

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

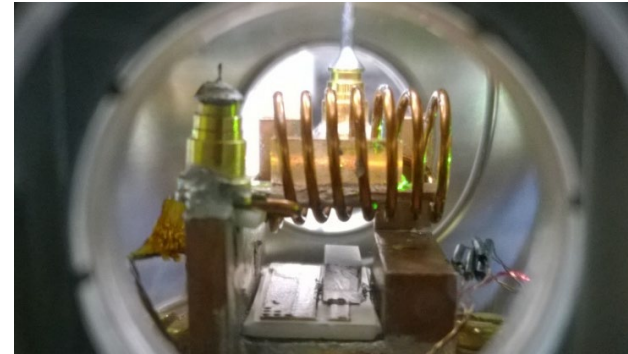


- Long distance networks
- Storage for quantum computing
- Precise metrology

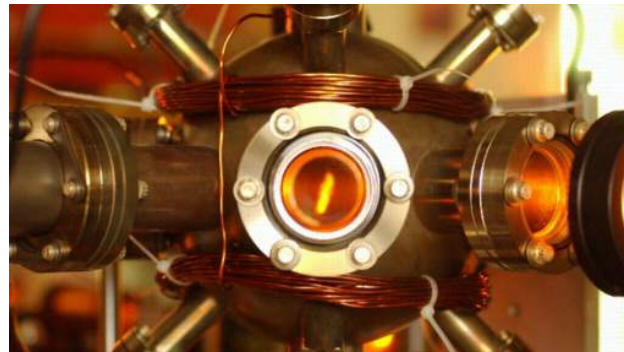
It's all about interfacing photons with something stable!



Alkali vapours

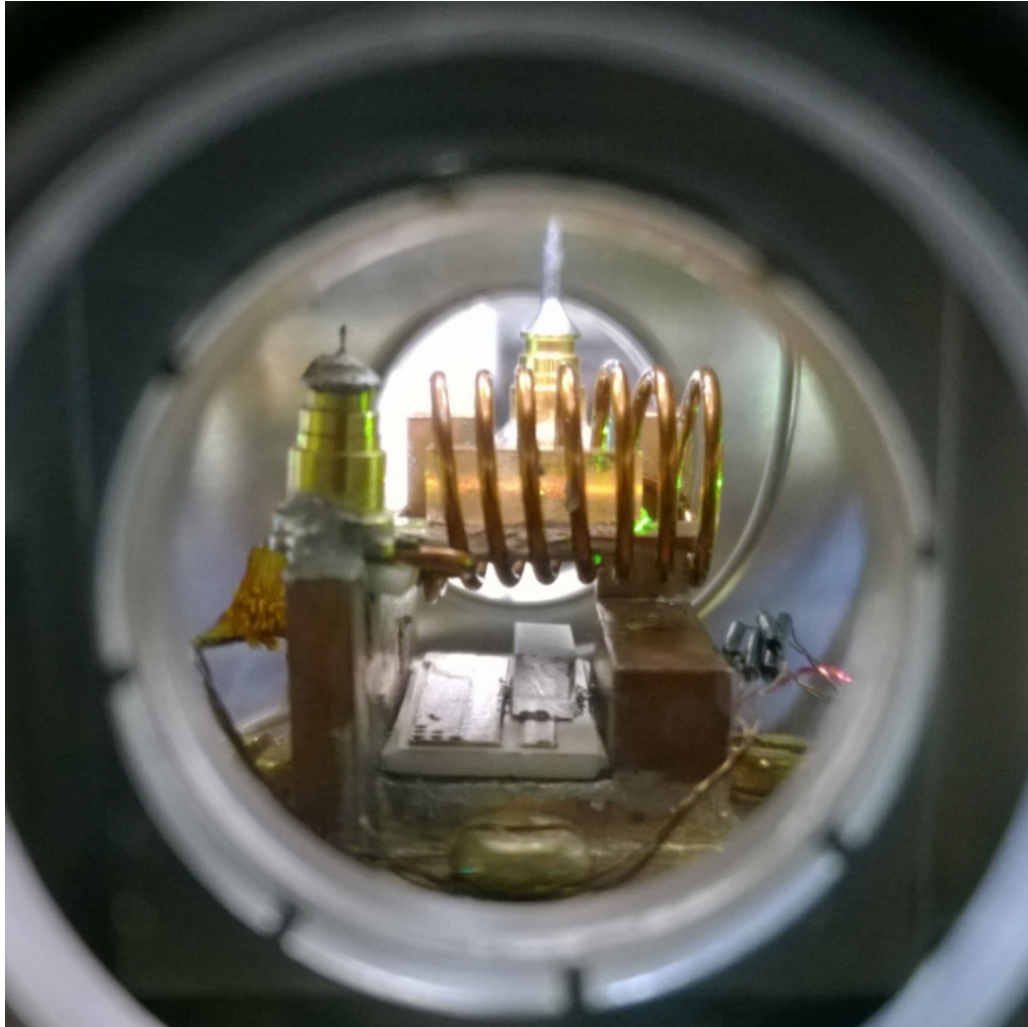


Solid state



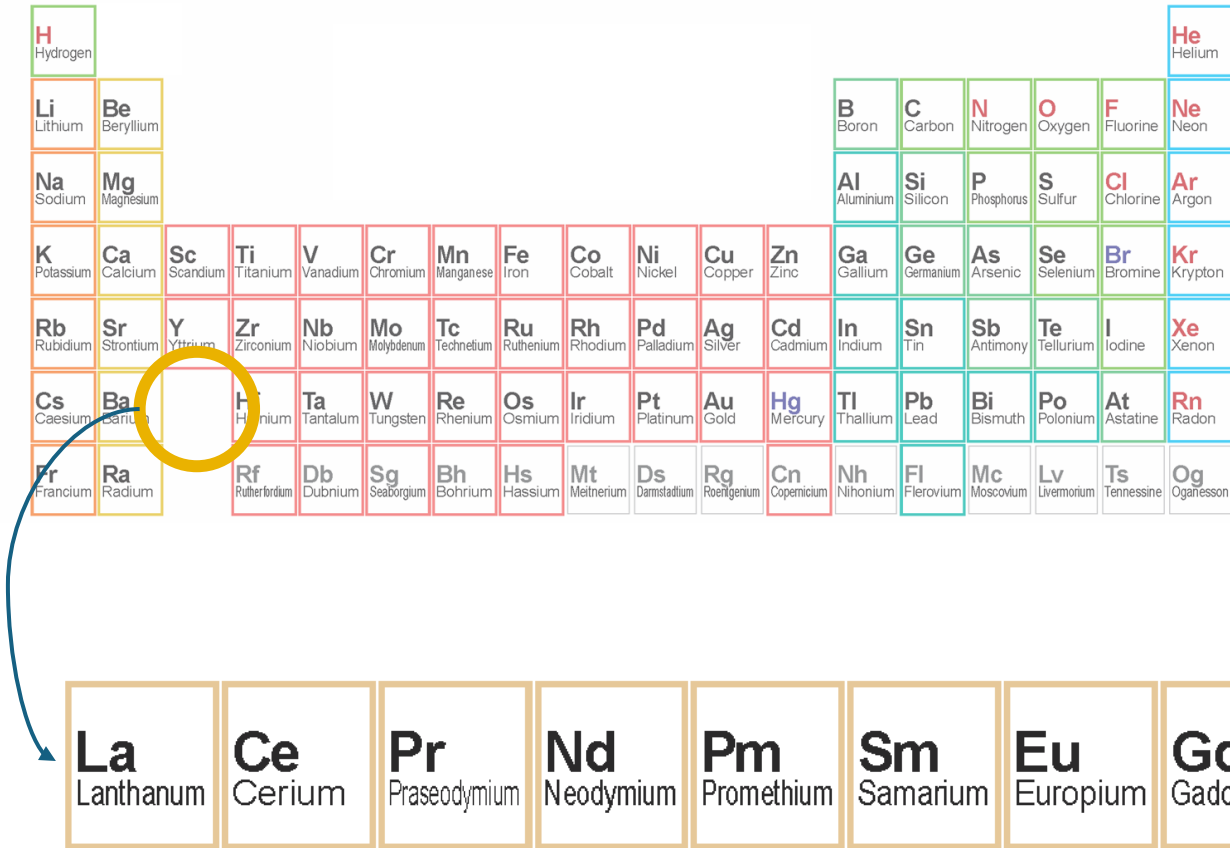
Single atoms

It's all about interfacing photons with something stable!



**Robust
&
Machinable**

Rare earth ion-doped crystals



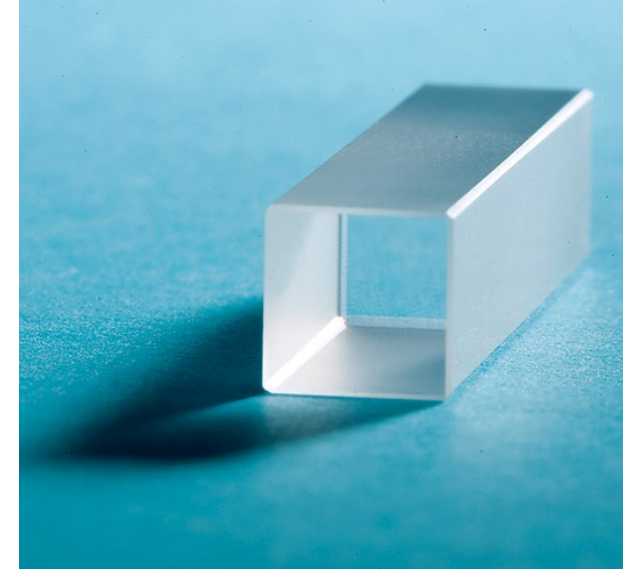
The periodic table shows elements from Hydrogen (H) to Oganesson (Og). A yellow circle highlights the Lanthanide and Actinide series, and a blue arrow points to the expanded list below.

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
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Long coherence times at
cryogenic temperatures

Rare earth ion-doped crystals

H Hydrogen																	He Helium						
Li Lithium	Be Beryllium																	B Boron	C Carbon	N Nitrogen	O Oxygen	F Fluorine	Ne Neon
Na Sodium	Mg Magnesium																	Al Aluminium	Si Silicon	P Phosphorus	S Sulfur	Cl Chlorine	Ar Argon
K Potassium	Ca Calcium	Sc Scandium	Ti Titanium	V Vanadium	Cr Chromium	Mn Manganese	Fe Iron	Co Cobalt	Ni Nickel	Cu Copper	Zn Zinc	Ga Gallium	Ge Germanium	As Arsenic	Se Selenium	Br Bromine	Kr Krypton						
Rb Rubidium	Sr Strontium	Y Yttrium	Zr Zirconium	Nb Niobium	Mo Molybdenum	Tc Technetium	Ru Ruthenium	Rh Rhodium	Pd Palladium	Ag Silver	Cd Cadmium	In Indium	Sn Tin	Sb Antimony	Te Tellurium	I Iodine	Xe Xenon						
Cs Caesium	Ba Barium			Hf Hafnium	Ta Tantalum	W Tungsten	Re Rhenium	Os Osmium	Ir Iridium	Pt Platinum	Au Gold	Hg Mercury	Tl Thallium	Pb Lead	Bi Bismuth	Po Polonium	At Astatine	Rn Radon					
Fr Francium	Ra Radium	Rf Rutherfordium	Db Dubnium	Sg Seaborgium	Bh Bohrium	Hs Hassium	Mt Meitnerium	Ds Darmstadtium	Rg Roentgenium	Cn Copernicium	Nh Nihonium	Fl Flerovium	Mc Moscovium	Lv Livermorium	Ts Tennessine	Og Oganesson							



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
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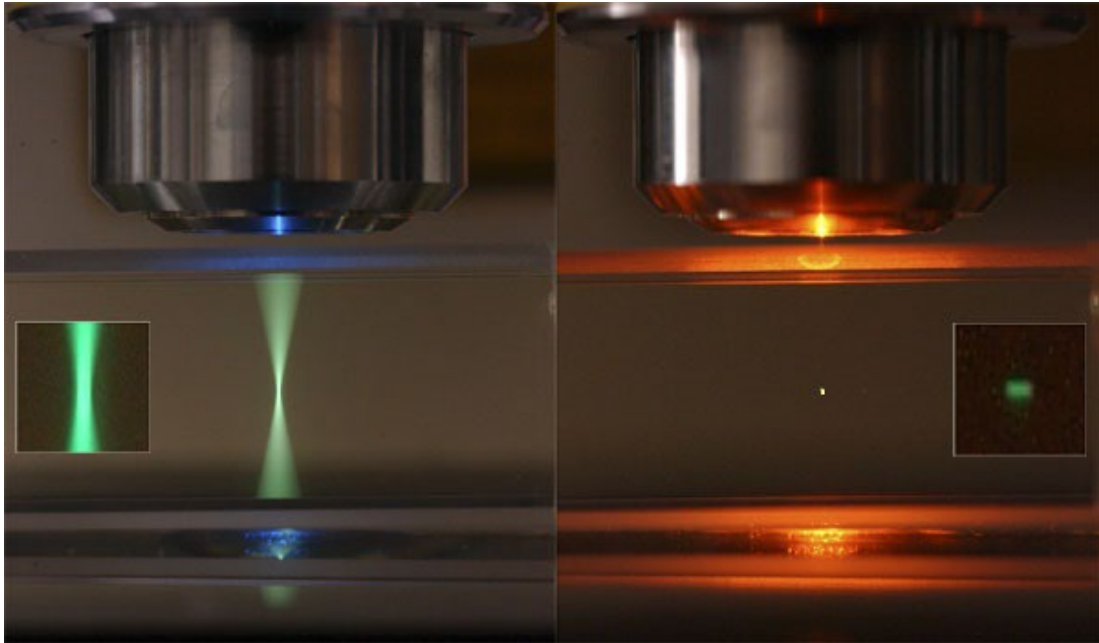


