A Laser-Written Directional Coupler Resonator

Perruccio Lorenzo

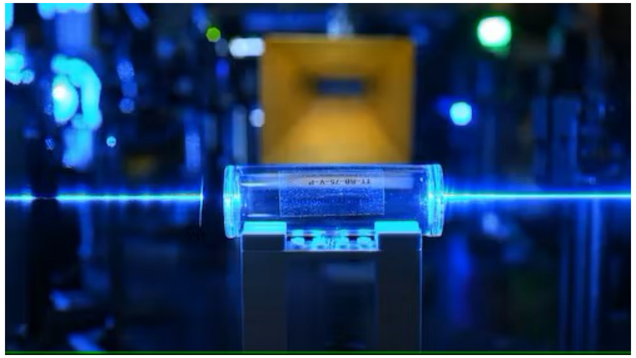
End of the Year seminar a.y. 2024/2025

XXXIX cycle

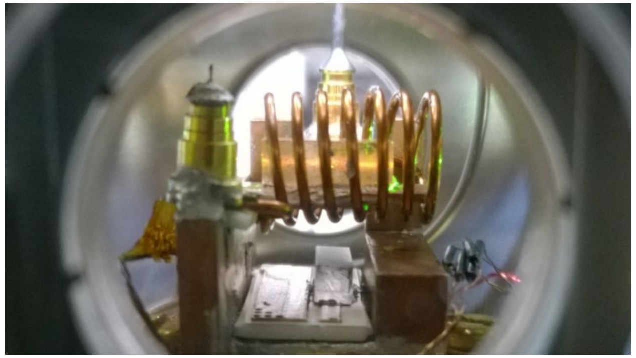
Storage, preservation and retrieval of photons

- Long distance networks
- Storage for quantum computing
- Precise metrology

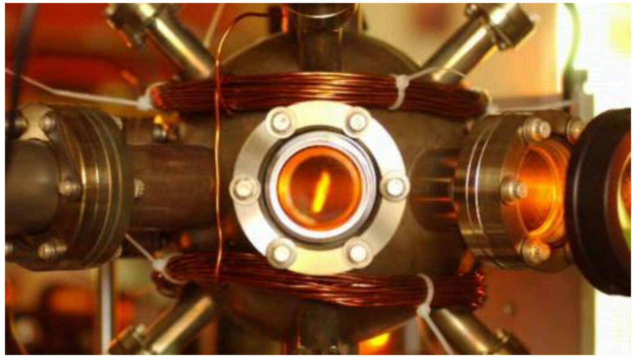
It's all about interfacing photons with something stable!



Alkali vapours

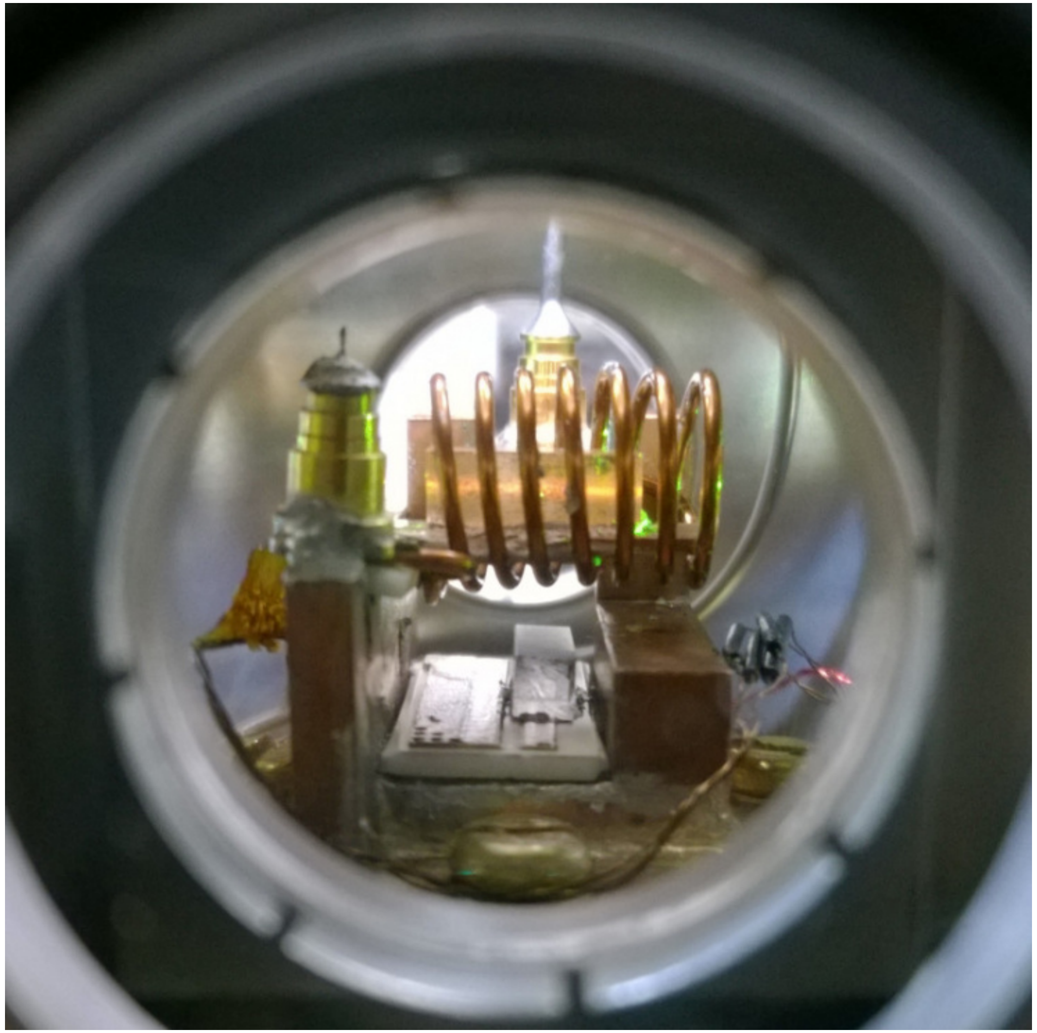


Solid state



Single atoms

It’s all about interfacing photons with something stable!

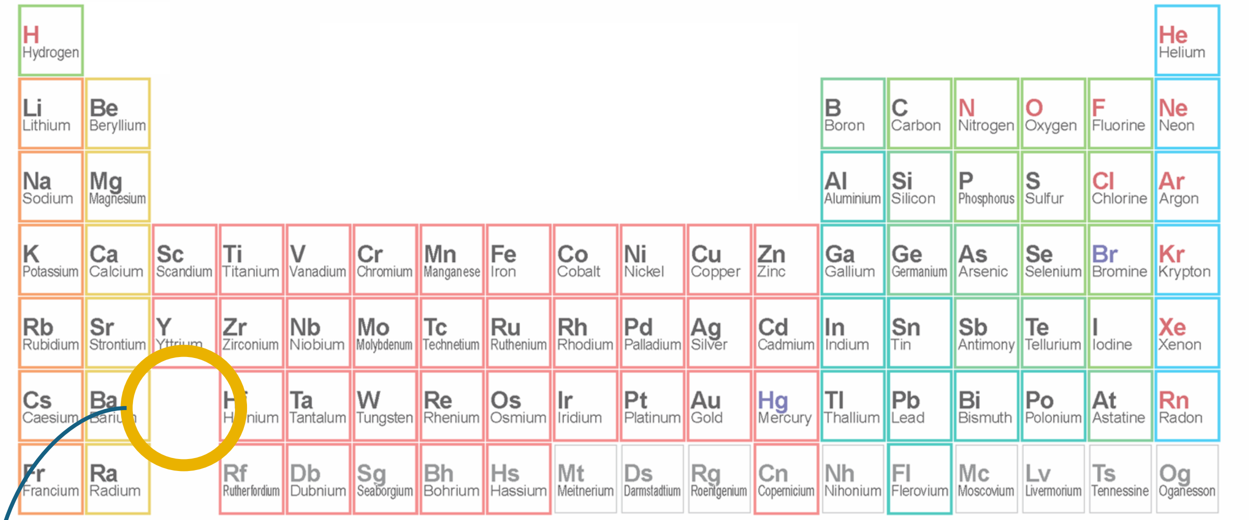


Robust

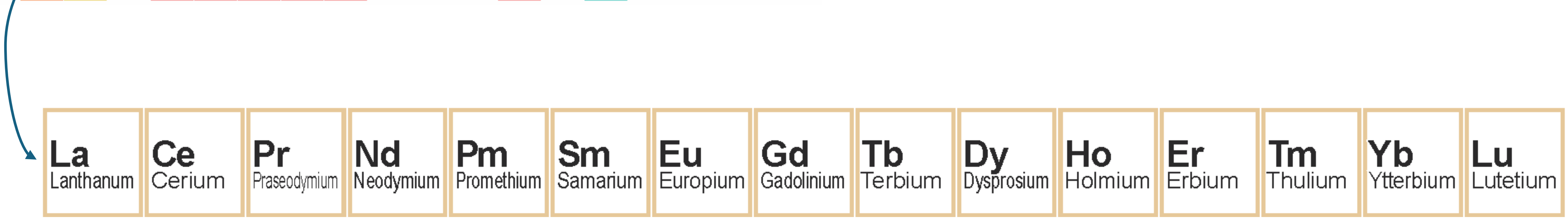
&

Machinable

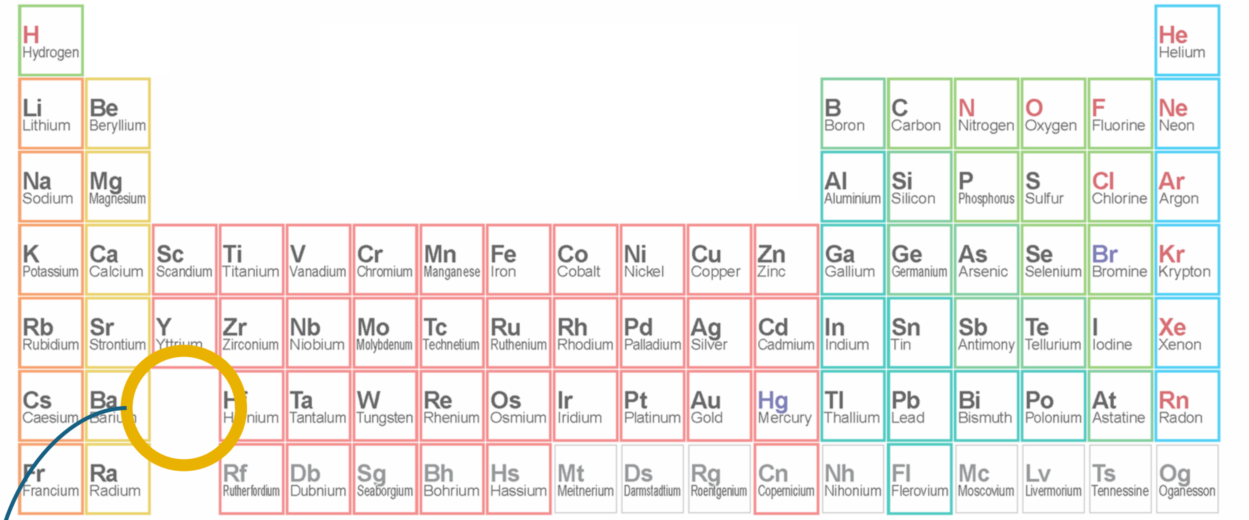
Rare earth ion-doped crystals

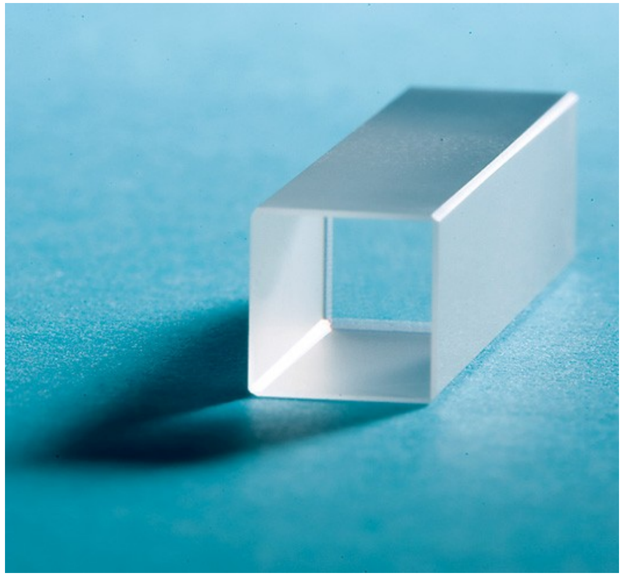


Long coherence times at **cryogenic** temperatures



Rare earth ion-doped crystals



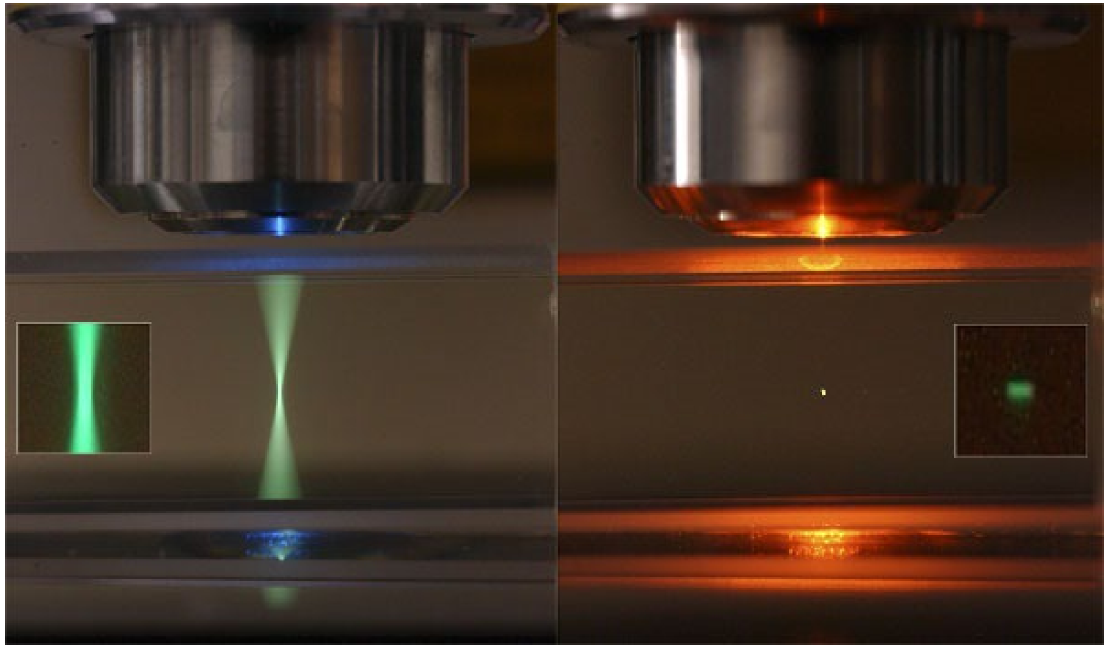


FLIR-Scientific Materials

La Lanthanum	**Ce** Cerium	**Pr** Praseodymium	**Nd** Neodymium	**Pm** Promethium	**Sm** Samarium	**Eu** Europium	**Gd** Gadolinium	**Tb** Terbium	**Dy** Dysprosium	**Ho** Holmium	**Er** Erbium	**Tm** Thulium	**Yb** Ytterbium	**Lu** Lutetium

