Multiheterodyne spectroscopy of $Eu^{3+}:Y_2SiO_5$ based on GNU Radio

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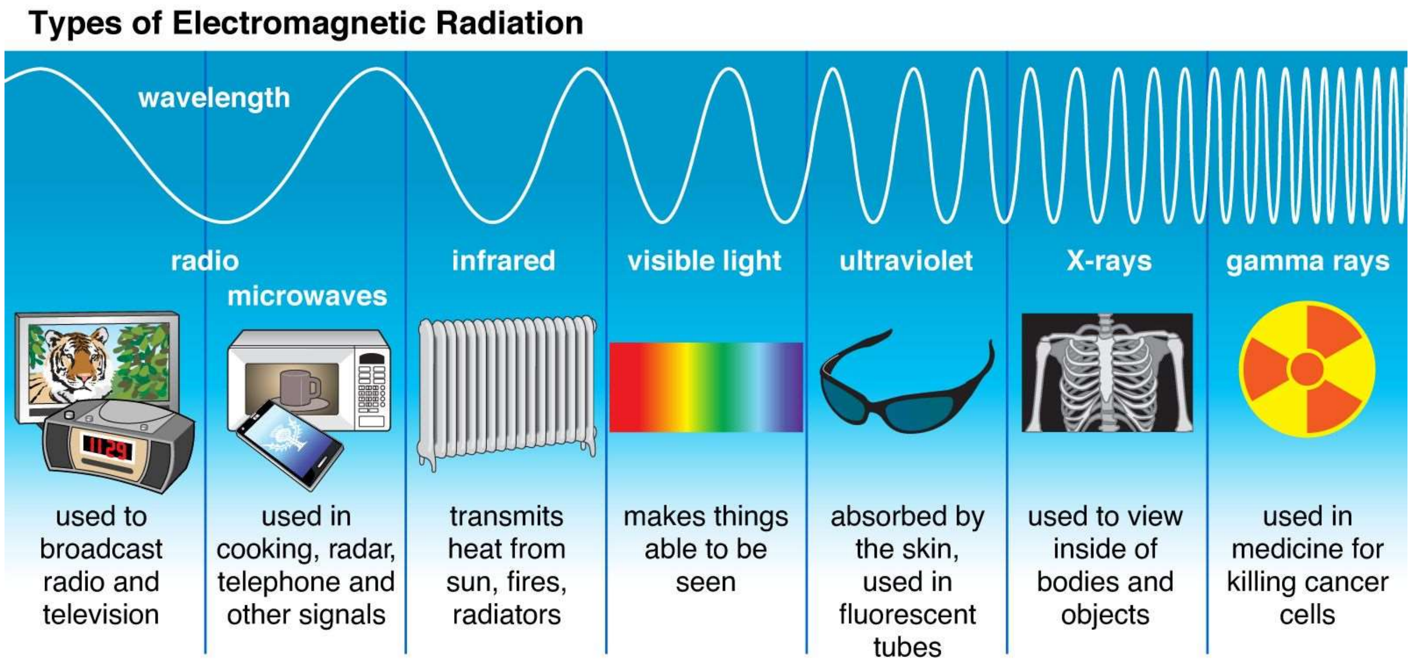
1. Introduction and Objective

2. GNU Radio Application

3. Results and Discussion

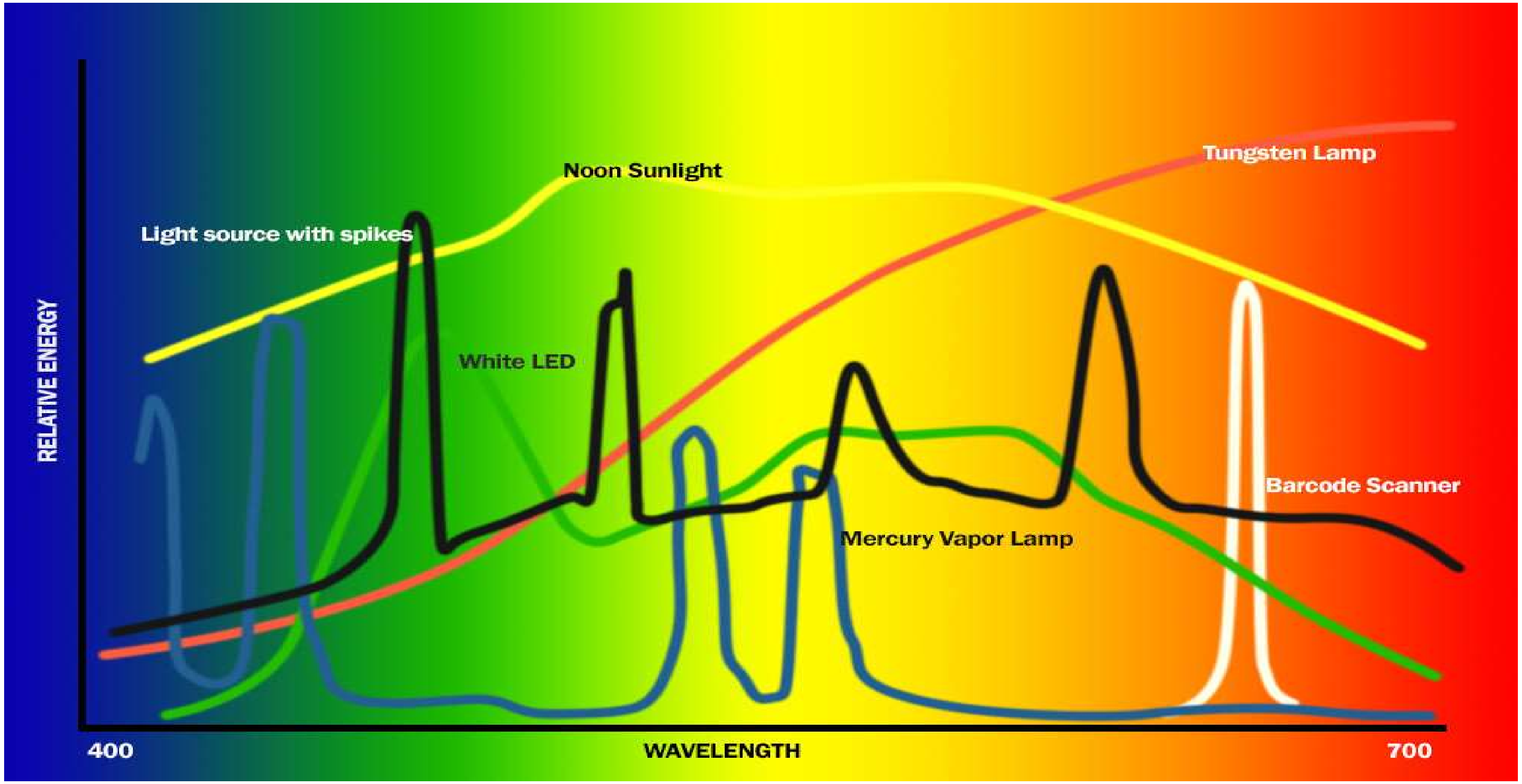
Light and its frequency

Light is an electromagnetic wave



We mainly focus on the visible light

Spectra of common light sources

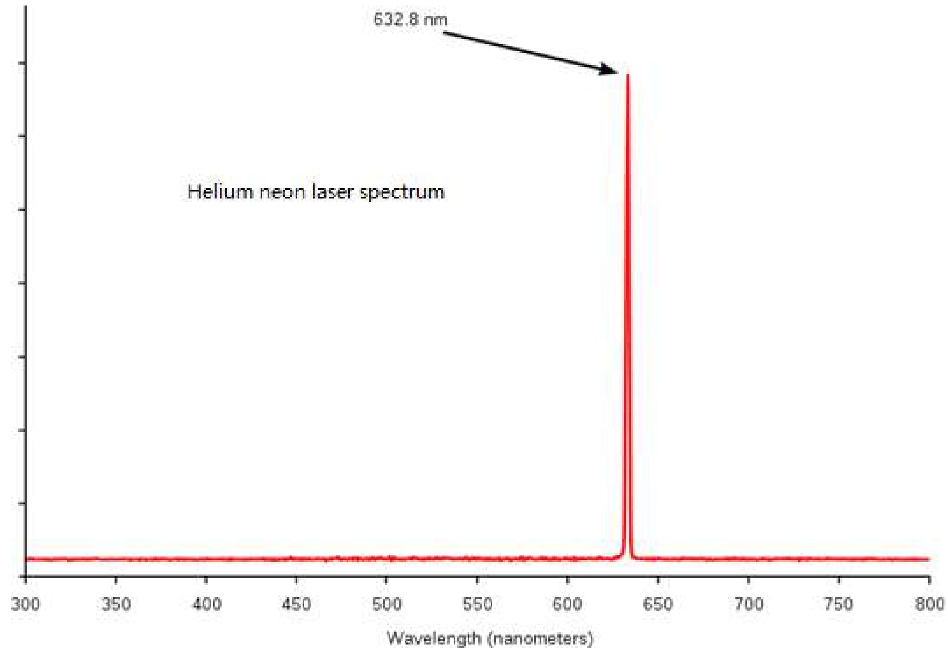


https://www.keptlight.com/use-your-passport/

Laser: a quasi-monochromatic light source

Linewidth: kHz level

www.laser2000.com/fr/fr/1001-laser-et-sources-lumineuses



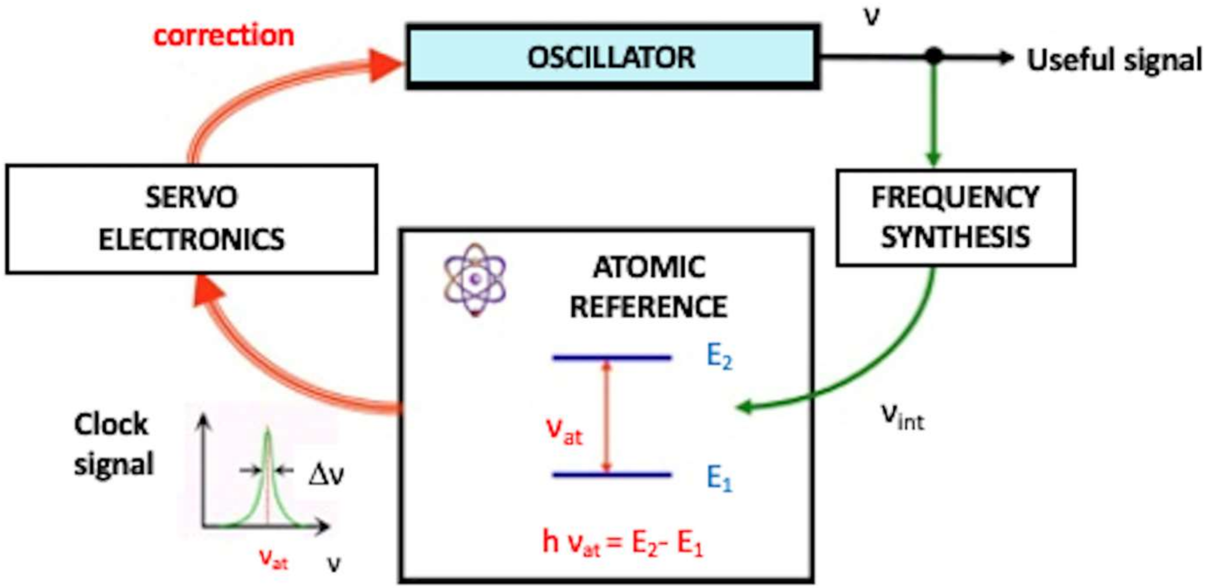
en.wikipedia.org/wiki/Helium%E2%80%93neon_laser

Applications need high laser monochromaticity

1. For optical lattice clocks
2. For precise laser detections
3. For precise physical state controls
4. …

Our objective is to make ultra-stable laser sources (highly monochromatic), which mainly aim at making the next generation of atomic clocks.

