CENTRE FOR ADVANCED LASER TECHNIQUES

Fazna stabilizacija lasera i redukcija šuma u optičkim vlaknima

Ana Kardum

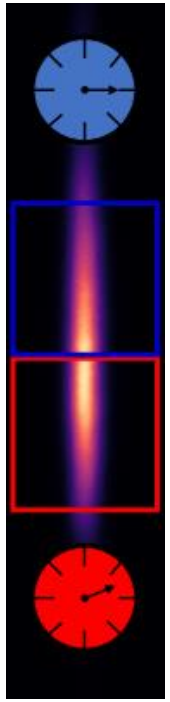
Projekt je sufinanciran u okviru OP Konkurentnost i kohezija, iz Europskog fonda za regionalni razvoj.

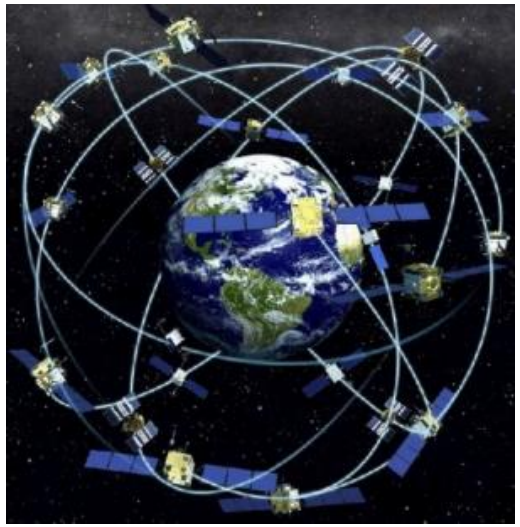
Europska unija
Zajedno do fondova EU

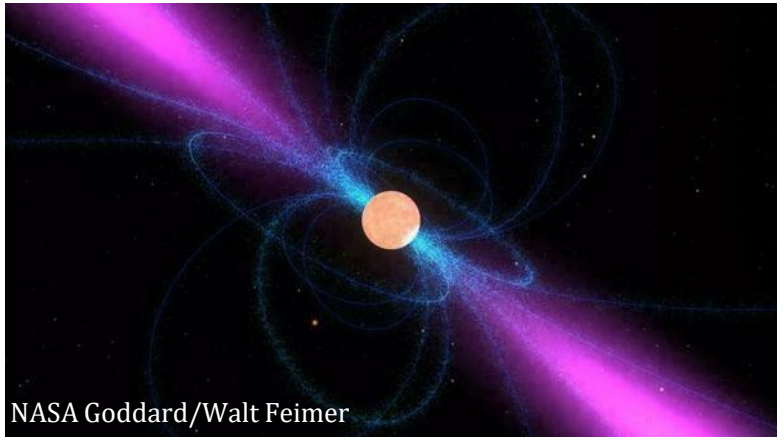
Operativni program
KONKURENTNOST
I KOHEZIJA

EUROPSKI STRUKTURNI
I INVESTICIJSKI FONDOVI

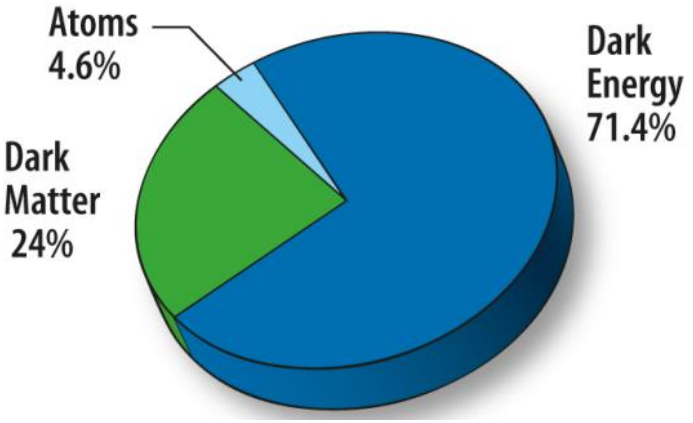
Motivacija



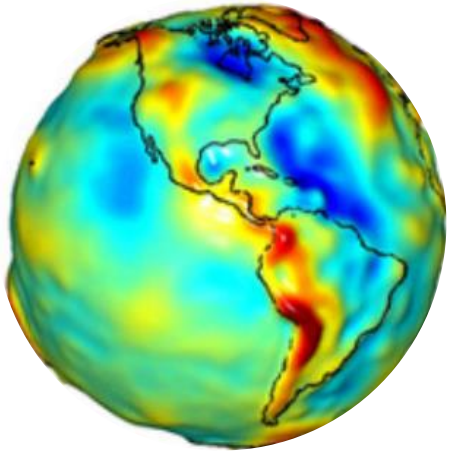




Precizno mjerenje vremena



Ref: Bothwell, T., Kennedy, C.J., Aeppli, A. et al.
Resolving the gravitational redshift across a millimetre-scale atomic sample. Nature 602, 420–424 (2022)



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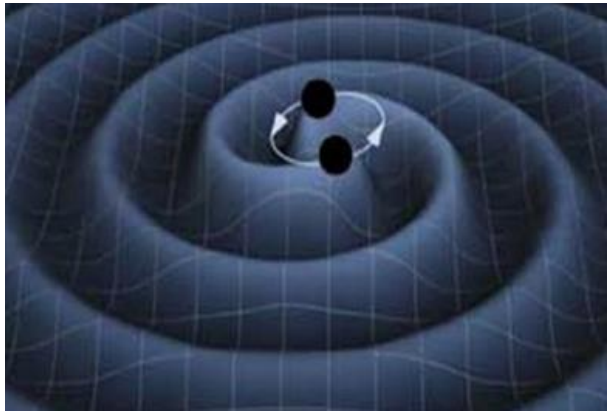


$$\nu \simeq cR_\infty AF(\alpha)$$

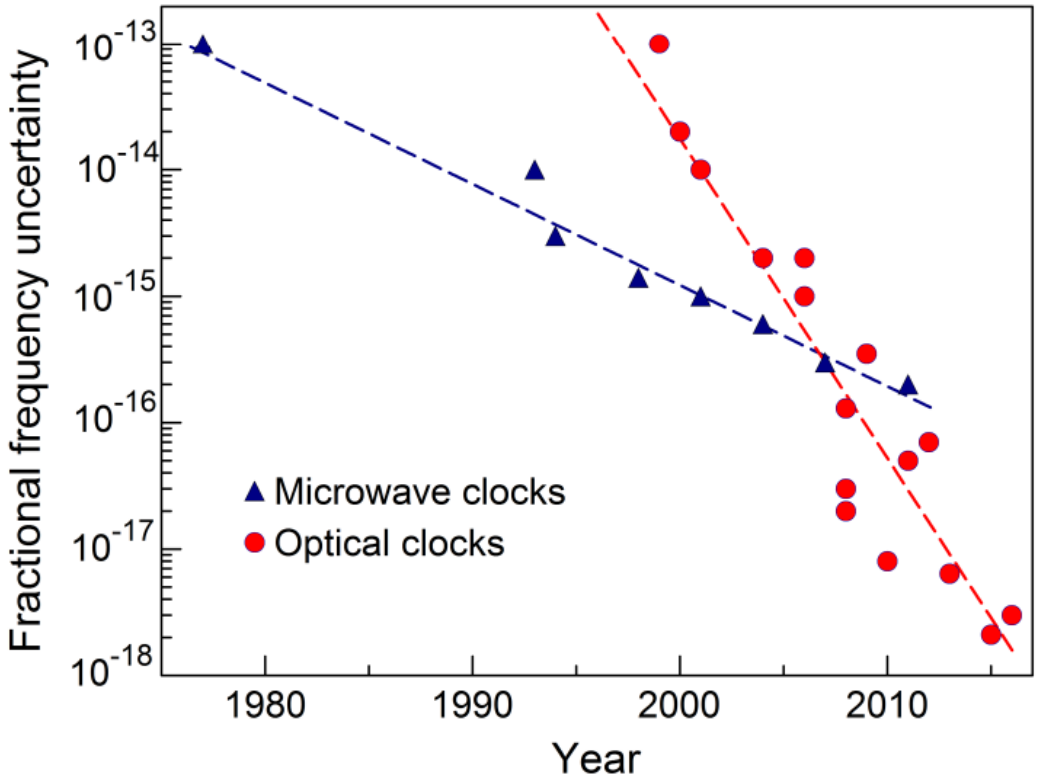
Ostale slike: Marianna Safronova, Atomic Clocks for Fundamental Physics: Time for Discovery

Atomski satovi

- 1950ih – cezijev atomski sat

$$\approx 9.2\ \mathrm{GHz}$$

- 1967. – redefinicija sekunde
- 1999. – izum frekventnog češlja
- optički satovi: $\mathrm{H}, \mathrm{Ca}, \mathrm{Hg}, \mathrm{Al}+, \mathrm{Yb}, \mathrm{Sr}$
- $\mathrm{Sr}: 4s^2\ {}^1S_0 \leftrightarrow {}^3P_0 \quad \approx 430\ \mathrm{THz}$



Ref: Rev. Mod. Phys. 90, 025008 (2018)

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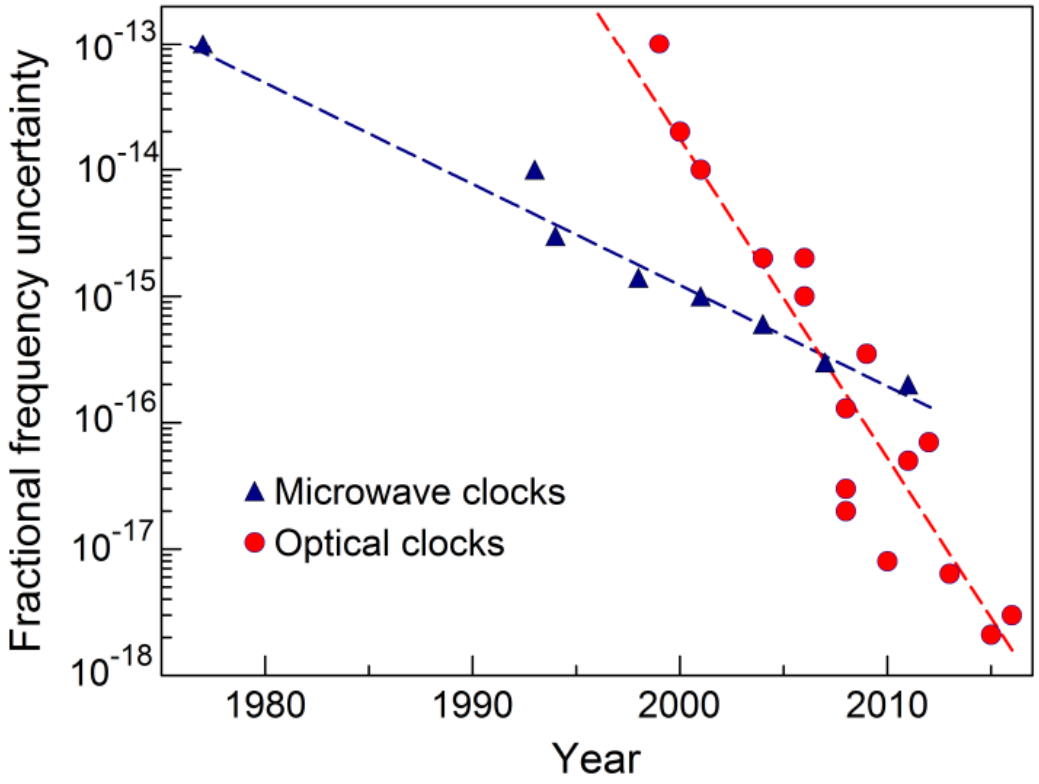


najtočniji sat na svijetu!

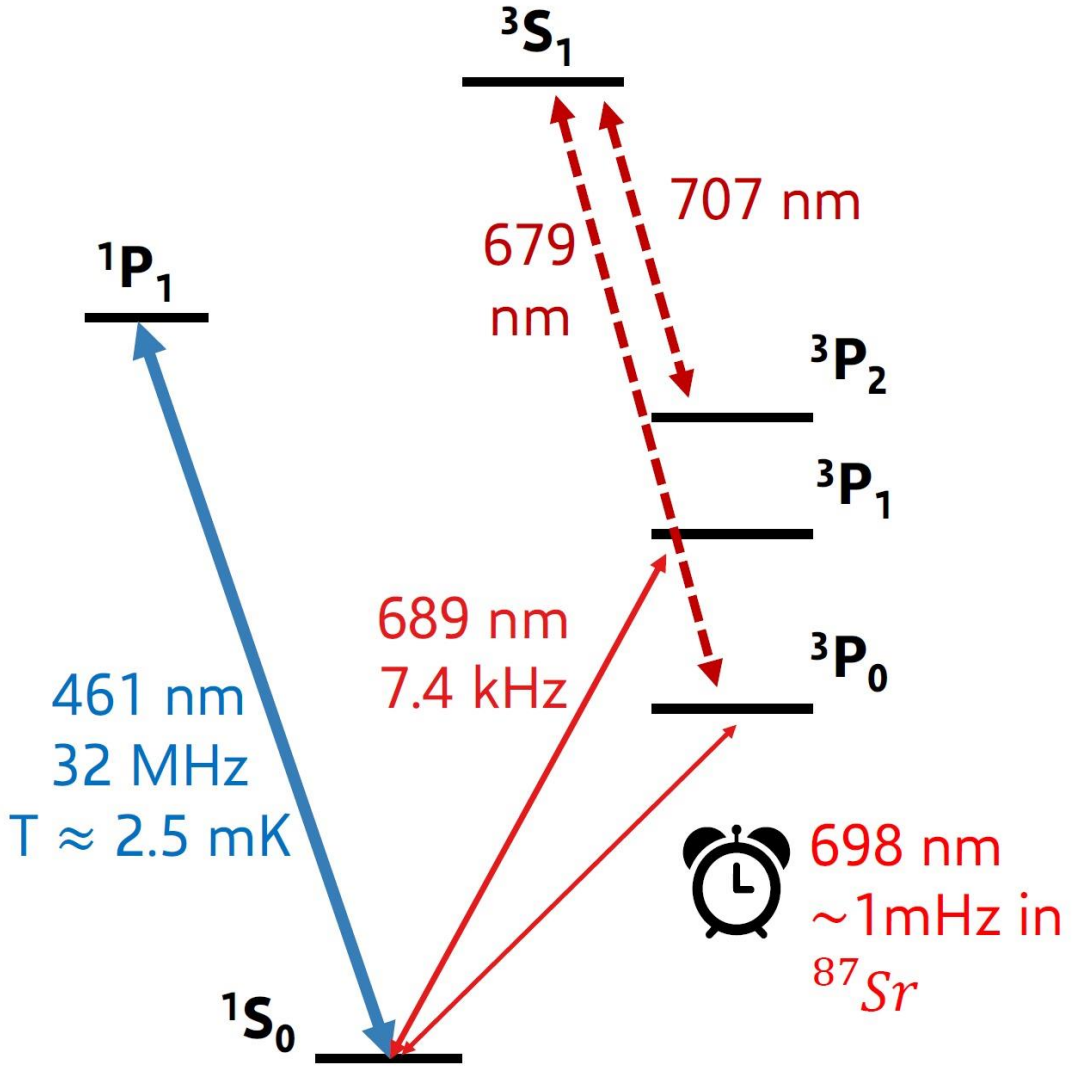
$8 \cdot 10^{-19}$

JILA institut, SAD, 2024.

Stroncijev sat u Grupi za kvantne tehnologije

prvi u Hrvatskoj!

- diodni laseri
- 698 nm (↔ 430 THz) - clock laser
- 461 nm, 689 nm – laseri za hlađenje
- 679 nm, 707 nm – *repumping* laseri



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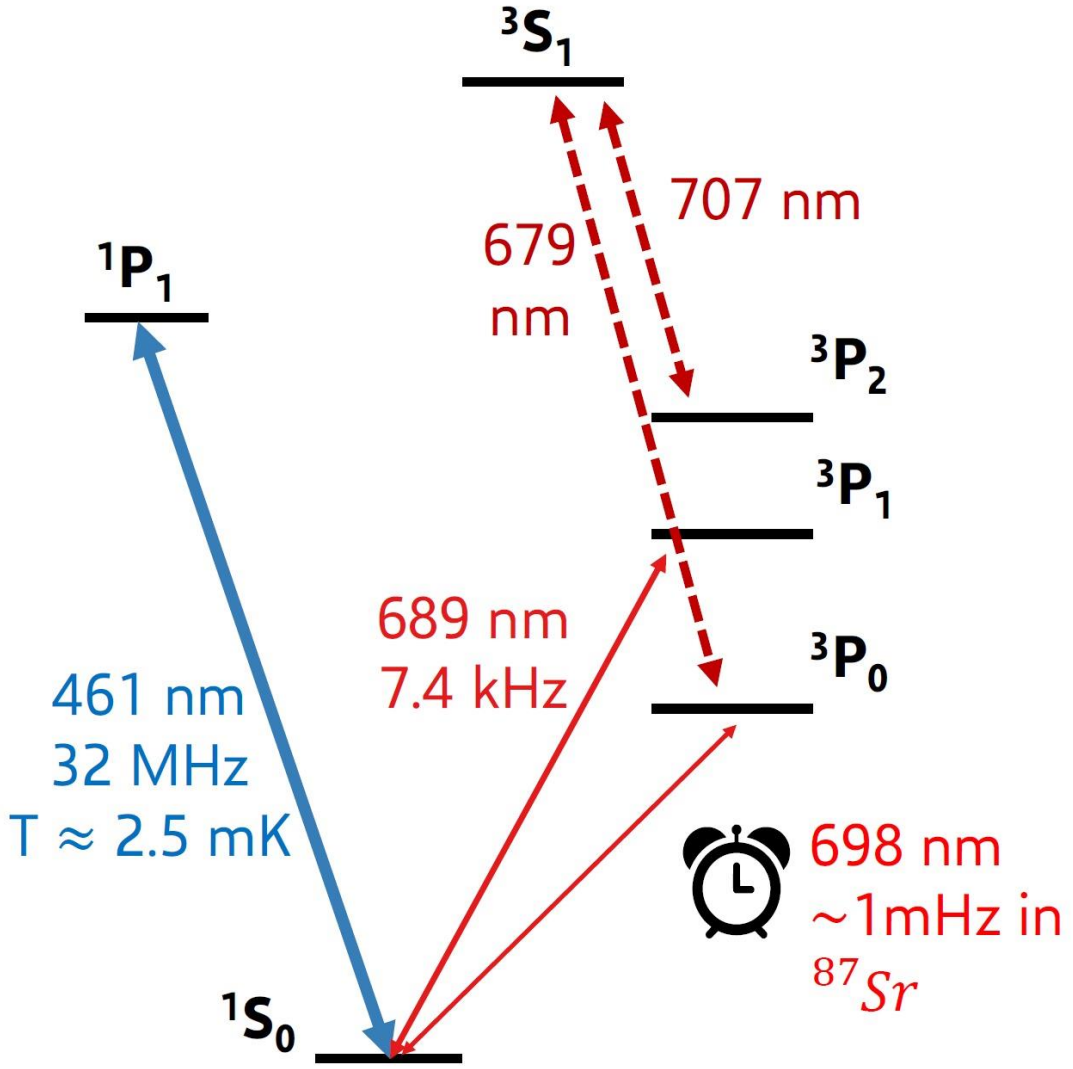
Preciznost



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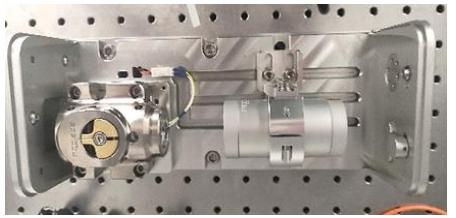
Preciznost → uska laserska linija

diodni laser

698 nm



optičko vlakno

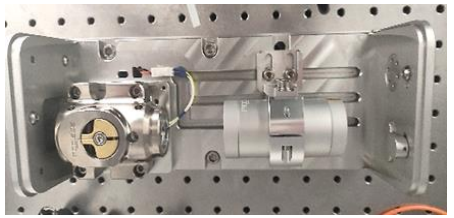
EKSPERIMENT

Preciznost → uska laserska linija

Fazna stabilizacija lasera

diodni laser

698 nm



optičko vlakno

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CALT

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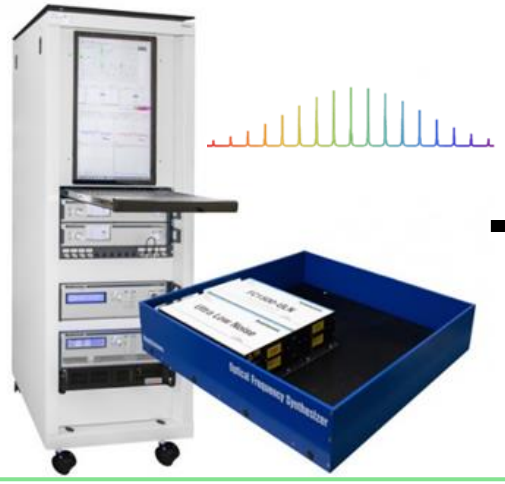
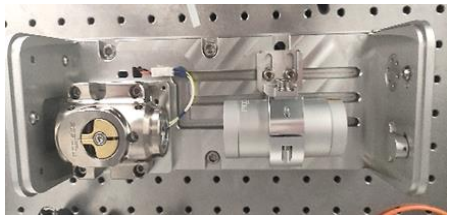
frekventni češalj niskog šuma



diodni laser 698 nm



optičko vlakno

EKSPERIMENT

Preciznost → uska laserska linija

Fazna stabilizacija lasera

cw laser 1542 nm

→

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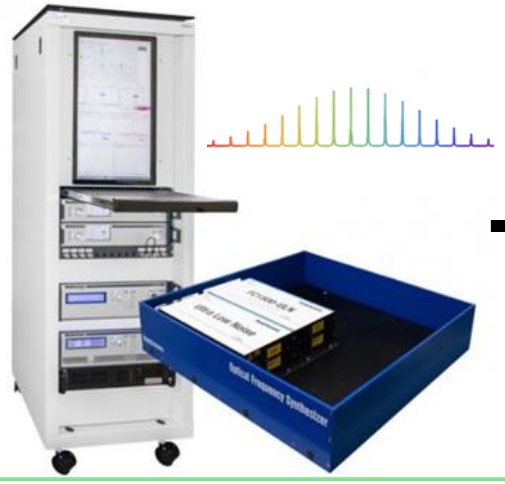