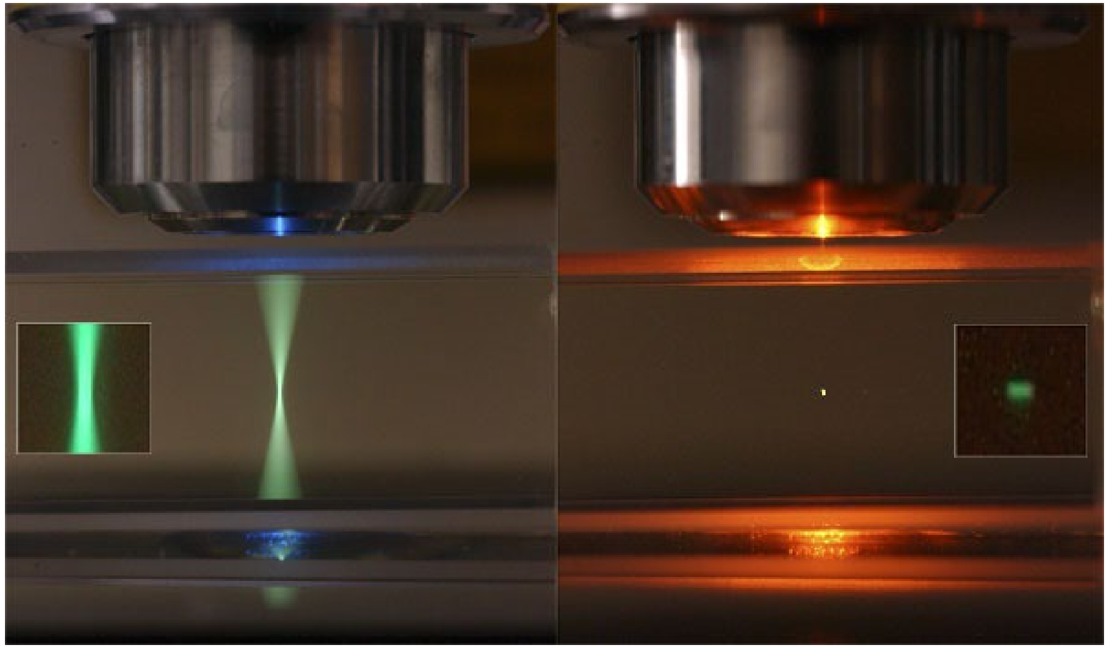
High efficiency (Pr) · Long storage time (Eu) · Telecom compatible (Er)

Femtosecond Laser Micromachining



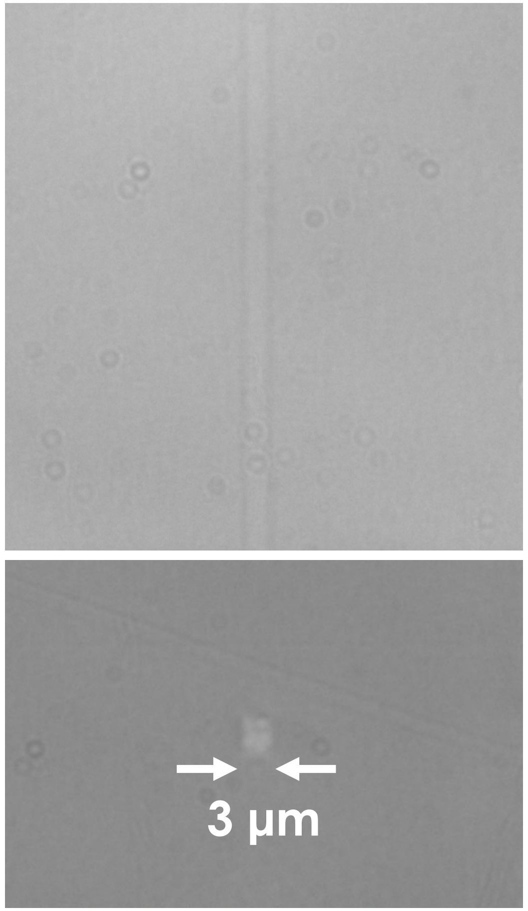
Localized index change to build **waveguides**

Femtosecond Laser Micromachining



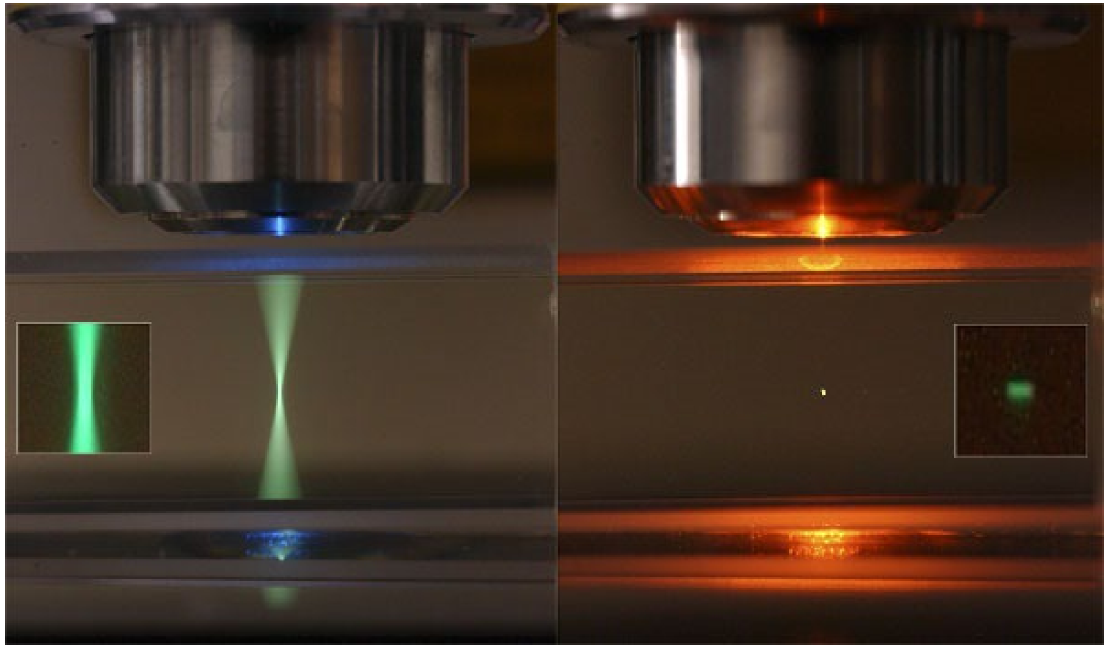
Localized index change to build **waveguides**

YSO waveguide

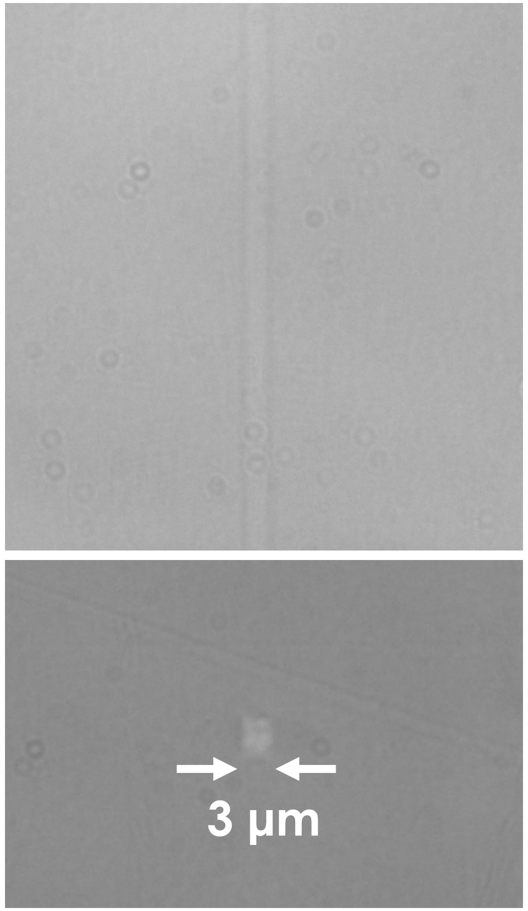


Femtosecond Laser Micromachining

YSO waveguide

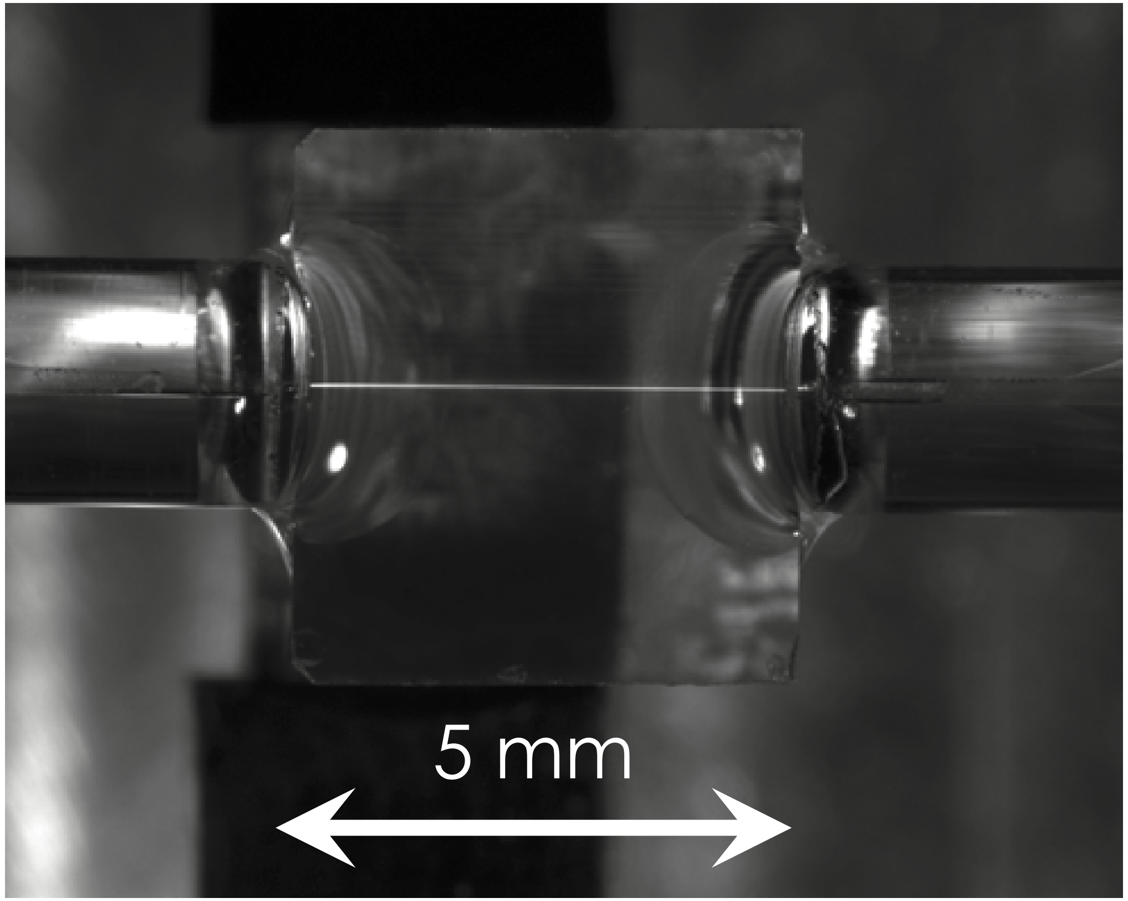


Localized index change to build **waveguides**



- Fast prototyping
- Material versatility
- Low-loss structures

Our state of the art: fiber-integrated memory in Pr:YSO



Science Advances 8.27 (2022): eabn3919.

