Research Progress of Yb^{3+} -Ho^{3+} co-doped Solid Laser at 2μm Wavelength

Qun Liu [1, *]

[1]Department of Physics, Harbin University, Harbin, 150080, China

Email: qunliu@126.com

[*]Corresponding author

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Abstract: The characteristics of 2μm wavelength laser, application background and approaches to realizing 2μm wavelength laser have been summarized in this paper. The energy level structure and luminescence mechanism of Yb^{3+} -Ho^{3+} co-doped laser crystals are analyzed in detail. This paper points out that the sensitizing ions Yb^{3+} doped in crystal can effectively improve the absorption efficiency, and makes it possible for the laser work material to effectively couple with InGaAs laser diode (LD), and this is applicable to LD pumping. The domestic and foreign research progresses of Yb^{3+}-Ho^{3+} co-doped laser crystals are summarized, and the development prospect of Yb^{3+}-Ho^{3+} co-doped laser material is expected. Finally, several kinds of Yb^{3+}-Ho^{3+} co-doped laser work materials which may have greater development prospects are analyzed.

1. Introduction

2μm wavelength laser is a waveband which is safe for human eyes and the light source within this waveband is located nearby the water molecular absorption peak with advantages such as good air permeability, small penetration depth into human tissues, possible optical fiber transmission, etc. Therefore, light sources at this wavelength have broad application prospects in fields such as laser medicine, environmental monitoring, laser radar, remote sensing detection and laser ranging [1-4]. Meanwhile, light sources at this wavelength are also ideal pumping sources realizing 3-12μm solid laser [5].

Nowadays which output 2μm wavelength are mainly solid laser and fiber laser. In comparison, solid laser has enormous advantages over fiber laser in aspects of pulse energy and peak power. There are mainly four paths to realize laser output at 2μm wavelength for the solid laser, all of which take a semiconductor laser as the pumping source, respectively being: OPO 2μm pumping at the 1μm light source, Tm laser pumping Ho laser, Tm^{3+}-Ho^{3+}co-doped laser and Yb^{3+}-Ho^{3+} co-doped laser. With appearance and development of high-power semiconductor lasers, pumping rare earth ion single-doped or co-doped crystals by taking a semiconductor laser (LD) as the pumping source becomes one of effective paths to realize solid laser output at 2μm wavelength, and it’s especially favored by scientific research personnel in aspects of improving laser output at 2μm wavelength and miniaturization and performance stability. To seek for Ho ion single-doped or Ho ion and other ions co-doped laser crystals featuring high ion doping concentration, large stimulated emission section, low threshold power, good mechanical properties, polarized laser output and suitability for LD pumping has always been a research hotspot in the field of 2μm solid lasers [6]. The emphasis in this paper is laid on introducing and analyzing research hotspots about Yb^{3+}-Ho^{3+} co-doped crystals and Yb^{3+}-Ho^{3+} co-doped crystals.

2. Luminescence mechanism and advantages of the Yb-Ho co-doped crystal at 2μm wavelength

2.1 Luminescence mechanism of Yb-Ho co-doped crystal at wavelength 2μm.

The Particles realize stimulated radiative transition within $^5I_7 \rightarrow {}^5I_8$ energy level of Ho ions so as to realize laser output at 2μm wavelength [7-8]. It's found in existing studies that Ho ions are weakly absorbed within the range of 900-1100nm and can't realize effective coupling with InGaAs laser diode (LD), so it's not suitable for LD pumping [9]. However, after pumping light is effectively absorbed by doping other rare earth ions in the laser work material, the light will be transferred to Ho ions through energy transfer so as to obtain high-efficiency laser output at 2μm wavelength, and these rare earth ions transferring energy are called sensitization ions. Research findings show that Yb ion-doped laser crystal is absorbed within the waveband scope of 910-1030nm, its main absorption peaks are nearby 930nm and 970nm[10-11], so it can effectively couple with LD and is suitable for LD pumping. Therefore, Yb^{3+} and Ho^{3+} ions are usually co-doped into the matrix and then used as a laser work material after growth, cutting, grinding and film coating to realize LD pumping at 976nm central output wavelength or so and then realize laser output at 2μm wavelength.

As shown in Fig. 1, the pumping source at 976nm central output wavelength pumps the Yb^{3+}-Ho^{3+} co-doped laser crystal, and the pumping light absorbed by Yb ions transits from $^2F_{7/2}$ energy level of Yb^{3+} to $^2F_{5/2}$ energy level of Yb^{3+}. As the pumping light energy gradually increases, particles on $^2F_{5/2}$ energy level of Yb^{3+} gradually increase, cross relation process occurs between ions on $^2F_{5/2}$ energy level of Yb3+ and ions on $^5I_6$ energy level of Ho^{3+}, partial particles on $^5I_6$ energy level of Ho^{3+}transit upward to $^5F_4$ （$^5S_2$)energy level of Ho3+, and the residual particles on $^5I_6$ energy level of Ho^{3+} transit downward to $^5I_7$ energy level of Ho^{3+}. As particles on $^5I_6$ energy level of $Ho^{3+}$are gradually accumulated and generate population inversion and particles on $^5I_7$ energy level of Ho^{3+} transit downward to energy level of Ho^{3+}. Under the effect of laser resonant cavity, laser transition at 2μm wavelength is formed [8].

