Multi-color visible laser using Pr doped fluoride glass excited by GaN laser diode

Yasushi Fujimoto
Institute of Laser Engineering, Osaka University

Masaaki Yamazaki
Sumita Optical Glass, Inc., Glass Research Division, R&D Depertment

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Outline

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- Back ground
  - Motivation
  - Pr visible laser and excitation source
  - fluoride glasses
- Pr doped fluoride glass (Pr:PAYAC)
  - Spectroscopic properties of Pr^{3+} doped fluoride glass
  - Stimulated emission cross section by Judd-Ofelt analysis
  - Laser oscillation
- Applications
- Conclusions

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Motivation

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Applications on visible lasers

1) Display technique
2) Medical equipments
3) Spectroscopy, and microscopy
4) Welding and cutting with several tens to hundreds watt

Research on Pr^{3+} lasers

1) Smart et al.[1] reported laser oscillation of Pr:ZBLAN fiber
2) Richter et al.[2] reported Pr doped fluoride crystal lasers excited by GaN semiconductor lasers.
3) High power laser diode (GaN:442 nm) is provided by Nichia Corporation (up to 1 W).

Progress in fluoride glass

1) Water-resistant fluoride glass was fabricated by AlF_3 glass system.
2) An optical fiber was drawn by AlF_3 glass system.

It is very curious that a visible laser emission is generated without nonlinear crystal.Then we tested the possibility of Pr-doped fiber laser.

[1] R. G. Smartet al., "Cw Room-Temperature Operation of Praseodymium-Doped Fluorozirconate Glass-Fiber Lasers in the Blue-Green, Green and Red Spectral Regions," Optics Communications 86(3-4), 333-340 (1991).

[2] A. Richter et al., “Power scaling of GaN laser diode pumped Pr-lasers”, in *Advanced Solid-State Photonics on CD-ROM* (The Optical Society of America, Washington, DC, 2008), MB2

Pr^{3+} Laser

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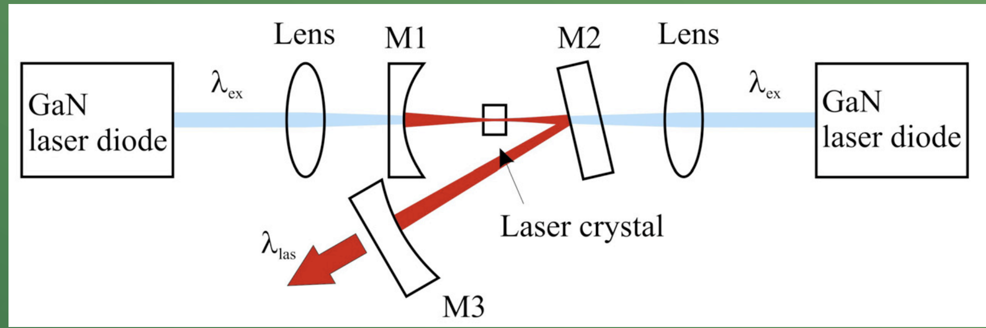
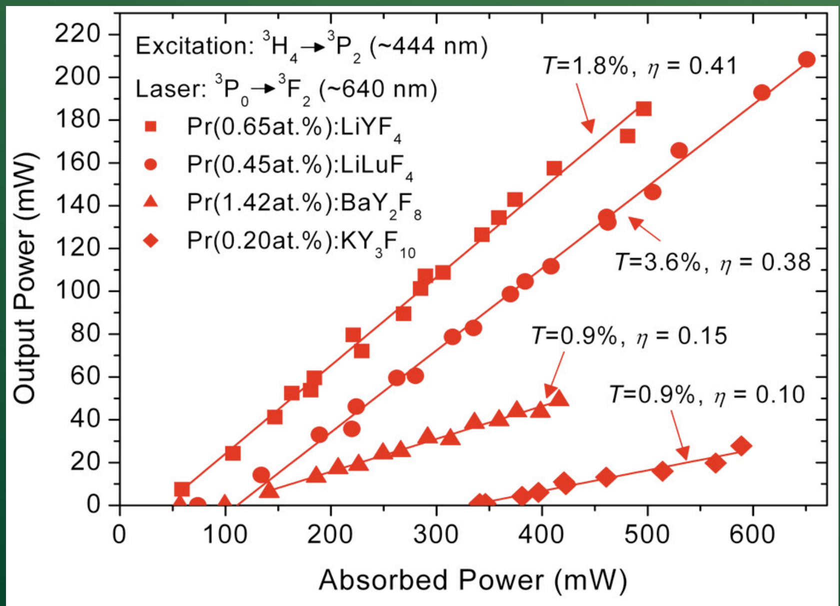
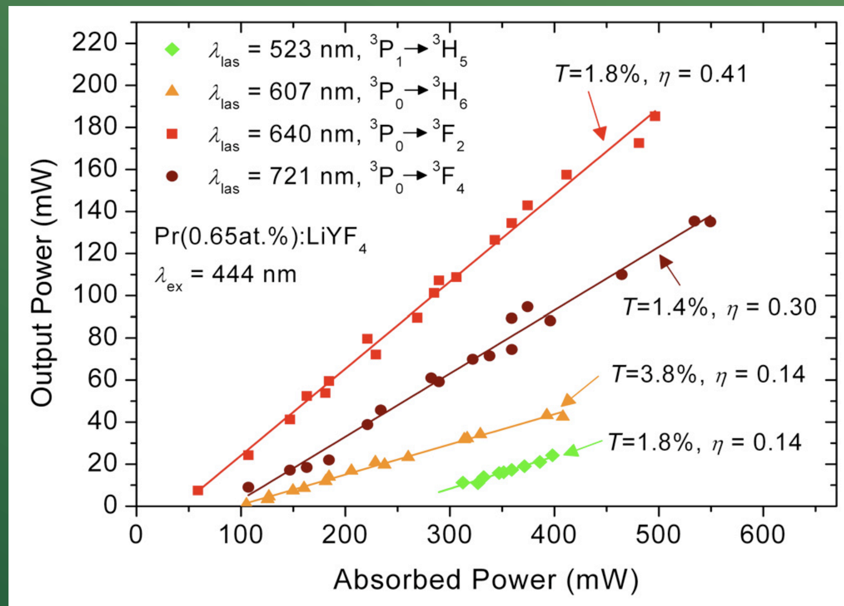
Power scaling of GaN laser diode pumped Pr-lasers

A. Richter, E. Heumann, and G. Huber Äb0
Institute of Laser-Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany Äi0
a.richter@physnet.uni-hamburg.de Äi0
D. Parisi, and M. Tonelli Äb0
NEST and Dipartimento di Fisica dell' Universita di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy Äi0

444nmGaN-LD for excitation source







Pr doped laser excited by 444-nm GaN-LD.
The slope efficiency reached to 41% at 640nm.