27 μs storage with up to 18% efficiency

Main open issues

Storage time

Target: hours

Current: 20 ms

Main open issues

Storage time

Target: hours

Current: 20 ms

Integrability

Current: optical fibers

Main open issues

Storage time

Target: hours

Current: 20 ms

Efficiency

Target: 90%

Current: 69%

Integrability

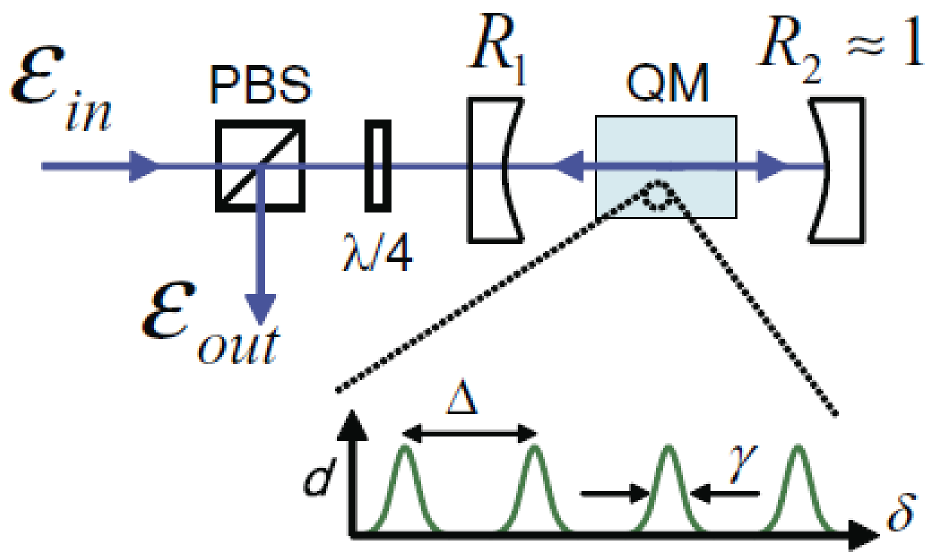
Current: optical fibers

Critical coupling to cavities

PHYSICAL REVIEW A **82**, 022310 (2010)

Impedance-matched cavity quantum memory

Mikael Afzelius[1] and Christoph Simon[2]



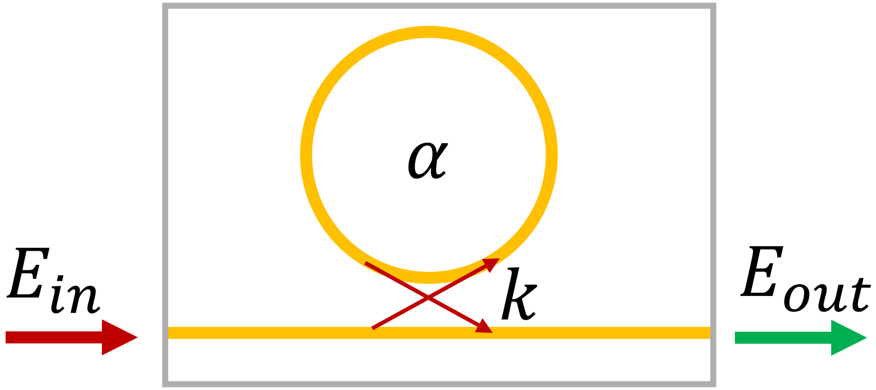
Force absorption of the ions for certain wavelengths to have unit efficiency

↓

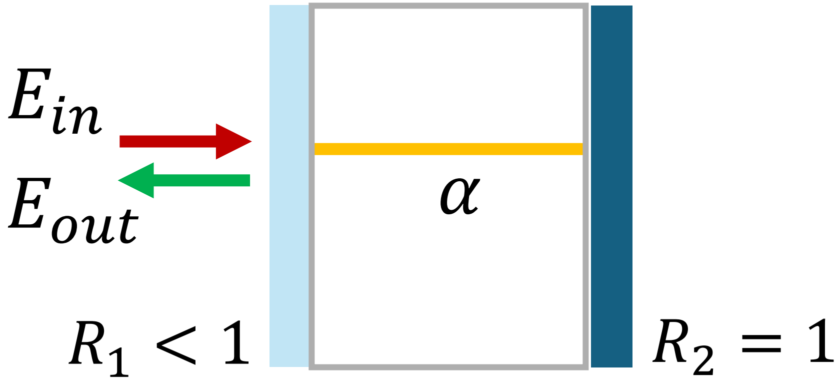
«Critical coupling» to a cavity

How it's done, usually

Ring resonators:



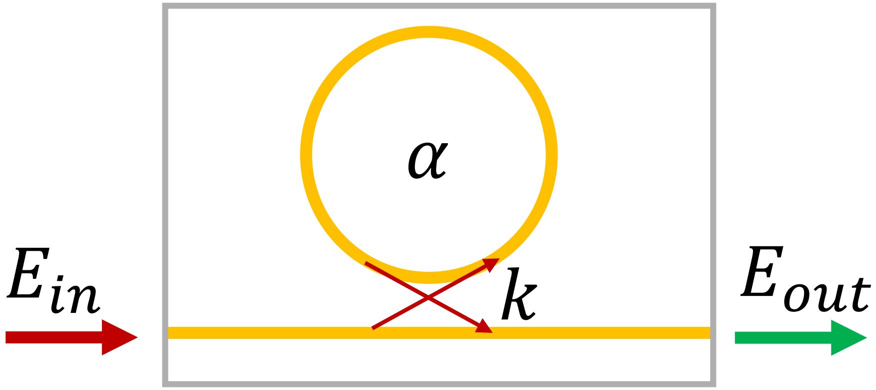
Fabry-Perot cavities:



Self-interference of the input field shapes the output

How it's done, usually

Ring resonators:



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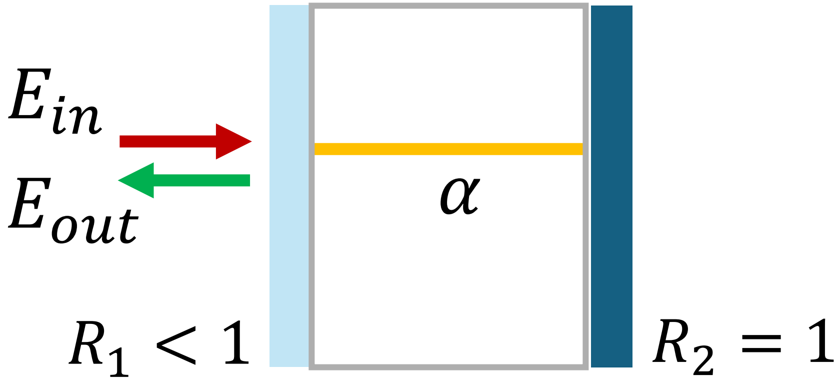

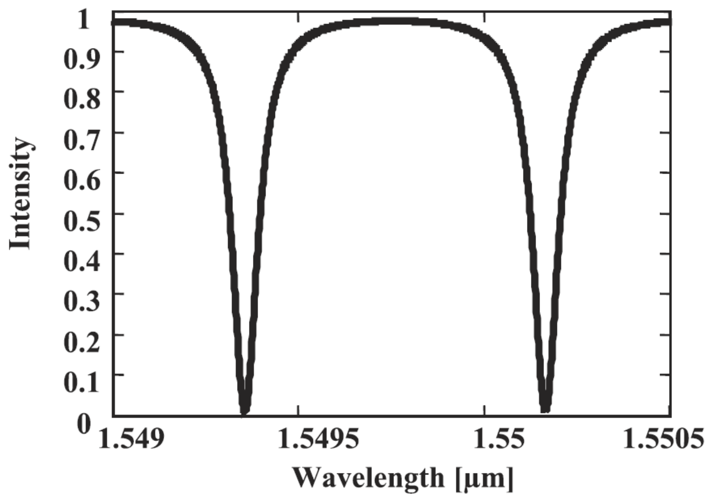

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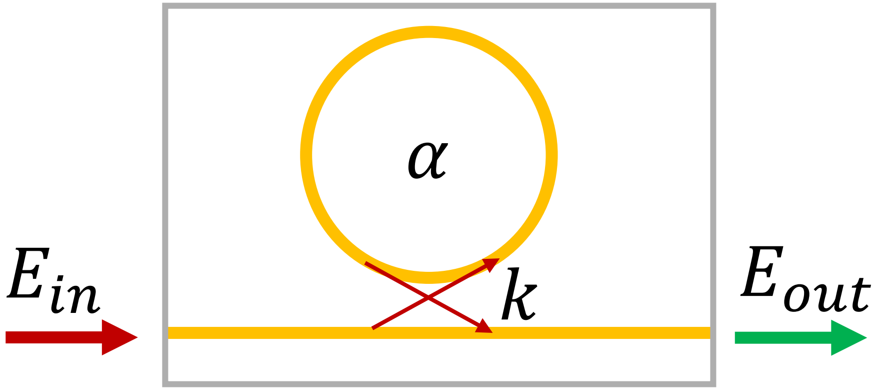
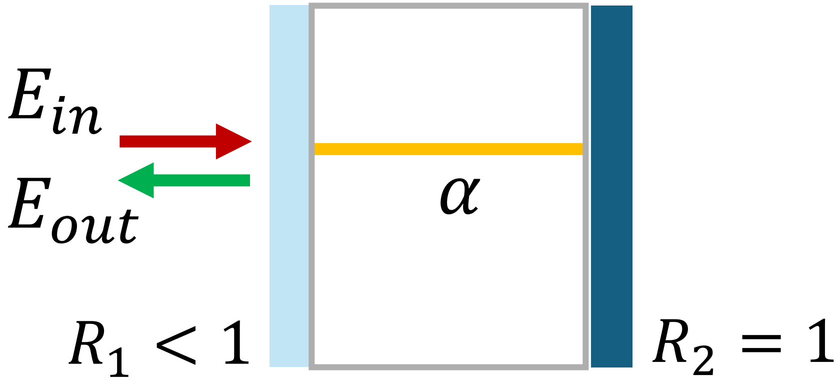


- Critical coupling for

$$1 - |k|^2 = |\alpha|^2$$

Fabry-Perot cavities:

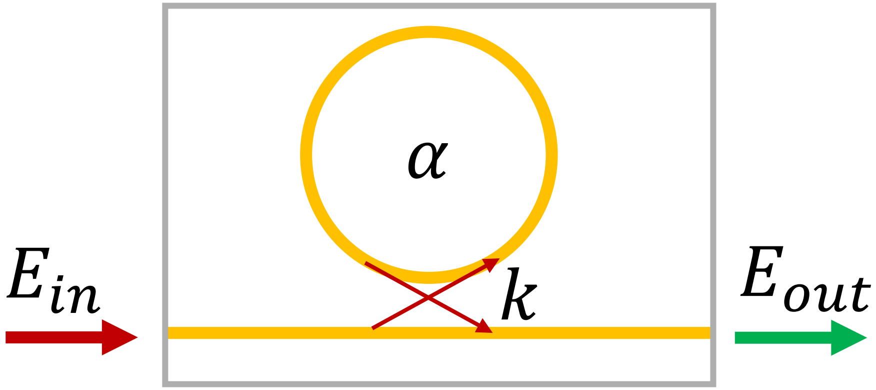


- Critical coupling for

$$\mathrm{R}_1 = |\alpha|^2$$

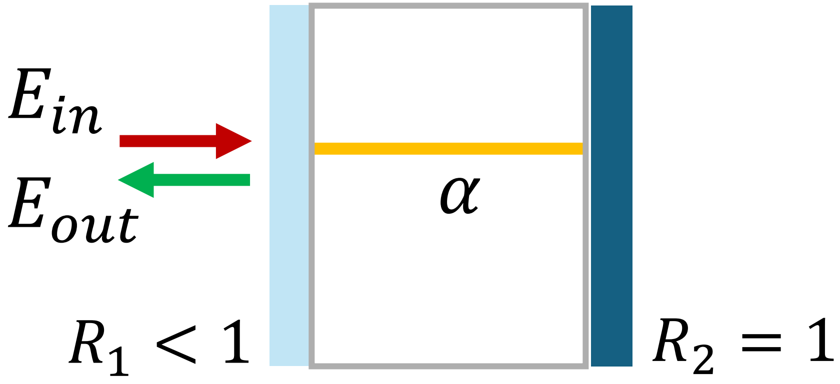
How it's done, usually

Ring resonators:



- Critical coupling for
$$1 - |k|^2 = |\alpha|^2$$
- Not FLM-compatible

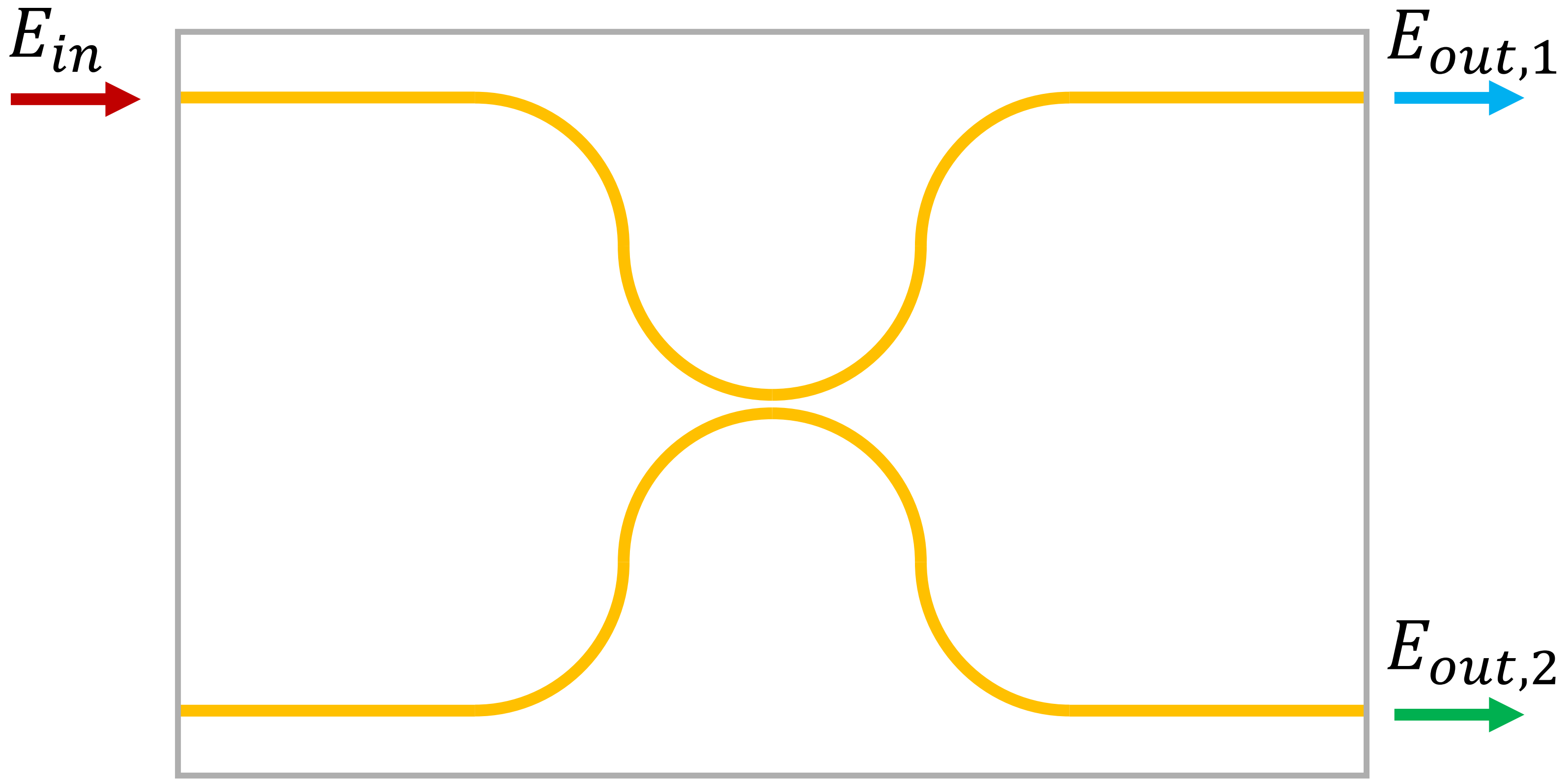
Fabry-Perot cavities:



- Critical coupling for
$$\mathrm{R}_1 = |\alpha|^2$$
- Technologically challenging

So what can we do?

