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# Visible lasing in femtosecond-laser-written $Pr:LiLuF_4$ waveguides

**LOW ENERGY PHYSICS**
**Ph. D. IN EXPERIMENTAL PHYSICS - XXXVII CYCLE**


- DIPARTIMENTO SCIENZE FISICHE, DELLA TERRA E DELL'AMBIENTE

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# SUMMARY

- **Introduction**
  - Diode-Pumped Solid State Lasers (DPSSL)
  - Praesodymium visible lasers in fluoride crystals
- **Femtosecond-laser-written waveguides**
- **«Comparative Performance Analysis of Femtosecond-Laser-Written Diode-Pumped Pr:LiLu$F_4$ Visible Waveguide Lasers»,** by Davide Baiocco et al.
  - Crystal growth and sample fabrication
  - Fs waveguide writing
  - Laser experiments
- **Conclusions**

# INTRODUCTION - DPSSL

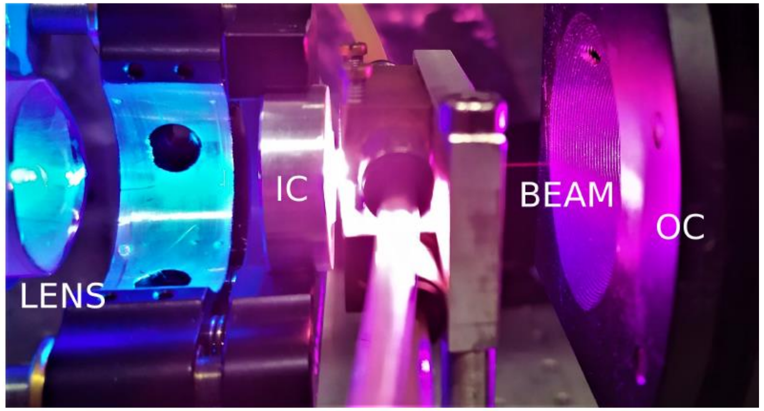
**Diode-pumped solid state lasers (DPSSLs)** are laser sources that use a solid state active medium placed within a resonant cavity, which is optically pumped with a laser diode (LD).

**Advantages:**

- Different emission wavelength
- Higher beam quality (greater collimation, and more narrow emission linewidth)

**Disadvantages:**

- Less compact (cavity is ~ 10 cm long)
- Lower wall-plug efficiency



# INTRODUCTION – RARE EARTH IONS IN FLUORIDE CRYSTALS

**Rare earth ions** (Lanthanides like Praesodymium, Thullium…) have very narrow optical emission lines even when inside a solid host, and their transitions have a very high quantum efficiency.

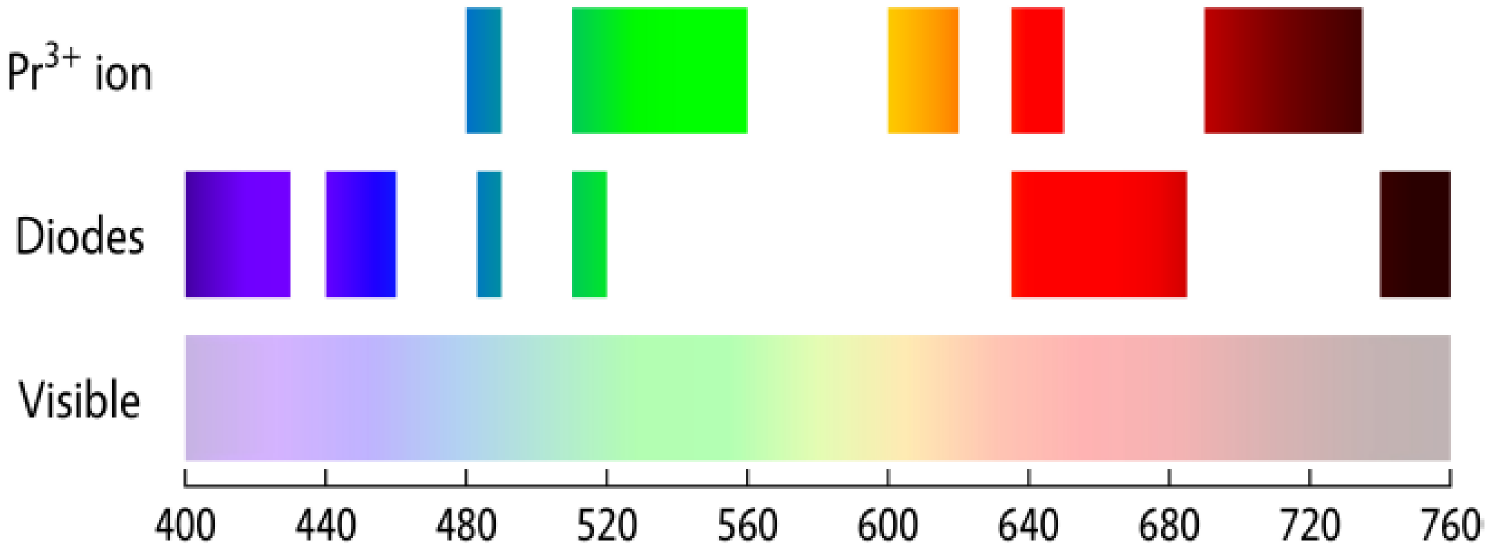
**Fluoride crystals** are ideal hosts for rare earth ions because they have:

