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High Resolution Electronic Measurements in Nano-Bio Science

ADVANCED LOCK-IN USES IN PHOTONIC APPLICATIONS
Dithering and pilot tones

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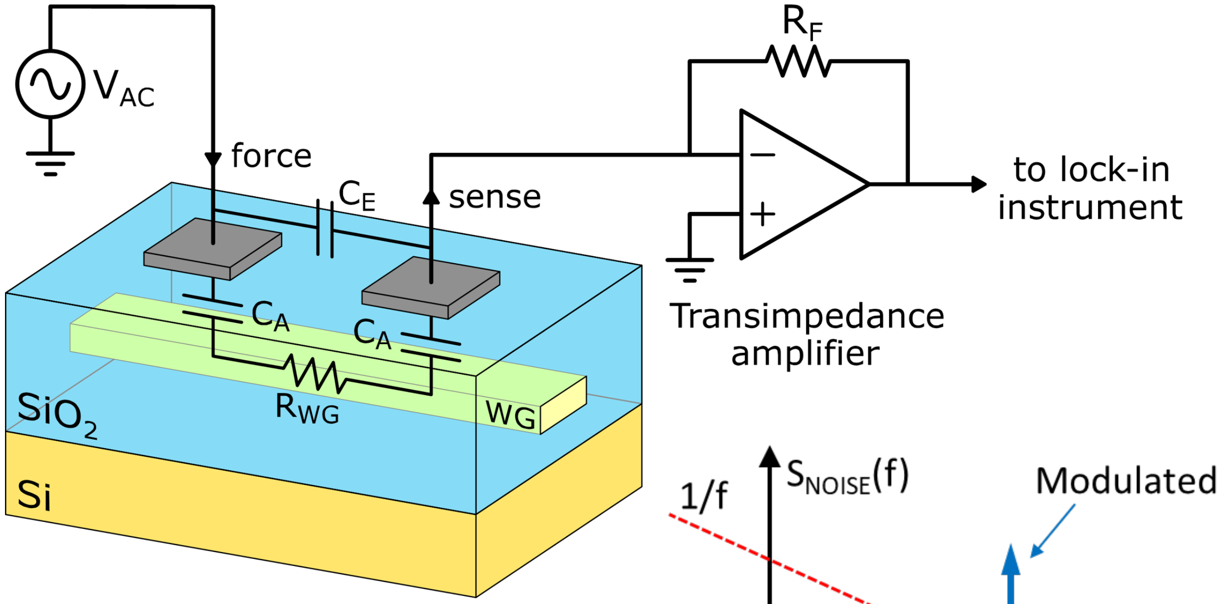
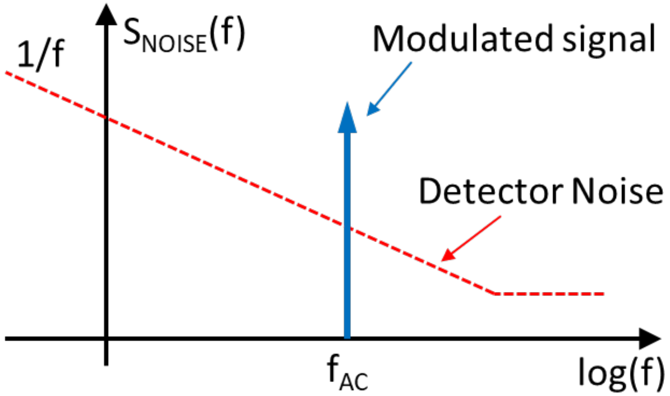
June 6th 2023

The lock-in technique in photonic applications

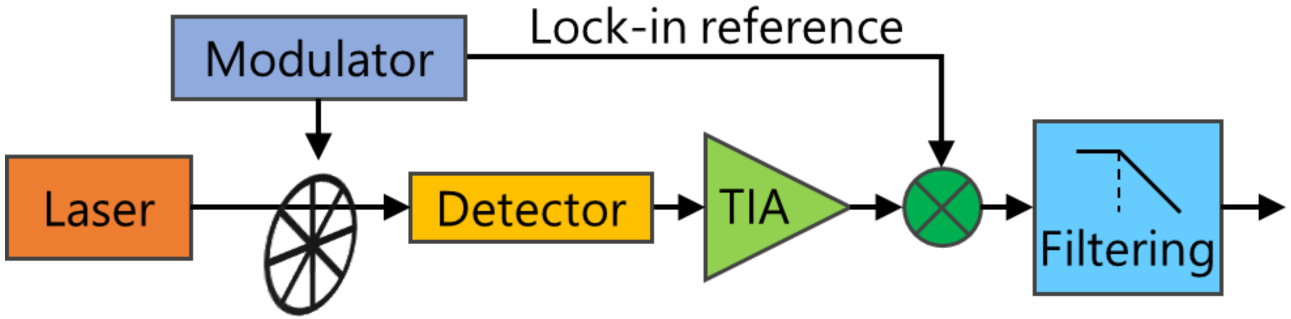
The lock-in technique can be used for sensor readout:

- Bypass access capacitance of CLIPPs.
- Improve readout resolution with WG-integrated photoconductors.
- In general, escape from 1/f noise of readout electronics.





Is there any other possible use of the lock-in approach in photonics?



The need for control electronics

Example: detuning of a ring resonator

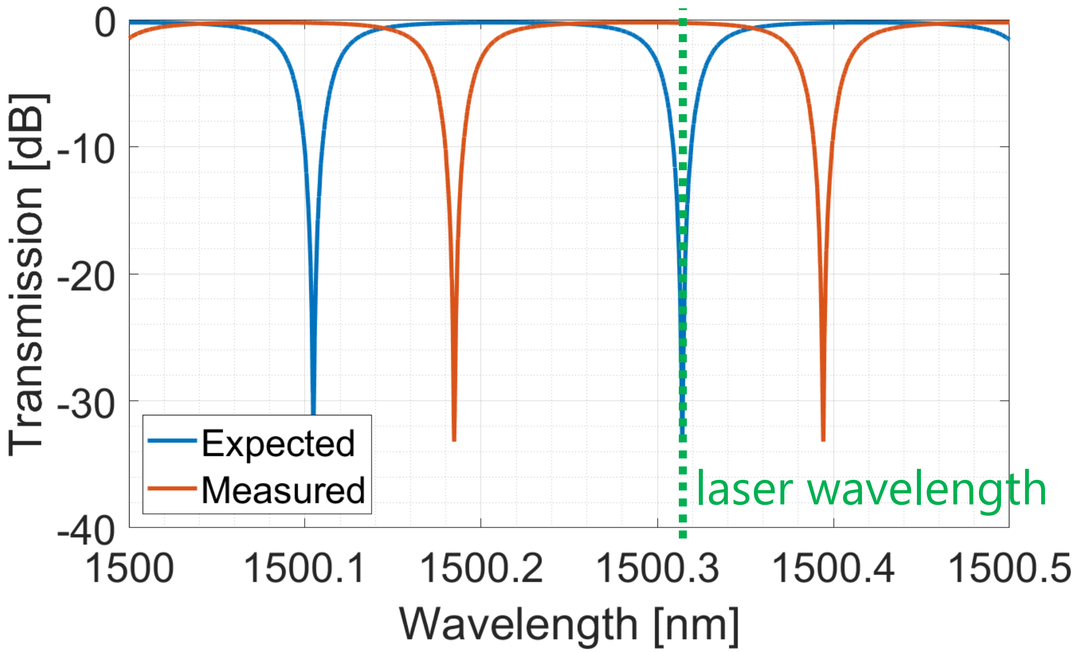
- Temperature sensitivity:

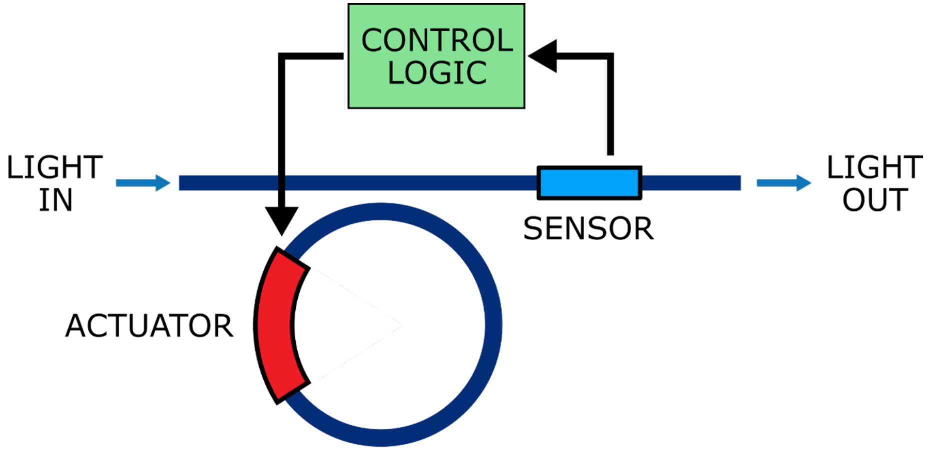
$\Delta T = 1K \longrightarrow$ $\Delta\lambda = 80pm$, $\Delta f = 10GHz$

- Sensitivity to fabrication tolerances:

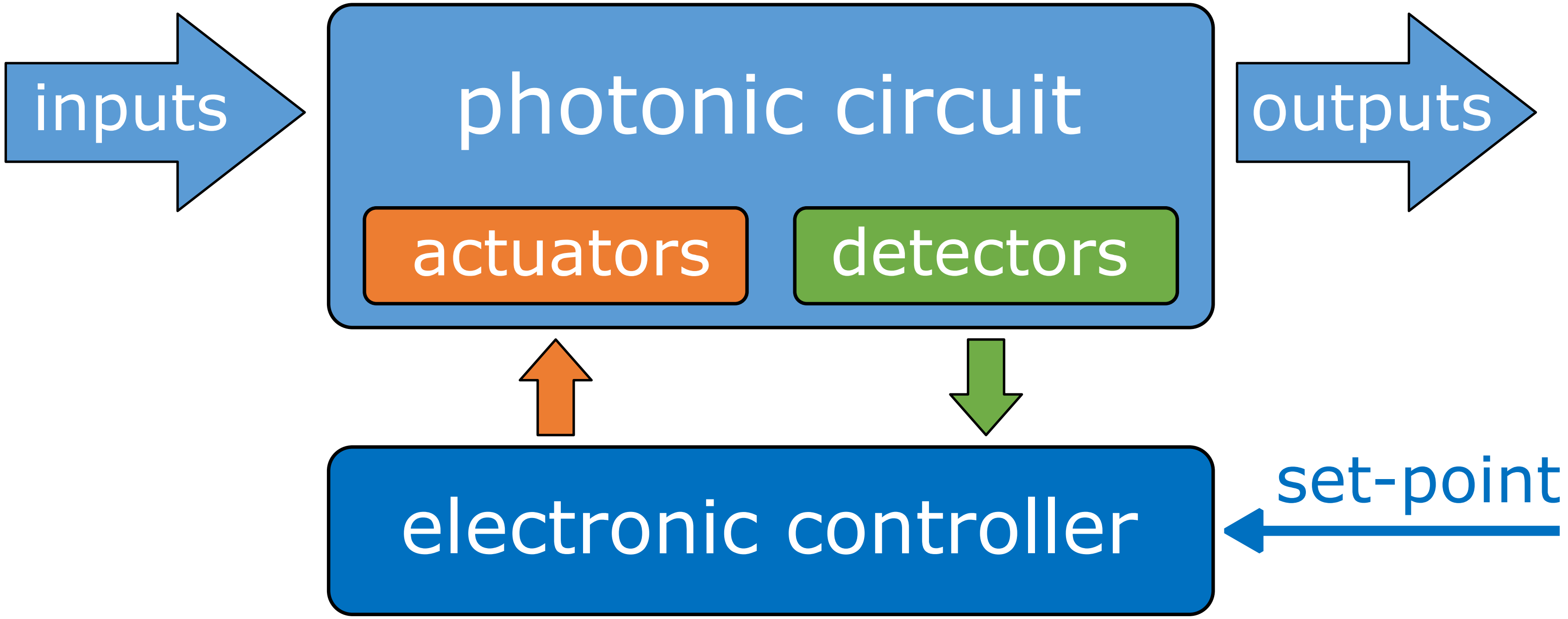
0.1 nm waveguide width mismatch $\longrightarrow$ $\Delta\lambda = 80pm$, $\Delta f = 10GHz$

The control electronics makes the photonic device behave as intended in the design phase.





Control strategies for photonic circuits



<u>Requirements for an effective control strategy for complex PICs:</u>

- Easy implementation on multiple devices
- No calibration required
- Insensitive to reciprocal coupling of cascaded devices

Possible control strategies

In many common applications a photonic device needs to be tuned to maximize or minimize light at its output. This can be obtained in several ways.

Perform a calibration of the system:

- Sweep the heater voltage to observe the device transfer function and find the correct tuning point.

→ Sensitive to variations of the chip temperature and of the input light power.

Stepper algorithm:

- Store the current sensor readout.
- Change the actuator command to shift the device transfer function in one direction.
- Perform a new readout and compare it with the old one, to update the direction of the next move.
- Repeat

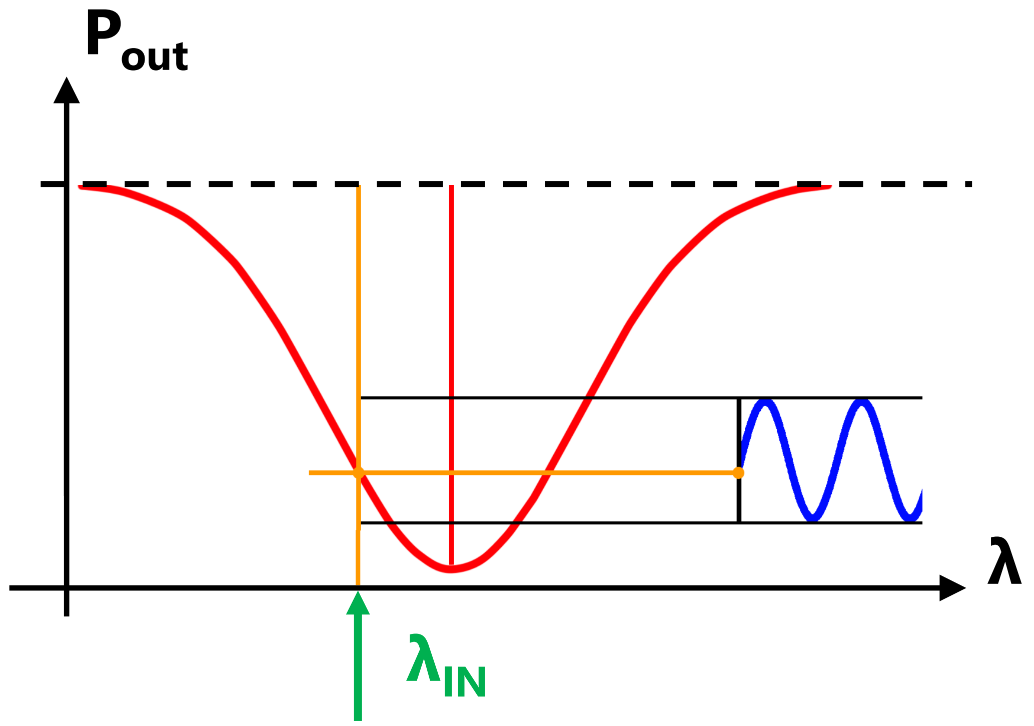
→ Sensitive to variations reciprocal coupling of cascaded devices.