Directional coupler:



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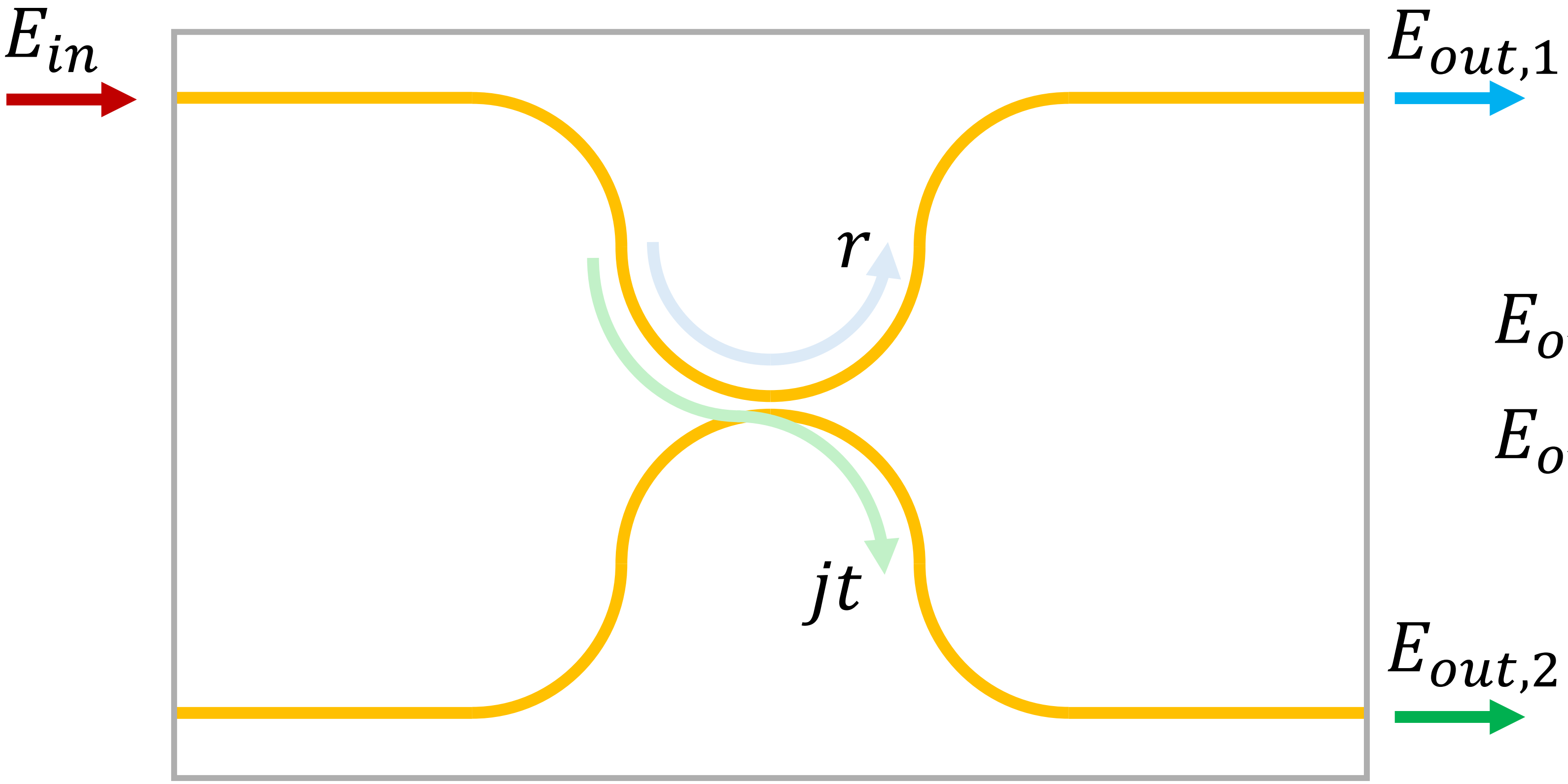
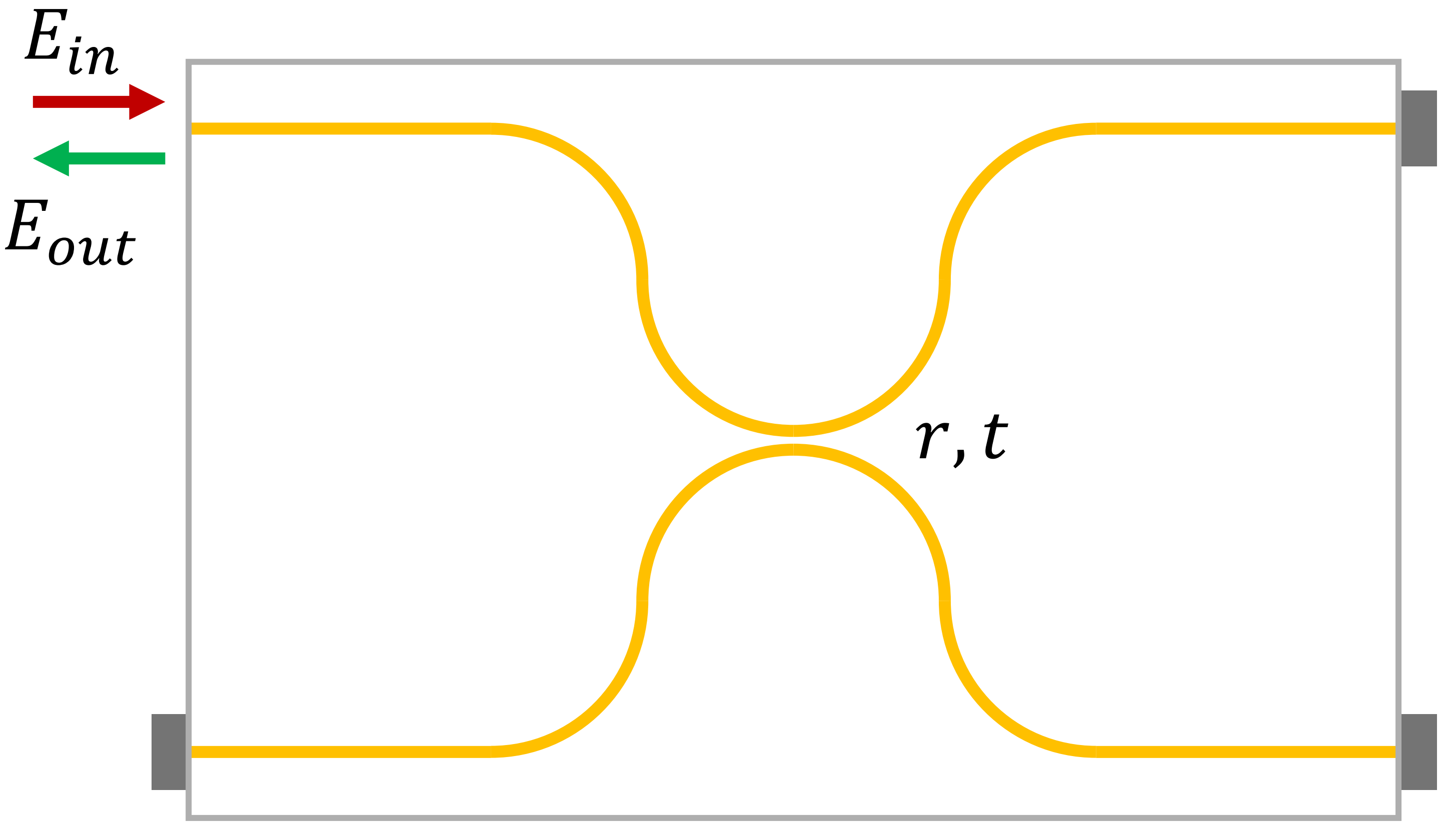


$$E_{out,1} = rE_{in} \text{ (bar)}$$
$$E_{out,2} = jtE_{in} \text{ (cross)}$$

So what can we do?

Directional coupler with mirrors:



Directional

Coupler

Resonator

Once upon a time..

Directional coupler resonators as guided-wave optical components: a proposal

Chin-Lin Chen

APPLIED OPTICS / Vol. 26, No. 13 / 1 July 1987

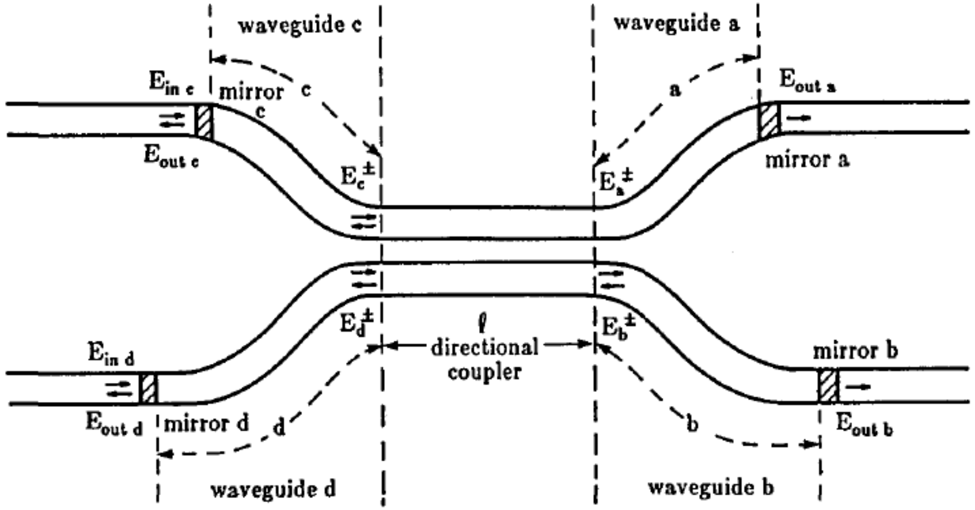


Fig. 1. Directional couplers with four reflectors.

Once upon a time..

Directional coupler resonators as guided-wave optical components: a proposal

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APPLIED OPTICS / Vol. 26, No. 13 / 1 July 1987

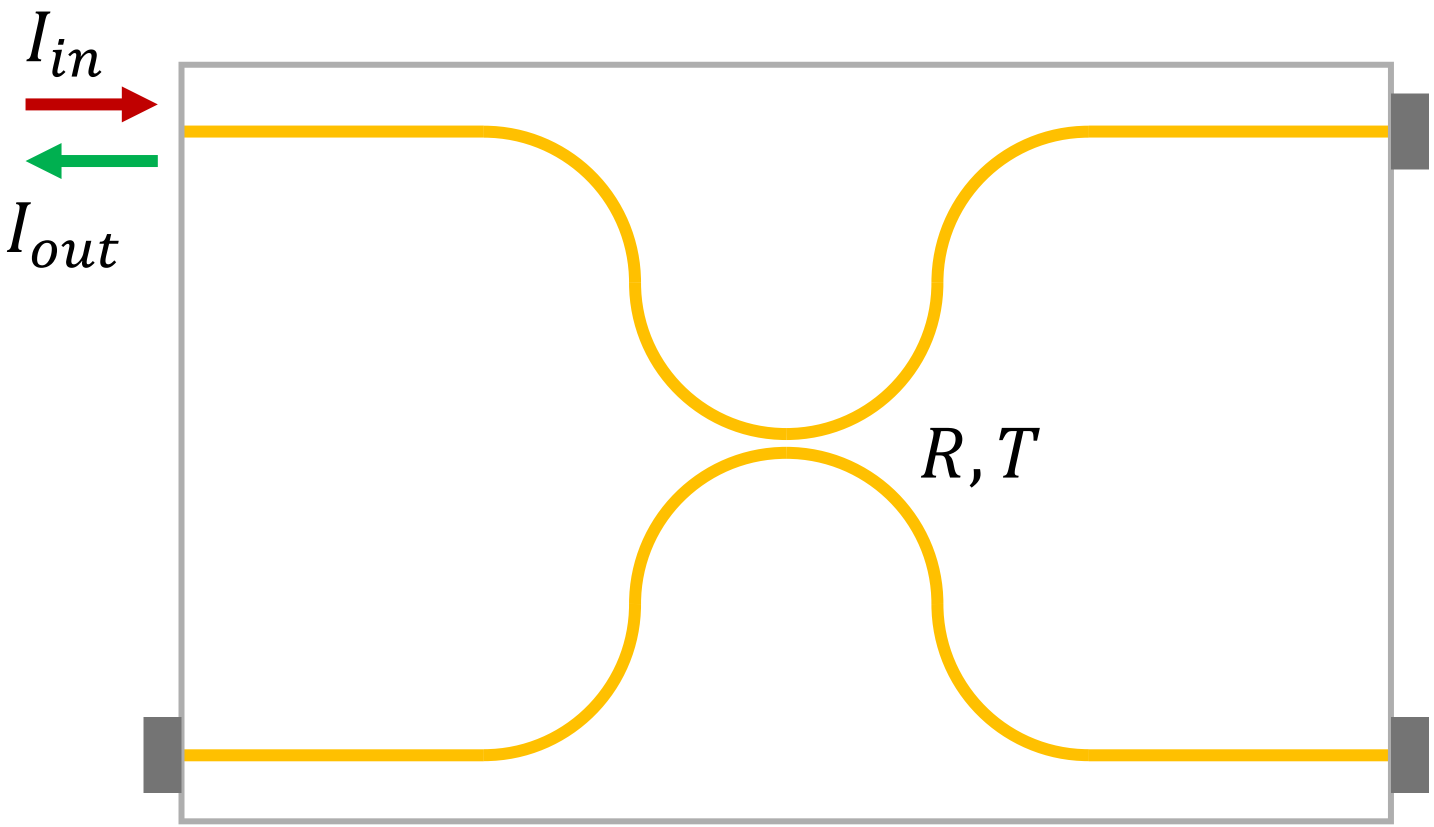
Directional coupler resonators as guided-wave optical components: a proposal