High efficiency

Long storage time

Telecom compatible

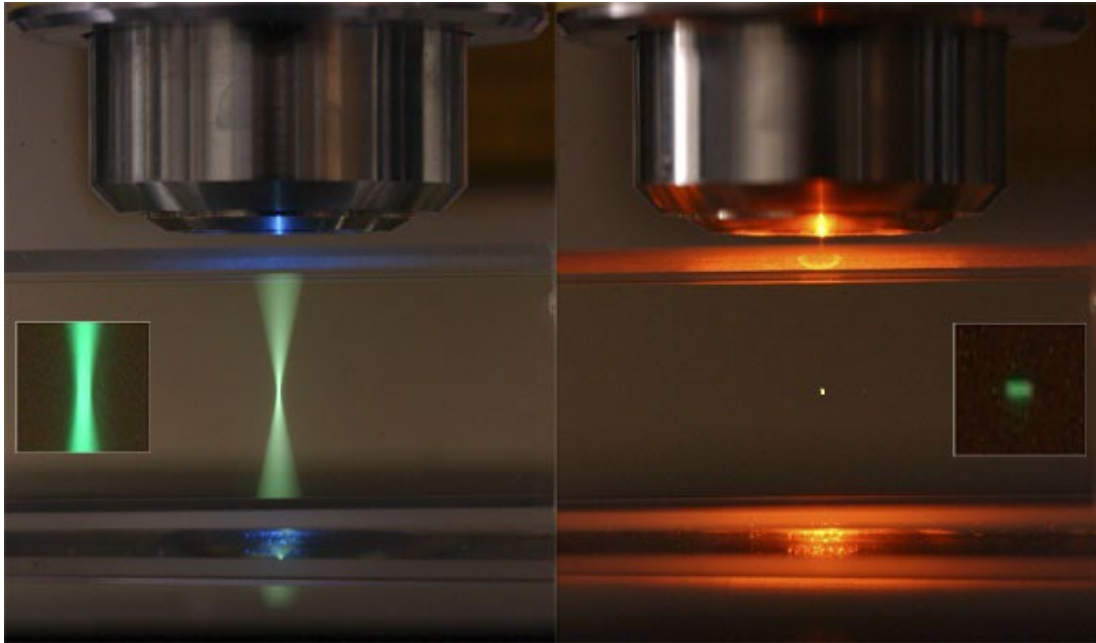
Femtosecond Laser Micromachining



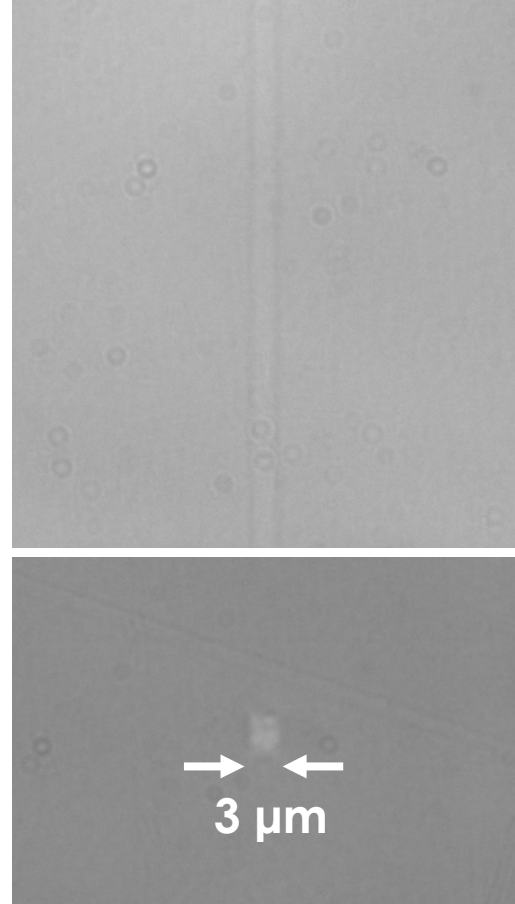
Localized index change to
build **waveguides**

Femtosecond Laser Micromachining

YSO waveguide

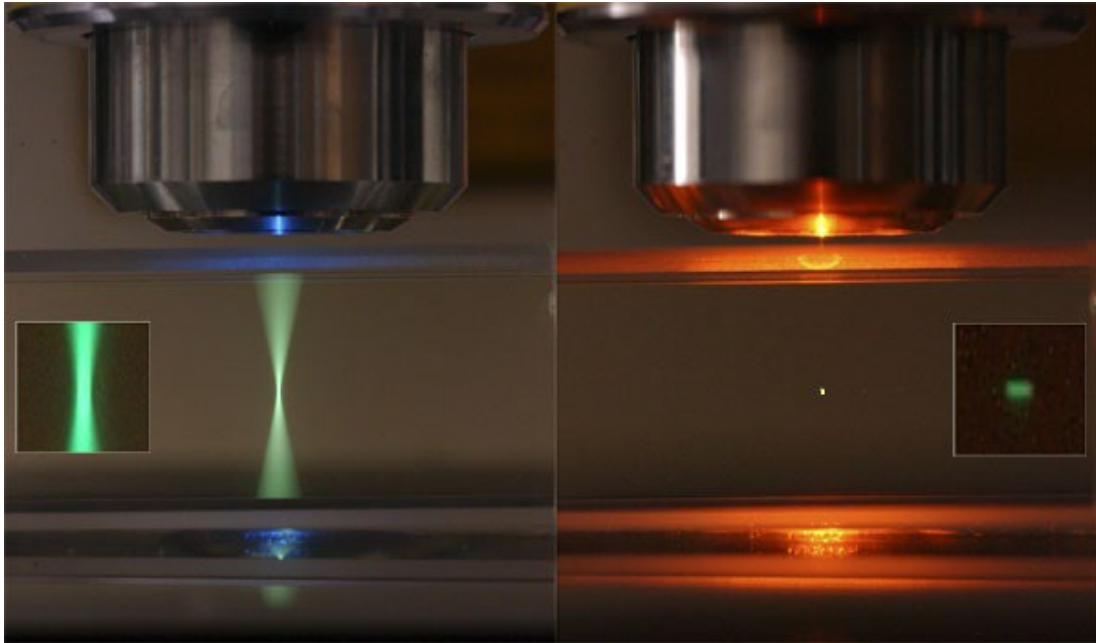


Localized index change to
build **waveguides**

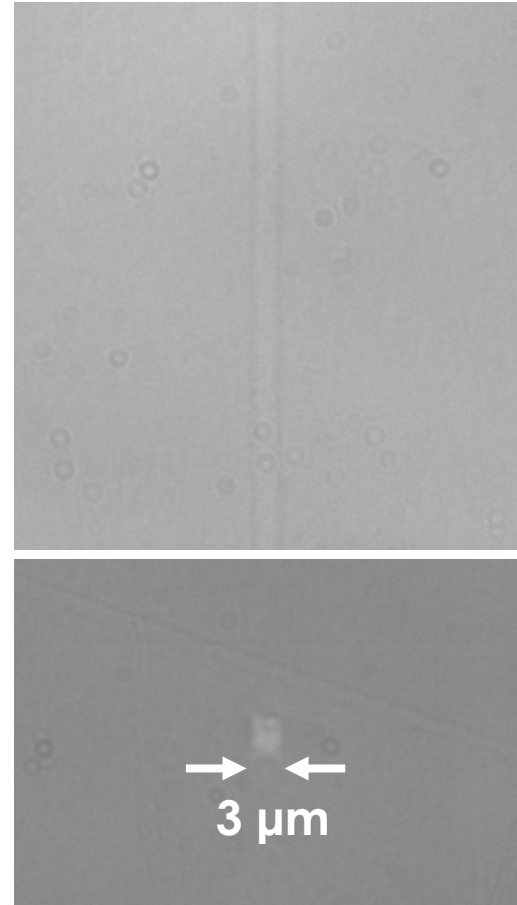


Femtosecond Laser Micromachining

YSO waveguide

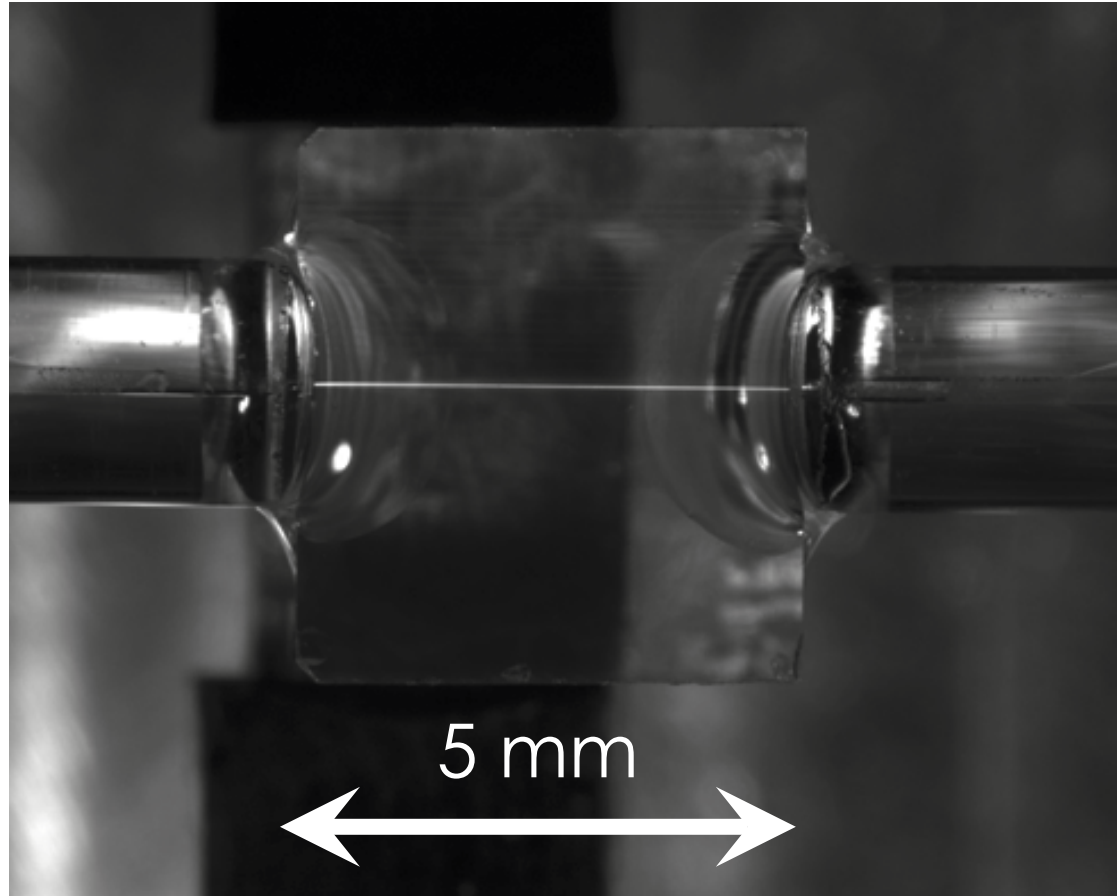


Localized index change to
build **waveguides**



- Fast prototyping
- Material versatility
- Low-loss structures

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



27 μ s storage with up to
18% efficiency

Science Advances 8.27 (2022): eabn3919.