Progress in Blue LD development

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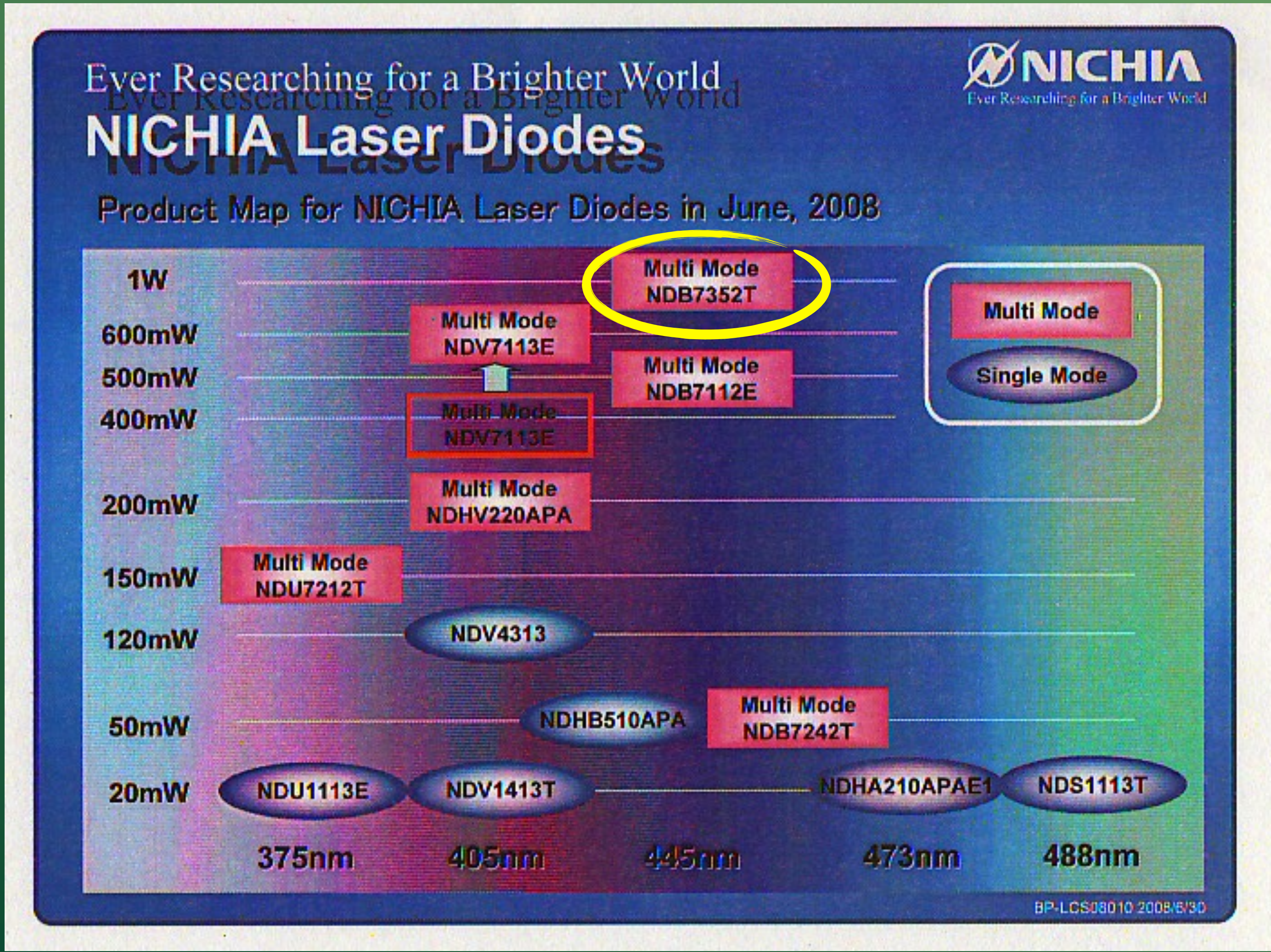

1-W blue LD at 445 nm is now available for excitation source.

Why fluoride glass ?

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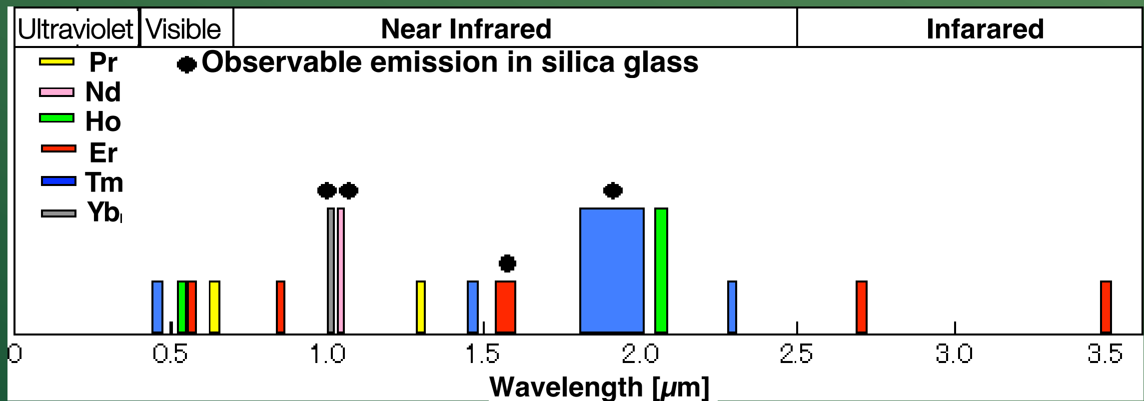
In general, fluoride glasses show poor chemical durability, especially weak water-resistance.

Advantage of fluoride glass

1) low refractive index (1.3-1.5)
2) low dispersion of refractive index
3) low phonon energy
4) wide band transmittance (200-3500nm) (in case of silica glass ; 200-2200nm)



Many rare-earth elements can emit in fluoride glass due to low phonon energy.

Summary of fluoride glasses

BeF_2

BeF_2 is vitrified by single component (1950).
Disadvantage -> Low water-resistant property and toxicity.