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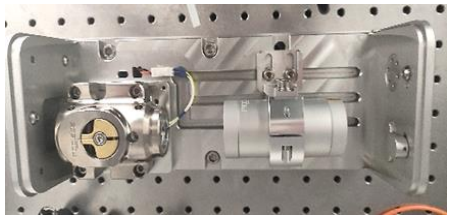

optičko vlakno

EKSPERIMENT

Preciznost → uska laserska linija

Fazna stabilizacija lasera

ultra stabilni optički rezonator

cw laser 1542 nm

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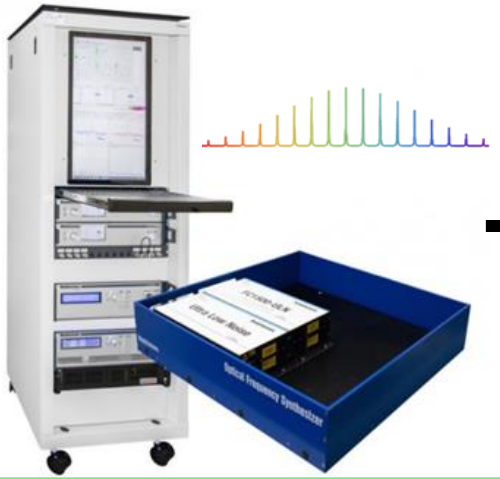
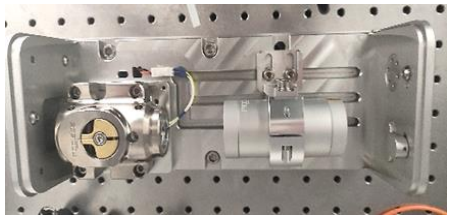


diodni laser 698 nm



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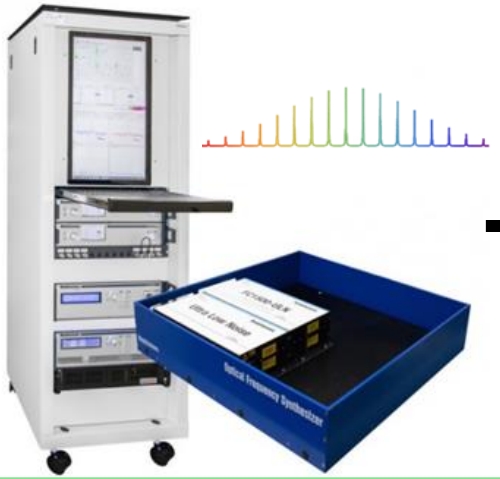

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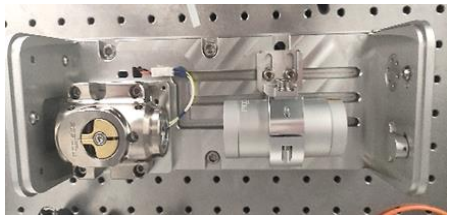


optičko vlakno

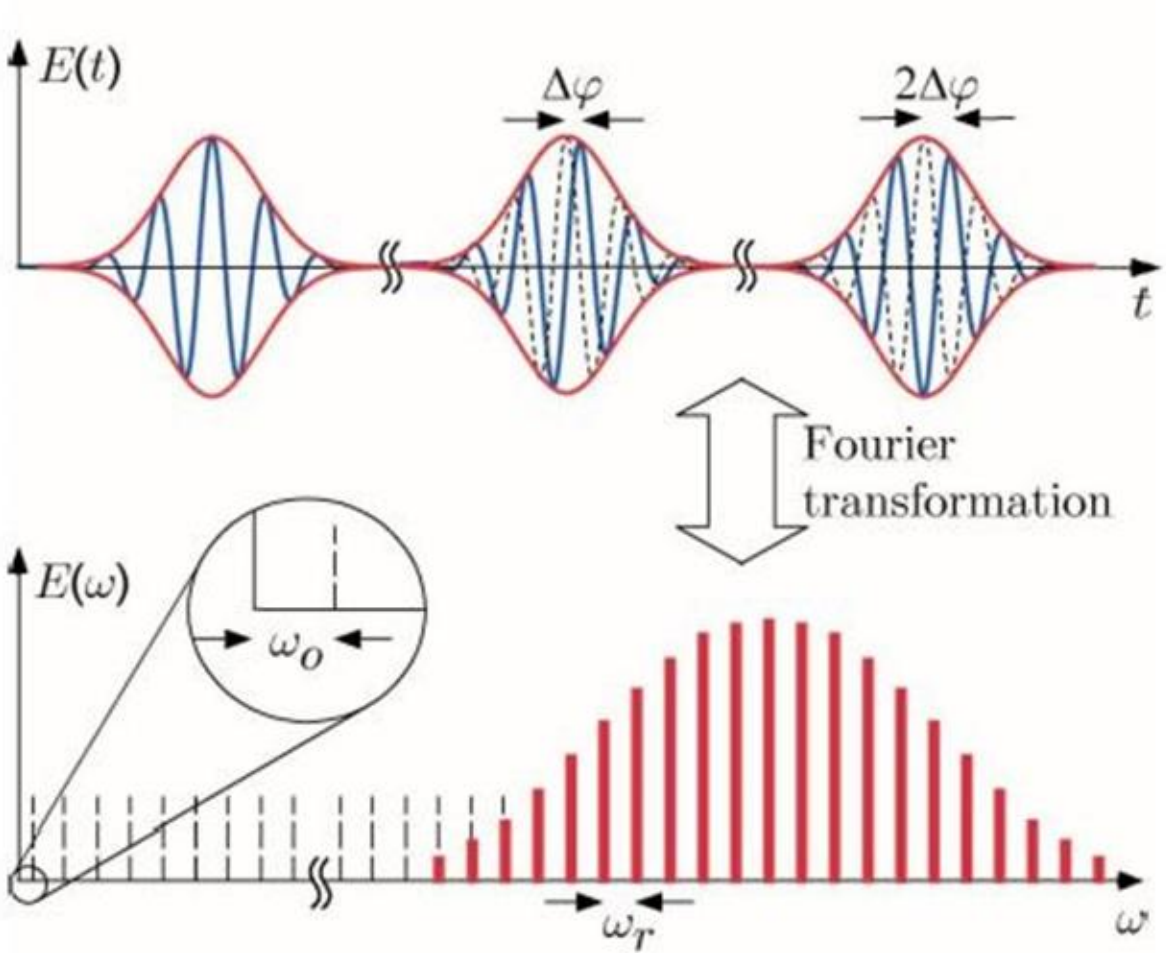
EKSPERIMENT

i redukcija šuma u optičkim vlaknima

Komponente
- princip rada

Frekventni češalj

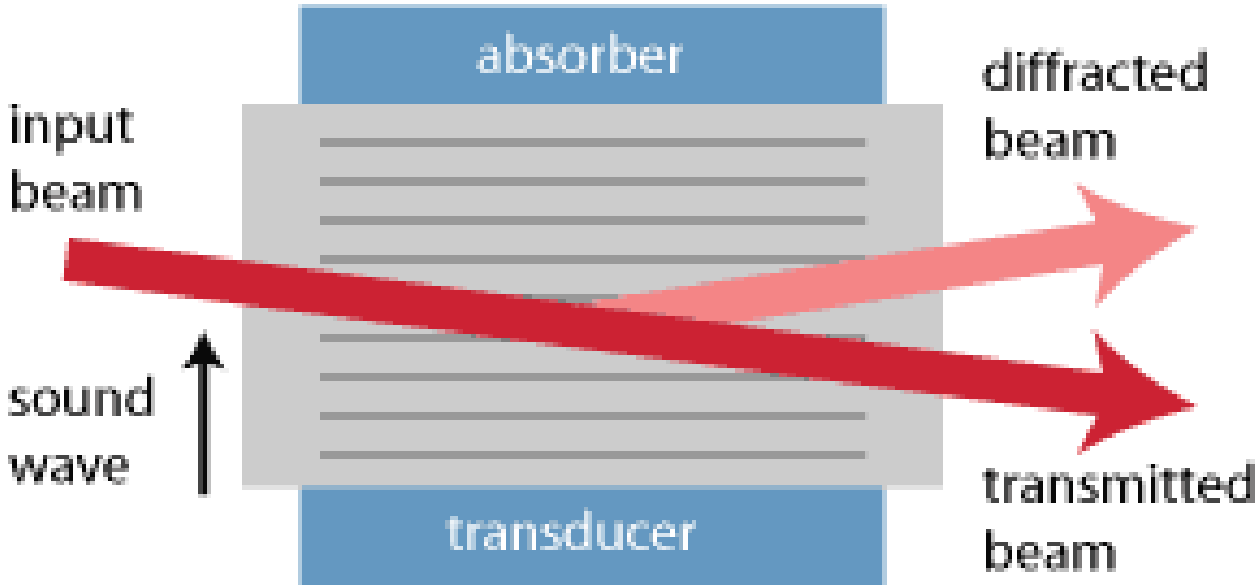
- koherentni modovi → ekvidistantni optički spektar
- $f_{rep} = \frac{c}{2L}$
- $f_{CEO} = \frac{\Delta\varphi}{T}$
- n mod: $f_n = f_{CEO} + n \cdot f_{rep}$



Slika: M. Systems, FC1500-250-ULN user manual

AOM

- akustičko optički modulator
- $f_{dif} = f + m \cdot F$
- mijenja frekvenciju!



Slika: R. Paschotta, Acousto-optic modulators, RP Photonics Encyclopedia

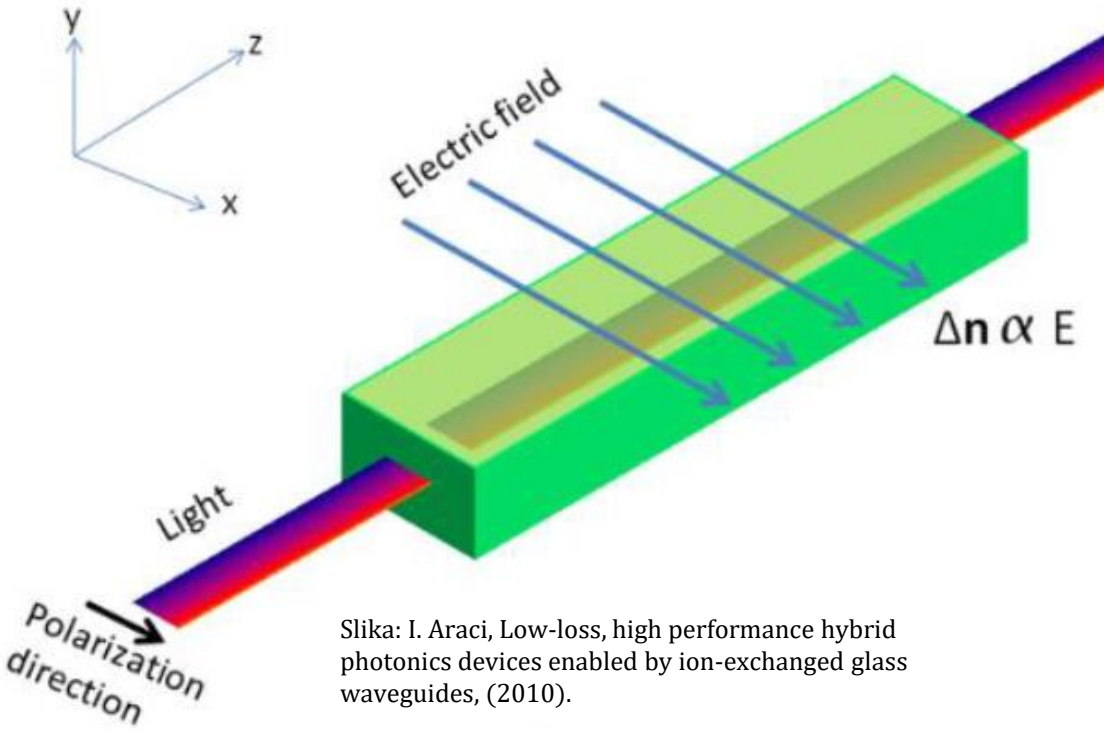
Fazni EOM

- $\Delta\varphi = \frac{2\pi \cdot \Delta n \cdot L}{\lambda}$ - mijenja fazu!

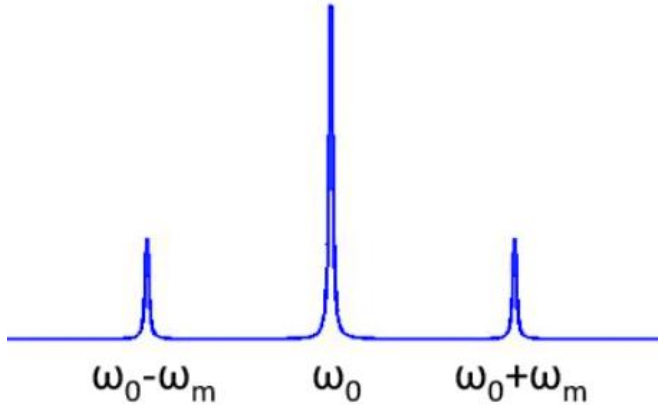
- $E_{mod} = E_0 e^{-i\omega t - im\sin(\omega t)}$

$$\approx J_0(m)E_0 e^{-i\omega t} + J_1(m)E_0 e^{-i(\omega+\omega_m)t}$$

$$+ J_1(m)E_0 e^{-i(\omega-\omega_m)t} + \text{viši redovi}$$



Slika: I. Araci, Low-loss, high performance hybrid photonics devices enabled by ion-exchanged glass waveguides, (2010).



Slika: J. Karlsson, Cerium as a quantum state probe for rare-earth qubits in a crystal, Ph.D. thesis, Lund University, Faculty of Engineering, LTH Department of Physics Division of Atomic Physics (2015).

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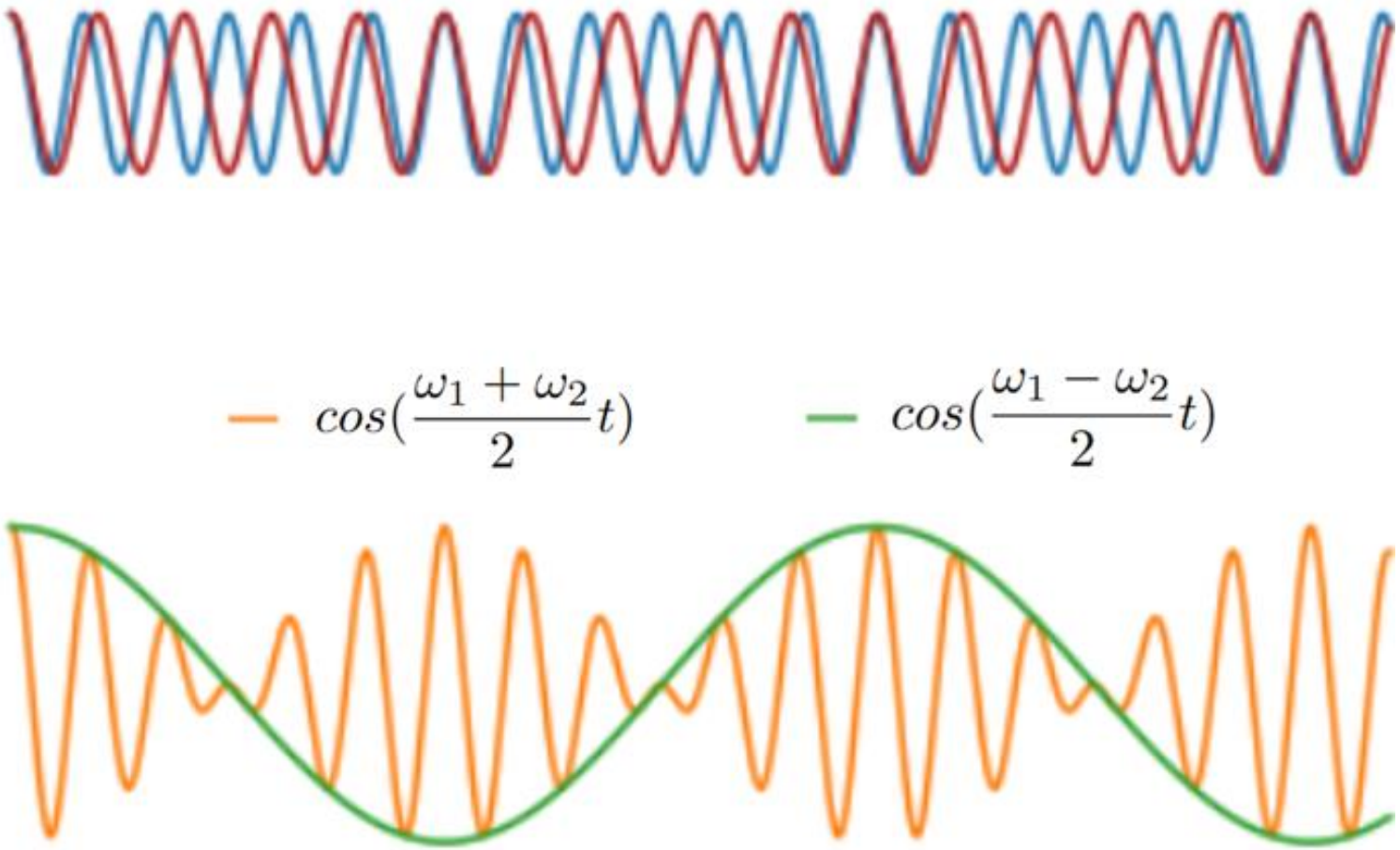
Udar

- $f_{udara} = |\omega_1 - \omega_2|$
- zbroj izvan dometa elektronike
- mikser – slično miješanje frekvencija



Eksperimentalni postav

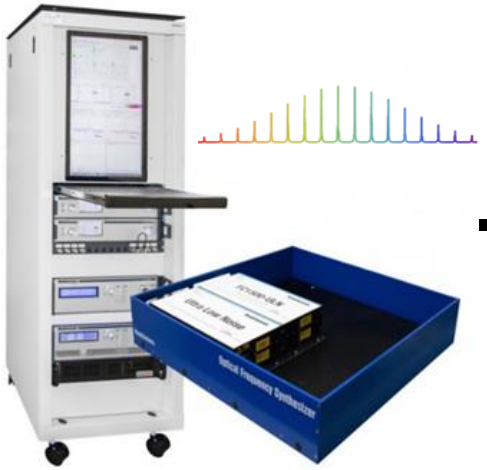
Stabilizacija

1) Ultra stabilni optički rezonator

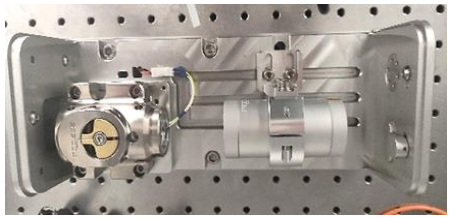
ultra stabilni optički rezonator

cw laser 1542 nm

frekventni češalj niskog šuma

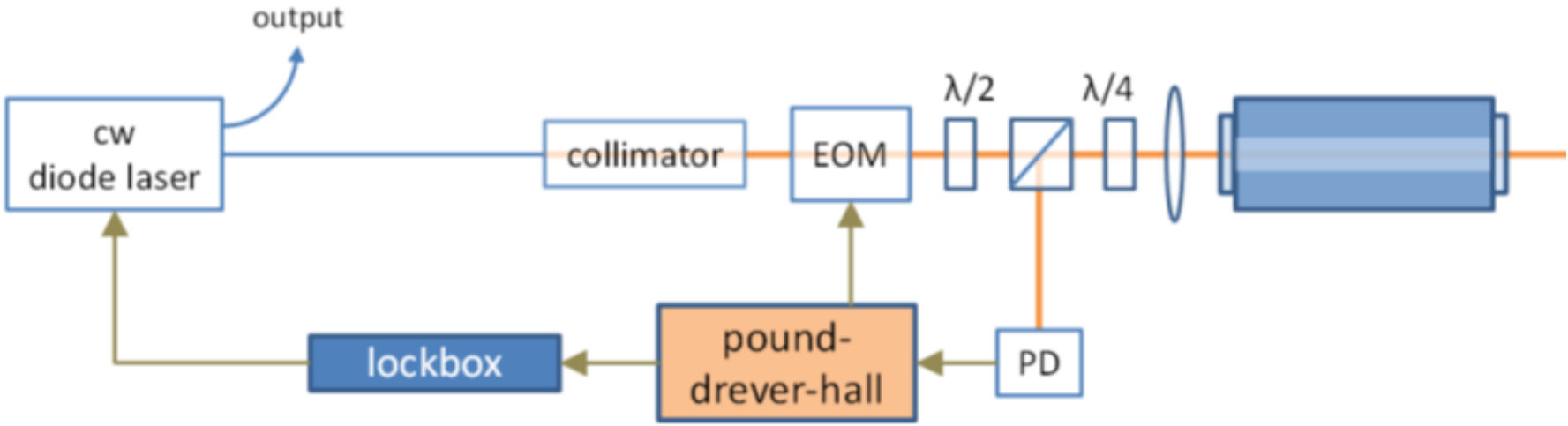


diodni laser 698 nm



1) Ultra stabilni optički rezonator

- erbij fiber jedno-modni kontinuirani laser 1542 nm
- optički rezonator
  - ULE staklo
  - visoki vakuum
  - aktivna temperaturna stabilizacija
  - zvučna izolacija
  - aktivna platforma za izolaciju od vibracija



Slika: M. Systems, UMAN ORS 1550 user manual

CALT

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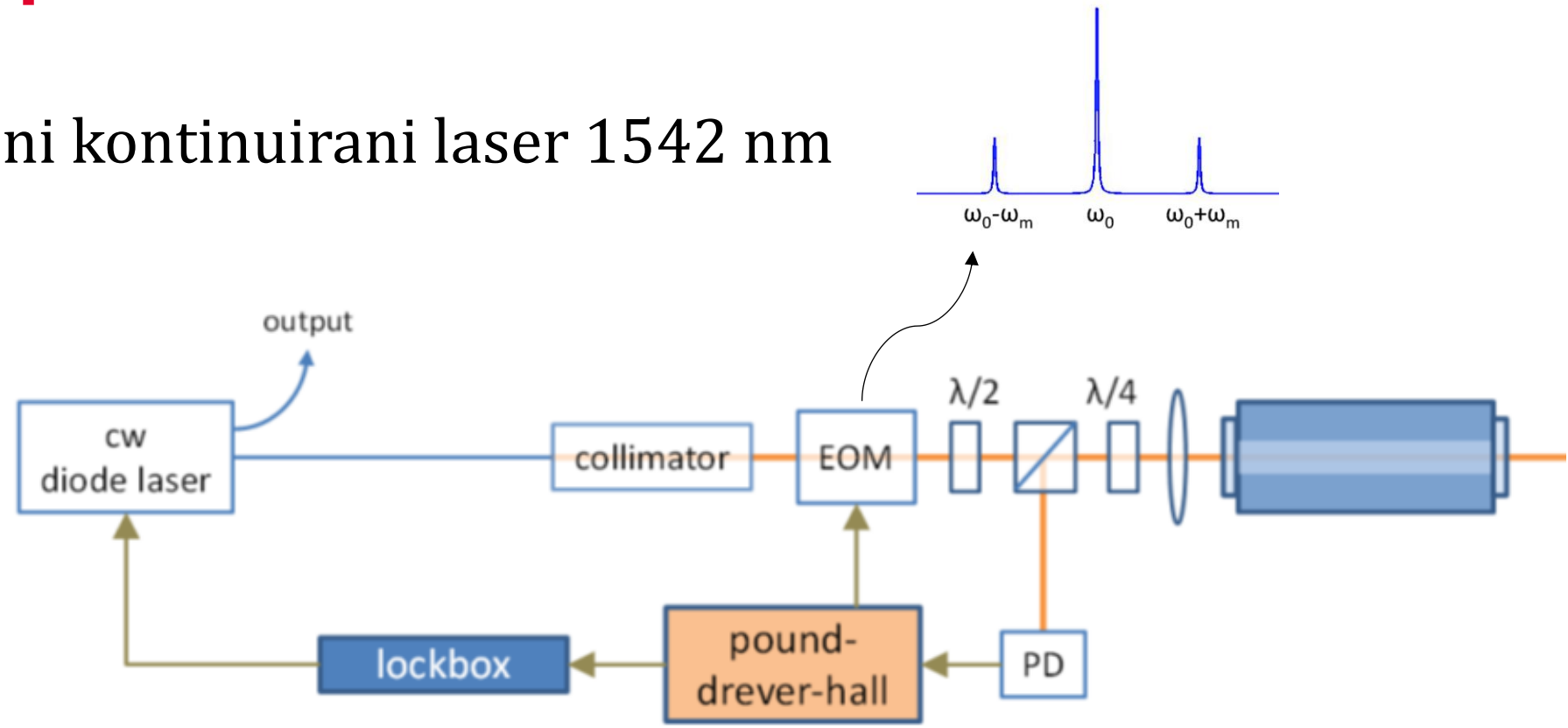