The dithering technique (1/2)

Working principle:

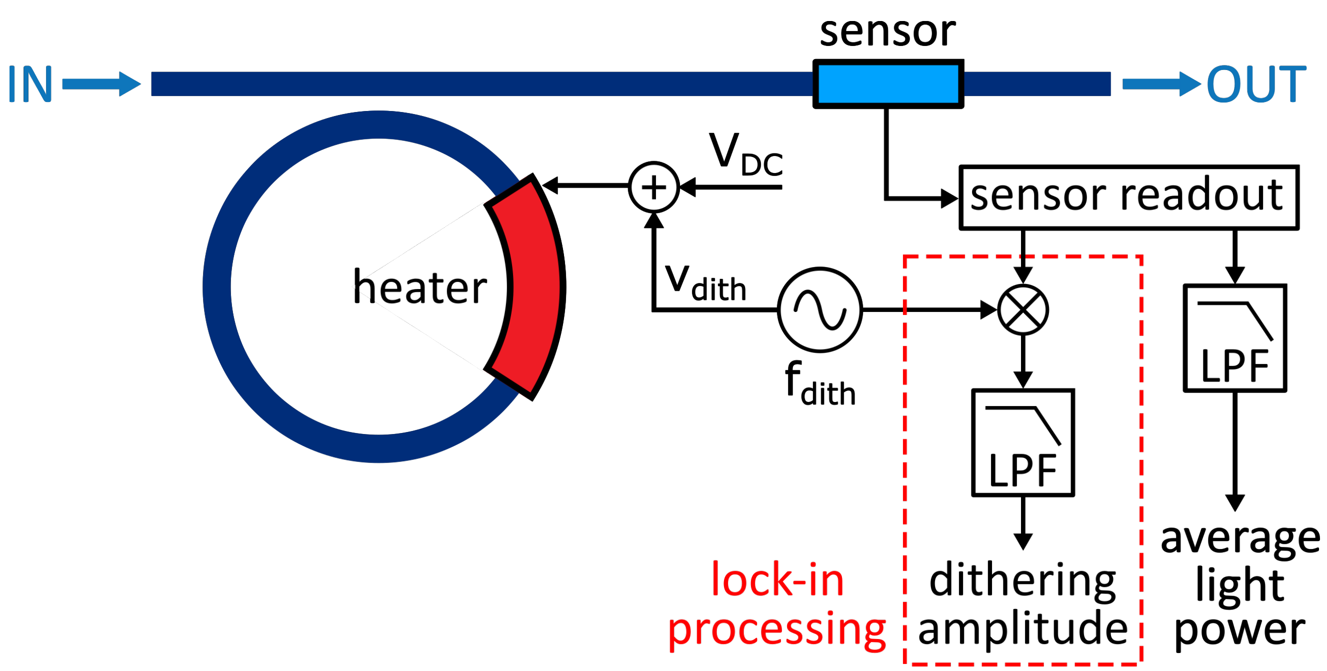
- Apply a small modulation (1mV to 100 mV) to the bias voltage of the actuator.
- Monitor the amplitude of the optical modulation at the output with a light sensor.

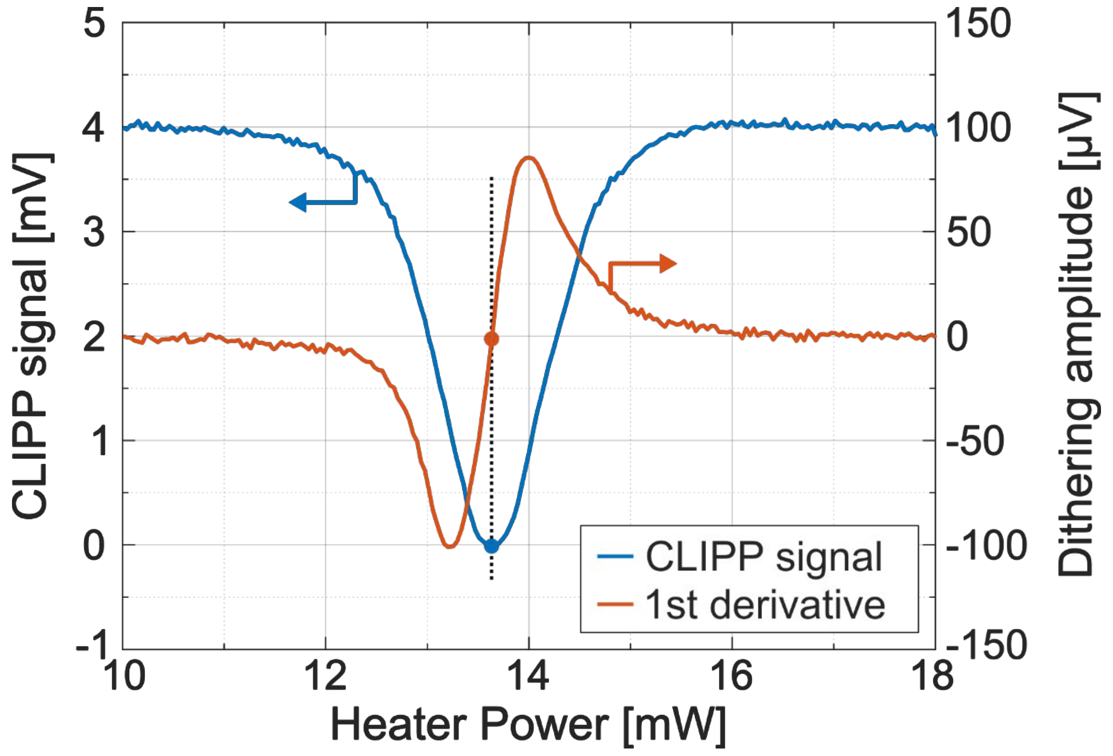
The output modulation is proportional to the device transfer function first derivative!



$$P_{OUT}(V_{ACT}) \approx P_{OUT}(V_{BIAS}) + \left.\frac{\partial P_{OUT}}{\partial V_{ACT}}\right|_{V_{ACT}=V_{BIAS}} \cdot [V_{DITH} \cdot \sin(2\pi f_{DITH} t)]$$

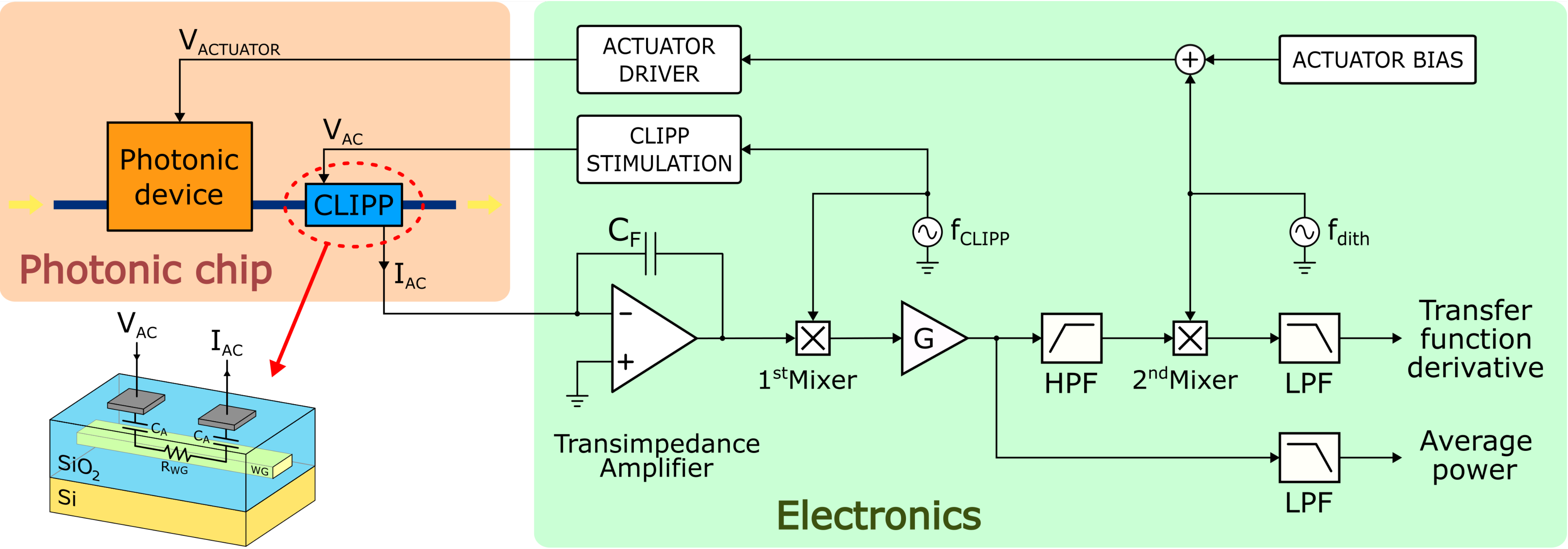
Dithering extraction with lock-in technique

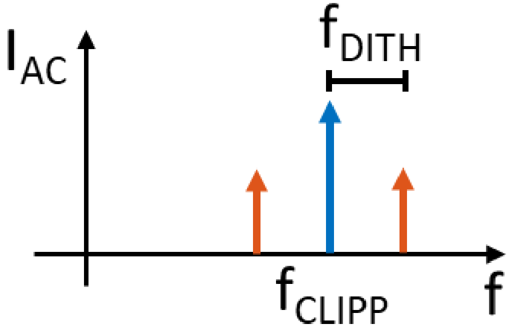




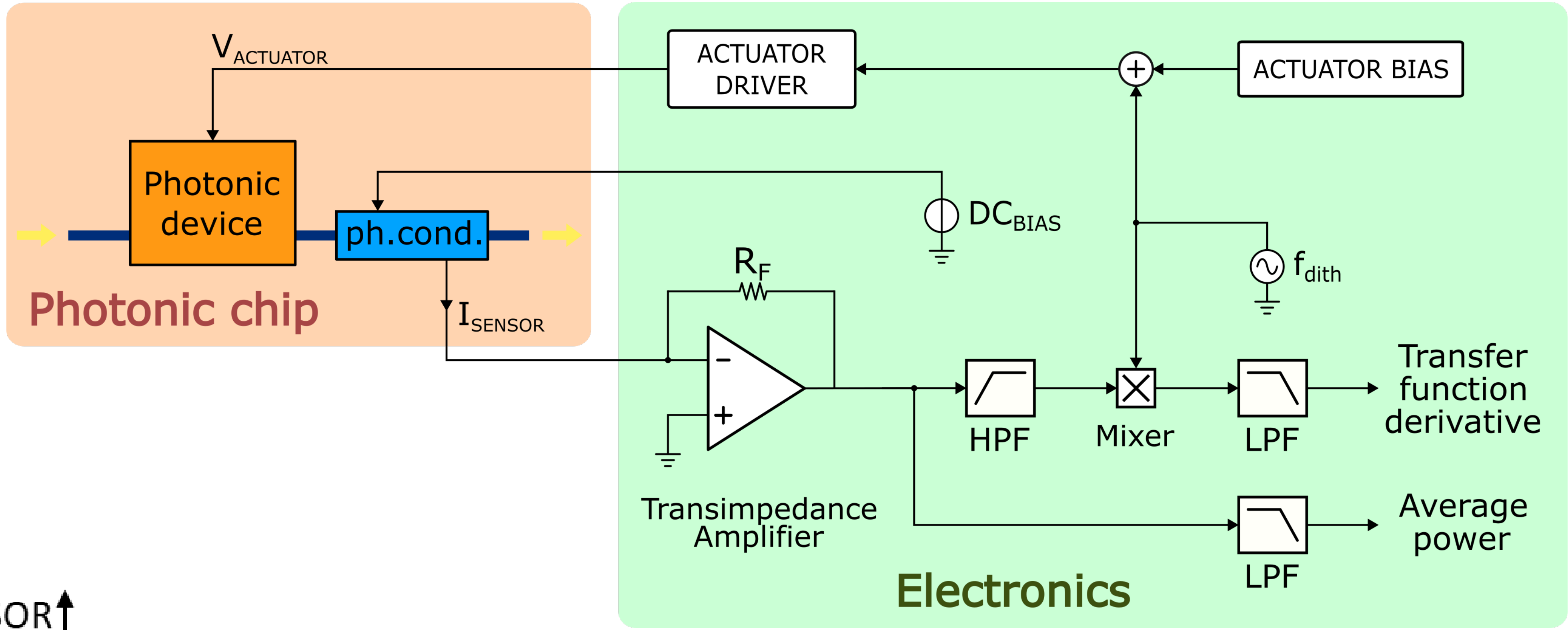
- The stationary points of the transfer function correspond to zero dithering amplitude.
- By choosing a different dithering frequency for each device, reciprocal coupling between cascaded devices is avoided thanks to the lock-in frequency selectivity!