$ZrF_4(HfF_4)$ system

Discovery of vitrification by $ZrF_4 \cdot BaF_2 \cdot NaF$ in 1975.
Then, an optical fiber is drawn by $ZrF_4 \cdot BaF_2 \cdot LaF_3 \cdot AlF_3 \cdot NaF$(ZBLAN).
Disadvantage -> Low water-resistant property and low transition temperature (Tg 250-300°C).

○ **AlF_3 system**

$AlF_3 \cdot YF_3 \cdot CaF_2 \cdot BaF_2$ glass system shows water-resistant property and higher transition temperature (Tg 350-400°C).
Disadvantage -> difficulty in crystallization.

Others

ThF_4, GaF_3, InF_3, ZnF_2, CdF_2 glass system

Progress on fluoride glass

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1. Chemical durability (water-resistance)
   1) Water-resistant property of AlF_3 system glass is remarkably increased compared to ZABLAN glass.
   2) Water is used in polishing treatment.

TABLE IV. Properties of AlF_3-based glasses compared with ZBLAN glass (bulk glasses).

Glass system	Refractive index (n_d)	Cutoff wavelength (t = 4 mm) UV (T = 50%) (μm)	IR (T = 50%) (μm)	Specific gravity (g/cm³)	Wt. loss at 23 °C %/24 h	Young's modulus E (Kg/mm²)	Knoop hardness H (Kg/mm²)	Poisson's ratio
ABCYS	1.436	0.29	6.08	3.90	0.01	5720	370	0.31
ABCYSNZ	1.445	0.195	6.94	3.85	0.10	6500	315	0.31
BATY	1.487	0.21	7.10	4.36	0.03	6021	···	0.31
ZBLAN	1.497	0.20	7.57	4.34	5.23	5380	225	0.31

2. AlF_3 system glass can be drawn to an optical fiber by way of suppressing crystallization.

→ Possibility of fiber drawing using AlF_3 system glass with water-resistant property

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- **Pr doped fluoride glass (Pr:PAYAC)**
  - **Spectroscopic properties of Pr^{3+} doped fluoride glass**
  - **Stimulated emission cross section by Judd-Ofelt analysis**
  - **Laser oscillation**
- **Applications**
- **Conclusions**

Photograph of Pr:PAYAC

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Pr:PAYAC is provided by Sumita Optical Glass, Inc.

Pr:Glass(PAYAC) Data

Sample Thickness = 10.053 [mm]

Pr doping = 3000 [ppm]

Number density = 5.94×10^{19} [#/cm^2]

Density = 4.63 [g/cm^3]

Refractive index =
1.49760@0.52μm,
1.49358@0.605μm,
1.49237@0.64μm,
1.49023@0.72μm

The refractive index is conformable to silica fiber. The connection loss is estimated to be 0.02% in PC-contact.
This glass is successfully drawn for an optical fiber.

Absorption spectrum Pr:PAYAC (1)

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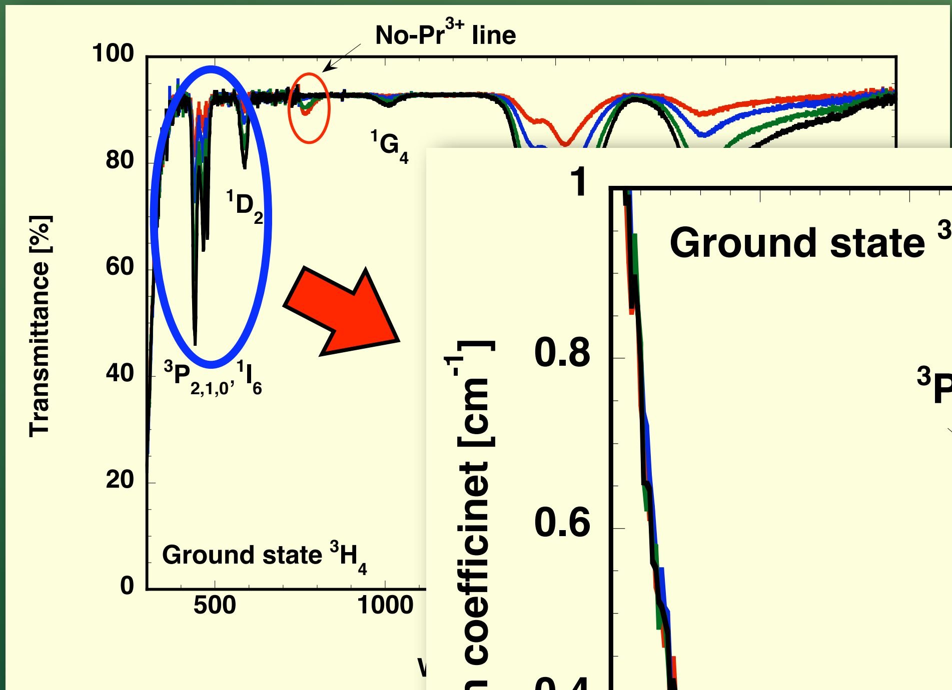