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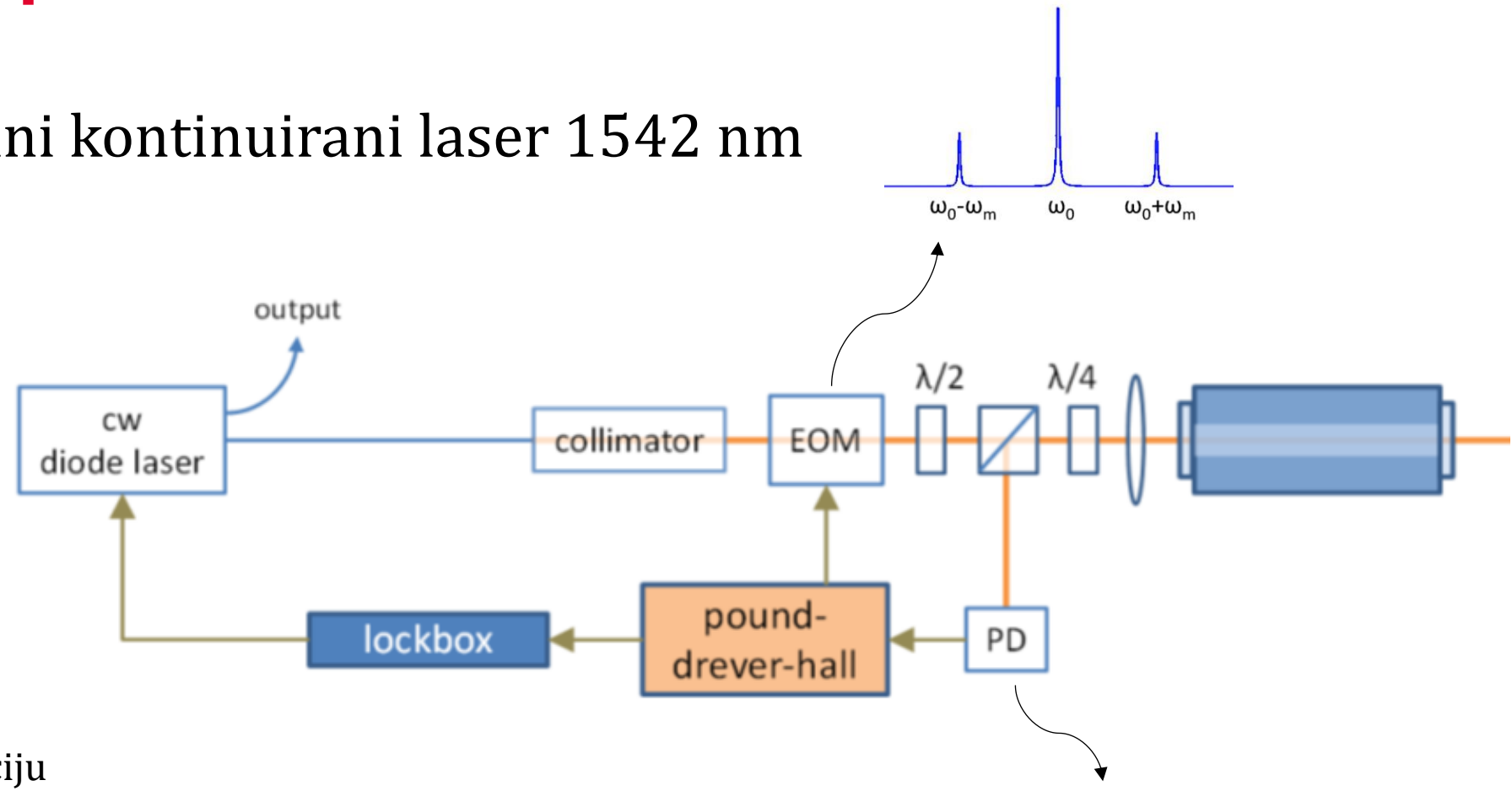

udar

nosioc + *sidebands*

CALT

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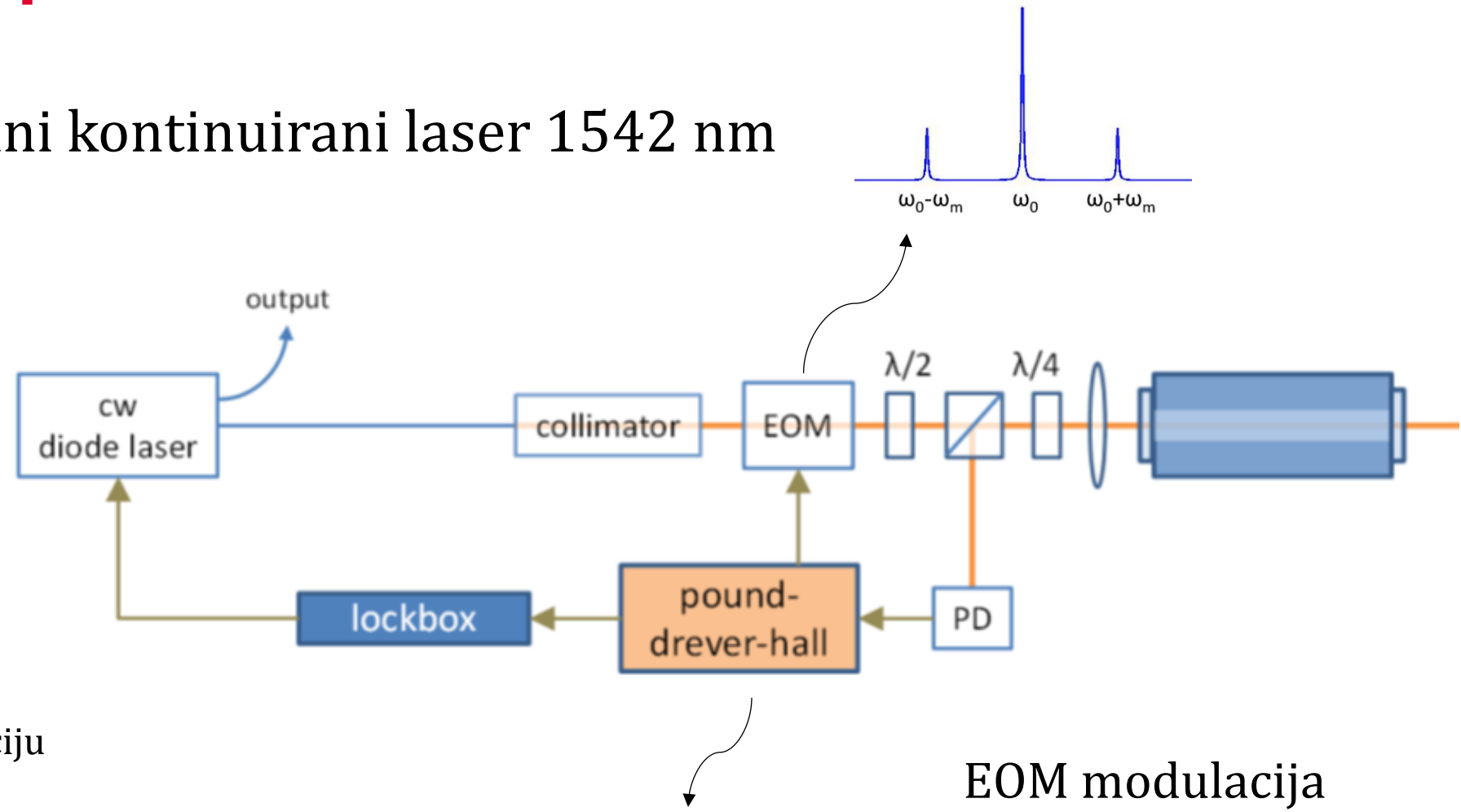

$$error\ signal = \text{EOM modulacija} + \text{signal iz PD}$$

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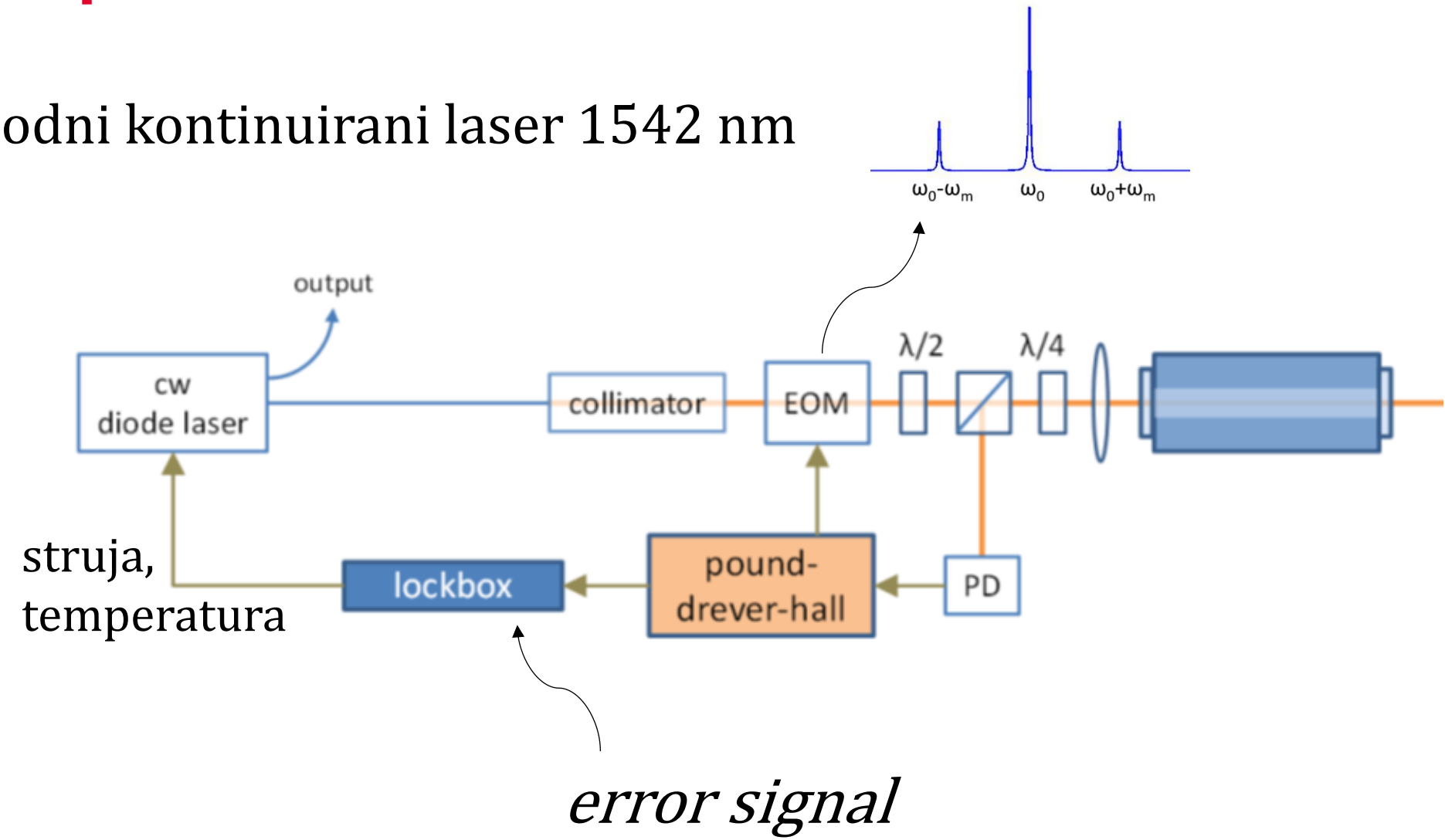
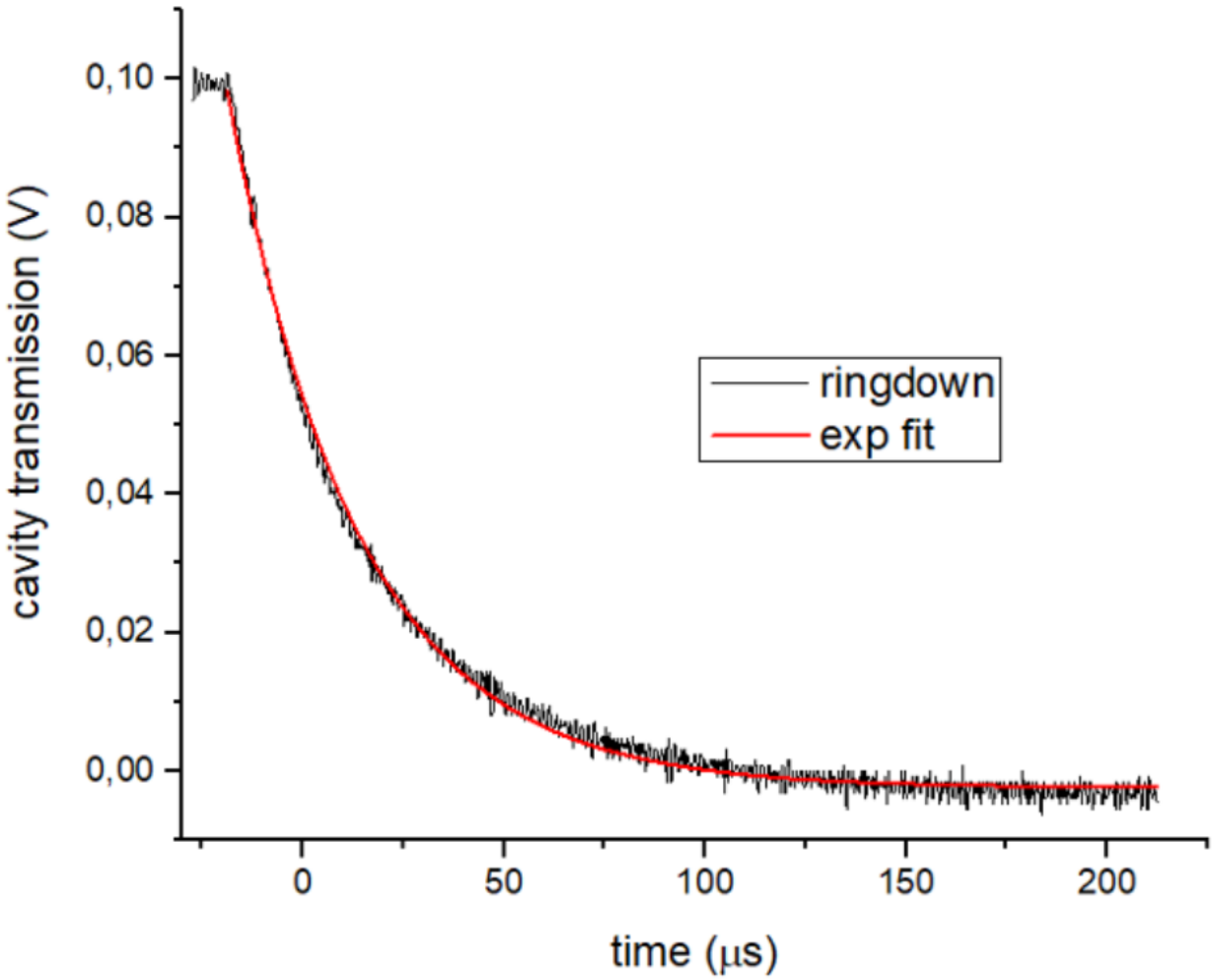


1) Ultra stabilni optički rezonator

→ **provjera**

- *ringdown* vrijeme τ
- $\tau = (32.3 \pm 0.2)\ \mu s$
- $\mathcal{F} = \frac{\pi \cdot c \cdot \tau}{L} = 252\,000 \pm 2\,000$
- $\mathrm{FWHM} = \frac{c}{2L} \cdot \frac{1}{\mathcal{F}} = (4\,960 \pm 40)\ \mathrm{Hz}$

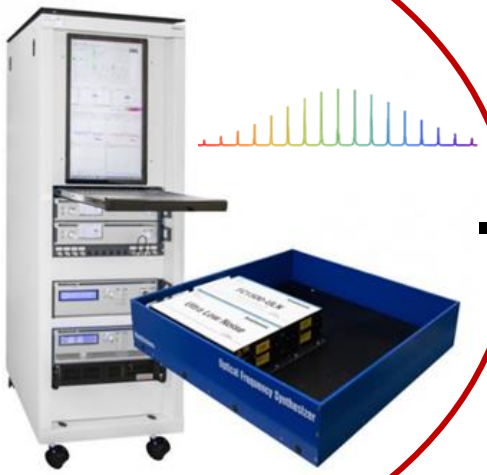


2) Stabilizacija frekventnog češlja

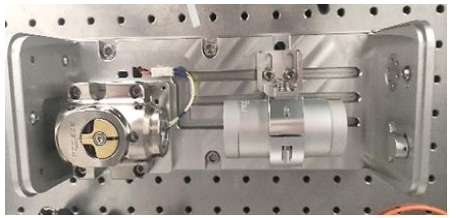
ultra stabilni optički rezonator

cw laser 1542 nm

frekventni češalj niskog šuma



diodni laser 698 nm



2) Stabilizacija frekventnog češlja

- $f_{rep} = \frac{c}{2L}$

- L = duljina rezonatora

(piezo kristal, unutarnji EOM)

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cw laser 1542 nm

+

1 mod frekventnog češlja (≈1542 nm)

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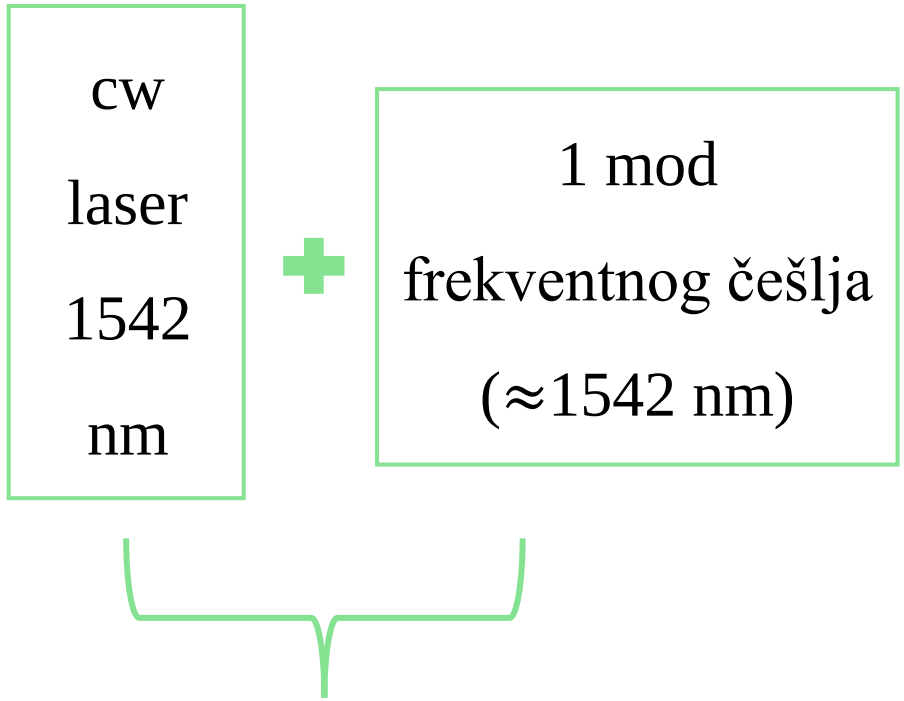

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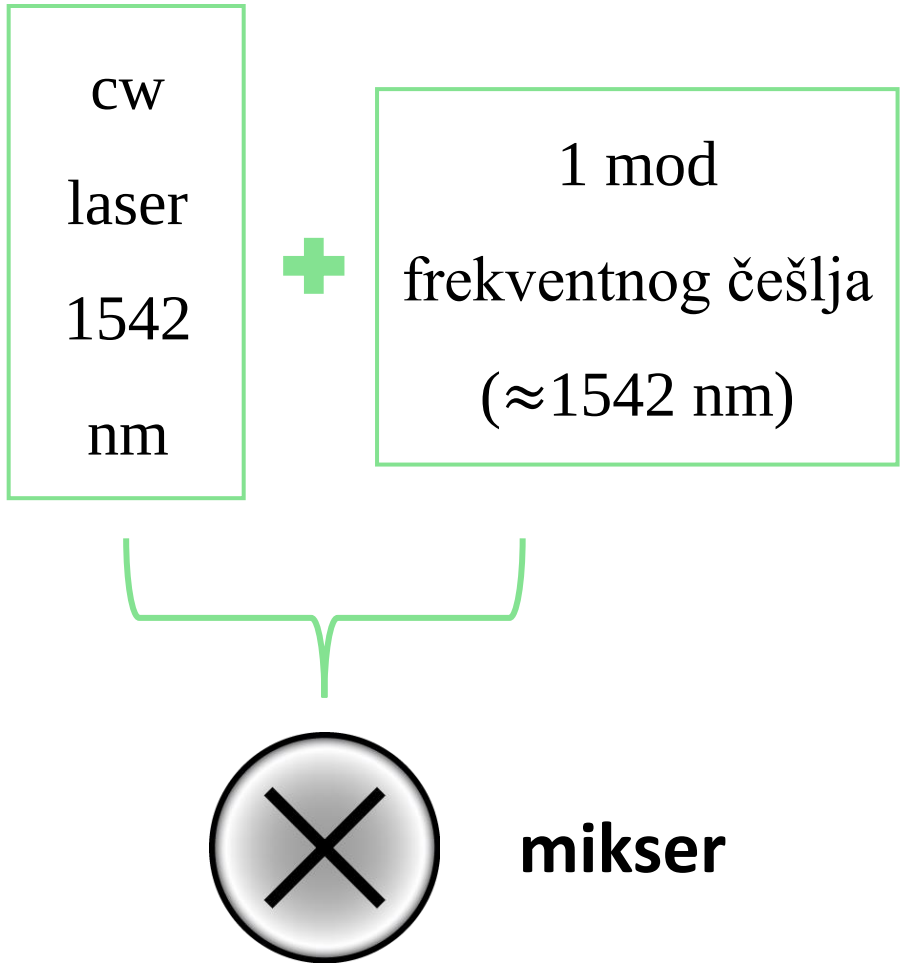