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

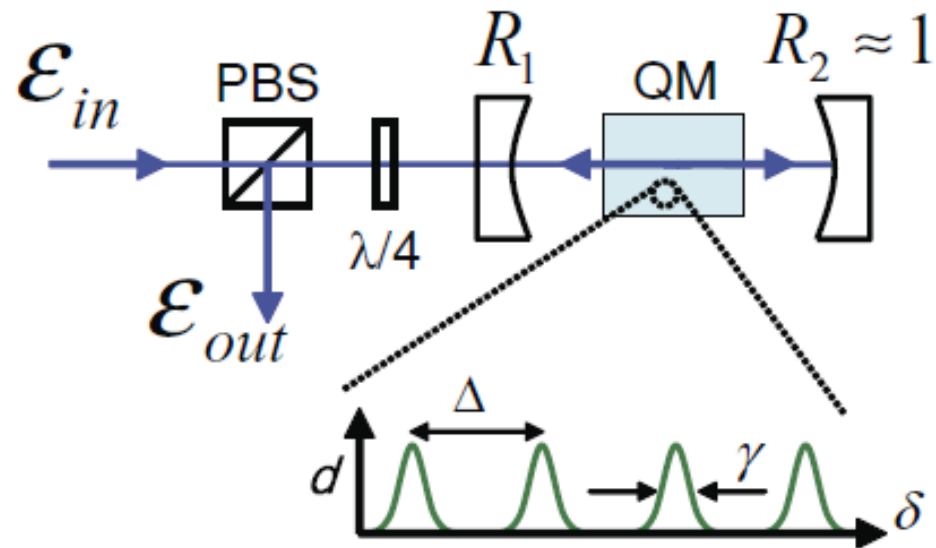
Current: optical
fibers

Critical coupling to cavities

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

Impedance-matched cavity quantum memory

Mikael Afzelius¹ and Christoph Simon²

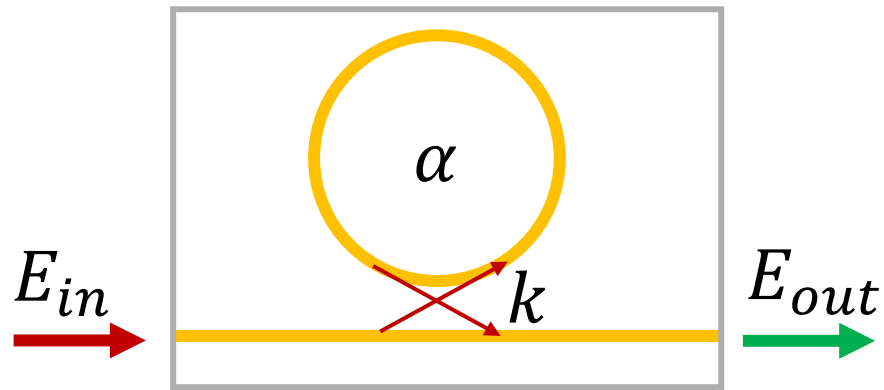


Force absorption of the ions for
certain wavelengths to have unit
efficiency

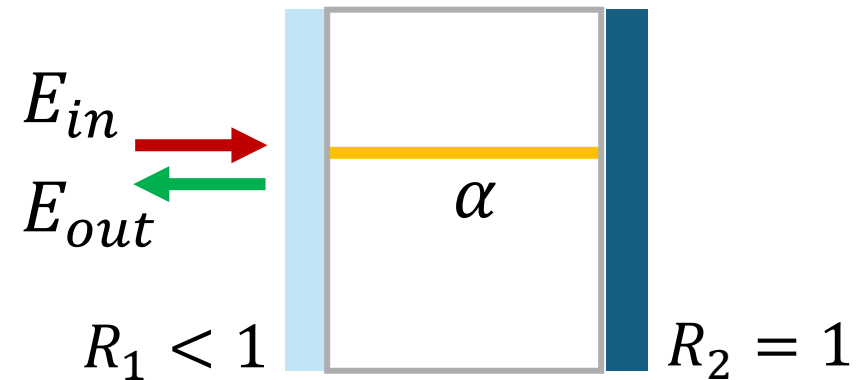
«Critical coupling» to a cavity

How it's done, usually

Ring resonators:



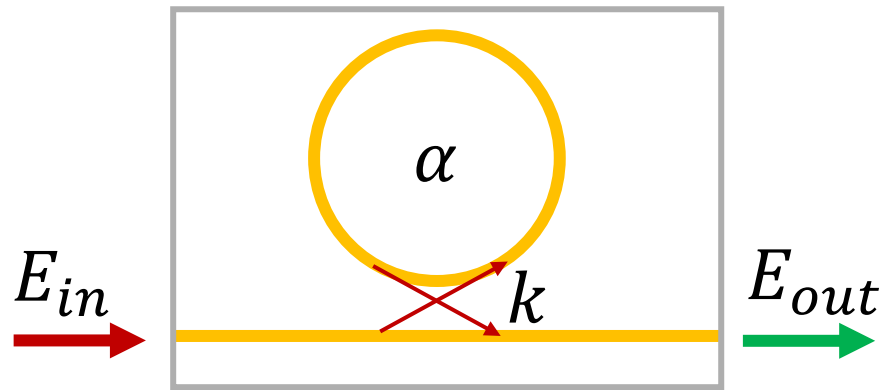
Fabry-Perot cavities:



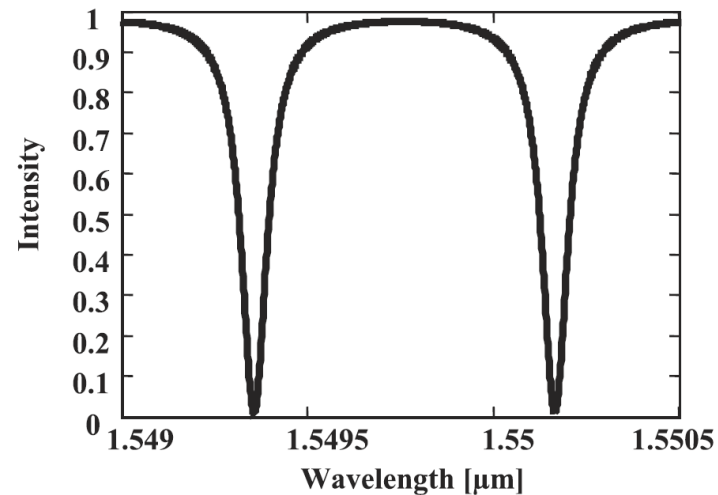
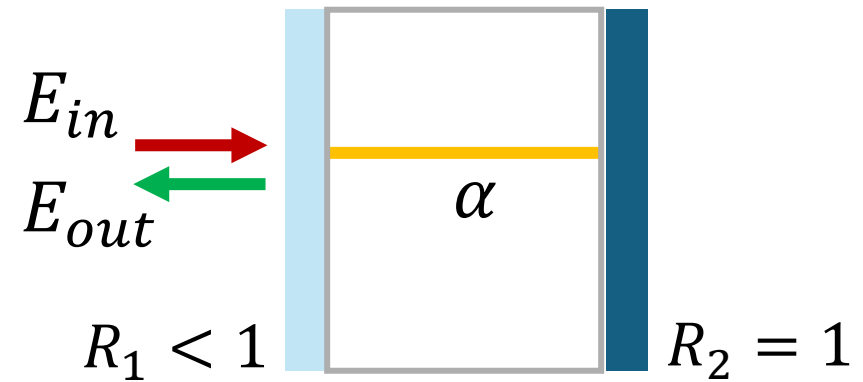
Self-interference of the input field shapes the output

How it's done, usually

Ring resonators:

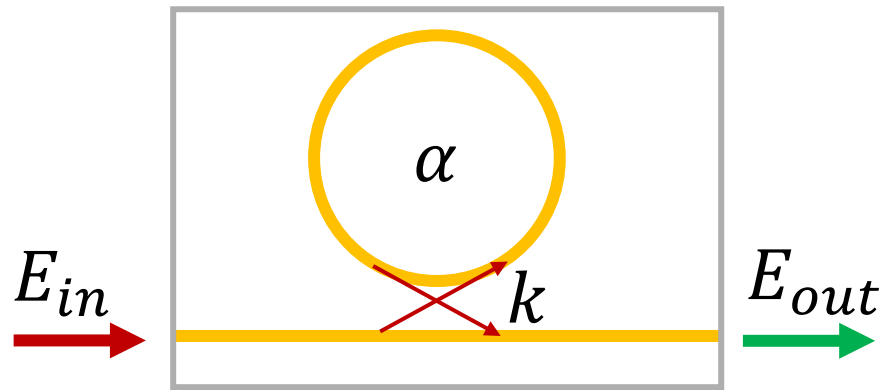


Fabry-Perot cavities:



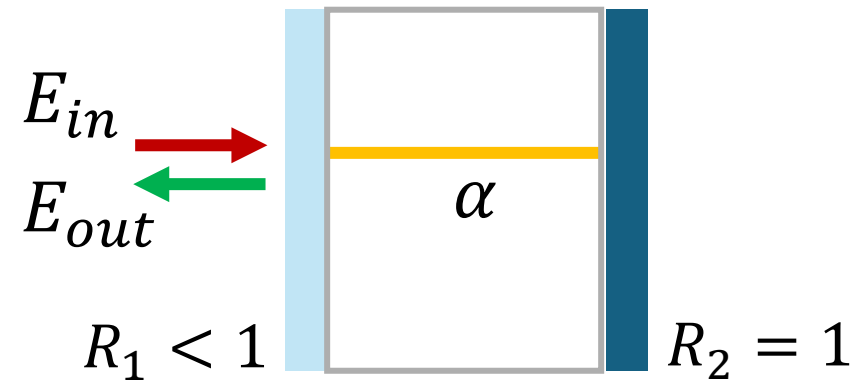
How it's done, usually

Ring resonators:



- Critical coupling for
$$1 - |k|^2 = |\alpha|^2$$

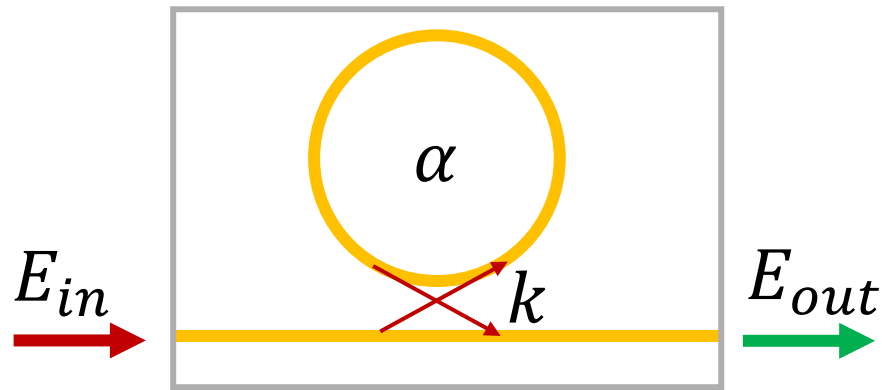
Fabry-Perot cavities:



- Critical coupling for
$$R_1 = |\alpha|^2$$

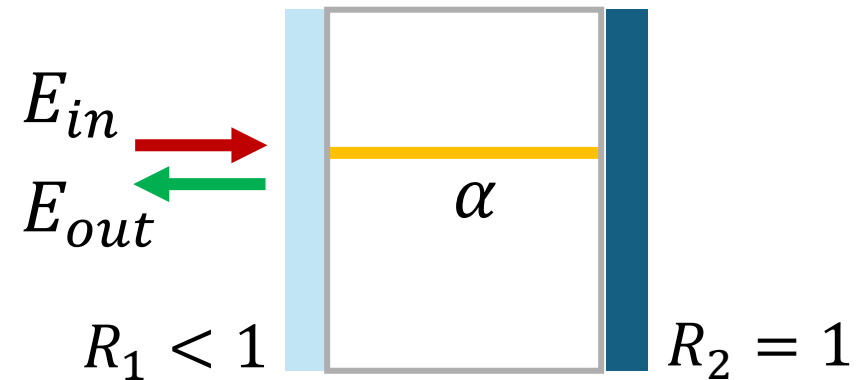
How it's done, usually

Ring resonators:



