VIPA spectrograph: Ultrahigh-resolution, multi-mode fiber fed and broadband

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Outline

1. Background

Problems & What is VIPA

2. Research progress in VIPA spectroscopy

Ultrahigh-resolution, multi-mode fiber fed, broadband spectrum…

3. Conclusion and prospective

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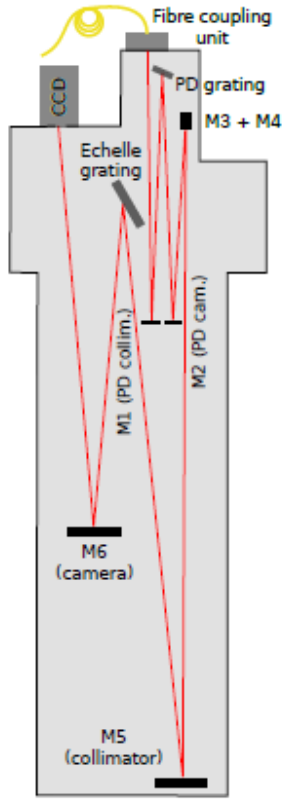
Astronomical Spectrograph faces challenges

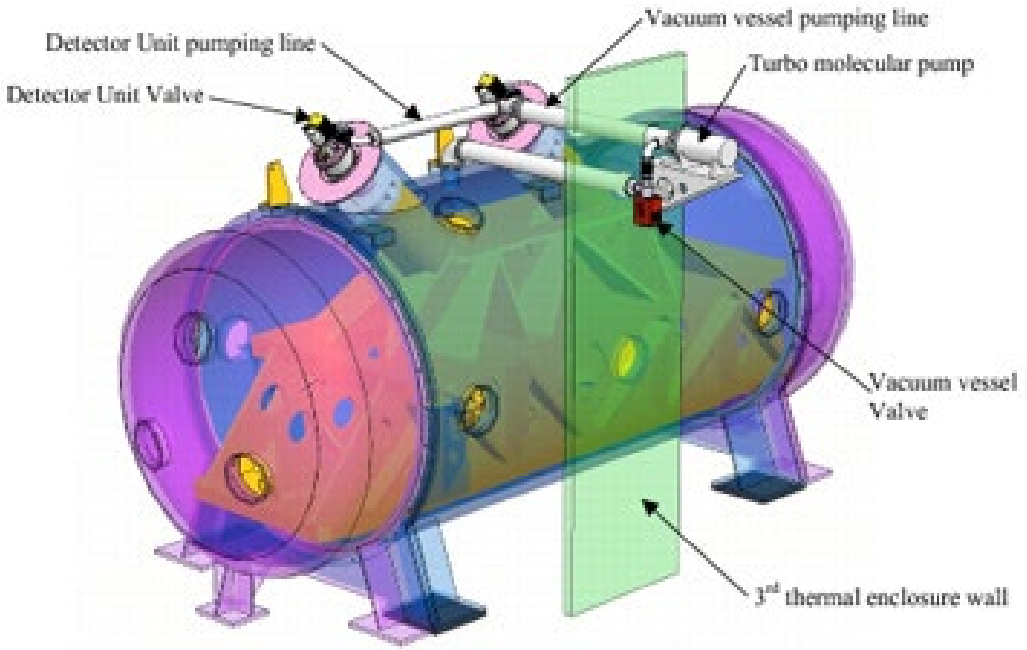
> 10 m



VTT spectrograph
Resolution: 0.5~1 million

1. Huge & Expensive

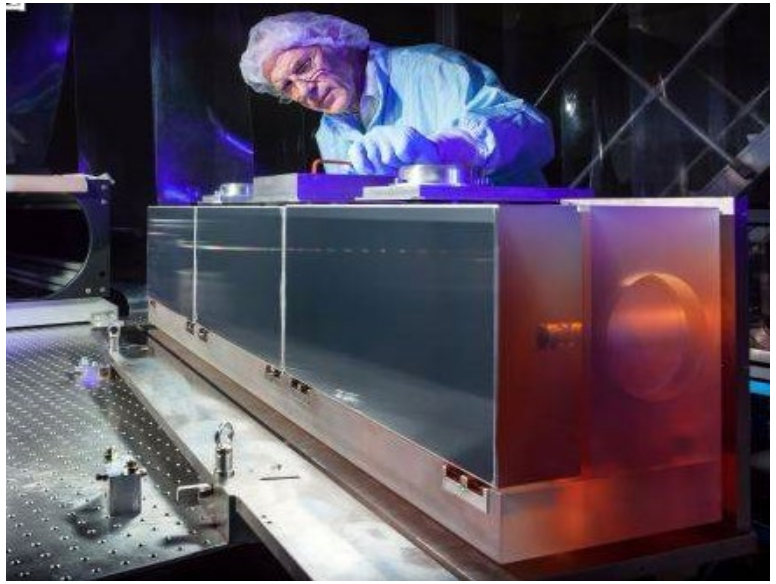
2. Extremely high accuracy & Difficulty



ESO-VLT ESPRESSO
Resolution: 70~190 k
Accuracy: ~30 cm/s

Questions：How to obtain a compact, cheap, multi-mode fiber fed, high resolution and broadband astronomical spectrograph?

Solutions?

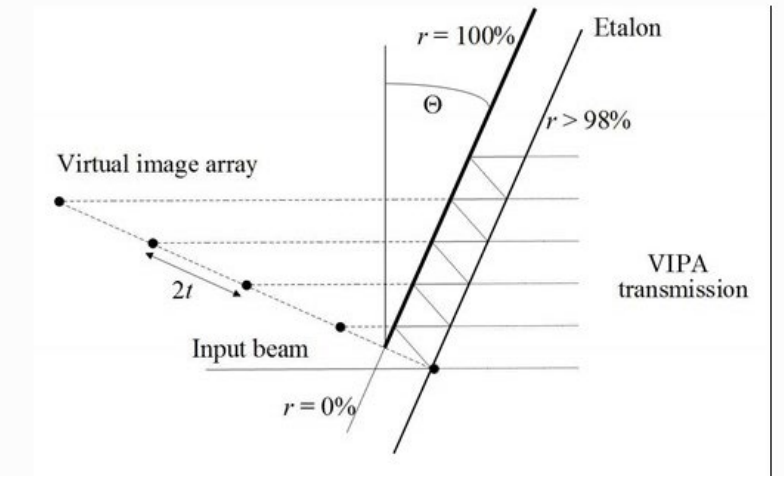


Grating in ESPRESSO
Size: 1.2 m

Limited dispersion !

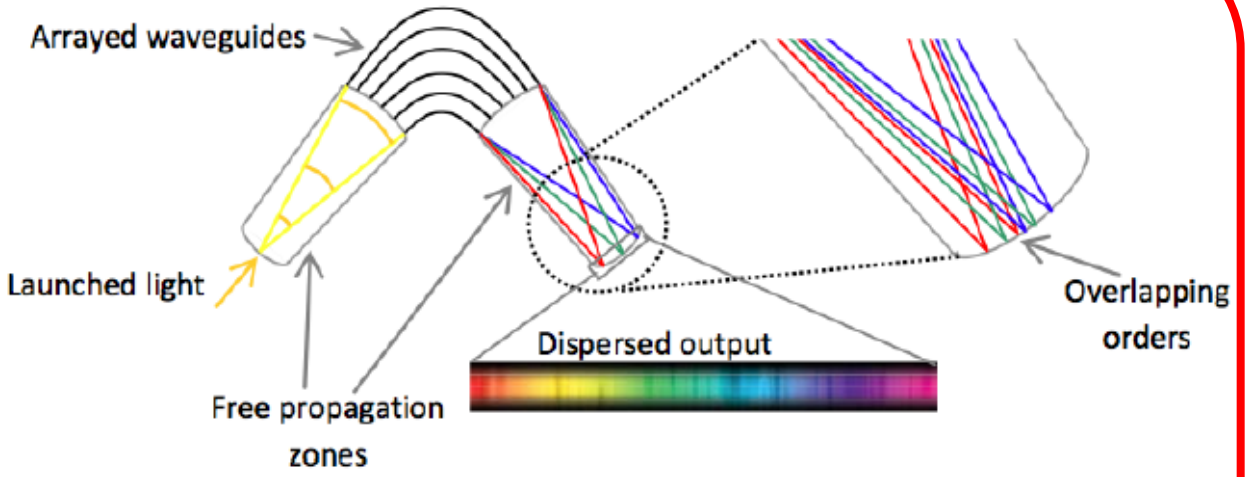
Replace grating?

