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Review Article

Laser Medium from Glass Material

Rajanavaneethakrishna Rajaramakrishna[1], Jakrapong Kaewkhao[2,*]

[1] Department of Post Graduate Studies and Research in Physics, The National College, Jayanagar, Bangalore 560070, India

[2] Center of Excellence in Glass Technology and Materials Science (CEGM), Nakhon Pathom Rajabhat University, Nakhon Pathom 73000, Thailand

* Corresponding author e-mail: jakrapong@webmail.npru.ac.th

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Abstract: This review paper provides detailed information on "LASER" and its applications. Significantly, the doping of rare-earth ions would improve the performance of glasses implemented in laser device applications. Details of the critical parameters such as emission cross-sections and other parameters related to the potential use of lasing glass have been discussed. A comparison of the recent literature with that of the commercially available phosphate glasses has been made. Specific oxide glasses doped with Nd^{3+} ions, which are fabricated in the Center of Excellence in Glass Technology and Material Science (CEGM) laboratory at Nakhon Pathom Rajabhat University, Thailand, were listed and presented.

Keywords: LASER, Laser fusion experiment, Nd^{3+} ions, oxide glass, CEGM Lab

1. Introduction

More than 50 years have passed since the discovery of Nd: phosphate laser glass [1-2]. Today, Nd: phosphate laser glass plays a vital role in inertial confinement fusion, laser processing, and a pumping source for ultrafast laser systems. A neodymium laser is used for efficient near-infrared (NIR) broadband laser emission around 1060 nm. The first application on Nd^{3+} doped glasses was to absorb ultraviolet (UV) rays for halogen lamps harmful to human eyes. [3–5]. National Ignition Facility (NIF) in the United States [6-7], Shanghai Institute of Optics and Fine Mechanics (SIOM), China [8], Schott and Hoya [9-10] have developed commercial phosphate laser glasses. High-average-power neodymium phosphate laser glasses, APG-1 and APG-2 (Schott) and HAP-4(Hoya) by Schott and Hoya, have been widely used in high average power lasers. In SIOM, two kinds of high average power Nd: phosphate laser glasses, NAP2, and NAP4 glasses, have been developed since 2007 [9-10]. The present review article will bring out the significance of the laser and laser medium.

2. Laser and its importance

The device produces a strong monochromatic collimated and highly coherent beam of light and depends on the phenomenon of 'stimulated emission' predicted by Einstein in 1917 [11]. In 1960, Theodore Maiman first practically observed the stimulated emission using a ruby crystal as the amplifier with a flashlamp as the energy source. Table 1 shows the chronology of inventions established in the field of laser technology. The term 'LASER' stands for Light Amplification by Stimulated Emission of Radiation. The laser is the process that amplifies the output light signals. The importance of laser is based on certain unique properties are 1) monochromaticity, 2) coherence 3) collimated beam. The light is used initially to pump inside the optical resonator cavity in which a saturable absorber will amplify the intensity of pumped light and highly collimated. Inside the optical cavity, the light passes back and forth between two mirrors which gains intensity by the stimulated emission of more photons at the same wavelength (monochromatic). One of the mirrors is made for almost complete reflections while the other mirror is partially transmitting, letting out the coherence beam termed as laser, as shown in Figure 1.

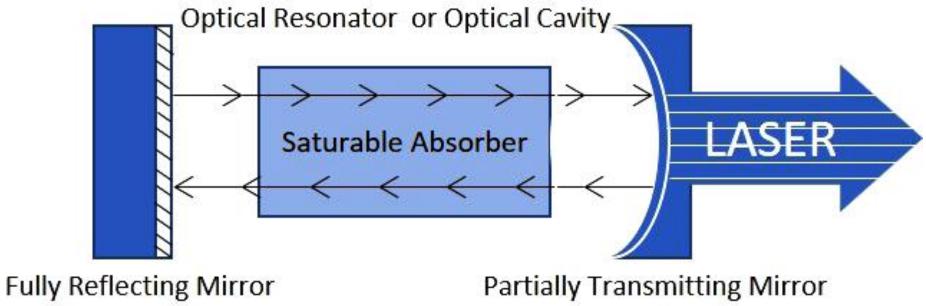

Figure 1 Schematic diagram of laser beams.