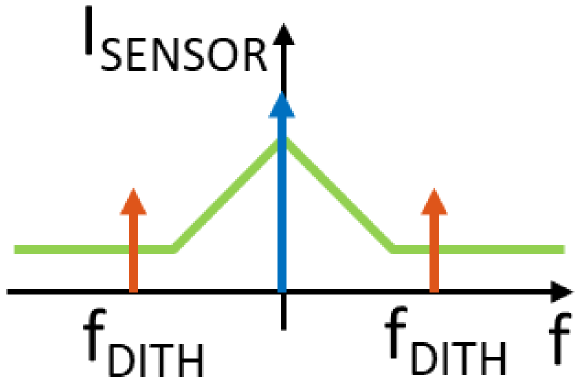
Dithering with CLIPPs





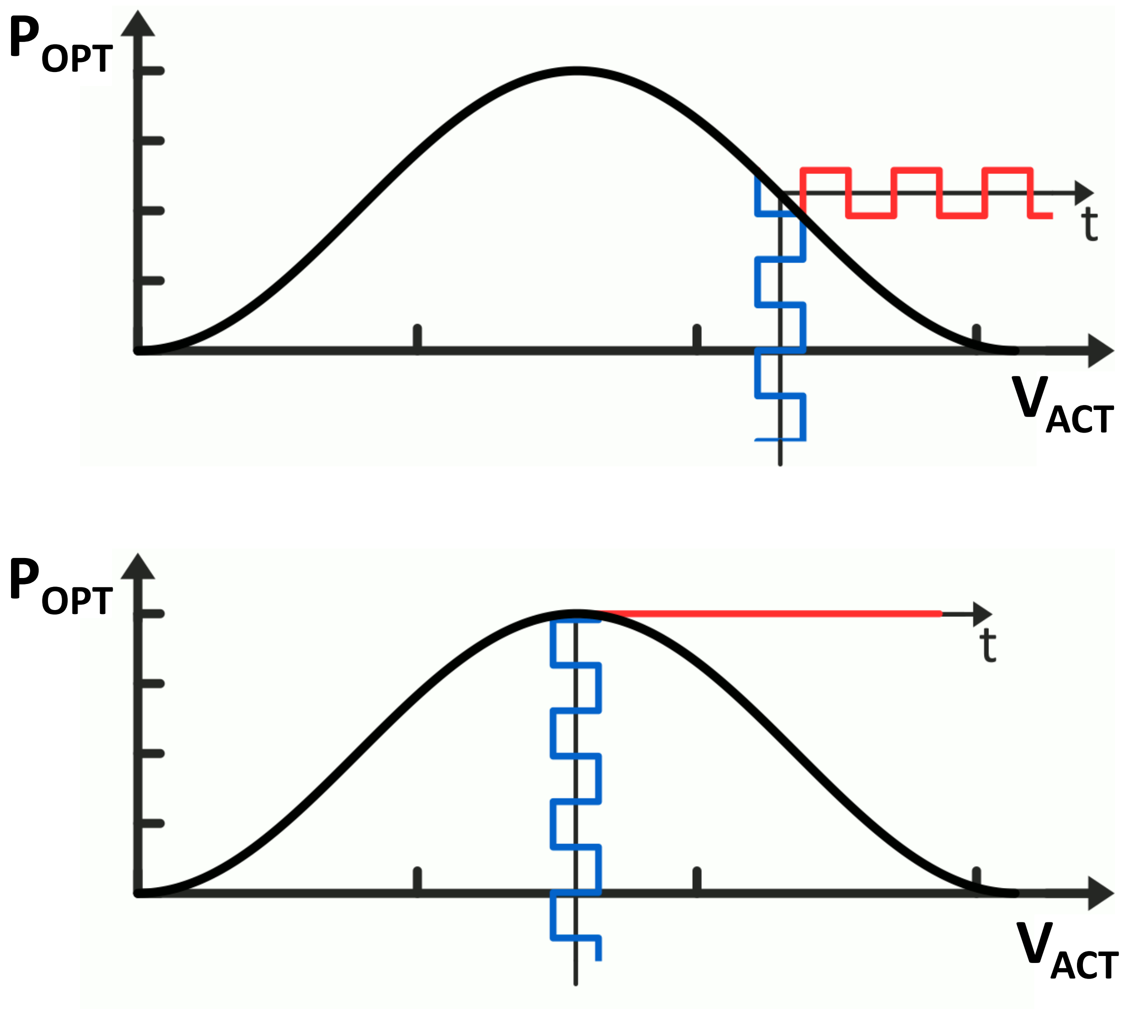
A cascade of two mixers is needed to downconvert and extract the dithering signal with the lock-in technique from the CLIPP readout.





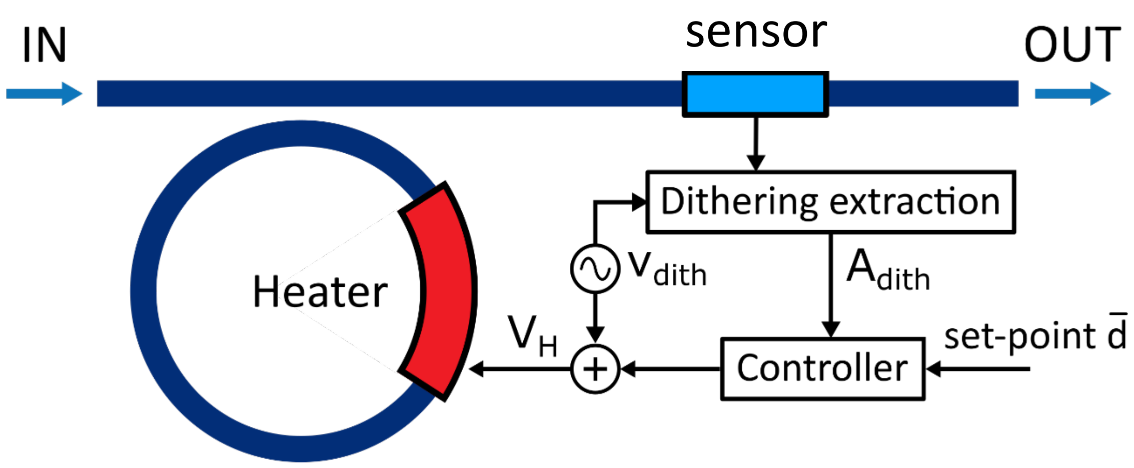
Bias the detector with a constant voltage, apply dithering to the heater and demodulate at f_{DITH} the sensor readout. This also allows to get away from the detector 1/f noise.

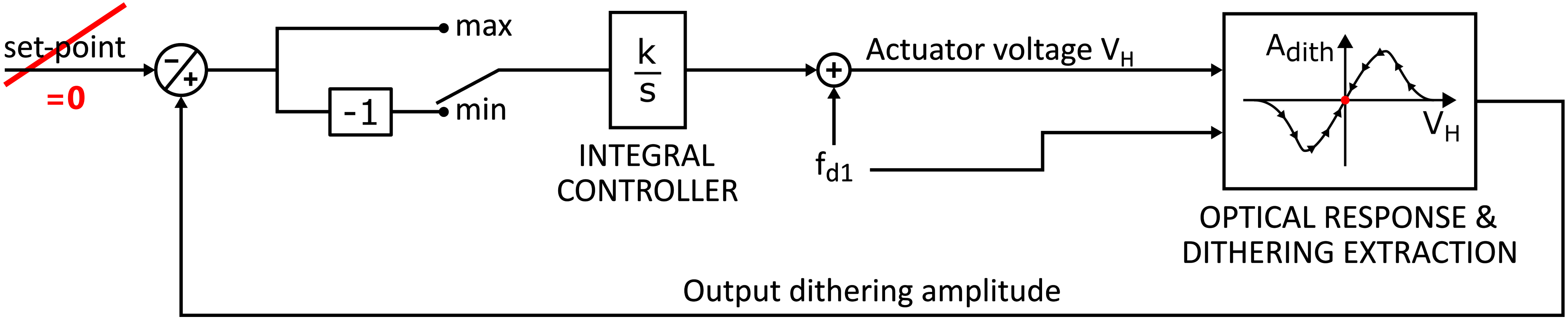
- The condition of zero dithering amplitude does not depend on:
  - Temperature
  - Average light power in the device
- The sign of the dithering signal (after demodulation) indicates the direction of the target stationary point.



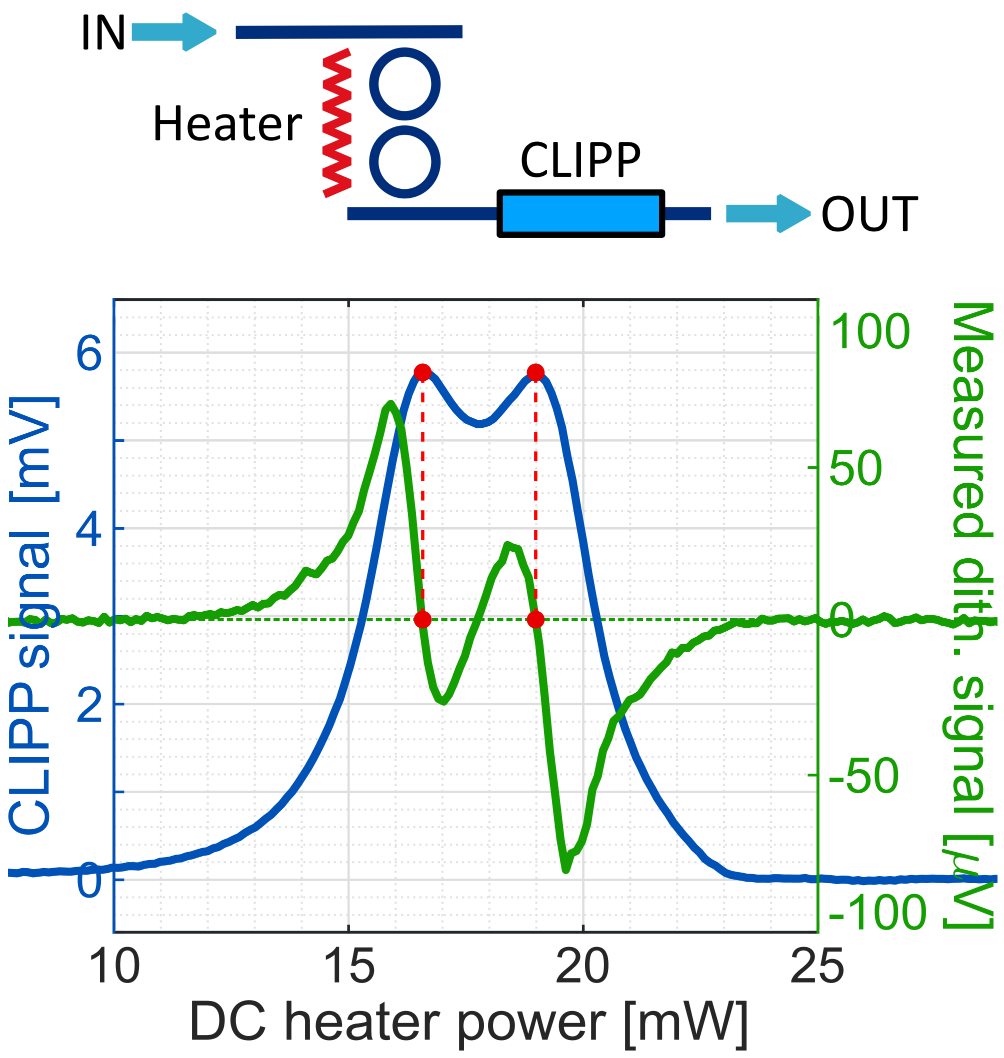
<u>The dithering information can be effectively used to stabilize the device without any calibration!</u>

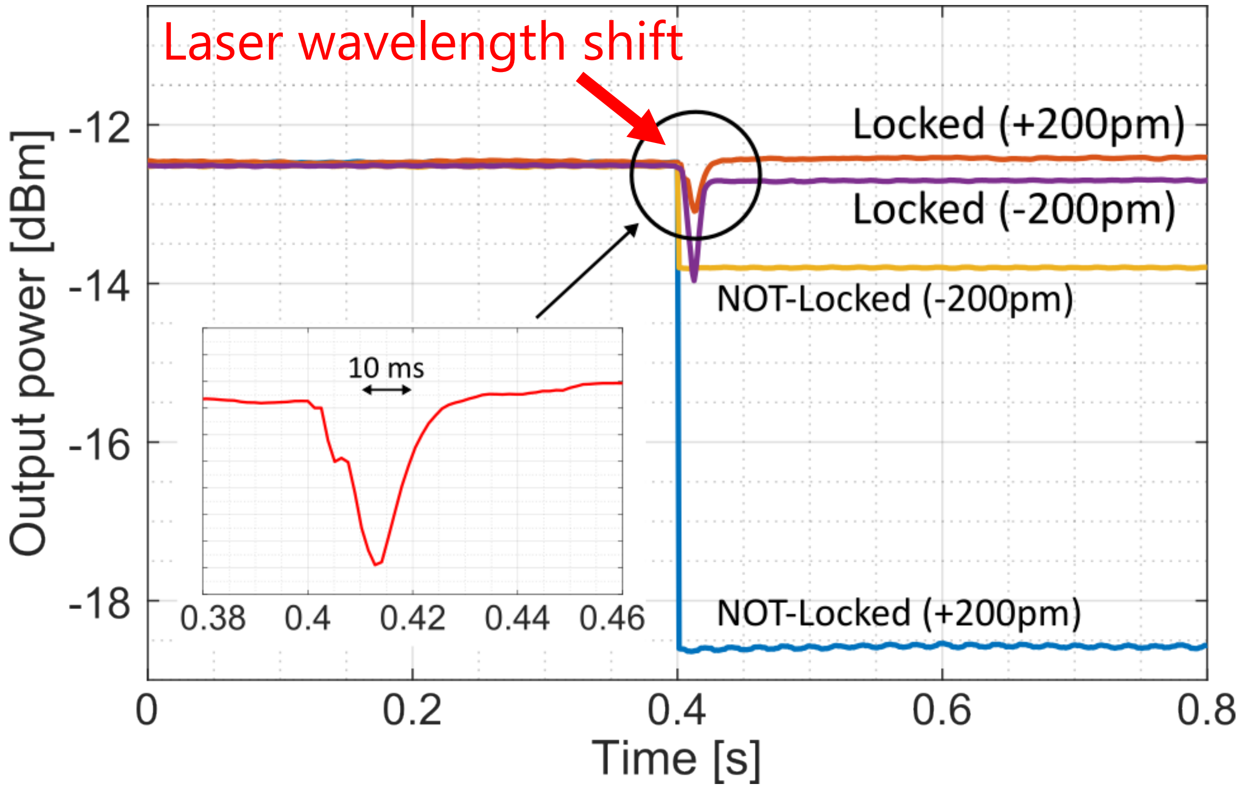
- The dithering signal can be used as the error signal of a control loop based on an integral controller.
- By zeroing the error signal, the system stabilizes the device on a stationary point of its transfer function.





F. Zanetto et al., IET Optoelectronics, 15, 2, 111-120 (2021)



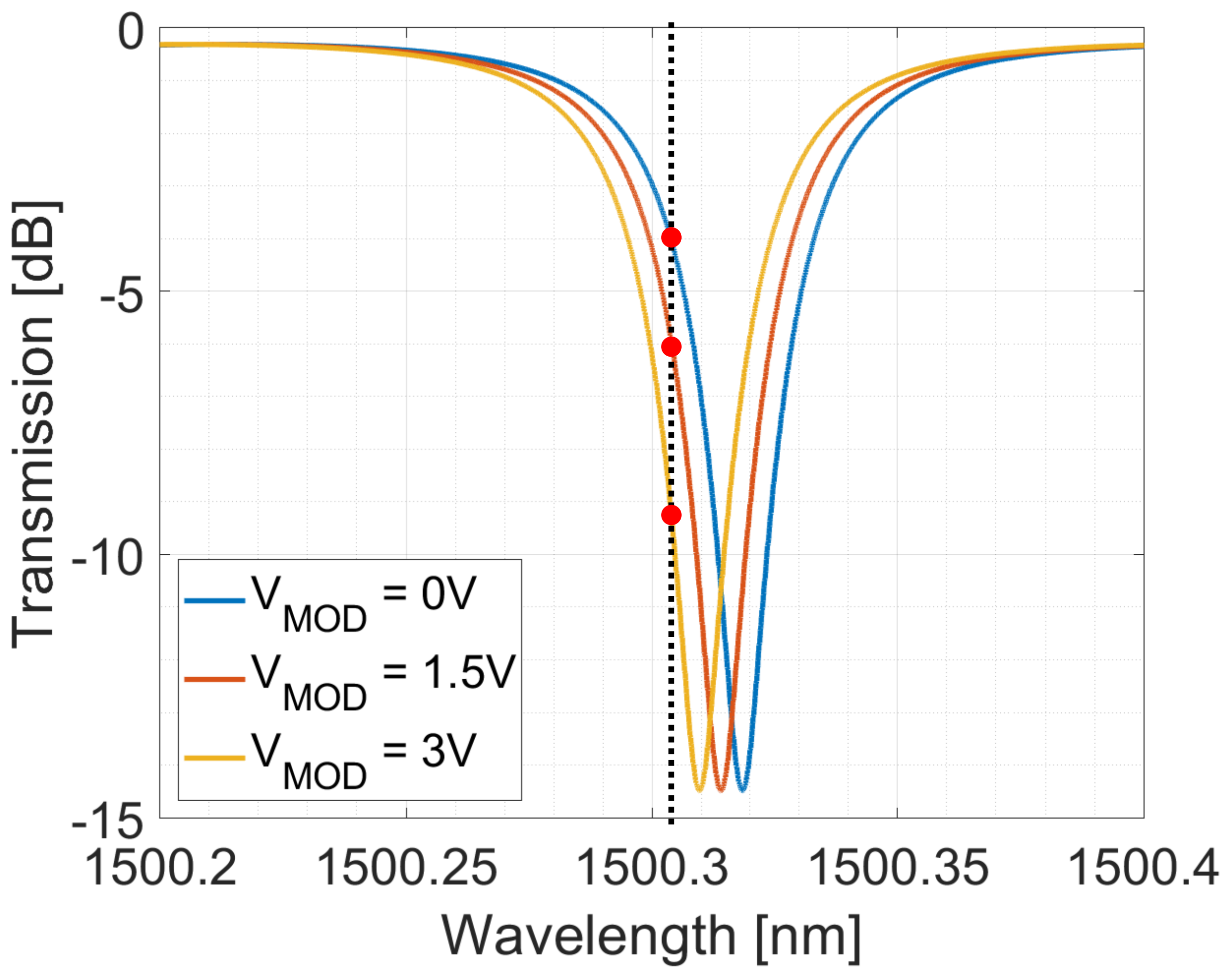


The control loop reacts to the working point perturbation and rapidly modify the heater voltage to recover the initial condition.