I



VIPA---Extremely high dispersion

II



Chip spectrometer---Integrated Optics

VIPA---Born for optical communication

366 OPTICS LETTERS / Vol. 21, No. 5 / March 1, 1996

VIPA

Large angular dispersion by a virtually imaged phased array and its application to a wavelength demultiplexer

M. Shirasaki

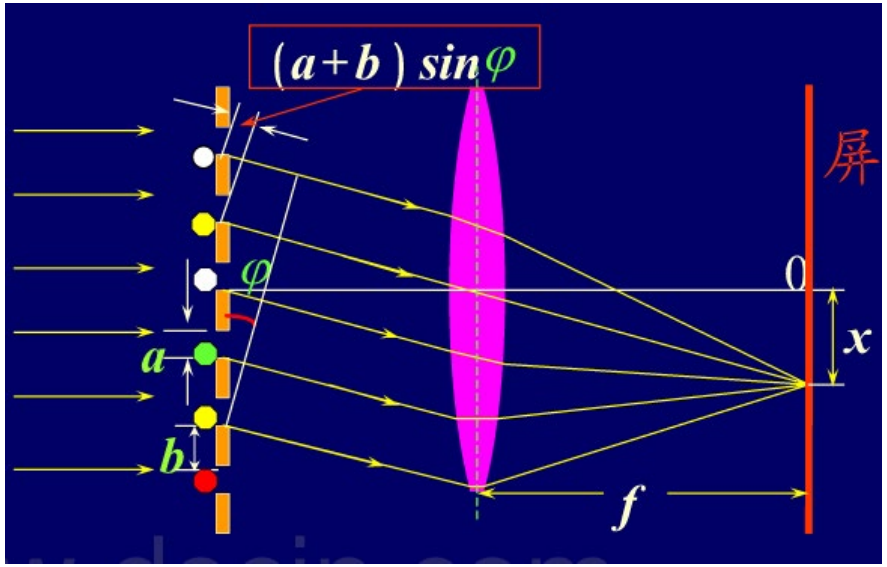
Fujitsu Laboratories Ltd., Optoelectronic Systems Laboratory, 4-1-1 Kamikodanaka, Nakahara-ku, Kawasaki, 211-88, Japan

Received September 29, 1995

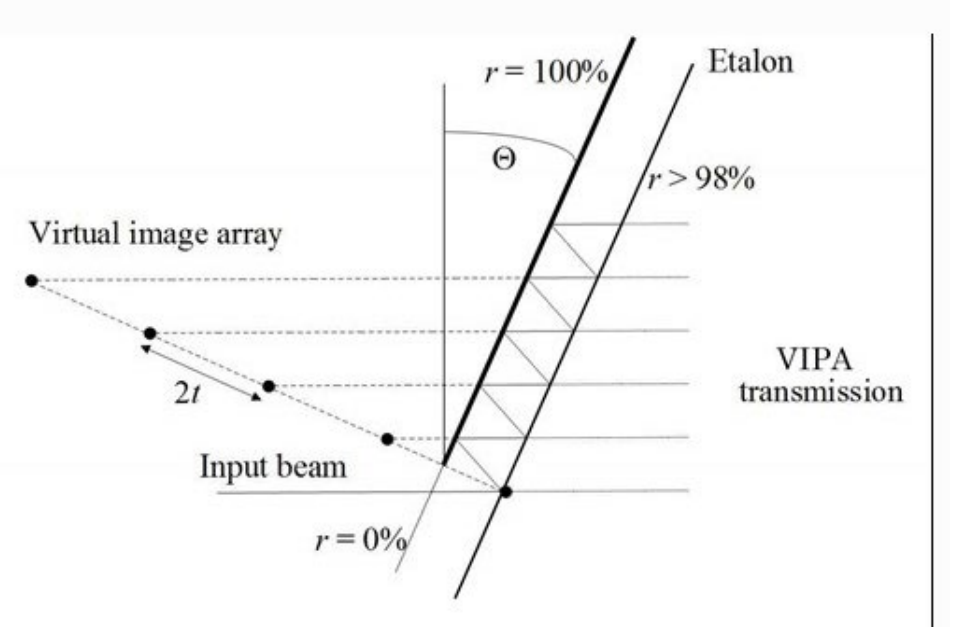
A new scheme that shows large angular dispersion is proposed and demonstrated. The key idea to this method is a virtually imaged phased array (VIPA). The angular dispersion of a VIPA is 10–20 times larger than those of common diffraction gratings, which have blaze angles of ~30 deg. With the VIPA, wavelength demultiplexing for 10 channels with 0.8-nm spacing is achieved. Low polarization-state dependence (~0.1 dB) is also confirmed. © 1996 Optical Society of America

In 1996，developed by Fujitsu Ltd.

Dispersion mechanism of VIPA



Grating



VIPA

Resolution R is proportional to L

L = N * △L

△L :