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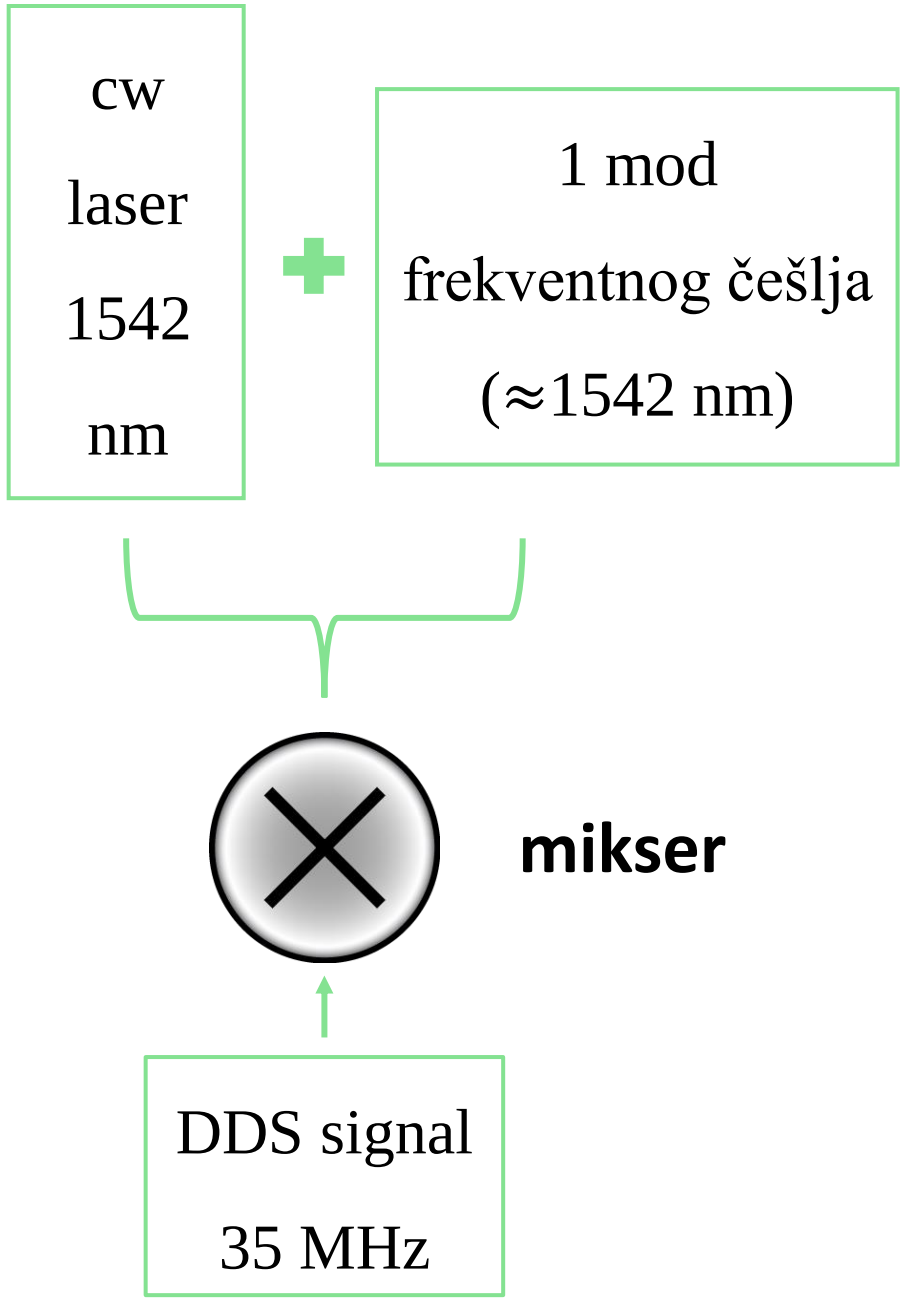

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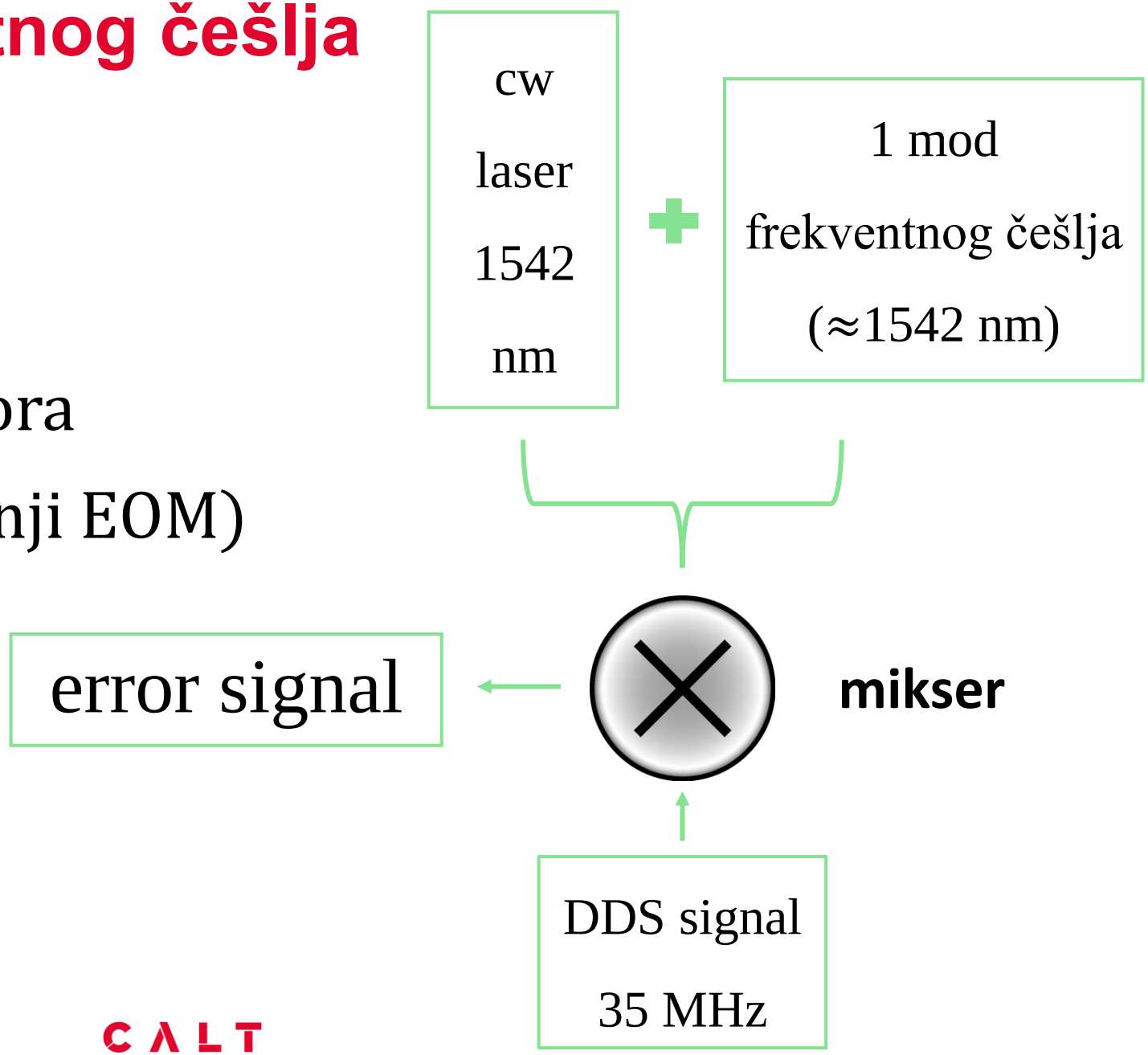

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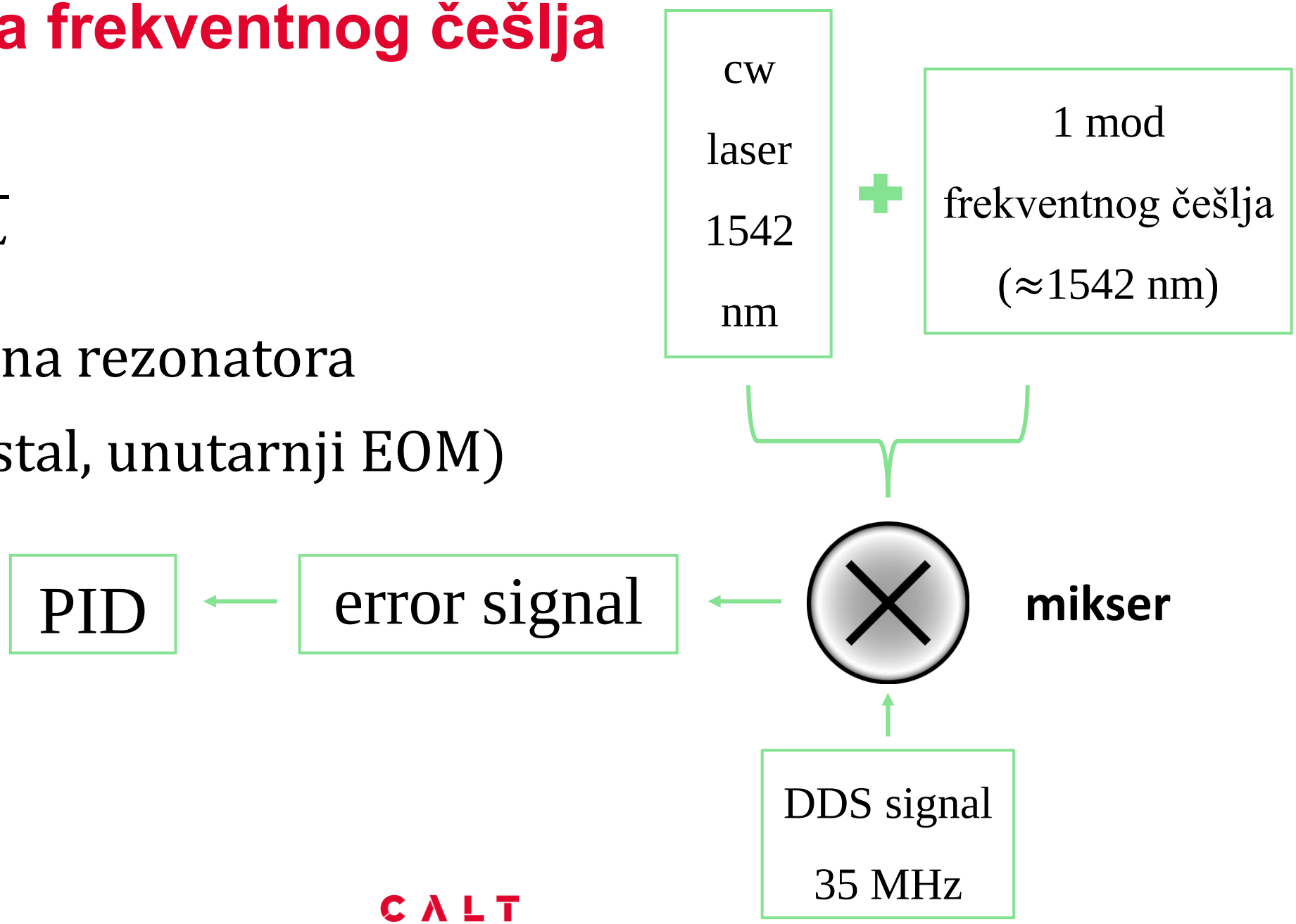
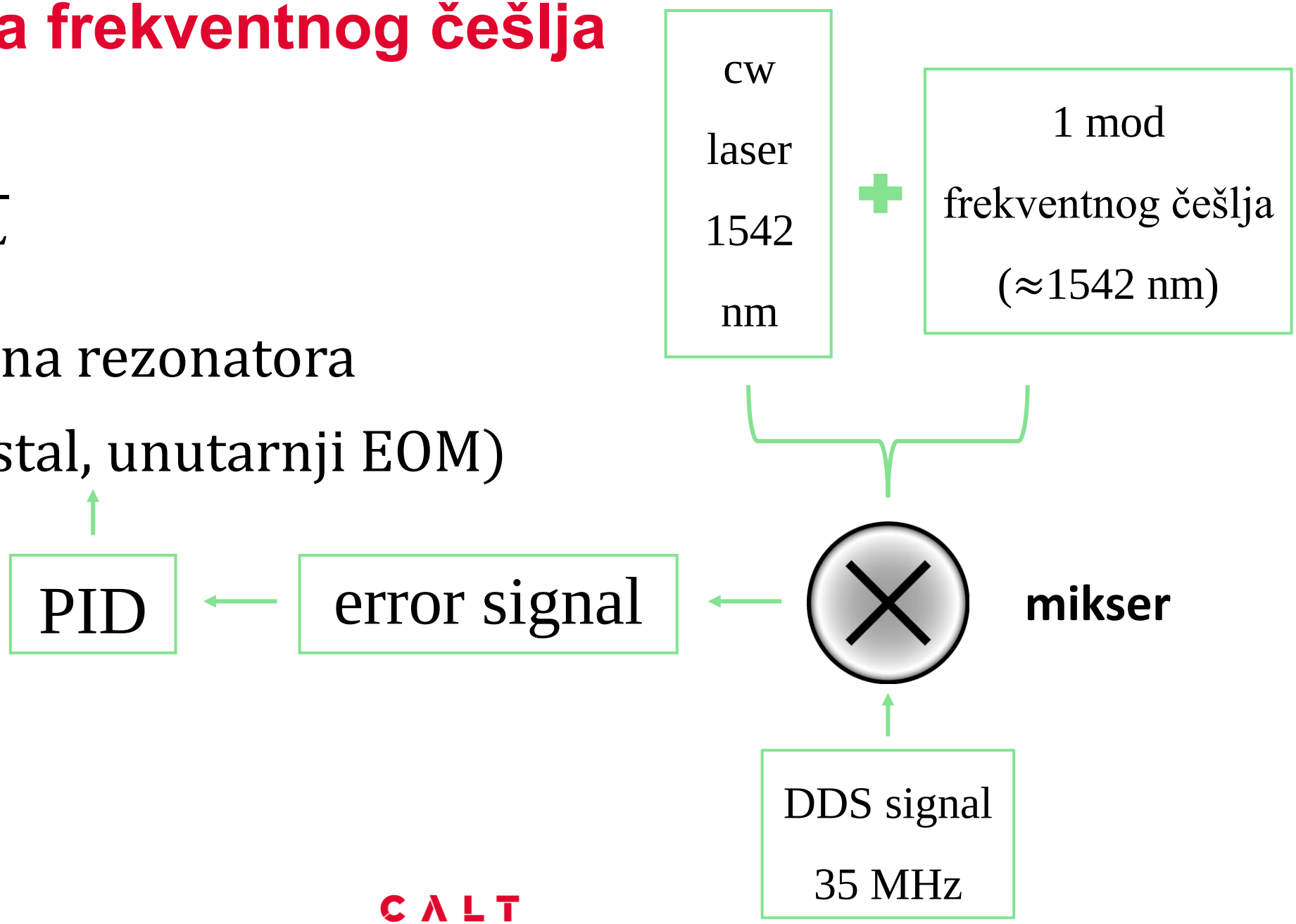


2) Stabilizacija frekventnog češlja

- $f_{rep} = \frac{c}{2L}$

- L = duljina rezonatora

(piezo kristal, unutarnji EOM)



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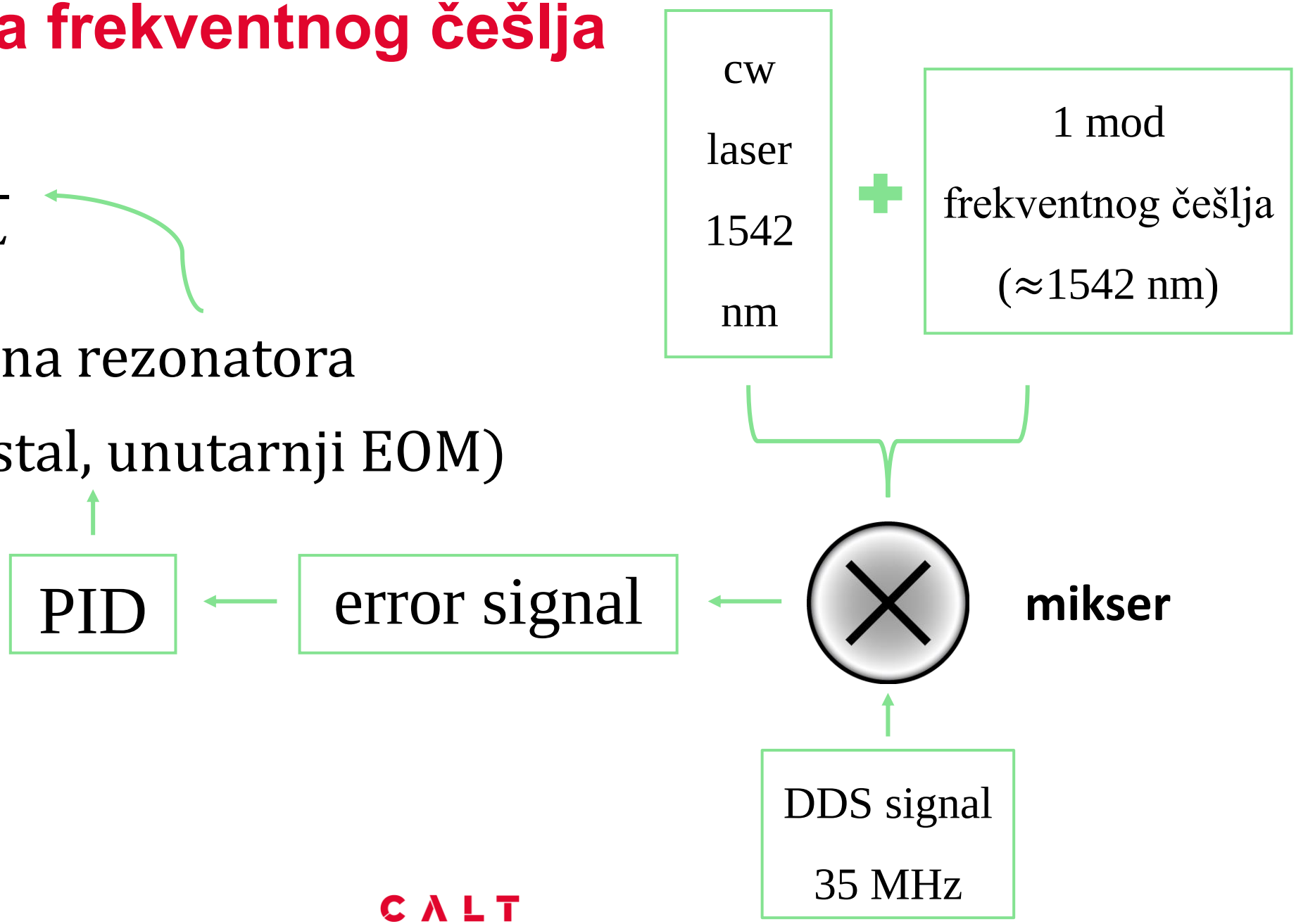

2) Stabilizacija frekventnog češlja

- f_{CEO}

(piezo kristal, struja lasera)

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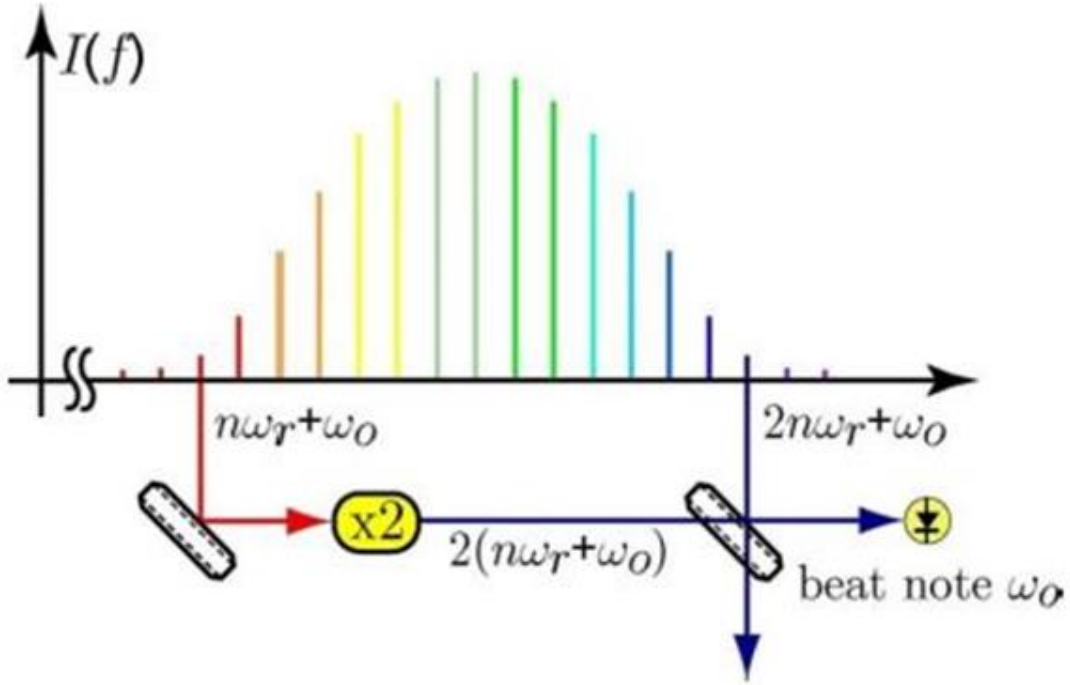

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Ref: M. Systems, FC1500-250-ULN user manual

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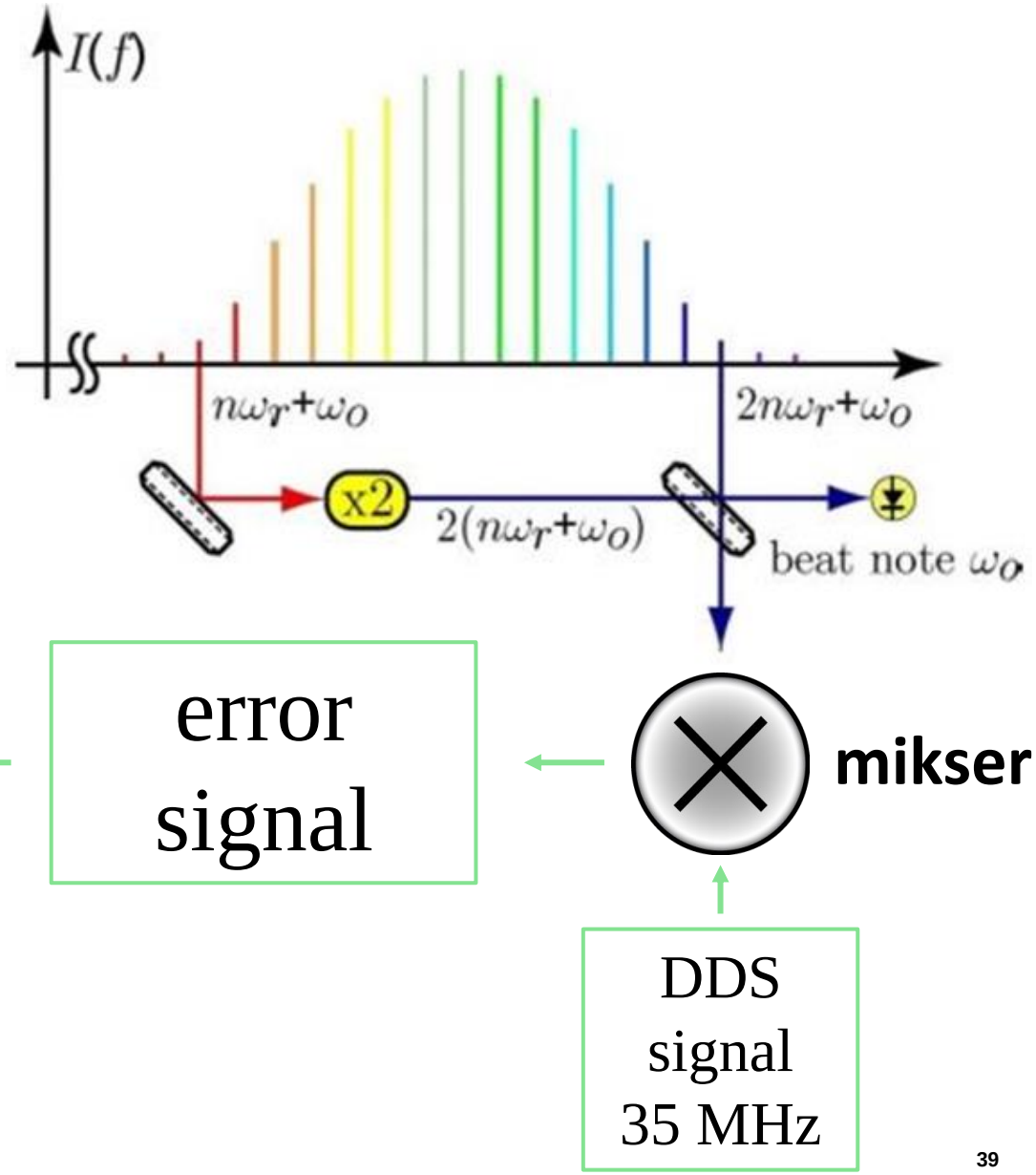
(piezo kristal, struja lasera)