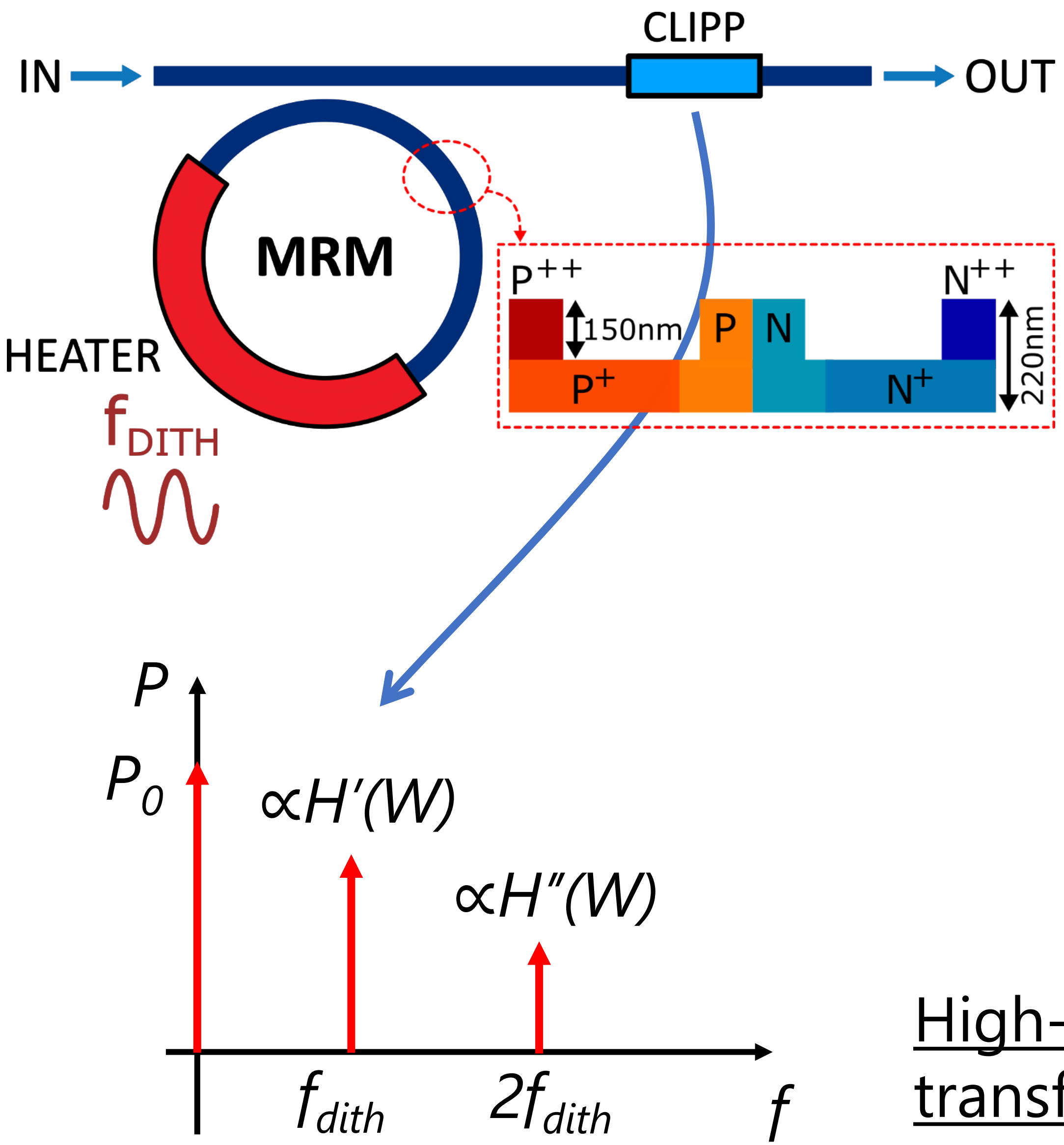
Locking to a different target point

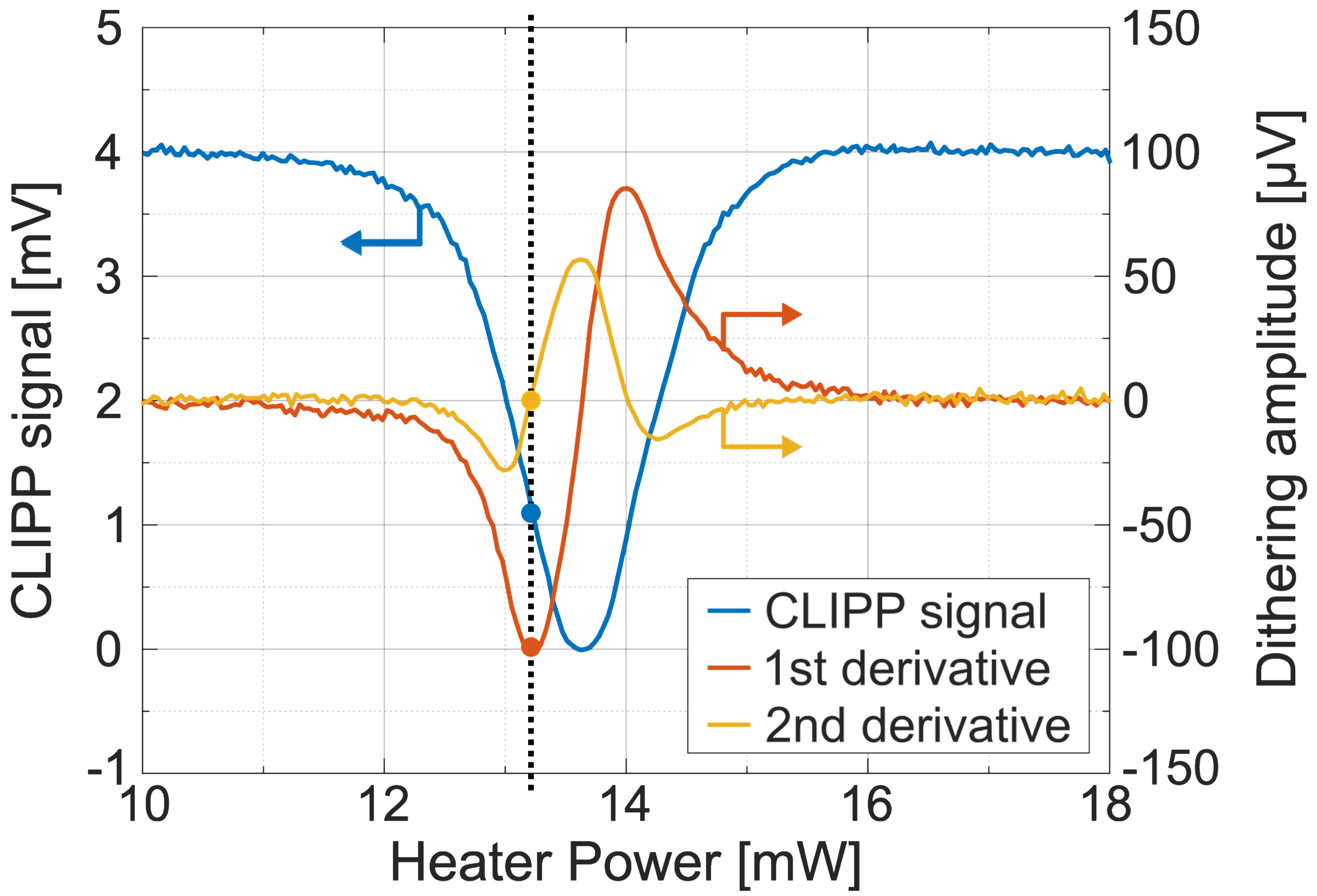
- What if we don't want to maximize or minimize the output power?
- Modulators for instance need to be tuned on the slope of their transfer function to operate correctly.

Can we extend the dithering technique also to other locking points to maintain its advantages?



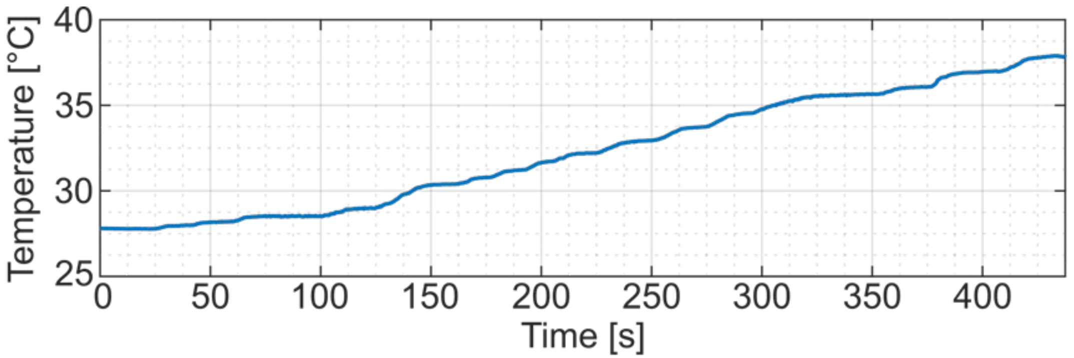
Extension of the dithering technique to the second derivative



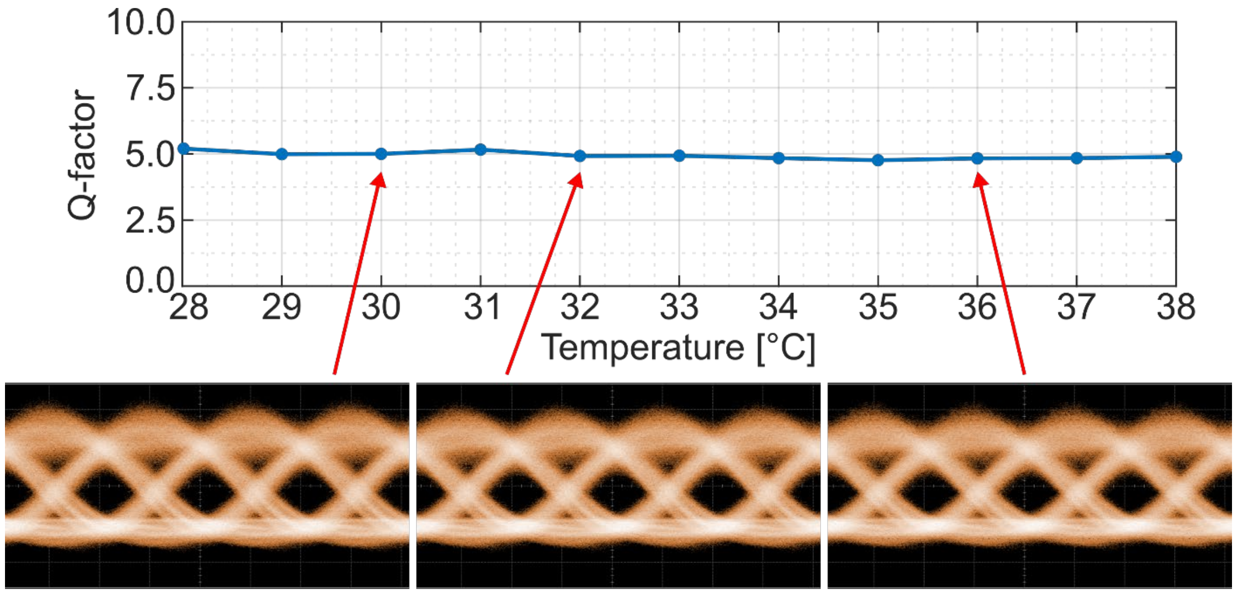


<u>High-order harmonics appear due to the non-linear transfer function of the ring.</u>

Stabilization of a ring modulator



- Same integral control loop as before, fed with 2nd harmonic demodulation.
- Stable performance of the modulation during the whole 8-minutes experiment (at a data-rate of 50 Gb/s).



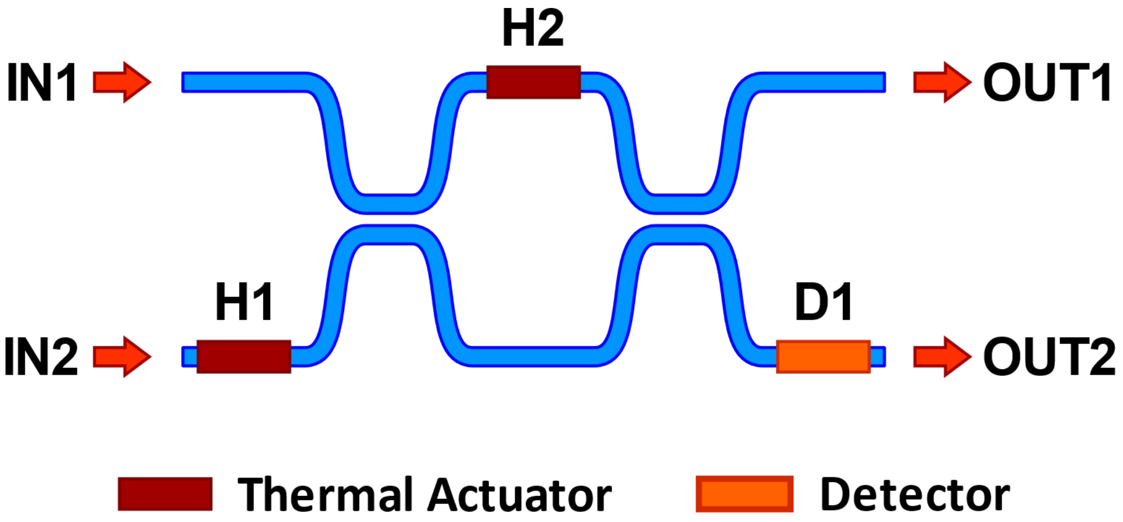
V. Grimaldi et al., IEEE JLT, 41, 1, 218-225 (2023)

Devices with multiple actuators

- What if a device needs multiple actuators to be operated?
- Mach-Zehnder interferometers for instance require two actuators to completely steer light to the two outputs.