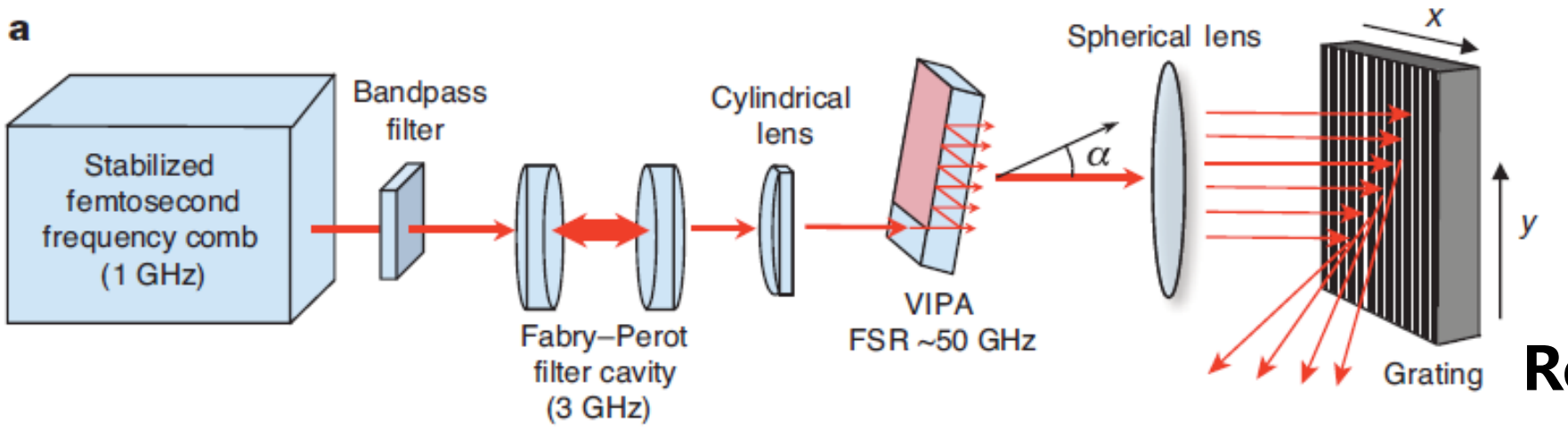
nm~ μm Grating

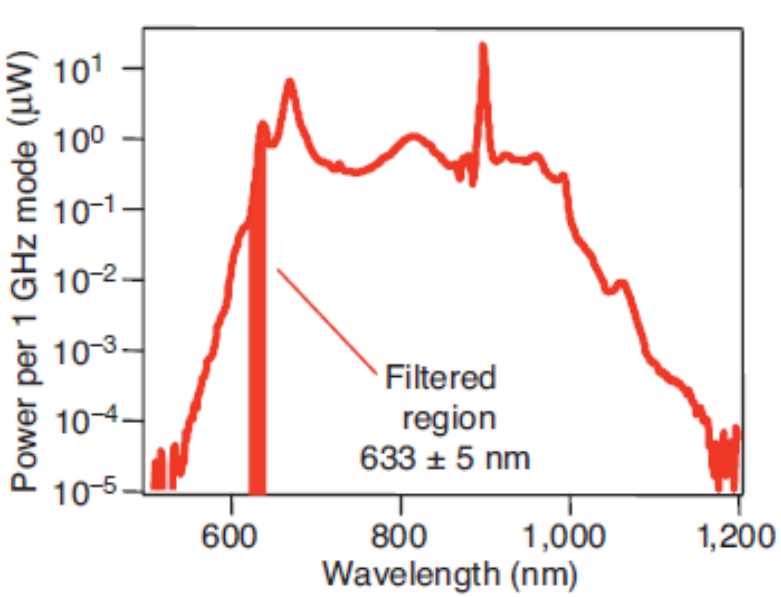
mm ~ cm VIPA

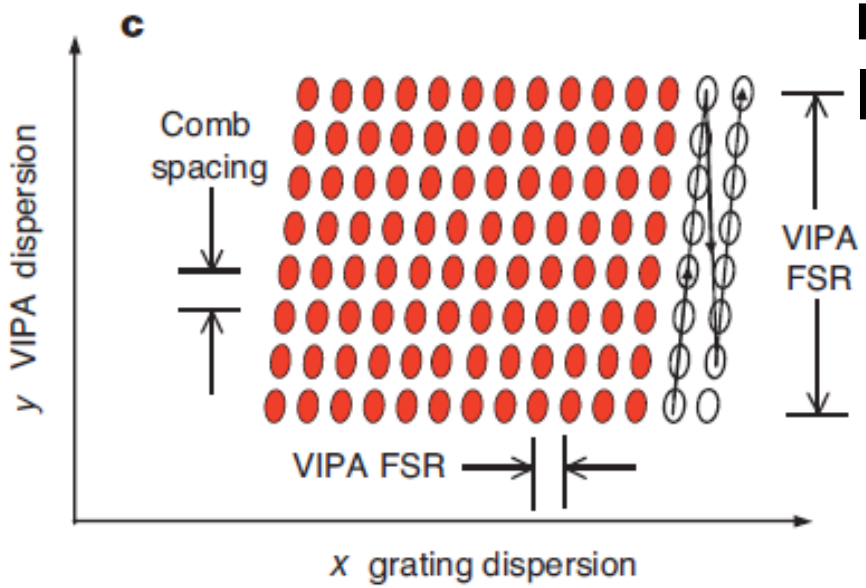
3 orders larger

Suitable for high resolution

Applications of VIPA spectroscopy





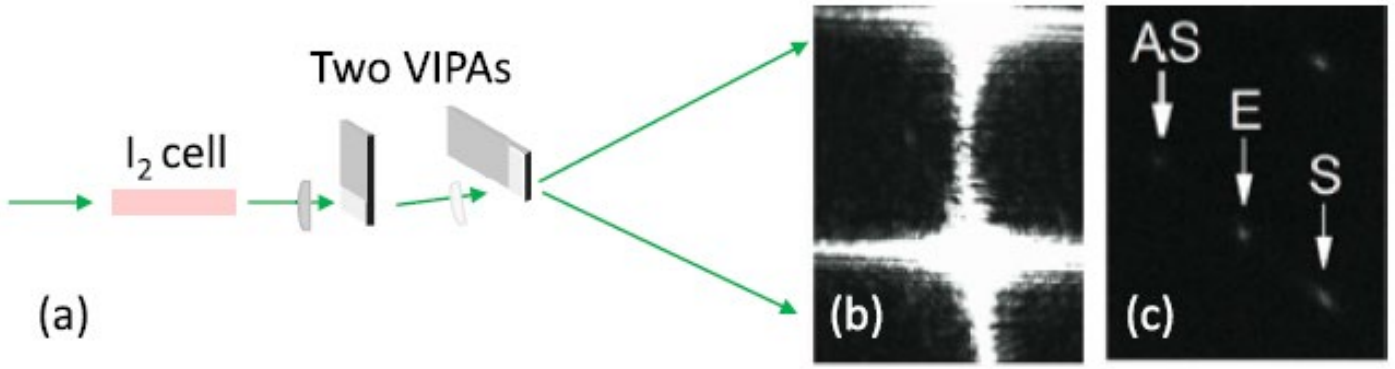


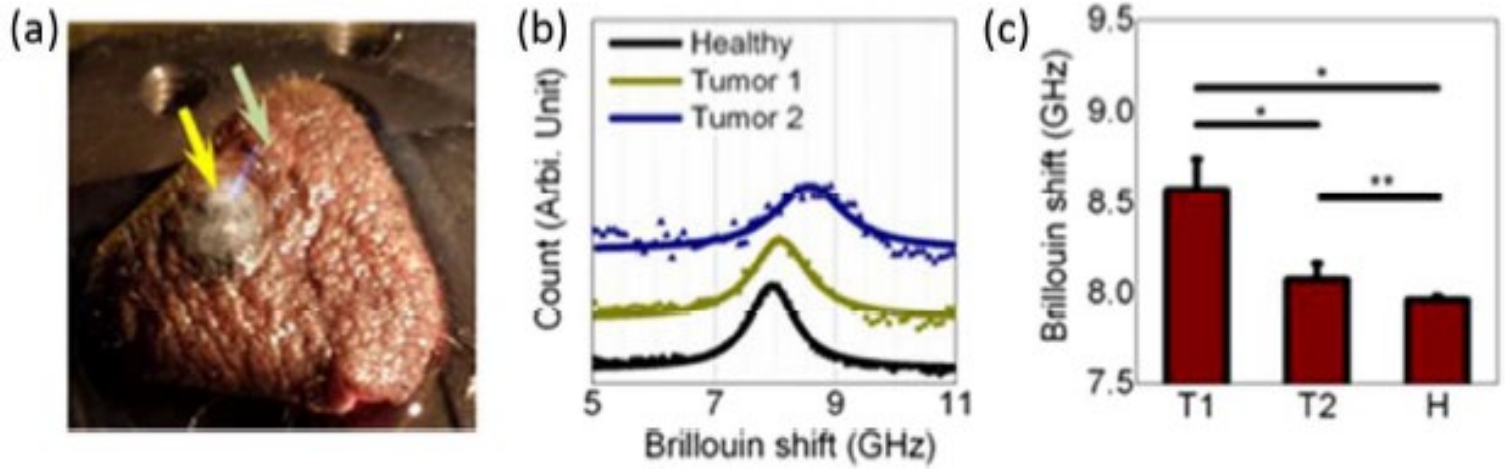
Resolution: ~50 million

Bandwidth: 5-10 nm

~ Absorption spectrum of gas~

Nature 445, 2007

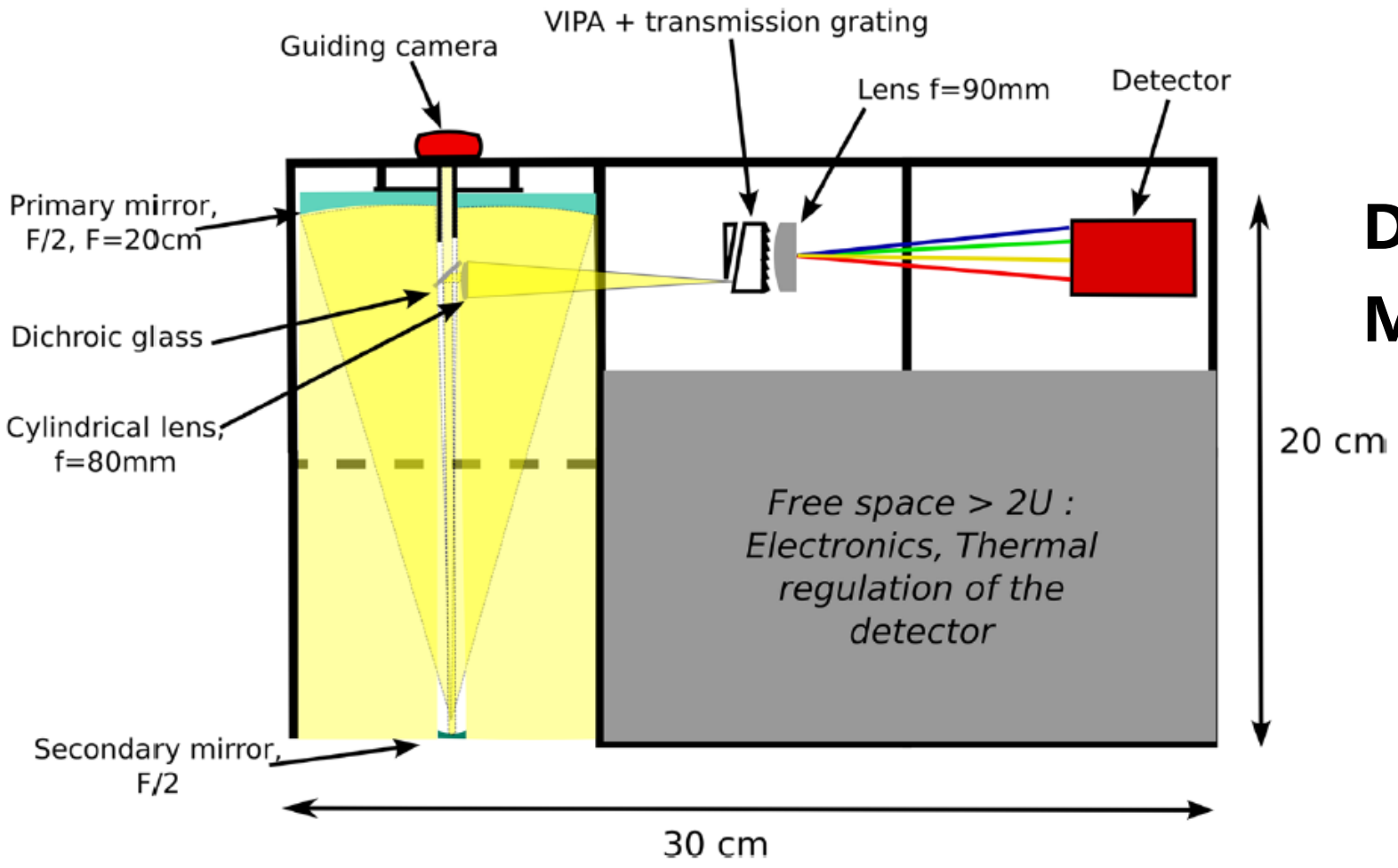




~ Mechanical characteristics of biological tissue~