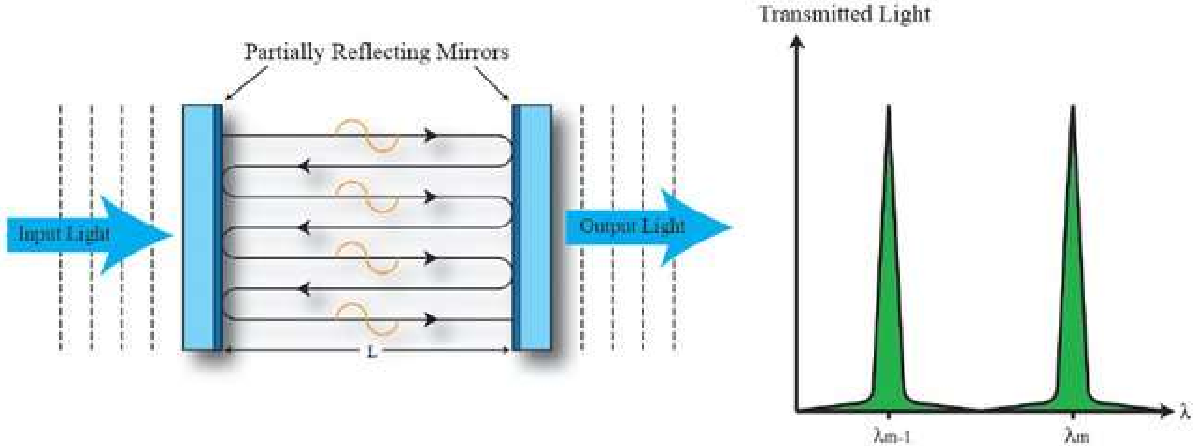
Our motivation: next generation of optical lattice clocks



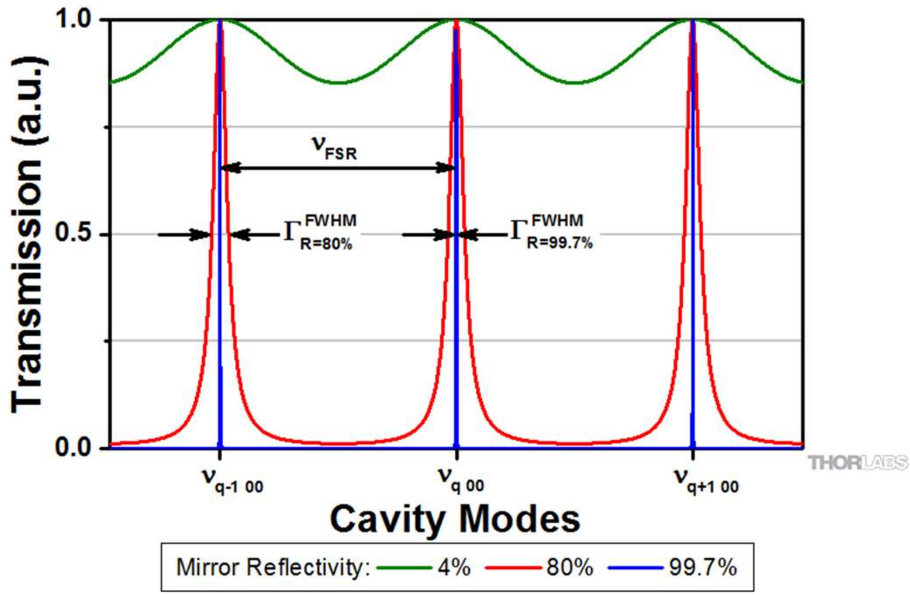
first-tf.com/general-public-schools/how-it-works/atomic-clocks/

To reach the quantum projection noise limitation, we need an optical oscillator with a better fractional frequency stability (at the level of 10^{-18} at 1 s).

Traditionally, high finesse Fabry-Pérot cavities are used to obtain ultra-stable lasers.



researchgate.net/publication/200028072_Self-Powered_Fiber_Bragg_Grating_Sensors/figures?lo=1

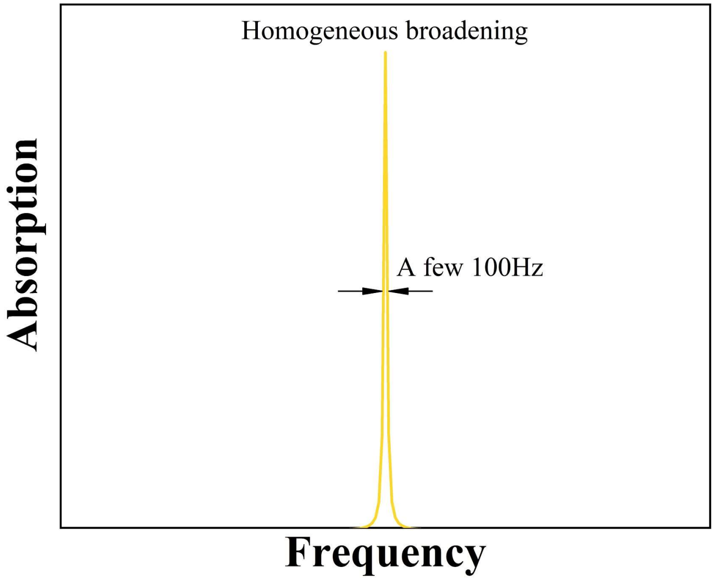


People usually use a servo loop to keep the laser frequency in the narrow transmission band. It is called “lock”.

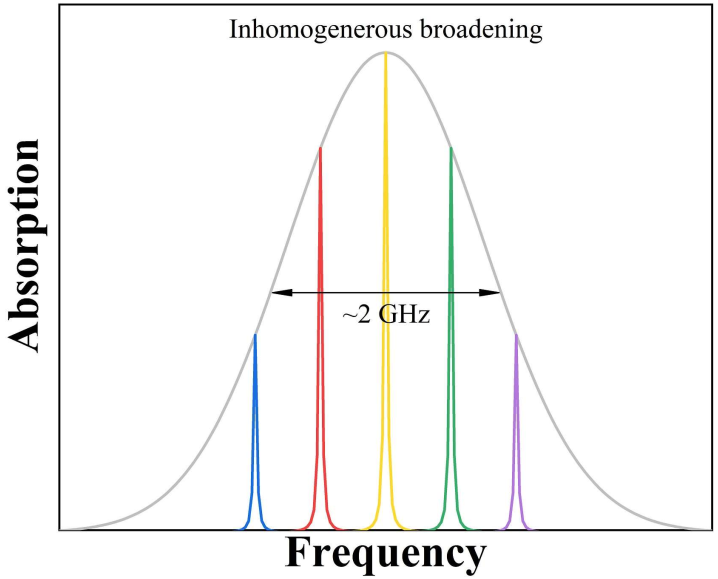
Ultra-stable lasers based on high finesse Fabry-Pérot cavities usually hold the fractional frequency stability in the range of a few 10^{-16} at 1s, which is mainly limited by the fundamental thermal Brownian noise (atom fluctuation induced cavity length change).

People are now trying to overcome this limitation by using several new approaches. Spectral hole burning (SHB) is promising one among them.

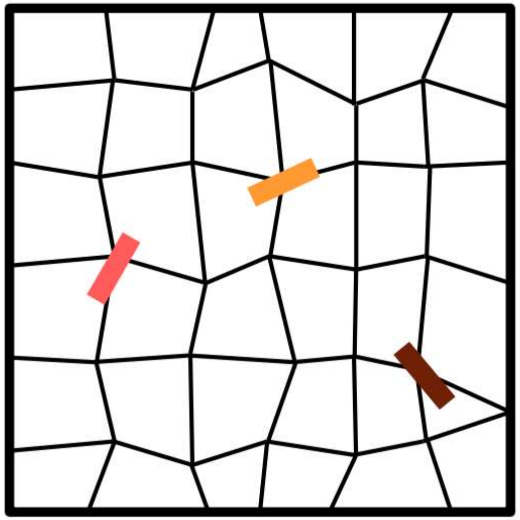
Eu^{3+} ions absorption spectrum in an Y_2SiO_5 crystal



Homogeneous spectral broadening of a Eu^{3+} ion in YSO crystal.

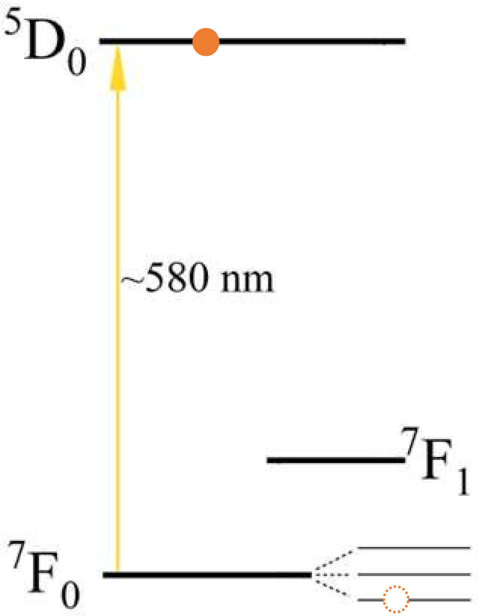


Inhomogeneous spectral broadening (doping concentration: 0.1 at. %) due to the lattice distortion (mainly caused by doping).



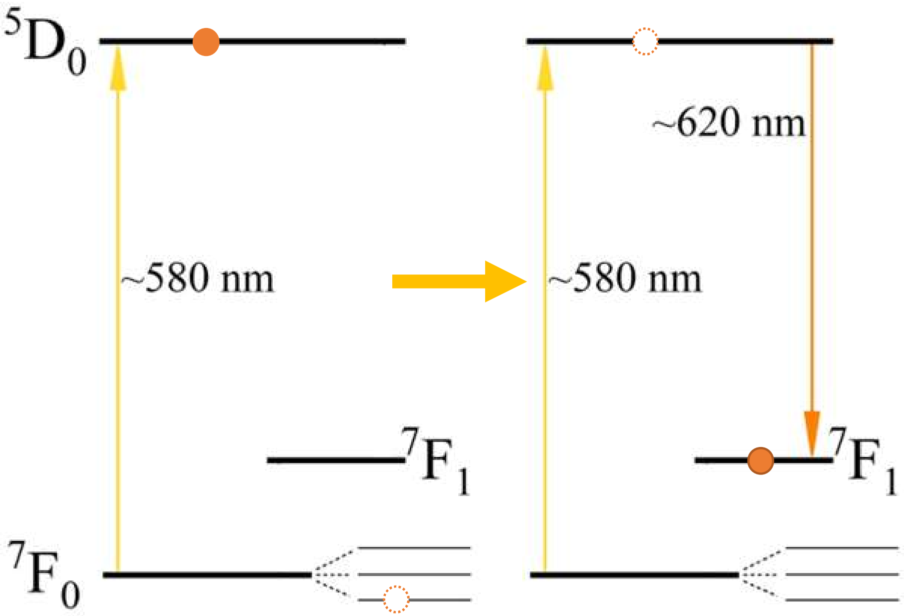
The crystal lattice distortion.