- very low phonon energy
- very high energy gap
- large interstitial sites

**Left:** boules of fluoride monocrystals doped with rare earth elements (from www.megamaterials.it)

# INTRODUCTION – $Pr^{3+}$ VISIBLE LASERS IN FLUORIDE CRYSTALS

**$Pr^{3+}$** is promising because it can emit at several wavelengths within the visible spectrum, some of which are not obtainable with LDs. It also shows high absorption in the blue range (444 nm).

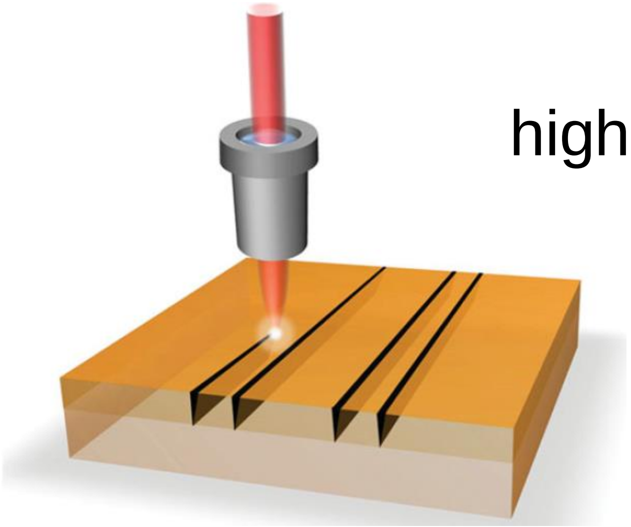



Comparison of the emission wavelengths of Pr and laser diodes. Taken from: A. Sottile, "Visible Solid-State Lasers in Praseodymium-Doped Fluoride Crystals," Ph.D. dissertation, University of Pisa, 2016.

# FEMTOSECOND-LASER-WRITTEN WAVEGUIDES

**Waveguides** can be created inside dielectric materials to increase the overlap between the pump and laser beams, leading to increased efficiencies and lower laser thresholds.