~ Brillouin scattering spectrum~

Adv. Opt. Photon. 8, 2016



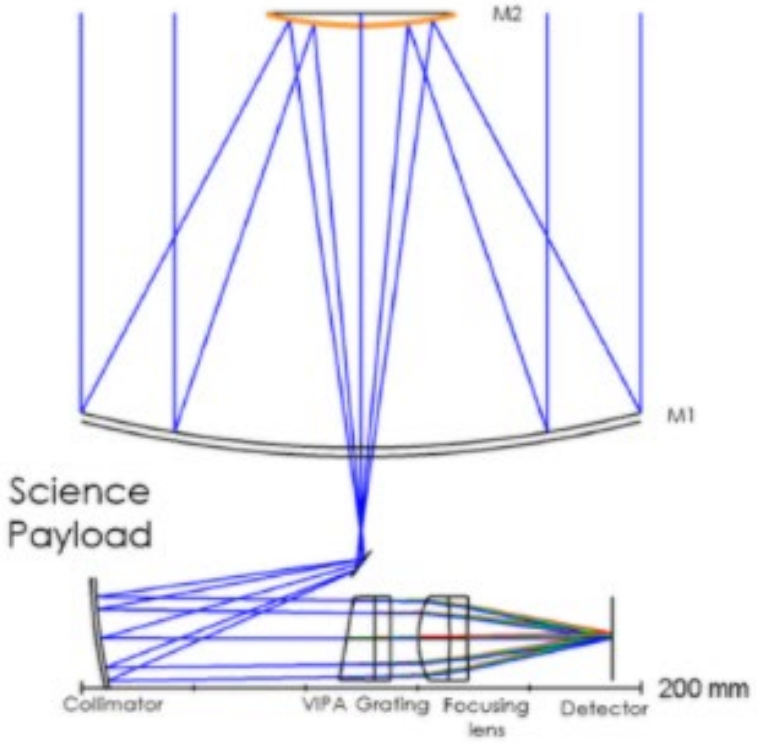
Design：50 k @ 653 nm

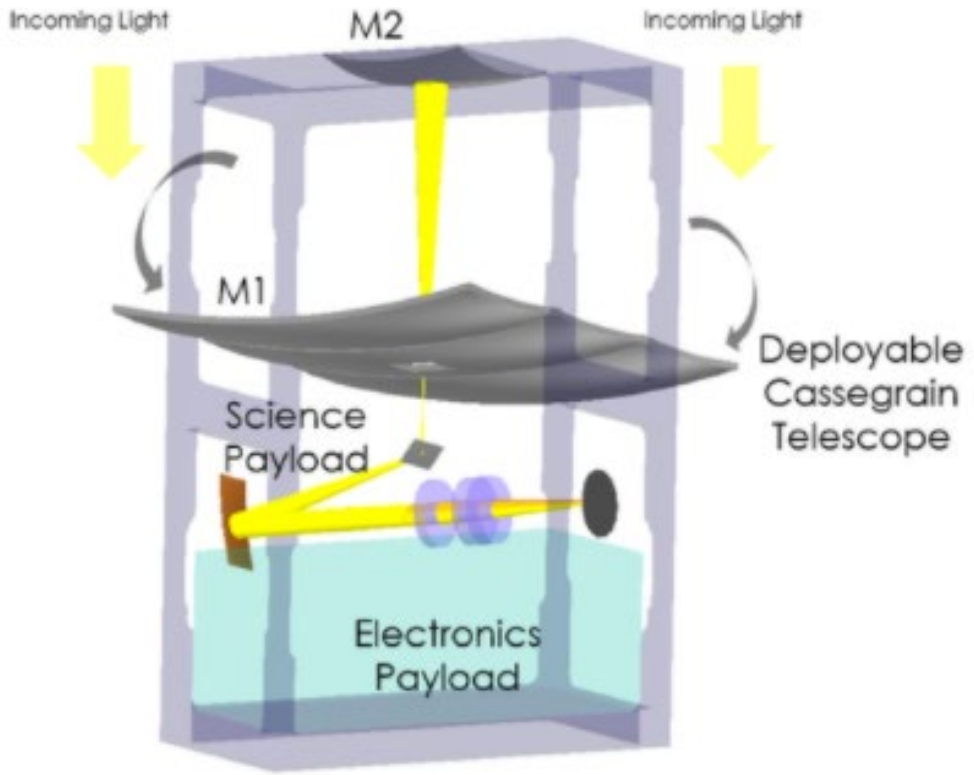
Measured： 200 k

~ Space observation~

CEAS Space J (2017) 9:411–419

~ Cube satellite for exoplanet detection~

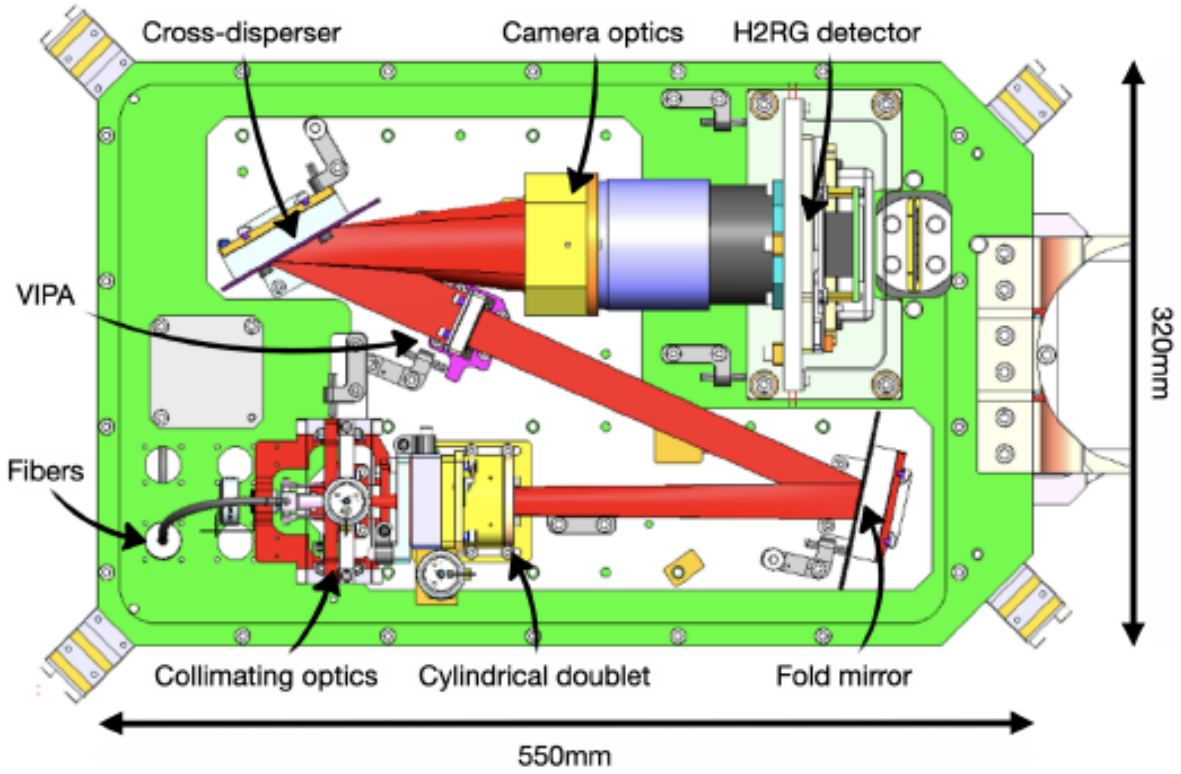




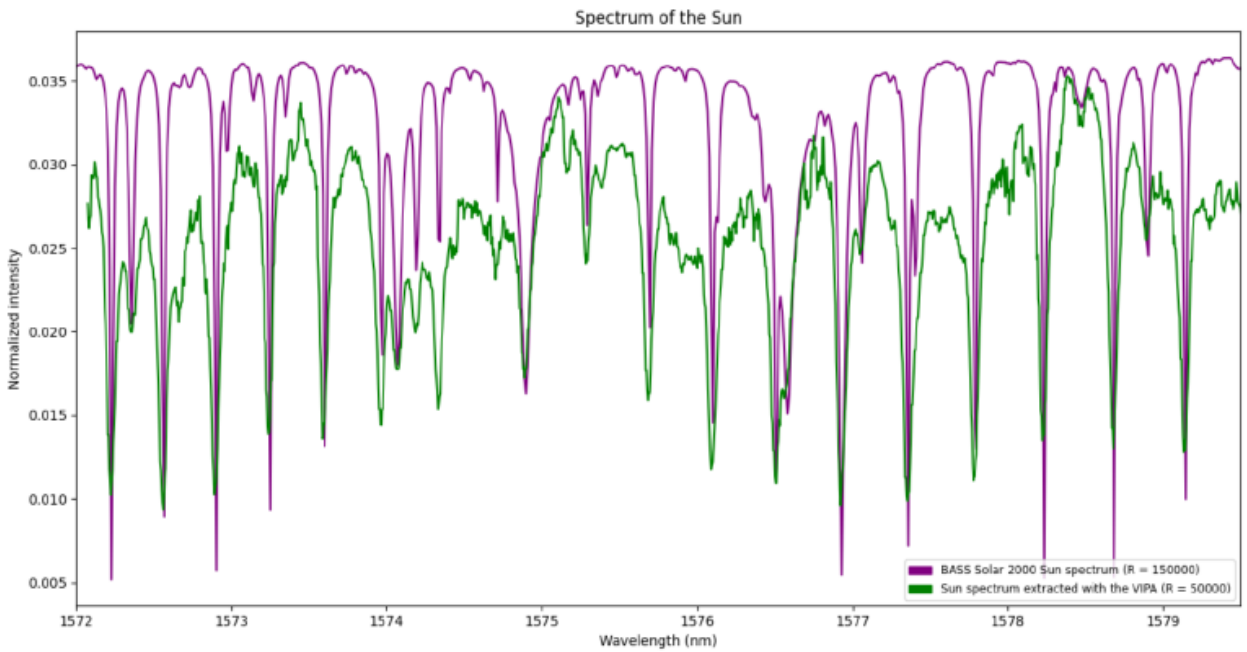
Design：50 k resolution；650~850nm；VIPA+VPH；Size：30cm*20cm*10cm

Surangkhana Rukdee, "Trade-off study of a high-resolution spectrograph on a CubeSat to study