3. Advantages of laser

Considered to be the best technological inventions in science, laser plays a vital role in medicine, laser machining and cutting for industrial applications, optical communication, storage, optical-fiber for entertainment, bar code readers, cancer treatment, precise navigation, military and defense applications, mode-locked femtosecond laser for metrological and geophysical applications, laser imaging and holography, laser isotope separation to enrich natural uranium, and laser for the fusion process. The CO_2 laser is used to remove tissues, whereas the Nd-YAG laser is for eye treatment such as cataract surgery, cosmetics laser treatments, biomedical imaging, and super-resolution.

Nd^{3+}ion is doped in various glasses, primarily silicates and phosphates, often used for neodymium-doped optical fibers, e.g., in fiber lasers and amplifiers. In general, high-power laser applications using Nd^{3+} doped phosphate glasses are classified into two types 1) high peak-power and 2) high-average-power. Composition of commercial Nd-phosphate glasses taken from Hoya, Schott, and SIOM:

1) High peak power phosphate laser glasses: P_2O_5-Al_2O_3-R_2O-MO doped with Nd_2O_3 (R_2O is an alkali oxide; MO is alkaline-earth oxides)

2) High average power phosphate laser glasses: P_2O_5-SiO_2-$A_{l2}O_3$-R_2O-MO doped with Nd_2O_3 (R_2O is an alkali oxide; MO is alkaline-earth oxides)

Table 1 Chronology of inventions in the field of laser technology

No.	Invention on laser	Year	Researcher's	Ref
1	MASER	1955	J. P. Gordon *et al.*	[12]
2	Optical masers	1958	A. L. Schawlow, C. H. Townes	[13]
3	LASER	1960	T. H. Maiman	[14]
4	He-Ne gas laser	1961	A. Javan *et al.*	[15]
5	Neodymium laser	1961	L. F. Johnson *et al.*	[16]
6	Semiconductor laser	1962	R. N. Hall *et al.*	[17]
7	Hg-He vapor ion laser	1963	W. E. Bell	[18]
8	CO_2 laser	1964	C. K. N. Patel	[19]
9	Argon ion laser	1964	W. Bridges	[20]
10	Nd:YAG laser	1964	J. E. Geusic *et al.*	[21]
11	He-Cd metal vapor laser	1966	W. Silfvast *et al.*	[22]
12	Copper vapor laser	1966	W. Walter *et al.*	[23]
13	Liquid laser	1967	P. P. Sorokin, J. R. Lankard	[24]
14	UV laser	1970	R. T. Hodgson	[25]
15	Rare-gas-halide excimer laser	1975	J. J. Ewing, C. Brau	[26]
16	Quantum-well laser (Ga-Ar)	1975	J. P. van der Ziel *et al.*	[27]
17	Free-electron laser	1977	J. M. J. Madey, D. A. G. Deacon	[28]
18	Tunable solid-state laser	1979	J. C. Walling *et al.*	[29]
19	Soft-X ray laser	1985	D. L. Matthews *et al.*	[30]
20	Ti-sapphire laser	1986	P. F. Moulton	[31]
21	Zn-Se, Blue-Green diode laser	1991	M. Hasse *et al.*	[32]
22	Quantum cascade laser	1994	F. Capasso *et al.*	[33]
23	Quantum dot laser	1994	N. N. Ledentsov *et al.*	[34]
24	Blue diode laser in GaN	1996	G. Fasol	[35]
25	InGaN laser diode	1996	S. Nakamura *et al.*	[36]
26	BEC and atomic lasers	1997	W. Ketterle	[37]
27	Electronic Raman laser	2005	O. Boyraz, B. Jalali	[38]
28	Low-cost hybrid Si laser	2006	J. Bowers *et al.*	[39]
29	Femtosecond laser	2009	T. Y. Hwang *et al.*	[40]
30	Mid IR 3 – 5 μm laser	2010	M. Razeghi	[41]
31	VECSEL laser	2011	H. Zogg *et al.*	[42]
32	500 Tera Watt shot laser	2012	National Ignition Facility (NIF)	[43]
33	Low spatial coherence random laser	2012	B. Redding *et al.*	[44]
34	Optical fiber boosted tenfold (10X)	2013	M. A. Soto *et al.*	[45]
35	Laser ablation proposed for rocket propulsion	2014	Y. Rezunkov, A. Schmidt	[46]
36	50-μm-wide reproduction of the "Mona Lisa" using laser	2015	A. Kristensen *et al.*	[47]
37	100W Extreme Ultra-Violet (EUV) laser	2016	Y. Shiraishi *et al.*	[48]
38	AC Josephson junction microwave laser	2017	M. C. Cassidy *et al.*	[49]
39	3D surfaces print on plastic skeleton toy using laser	2018	E. Baumann *et al.*	[50]
40	1.9 μm Thulium laser	2019	C. M. Wynn *et al.*	[51]