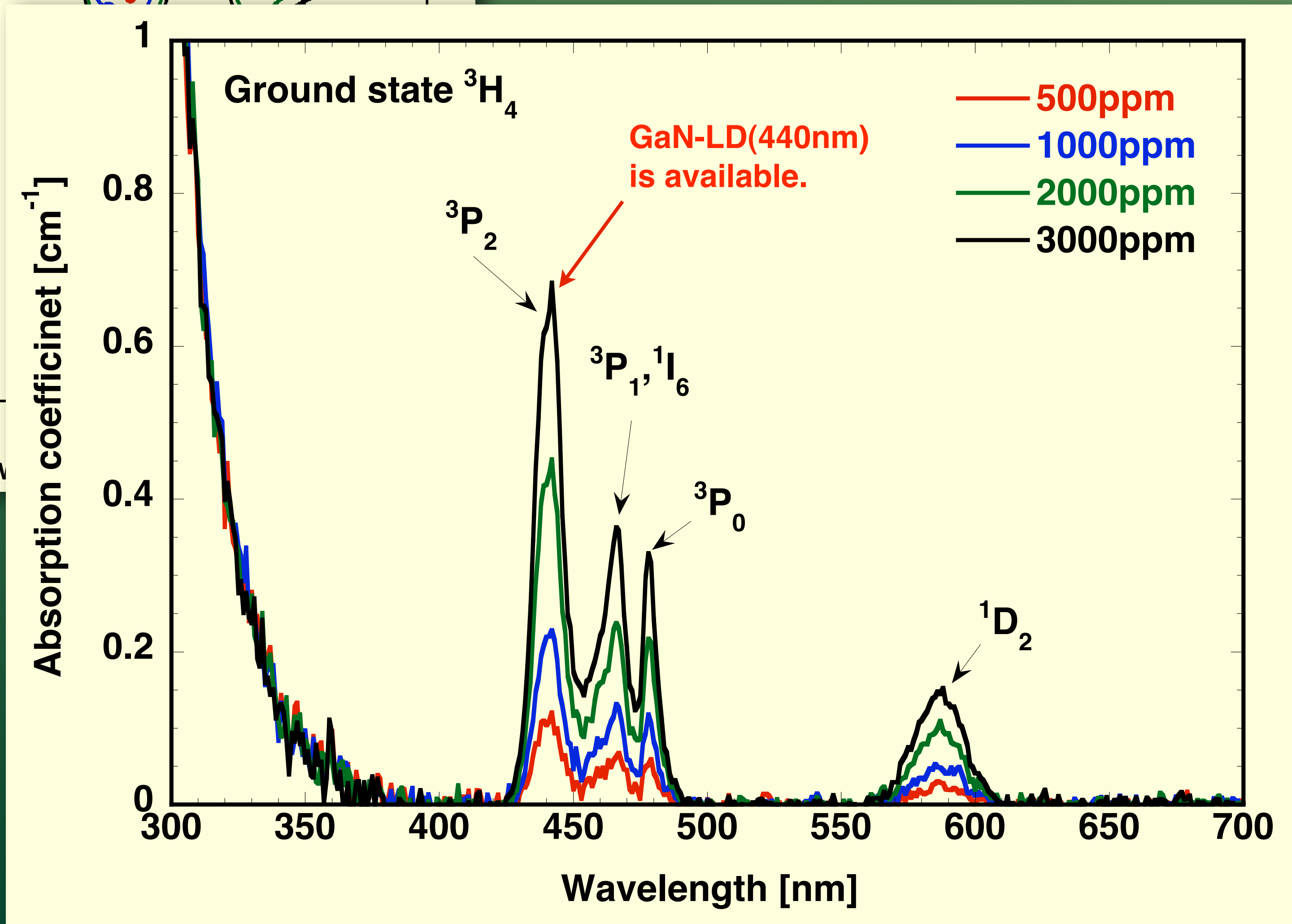

Excitation spectra of Pr:PAYAC(3000ppm)

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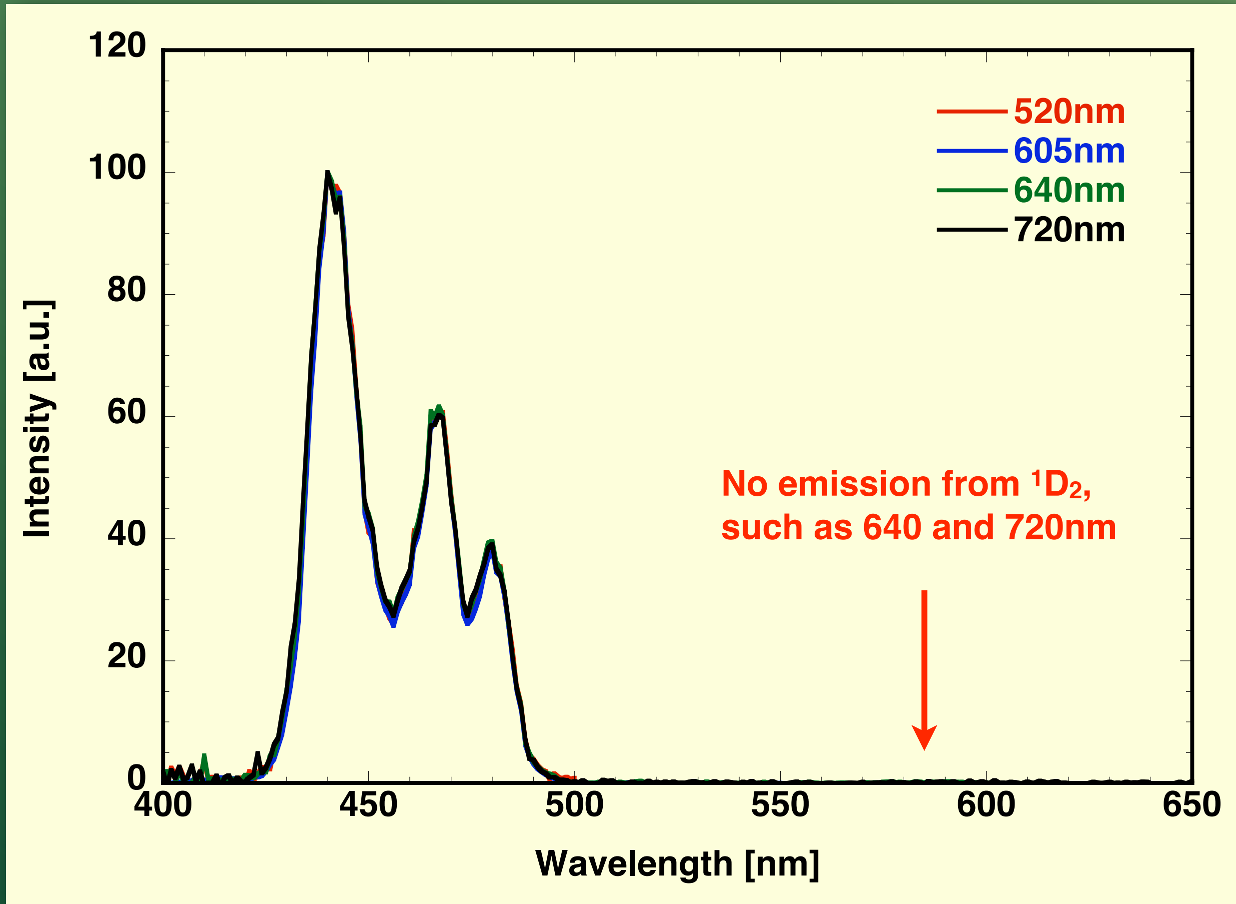

Excitation spectra are bery similar to absorption spectra except $^3H_4$ -> $^1D_2$ transition. Therefore, initial state of fluorescence at 520, 605, 635, 720 nm is $^3P_{1,0}$.