CL Chen

Applied optics, 1987 · opg.optica.org

☆ Salva 99 Cita Citato da 5 Articoli correlati Tutte e 8 le versioni Web of Science: 3 »

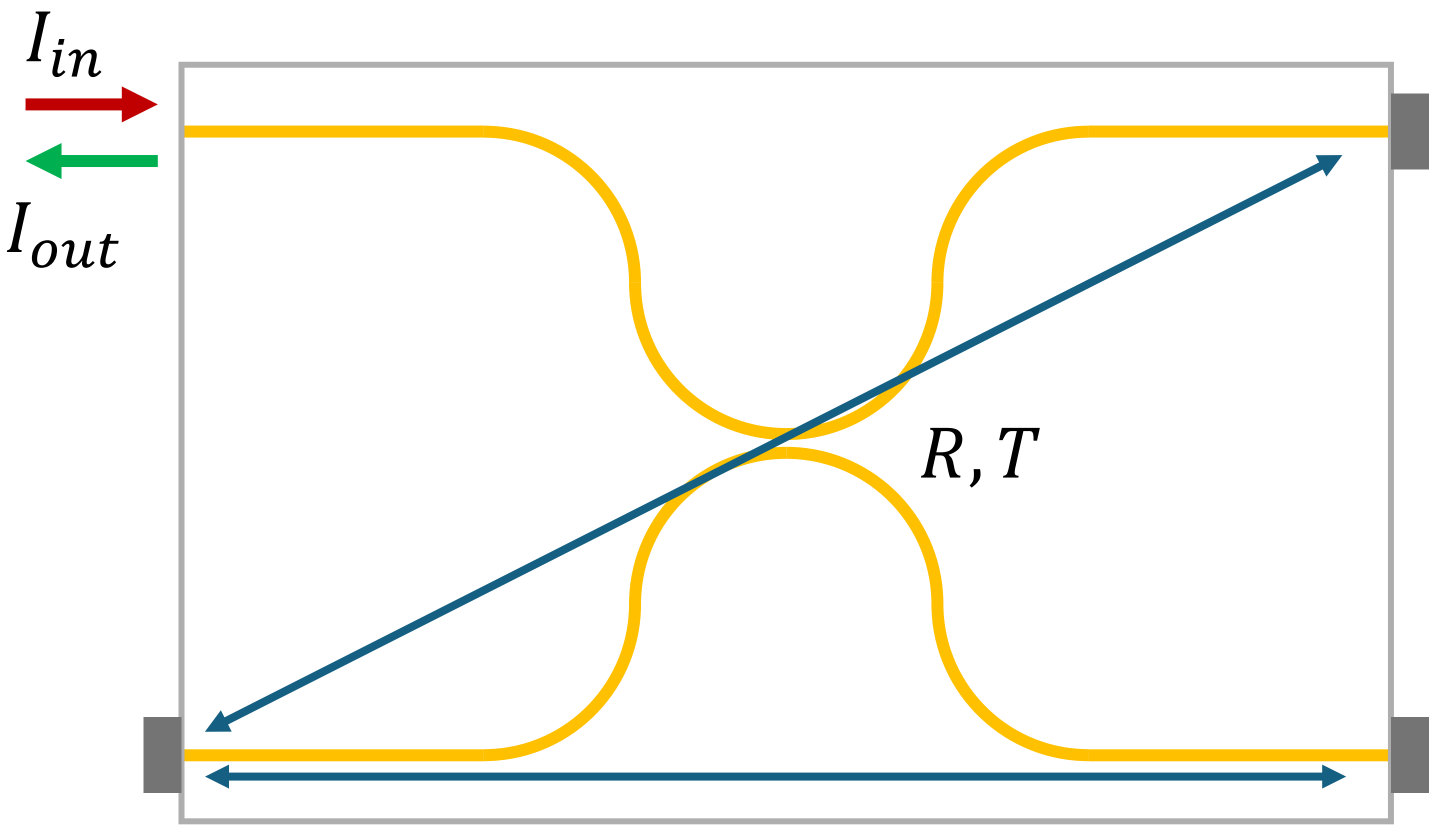
Our design



With overall losses G, critical coupling is achieved when

$$\boldsymbol{R - T = G}$$

Our design



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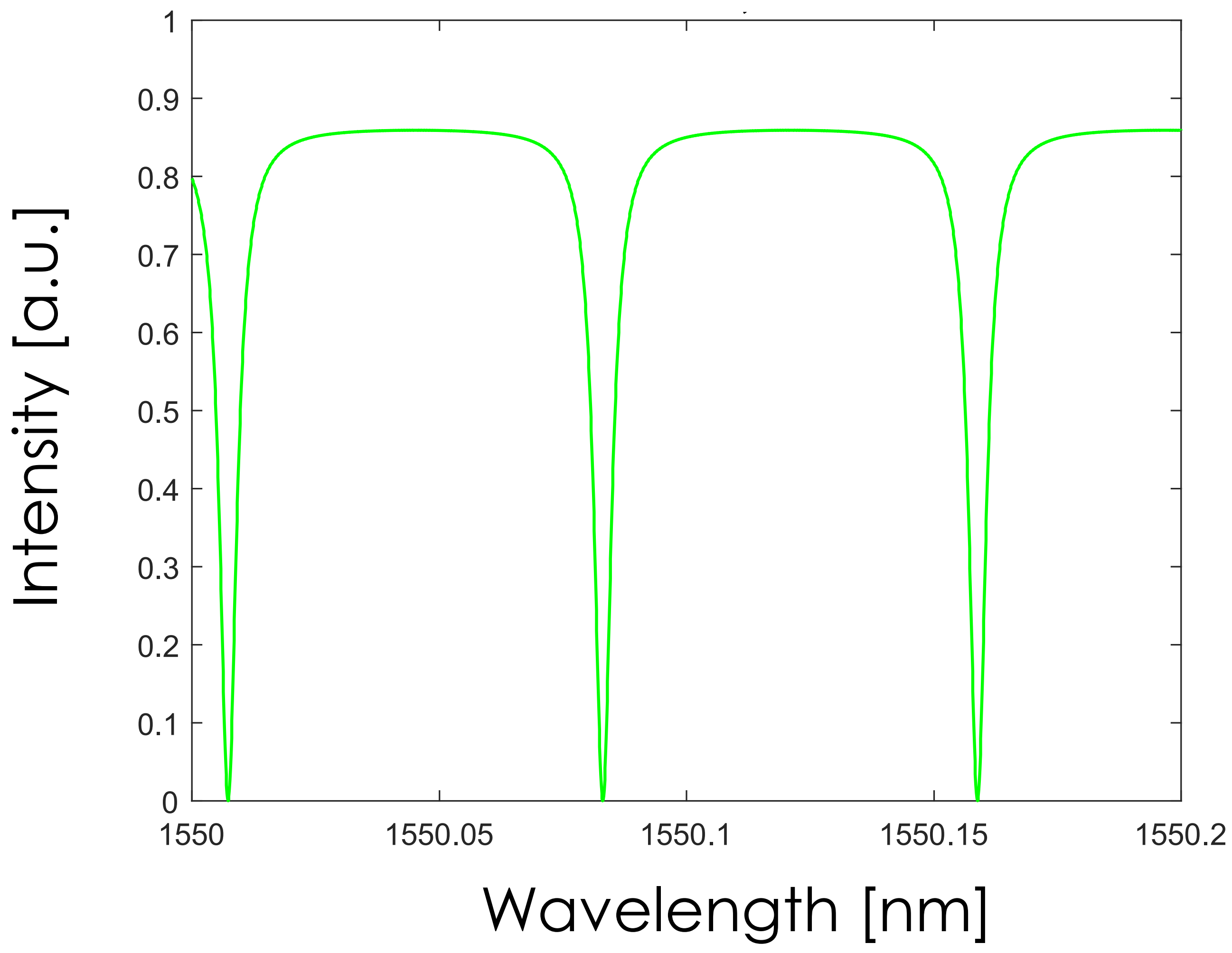

With realistic parameters:

- $G = 0.92$ (1 cm long)
- $R = 0.96$
- $\Delta v = 525$ MHz
- $Q = 3.7 \cdot 10^5$ at 1551 nm

Prototyping

- First prototype in borosilicate glass
- Operational wavelength 1550 nm
- Aluminum mirrors

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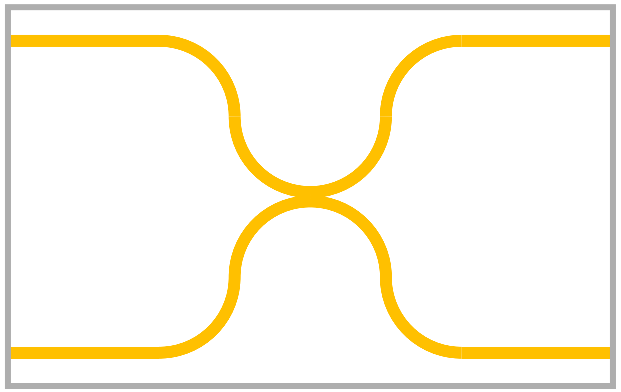
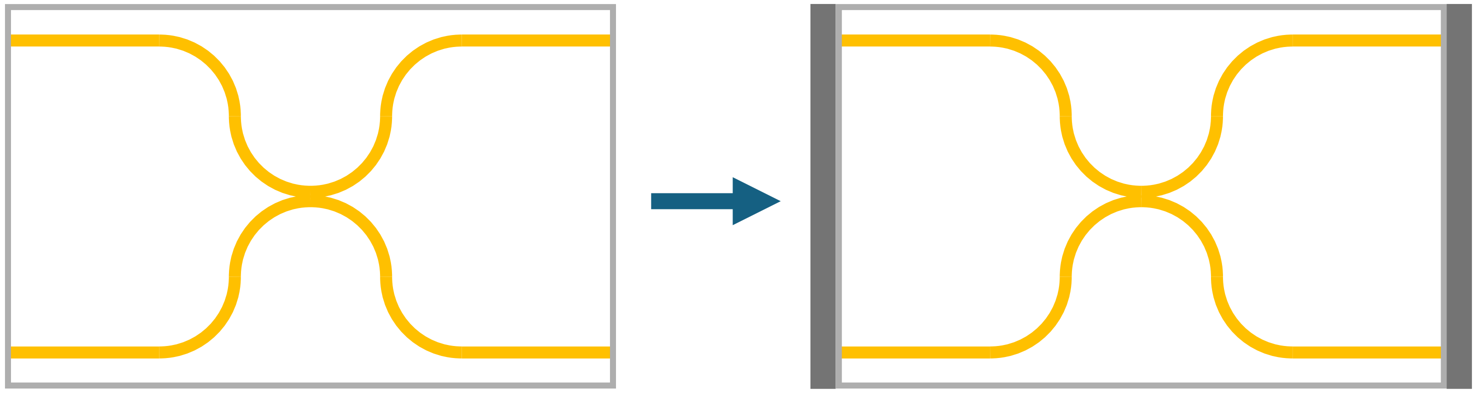
Waveguide writing



Prototyping

- First prototype in borosilicate glass
- Operational wavelength 1550 nm
- Aluminum mirrors

