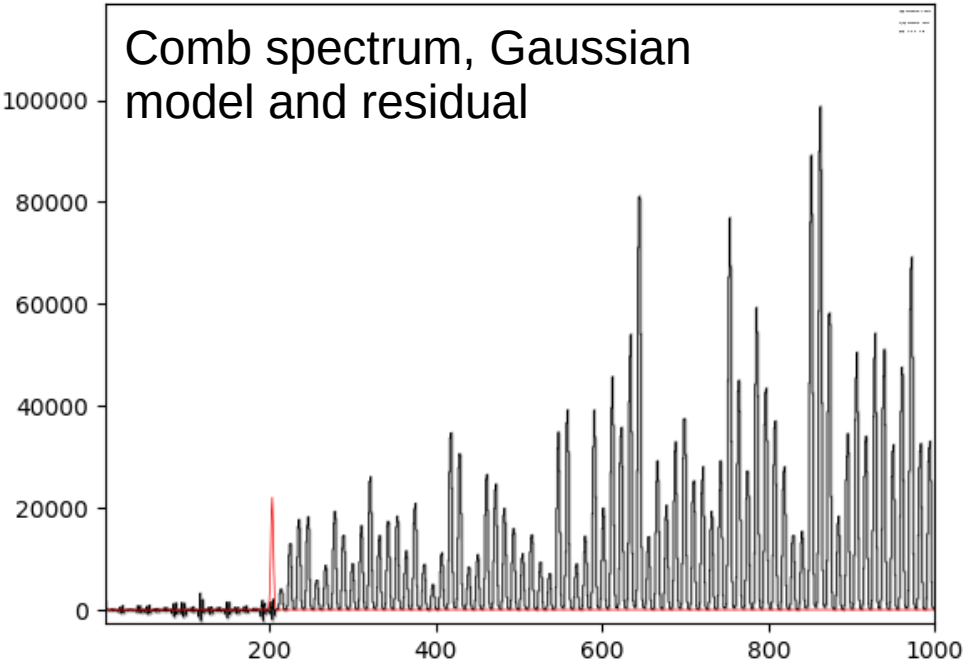
✱ The comb was running with a stable mode lock over
several hours taking alternate spectra from Th-Ar lamp and the comb itself

✱ We observed some breathing but with little effect on the absolute calibration over short time scales (several min)