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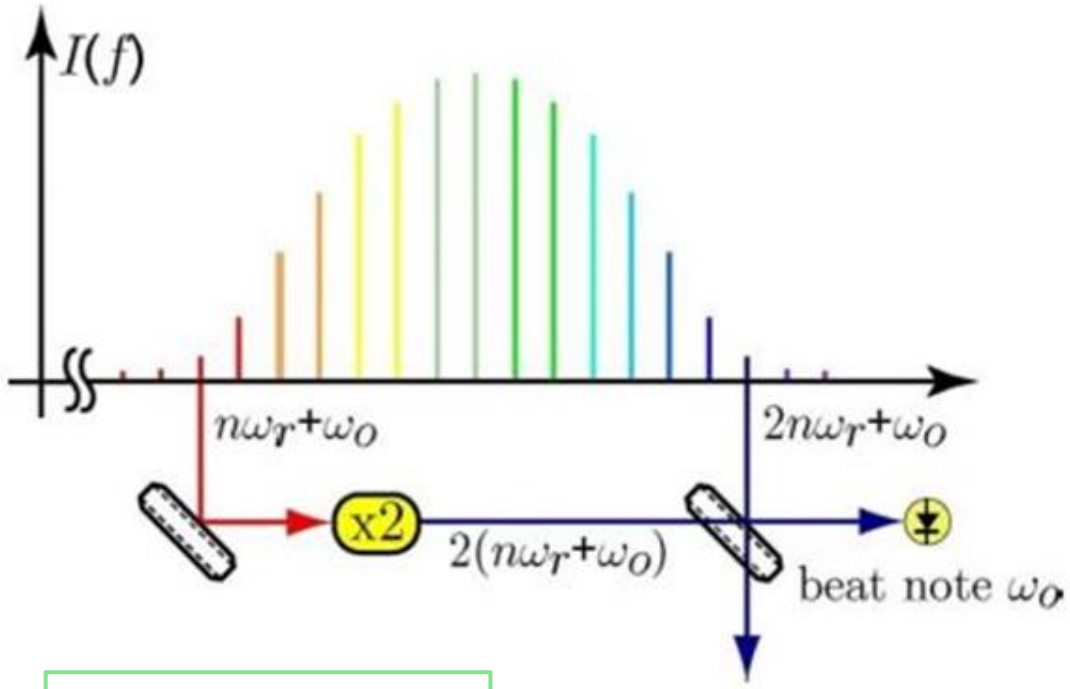


spori aktuator

PID

error signal

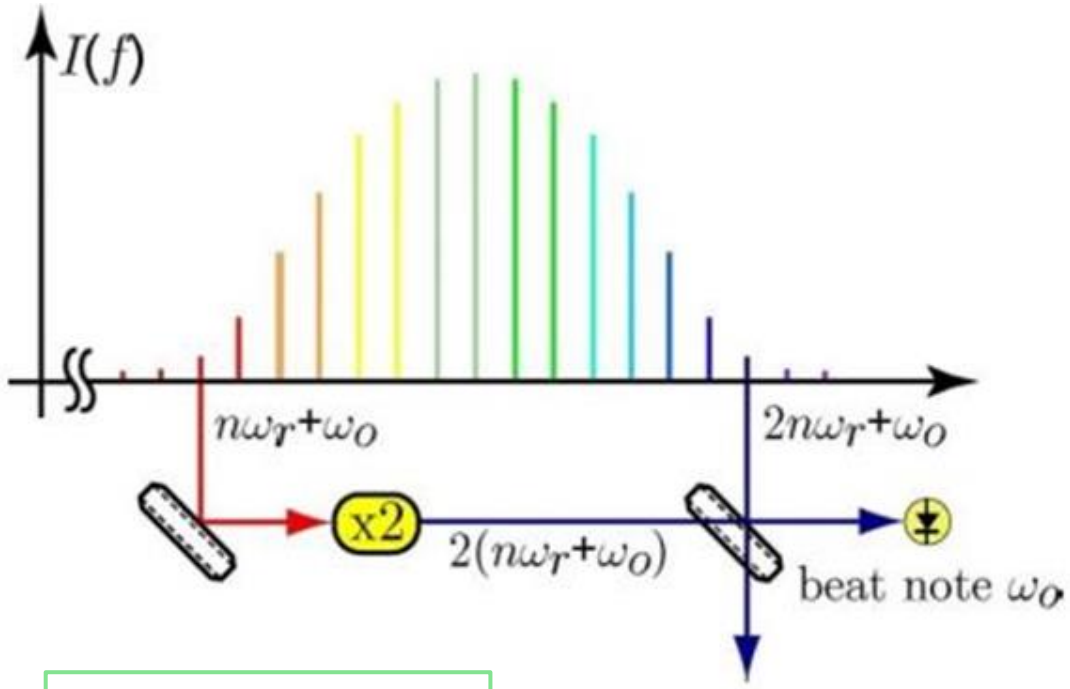
mikser

DDS signal 35 MHz

2) Stabilizacija frekventnog češlja

- f_{CEO}

(piezo kristal, struja lasera)



brzi aktuator

spori aktuator

PID

error signal

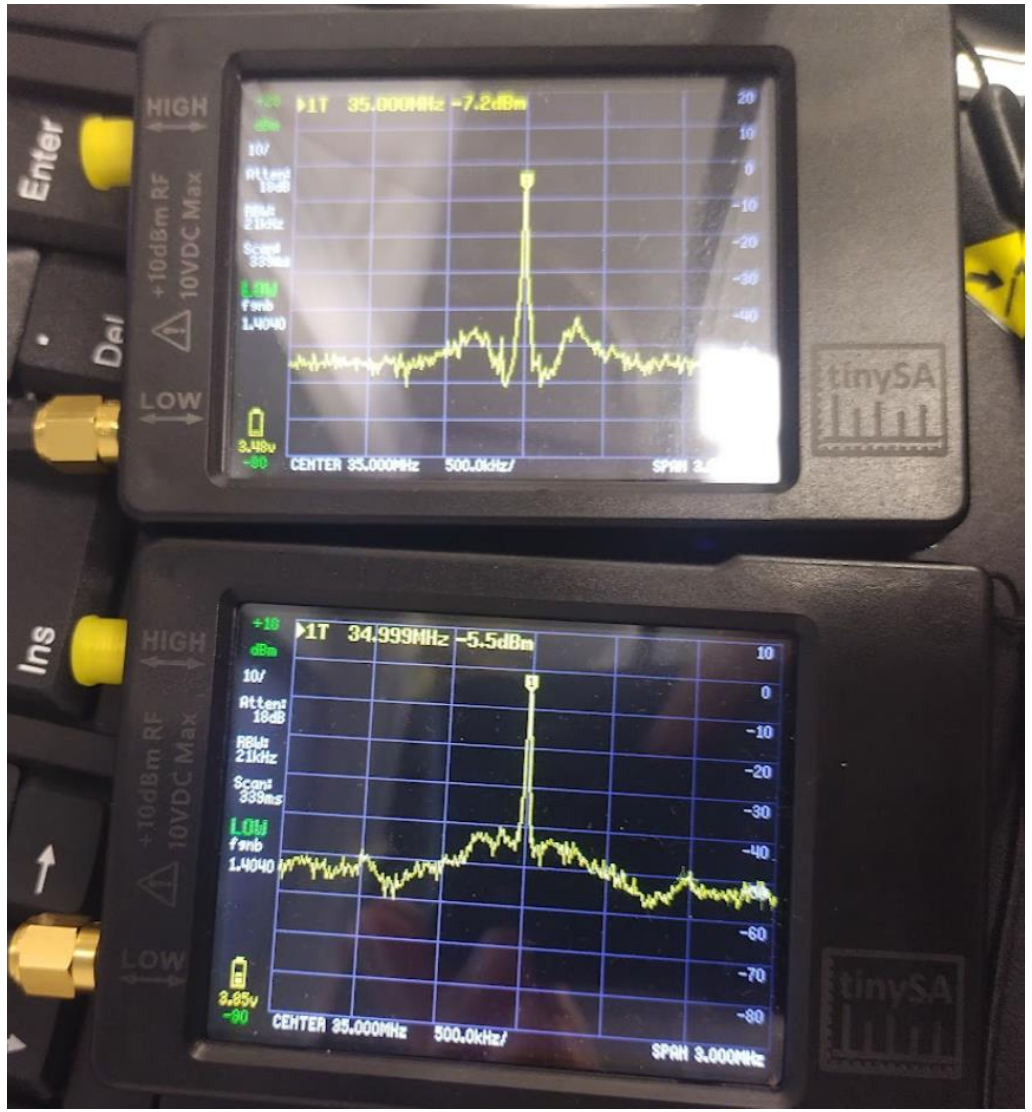
mikser

DDS signal 35 MHz

2) Stabilizacija frekventnog češlja

provjera

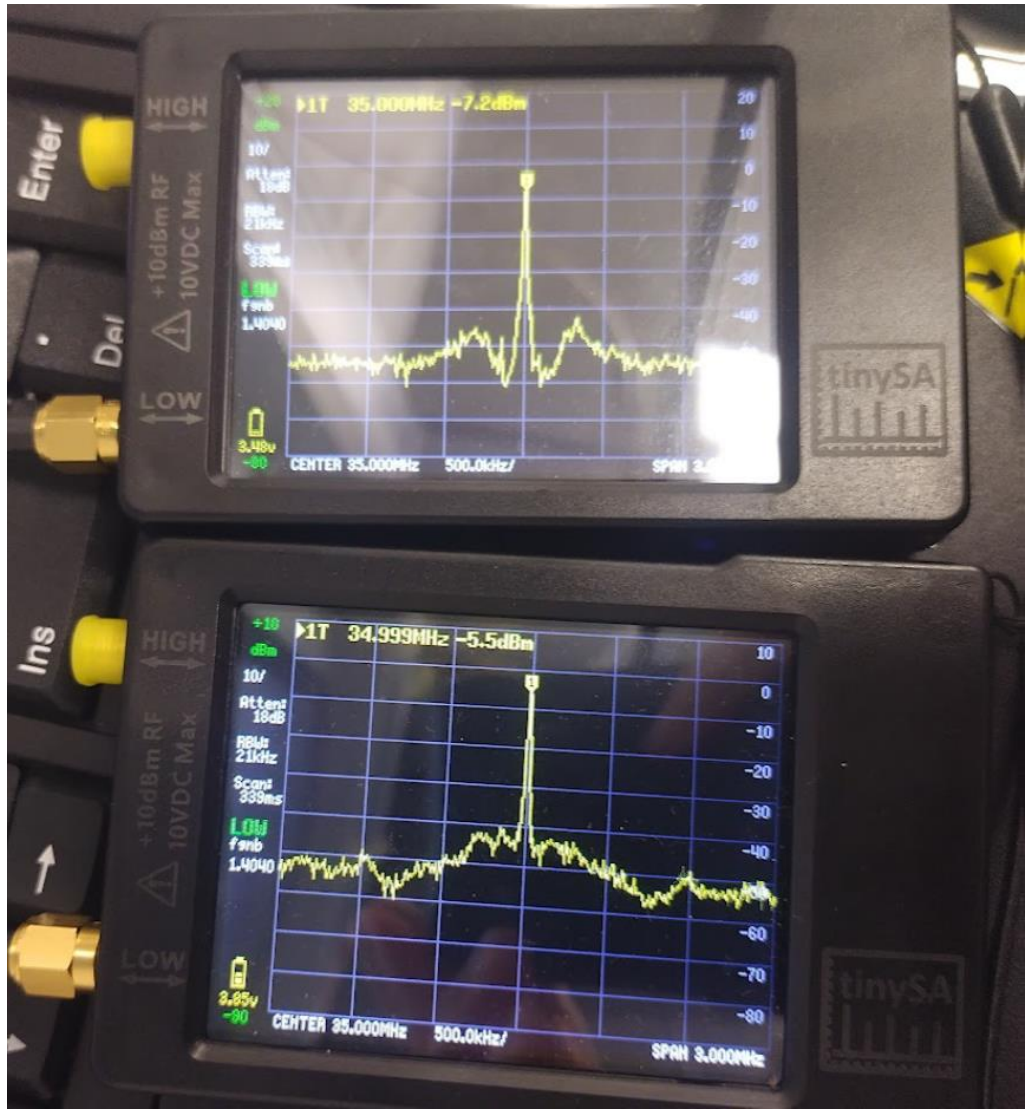
- lijepi *phase lock*:
  - f_{rep}
  - f_{CEO}