Based on some of the critical parameters such as density (ρ), refractive index (n), emission cross-section (σ_{emi}), emission bandwidth ($\Delta\lambda_{eff}$), Judd-Ofelt parameters (Ω_λ, λ=2,4,6), experimental (τ_{exp}) and radiative (τ_{rad}) lifetimes, the conventional glasses are compared with that of the commercial glasses as shown in Table 2.

Table 2 Important parameters for commercializing the laser glass

Glass properties	Density, ρ	Refractive index, n	Emission cross-section, σ_{emi} (cm^2)	Judd-Ofelt lifetime τ_{exp} (μs)	Radiative lifetime τ_{rad} (μs)	Judd-Ofelt parameters ×10^{-20} (cm^2)			Emission bandwidth $\Delta\lambda_{eff}$ (nm)
						Ω_2	Ω_4	Ω_6	
Commercially available phosphate laser glasses									
Hoya [52] LHG-80	2.92	1.5429	4.2×10^{-20}	337	327				23.9
LHG-8 [52]	2.83	1.5296	3.6×10^{-20}	365	351	4.4	5.1	5.6	26.5
Schott LG-770 [52]	2.59	1.5267	3.9×10^{-20}	364	349	4.3	5.0	5.6	25.4
LG-750 [52]	2.83	1.5260	3.7×10^{-20}	383	367	4.6	4.8	5.6	25.3
Kigre Q88 [52]	2.71	1.5449	4.0×10^{-20}	326	326	3.3	5.1	5.6	21.9
N31 [53]	2.87	1.540	3.8×10^{-20}	-	348	-	-	-	-
Hoya [53] HAP-4	2.70	1.5433	3.6×10^{-20}	-	350	-	-	-	27.0
Schott APG-1 [53]	2.64	1.5370	3.4×10^{-20}	-	385	-	-	-	27.8
Schott APG-2 [53]	2.56	1.5127	2.4×10^{-20}	-	464	-	-	-	31.5
SIOM NAP-2 [53]	2.76	1.542	3.7×10^{-20}	-	380	-	-	-	27.0
SIOM NAP-4 [53]	2.60	1.530	3.2×10^{-20}	-	400	-	-	-	29.0
SIOM NF1 [53]	-	1.4647	2.7×10^{-20}	510	-				32.8
SIOM NF1 [53]	-	1.5146	3.4×10^{-20}	430	-				30.4
Schott LG810 [53]	-	1.434	2.5×10^{-20}	470	-				-
Hoya [53] LHG10	-	1.467	2.6×10^{-20}	384	-				31.25
Literature on laser glasses									
BSGdCa-Nd0.5 [54]	4.09	1.655	1.3×10^{-20}	342	600	2.1	2.5	1.9	32.9
SLBNd0.5[55]	2.47	1.538	4.0×10^{-20}	72	127	6.0	0.3	0.4	37.0
SPbKNLFNd10 [56]	4.01	1.651	4.1×10^{-20}	253	240	6.8	10	9.0	36.4
PKCFAN [57]	2.896	1.536	3.4×10^{-20}	254	237	5.4	7.0	6.5	-

4. Future research and applications for glass laser medium

4.1 Optical Fiber

The fiber optics are made from glass or plastic and would be as small as human hair, as shown in Figure 2 [59]. These fiber-optic cables are widely used in recent days for communication purposes. In the medical field, fiber-optic instruments are used to see inside the human body. Ytterbium-doped glass fibers, show quantum defect <10%, can provide optical-to-optical efficiencies well above 80% [60]. This is why ytterbium is the first choice among all rare-earth ions, along with Nd^{3+} ions. Recent developments on non-circular double cladding have been developed by Tünnermann *et al.* [61].