Can we extend the dithering technique also to this situation?

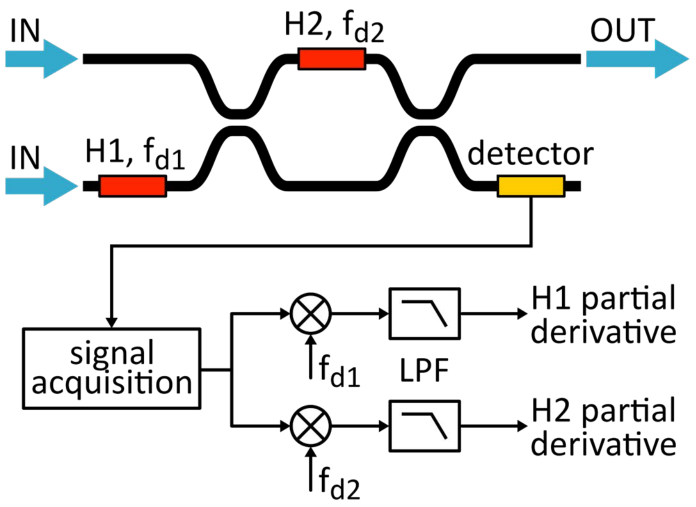
A MZI is a light switch, where the ratio of the power at the two outputs is determined by the actuators setup.

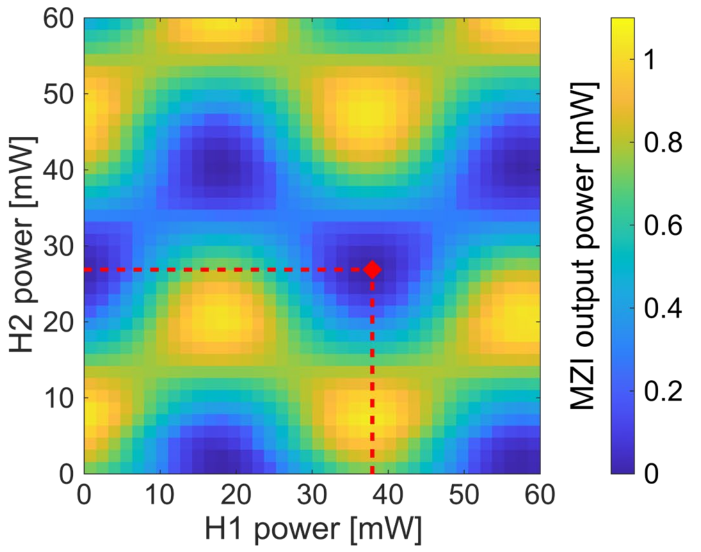


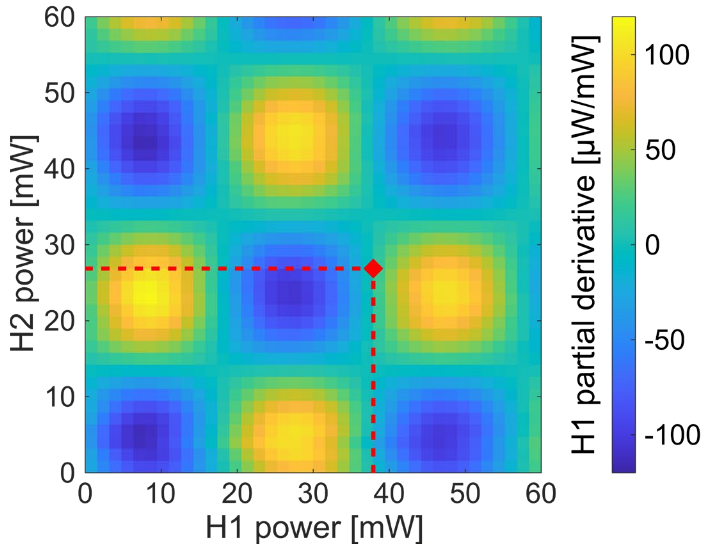
Lock-in frequency selectivity

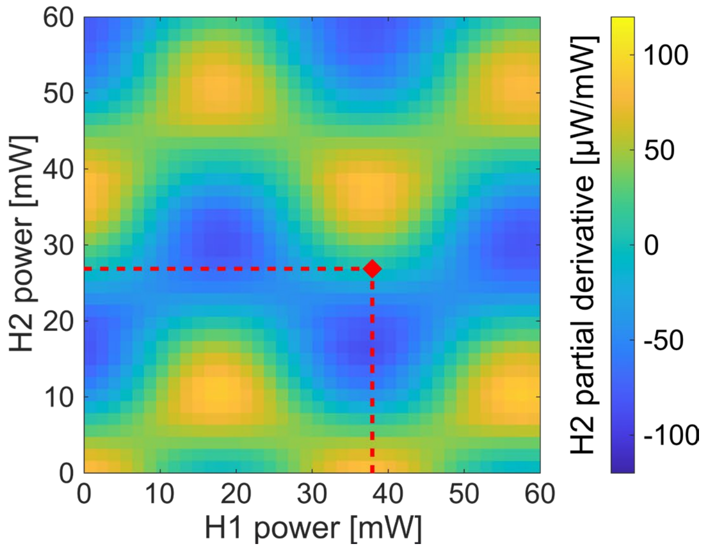
- The two actuators are dithered at different frequencies.
- The lock-in frequency selectivity allows to isolate each contribution.
- The two partial derivatives of the device transfer function are independently extracted.

They can be used to automatically tune the device!

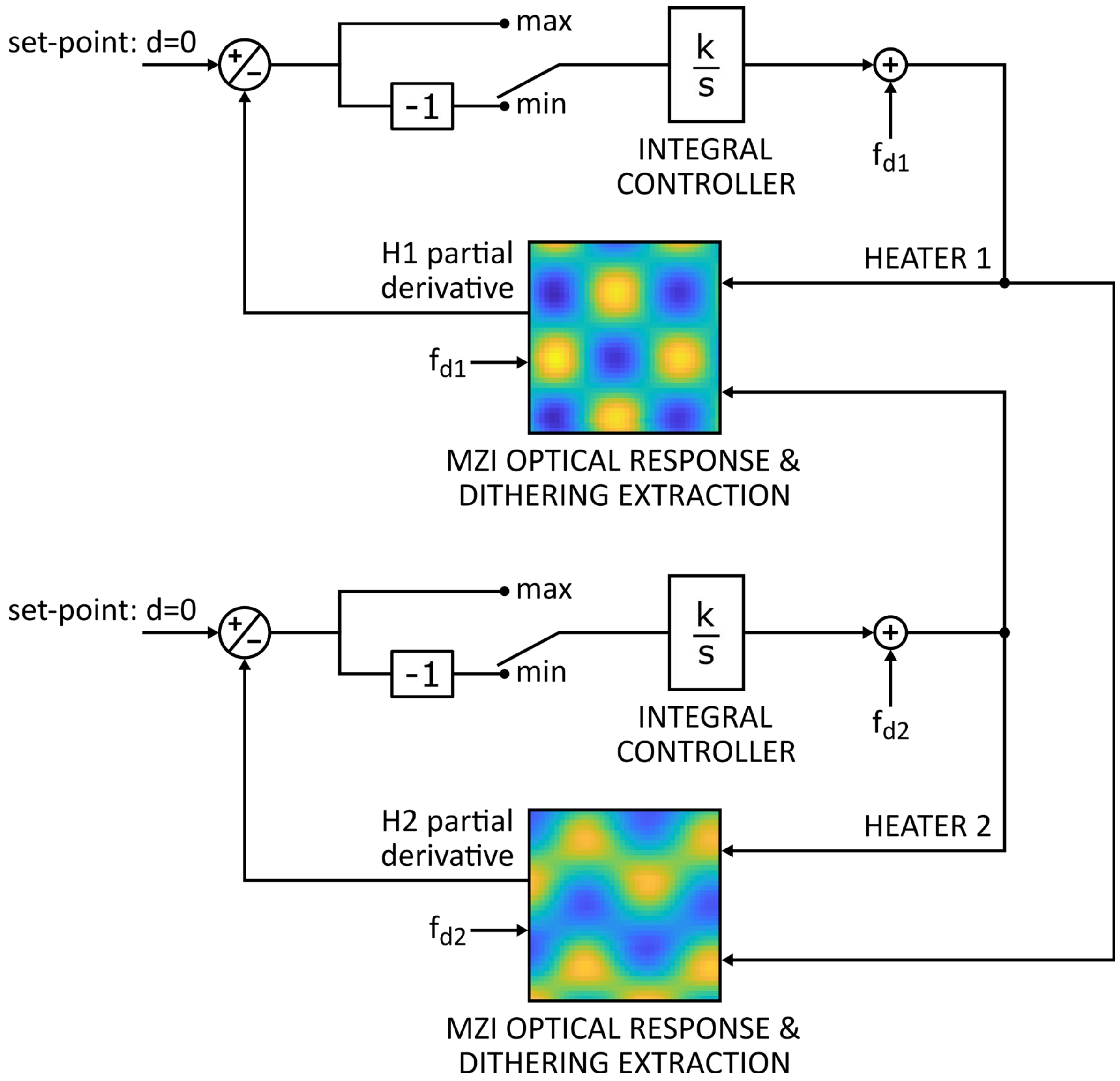








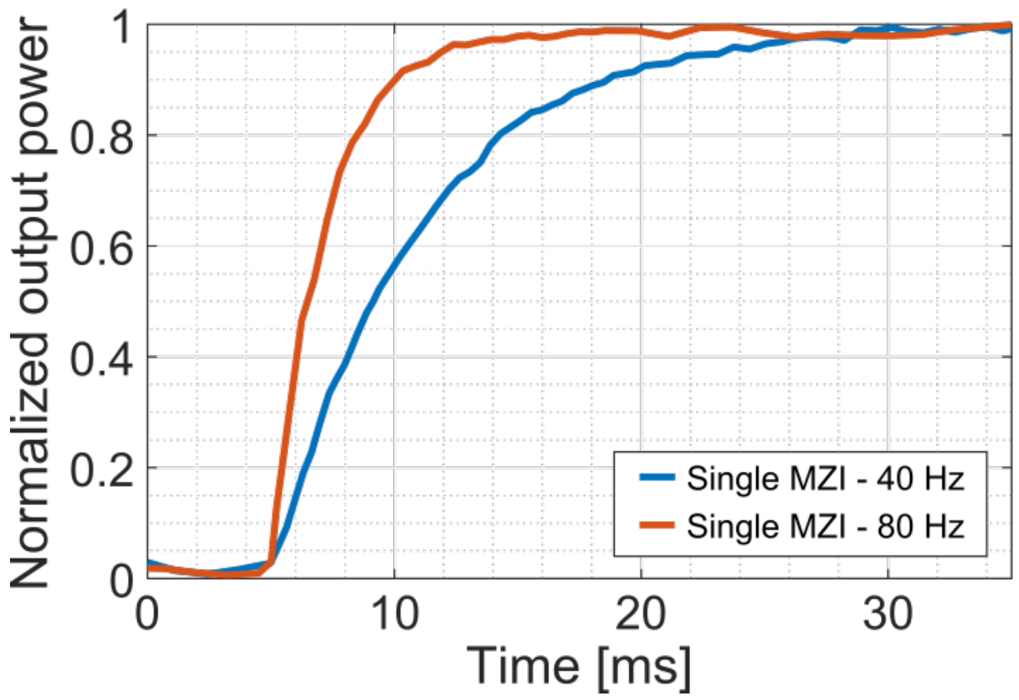
Closed-loop MZI control

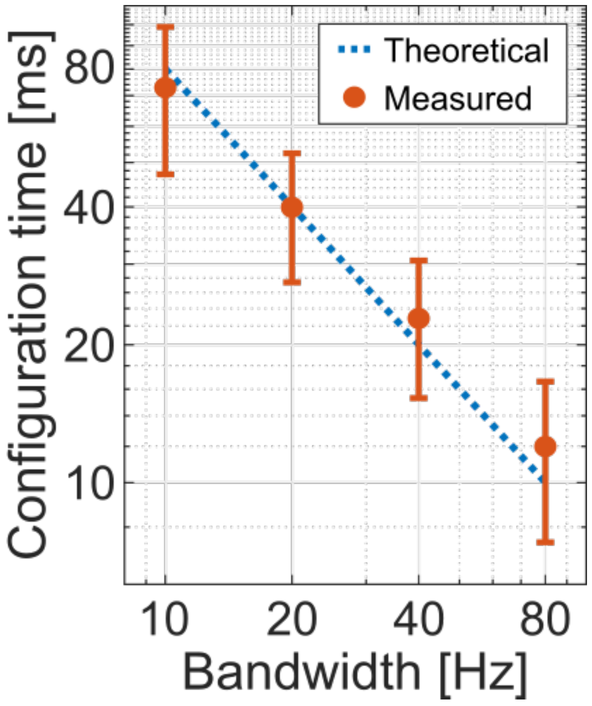


- Two independent control loops in parallel, with the same integral architecture shown previously.
- Each actuator is automatically tuned so that all light is steered to one of the two outputs.
- No need for calibrations, insensitive to temperature and other devices.