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

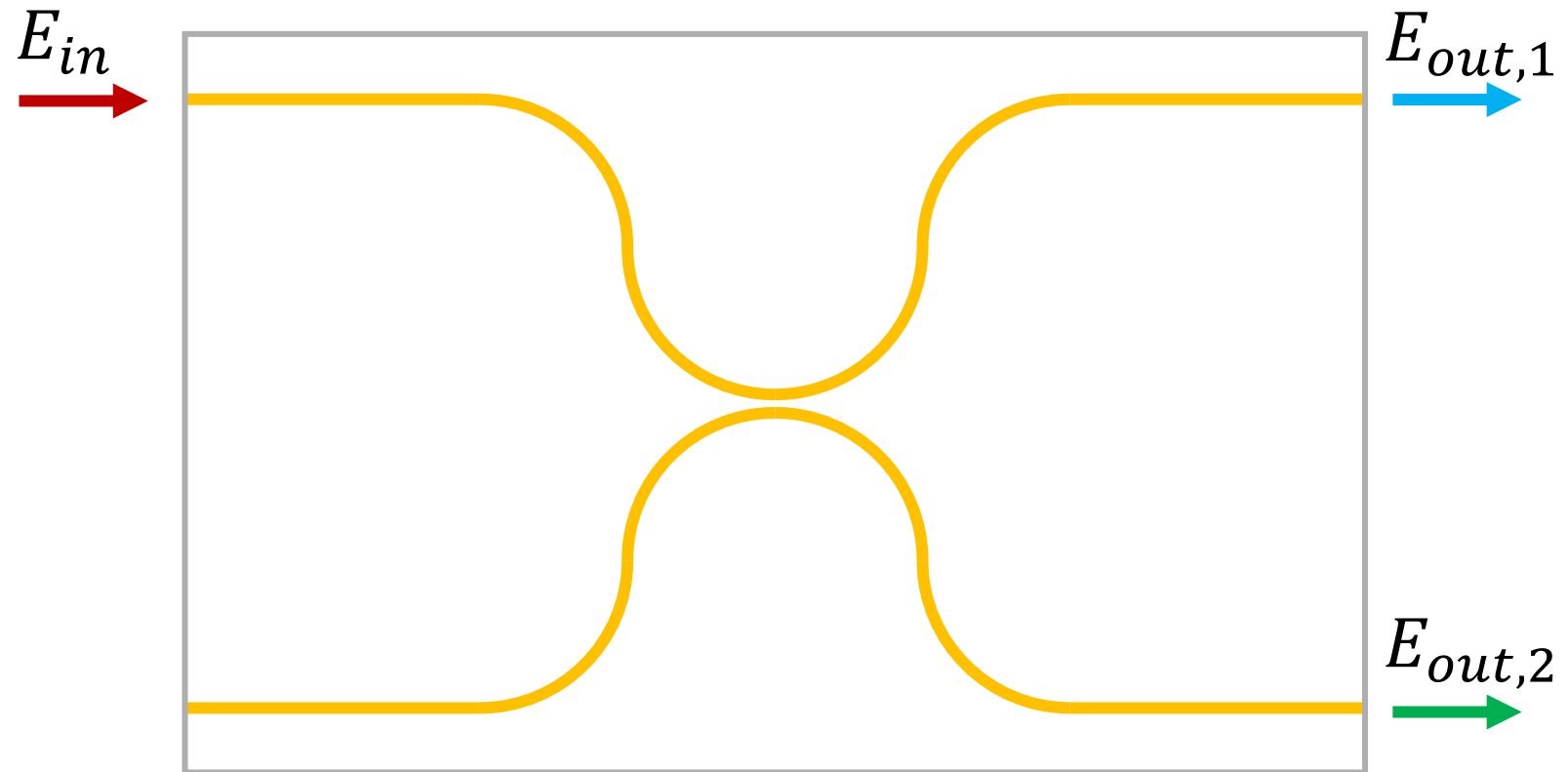
Fabry-Perot cavities:



- Critical coupling for
$$R_1 = |\alpha|^2$$
- Technologically challenging

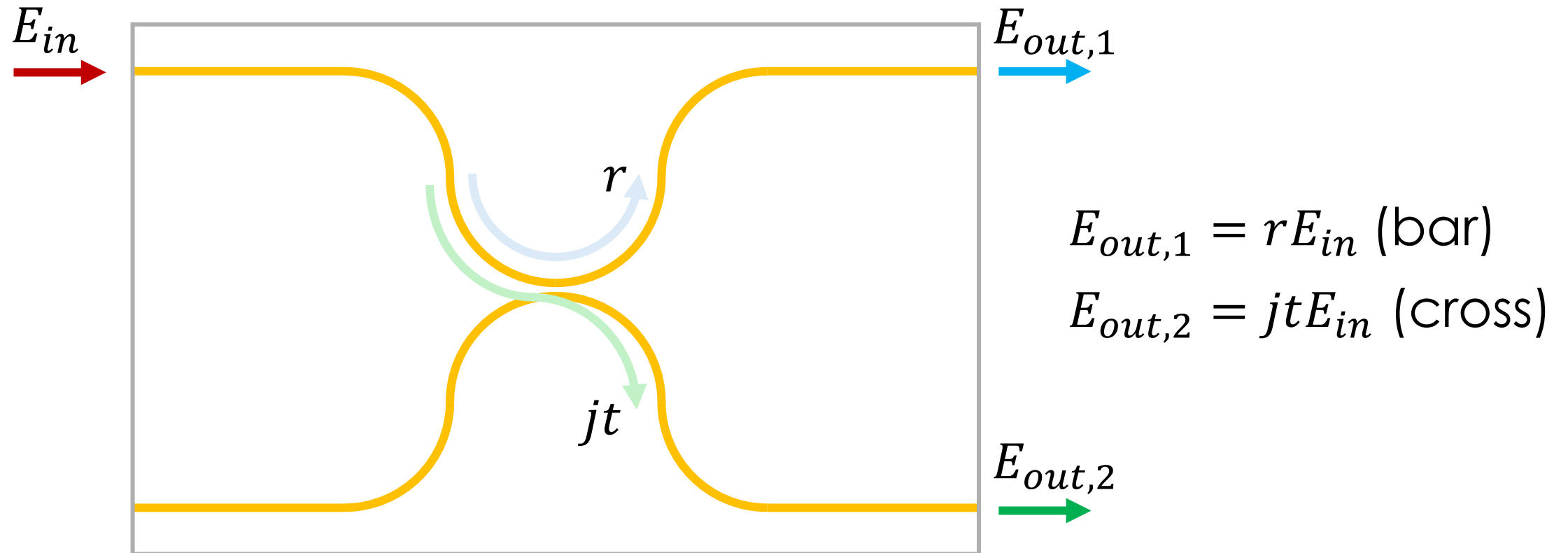
So what can we do?

Directional coupler:



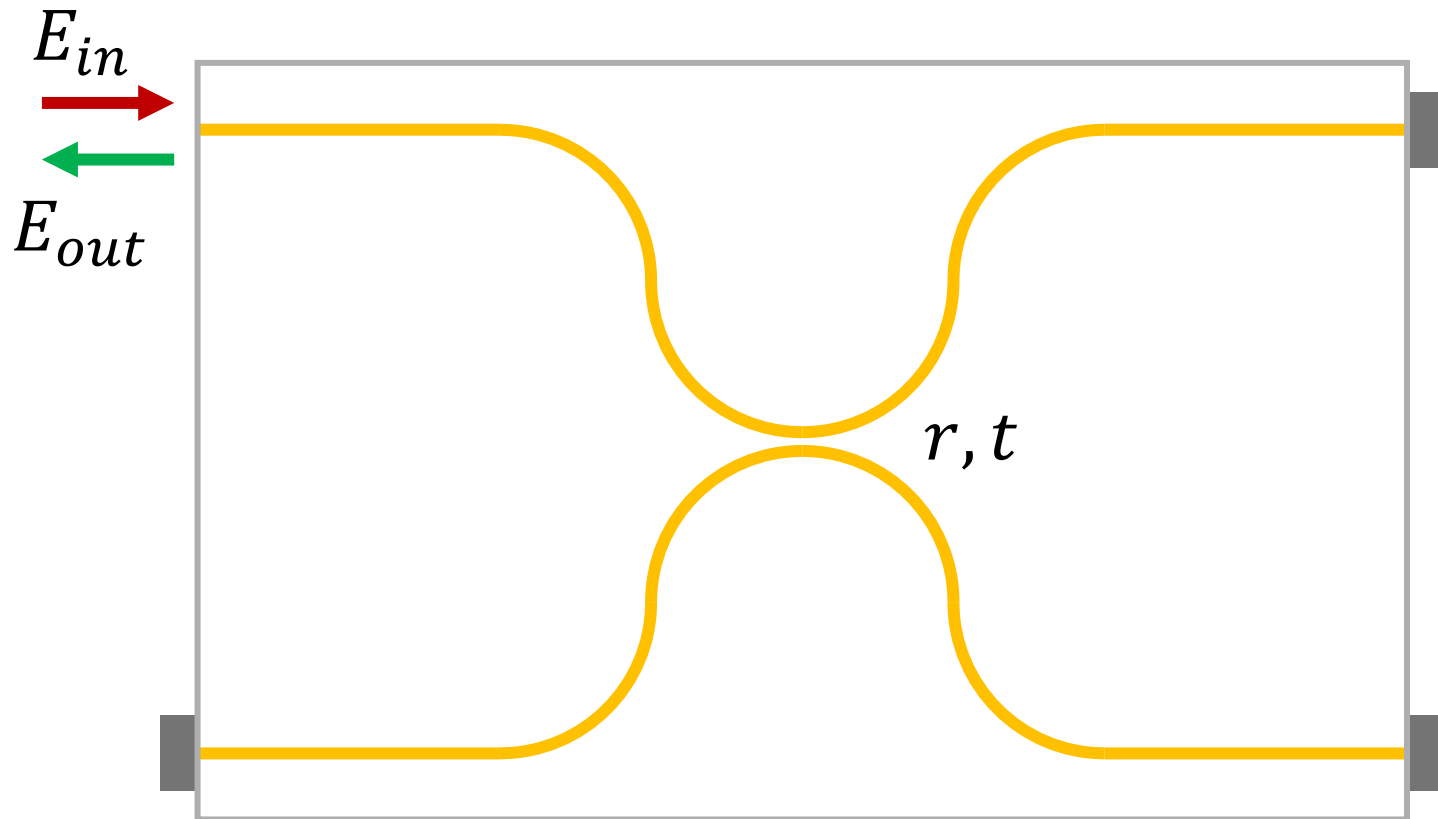
So what can we do?

Directional coupler:



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

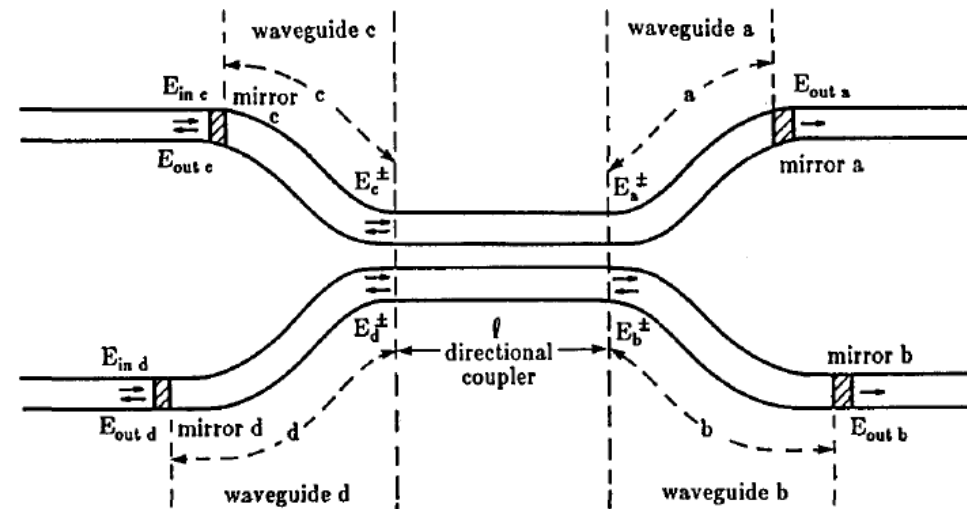


Fig. 1. Directional couplers with four reflectors.

Once upon a time..

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

Chin-Lin Chen

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

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

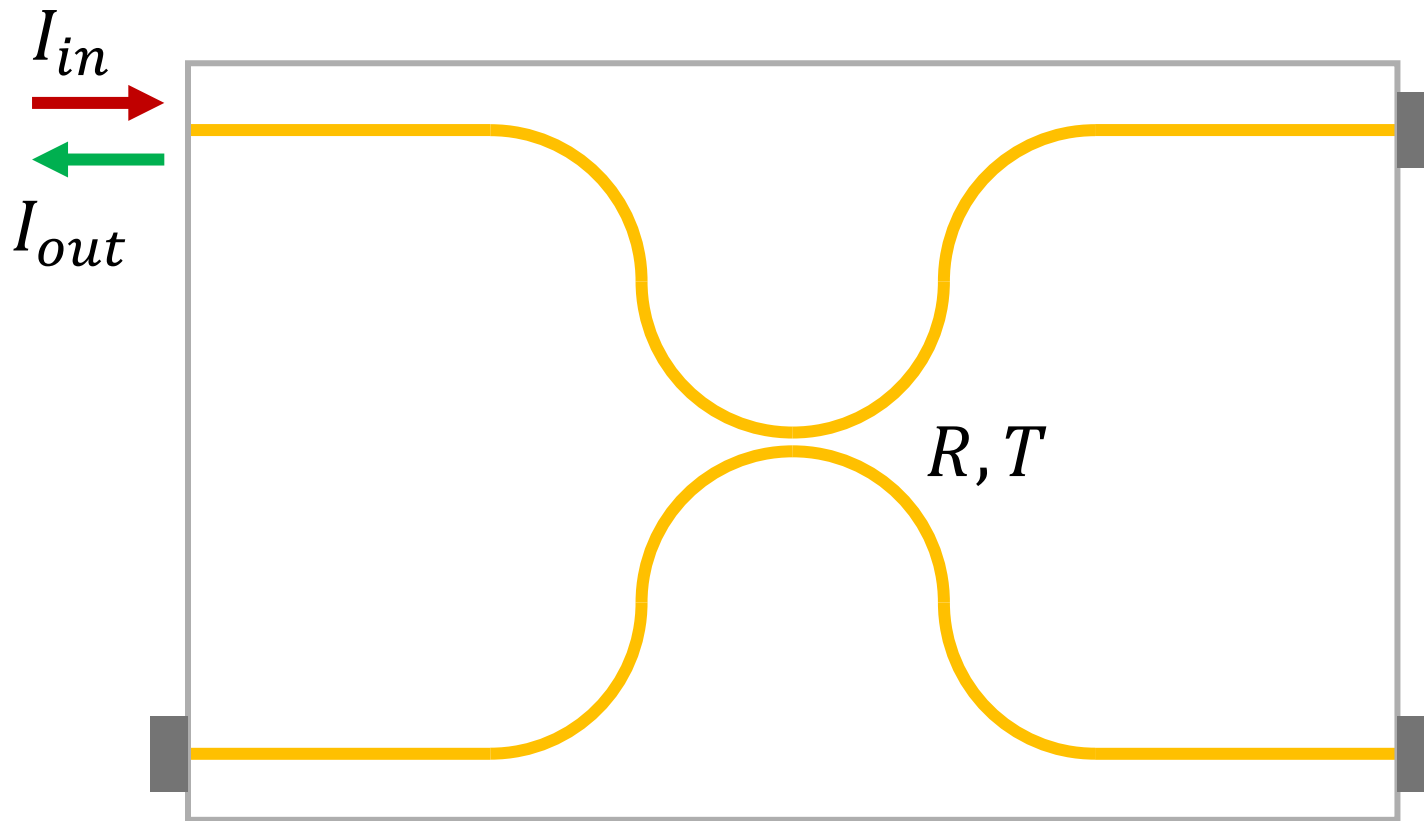
CL Chen

Applied optics, 1987 - opg.optica.org

☆ Salva ㉞ Cita Citato da 5 Articoli correlati Tutte e 8 le versioni Web of Science: 3 ㉞