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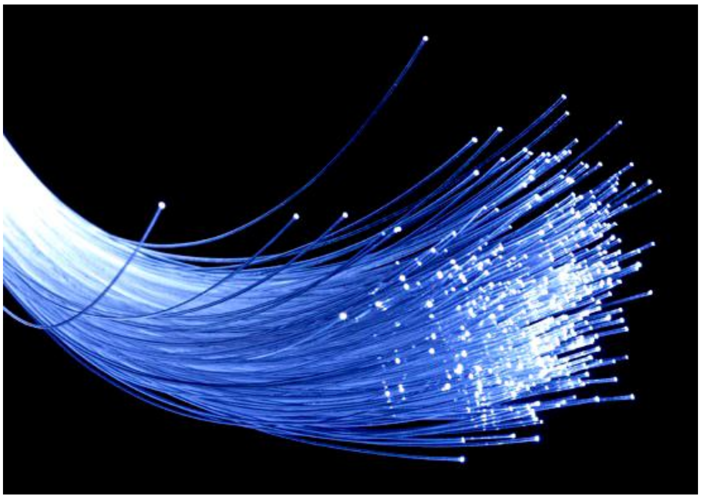


Figure 2 Optical fiber [59].

4.2 Advanced laser fusion experiment: Laser generation from glass

To generate fusion reactions, an ignition is required, which is a crucial step to achieve. An achievement of such fusion was successfully tested in US National Ignition Facility using a high-foot implosion method as shown in Figure 3(a) [62-63]. Figure 3(b) represents the NIF hohlraum fuel capsule [64], and Figure 3(c) represents the laser beams entering the hohlraum to generate X-rays. The laser beams are arranged in two cones, i.e., an inner cone pointed toward the waist of the hohlraum and an outer cone that is pointed near the ends. Ignition is achieved using a self-sustained fusion reaction which produces more energy than the energy absorbed by the target capsule [65].

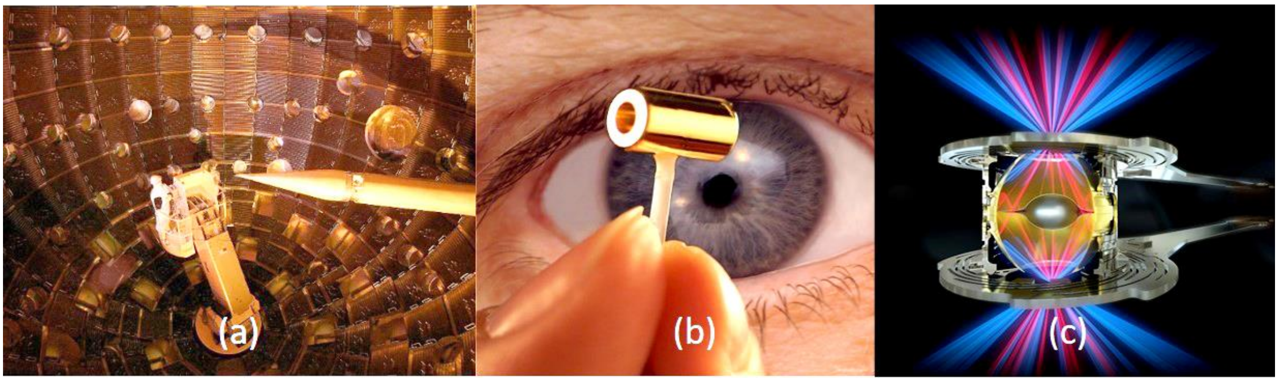


Figure 3 (a) Facility for a high-foot implosion method, (b) hohlraum fuel capsule, and (c) laser beams to generate X-rays. *Courtesy*: Lawrence Livermore National Laboratory: National Ignition Facility & Photon Science [64-65].

Another direct-drive fast-ignition (FI) approach for inertial confinement fusion ignition with high contrast kilo-joule petawatt LFEX laser [66-67] was demonstrated by GEKKO XII as shown in Figure 4 at Institute for Laser Engineering, Osaka University [68].

Figure 4 The facility for direct-drive fast-ignition (FI) approach. *Courtesy*: Institute of Laser Engineering Osaka University [69].