Spectral hole burning process



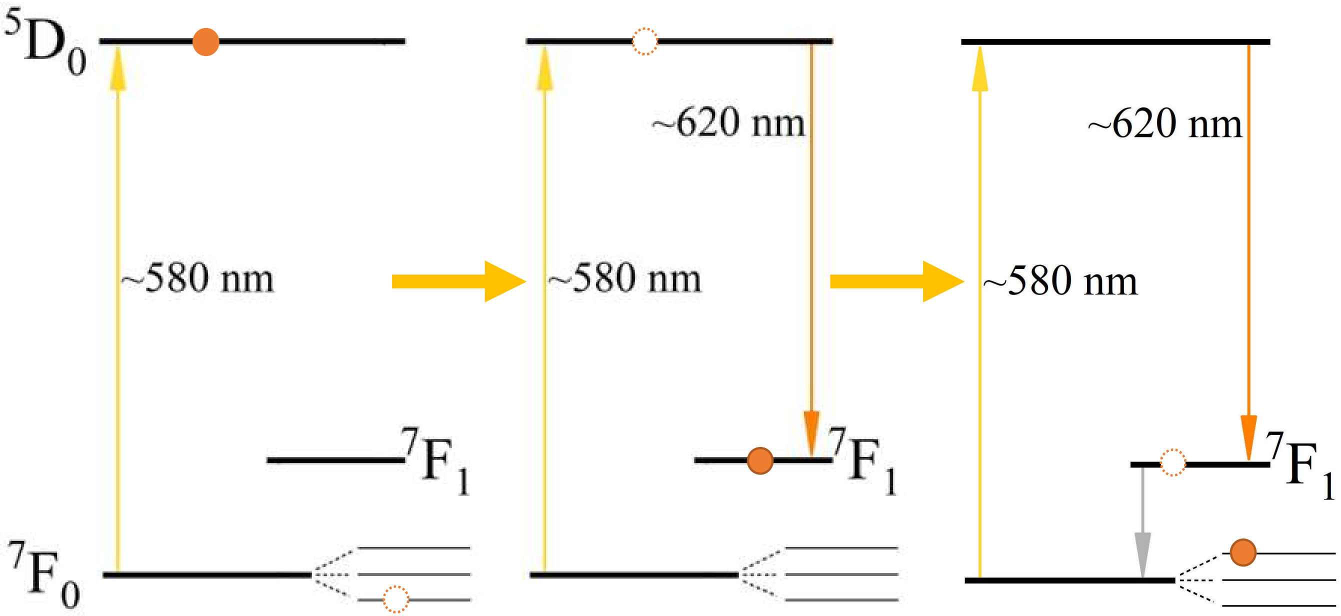
From the ground state to $^5D_0$

Spectral hole burning process



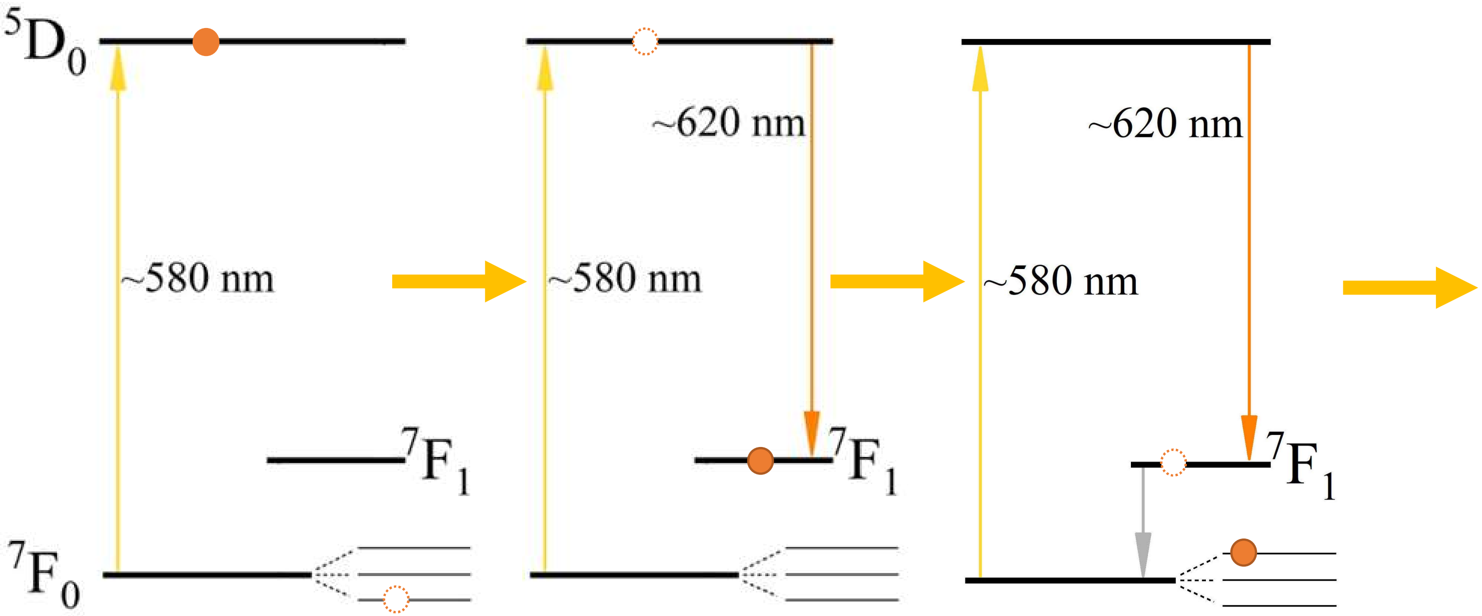
From the ground state to $^5D_0$ From $^5D_0$ to $^7F_1$

Spectral hole burning process

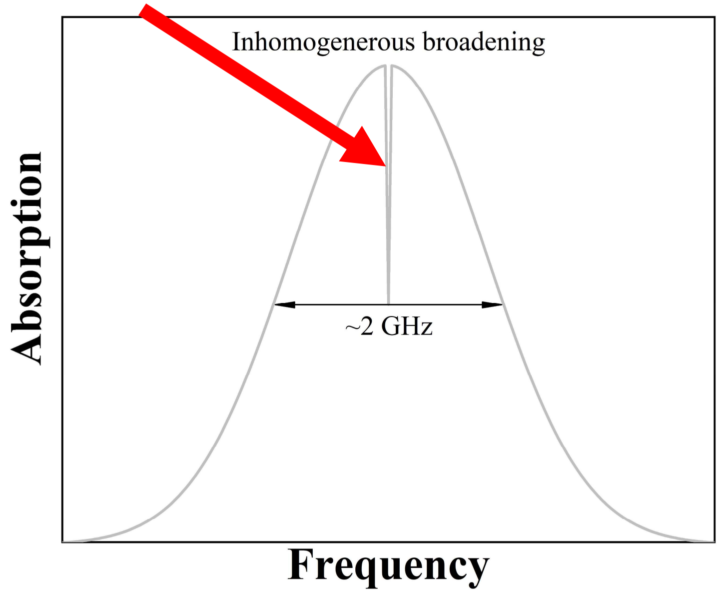


From the ground state to $^5D_0$ From $^5D_0$ to $^7F_1$ From $^7F_1$ to the ground

Spectral hole burning process

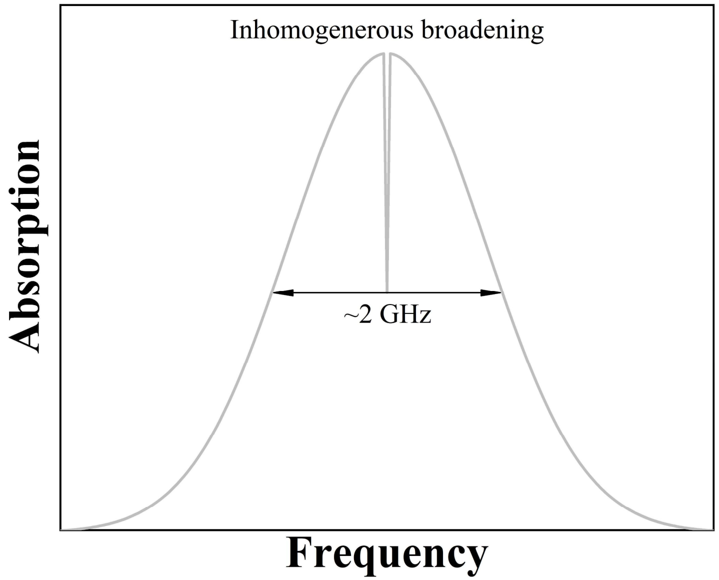


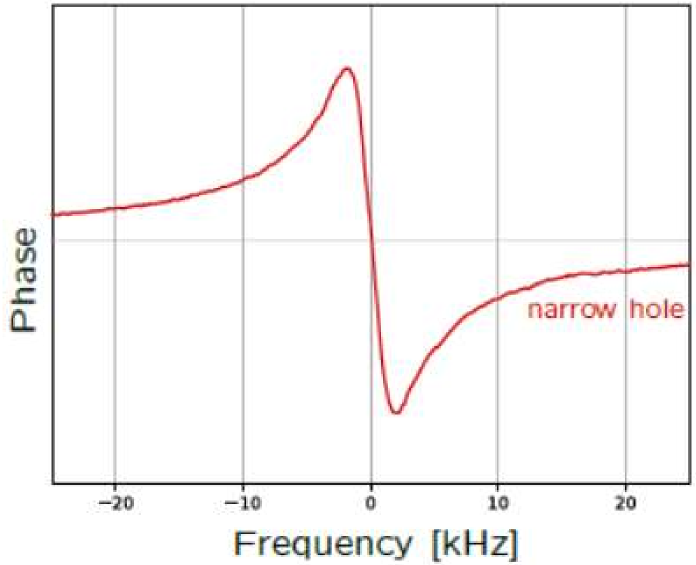
From the ground state to $^5D_0$ From $^5D_0$ to $^7F_1$ From $^7F_1$ to the ground