**Femtosecond (fs) laser writing:**



high-energy pulses absorbed through non-linear processes

↓

avalanche ionization in a very short time

↓

localized, stable modifications of refractive index

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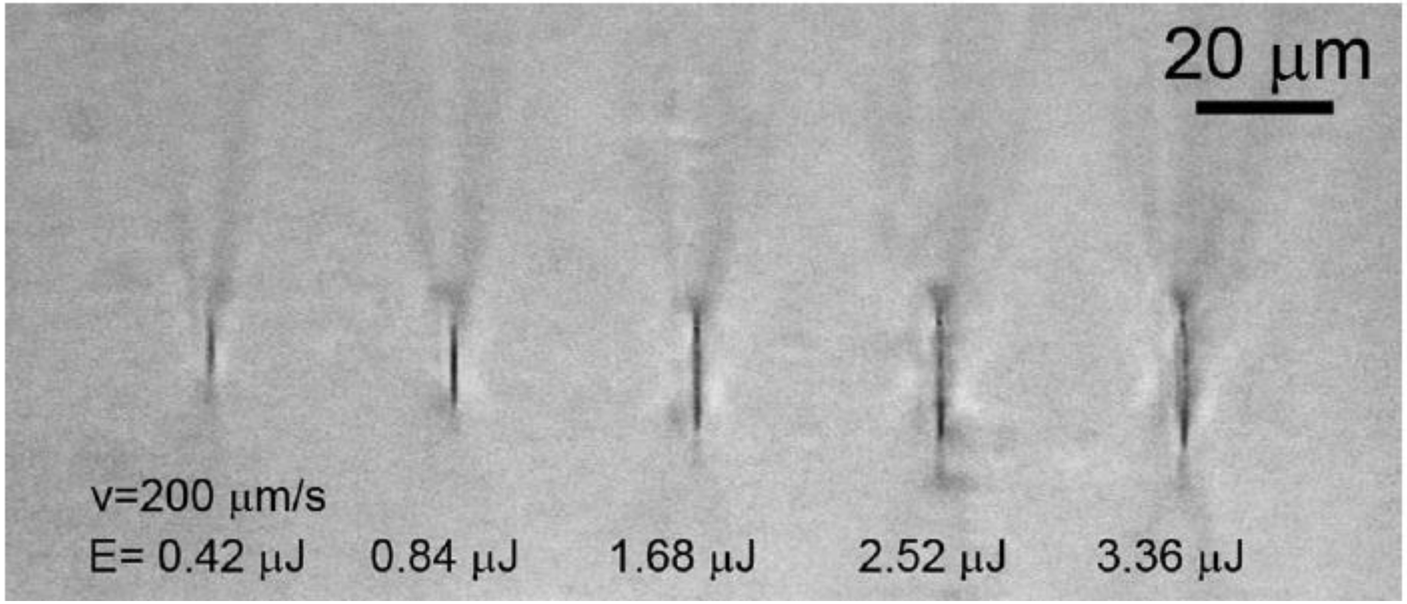
# FEMTOSECOND-LASER-WRITTEN WAVEGUIDES (2)

**Method:** fs laser beam is focused with a microscope objective inside the target, which is then moved to obtain the desired pattern.

- **Pulse energy and duration:** size, morphology and type of the modification
- **Numerical aperture of the objective (0,3-0,8):** larger values reduce the length of the damage tracks
- **Scanning velocity:** determines whether multiple pulses hit the same spot
- **Repetition rate:** nonthermal vs thermal regime

# FEMTOSECOND-LASER-WRITTEN WAVEGUIDES (3)



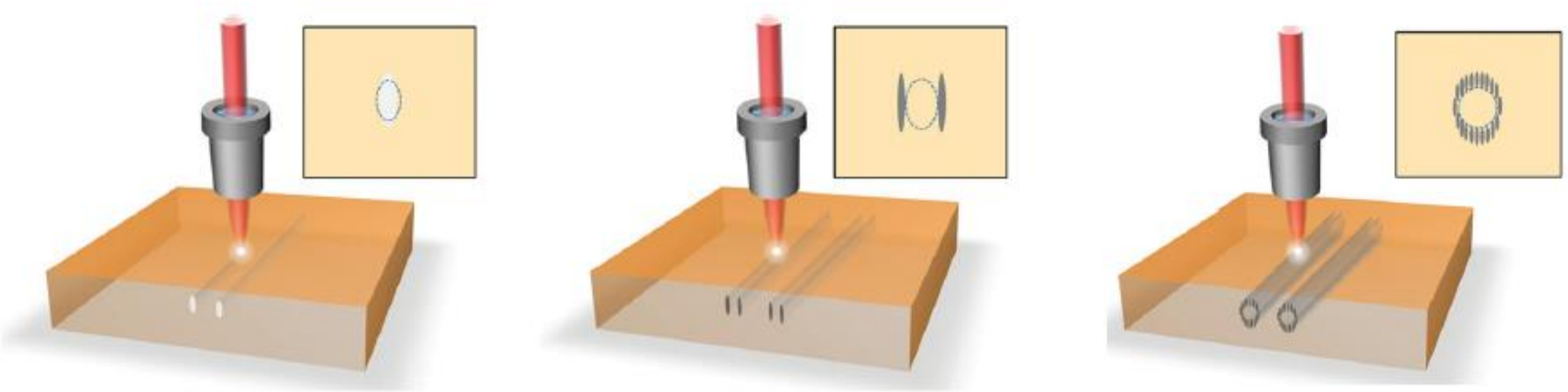

Here we can see how, by changing the energy of pulses while keeping the pulse duration fixed at 120 fs, the damage tracks get longer. Taken from ref. 2