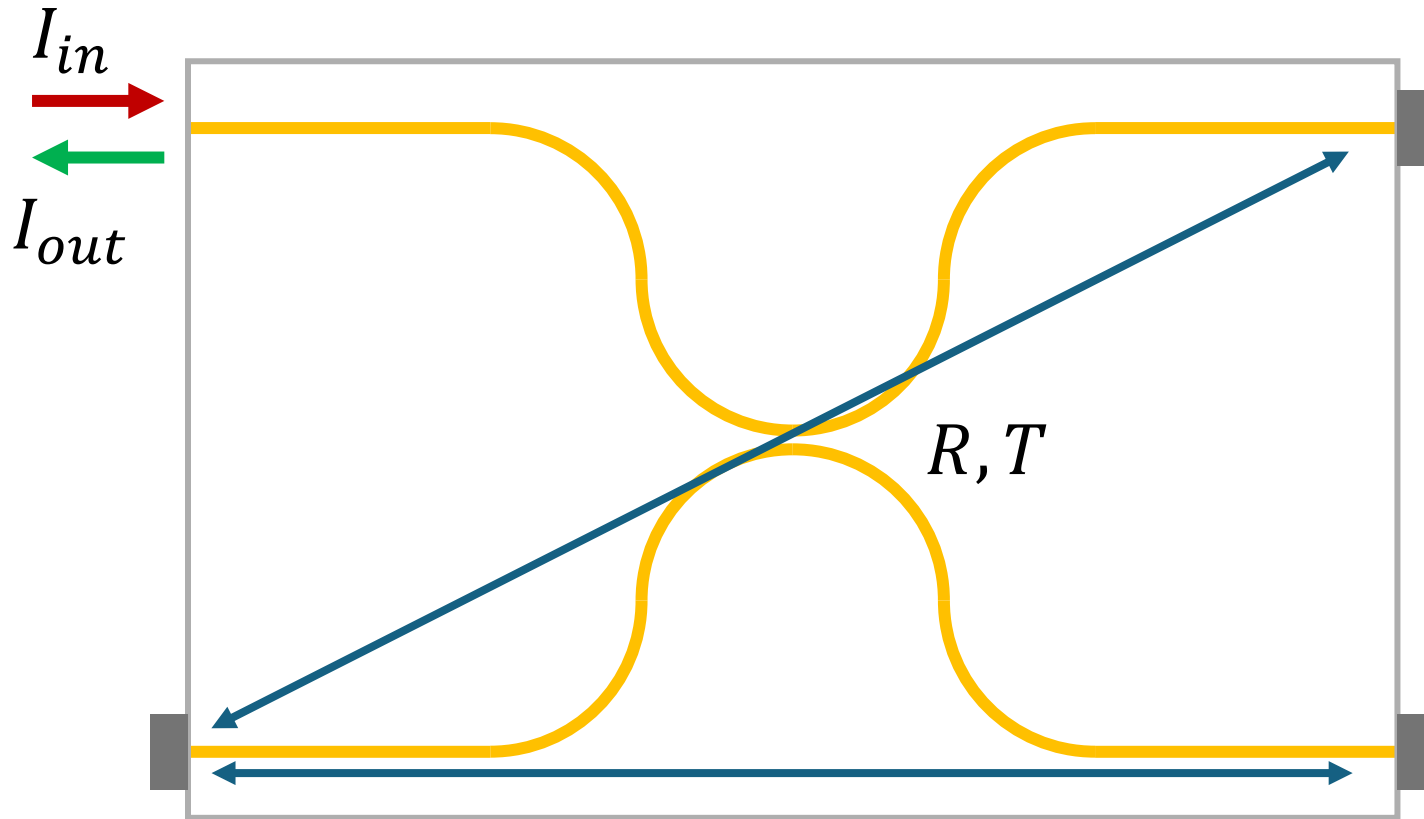
Our design



With overall losses G ,
critical coupling is
achieved when

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

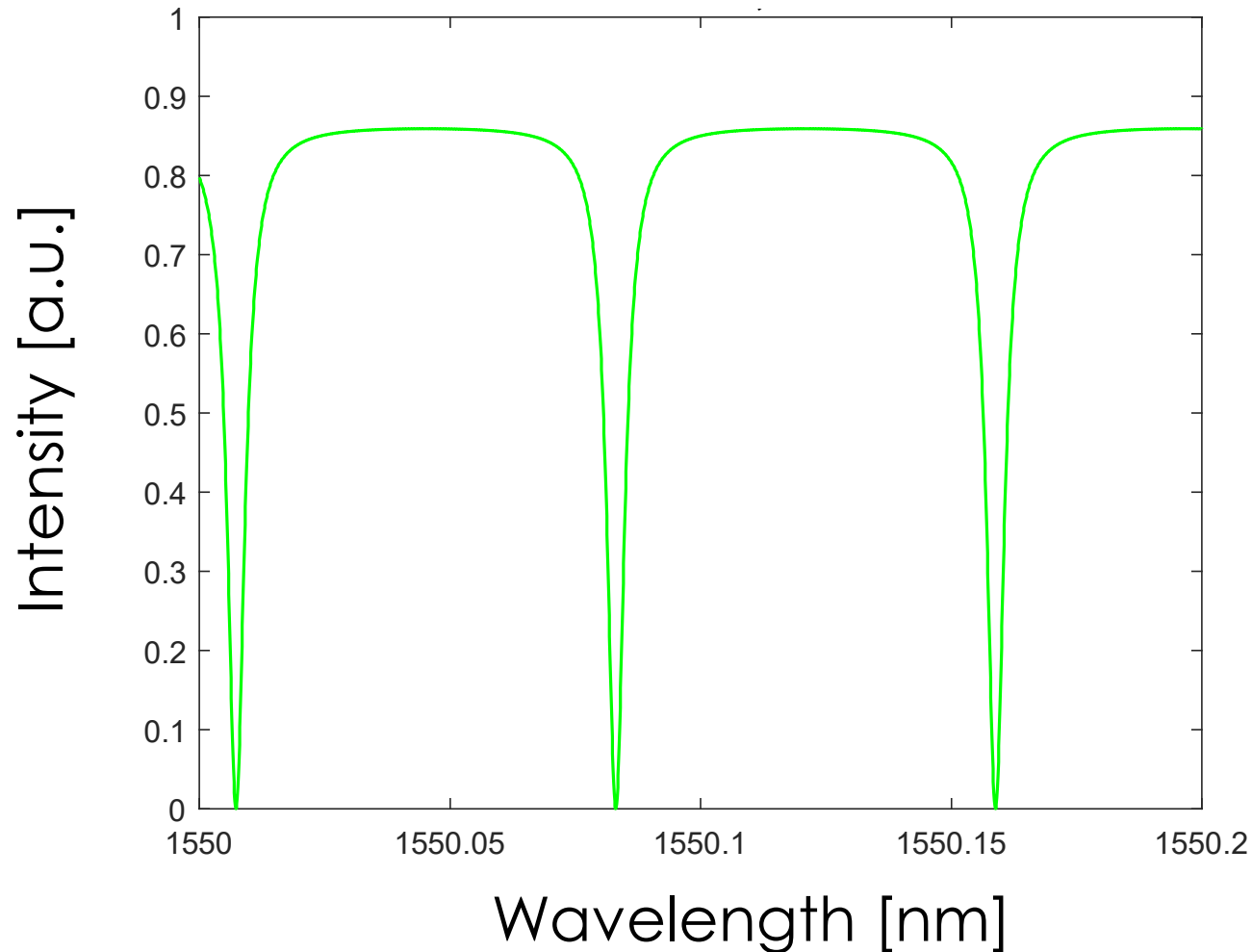
Our design



With overall losses G ,
critical coupling is
achieved when

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

Our design



With realistic parameters:

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

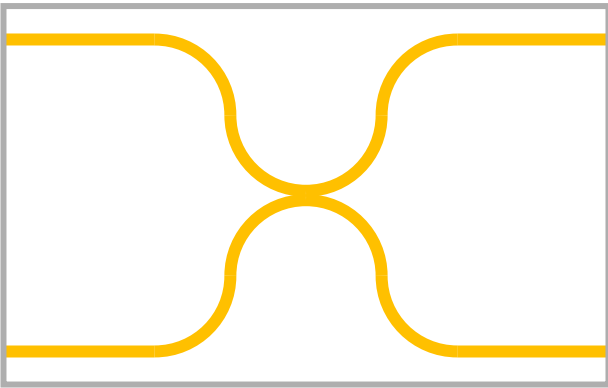
Prototyping

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

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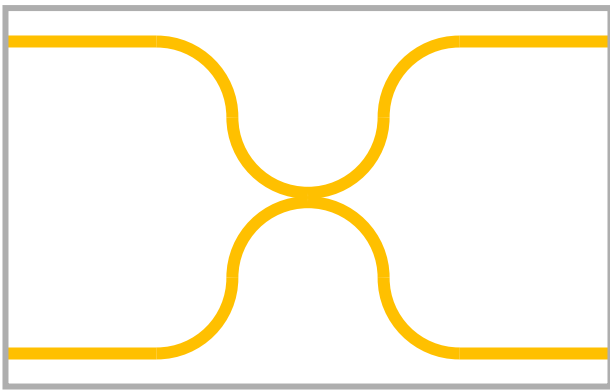
Waveguide writing



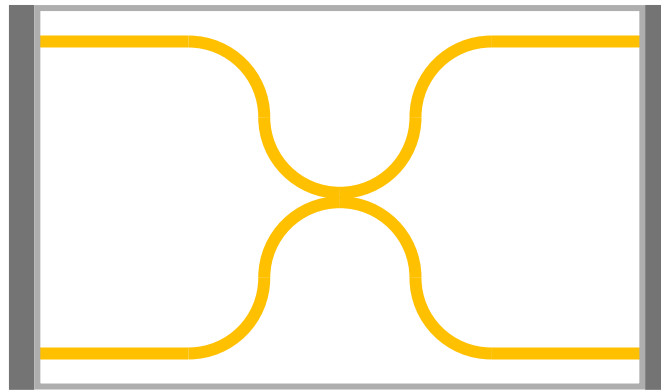
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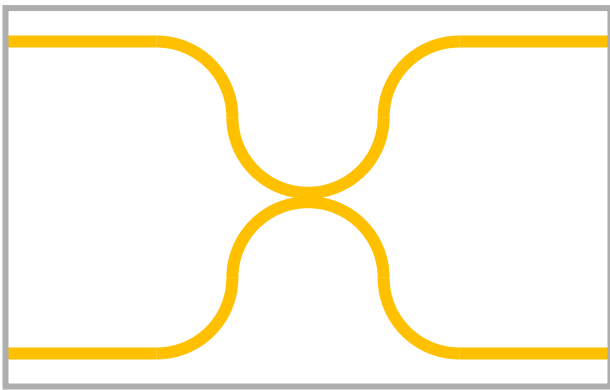
Mirror deposition