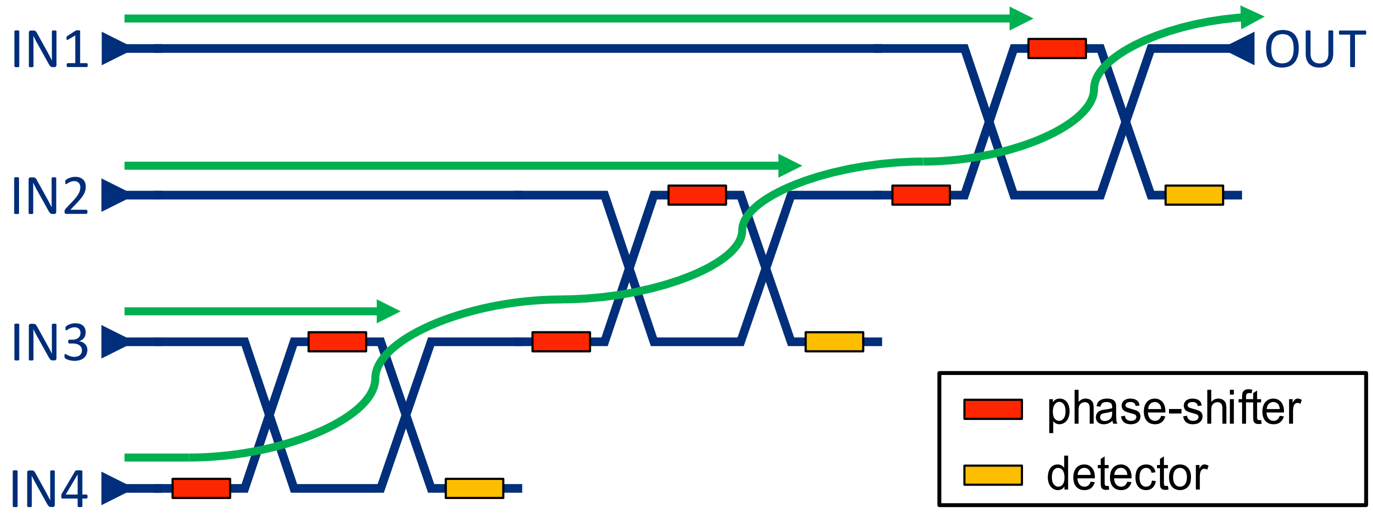
Experimental verification

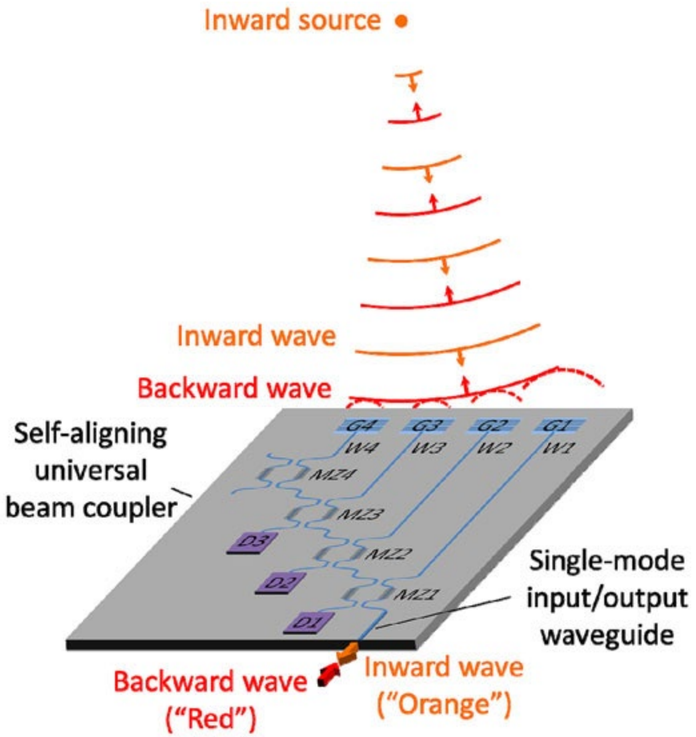
- Heater voltage initialized at a random starting condition, then activation of the control loop to maximize light at the output.
- The configuration is exponential (as expected with an integral controller) and the configuration time is in agreement with the loop bandwidth.





Mesh of Mach-Zehnder interferometers





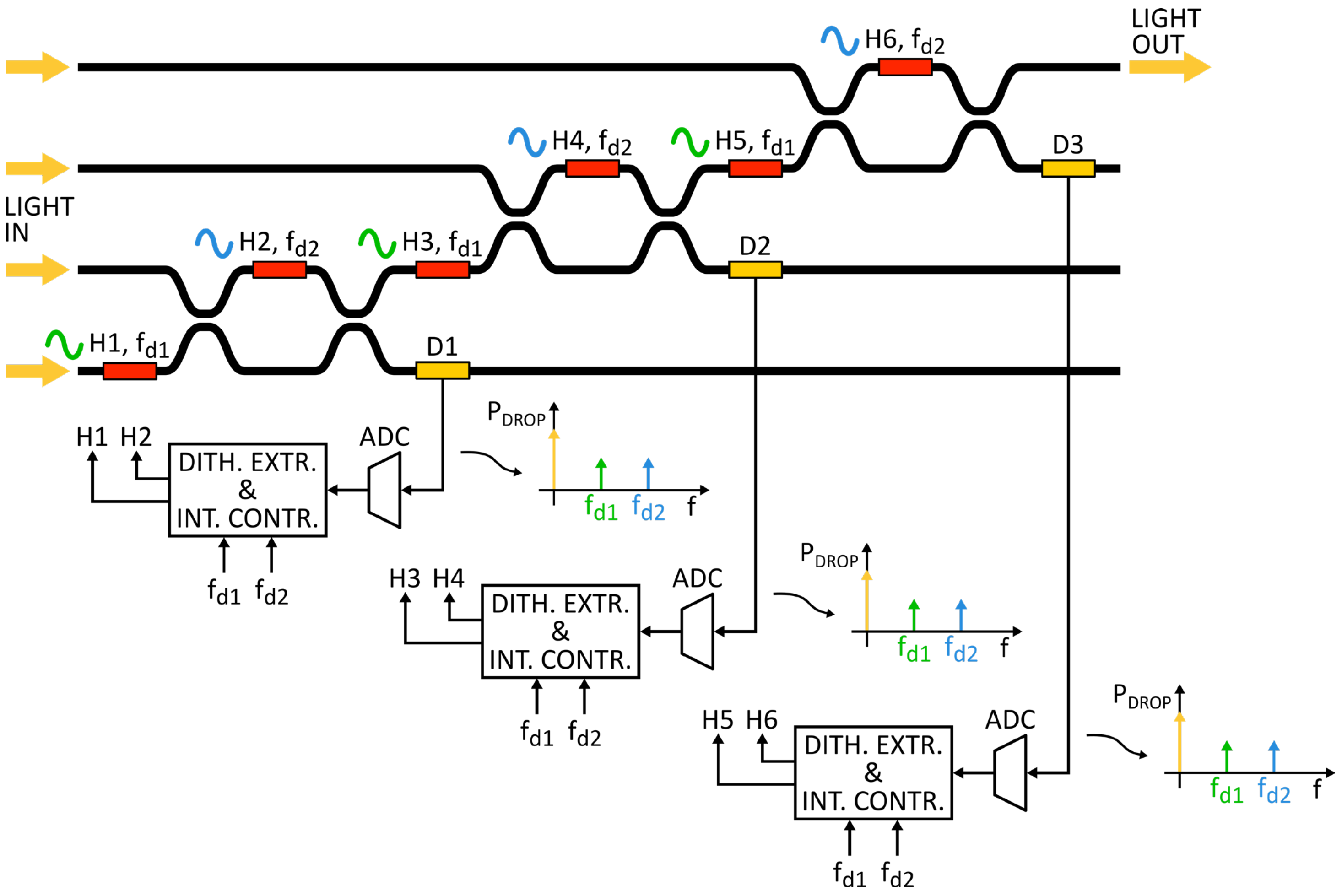
A mesh of MZI can be used as a universal optical processor, able to perform linear operations on the input beams.

Applications:

- Optical signal routing and processing
- Receivers/Transmitters for telecommunications
- Phase-sensitive light sensors

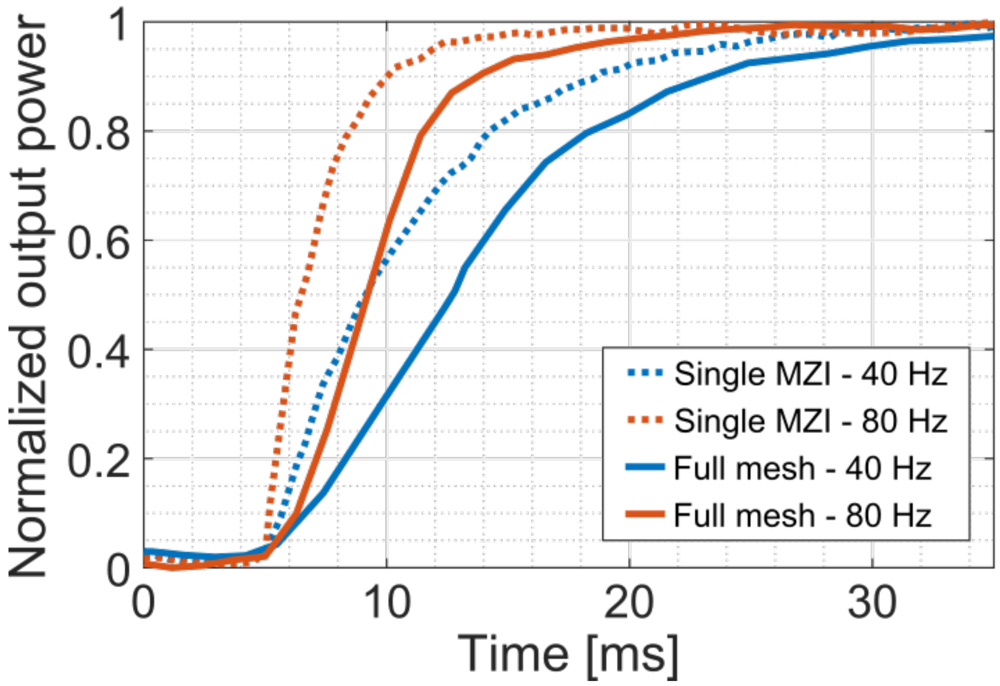
Automated control of a MZI mesh

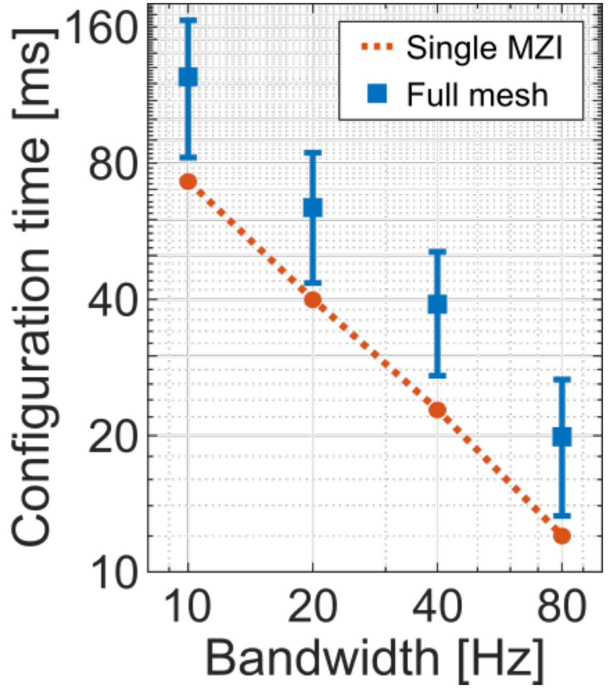
- The configuration of the mesh is inherently sequential.
- This allows to easily extend the approach for the single MZI to the mesh.
- The dithering frequencies can be reused, since when one MZI is tuned the residual oscillation at its output is zero.
- The maximum control bandwidth is determined by the difference between f_{D1} and f_{D2}.



Experimental results

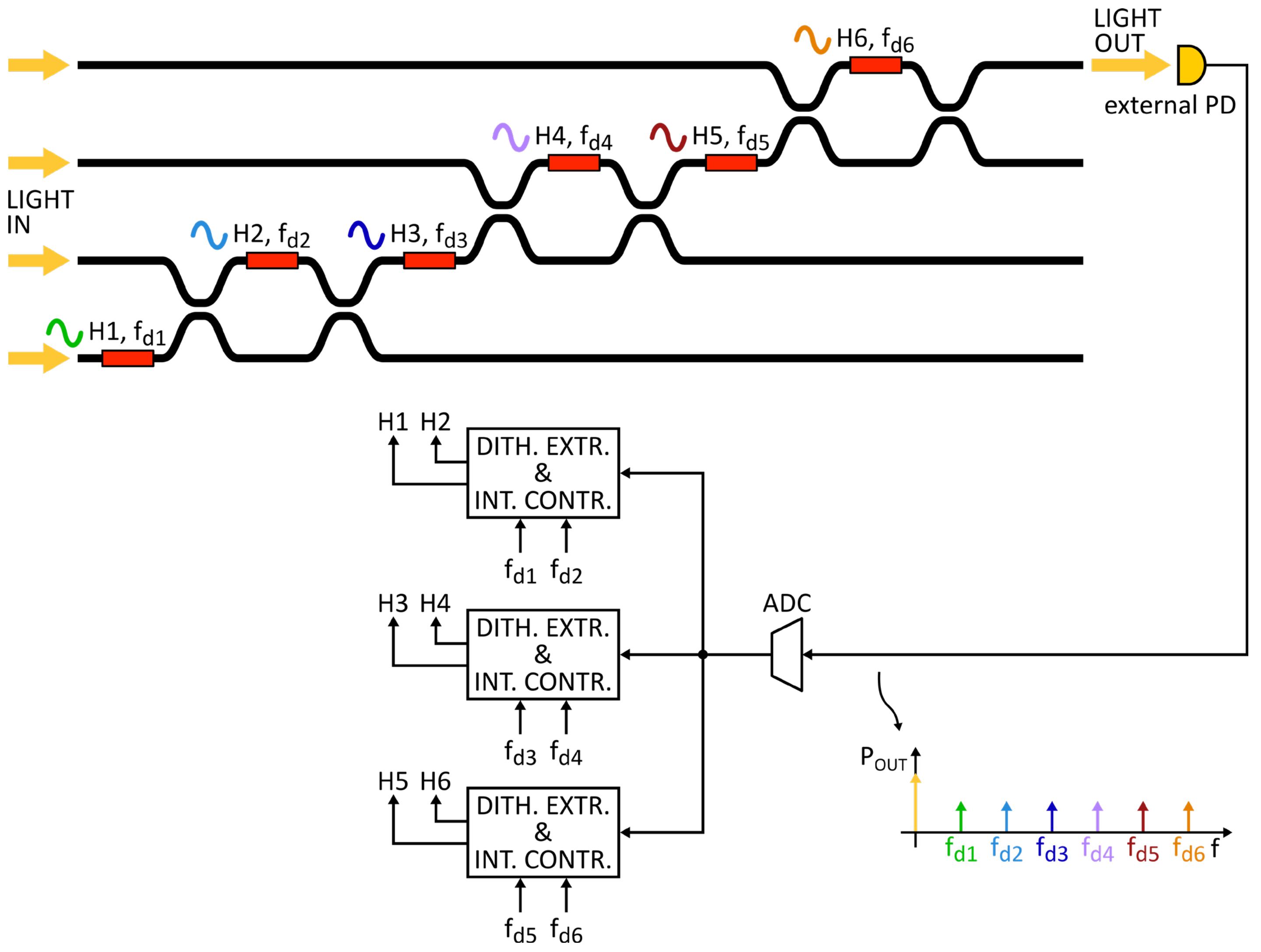
- The approach has been validated on a mesh of 3 MZIs.
- The evolution of the power at the output is no more exponential, since it results from multiple loops in cascade.
- The configuration time scales less than linearly with the number of devices.