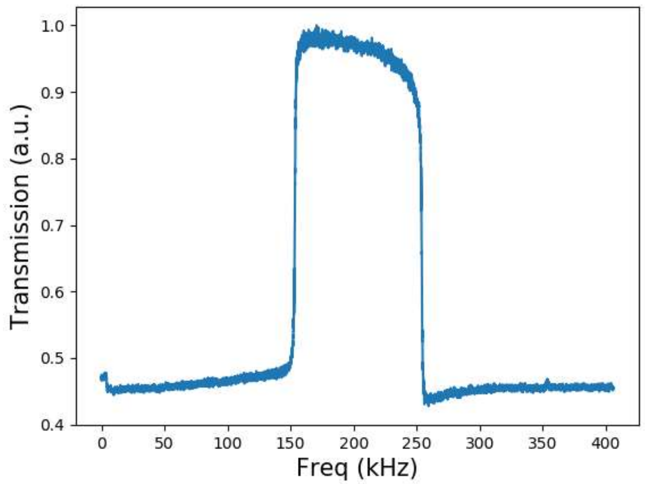
Hole life time: a few days

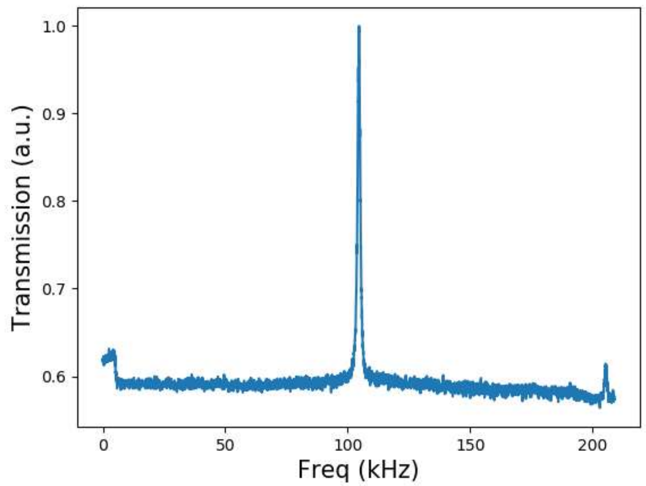
Kramers-Kronig relationship





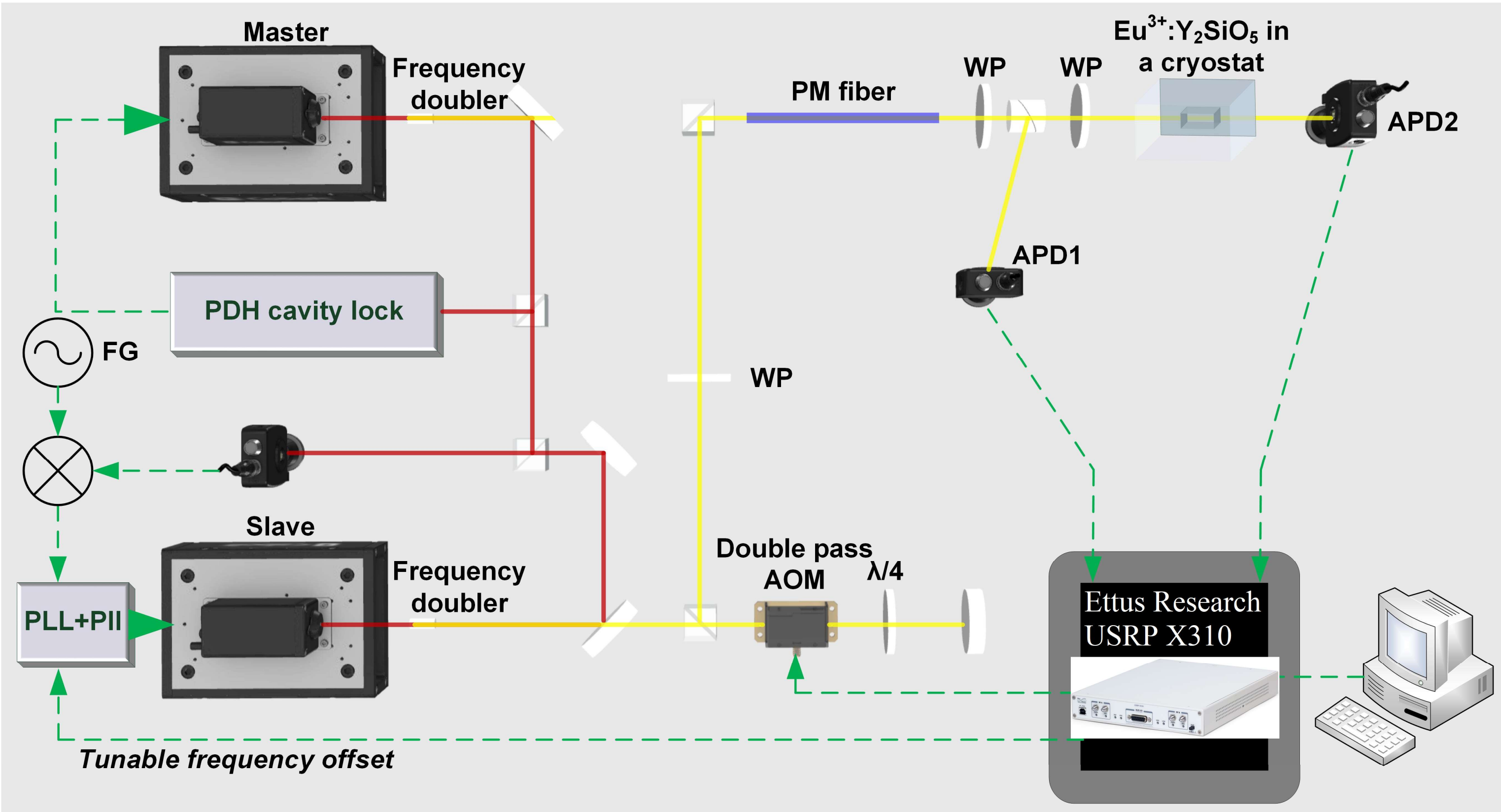
Typical spectral holes in our experiment to lock the laser



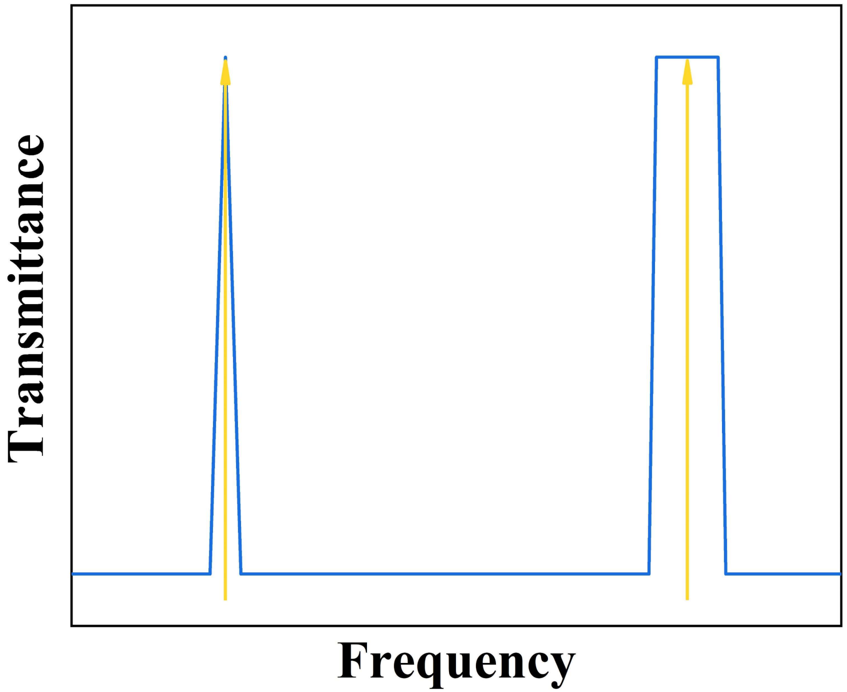


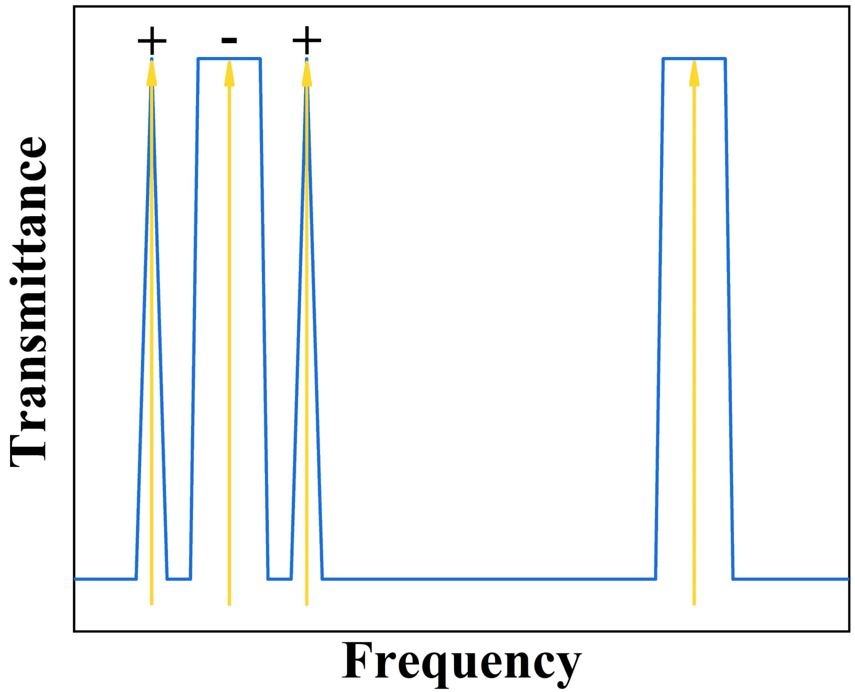
We can burn the holes with the patterns we need, which is different to the cavity solution.

Experimental scheme



Typical interrogation schemes





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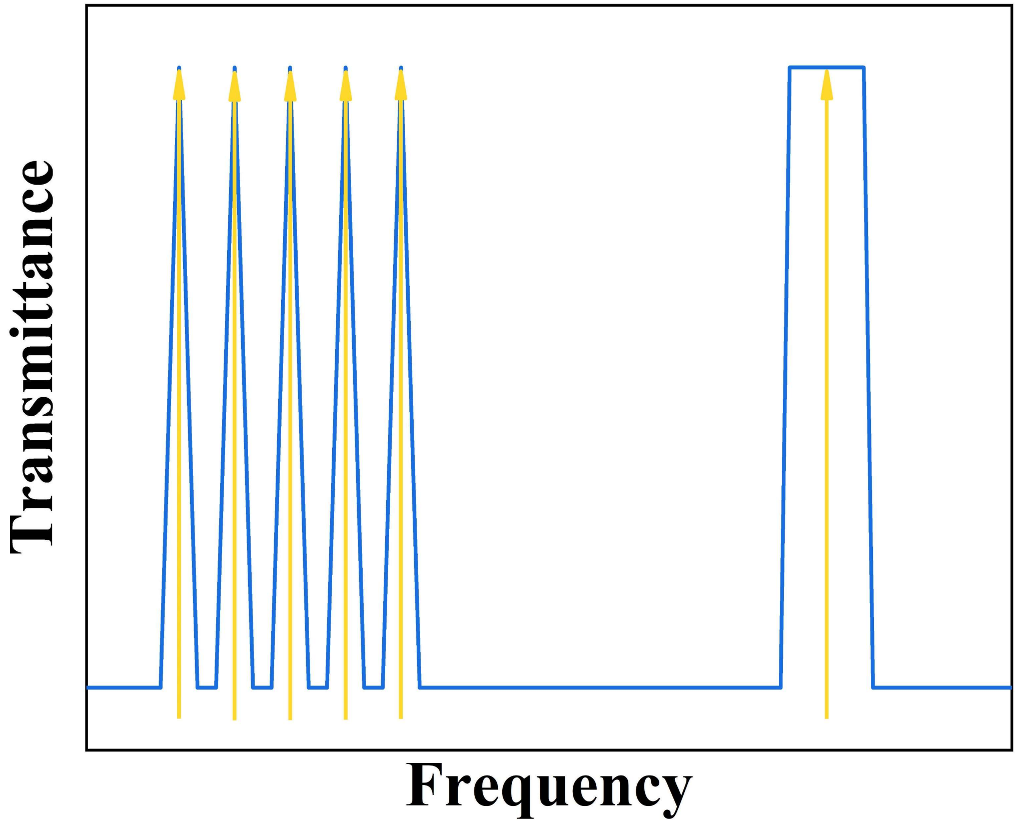
Multi-mode interrogation scheme

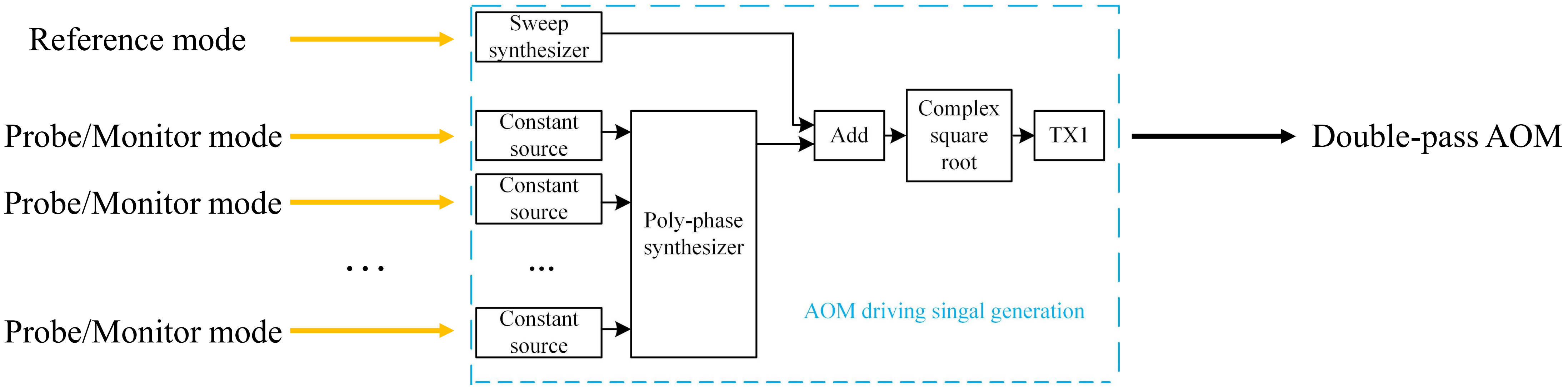


To realize SHB based ultra-stable laser, we need several RF signal generation and processing abilities:

1. Flexible optical frequency manipulation
2. Flexible multiple laser mode signal generation
3. Flexible and high-speed digital signal processing
4. …

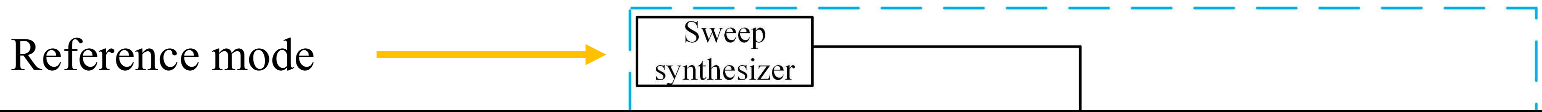
GNU Radio meets most of the requirements!