Transition assignment on Pr:PAYAC and energy diagram of Pr^{3+}

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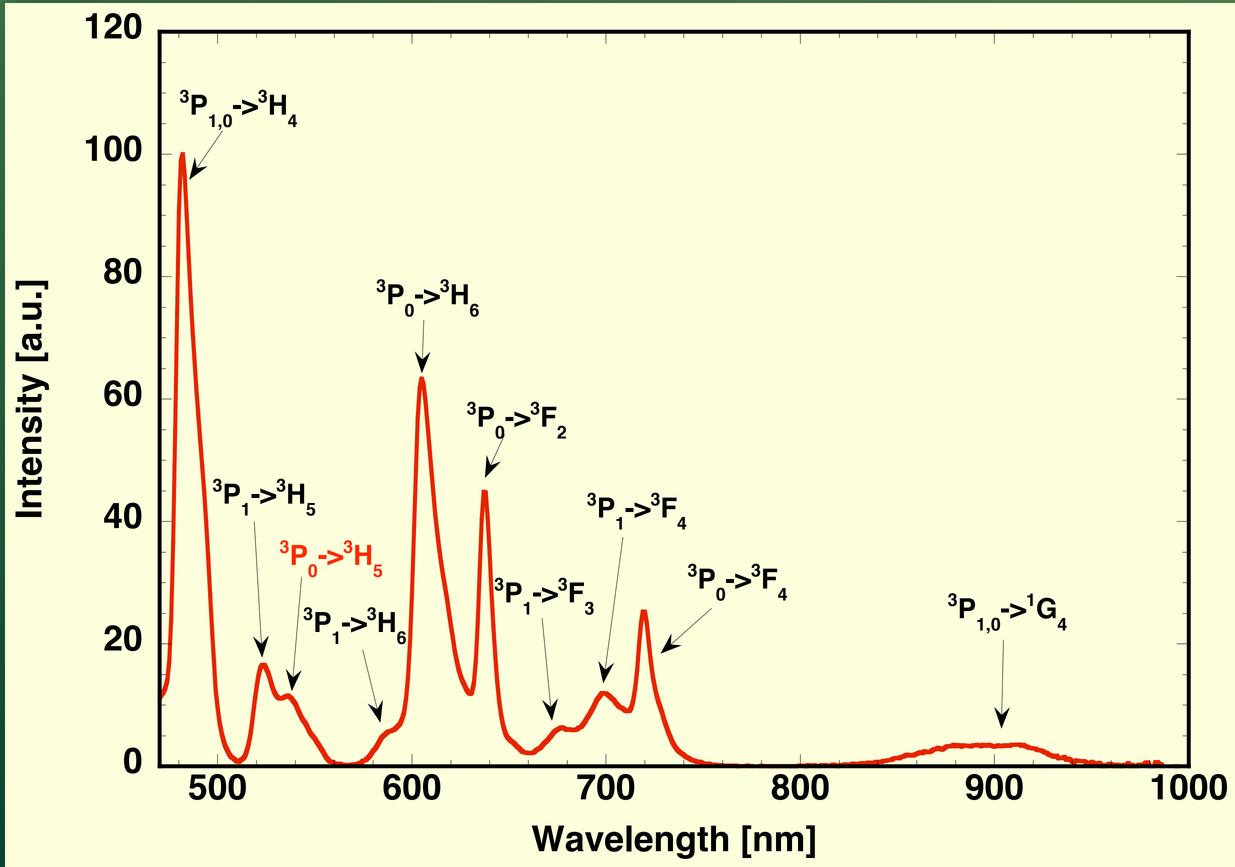