Table 3 Glass Materials and Advantages for laser Medium applications

LASER Medium	Wavelength (nm)	Applications
Hydrogen (H_2)	116 – 123, 160	[70]
Fluorine (F_2)	157	[71]
Argon Fluoride (ArF)	193	[72]
Krypton Fluoride (KrF)	248	[73]
Yb:YAG	257	[74]
Nd:YAG or Nd:YVO_4	266	[74]
Xenon Bromide (XeBr)	282	[75]
Xenon Chloride (XeCl)	308 and 459	[73]
Xenon Fluoride (XeF)	353 and 459	[76]
Helium Cadmium (He:Cd)	325 - 442	[77]
Argon	457 - 528 (514.5 and 488 most used)	[78]
Rhodamine 6G	450 - 650	[79-80]
Copper Vapor	511 and 578	[81]
Frequency doubled Nd:YAG	532	[74]
Helium Neon	543, 594, 612, and 632.8	[82-83]
Krypton	337.5 - 799.3 (647.1 - 676.4 most used)	[84]
Ruby	695	[85]
Laser Diodes	630 - 950	[86-87]
Ti:Sapphire	690 - 960	[88]
Alexandrite	720 - 780	[89]
Nd:YAG	1064-1444	[74]
Er:YAG	1617-1645, 2940	[90]
Hydgrogen Fluoride	2700 - 3000	[91]
Erbium:Glass	1540	[92]
Carbon Monoxide	4800- 8300	[93]
Carbon Dioxide	10600	[94]

5. Research by GEGM Laboratory at Nakhon Pathom Rajabhat University

Center of Excellence in Glass Technology and Material Science (CEGM) laboratory, located in Nakhon Pathom, Rajabhat University, Thailand. The part of the research work performed in the CEGM laboratory has been reviewed.

Rare-earth doped glass materials are attractive for developing solid-state lasers and optical amplifiers. Especially doping with neodymium trioxide in glasses shows special interests and has several uses as follows.

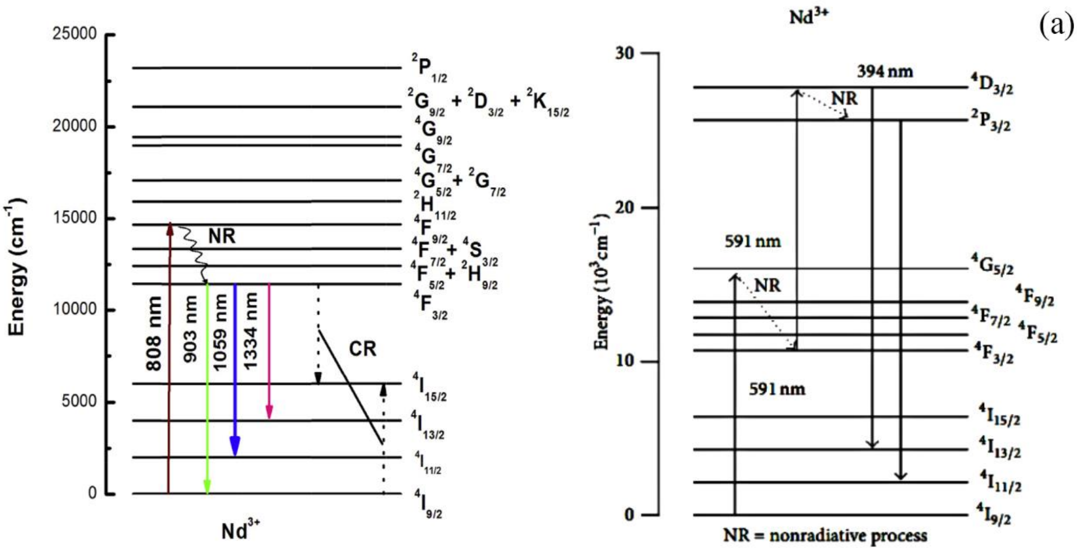
1) Nd_2O_3 has been used for special glasses used in halogen lamps to absorb UV rays, which are harmful to humans.

2) The glasses containing Nd_2O_3 can have high hardness and excellent chemical durability as refractory glasses.

3) Neodymium contained in glass can be used as a band rejection filter for image display devices, owing to absorption originating in the inter-transition within the 4f shell of the Nd^{3+} ions.

The phosphate glass can also be a suitable host matrix for Nd^{3+} ion since it has good fluorescence properties, low thermal-optic, and low nonlinear refractive index. Moreover, the glass phosphates have low transition temperatures, low boiling points, and high thermal expansion coefficients. Those properties provide suitable requirements for optic fiber and waveguide laser [95].