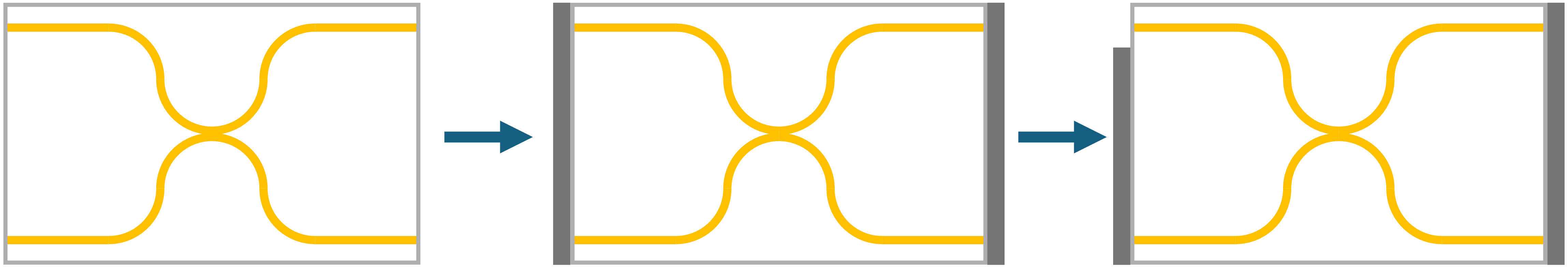
Waveguide writing Mirror deposition



Prototyping

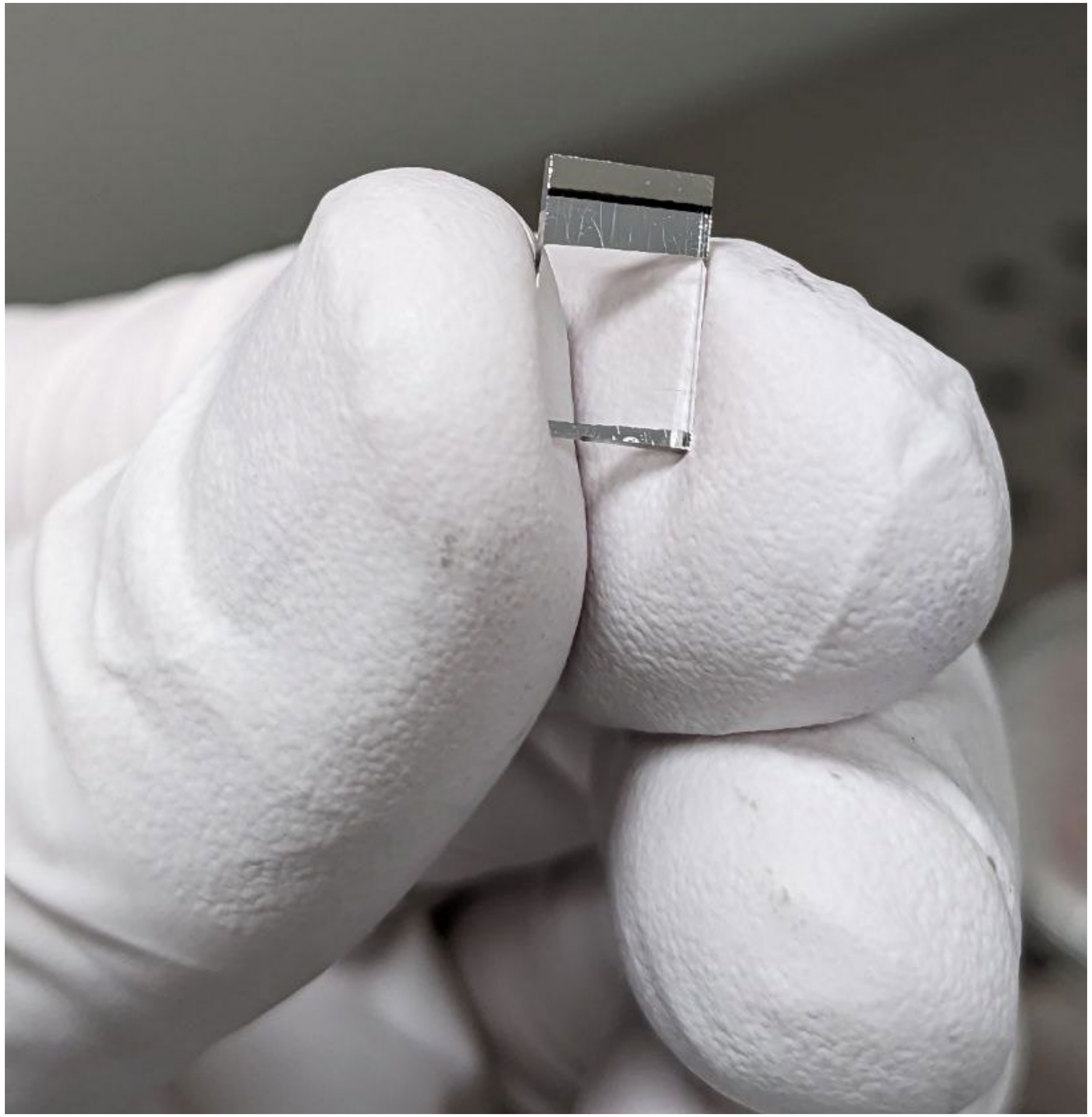
- First prototype in borosilicate glass
- Operational wavelength 1550 nm
- Aluminum mirrors