Fig.1 Transition assignment on Pr:PAYAC

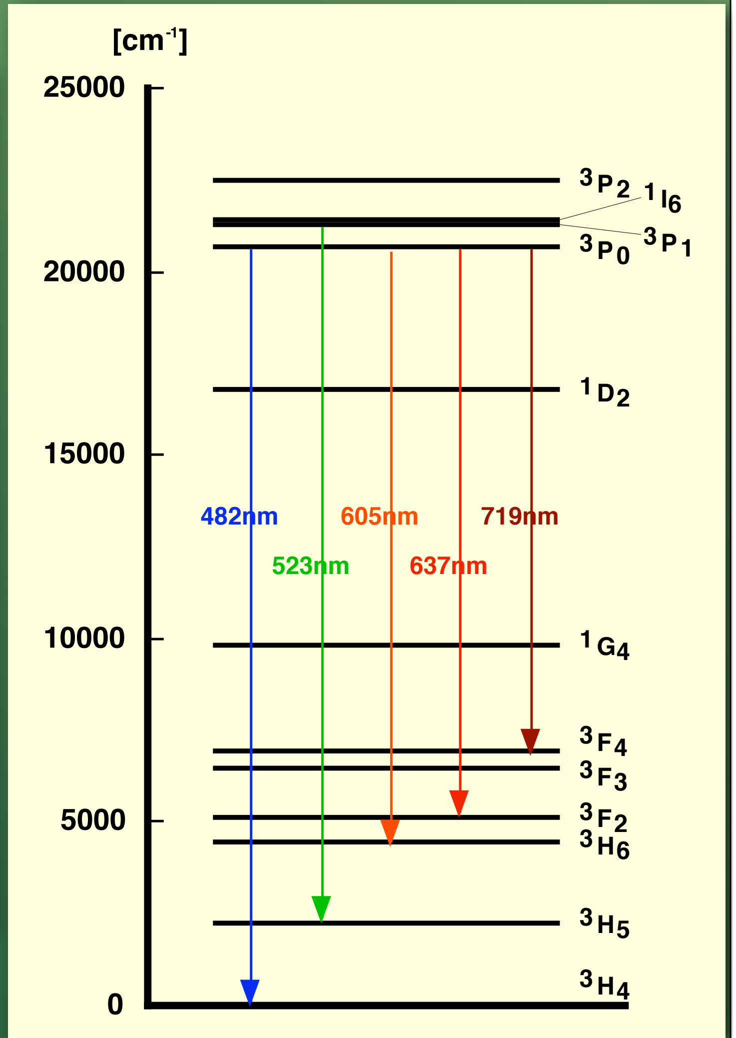

Fig.2 Energy diagram of Pr^{3+}

Judd-Ofelt analysis results on Pr:PAYAC

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Transition	Bandwidth [nm]	Level System	Peak wavelength [nm]	Effective line width	Stimulated emission cross section	Transition probability [s^{-1}]
				$\Delta\lambda$ [nm]	σ [$\times 10^{-20} cm^2$]	
$^3P_{1,0}$ -> $^3H_4$	466~510	Quasi-three	482	15.3	**2.73**	12640
$^3P_{1,(0)}$ -> $^3H_5$	510~566	Four	523	23.8	**0.51**	2528
$^3P_{1,0}$ -> $^3H_6$ $^3P_1$ -> $^3F_2$	566~630	Four	605	18.9	**1.41**	3252
$^3P_0$ -> $^3F_2$	630~660	Four	637	10.3	**1.55**	1600
$^3P_{1,0}$ -> $^3F_3$ $^3P_1$ -> $^3F_4$	660~710	Four	698	29.9	0.41	902.5
$^3P_0$ -> $^3F_4$	710~800	Four	719	13.9	**2.67**	2279
$^3P_{1,0}$ -> $^1G_4$	800~1000	Four	913	77.8	0.19	392.1

1) Calculated Ω parameters

   $\Omega_2 = 0.95 \times 10^{-20}$ [cm^2], $\Omega_4 = 4.76 \times 10^{-20}$ [cm^2], $\Omega_6 = 5.12 \times 10^{-20}$ [cm^2]

2) Calculated Lifetime $\tau = 40.7$ [μs]

3) Measured Lifetime $\tau = 30\text{-}50$ [μs]

4) Calculated quantum yield $\eta > 73.7\%$

Experimental setup of Pr-doped fiber laser oscillation.

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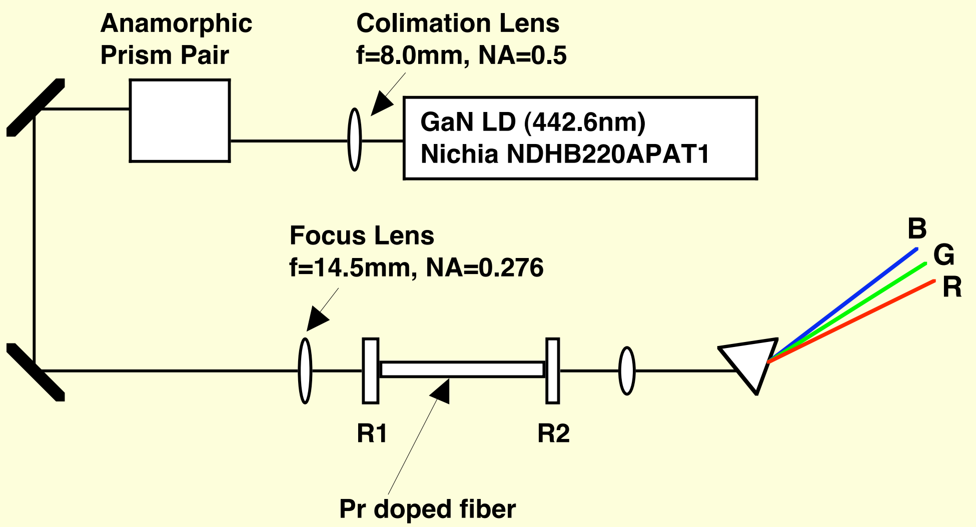

Pr-doped fiber specification
Pr concentration; 3000 ppm
Core diameter; 6 μm
NA; 0.28
length; 4 cm (inserted into a zirconia-ferrule)

Mirror #	Reflectivity [%]					
	440 nm	490 nm	522 nm	605 nm	635 nm	719 nm
#1	5.2	20	99.98	100	100	63.5
#2	1.5	1.8	0.4	43.6	79.4	0.9
#3	3.2	63.7	99.98	2	1.8	0.9
#4	4.6	40.5	96.7	1.9	2.3	3.4
#5	5.1	99.9	99.98	37.5	54.3	21.9
#6	3.1	90.1	4.4	1.9	5.9	2

Mirror selection
635 nm ; R1 => #1, R2 => #2
605 nm ; R1 => #1, R2 => #2
523 nm ; R1 => #3, R2 => #4
635 nm ; R1 => #5, R2 => #6

Laser oscillation in visible region

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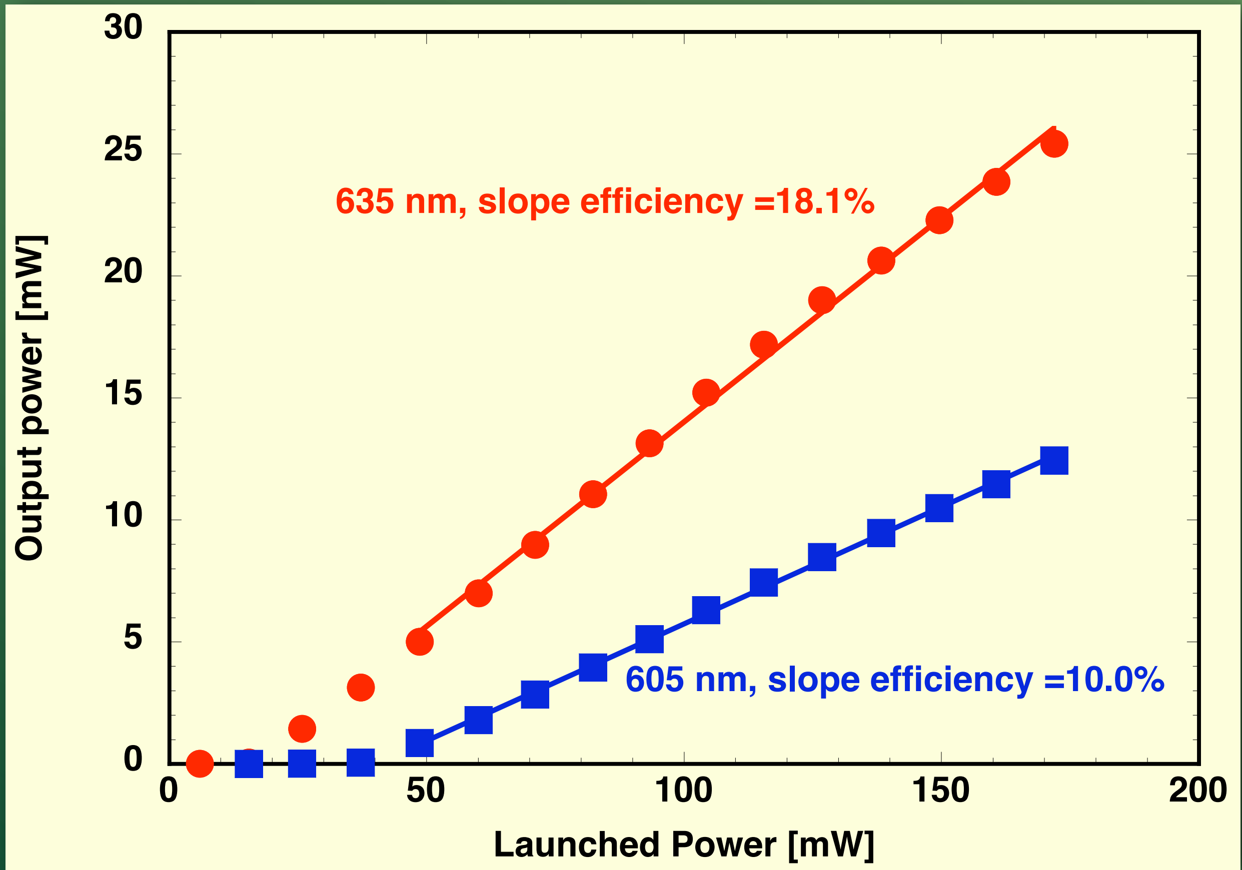