To demonstrate a glass for visible to solid-state device application, it must be having good density and refractive factors with host matrices. Glasses synthesized in the CEGM laboratory and other reports are presented in Table 4. In Table 4, we have listed refractive index (n), density (ρ), emission wavelength (λ_{emi}), effective line width ($\Delta\lambda_{eff}$) and stimulated-emission cross-section ($\sigma(\lambda_p)$) of certain oxide glasses. The transition of the Nd^{3+} ions doped with certain oxide glasses is shown in Figure 5. The gadolinium-calcium silica borate (BSGdCaNd) glasses doped with Nd^{3+} ions showed strong emission at 1.059 μm in NIR region with emission cross-section $\sigma(\lambda_p)$ = 1.39 × 10^{-20} cm^2 [54]. Also, with high density, it has potential suitability for optical amplification with better stability and efficient NIR emission. Nd^{3+} doped soda-lime-borate glasses showed strong emission at 1.069 μm in NIR region having stimulated emission cross-section $\sigma(\lambda_p)$ = 4.0 × 10^{-20} cm^2 [55]. Nd^{3+}-doped lead fluorosilicate glasses showed strong emission at 1.056 μm in NIR region with emission cross-section $\sigma(\lambda_p)$ = 4.11 × 10^{-20} cm^2 [56]. Bi_2O_3–BaO–B_2O_3-0.5Nd_2O_3 [58] shows strong emission at 1.060 μm in the NIR region and observed up-conversion phenomenon when excited at 591 nm at 394 nm. Interestingly, the up-conversion process is due to the excited state absorption (ESA) mechanism, as shown in Figure 5(a). In one of our research, we found that the addition of strontium oxide would enhance the luminescence behavior compared to calcium oxide [98].



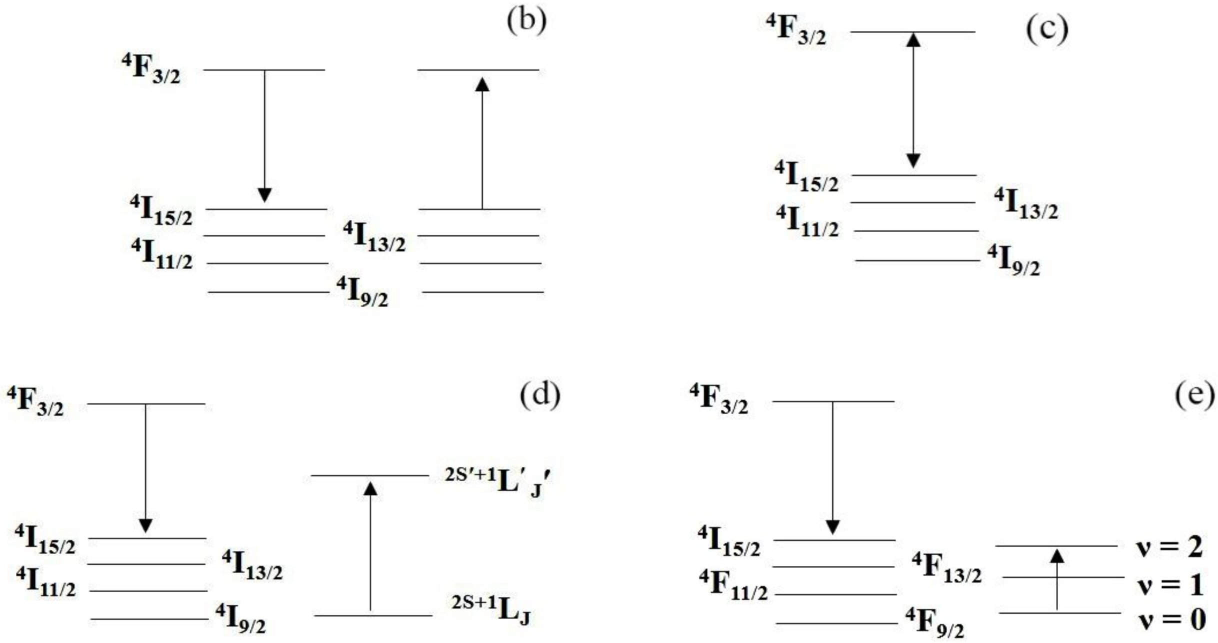


Figure 5 Transition of Nd^{3+} doped laser medium (a) possible energy levels transition pathways of Nd^{3+} doped glasses [54, 58], (b) Nd^{3+}-Nd^{3+} concentration quenching, (c) Nd^{3+} multi-phonon relaxation, (d) Nd^{3+}-ion to other RE^{3+} ion, and (e) Nd^{3+}-OH phonon transition.