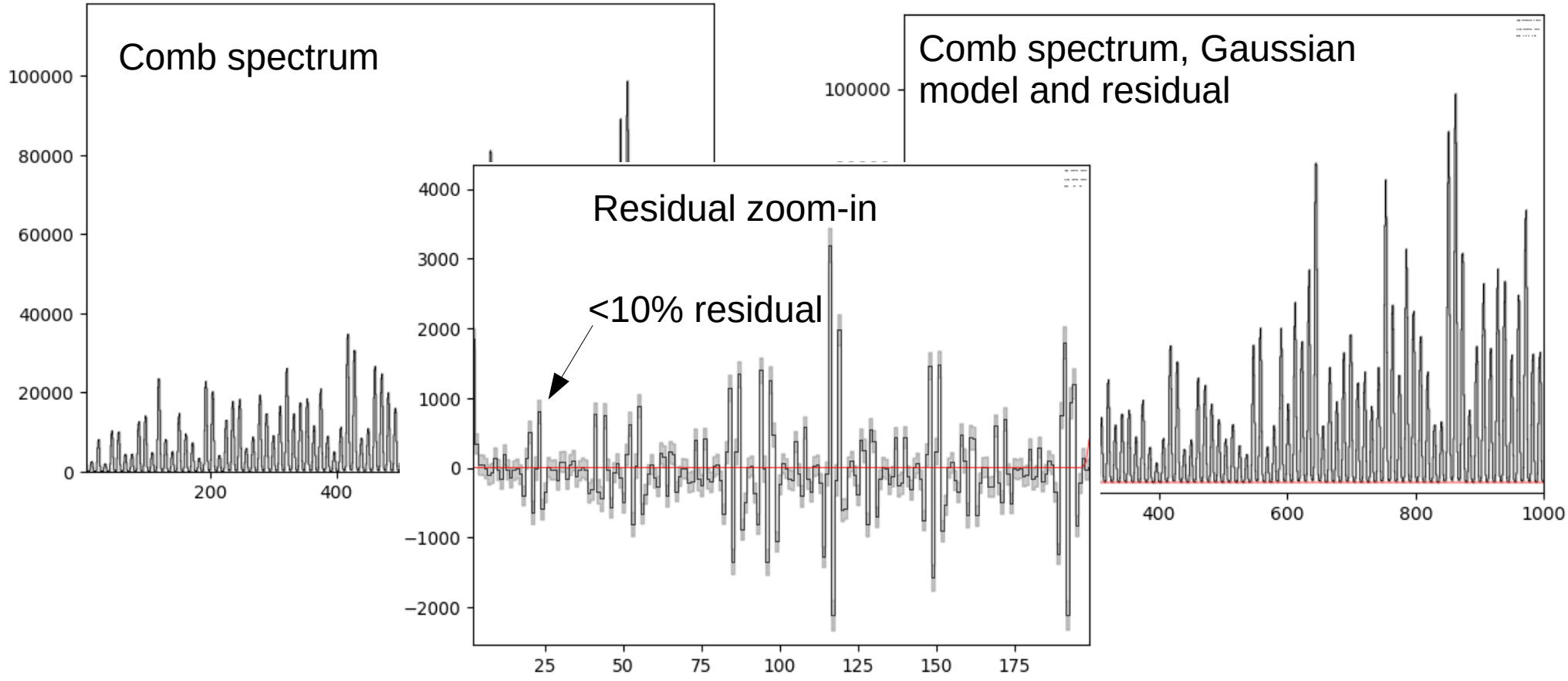


First Performance Tests



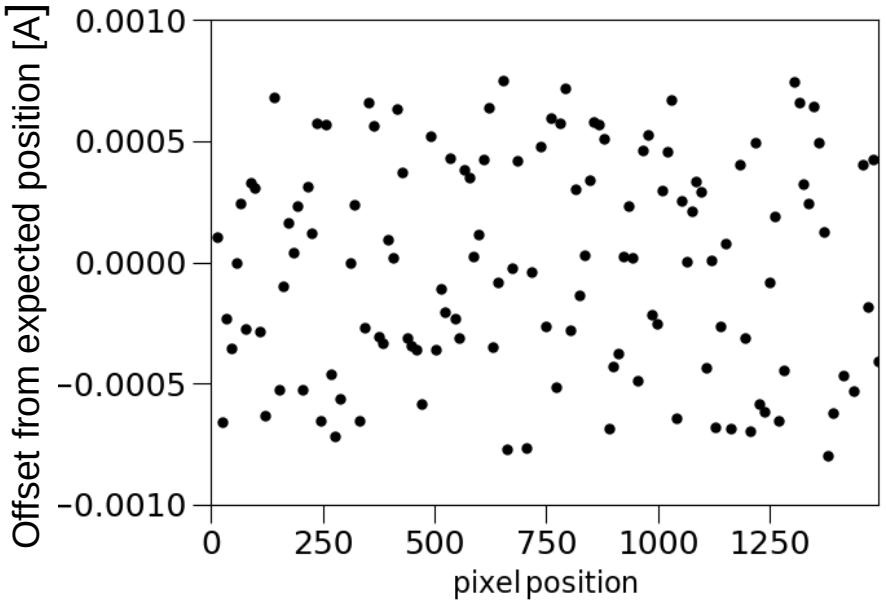


First Performance Tests



First Performance Tests

✱ We fit the comb spectrum with single Gaussian models and compute the wavelength solution using the known position of each comb mode. We achieve an rms as low as 0.00020A for several well exposed orders which corresponds to an systematic uncertainty for the absolute calibration of 12 m/s



✱ The Astro comb has much better line coverage compared to the very few ThAr lines and we typically achieved a factor 10 better rms in the wavelength solution

✱ The relative accuracy over hour time scale is even better <10m/s for small wavelength regions

Summary

- First tests show very bright Astro-comb spectrum
- Expected wavelength coverage achieved
- Absolute wavelength calibration ~12 m/s systematic uncertainty in green region
- Relative accuracy <10m/s over hour time scale for small wavelength regions

Improvements: * HIDES Echelle grating not in optimal setup for the comb during test, HIDES is also not an Ultra-stable spectrograph

* absolute Wavelength calibration varies factor 2-4 from blue to red depending on available comb modes and their intensity