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

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Outline

- Background
  - 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

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.

Pr\(^{3+}\) Laser

Power scaling of GaN laser diode pumped Pr-lasers

A. Richter, E. Heumann, and G. Huber

Institute of Laser-Physics, University of Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

D. Parisi, and M. Tonelli

NEST and Dipartimento di Fisica dell’Università di Pisa, Largo B. Pontecorvo 3, 56127 Pisa, Italy

Pr doped laser excited by 444-nm GaN-LD.
The slope efficiency reached to 41% at 640nm.
1-W blue LD at 445 nm is now available for excitation source.
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$_4$·BaF$_2$·NaF in 1975.
Then, an optical fiber is drawn by
ZrF$_4$·BaF$_2$·LaF$_3$·AlF$_3$·NaF(ZBLAN).
Disadvantage -> Low water-resistant property and low transition temperature (Tg 250-300°C).

AlF$_3$ system

AlF$_3$·YF$_3$·CaF$_2$·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

1. Chemical durability (water-resistance)
   1) Water-resistant property of AlF$_3$ system glass is remarkably increased compared to ZBLAN glass.
   2) Water is used in polishing treatment.

<table>
<thead>
<tr>
<th>Glass system</th>
<th>Refractive index ($n_d$)</th>
<th>Cutoff wavelength ($UV (T = 50%)$) (µm)</th>
<th>Cutoff wavelength ($IR (T = 50%)$) (µm)</th>
<th>Specific gravity (g/cm$^3$)</th>
<th>Wt. loss at 25 °C %/24 h</th>
<th>Young’s modulus $E$ (Kg/mm$^2$)</th>
<th>Young’s modulus $H$ (Kg/mm$^2$)</th>
<th>Knoop hardness $H$ (Kg/mm$^2$)</th>
<th>Poisson’s ratio</th>
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<tbody>
<tr>
<td>ABCYS</td>
<td>1.436</td>
<td>0.29</td>
<td>6.08</td>
<td>3.90</td>
<td>0.01</td>
<td>5720</td>
<td>370</td>
<td>0.31</td>
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<tr>
<td>ABCYSNZ</td>
<td>1.445</td>
<td>0.195</td>
<td>6.94</td>
<td>3.85</td>
<td>0.10</td>
<td>6500</td>
<td>315</td>
<td>0.31</td>
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<tr>
<td>BATY</td>
<td>1.487</td>
<td>0.21</td>
<td>7.10</td>
<td>4.36</td>
<td>0.03</td>
<td>6021</td>
<td>⋯</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td>ZBLAN</td>
<td>1.497</td>
<td>0.20</td>
<td>7.57</td>
<td>4.34</td>
<td>5.23</td>
<td>5380</td>
<td>225</td>
<td>0.31</td>
<td></td>
</tr>
</tbody>
</table>

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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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)

GaN-LD(440nm) is available.
Excitation spectra of Pr:PAYAC(3000ppm)

Excitation spectra are very similar to absorption spectra except $^3H_4 \rightarrow \ ^1D_2$ transition. Therefore, initial state of fluorescence at 520, 605, 635, 720 nm is $^3P_{1,0}$. No emission from $^1D_2$, such as 640 and 720 nm.
Transition assignment on Pr:PAYAC and energy diagram of Pr$^{3+}$

**Fig. 1** Transition assignment on Pr:PAYAC

**Fig. 2** Energy diagram of Pr$^{3+}$
Judd-Ofelt analysis results on Pr:PAYAC

1) Calculated $\Omega$ parameters

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

2) Calculated Lifetime $\tau = 40.7 \text{[\mu s]}$

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

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

<table>
<thead>
<tr>
<th>Transition</th>
<th>Bandwidth [nm]</th>
<th>Level System</th>
<th>Peak wavelength [nm]</th>
<th>Effective line width $\Delta \lambda$ [nm]</th>
<th>Stimulated emission cross section $\sigma \times 10^{-20}\text{cm}^2$</th>
<th>Transition probability [s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{P}_{1,0} \rightarrow ^3\text{H}_4$</td>
<td>466-510</td>
<td>Quasi-three</td>
<td>482</td>
<td>15.3</td>
<td>$2.73$</td>
<td>12640</td>
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<tr>
<td>$^3\text{P}_{1,0} \rightarrow ^3\text{H}_5$</td>
<td>510-566</td>
<td>Four</td>
<td>523</td>
<td>23.8</td>
<td>$0.51$</td>
<td>2528</td>
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<tr>
<td>$^3\text{P}_{1,0} \rightarrow ^3\text{H}_6$</td>
<td>566-630</td>
<td>Four</td>
<td>605</td>
<td>18.9</td>
<td>$1.41$</td>
<td>3252</td>
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<tr>
<td>$^3\text{P}_{1} \rightarrow ^3\text{F}_2$</td>
<td>630-660</td>
<td>Four</td>
<td>637</td>
<td>10.3</td>
<td>$1.55$</td>
<td>1600</td>
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<td>$^3\text{P}_{0} \rightarrow ^3\text{F}_2$</td>
<td>660-710</td>
<td>Four</td>
<td>698</td>
<td>29.9</td>
<td>$0.41$</td>
<td>902.5</td>
</tr>
<tr>
<td>$^3\text{P}_{1,0} \rightarrow ^3\text{F}_3$</td>
<td>710-800</td>
<td>Four</td>
<td>719</td>
<td>13.9</td>
<td>$2.67$</td>
<td>2279</td>
</tr>
<tr>
<td>$^3\text{P}_{0} \rightarrow ^3\text{F}_4$</td>
<td>800-1000</td>
<td>Four</td>
<td>913</td>
<td>77.8</td>
<td>$0.19$</td>
<td>392.1</td>
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</tbody>
</table>
Experimental setup of Pr-doped fiber laser oscillation.

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

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

<table>
<thead>
<tr>
<th>Mirror #</th>
<th>Reflectivity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>440 nm</td>
</tr>
<tr>
<td>#1</td>
<td>5.2</td>
</tr>
<tr>
<td>#2</td>
<td>1.5</td>
</tr>
<tr>
<td>#3</td>
<td>3.2</td>
</tr>
<tr>
<td>#4</td>
<td>4.6</td>
</tr>
<tr>
<td>#5</td>
<td>5.1</td>
</tr>
<tr>
<td>#6</td>
<td>3.1</td>
</tr>
</tbody>
</table>
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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Spectral width of Pr:PAYAC at 523nm emission is 25 nm. A short pulse laser operation is expected.
Laser wavelength under 0.6 µm is useful for copper welding and cutting. For copper:
- 520nm: 50-60%
- 630nm: 20%
- 1µm: 10%
- 10µm: 1%
Pr:PAYAC covers wider area than sRGB liquid crystal display, therefore, color reproducibility is better than sRGB.
Conclusions

• 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 of 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!