# FEMTOSECOND-LASER-WRITTEN WAVEGUIDES (4)

**Type I :
Single track**

**Type II :
Stress induced**

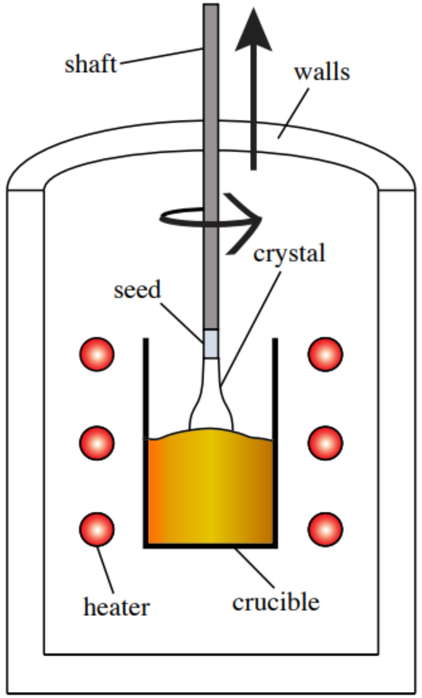
**Type III :
Depressed cladding**



Three main types of waveguides with schemes of their geometry. Taken from ref 2

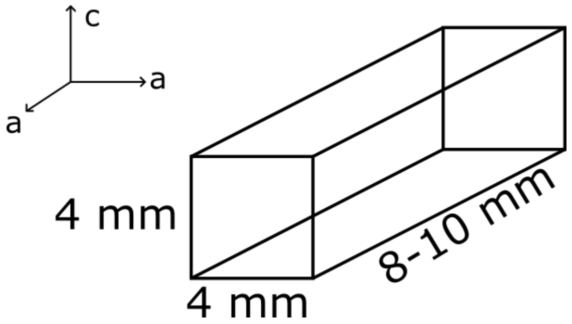
# 0,2% Pr:LLF SAMPLE PREPARATION

## Crystal growth by Czochralski technique

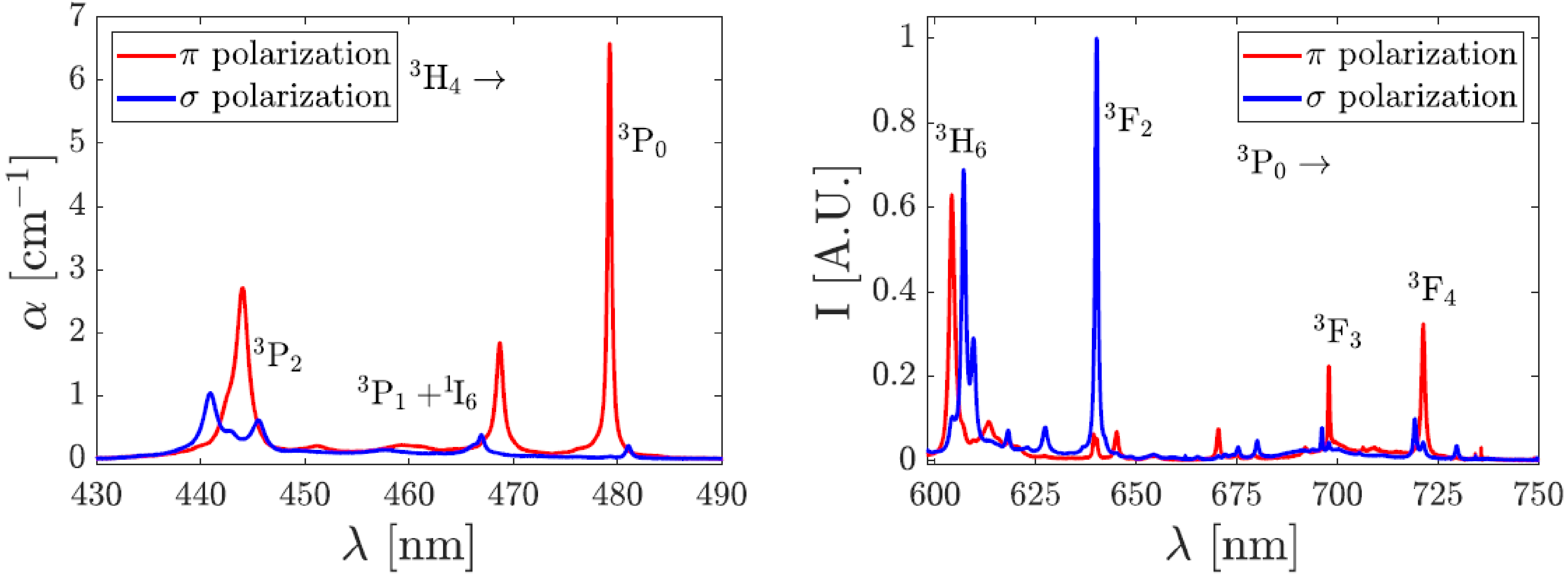