2) Stabilizacija frekventnog češlja

→ provjera

- lijepi *phase lock*:
  - f_{rep} - 1 mod
  - f_{CEO}



2) Stabilizacija frekventnog češlja

provjera

- lijepi *phase lock*:
  - f_{rep} - 1 mod
  - f_{CEO}

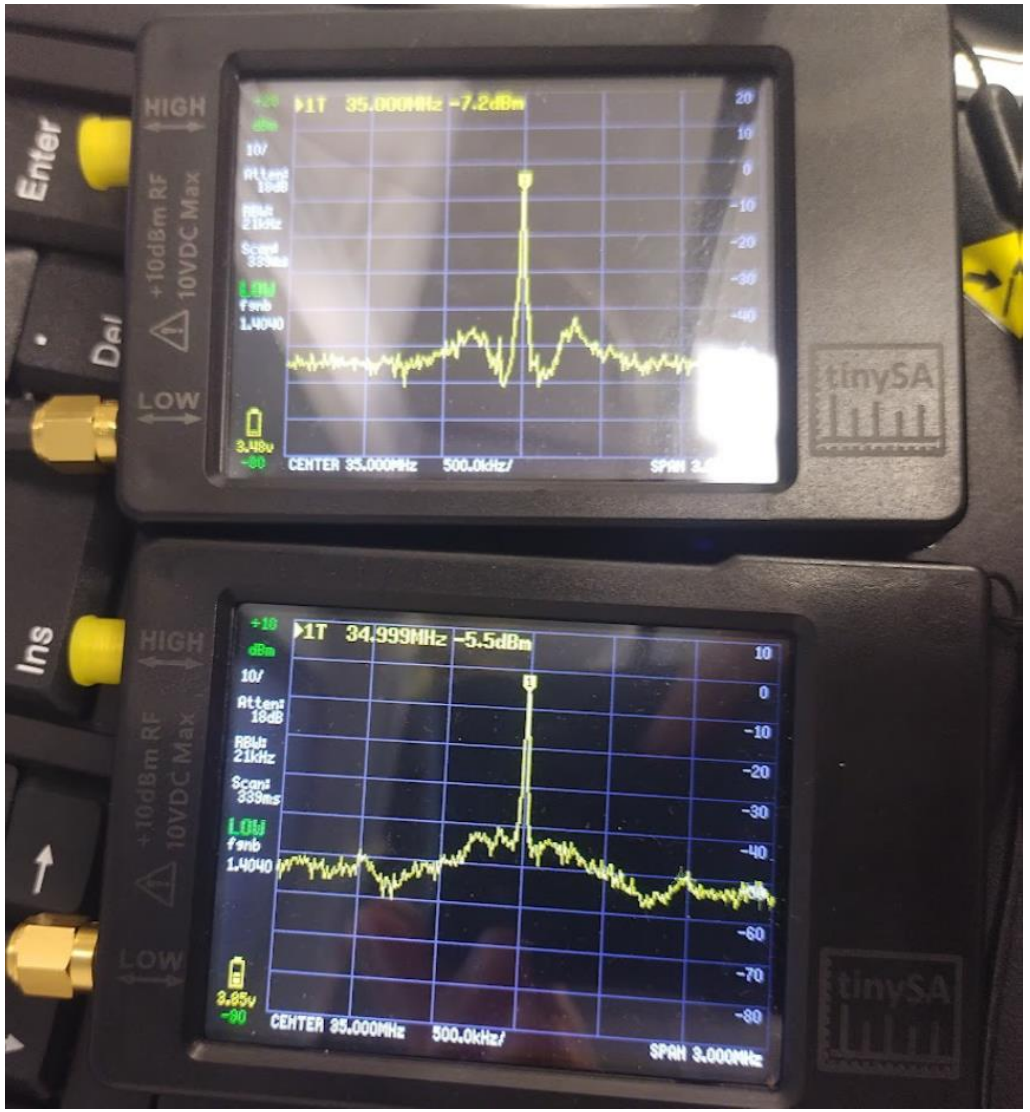
} koherencija →

2) Stabilizacija frekventnog češlja

provjera

- lijepi *phase lock*:
  - f_{rep} - 1 mod
  - f_{CEO}

} koherencija → svi modovi

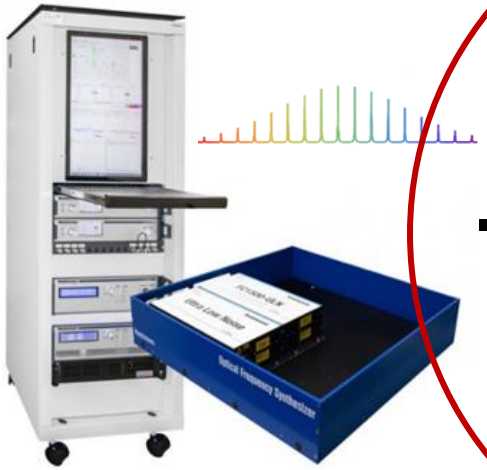


3) Stabilizacija 698 nm lasera

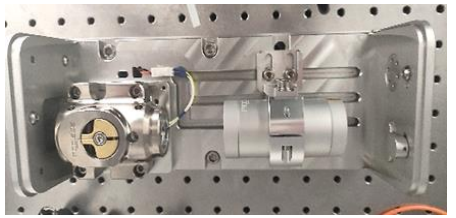
ultra stabilni optički rezonator

cw laser 1542 nm

frekventni češalj niskog šuma



diodni laser 698 nm



3) Stabilizacija 698 nm lasera

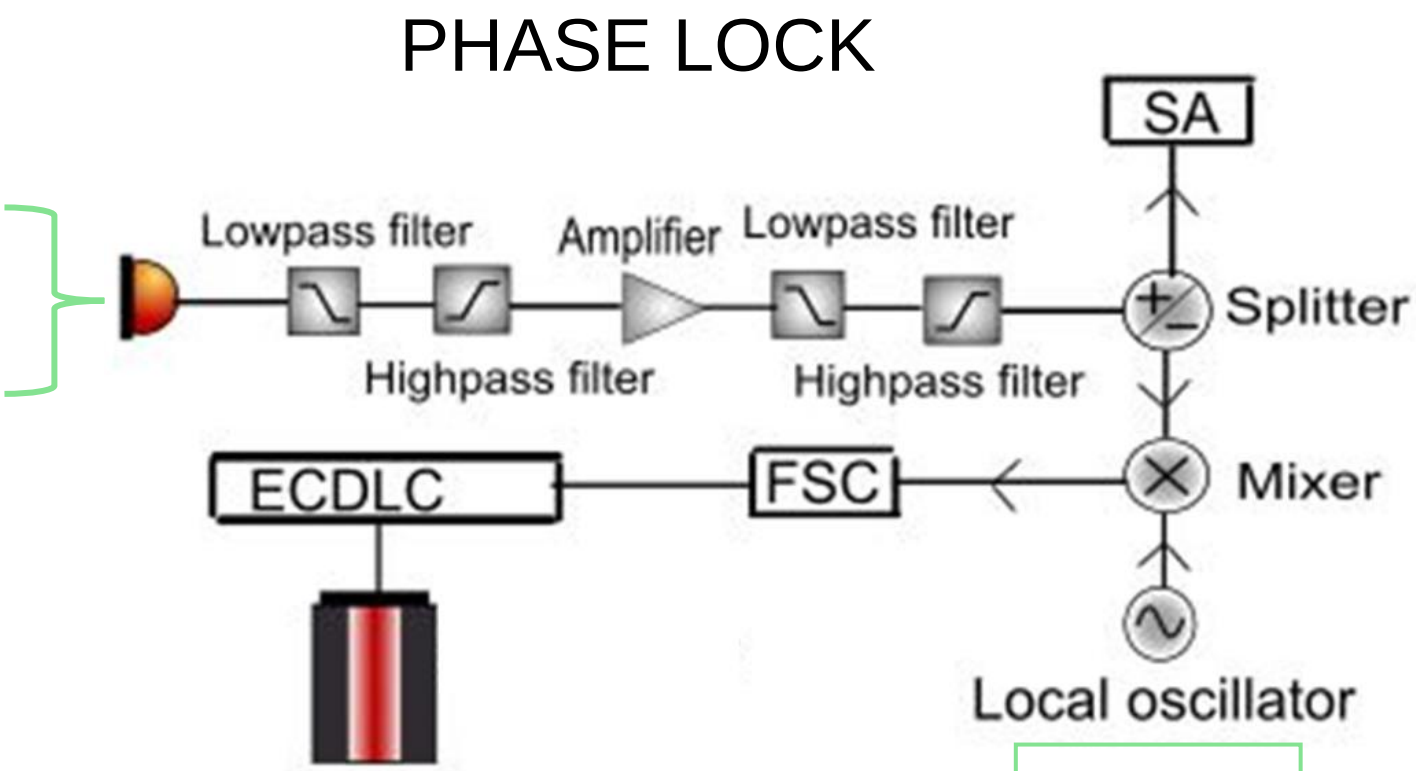
diodni laser

698 nm

+

1 mod

frekventnog češlja



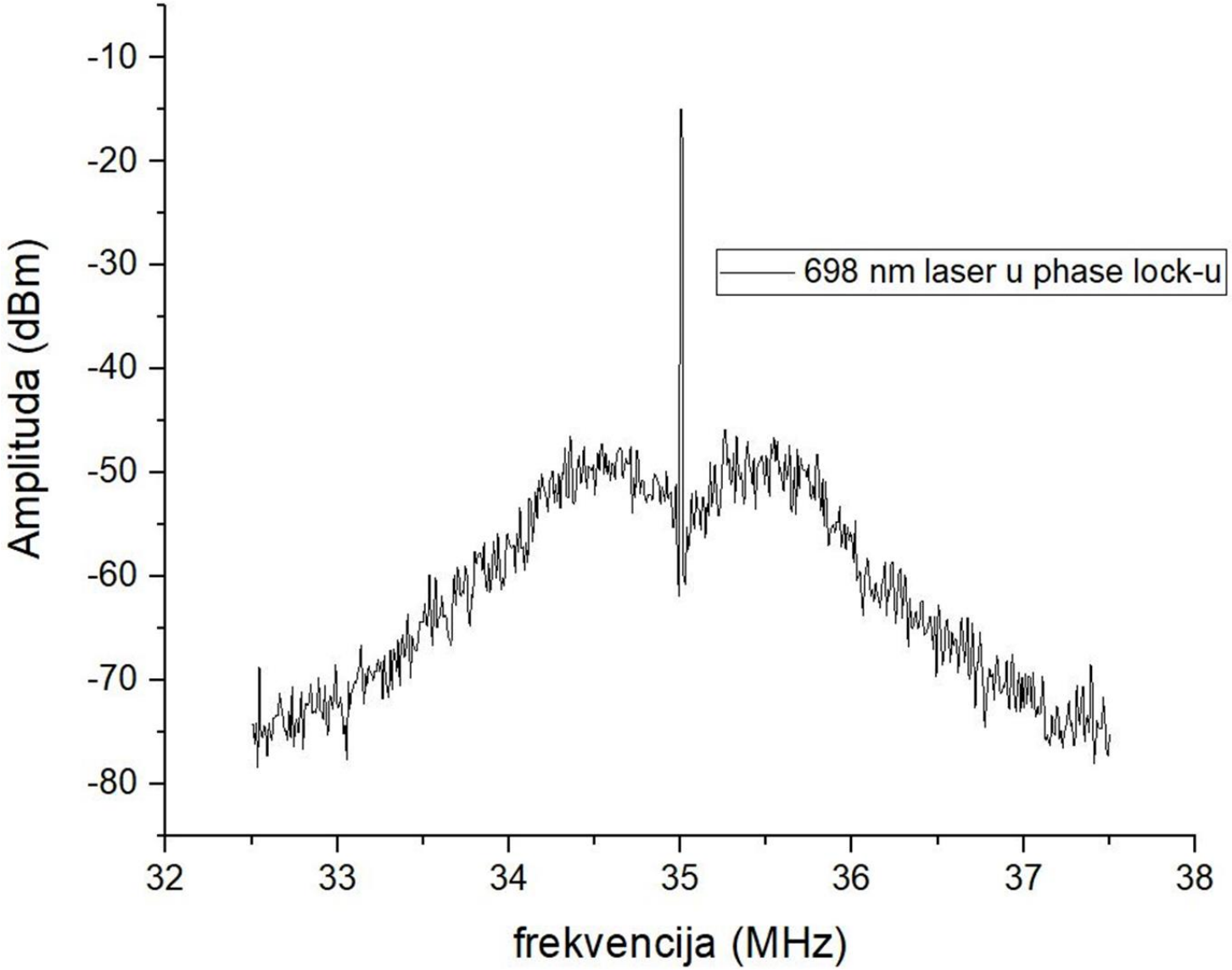
35 MHz

3) Stabilizacija 698 nm lasera

rezultat

- Lijepi *phase lock*
  - uski vrh
  - niski šum
  - širok *bandwidth*

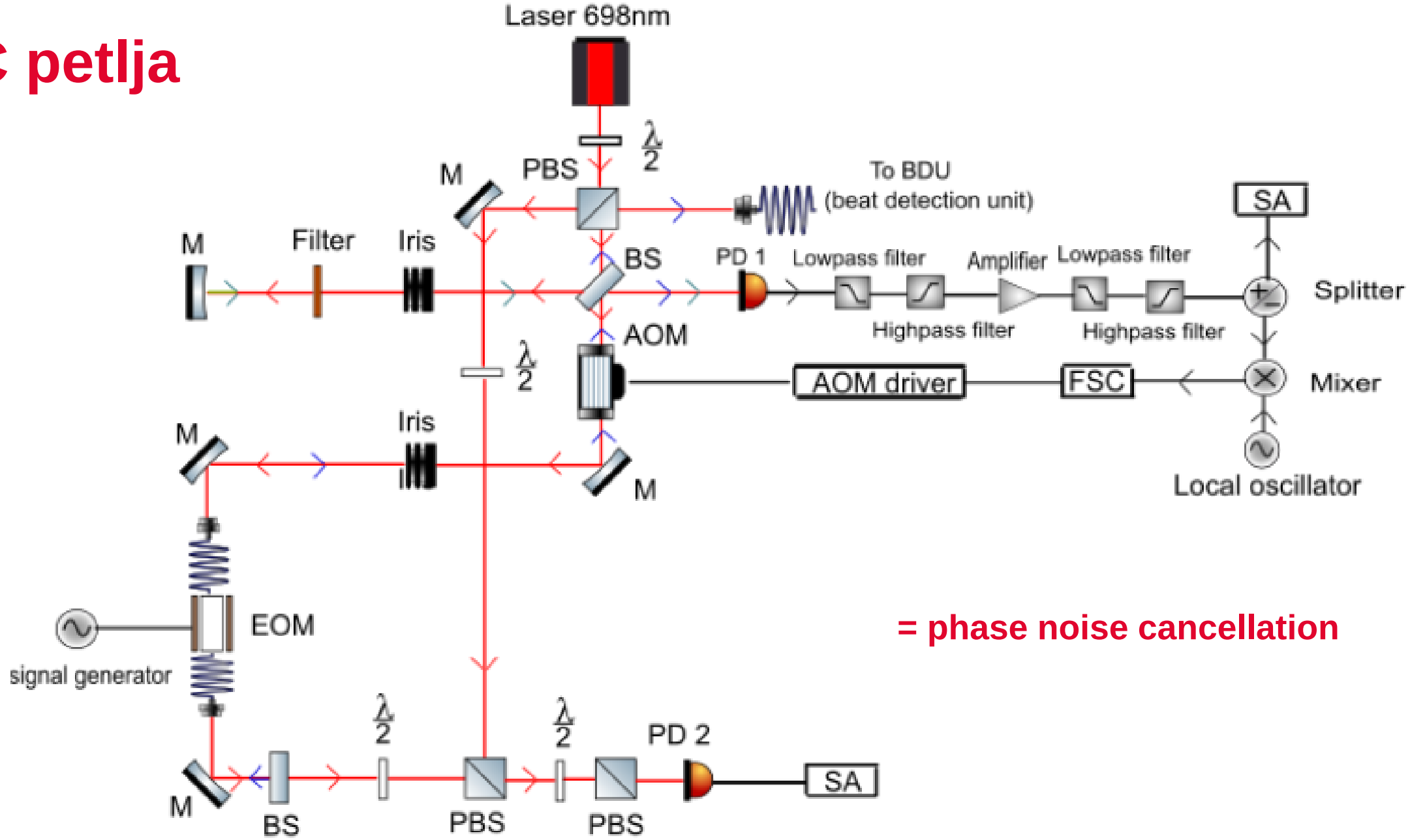
    (oko pola MHz)



Eksperimentalni postav

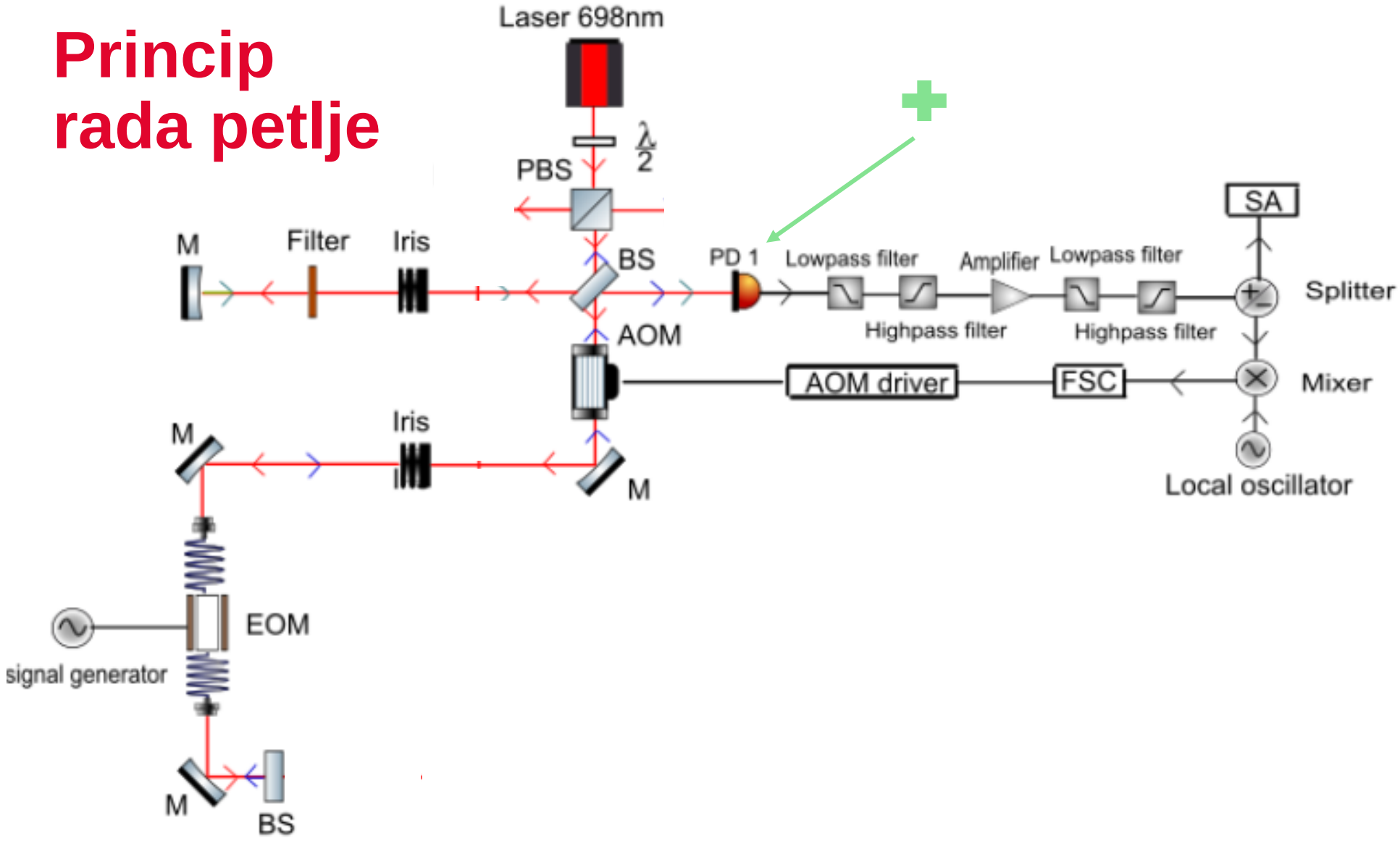
Redukcija šuma

PNC petlja

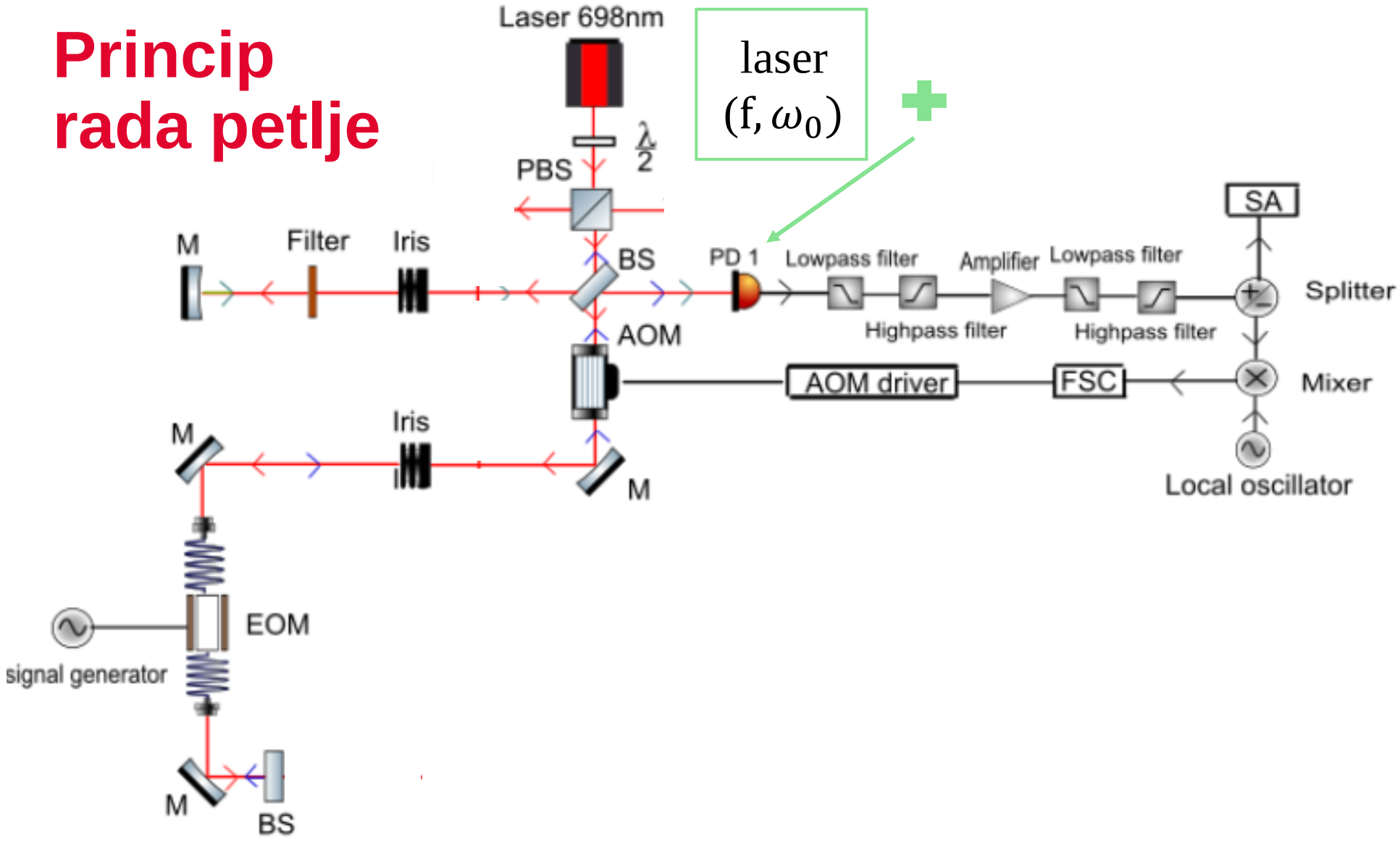


= phase noise cancellation

Princip rada petlje



Princip rada petlje



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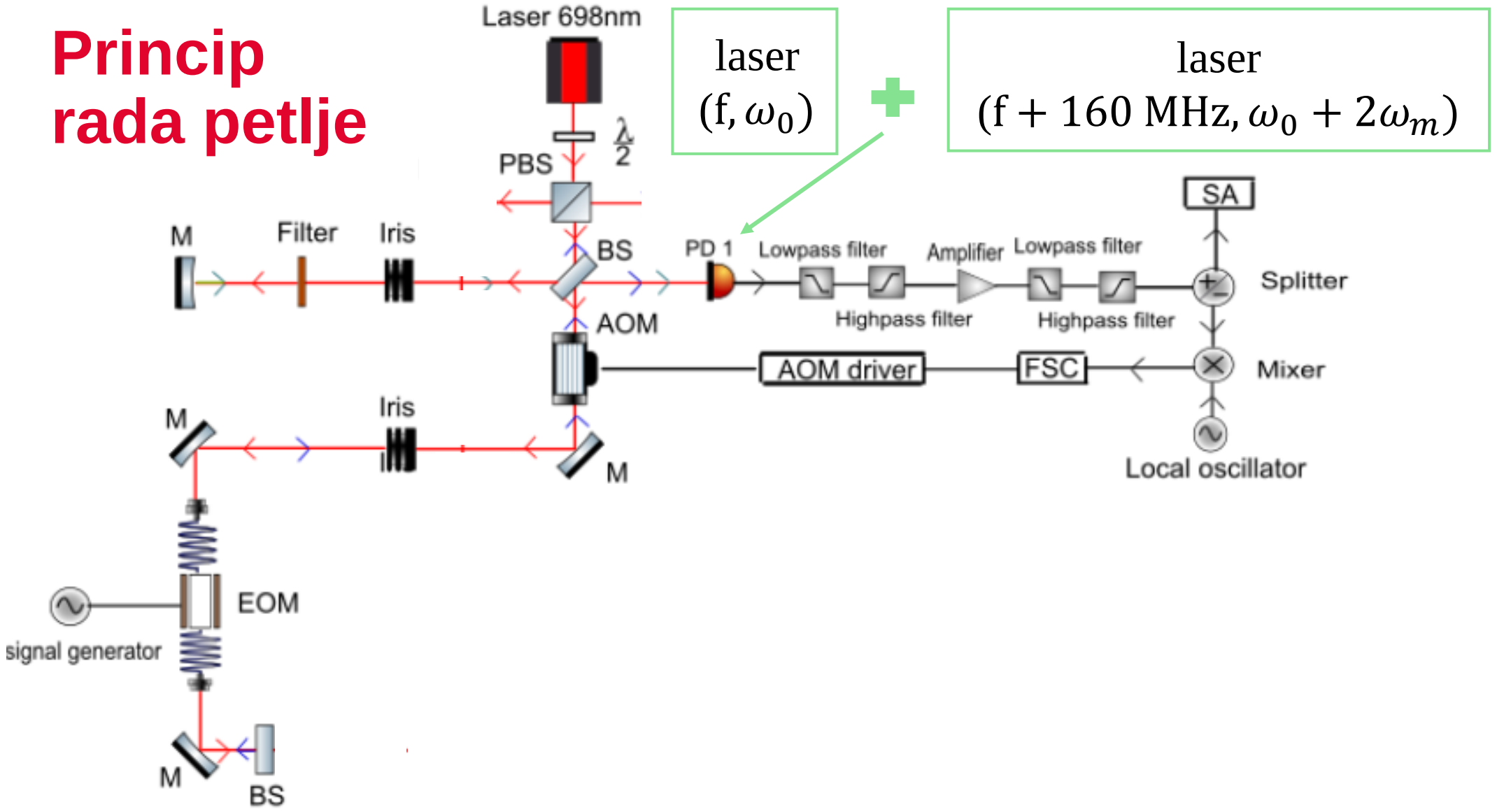
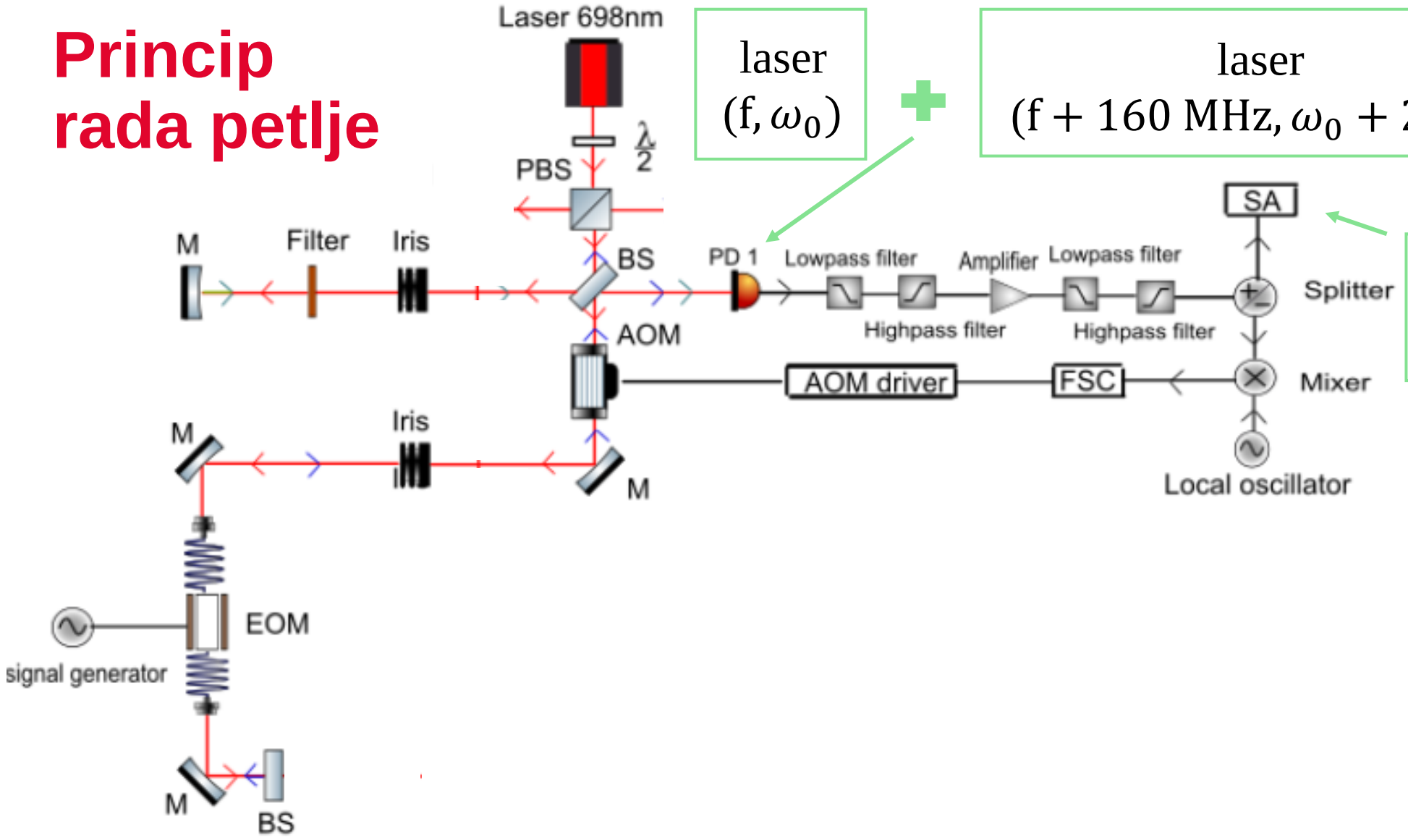


Princip rada petlje



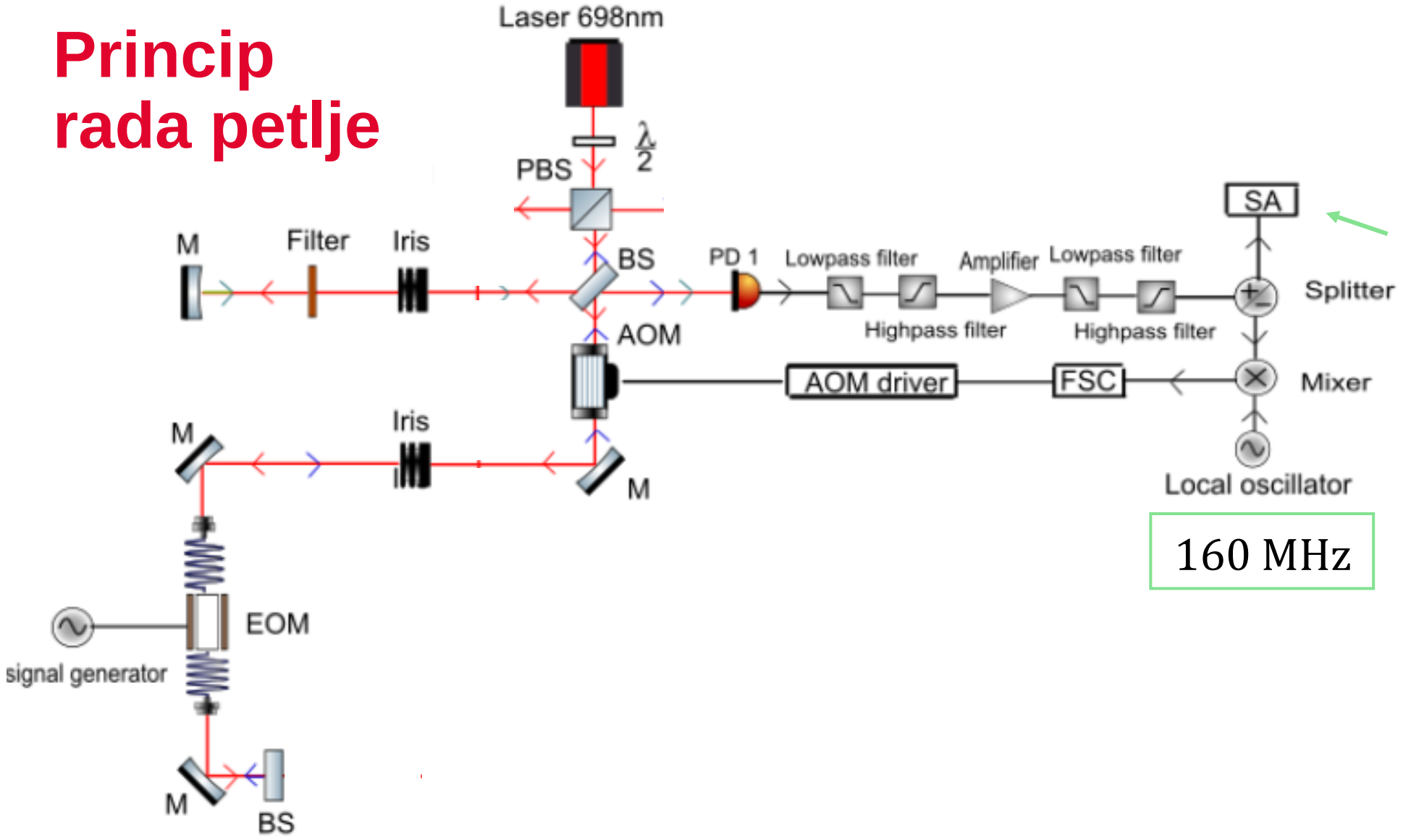
laser
(f, ω_0)