The 523 and 488 nm output power was obtained to be 1.0 and 0.7 mW, respectively, however the output power is unstable.

➡ Pr:PAYAC covers wider area than sRGB liquid crystal display, therefore, color reproducibility is better than sRGB.

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Application (1) -Short pulse laser operation-

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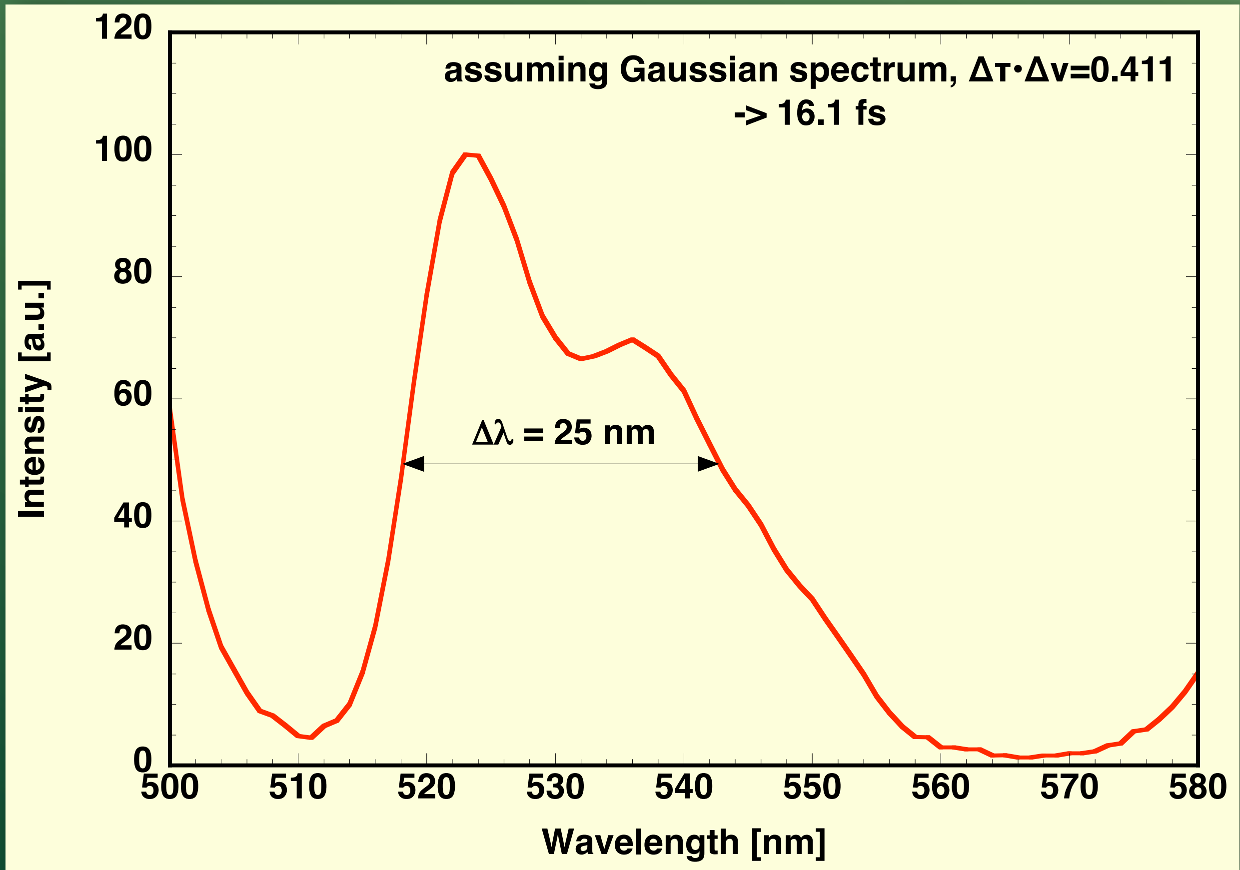

Spectral width of Pr:PAYAC at 523nm emission is 25 nm. A short pulse laser operation is expected.