exoplanets," Proc. SPIE 11823, Techniques and Instrumentation for Detection of Exoplanets X, 118230K (1 September 2021); doi: 10.1117/12.2595859

~ Astronomical observation at Palomar~



0.25 m^3



Resolution: 80,000
H-band: 1.57~1.7μm
Solar spectrum

SPIE 12184, 2022

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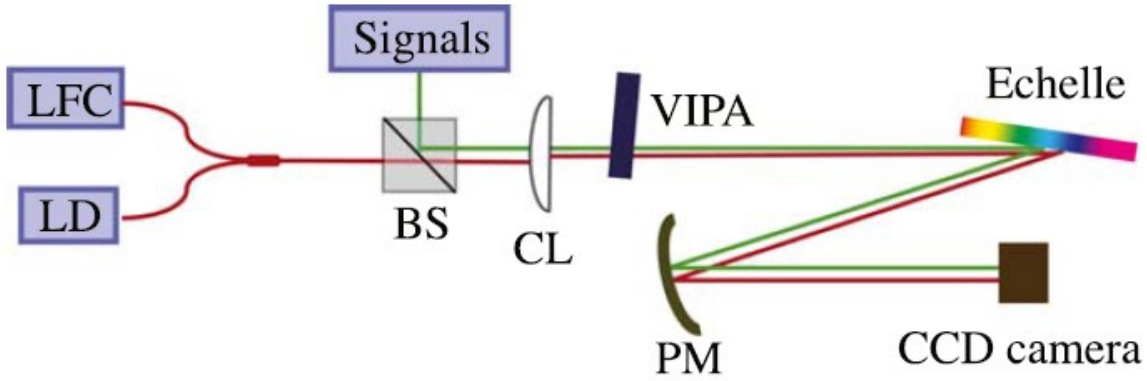
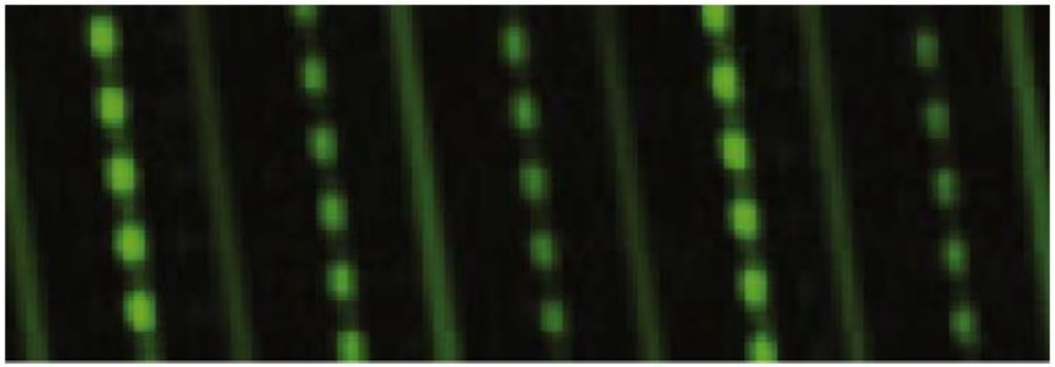
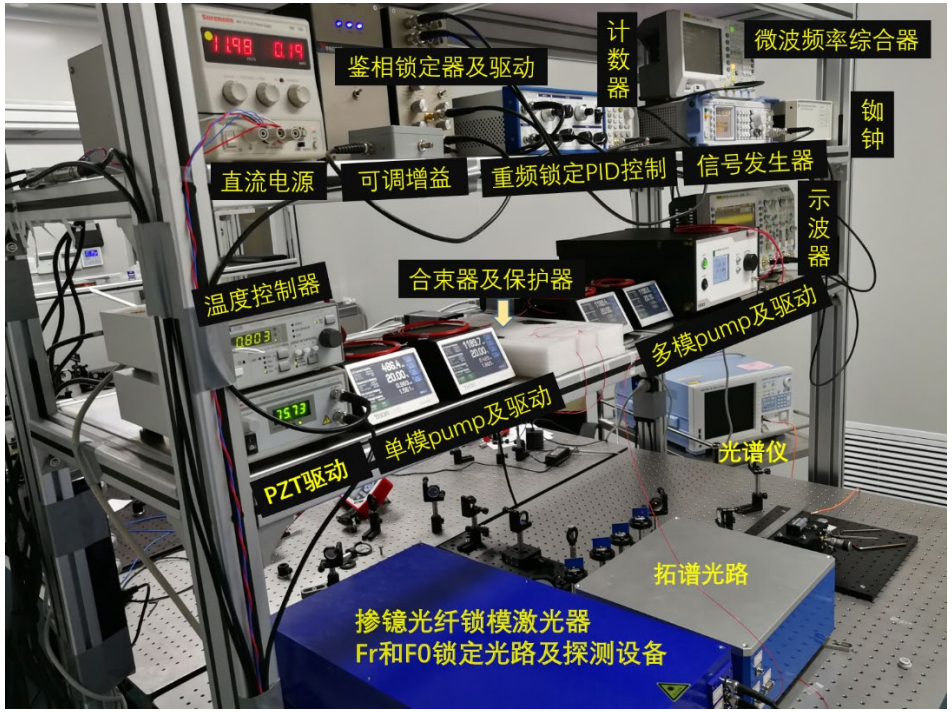
VIPA spectrograph simultaneously calibrated by laser frequency comb