The simplified scheme of our flowgraph



Signal generation part

The simplified scheme of our flowgraph



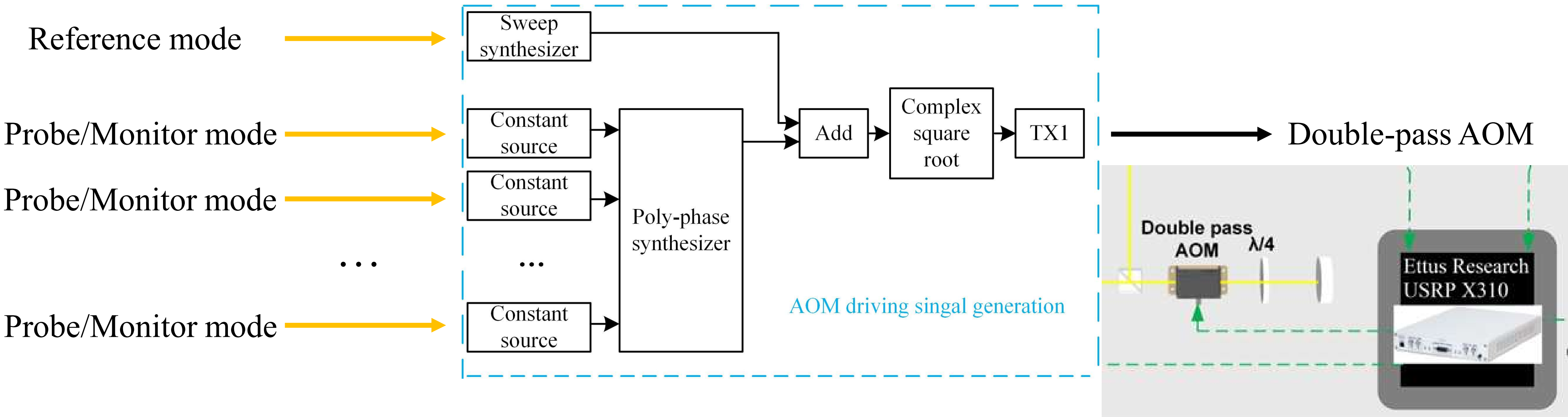

```
gr_complex *out = (gr_complex *) output_items[0];

for (int i=0; i<noutput_items; i++)
{
   out[i] = gr_complex(gr::fxpt::cos(d_phase>>32)*d_ampl, gr::fxpt::sin(d_phase>>32)*d_ampl);
   d_phase += d_phase_incr;
   d_phase_incr += d_phase_incr_incr;
}

return noutput_items;
```