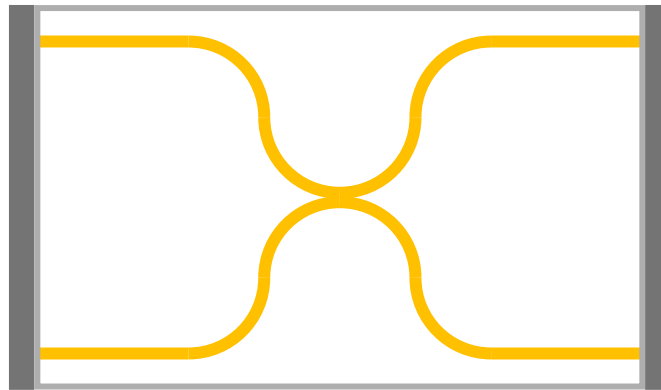
Prototyping

- First prototype in borosilicate glass
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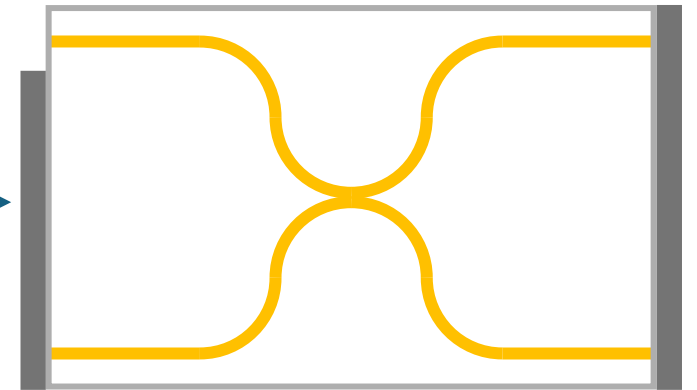
Waveguide writing



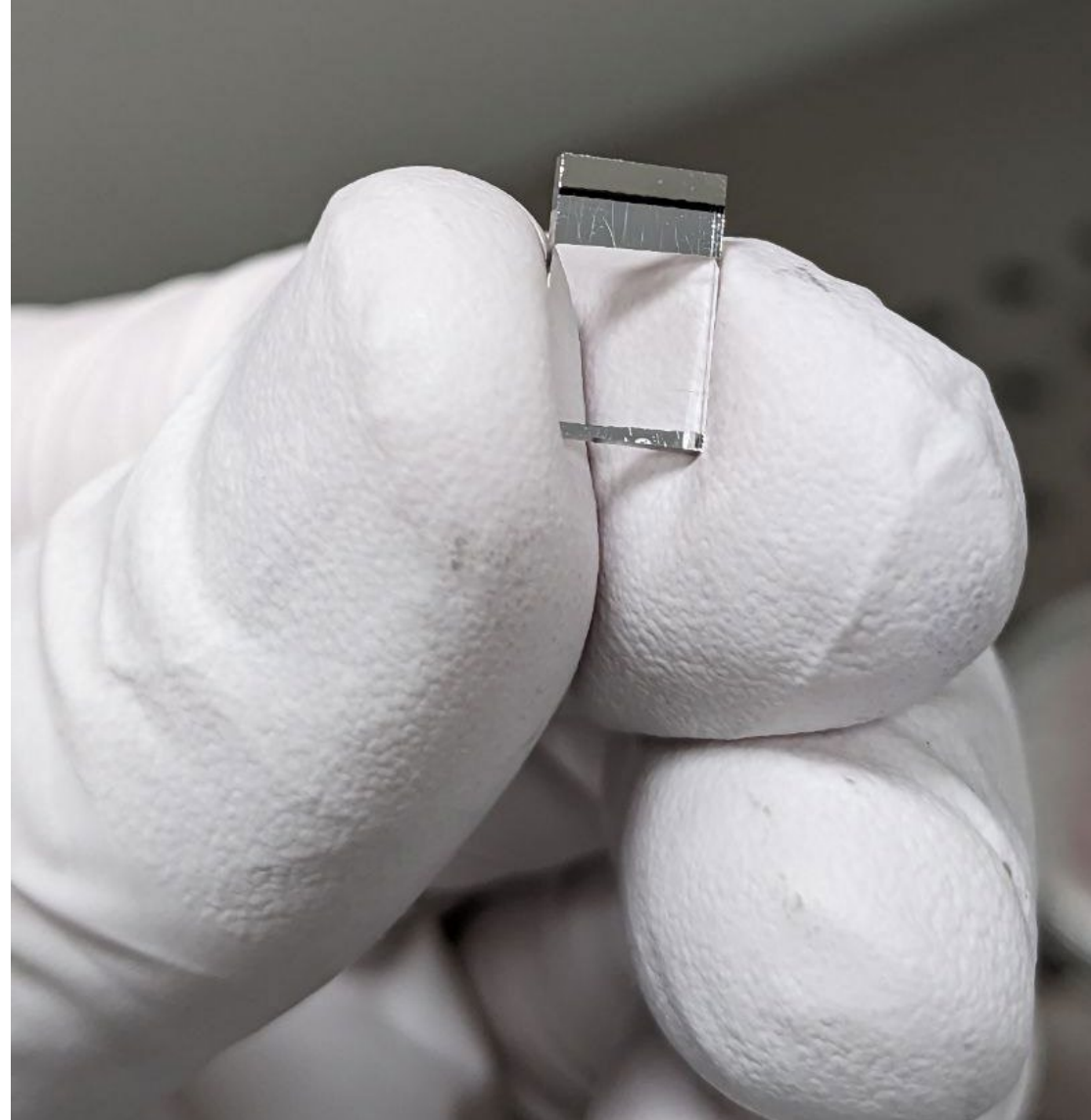
Mirror deposition



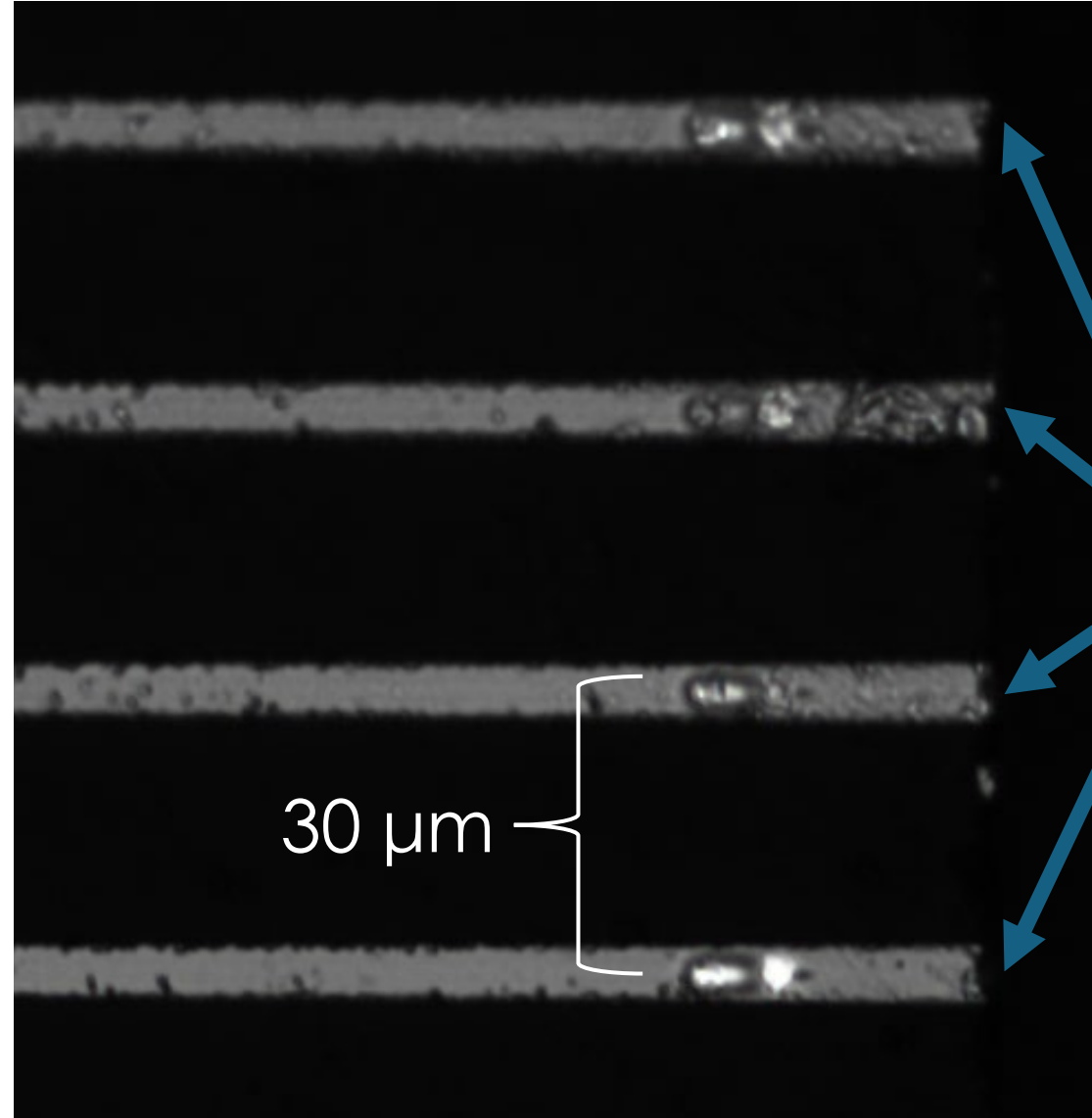
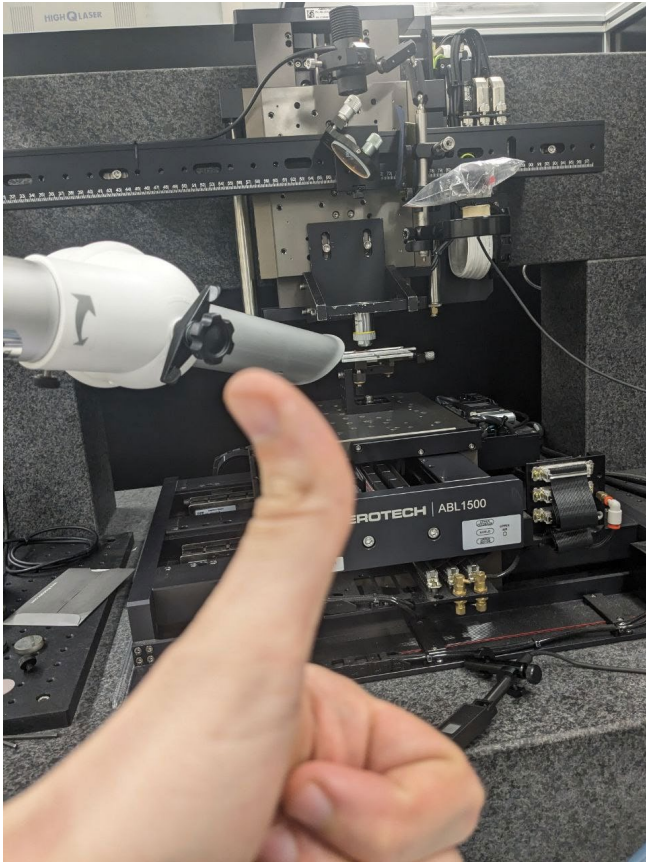
Facet patterning