+

laser
$(f + 160\ \mathrm{MHz}, \omega_0 + 2\omega_m)$

signal
$(160\ \mathrm{MHz}, 2\omega_m)$

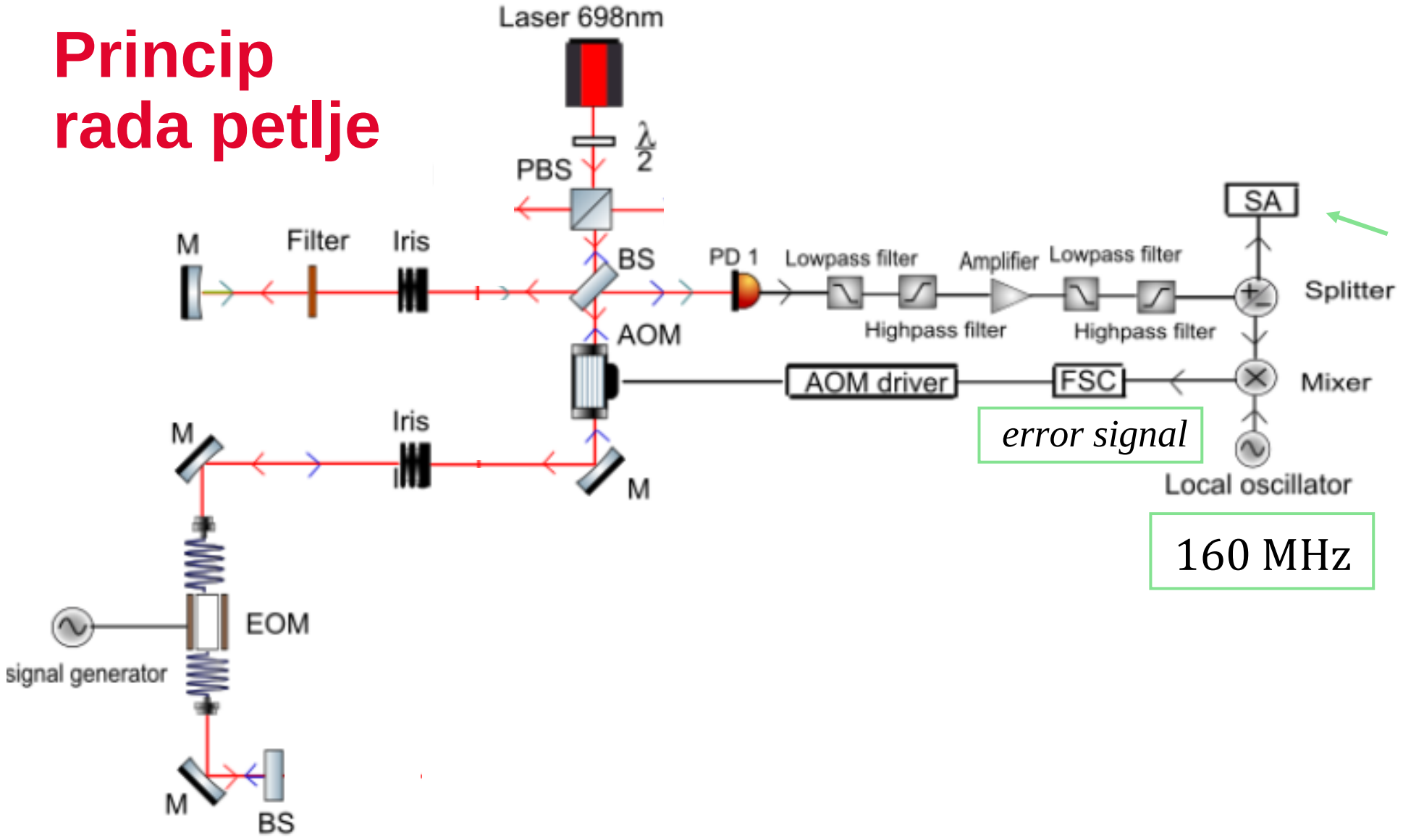
Princip rada petlje



signal
(160 MHz, $2\omega_m$)

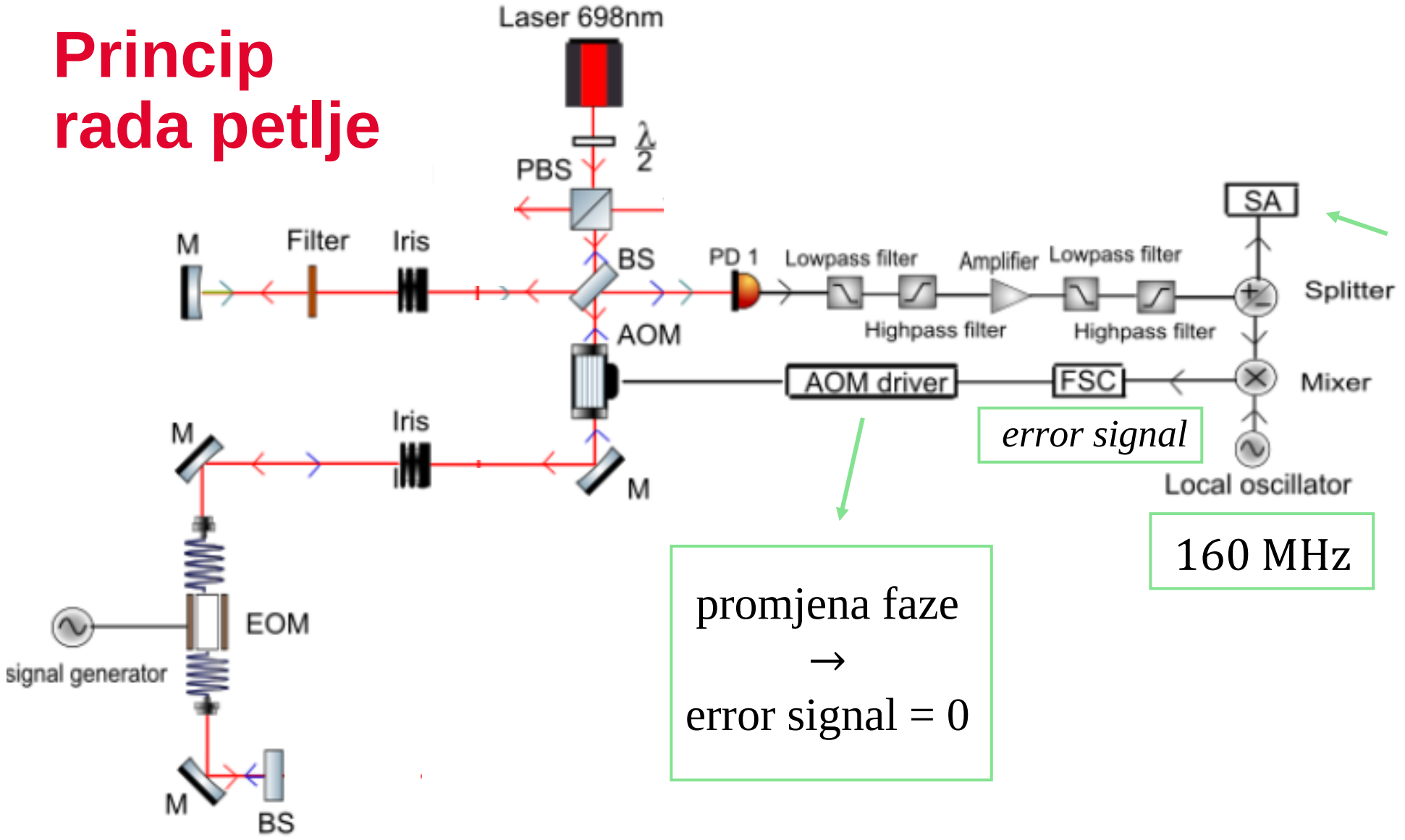
160 MHz

Princip rada petlje



signal
(160 MHz, $2\omega_m$)

Princip rada petlje



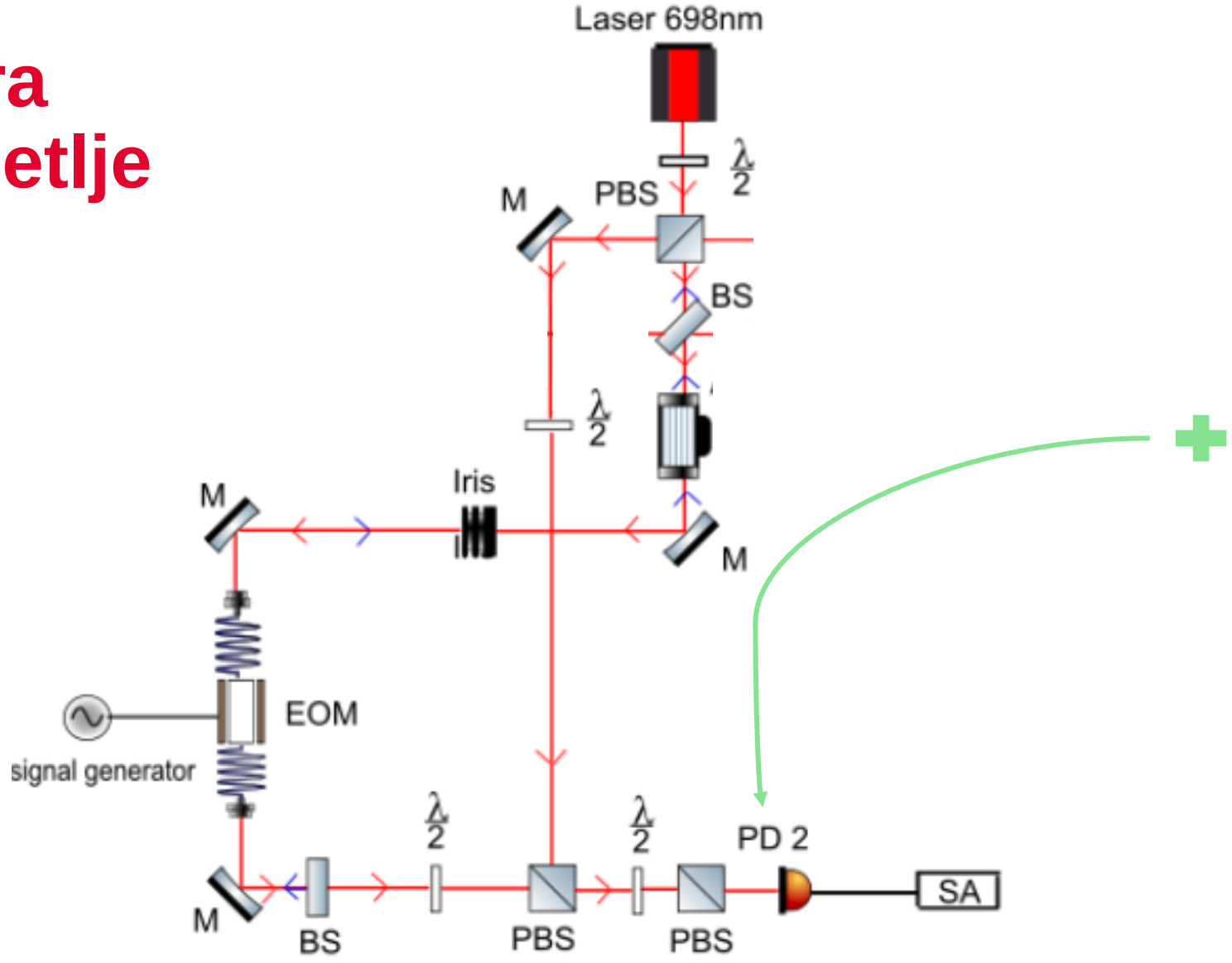
signal
$(160\ \text{MHz}, 2\omega_m)$

error signal

160 MHz

promjena faze
→
error signal = 0

Provjera izvan petlje



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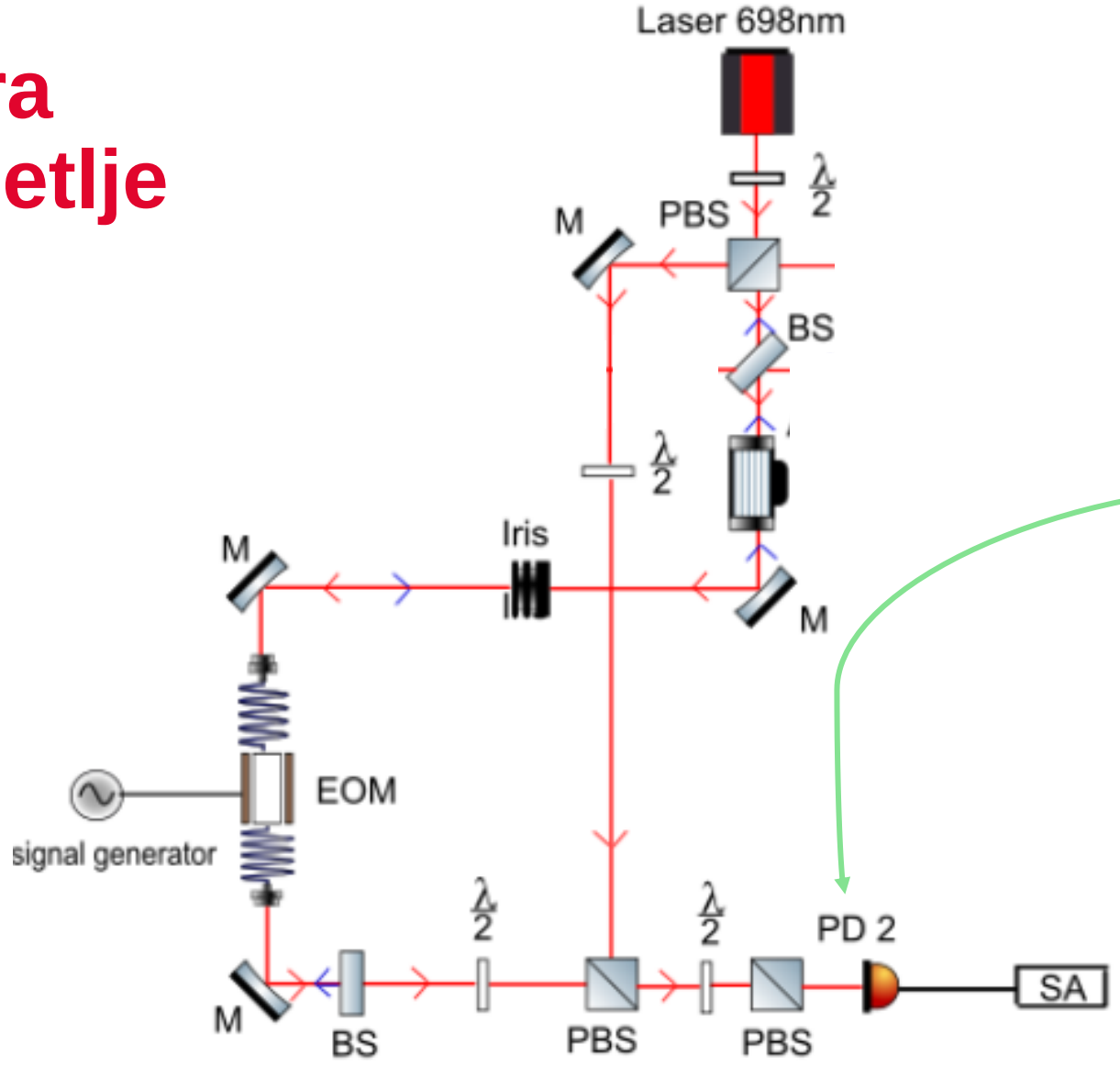
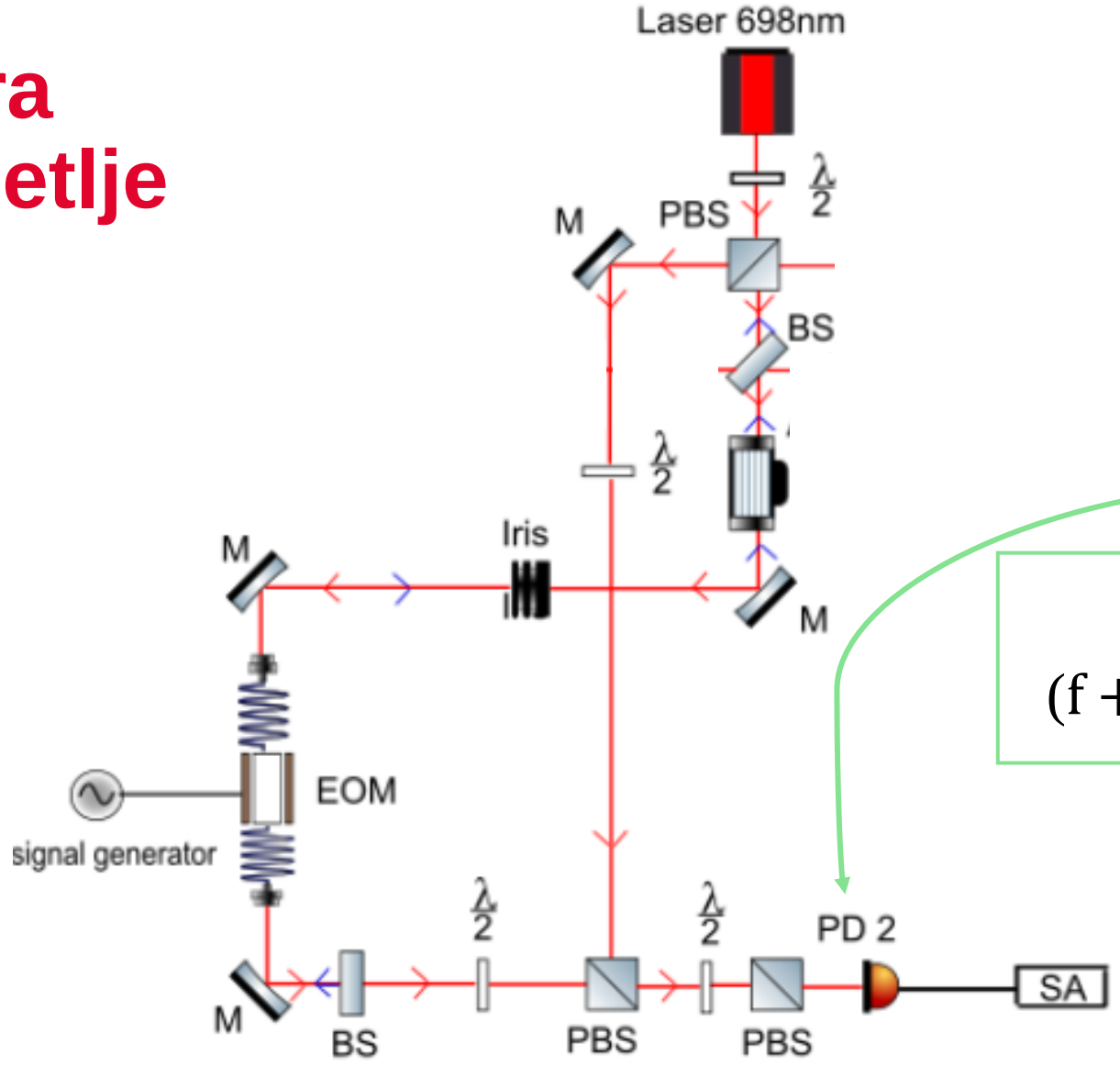


laser
(f, ω_0)

Provjera izvan petlje



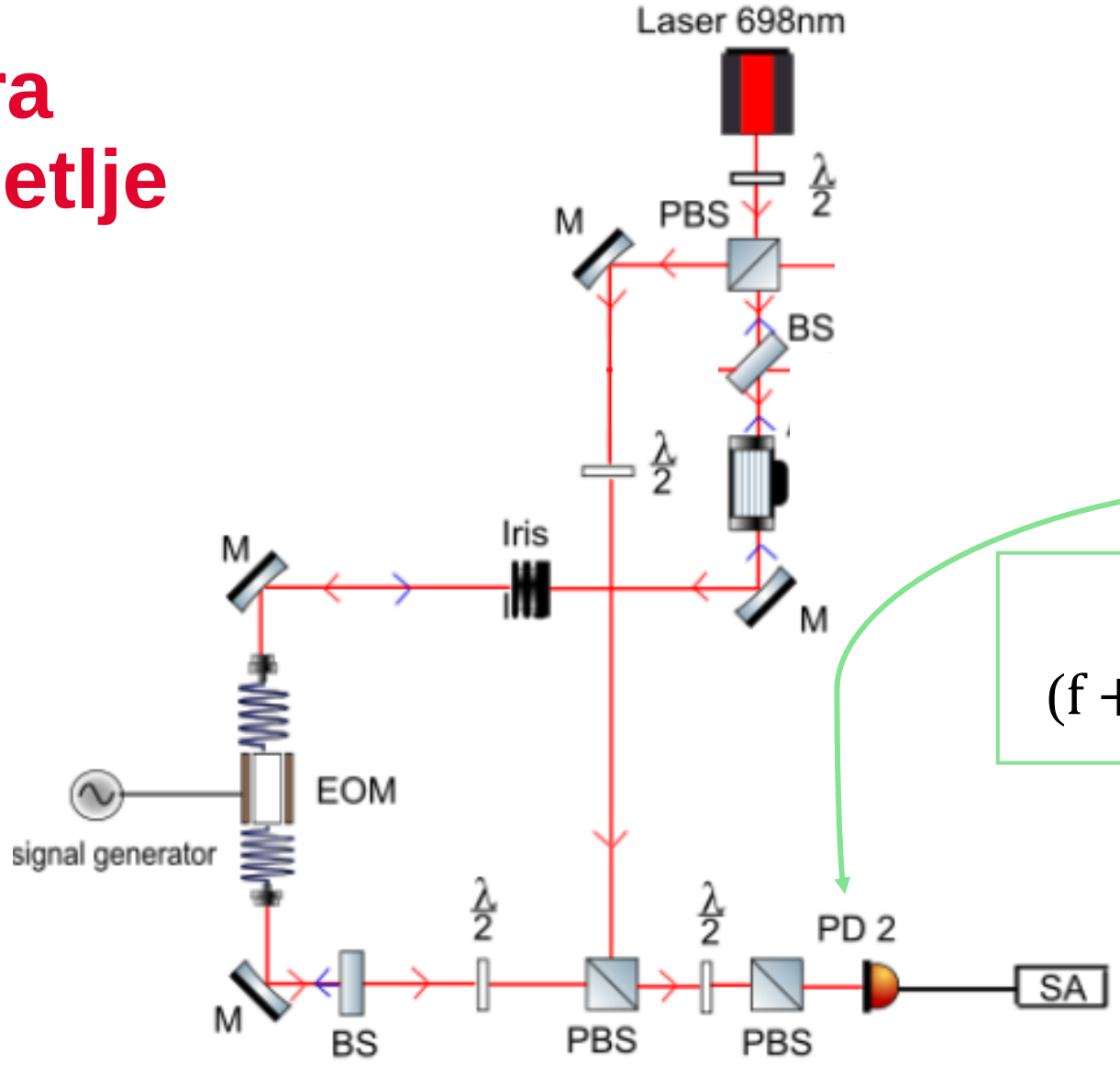
laser
(f, ω_0)