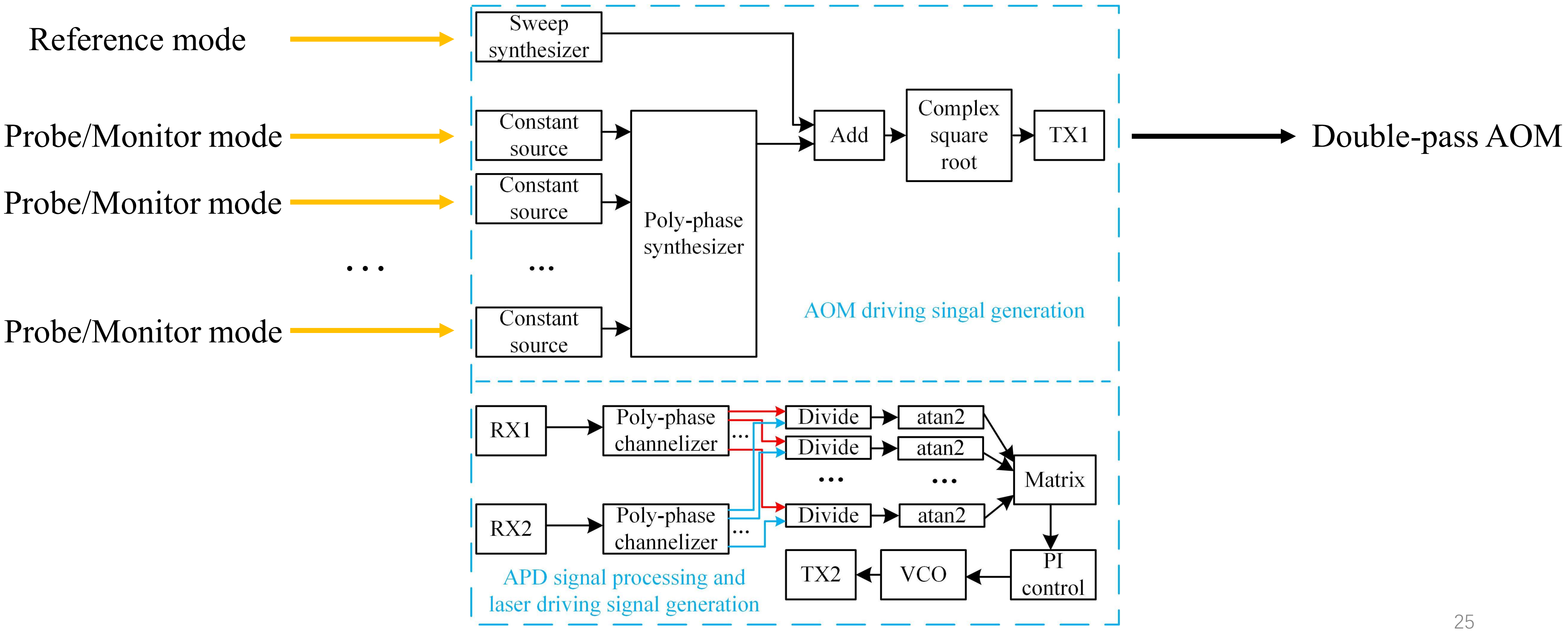
Signal generation part

The simplified scheme of our flowgraph

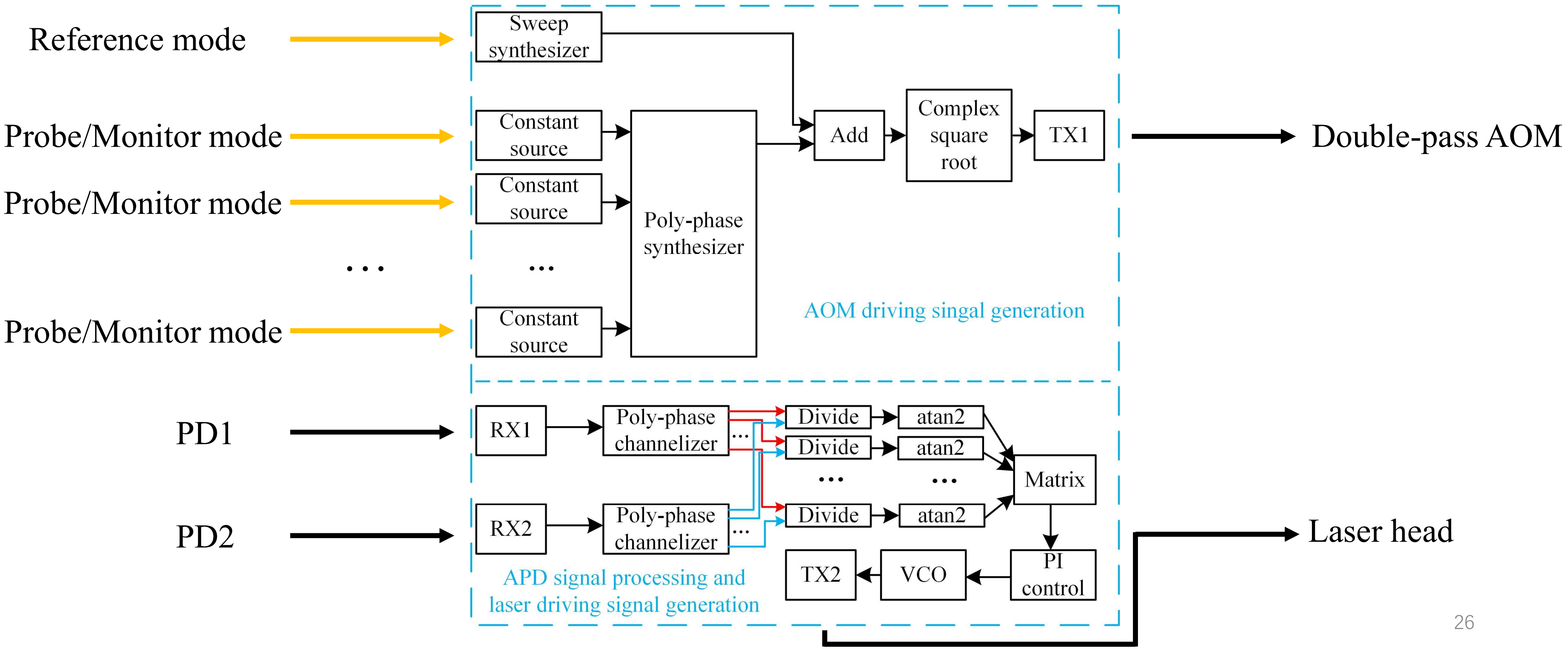


Signal generation part

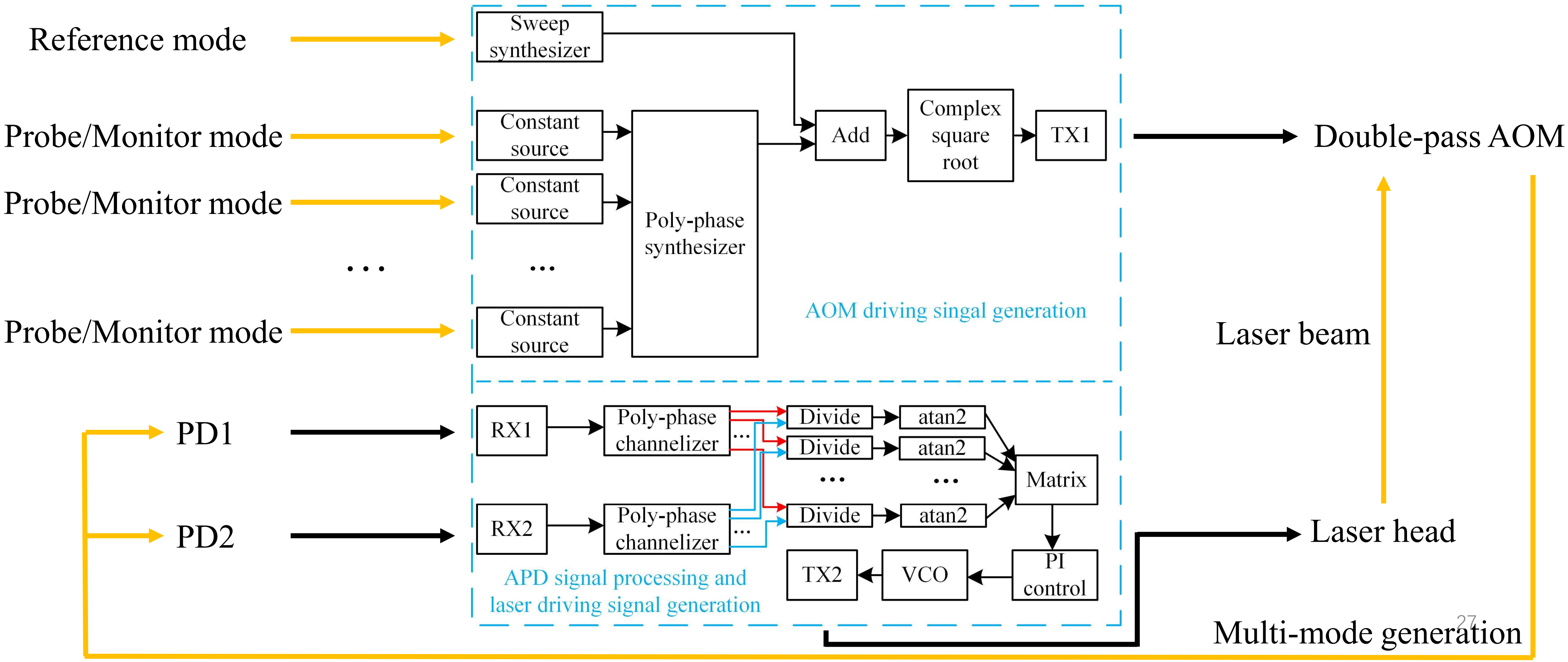
The simplified scheme of our flowgraph



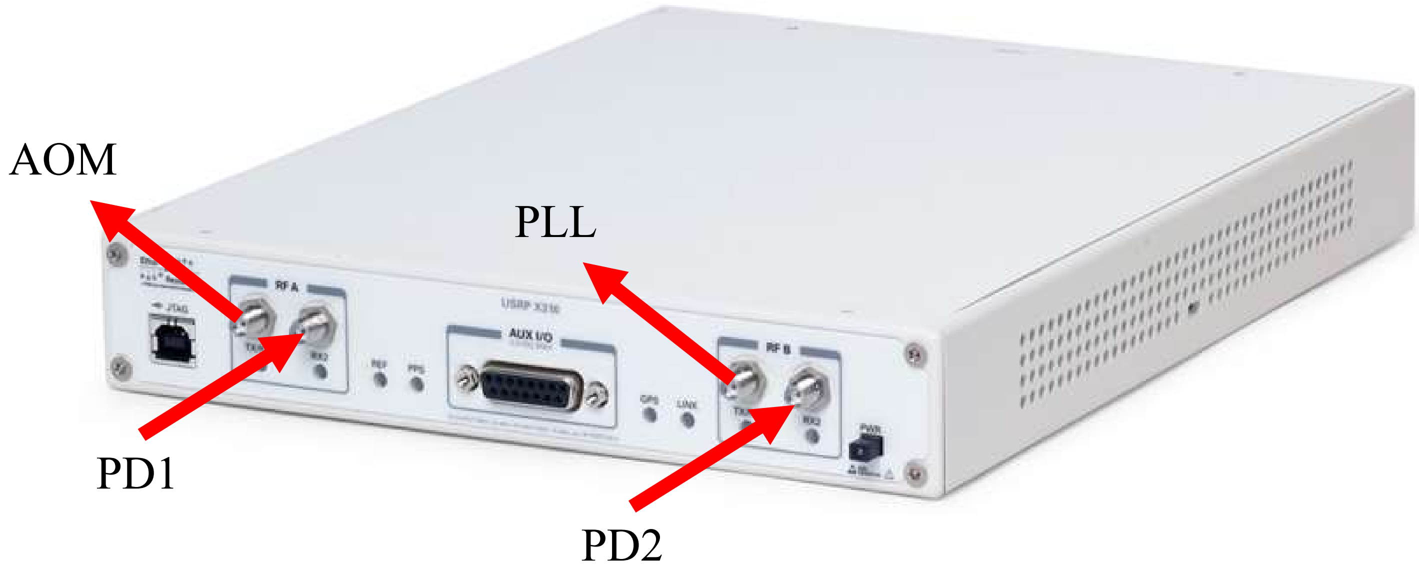
The simplified scheme of our flowgraph



The simplified scheme of our flowgraph

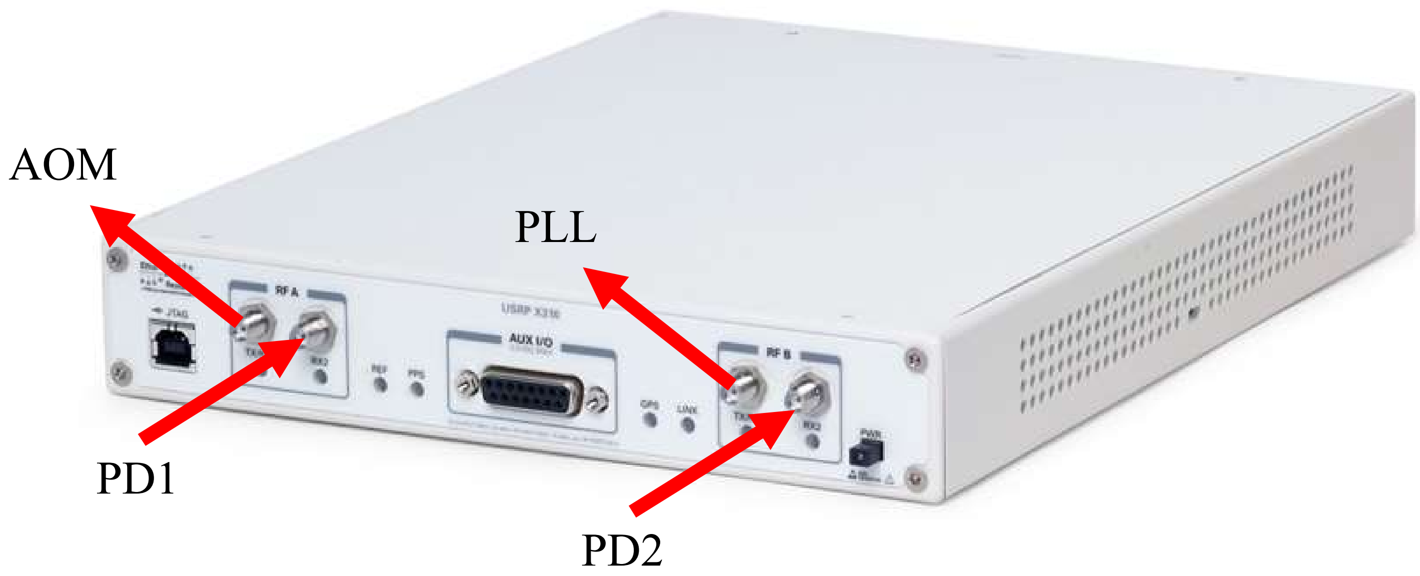


RX and TX



We use in our applications exclusively the BasicRX and BasicTX daughterboards, which simply provide (almost) direct access to the ADC and DAC through a balun transformer.

RX and TX



RX: Down converting the detected signal frequency from a few MHz to base band.

TX: Up converting the signal from the flowgraph run by the computer to the carrier frequency.

Synchronization of two RX ports

```
now = self.USRP_RX.get_time_now()
cmd_time = now + uhd.time_spec(1)
self.USRP_RX.set_command_time(cmd_time)
self.USRP_RX.set_center_freq(freq, 0)
self.USRP_RX.set_center_freq(freq, 1)
self.USRP_RX.clear_command_time()
```

RX to TX delay

The delay from RX to TX directly determines the locking band width of the control loop, which is very important for noise suppression.

The delay can be designated through:

```
now = self.USRP_RX.get_time_now()
t0 = now + uhd.time_spec(1)
dt = uhd.time_spec(delay_time)
self.USRP_RX.set_start_time(t0)
self.USRP_TX.set_start_time(t0+dt)
```

RX to TX delay

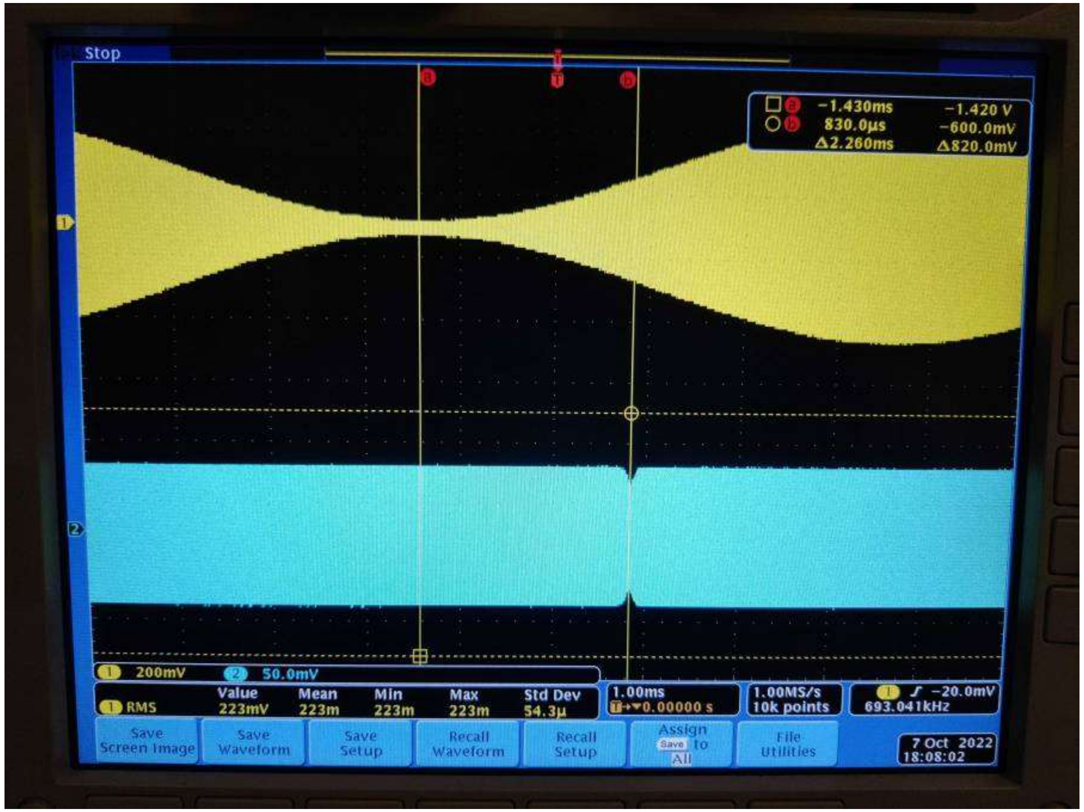
Due to the limited processing speed of the computer, a too low delay value could lead to a data package loss problem.

To improve this:

- We optimized the CPU core allocation for every block in the program.
- We overcame a possible bug (in version 3.8, the polyphase interpolator can not be pinned to a specified core) by a serial of bash commands.
- We turned off the hyper-threading technology (28 threads) to improve the performance of every single core. We have 14 cores in our PC, so with the hyper-threading technology, we have 28 threads.

RX to TX delay

Finally, we got a minimum loop delay of ~2 ms.