## Crystal boule

## Final sample



# OPTICAL PROPERTIES OF Pr:LLF

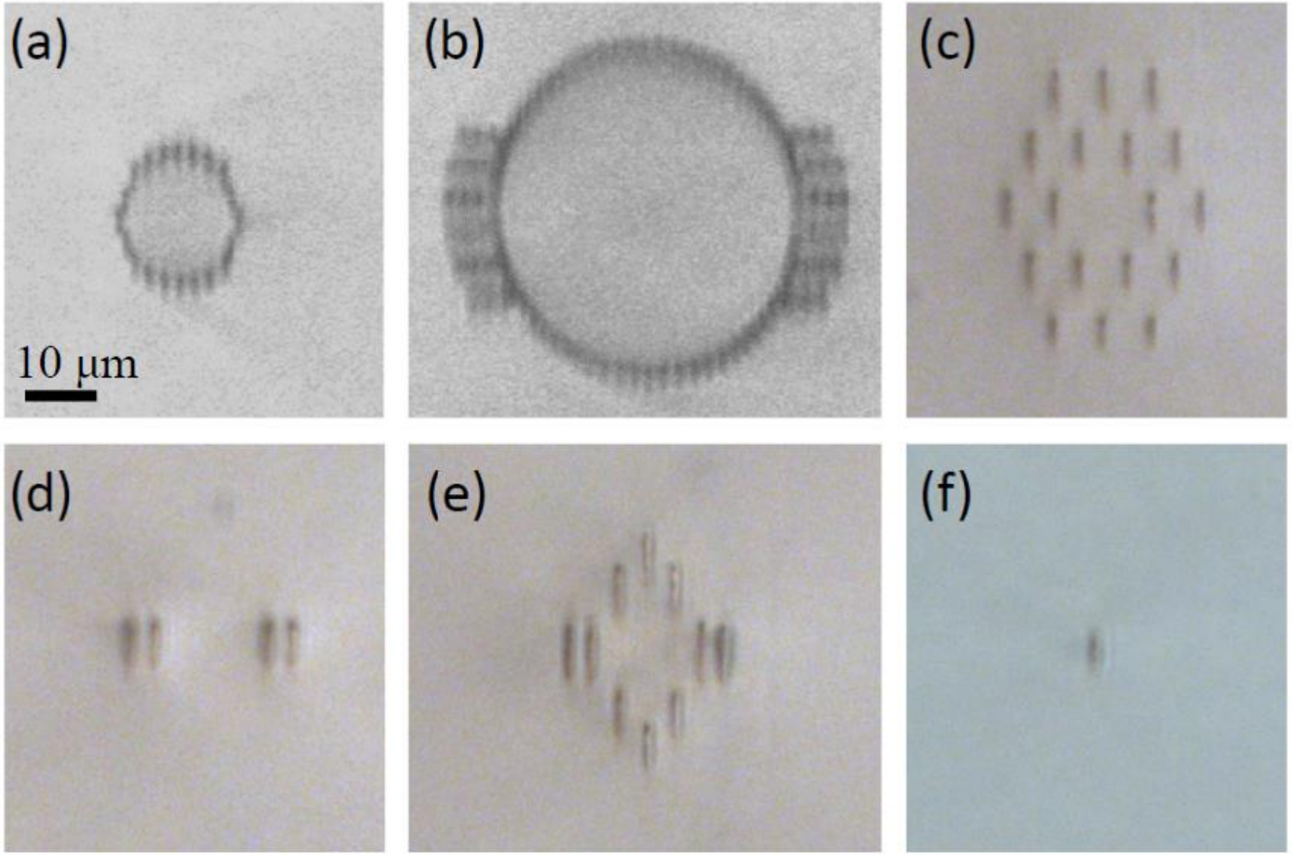



Absorption (left) and emission spectra (right) for the 0,2% Pr:LLF samples. Since LLF is uniaxial, we have different spectra depending on the light polarization.

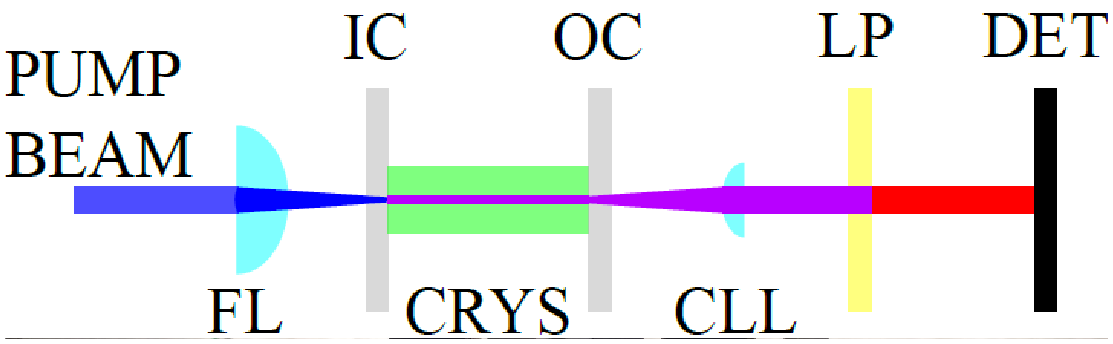
# WAVEGUIDE GEOMETRY

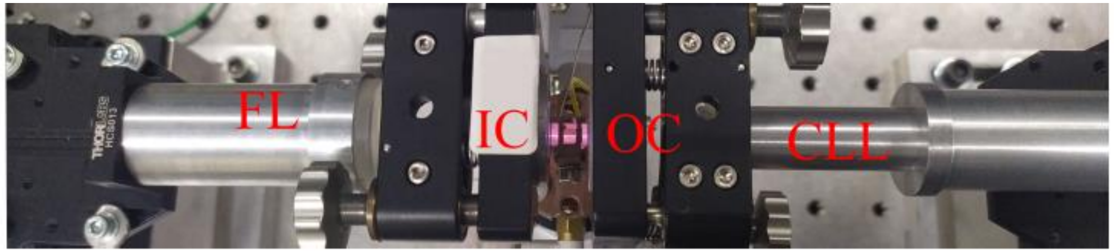
Images of the various types of waveguides fabricated in Pr:LLF crystal samples:

a) Circular cladding (CC)
b) Circular cladding «with ears» (CC-E)
c) Hexagonal cladding (HC)
d) Stress-induced double-line (DL)
e) Stress-induced double line with rhombic cladding (DL-RC)
f) Single line (SL)



# Pr:LLF LASER CAVITY




**Above:** scheme and picture of the laser cavity

**Right:** table with the characteristics of the 4 different output coupler mirrors used during the laser experiments

Scheme of the laser cavity:

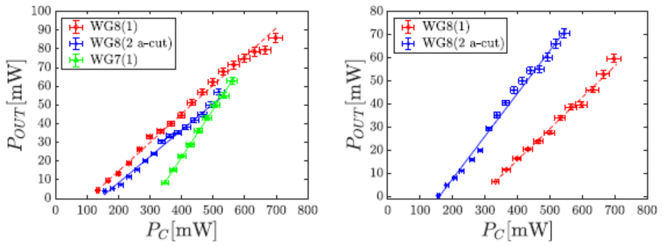
- **FL:** focusing lens (f=30 mm);
- **IC:** input coupler mirror
    - high transmittance (>98%) at 444 nm;
    - high reflectance (T<0,1%) at 604 nm;
    - high reflectance (T<10-5) for 630 nm<λ<740 nm;
- **OC:** output coupler mirror (see below);
- **CLL:** collection lens (f=20 mm);
- **LP:** long-pass dielectric filter at 510 nm

| Mirror | R [mm] | Transmittance [%] at λ [nm] | | | |
|---|---|---|---|---|---|
| | | 604 | 645 | 698 | 721 |
| 1 | plane | 77 | 0.8 | 0.03 | 0.05 |
| 2 | plane | 16 | 96 | 58 | 71 |
| 3 | plane | 96 | 74 | 69 | 46 |
| 4 | 50 | 75 | 7 | 0.9 | 0.8 |

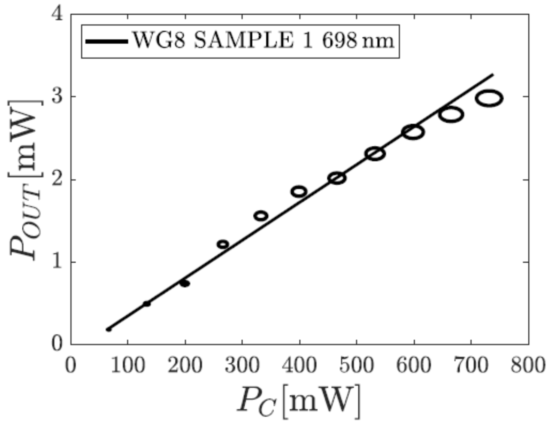
# Pr:LLF LASER EXPERIMENTS

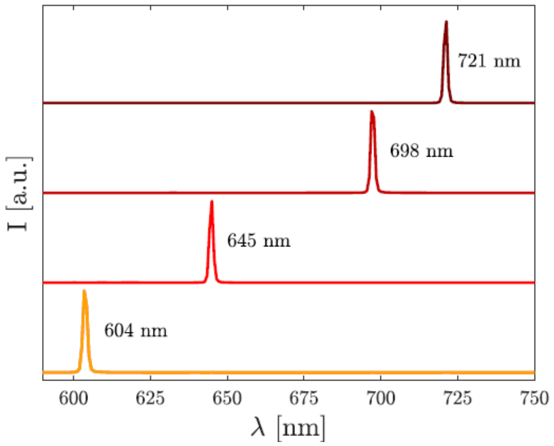
- **604 nm:** $P_{max}$ = 86 mW (mirror 2)
- **721 nm:** $P_{max}$ = 70 mW (mirror 3)
- **645 nm:** $P_{max}$ = 1 mW (mirror 4) at maximum pump power, reduction in power lead to lasing at 604;
- **698 nm:** $P_{max}$ = 3 mW (mirror 1)

| $\lambda$ [nm] | WG | $T_{OC}$ [%] | $\eta_c$ [%] | $P_{THR}$ [mW] | $P_{MAX}$ [mW] |
|---|---|---|---|---|---|
| 604 | WG8(1) | 16 | 16 | 100 | 86 |
| | WG8 (2 a-cut) | 16 | 14 | 140 | 56 |
| | WG7(1) | 77 | 26 | 310 | 63 |
| 721 | WG8(1) | 46 | 14 | 280 | 60 |
| | WG8 (2 a-cut) | 46 | 18 | 150 | 70 |



(a) 604 nm (b) 721 nm



# CONCLUSIONS

- **Fs-laser-written waveguides** with different geometries and parameters were tested inside 0,2% Pr:LLF crystal samples.
- **Laser emission** was obtained at **604, 721, 645, and 698 nm**. In the first two cases, new record output powers were obtained, while for the latter laser operation was reported for the first time.
- **Application:** waveguide lasers can be used to miniaturize DPSSLs, by applying a mirror coating directly on the facets of the crystals. Lasers at 698 nm can be used for Strontium atomic clocks, while lasers at 645 nm can be used for ammonia gas detection.

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# Thank you very much for your attention!

# REFERENCES


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