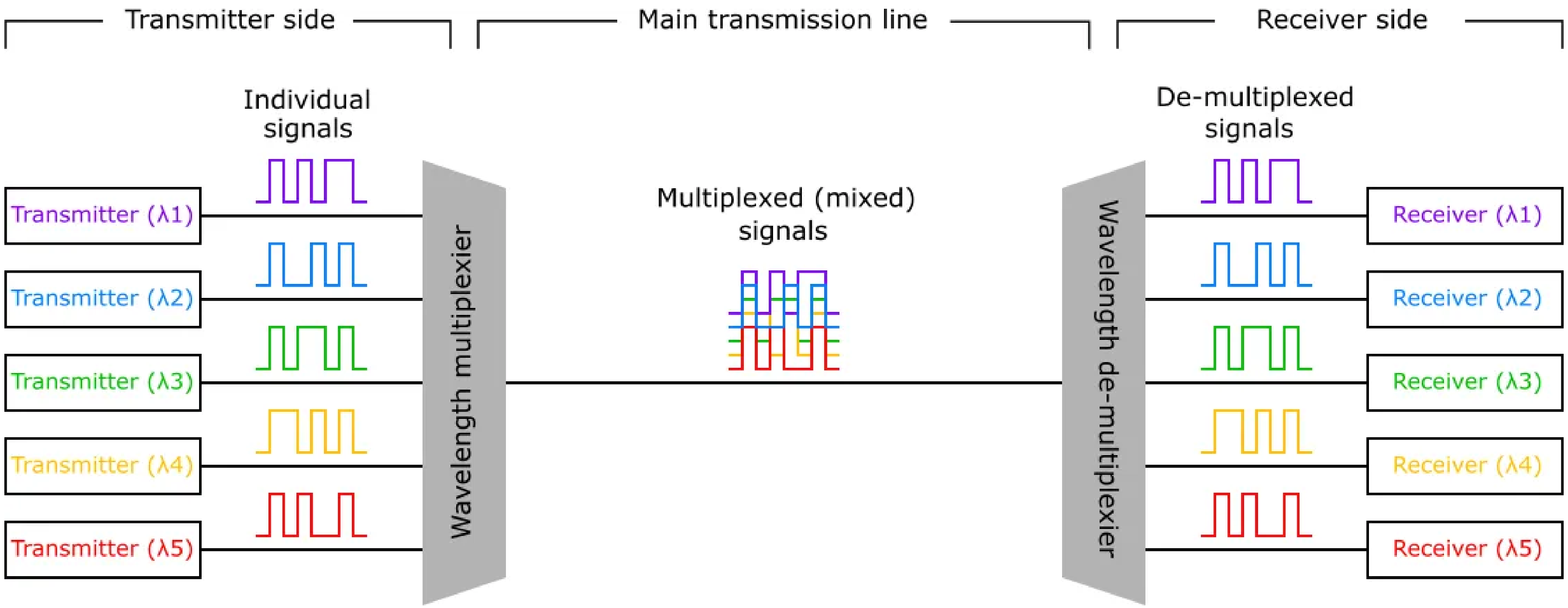
Controlling a mesh with a single photodetector

- The lock-in frequency selectivity allows also to use a single photodetector to tune the whole mesh.
- Each actuator needs a different dithering frequency to be able to discriminate them, so practical limitations to this approach exist.
- This technique solves a multivariable optimization problem in an easy way.



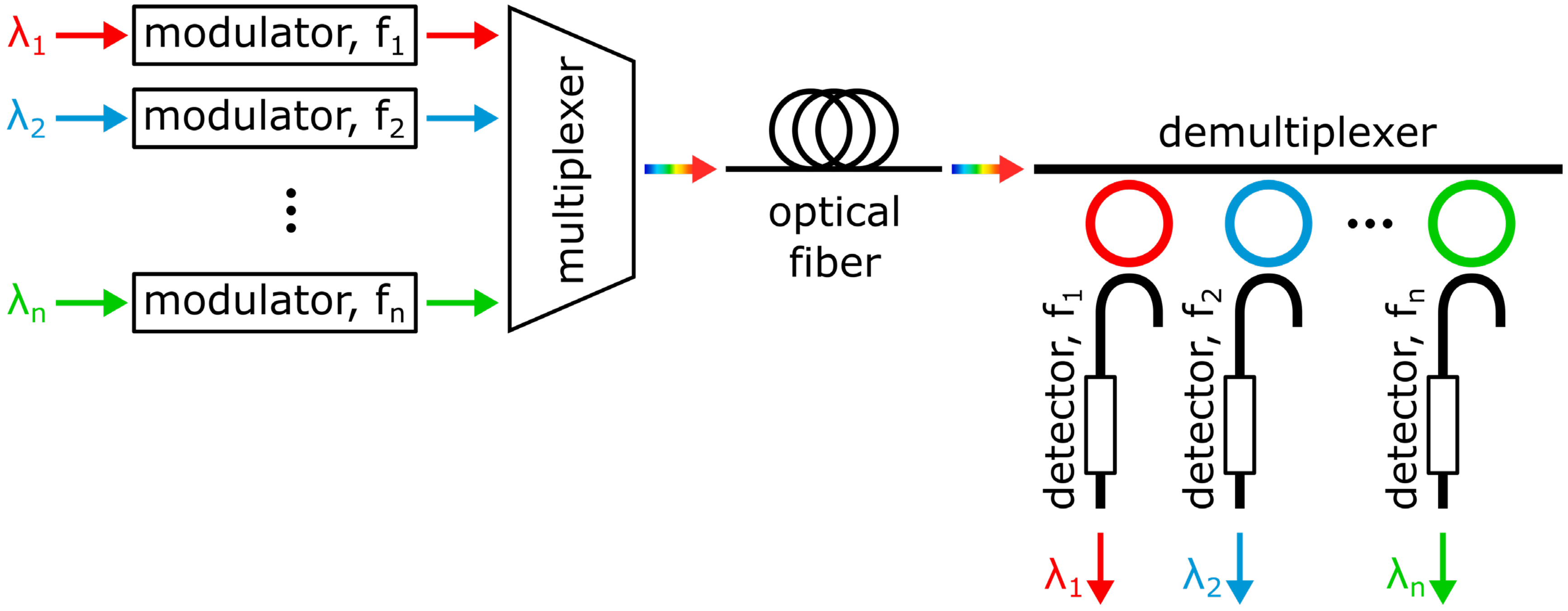
Identifying beams in multi-wavelength systems

- A common way to increase the capacity of fiber optics links is to use multiple wavelengths to transmit several communication channels in parallel.
- At the receiver side, each wavelength needs to be separated from the others to recover the useful data.
- How can we discriminate them?

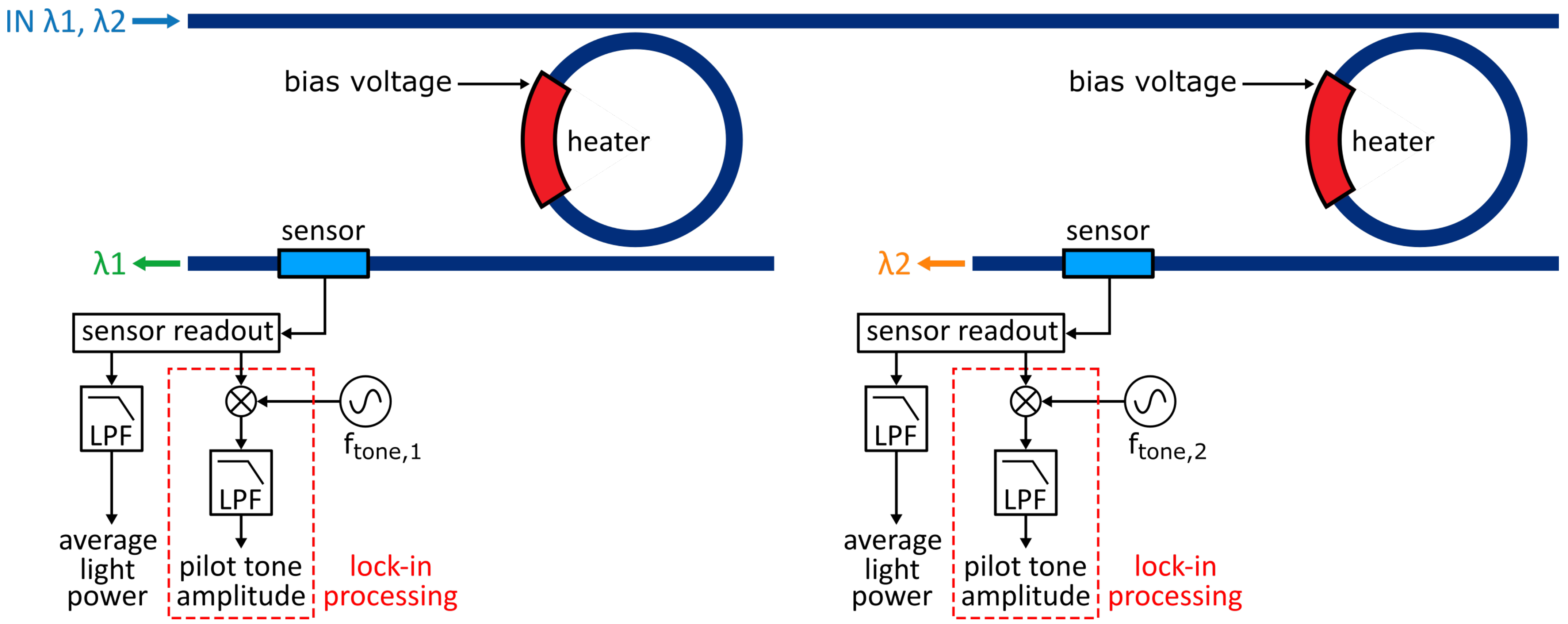


Pilot tones

- Each wavelength can be labelled before the multiplexer, by superimposing a weak amplitude modulation at a specific frequency.
- At the demux side, a lock-in amplifier allows easily isolate each contribution and separate the wavelengths by detecting each frequency.
- The labelling frequencies are usually called “pilot tones”.

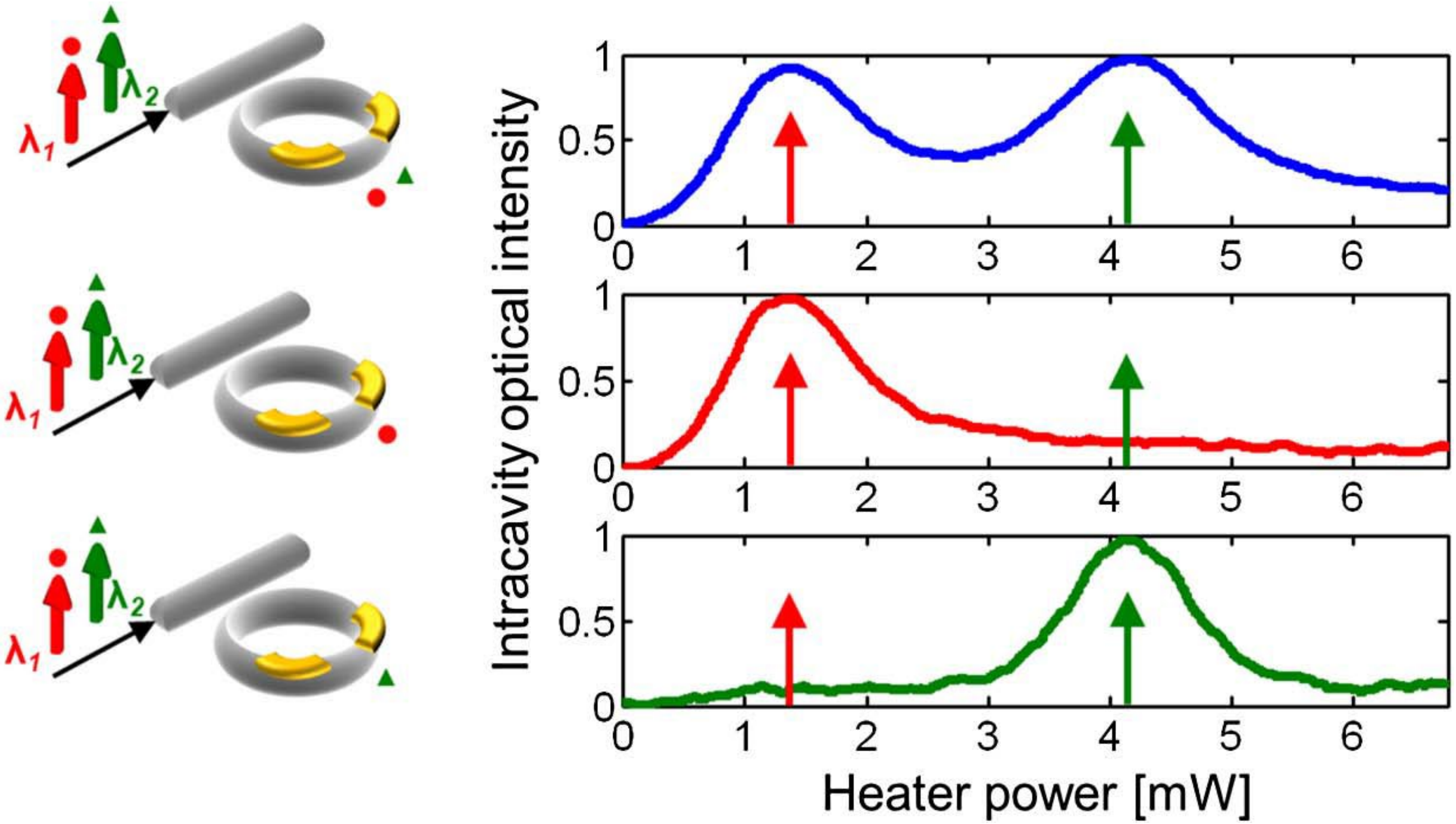


Lock-in detection of pilot tones



- The same approach used to detect dithering signals can be used to identify pilot tones.
- By demodulating the sensor readout with a lock-in, each wavelength can then be separated without ambiguity.