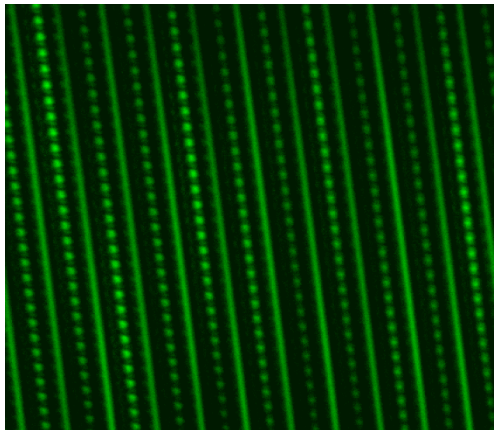
Experimental setup



A home-made laser frequency comb/ ~800 MHz

X. Zhu, et al., AJ, 2020

Ultra-high resolution and wavelength calibration accuracy

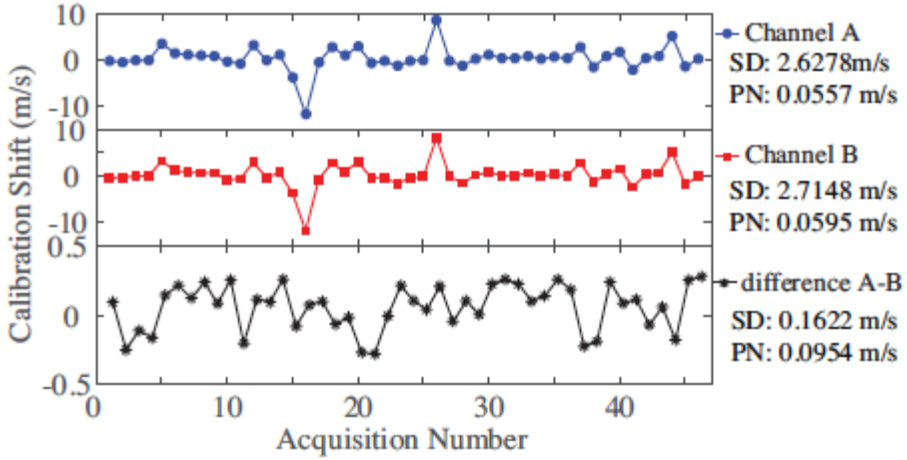


2D spectrum

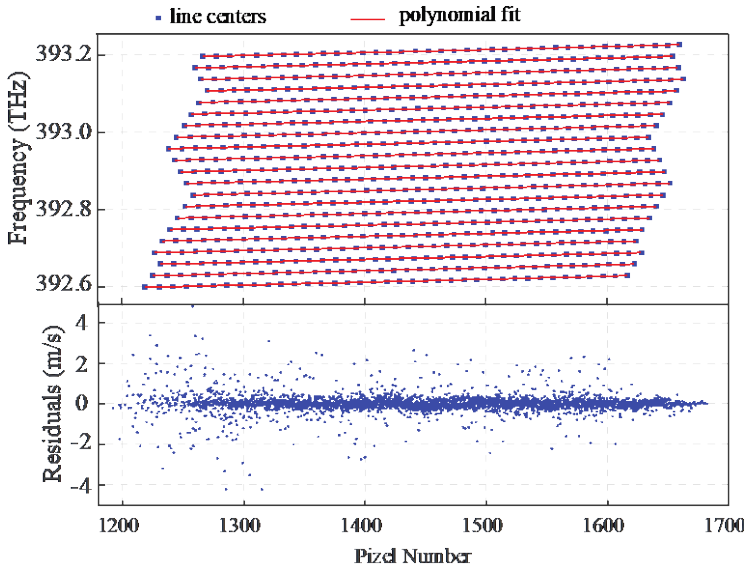
Resolution~1.1million

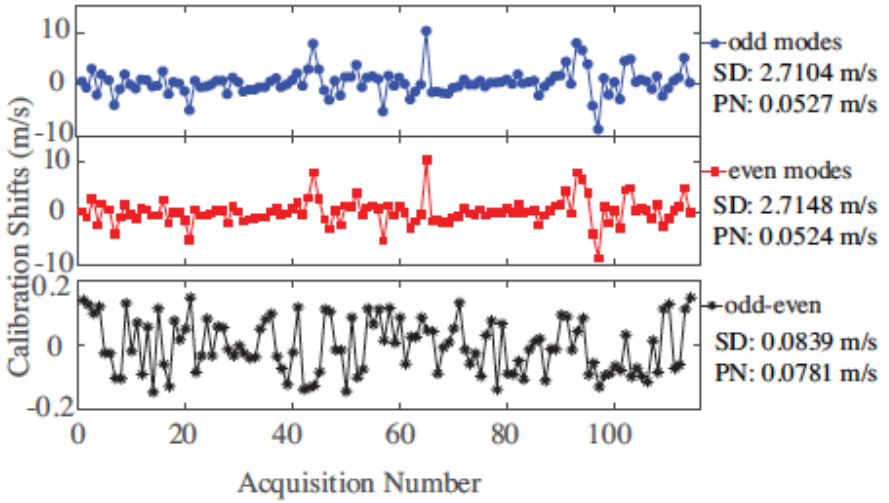
Spectral range:

755~765nm



Dual channel calibration: 16 cm/s





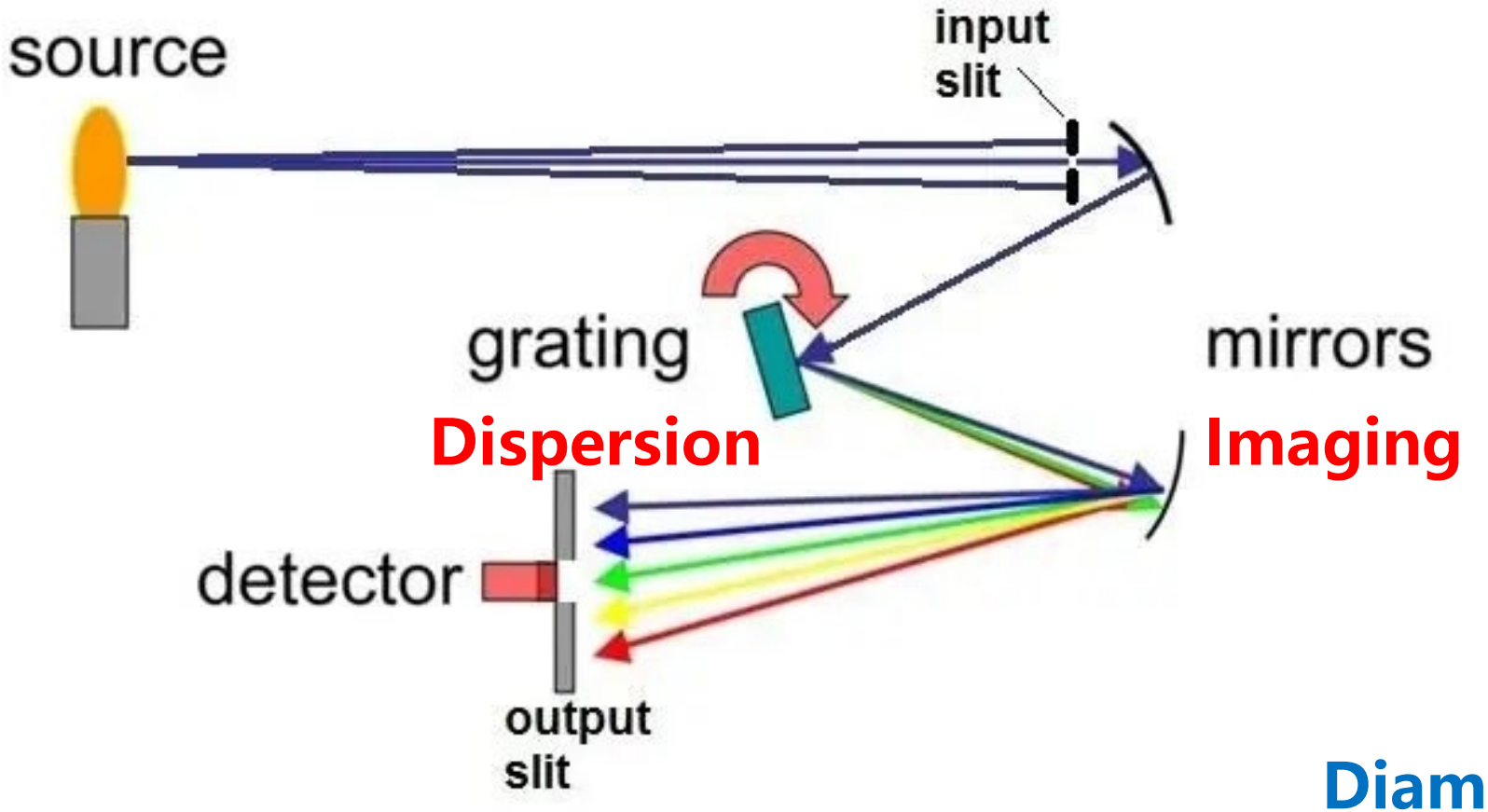
Absolute calibaration: 1.49 m/s

Photon noise: 0.65 m/s

Odd and even mode calibration: 8.4 cm/s

X. Zhu, et al., AJ, 2020

Multi-mode fiber fed grating spectrograph



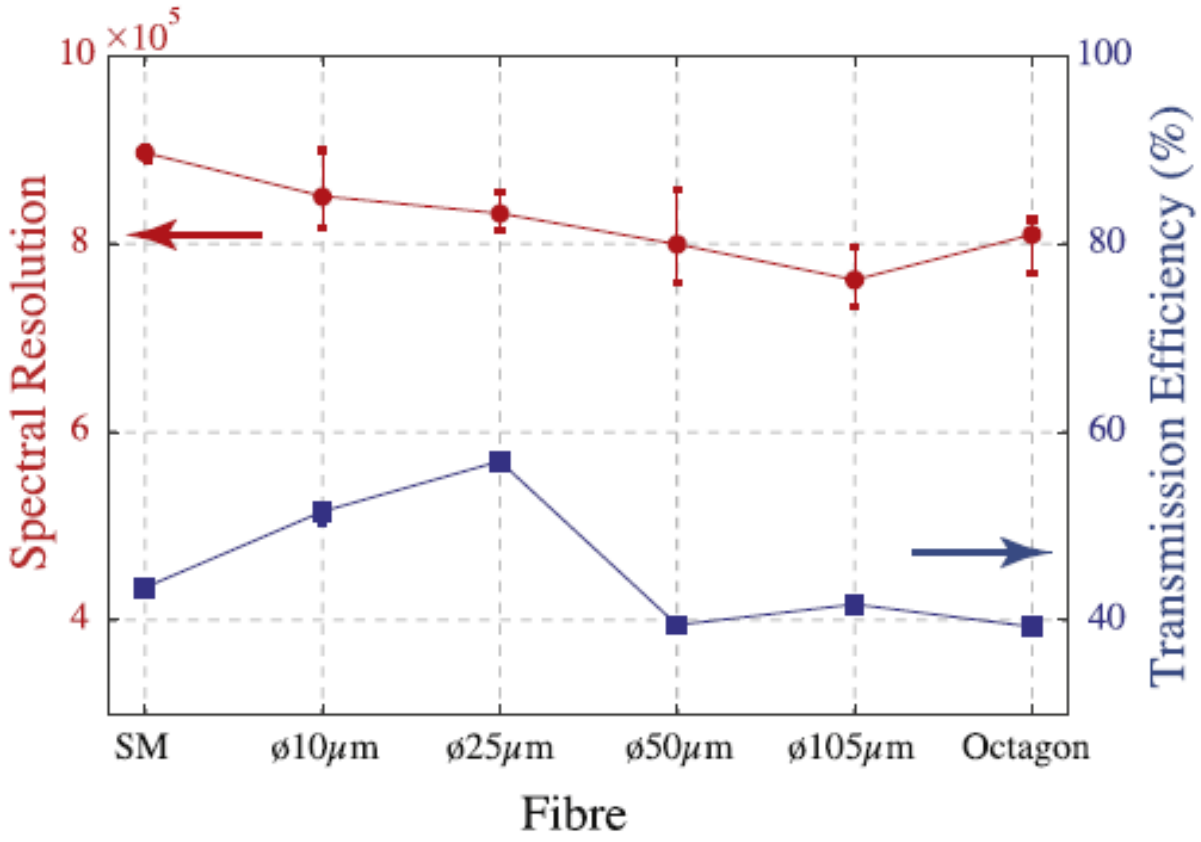
A typical grating spectrograph

Spectral resolution:

Dispersion of grating & Imaging quality of system & Complex object

Diameter of the fiber influence spectral resolution largely

Dispersion characteristics of multi-mode fed VIPA spectrograph



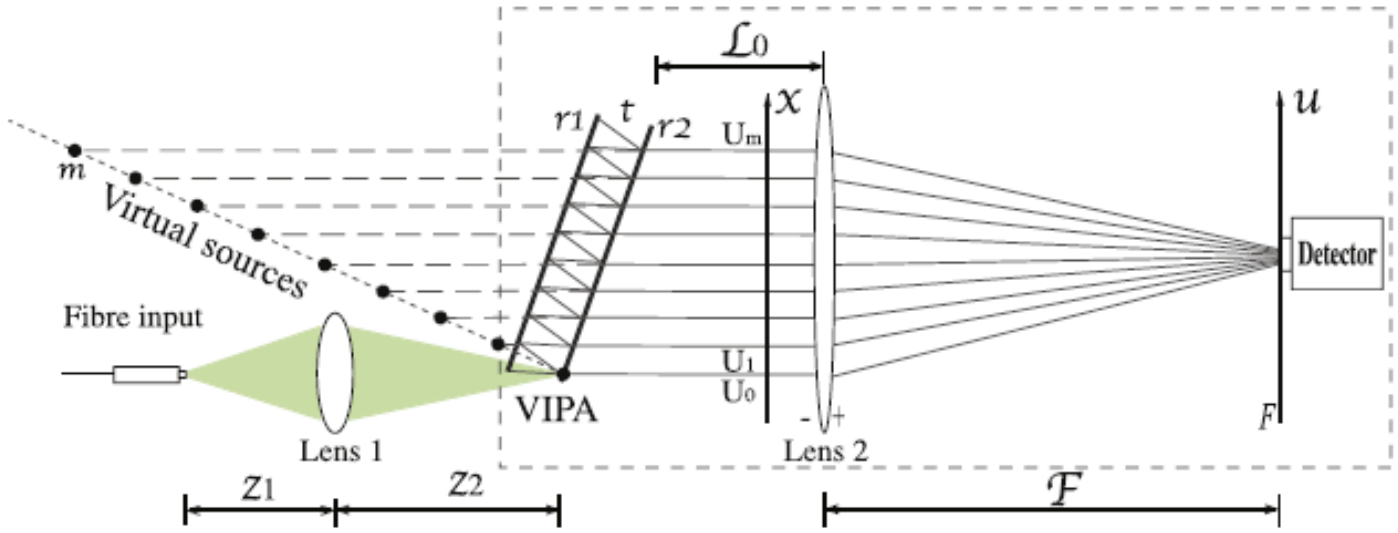
Fiber diameter does not influence spectral resolution largely !