+

laser
$(f + 80\ \mathrm{MHz}, \omega_0 + \omega_m)$

CALT

Provjera izvan petlje



laser
(f, ω_0)

+

laser
$(f + 80\ \mathrm{MHz}, \omega_0 + \omega_m)$

signal
$(80\ \mathrm{MHz}, \omega_m)$

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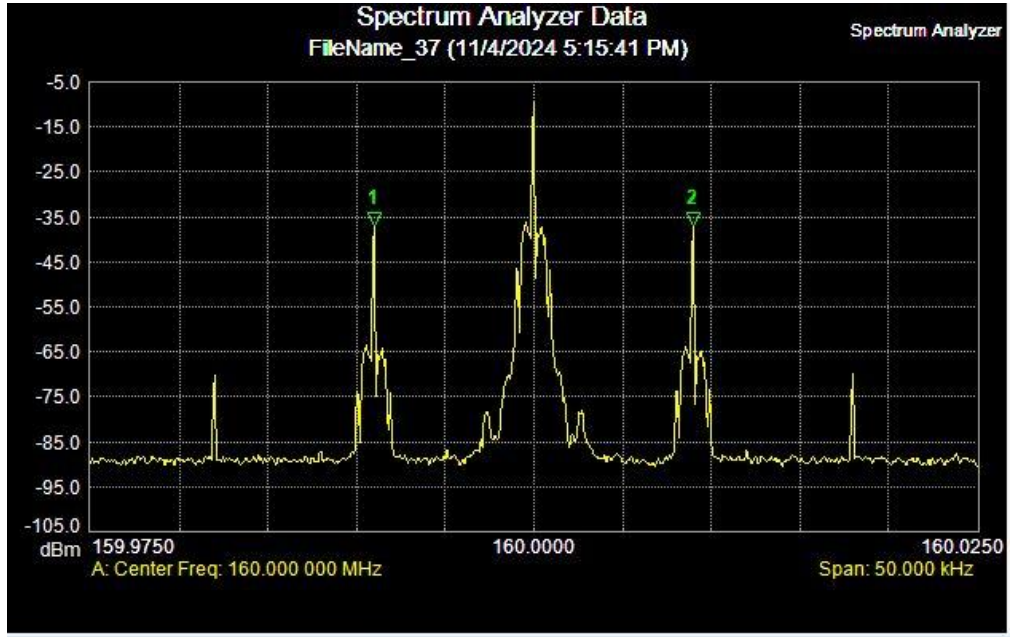
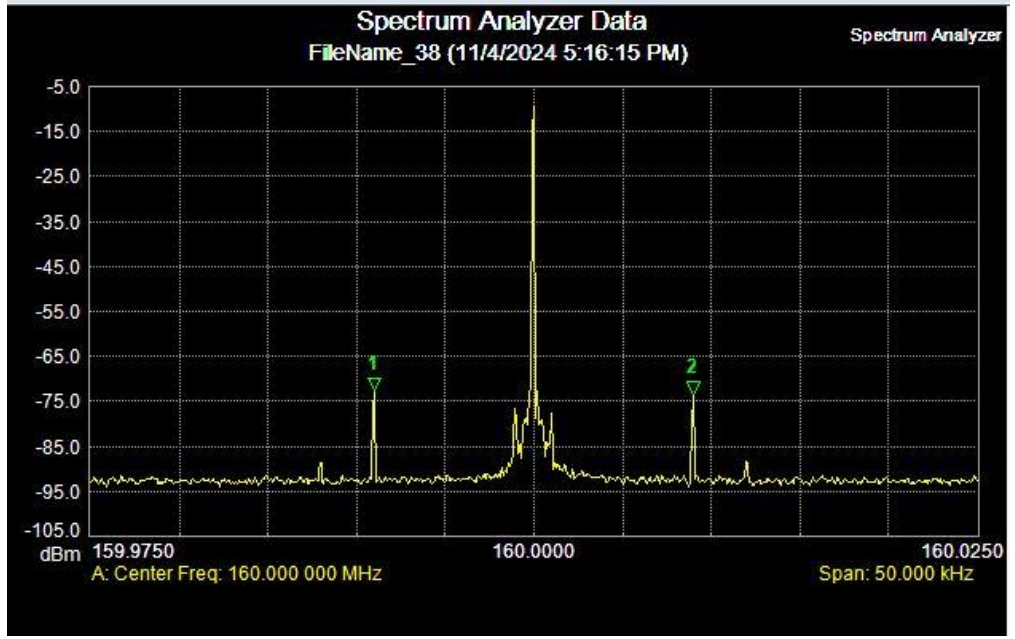
Mjerenja

- srednja vrijednost lijevog i desnog sideband-a
- prije i poslije uključivanja PNC-a
- unutar i izvan petlje
- šum frekvencije 1-80kHz





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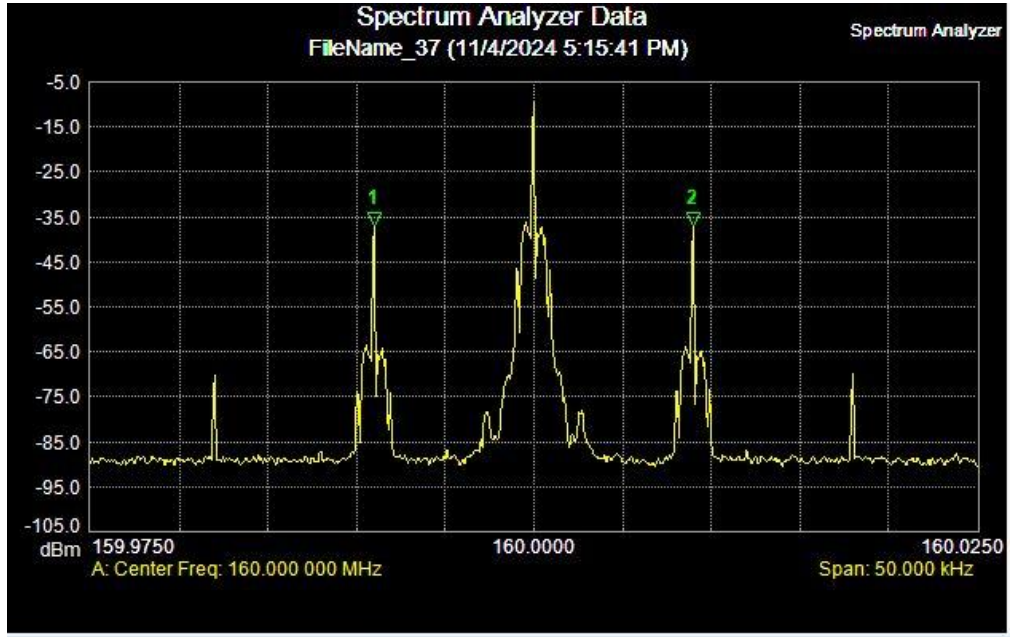

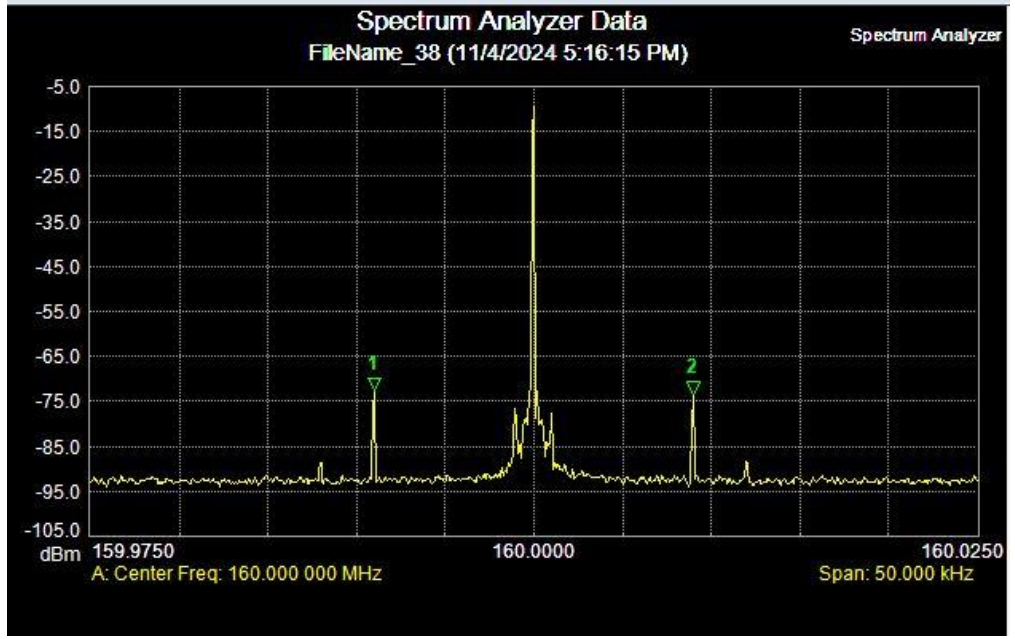

CALT

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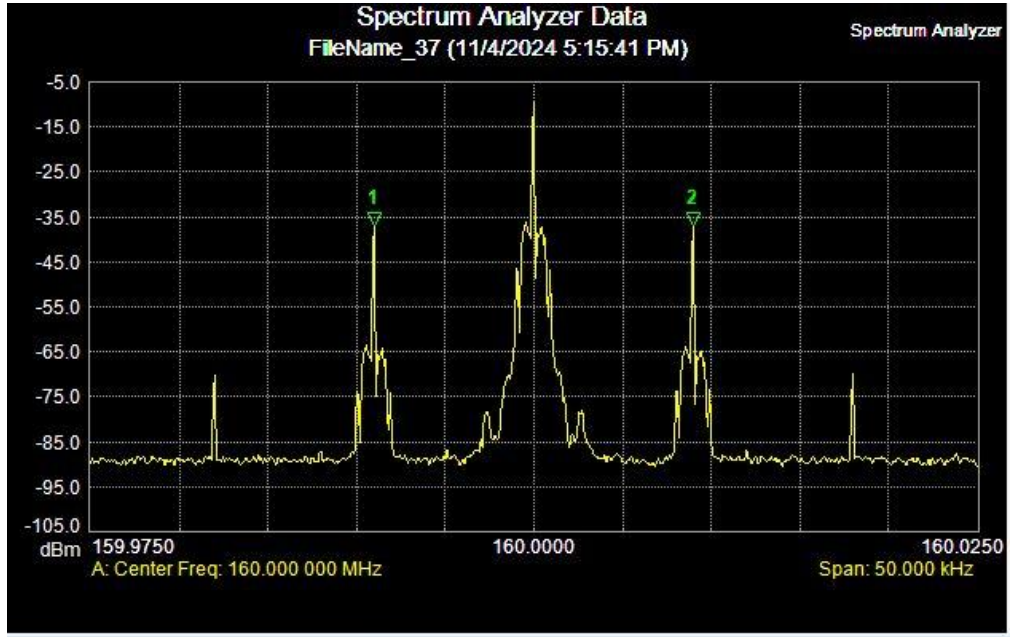

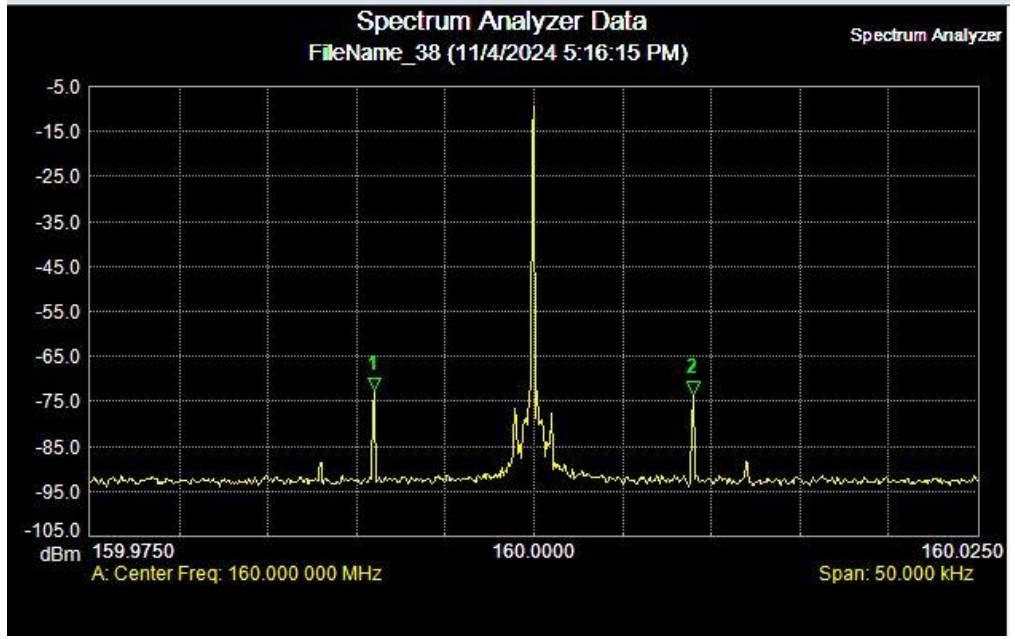

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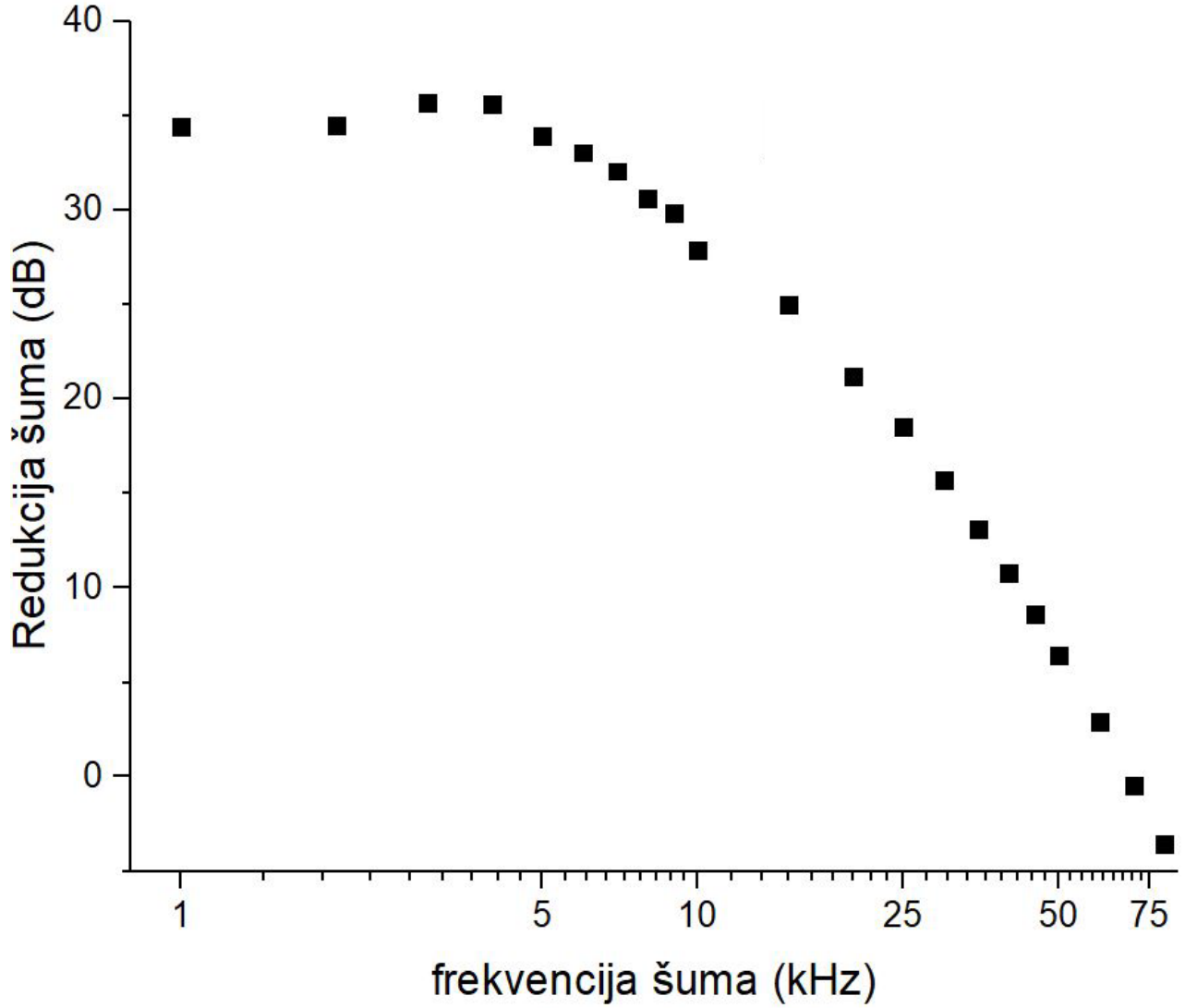
Rezultati

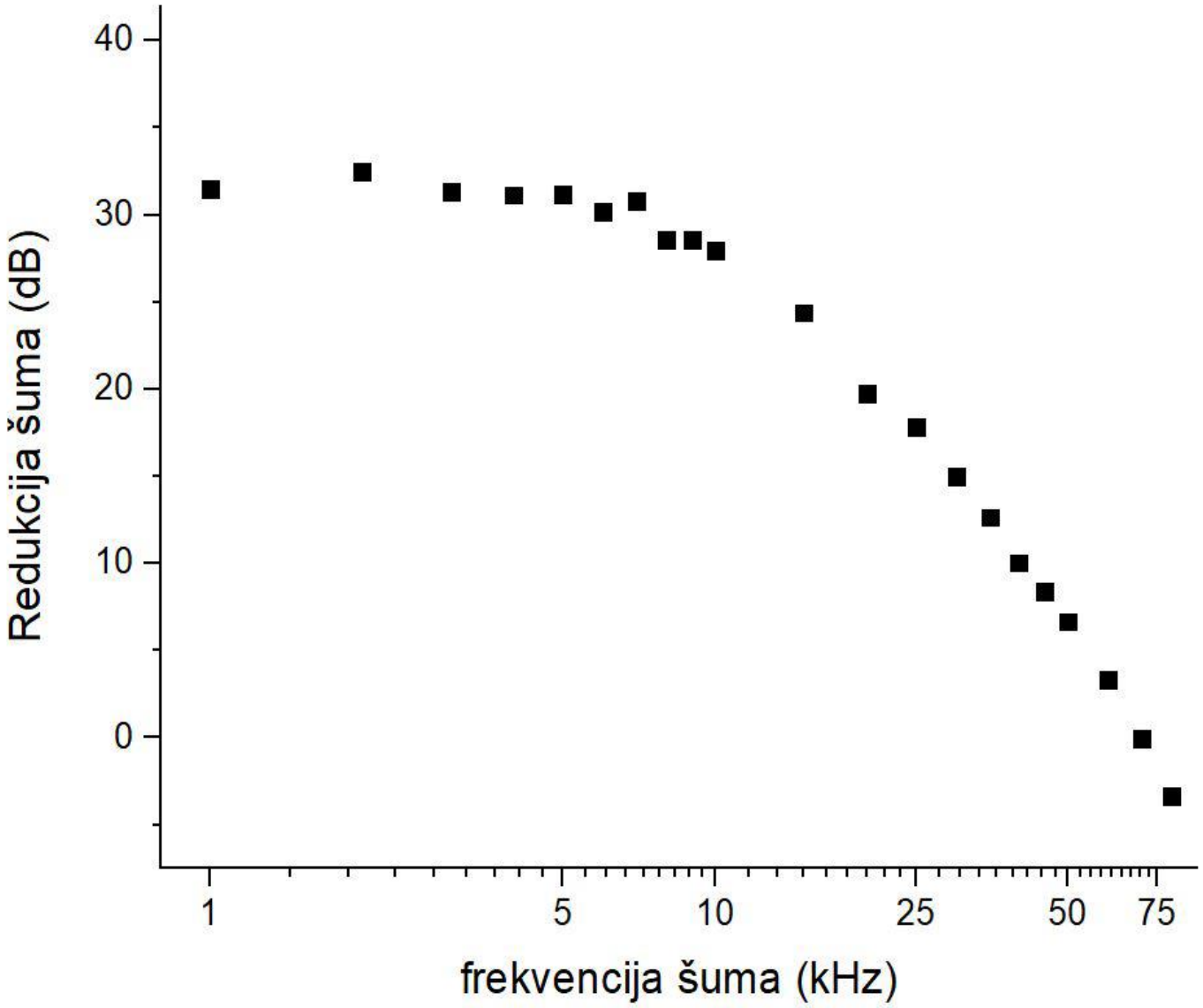
Redukcija šuma unutar petlje

- do 10 kHz:
  - velika efikasnost
  - 35 dB redukcije, umanjenje ≈ 3000 puta
- iznad 10 kHz:
  - eksponencijalni pad efikasnosti
  - negativna redukcija za 70-80 kHz !



Redukcija šuma izvan petlje

- do 10 kHz:
  - velika efikasnost
  - 30 dB redukcije, umanjenje 1000 puta
- iznad 10 kHz:
  - eksponencijalni pad efikasnosti
  - negativna redukcija za 70-80 kHz !



Zaključak

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Fazna stabilizacija

- uspješno provedena
- finesa rezonatora $> 200\,000$
- lijepi *phase lock* za f_{rep}, f_{CEO}
- lijepi *phase lock* za 698 nm laser

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- uspješno provedena
- finesa rezonatora $> 200\,000$
- lijepi *phase lock* za f_{rep}, f_{CEO}
- lijepi *phase lock* za 698 nm laser

Redukcija šuma

- optimiziran i okarakteriziran rad petlje za redukciju šuma
- potvrđen efikasan rad za potrebe laboratorija
  - oko 30 dB redukcije (smanjenje 1000 puta) za frekvencije šuma ispod 10 kHz

CENTRE FOR ADVANCED LASER TECHNIQUES

Hvala na pažnji!

Projekt je sufinanciran u okviru OP Konkurentnost i kohezija, iz Europskog fonda za regionalni razvoj.

Europska unija
Zajedno do fondova EU

Operativni program
KONKURENTNOST
I KOHEZIJA

EUROPSKI STRUKTURNI
I INVESTICIJSKI FONDOVI