Waveguide writing Mirror deposition Facet patterning

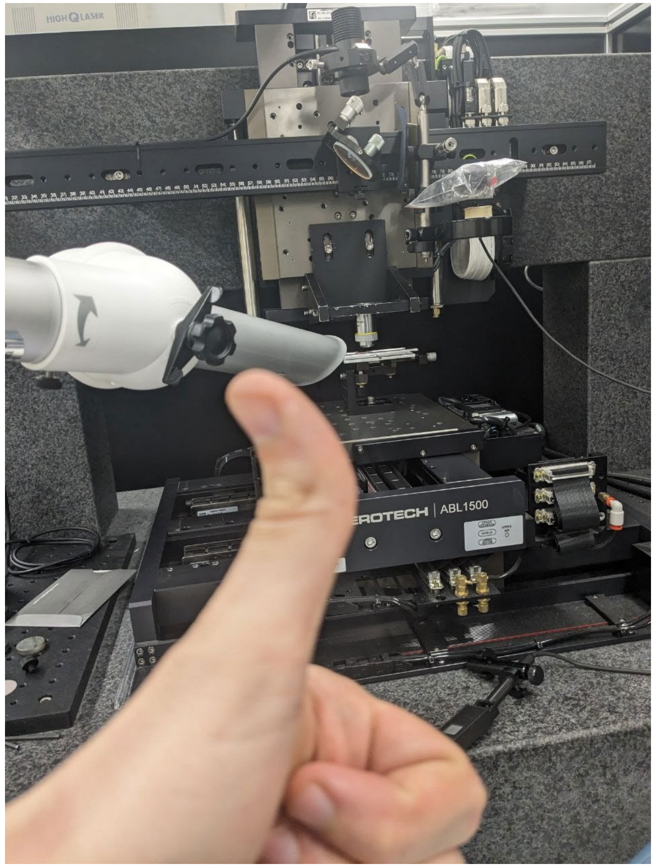


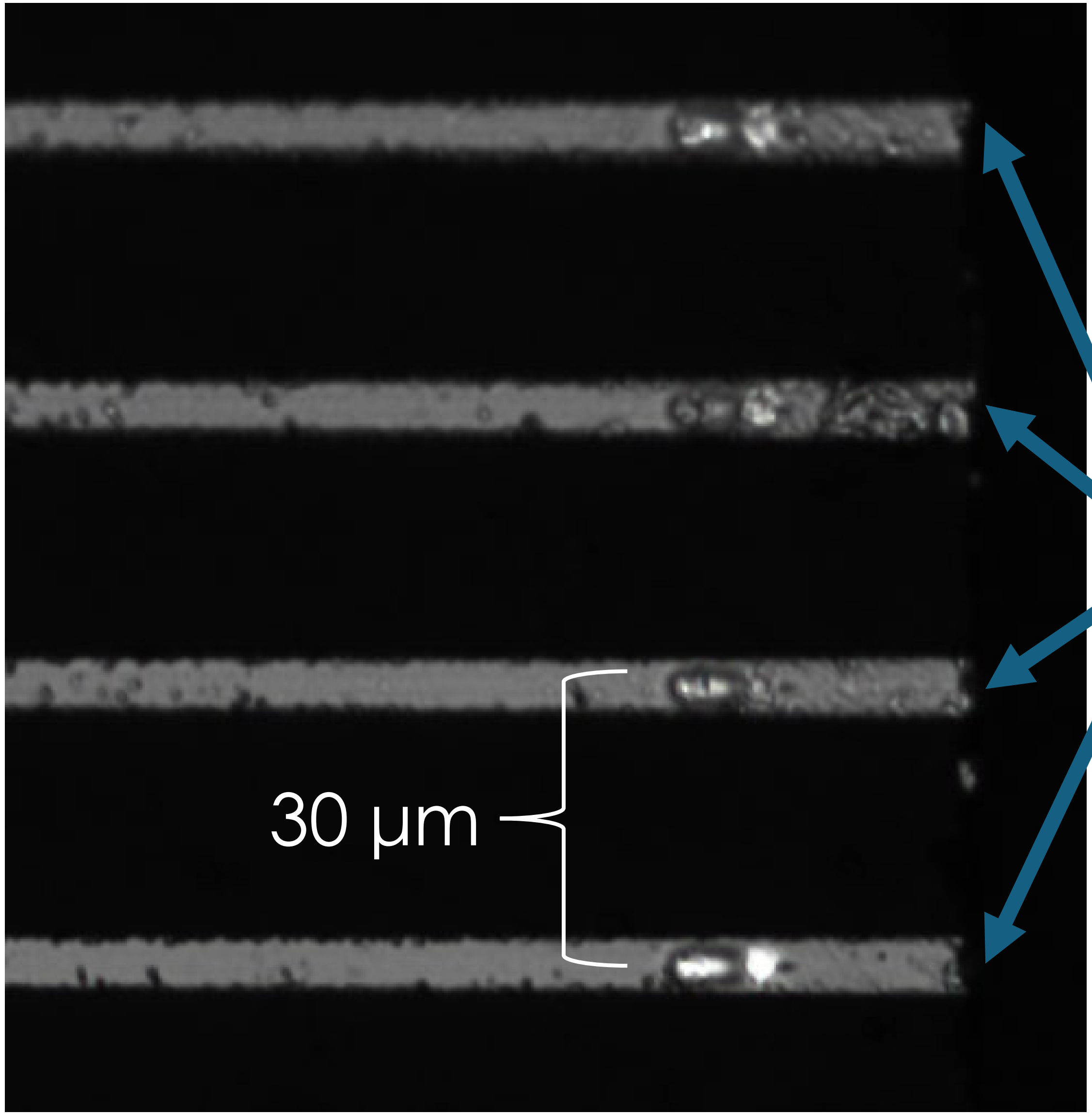
Prototyping

polifab
POLITECNICO DI MILANO



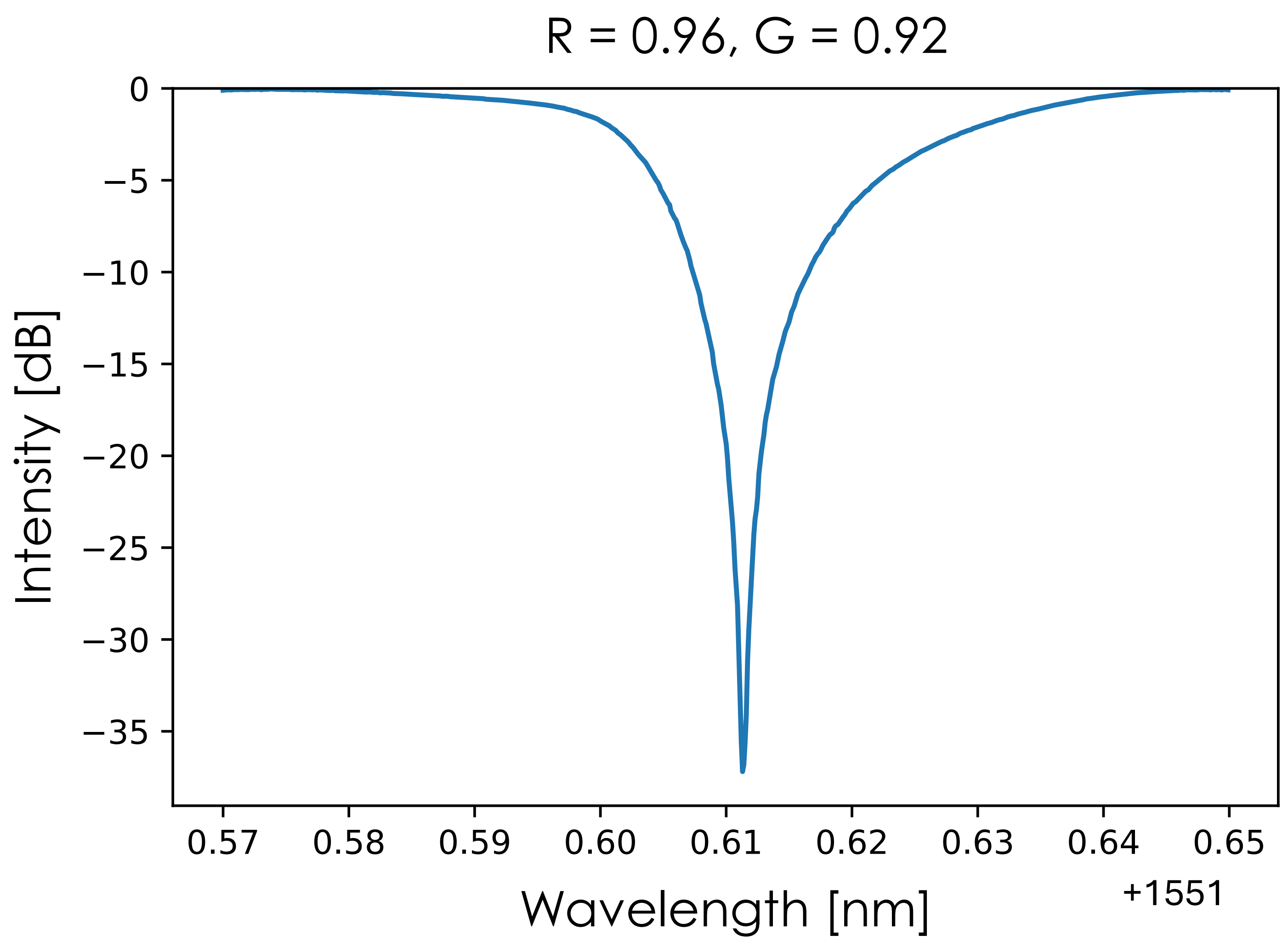
Prototyping





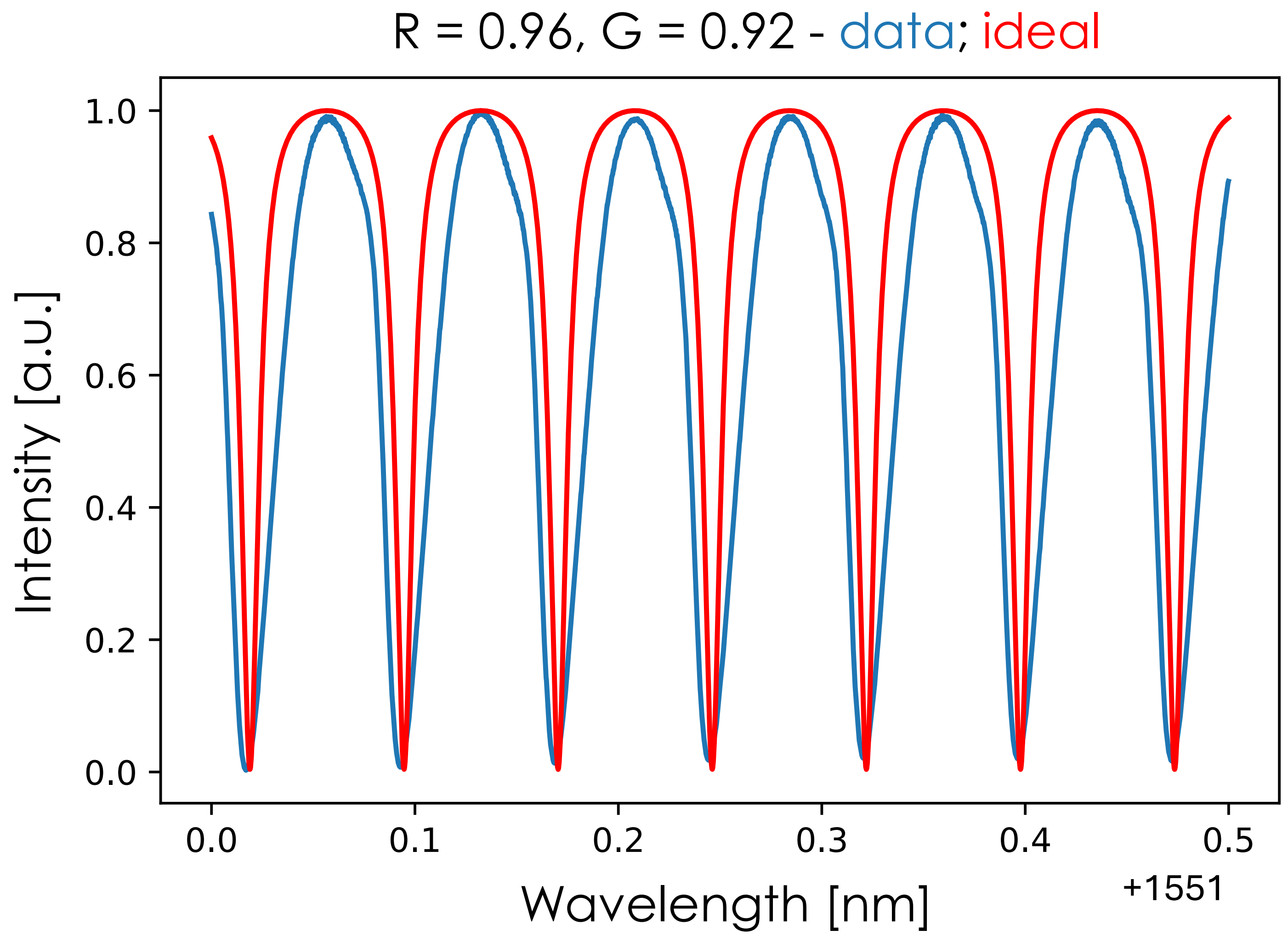
Residual metal after laser ablation

First results



Good extintion ratio can be achieved by tuning the fabrication (> 35 dB)

First results



Lineshape is affected by fabrication imprecision

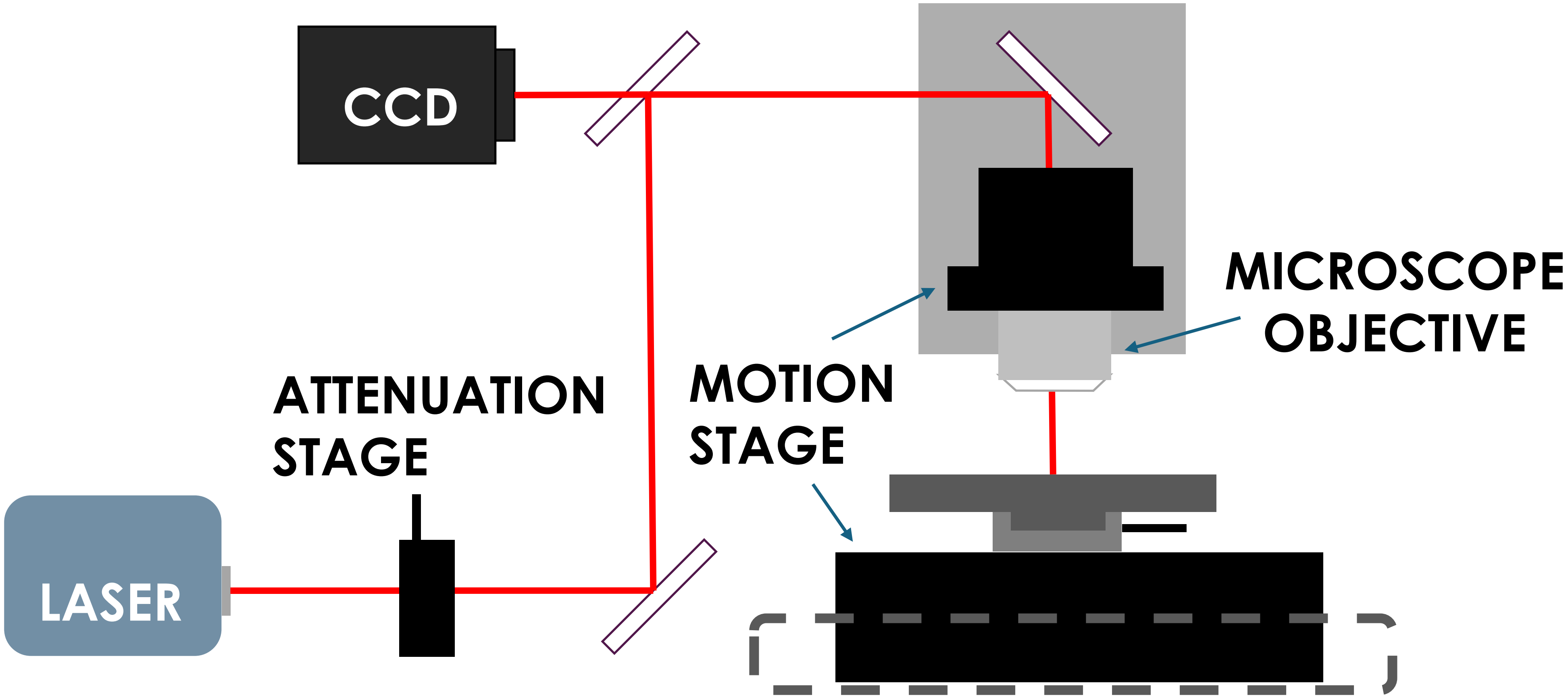
- $\Delta\nu = 3.1$ GHz
- $Q = 6.2 \cdot 10^4$ at 1551 nm

Summing up

- A FLM-compatible resonator was designed and prototyped
- Good extintion ratio can be reliably achieved
- Fabrication process requires further optimization:
  - Removal of residual metal
  - Extend operation to visible spectral region

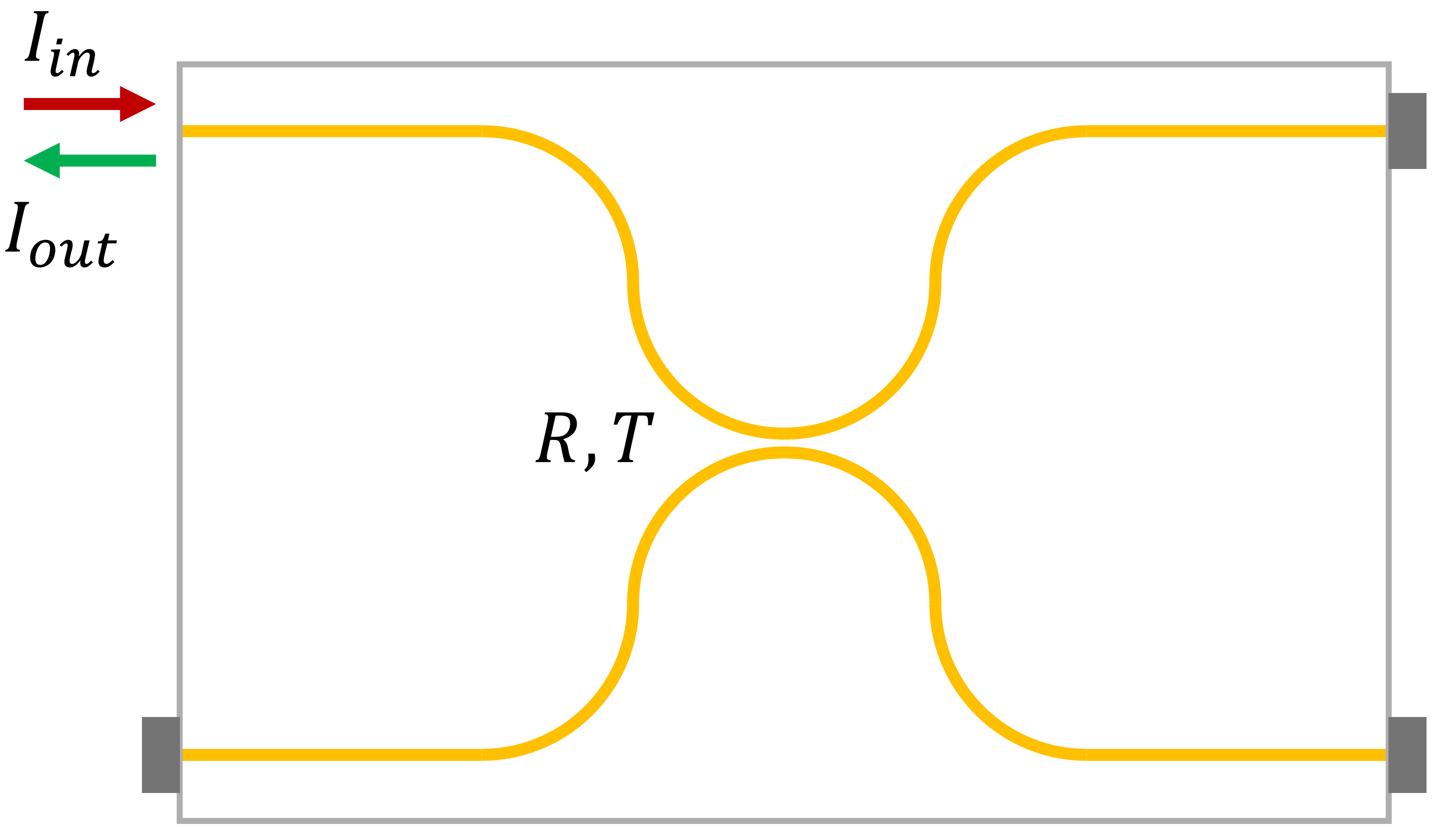
Backup Content

FLM Manufacturing Setup



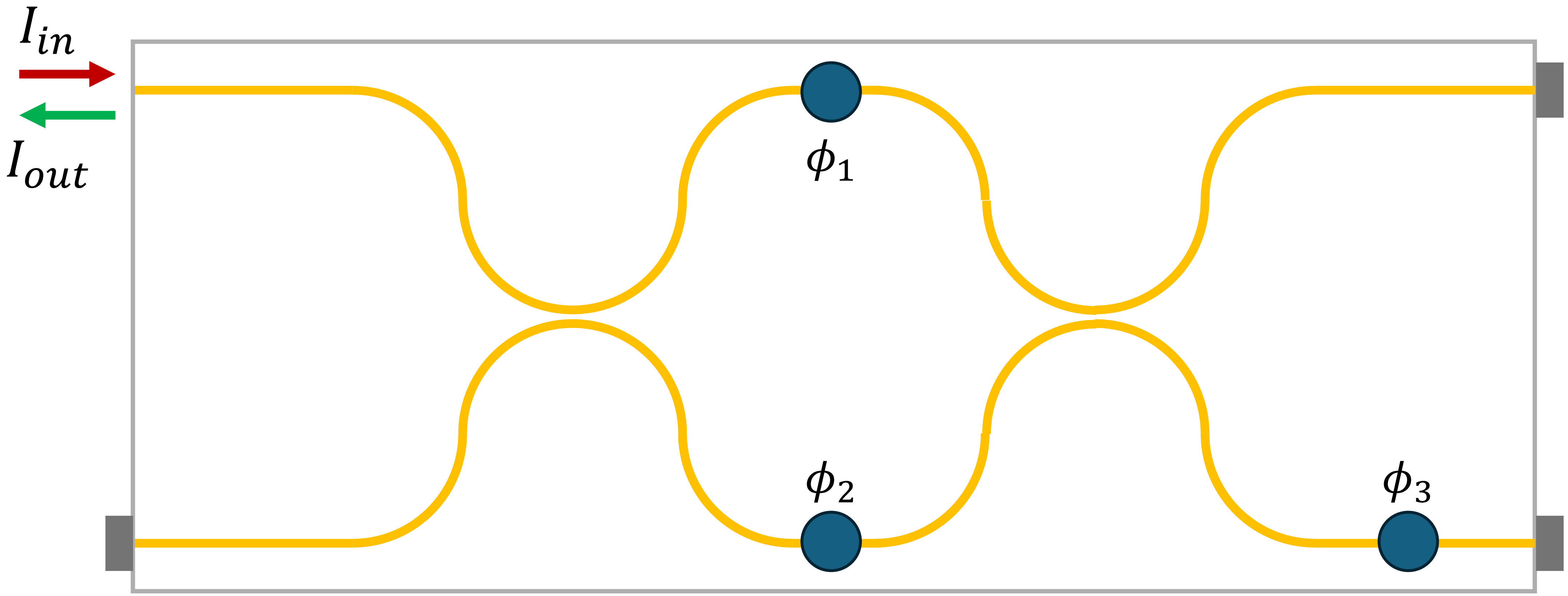
DCR transfer function

$$\frac{I_o}{I_{in}} = \frac{[(R-T)-G]^2 + 4(R-T)G\sin^2\phi}{[1-(R-T)G]^2 + 4(R-T)G\sin^2\phi}$$