Table 4 Refractive index (n), density (ρ), emission wavelength (λ_{emi}), effective line width ($\Delta\lambda_{eff}$) and stimulated-emission cross-section ($\sigma(\lambda_p)$) of certain oxide glasses synthesized in CEGM laboratory and those reported in the literature

Glass	Refractive Index, n	Density (g/cm^3)	λ_{emi} (nm)	$\Delta\lambda_{eff}$	$\sigma(\lambda_p)$ ($\times10^{-20}$ cm^2)
BSGdCaNd0.5 [54]	1.6550	4.091	1059	32.87	1.39
BSGdCaNd1.0 [54]	1.6551	4.093	1059	-	-
BSGdCaNd1.5 [54]	1.6552	4.116	1059	-	-
BSGdCaNd2.0 [54]	1.6555	4.144	1059	-	-
BSGdCaNd2.5 [54]	1.6560	4.181	1059	-	-
SLBNd0.5 [55]	1.538	2.471	1069	37	4.0
SLBNd1.0 [55]	1.539	2.504	1069	-	-
SLBNd1.5 [55]	1.540	2.550	1069	-	-
SLBNd2.0 [55]	1.542	2.566	1069	-	-
SLBNd2.5 [55]	1.543	2.604	1069	-	-
SPbKNLFNd10 [56]	1.651	4.010	1056	36.4	4.11
S65ND1 [96]	1.534	2.617	-	-	-
S65ND2 [96]	1.544	2.702	-	-	-
S65ND3 [96]	1.554	2.779	-	-	-
S65ND4 [96]	1.562	2.853	-	-	-
S65ND5 [96]	1.567	2.918	-	-	-
CaNd1 [97]	1.544	3.001	1065	-	-

Glass	Refractive Index, n	Density (g/cm^3)	λ_{emi} (nm)	$\Delta\lambda_{eff}$	$\sigma(\lambda_p)$ ($\times10^{-20}$ cm^2)
CaNd2 [97]	1.549	3.004	1065	-	-
CaNd3 [97]	1.554	3.031	1065	-	-
CaNd4 [97]	1.556	3.054	1065	-	-
CaNd5 [97]	1.563	3.104	1065	-	-
SrNd1 [98]	-	3.335	1065	-	-
SrNd2 [98]	-	3.337	1065	-	-
SrNd3 [98]	-	3.360	1065	-	-
SrNd4 [98]	-	3.390	1065	-	-
SrNd5 [98]	-	3.450	1065	-	-
Bi_2O_3–BaO–B_2O_3-0.5Nd_2O_3 [58]	-	5.050	-	-	-
Bi_2O_3–BaO–B_2O_3-1.0Nd_2O_3[58]	-	5.082	-	-	-
Bi_2O_3–BaO–B_2O_3-1.5Nd_2O_3 [58]	-	5.100	-	-	-
Bi_2O_3–BaO–B_2O_3-2.0Nd_2O_3 [58]	-	5.120	-	-	-
Bi_2O_3–BaO–B_2O_3-2.5Nd_2O_3 [58]	-	5.200	-	-	-
LCB [99]	1.531	4.53	1058	30	2.965
NCB [99]	1.534	4.37	1060	38	2.465
KCB [99]	1.532	4.21	1061	32	3.195
PKCFAN [100]	1.536	2.896	1056	-	3.420
BBONd [101]	1.62	4.22	1062	39.4	2.49
ZnAlBiB [102]	1.805	3.29	1060	30	3.67
TZN10 [103]	-	-	1061	31	4.27
BiZNd [104]	-	6.45	1065	37	3.36
TZNLN [105]	-	-	1061	28.35	4.27
TZONd [106]	-	-	1062	24	4.2
BNaNf [107]	1.629	2.58	1062	18	4.18
LTTNd [108]	-	-	1062	41	4.75
GSBNd [109]	-	-	1070	49	2.1
TznNd [110]	-	-	1062	30.2	4.27

6. Conclusions

In the present work, the detailed statement of laser and its importance has been discussed. The inventions and their inventor's details over a century have been listed. The vital parameters required for commercializing the glasses have also been underlined. Future research on laser medium and optical fiber glasses has been highlighted. NIF hohlraum, LFEX and GEKKO XII laser fusion experiments are reviewed and presented. The wavelength of the laser defines their particular applications in various fields is provided. Specific oxide glasses doped with Nd^{3+} ions synthesized in the CEGM laboratory have been presented and discussed. The BSGdCaNd glasses doped with Nd^{3+} ions show strong luminescence and high density opted for solid-state laser device applications.

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