VIPA suitable for multi-mode fiber fed spectrograph ?

Spectral resolution vs. Fiber diameter

AJ, 2023

Dispersion mechanism of VIPA



No fixed Object-Image relations

Intensity on detector

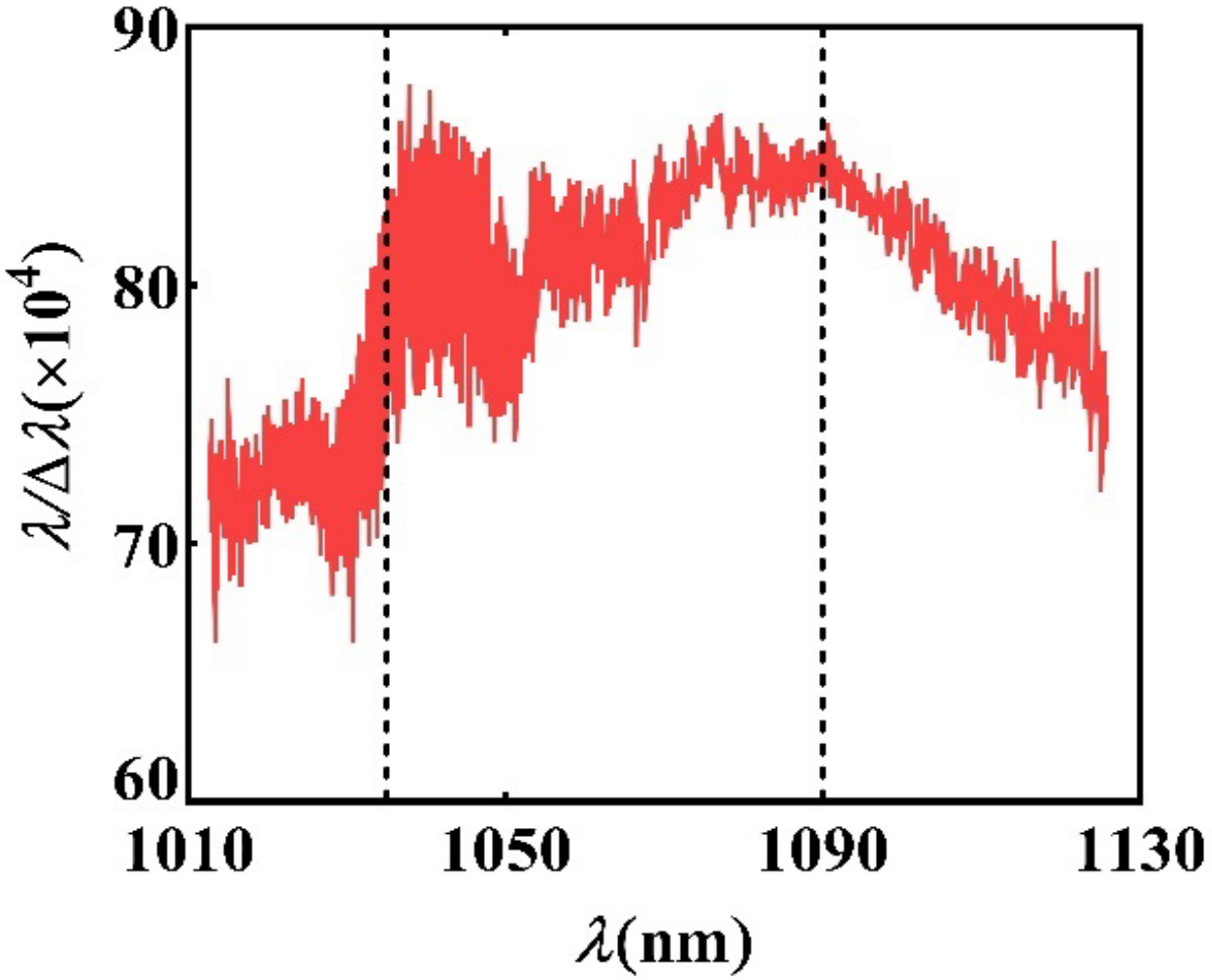
$$I_F(u) = |U_F(u)|^2 \propto \frac{\tilde{U}_0^2(u)}{(1 - r_1 r_2)^2 + 4 r_1 r_2 \sin^2(k\xi/2)}$$

$$\propto \tilde{U}_0^2(u) \frac{1}{1 + P \sin^2(k\xi/2)},$$

Input field---envelope of spectrum

Multi beam interference---resolution of spectrum

Broadband @ High resolution



Bandwidth >100 nm

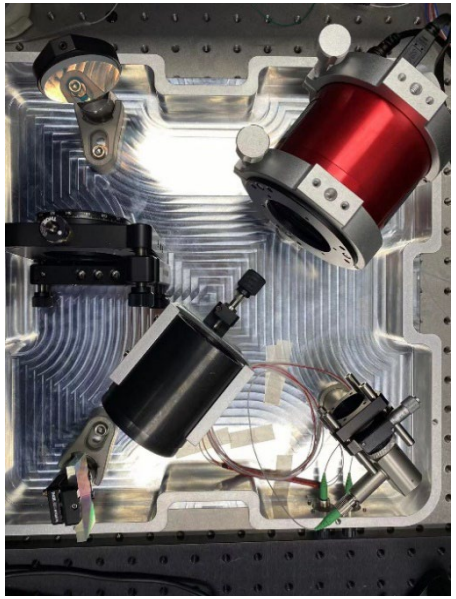
@ 0.65~0.85 million

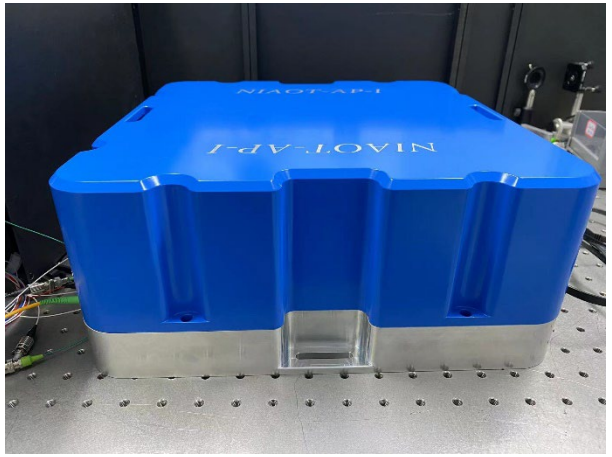
Difficulties:

Aberration control &

data processing

VIPA spectrograph





Home-made VIPA spectrograph--NIAOT-AP-I

Typical parameters

Resolution：0.6~0.87 million

Bandwidth：~110 nm（1010~1130 nm）

Wavelength accuracy：<1 pm

Size：35 cm × 35 cm × 15 cm

Commercial VIPA spectrograph

Resolution：0.34~1.0 million

Bandwith：1~25 nm

Wavelength accuracy：±10 ~ ±50 pm

Size：25 cm × 60 cm × 15 cm

https://lightmachinery.com/media/2082/hyperfine-detailed-technical-specifications-and-datasheet.pdf

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1. VIPA spectrograph can obtain ultra-high resolution (~1 pm), high wavelength accuracy (10 cm/s) and broadband (> 100 nm), with spectral resolution nearly not influenced by fiber diameter； Compact & Cheap

2. Can VIPA replace grating in astronomical observation?

Solar spectrum observation: 200,000~1,000,000

Night observation: 50,000~200,000

Space high resolution spectral observation

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Thanks !

Any discussion or cooperation is welcome