Identifying wavelengths in ring resonators



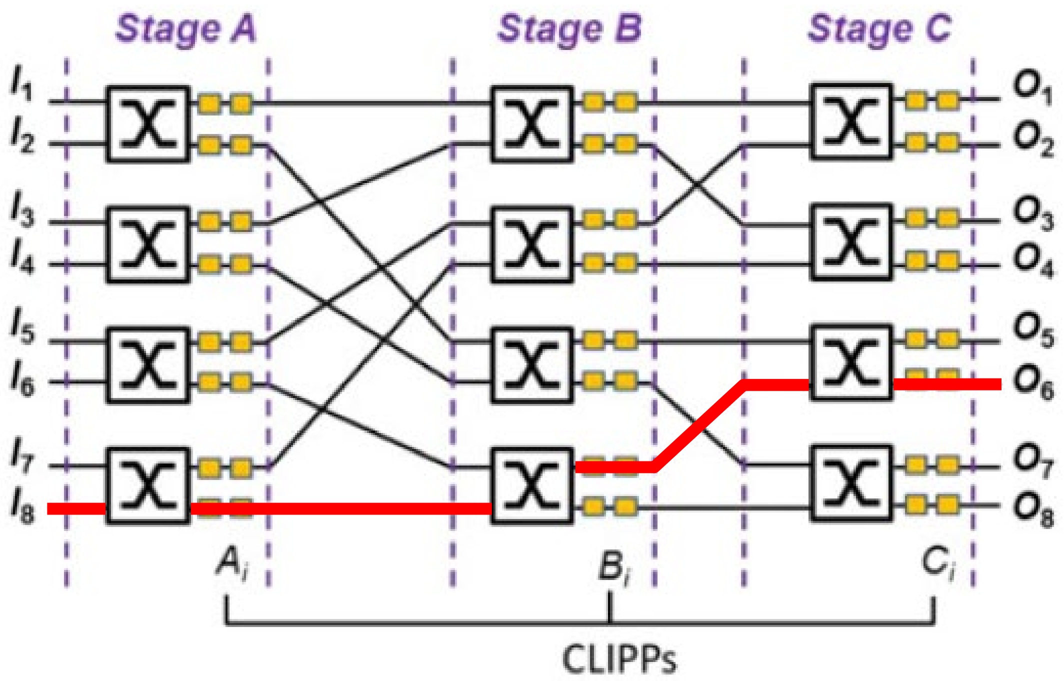
Total power in the ring

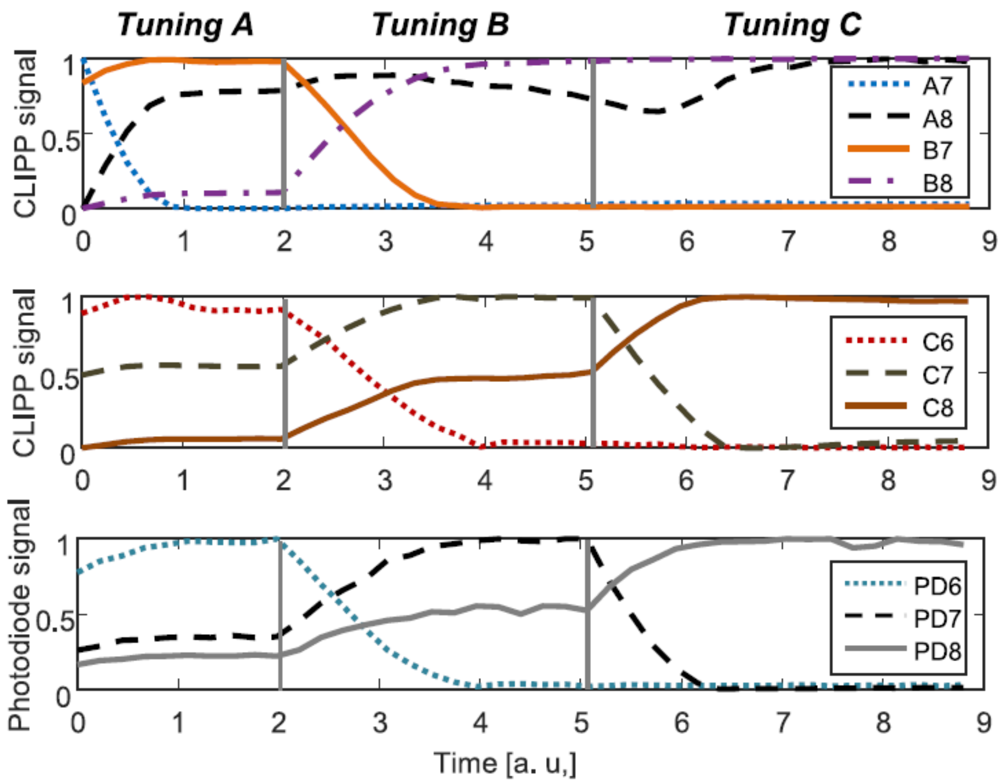
Demodulation at 7 kHz

Demodulation at 11 kHz

- λ_1 and λ_2 labelled with two different pilot frequencies (7 kHz and 11 kHz).
- By monitoring the total power in the ring, both contributions are observed.
- If a pilot tone is demodulated, each wavelength is correctly identified.

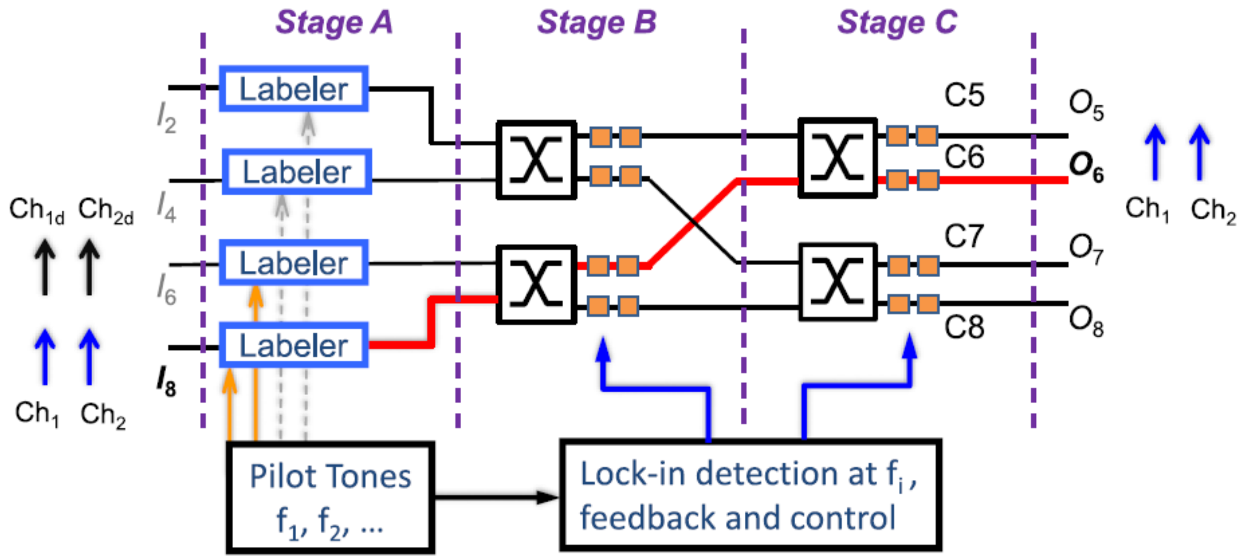
Integrated 8x8 optical router

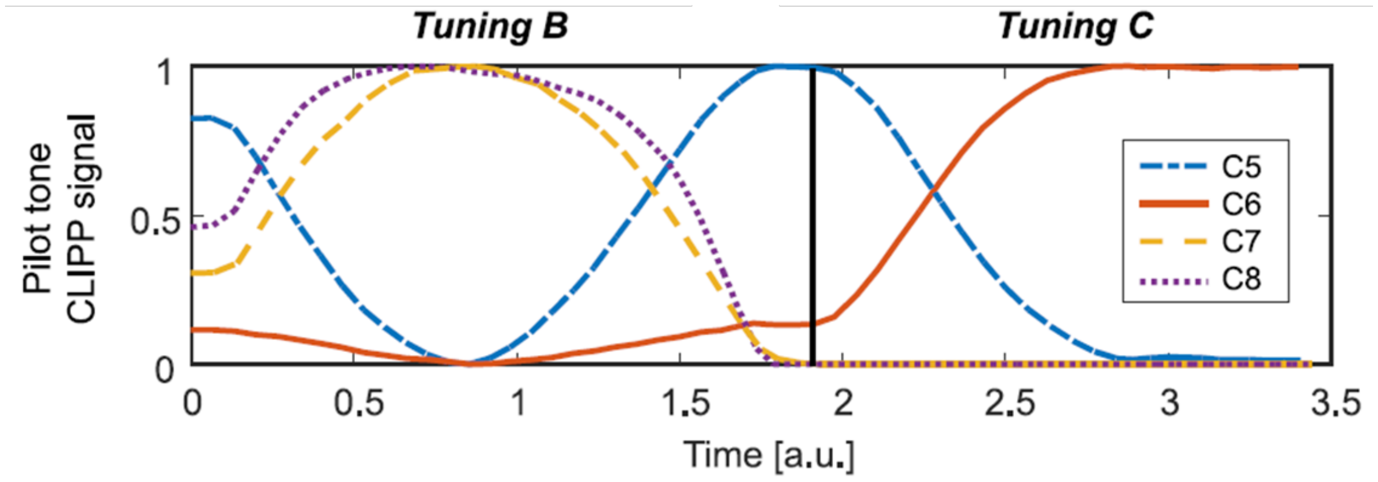




- 3 switching stages, each comprising 4 thermally-actuated MZIs, allow to route any input to any output.
- CLIPP detectors monitor the configuration of each MZI, feedback loops to obtained the desired behavior.

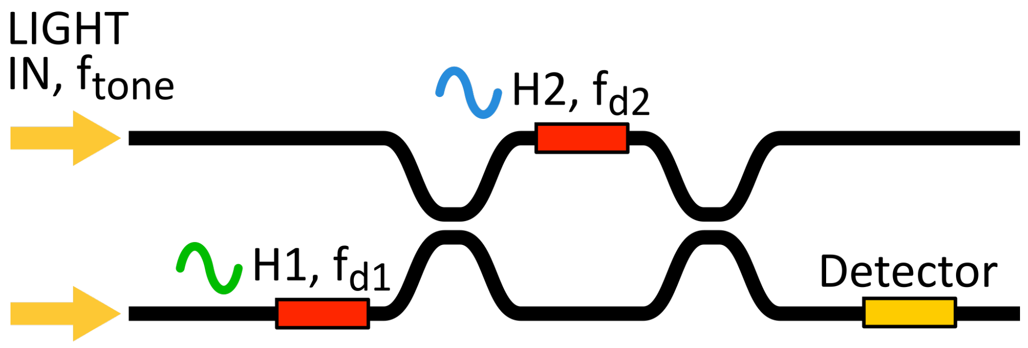
- The first stage can be also used to label the channels at each input directly on-chip.
- This is obtained by biasing the first MZIs on the slope and by superimposing a small sinusoid to the DC voltage.
- Wavelength selective routing is achieved by using the pilot tone readout to tune each MZI.





Dithering technique with pilot tones

<u>Can we use the dithering technique and the pilot tones simultaneously?</u>



PROS

- This approach would allow to easily tune any device while being wavelength selective!

CONS

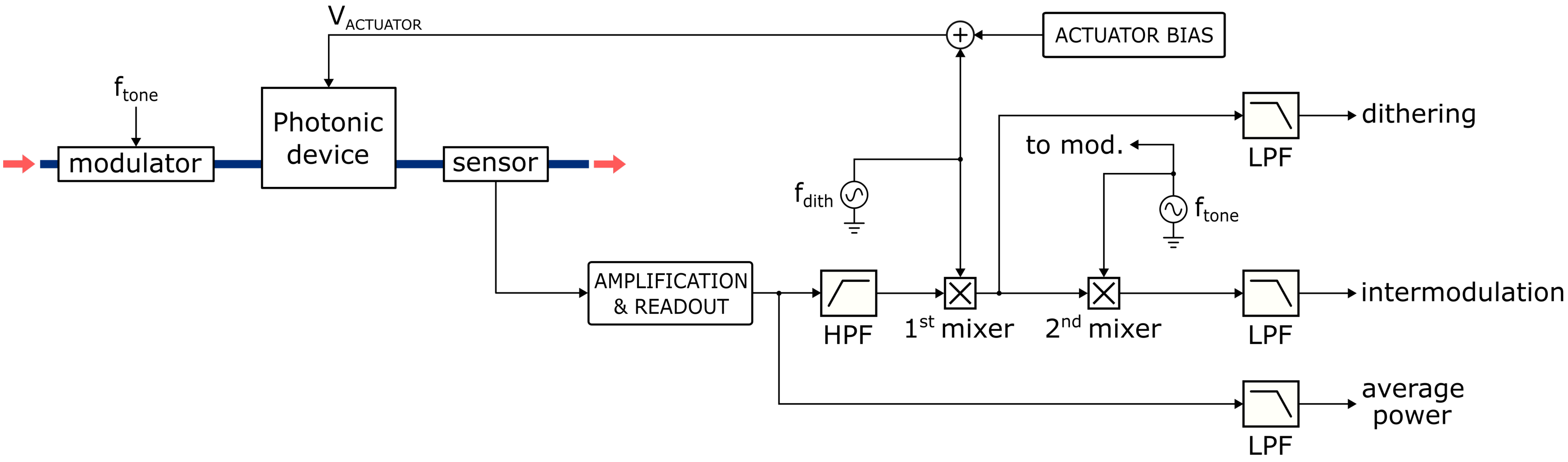
- The spectrum of the detected signals becomes more complex.
- The signals to be measured become very small.

The dithering and pilot tone frequencies should be chosen such that:

$$f_{DITH,N} - f_{DITH,N-1} > 2 \cdot f_{TONE,MAX}$$

to accommodate all the harmonics.

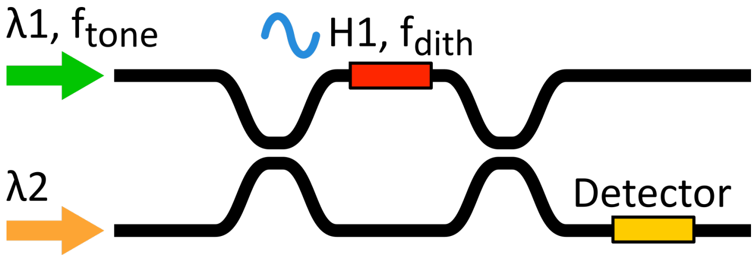
Extraction of dithering & pilot tones intermodulation



- A double lock-in demodulation is needed to extract the intermodulation signal.
- It's also possible to perform a single demodulation with a signal containing both harmonics at $f_{DITH} \pm f_{TONE}$

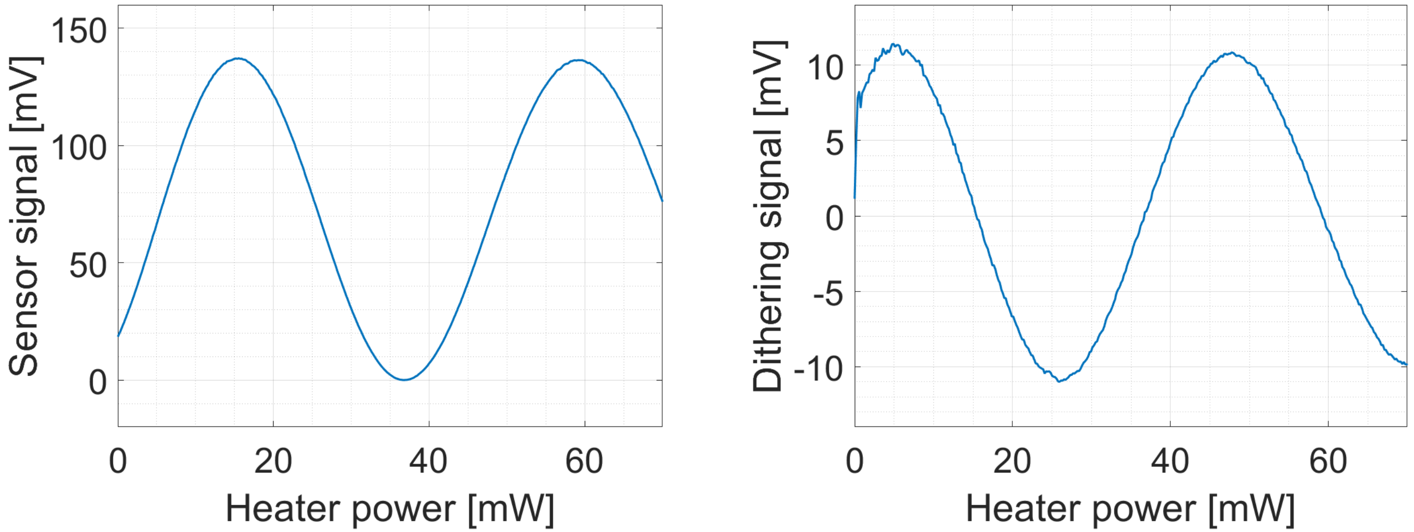
Experimental validation

Experimental setup



$$f_{dith} = 10\ \text{kHz}$$
$$f_{tone} = 3\ \text{kHz}$$

λ1 only



λ1 and λ2