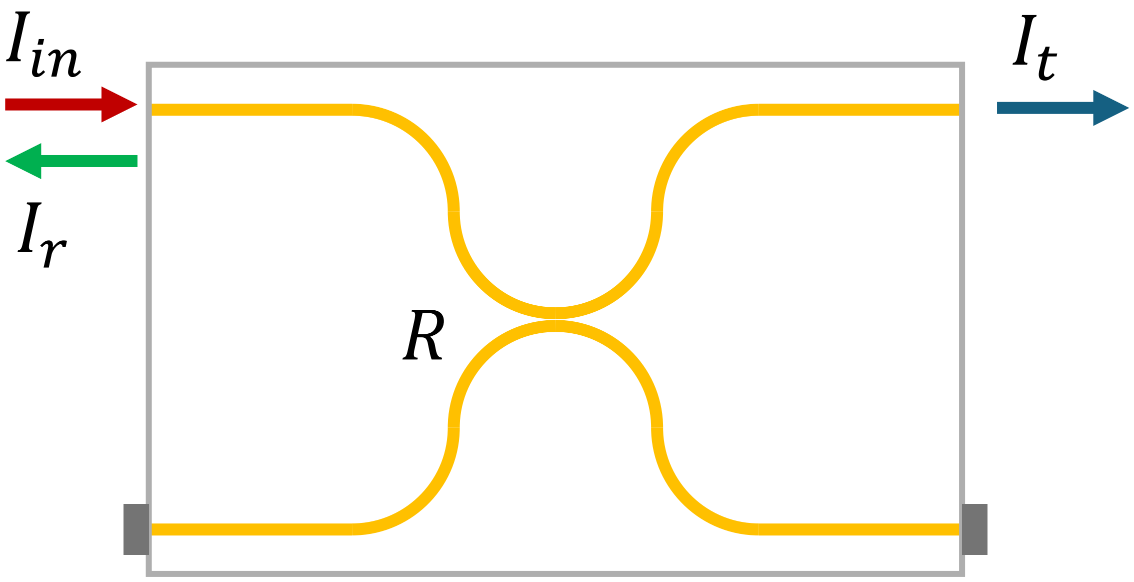


Active device

Internal and external phase control by thermal phase shifters

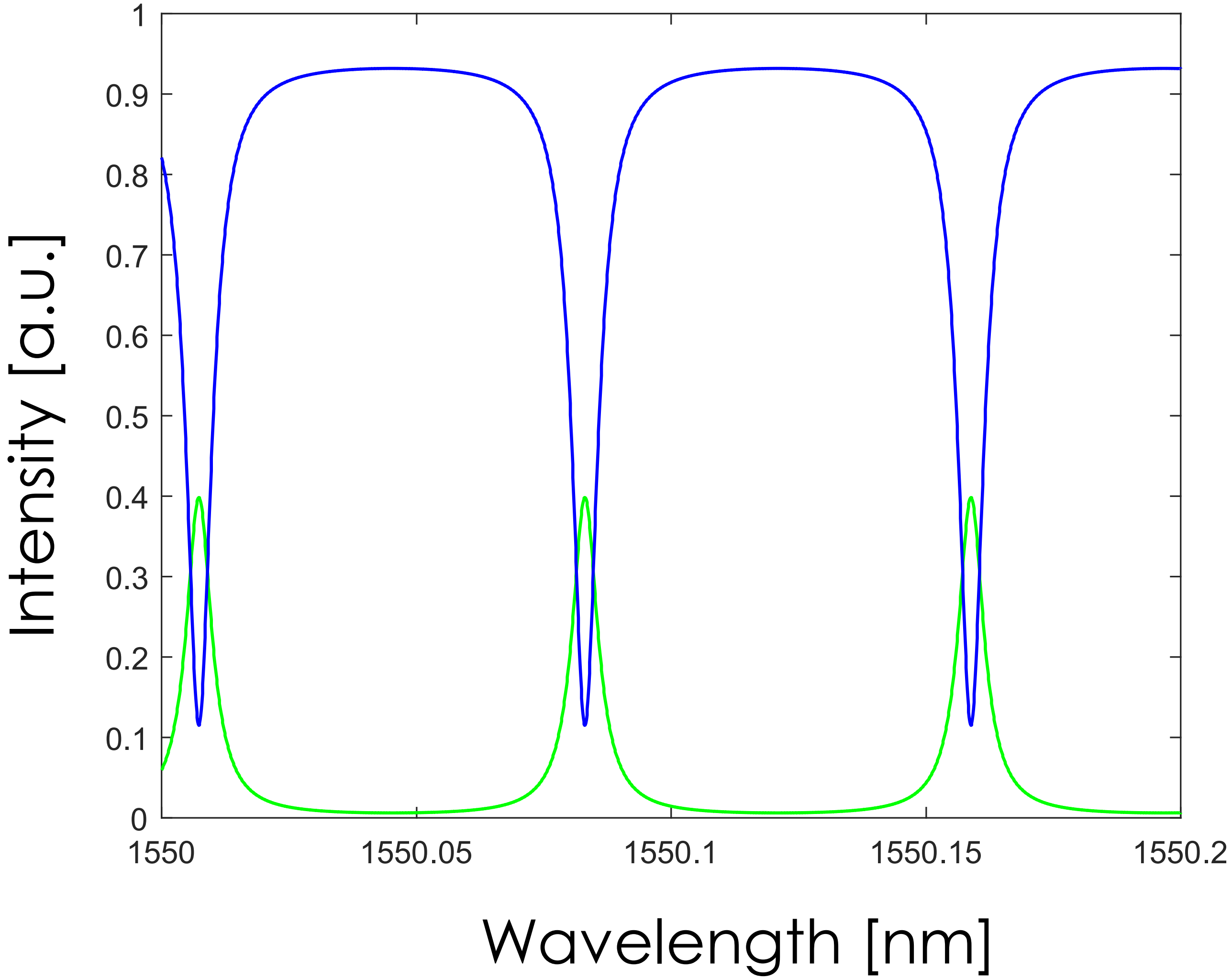


Device Variations

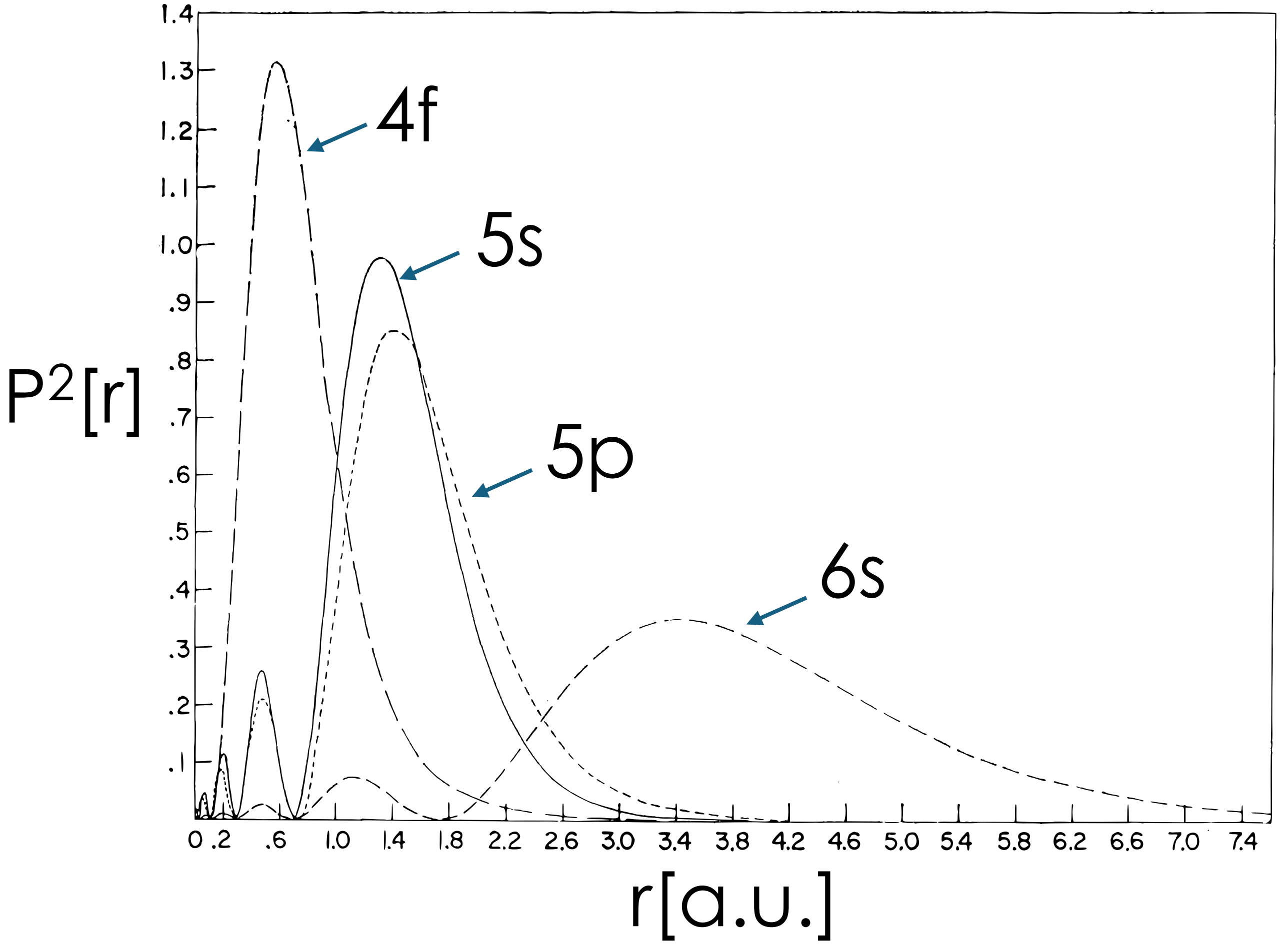


$$\frac{I_r}{I_{in}} = \frac{(1-R_0)^2 G}{(1-R_0 G)^2 + 4R_0 G \sin^2(\phi)}$$

$$\frac{I_t}{I_0} = G^2 \frac{(1-G)^2 + 4G \sin^2(\phi)}{(1-R_0 G)^2 + 4R_0 G \sin^2(\phi)}$$



Rare Earth-Ion Doped Crystals



Electronic configuration:

$[Xe]6s^2 4f^N$

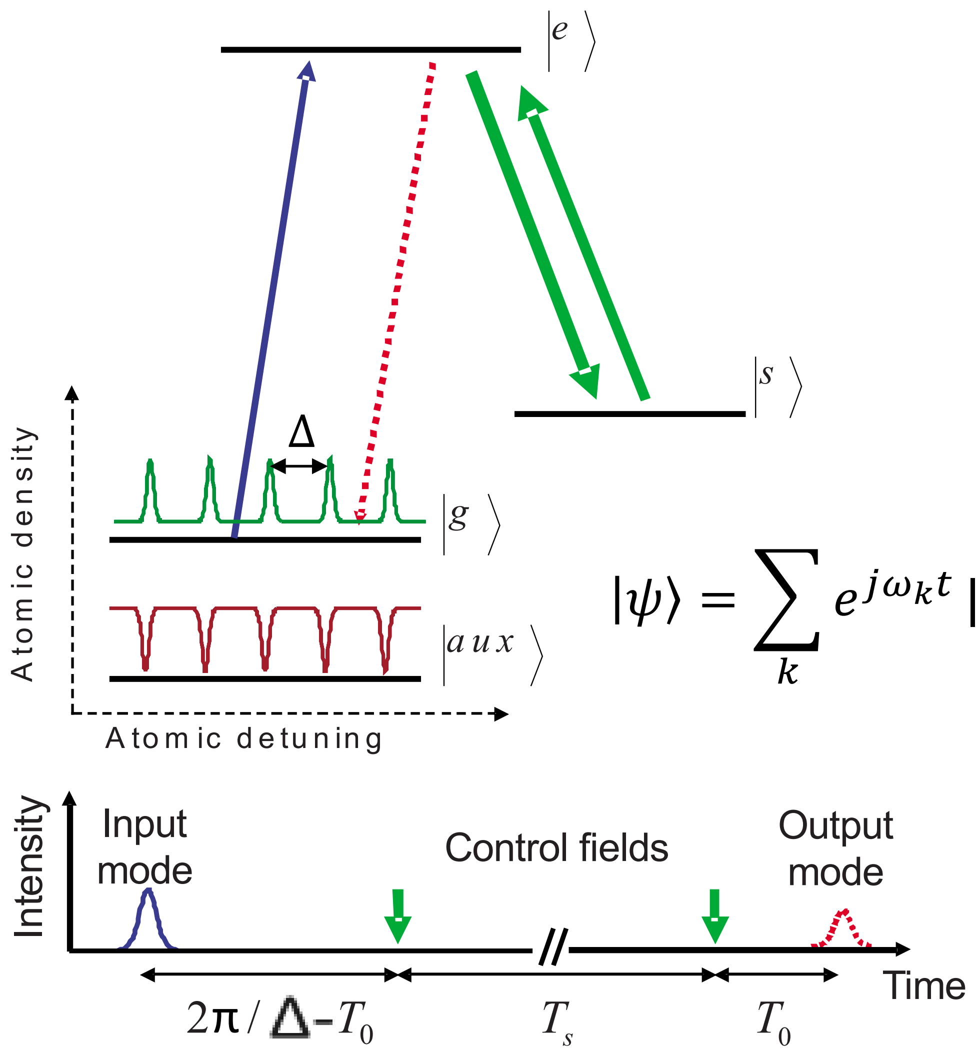
4f-4f transition is shielded by the outer shells

$\Gamma_{hom} \sim kHz$

$\Gamma_{inhom} \sim MHz - GHz$

Memory Protocols: Atomic Frequency Comb

- Tailor the inhomogeoeus line to a comb structure
- Storage time is given by the comb spacing



$$|\psi\rangle = \sum_k e^{j\omega_k t} |g_1 g_2 \dots e_k \dots g_N\rangle$$