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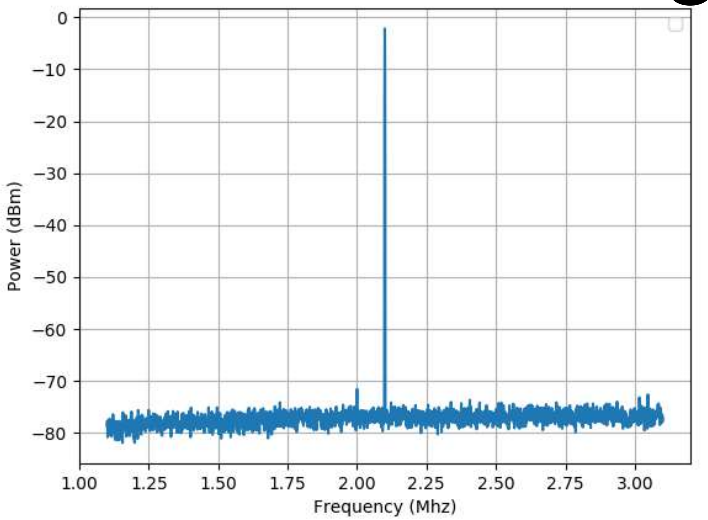
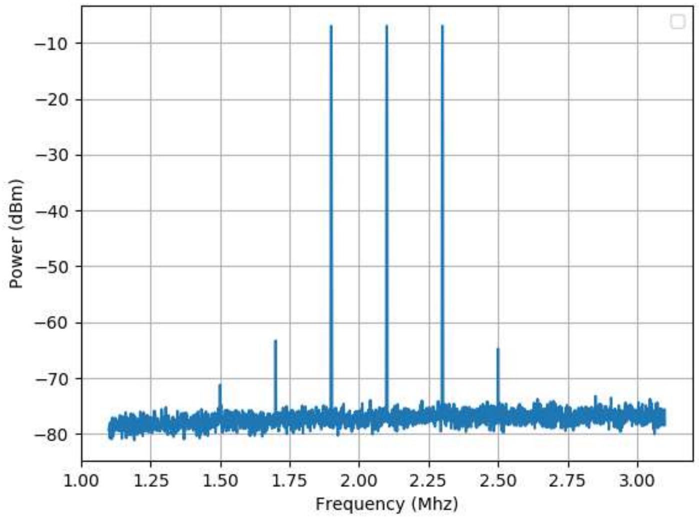
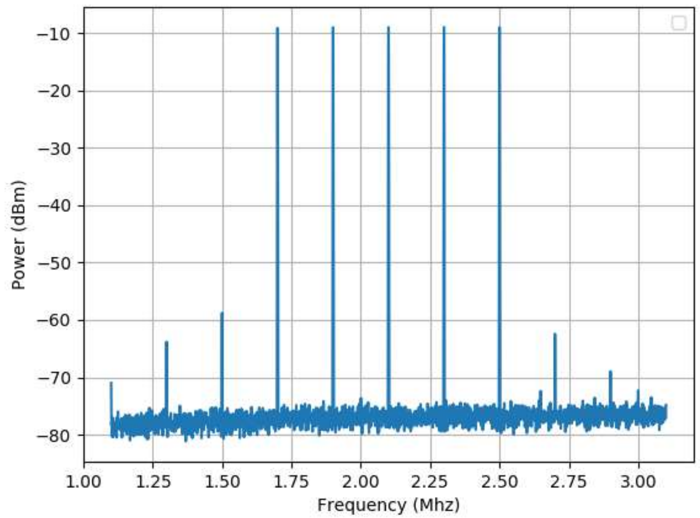
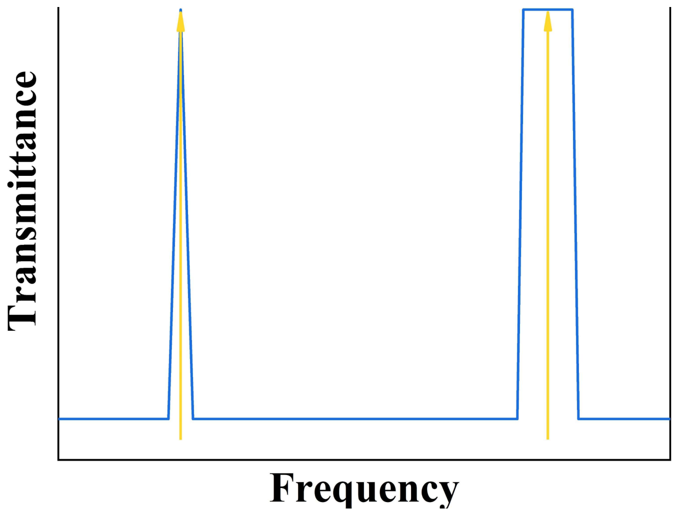
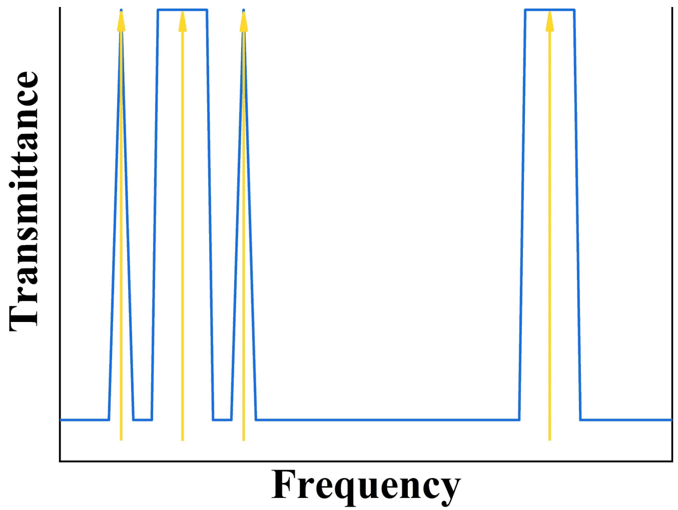
Multi-mode laser generation

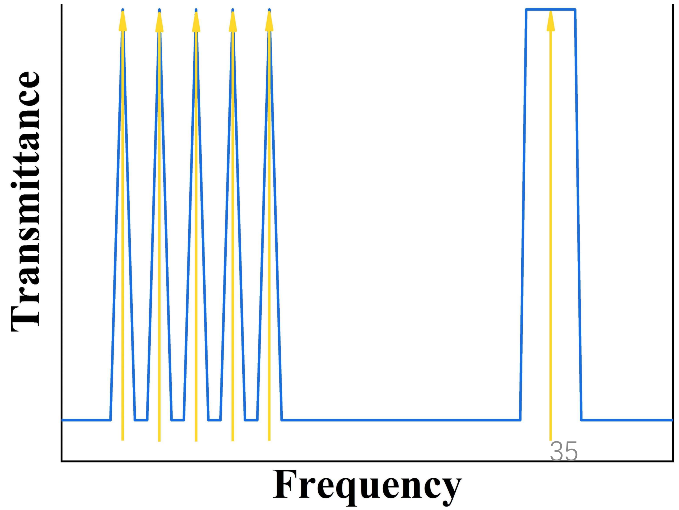




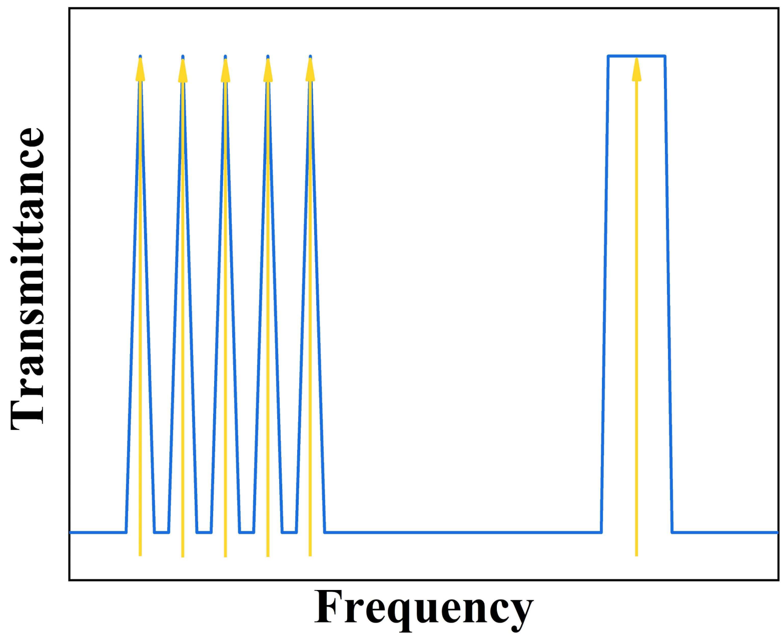


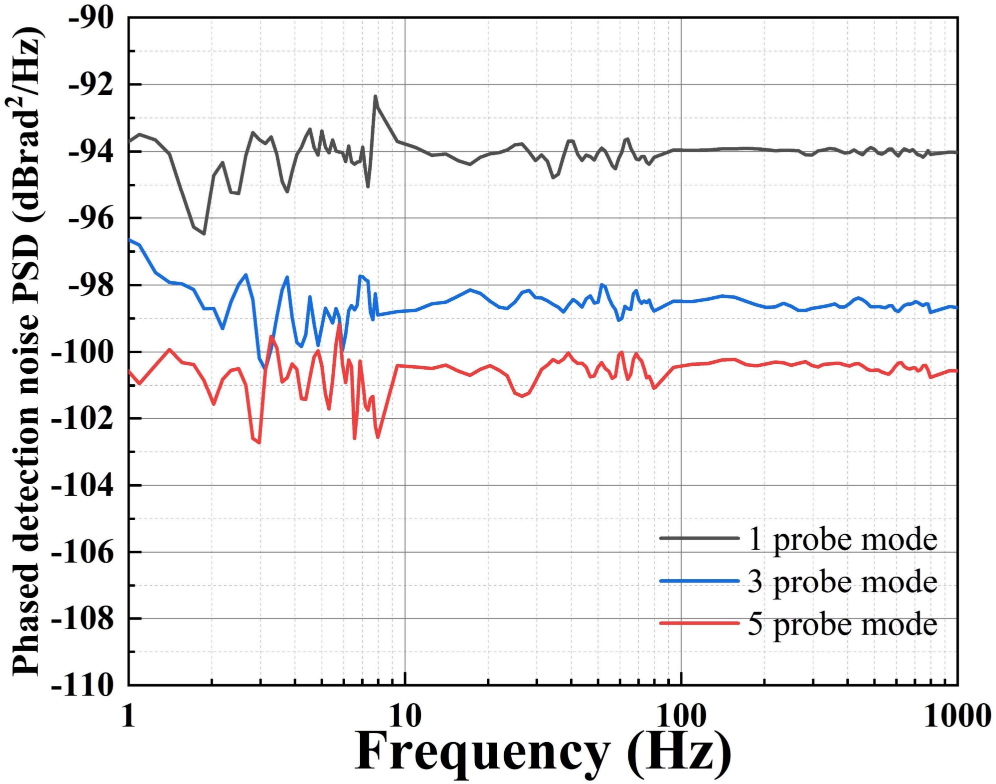




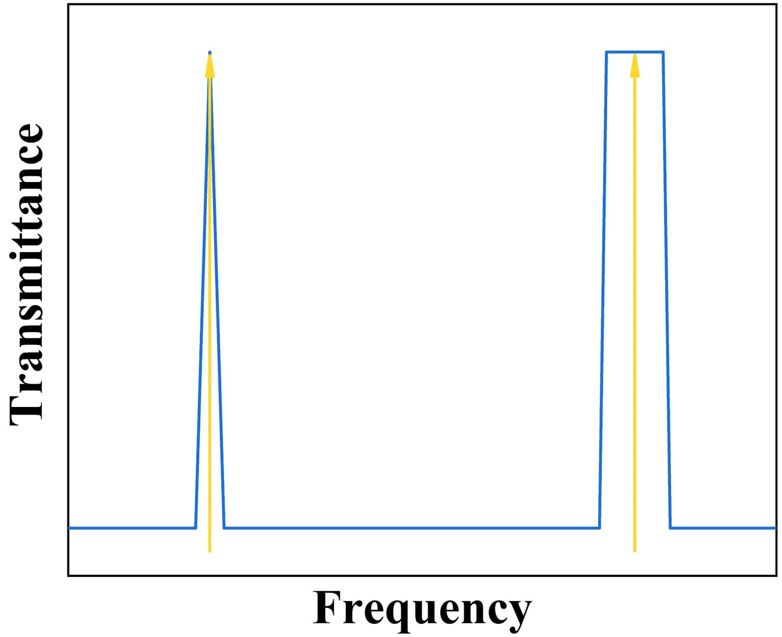


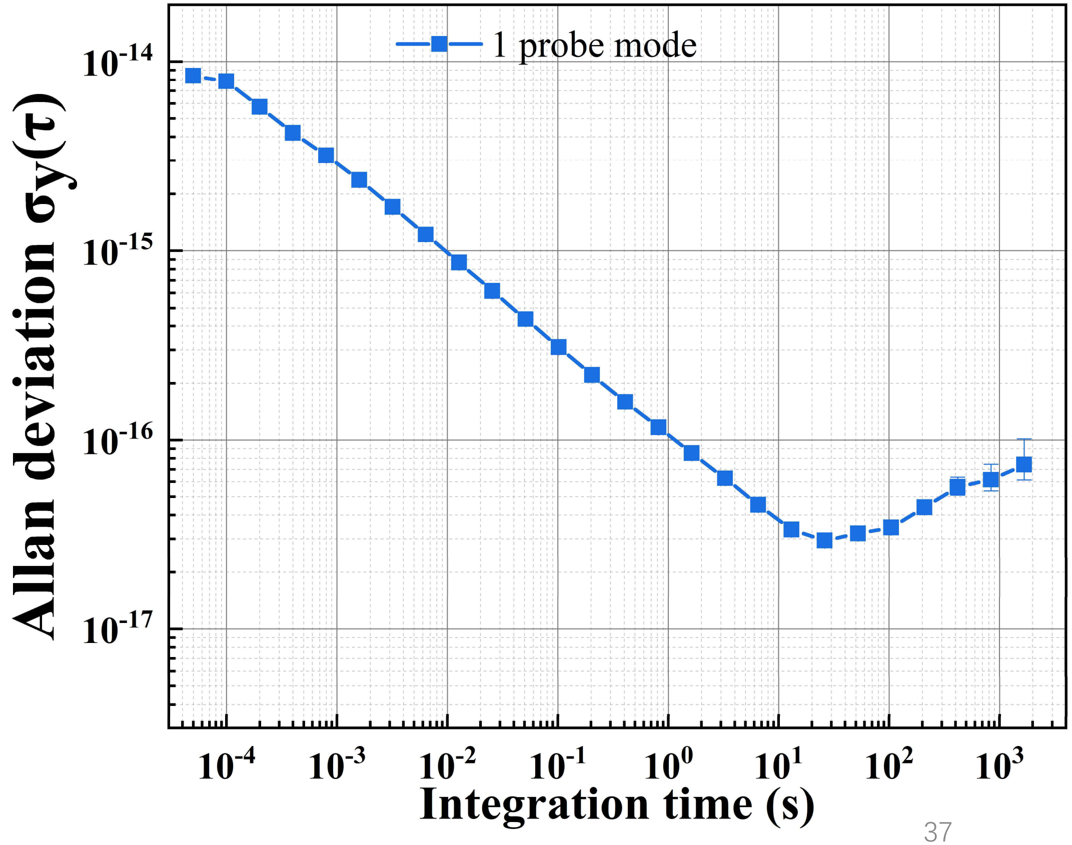
Multi-mode interrogation results (no monitor mode)