Prototyping



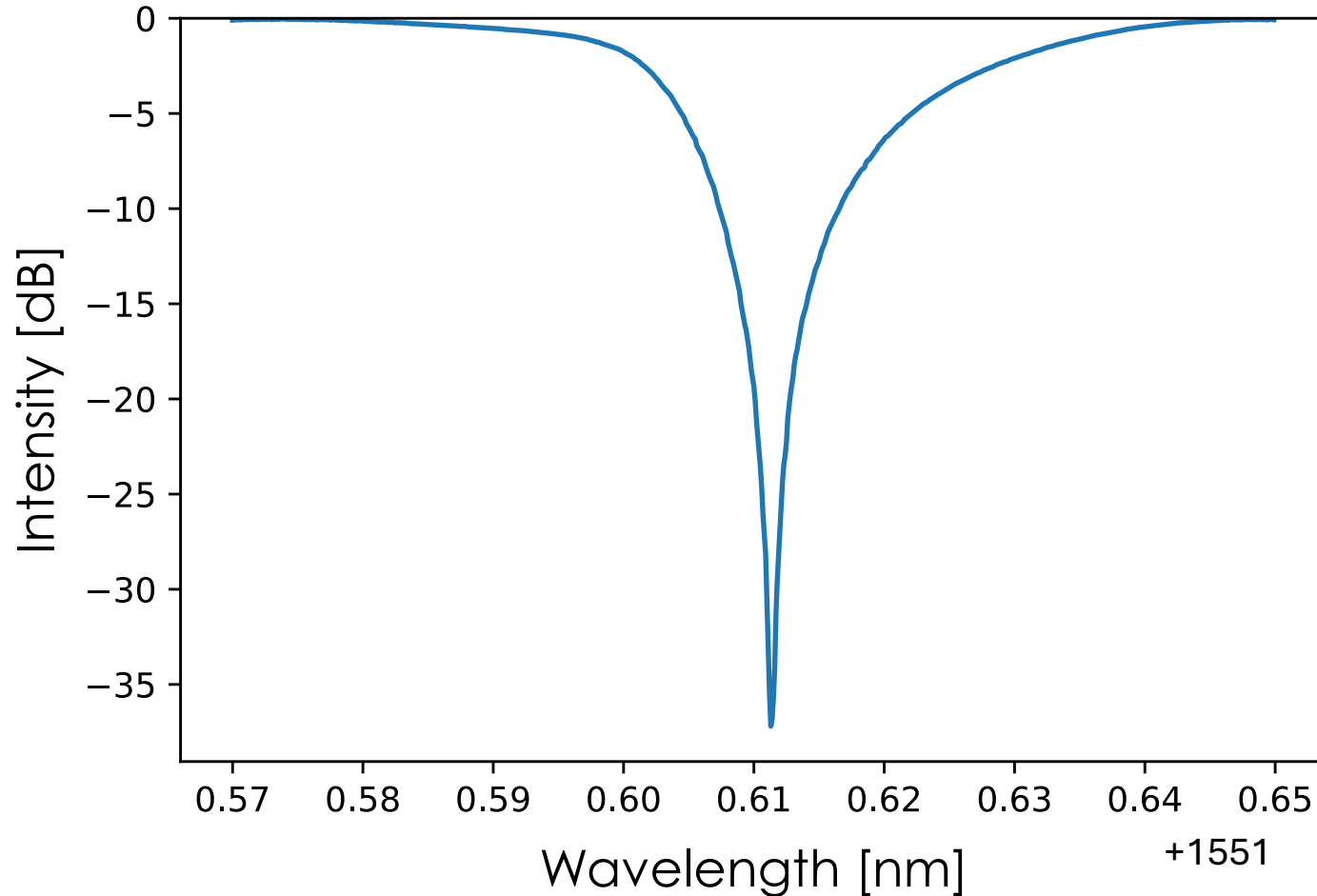
Prototyping



Residual
metal after
laser ablation

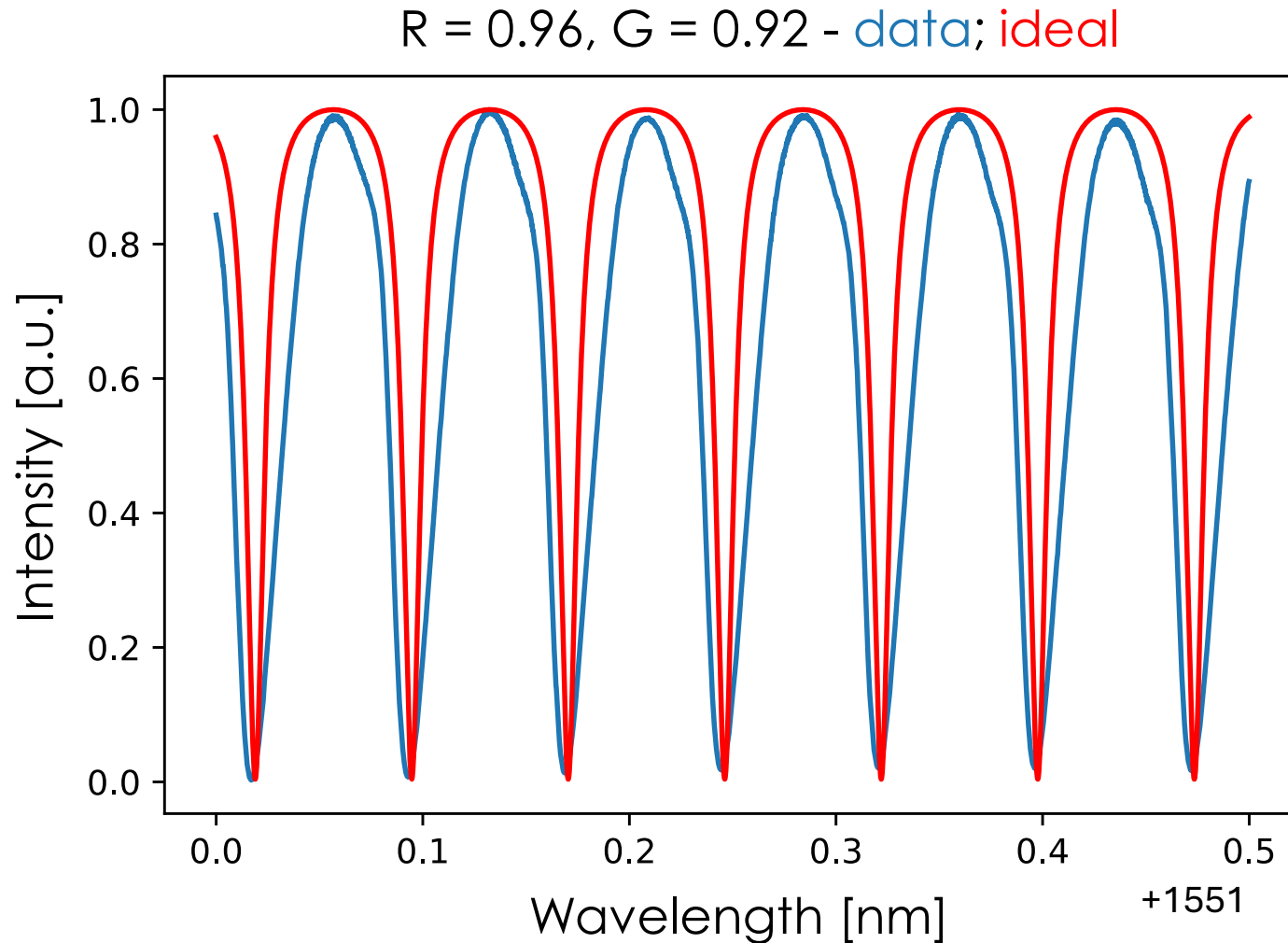
First results

$R = 0.96, G = 0.92$



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

First results



Lineshape is affected by fabrication imprecision

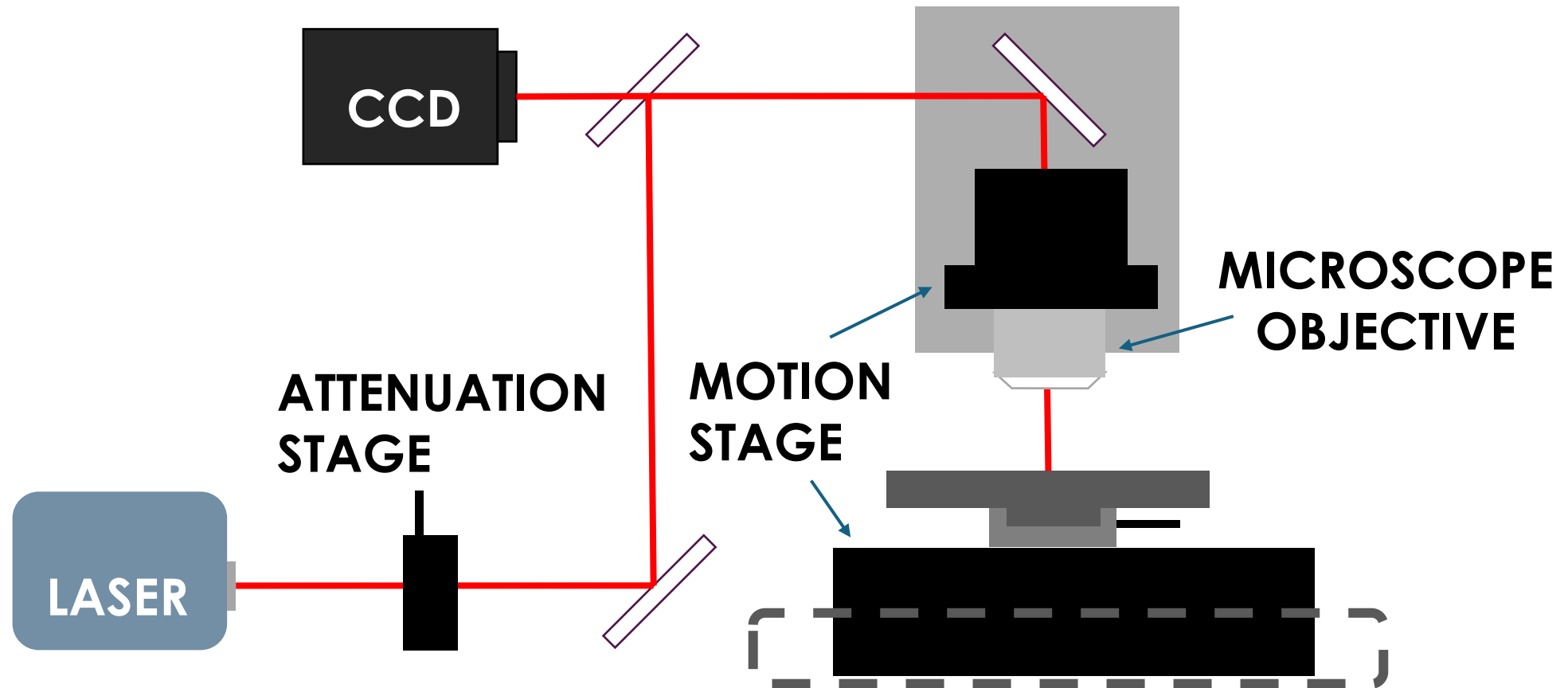
- $\Delta\nu = 3.1$ GHz
- $Q = 6.2 \cdot 10^4$ at 1551 nm