Application (2) -Absorption rate of metal materials-

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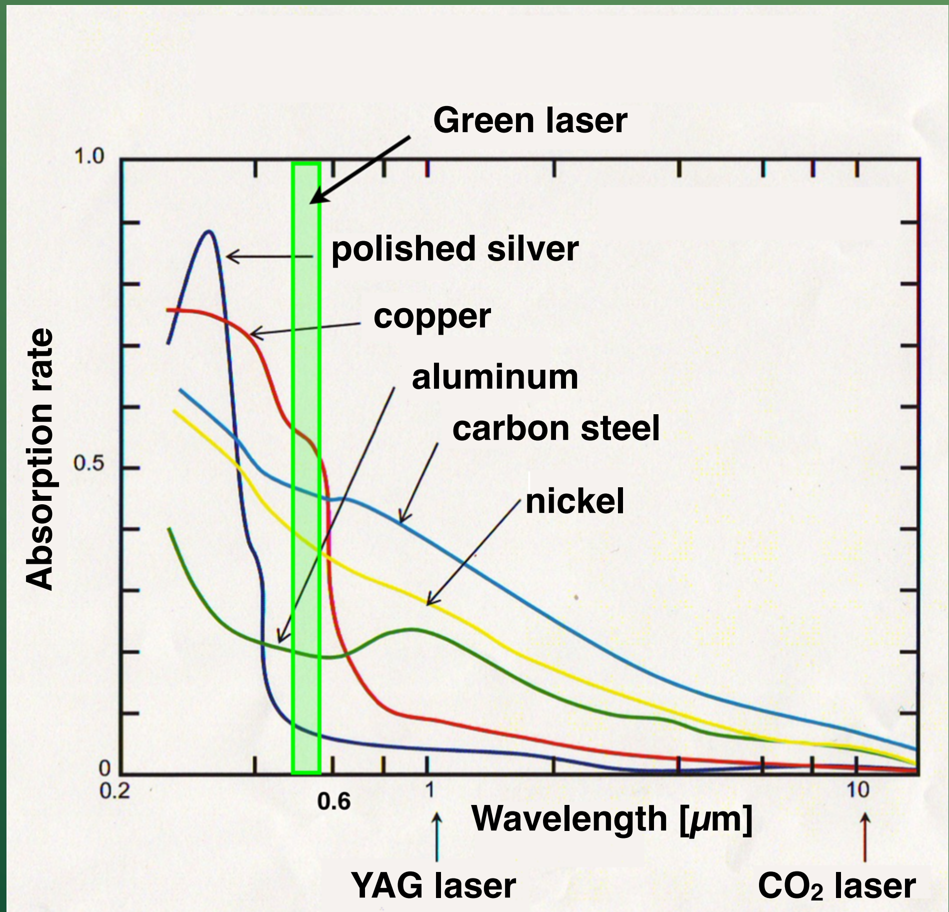

for copper
520nm:50-60%
630nm:20%
1μm:10%
10μm:1%

Laser wavelength under 0.6 μm is useful for copper welding and cutting.

Application (3) -for display use-

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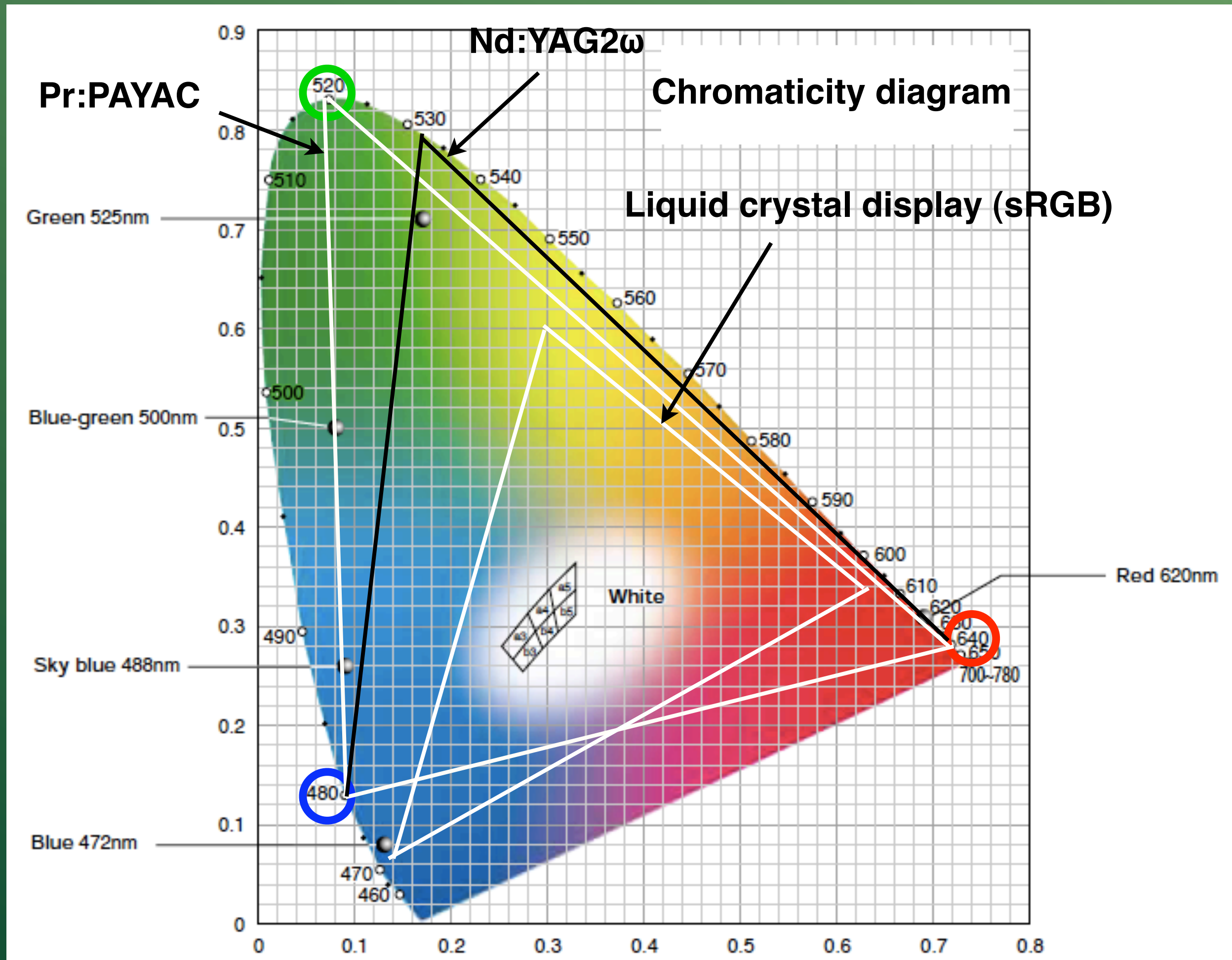

Pr:PAYAC covers wider area than sRGB liquid crystal display, therefore, color reproducibility is better than sRGB.

Conclusions

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- We demonstrated multi-colored laser oscillation in Pr^{3+}-doped fluoro-aluminate glass fiber pumped by 440 nm GaN-semiconductor laser at 488, 523, 605, 635nm.
- The slope efficiency of laser oscillation at 635-nm ofn 605-nm are 18.1% and 10.0%.
- The stimulated emission cross section o Pr^{3+} doped fluoride glass (Pr:PAYAC) with water-resistant property by Judd-Ofelt analysis.

- Future plan
  - Simulation of laser oscillation of Pr doped fiber laser
  - High power laser oscillation experiment

Thank you for your attention!