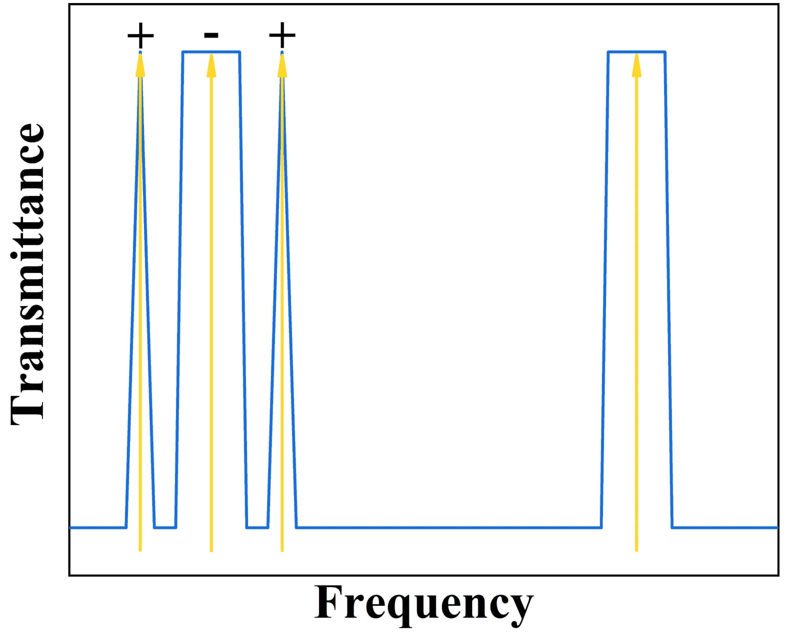


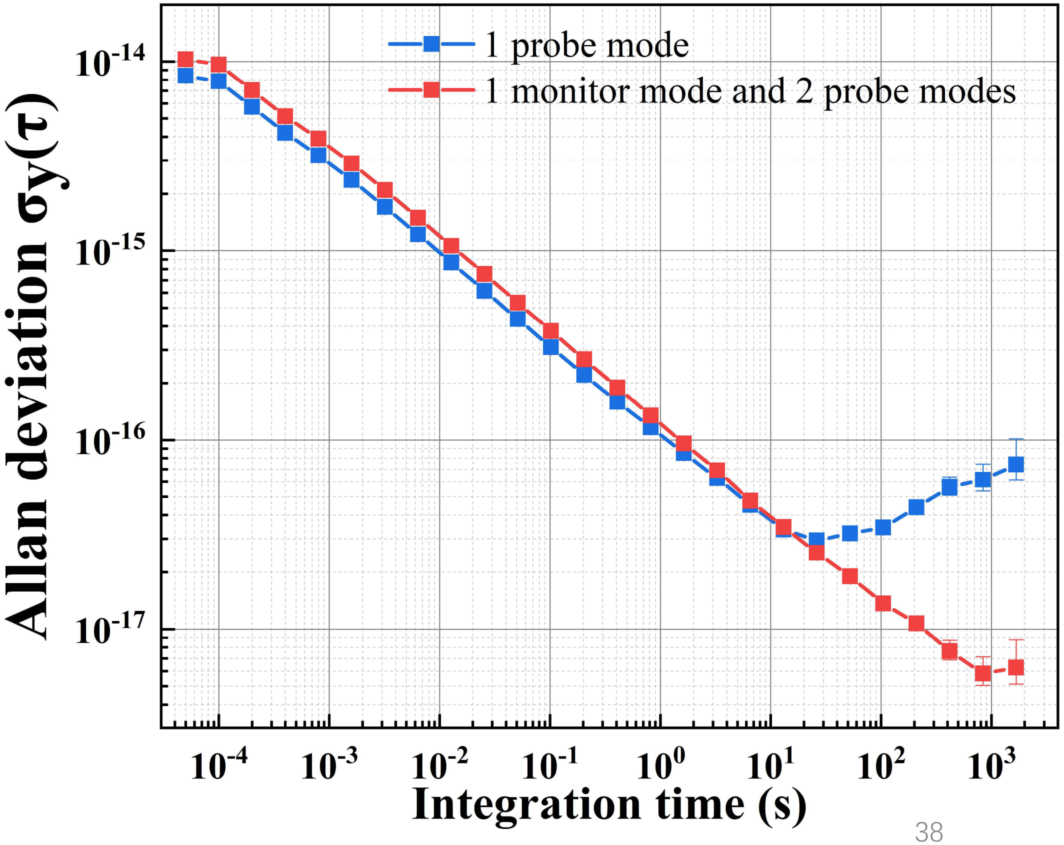
Multi-mode interrogation (with monitor mode)



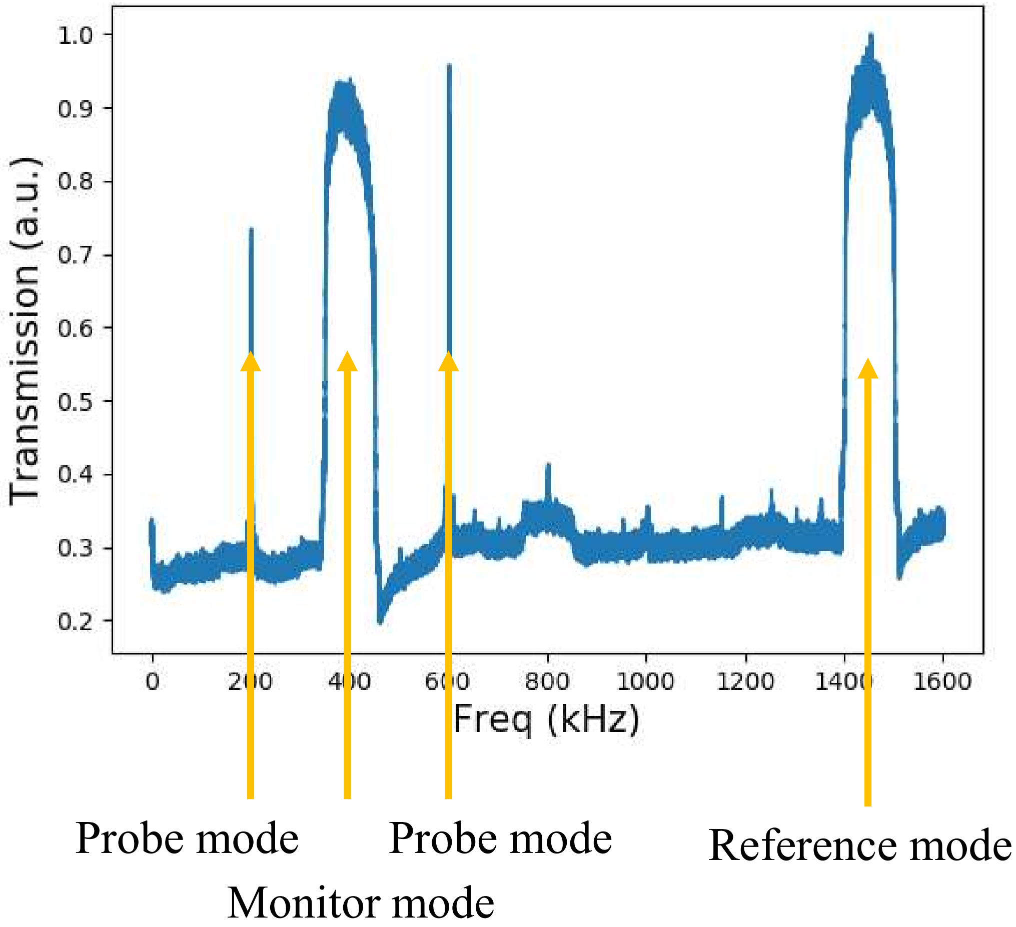


Multi-mode interrogation (with monitor mode)

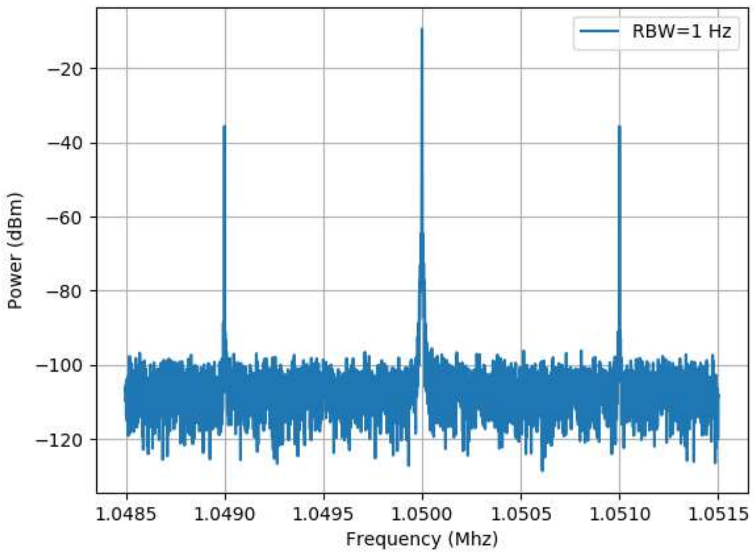




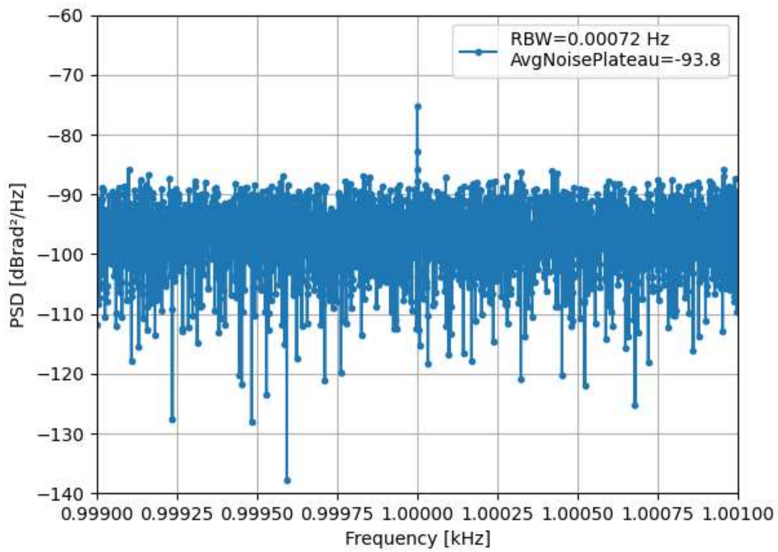
Real spectral hole patterns



AMPM noise rejection (10% amplitude modulation depth)



AM spectrum



Phase noise high resolution PSD

We get a PM response of $4.8*10^{-5}$ rad per relative AM

Thank You!

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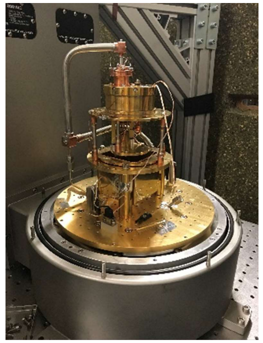

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OC 18

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