Summing up

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

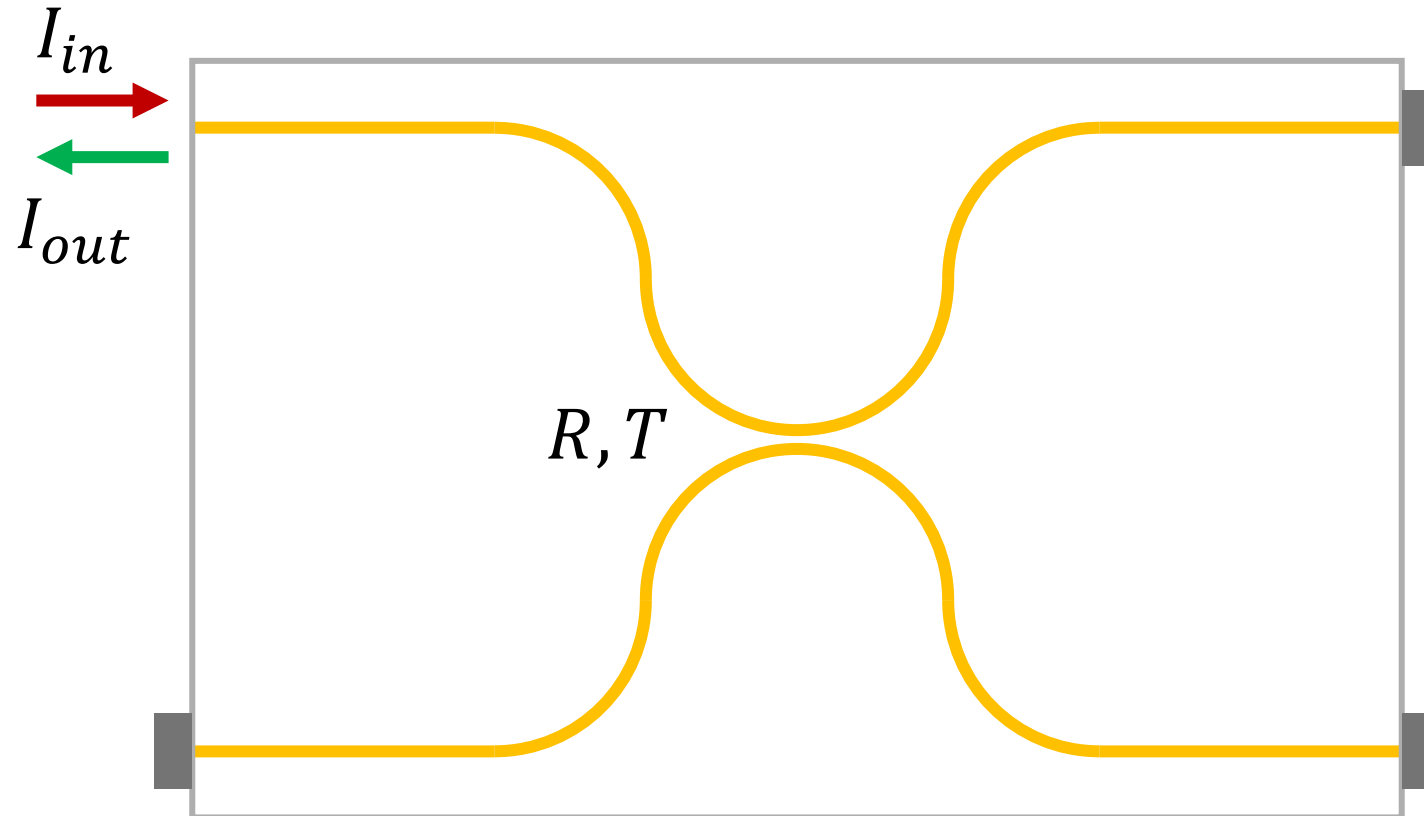
Backup Content

FLM Manufacturing Setup



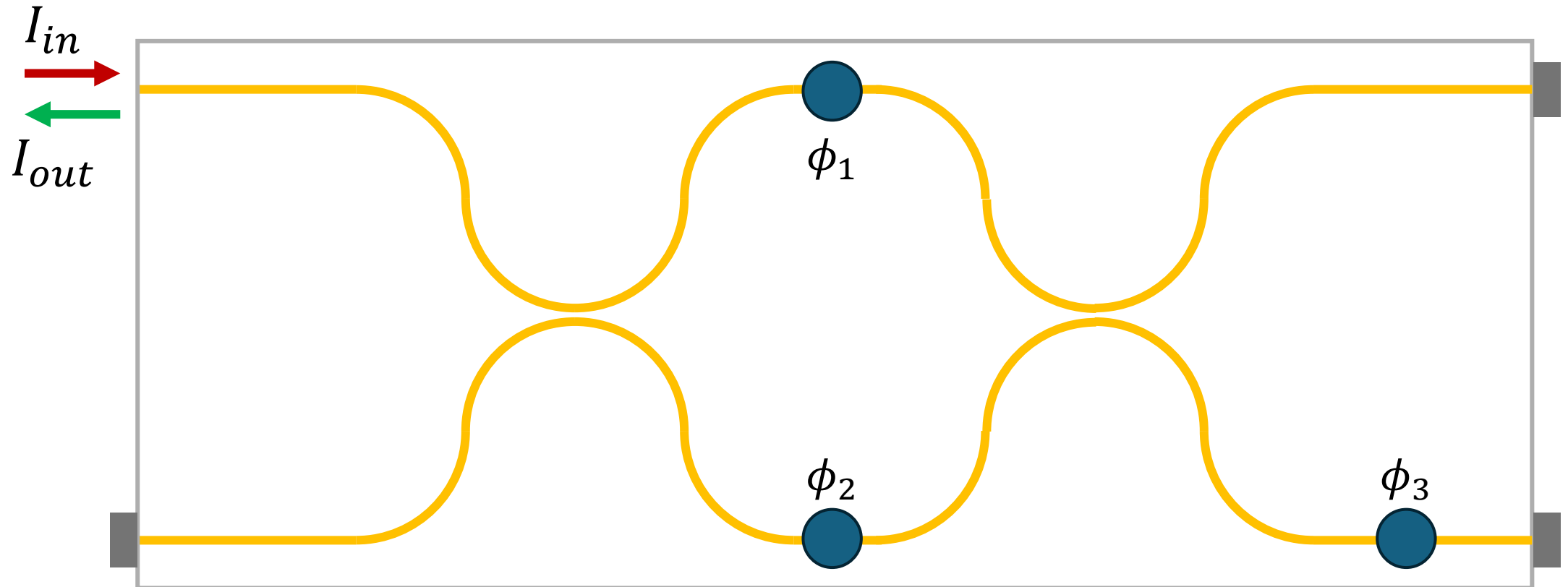
DCR transfer function

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

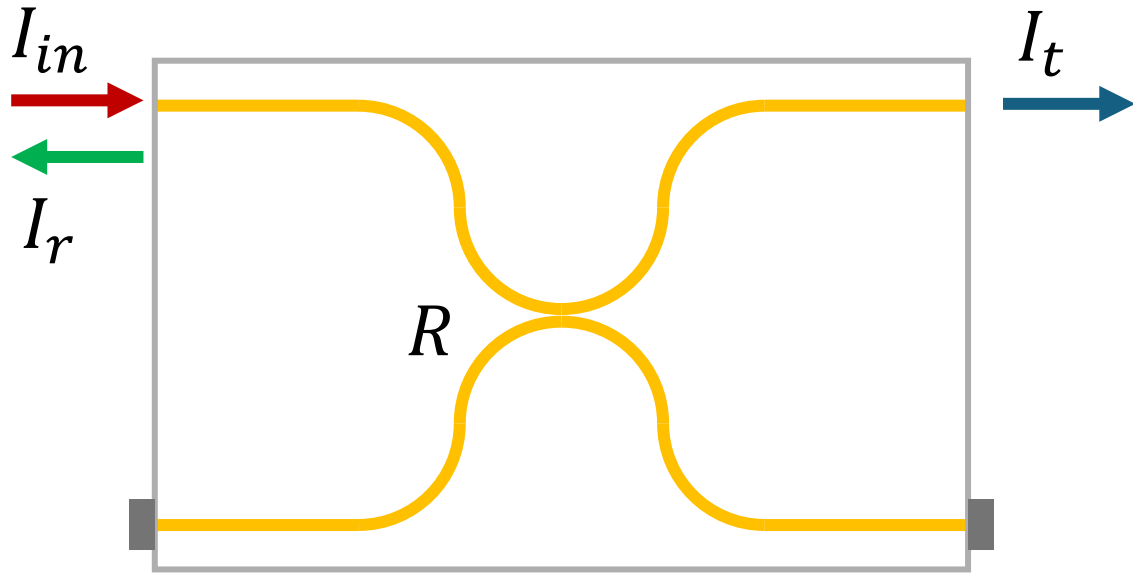


Active device

Internal and external phase control by thermal phase shifters

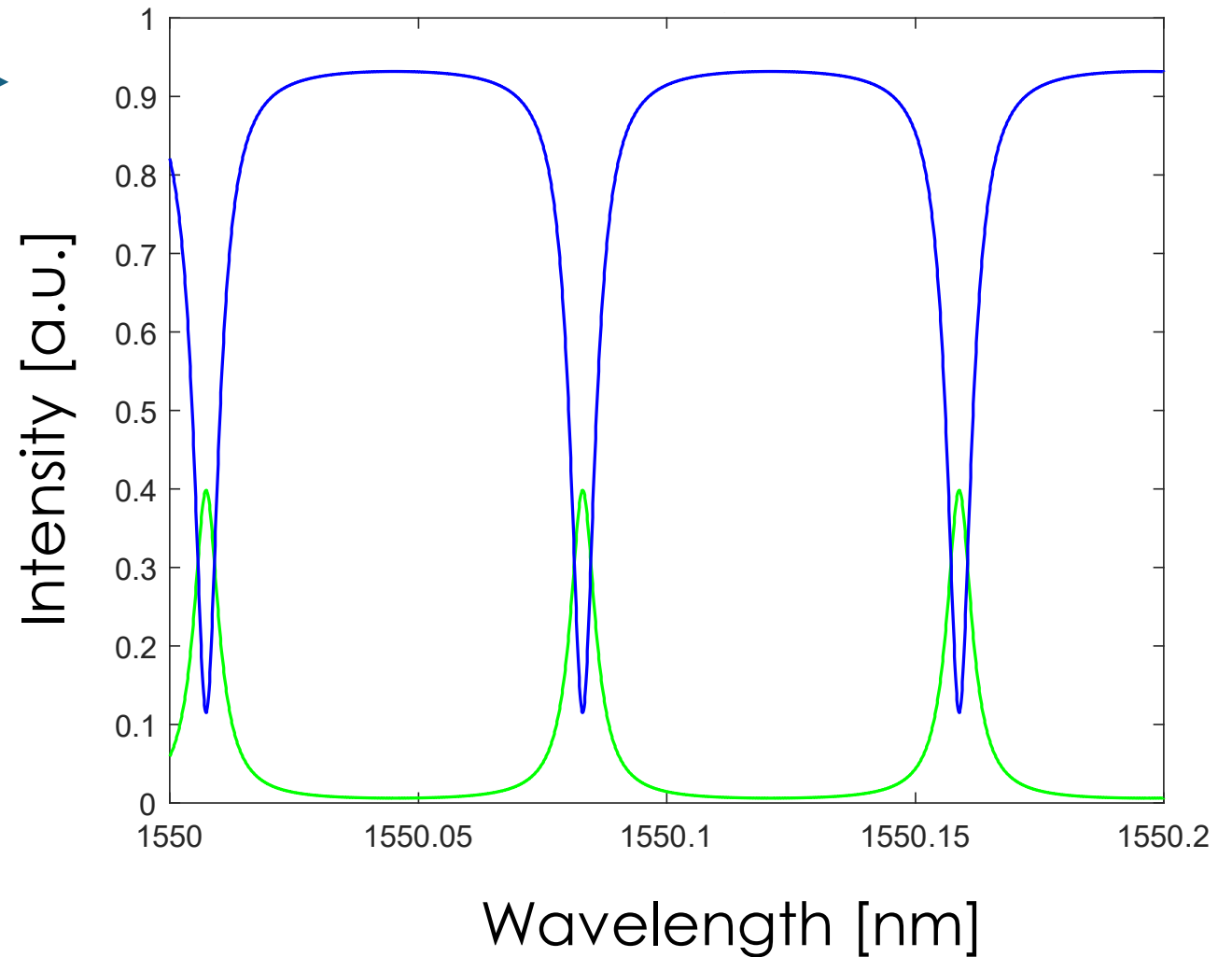


Device Variations

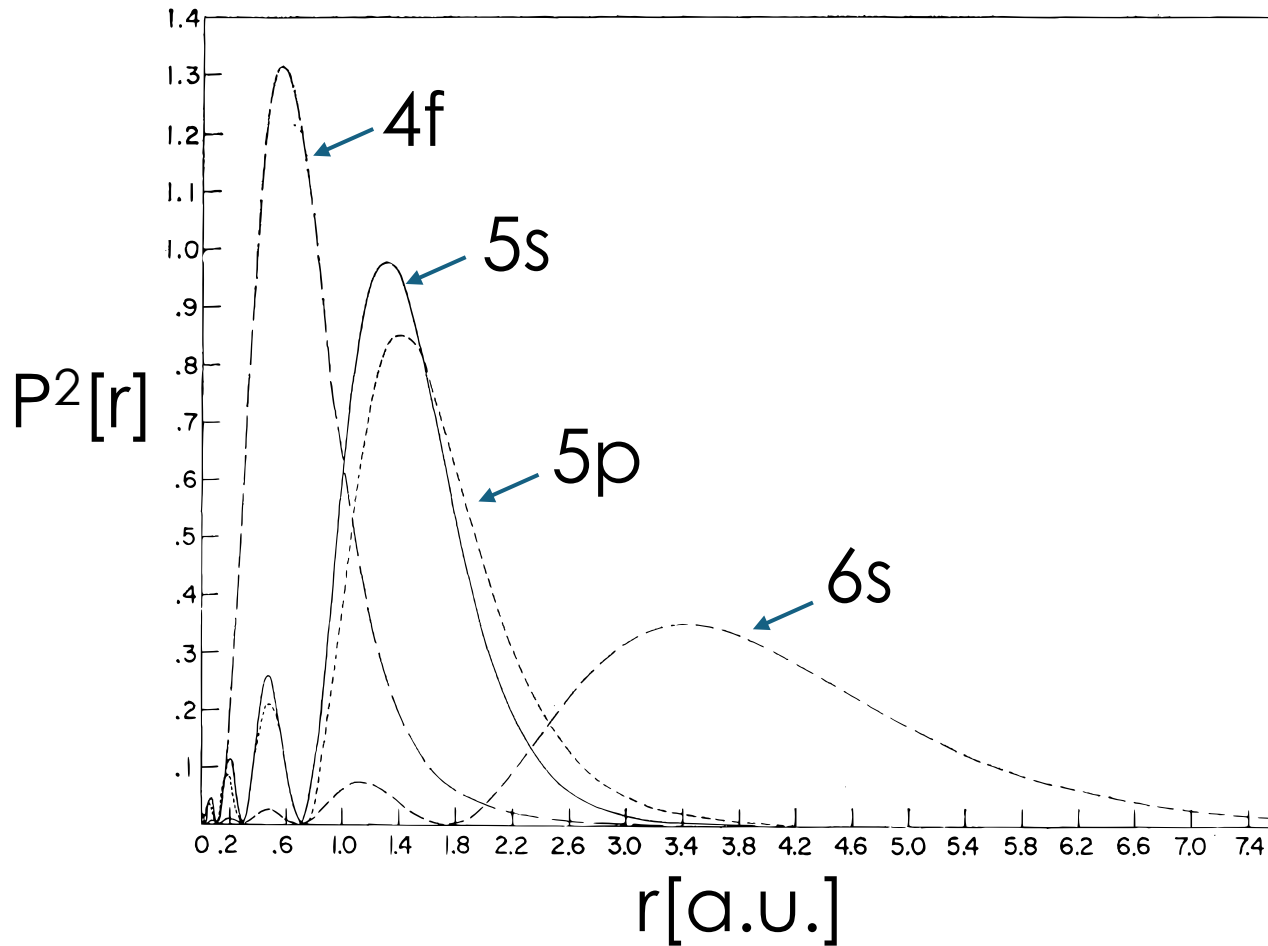


$$\frac{I_r}{I_{in}} = \frac{(1 - R_0)^2 G}{(1 - R_0 G)^2 + 4R_0 G \sin^2(\phi)}$$

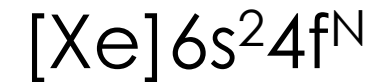
$$\frac{I_t}{I_0} = G^2 \frac{(1 - G)^2 + 4G \sin^2(\phi)}{(1 - R_0 G)^2 + 4R_0 G \sin^2(\phi)}$$



Rare Earth-Ion Doped Crystals



Electronic configuration:



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