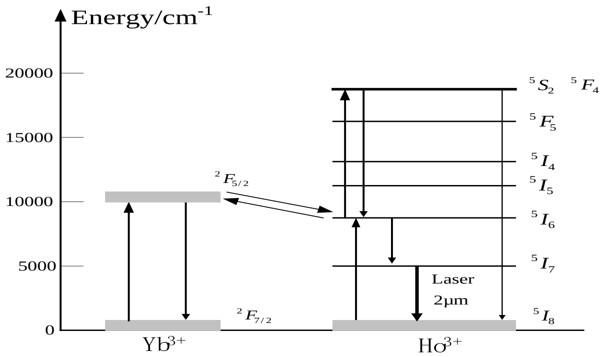

Fig 1. Energy level structure chart of Yb^{3+} and Ho^{3+}

2.2 Luminescence advantages of the Yb-Ho co-doped crystal at 2μm wavelength.

The paths to realize laser output at 2μm wavelength by doping LD pumping rare earth ions doped crystal mainly include: LD pumping Tm-Ho co-doped crystal realizes laser output at 2μm wavelength; LD pumping Yb-Ho co-doped crystal realizes laser out at 2μm wavelength. In the two paths to realize laser output at 2μm wavelength, Tm^{3+} and Yb^{3+} are both sensitization particles used to absorb pumping light while Ho^{3+} is used as activating particle. In the process of realizing laser output at 2μm wavelength through LD pumping Tm-Ho co-doped crystal, Tm^{3+} is sensitization particle, it's pumping absorption energy level transits to $^3H_6 \rightarrow {}^3H_4$ of Tm^{3+}, and the corresponding absorption band is nearby 800nm; when particles on $^3H_4$ energy level of Tm^{3+} are accumulated to a certain degree, they will transit downward to 3F4 energy level of Tm3+; when particles on $^3F_4$ energy level of Tm^{3+} are accumulated to a certain degree, resonant energy transfer occurs between $^3F_4$ energy level of Tm^{3+} and $^5I_7$ energy level of Ho^{3+}, Ho^{3+} is activated, and this process is complicated with great energy loss.

Energy transfer process of the Tm^{3+}-Ho^{3+} co-doped laser crystal is shown in Fig. 2.2, mainly including five processes. The first process: particles on $^3H_6$ energy level of Tm^{3+} absorb energy of LD pumping light to generate stimulated absorption transition to $^3H_4$ energy level, and this process is recorded as $^3H_6 \rightarrow ^3H_4$. The second process: cross relaxation process occurs between particles on $^3H_4$ energy level and particles on $^3H_6$ energy level, particles on $^3H_4$ energy level transit downward to $^3F_4$ energy level, energy released in this process is rightly absorbed by particles on $^3H_6$ energy level and transits to $^3F_4$ energy level, and this is recorded as ($^3H_6$,$^3H_4 \rightarrow 2\ ^3F_4$). The third process: resonant energy transfer occurs between $^3F_4$ energy level of Tm^{3+} and energy level $^5I_7$ of Ho^{3+}, and particles on $^3F_4$ energy level are relaxed onto $^3H_6$ energy level. Meanwhile, the released energy is absorbed by particles on $^5I_8$ energy level of Ho^{3+} and transited to $^5I_7$ energy level of the laser so that distribution for population inversion is realized. This is a reversible process. With continuous pumping of pumping light and laser output, this process will reach a dynamic equilibrium state, and this is recorded as ($^3F_4$,$^5I_8 \leftrightarrow ^3H_6$,$^5I_7$).

3. Development of common Yb-Ho co-doped solid laser crystals

Commonly used laser work materials doped with Yb^{3+} and Ho^{3+} are mainly divided into two types: oxide crystals and fluoride crystals. The former has good physical properties such as high hardness and mechanical strength, good chemical stability and thermal properties, and it has potentials of realizing high-power and high-efficiency laser output [12]. Laser crystals represented by aluminate, tungstate, vanadate and borate are exerting more and more important effects in the field of solid laser. Fluoride laser crystals have advantages like long autofluorescence life, minor temperature influence on reflection rate and small thermal lens effect, and moreover, they have favorable thermal stability. They have special application values in the field of solid lasers, and fluoride laser matric materials represented by YLF have been playing a significant role in the field of solid lasers [13]. Research status of commonly used Yb^{3+}-Ho^{3+} co-doped laser crystals among oxides and fluorides will be respectively introduced herein.

3.1 Oxide laser crystals

1)Aluminate laser crystals

①Yb,Ho:YAG

YAG is the abbreviation of yttrium aluminum garnet (YAG). YAG crystal has had over 50-year history as a laser medium [14]. It belongs to a cubic crystal system with optical isotropy and it is applicable to doping of multiple activating ions. As YAG has characteristics needed by many laser work materials such as stable physical and chemical properties, good mechanical properties and high thermal conductivity, it has been usually used as a laser matrix. However, this crystal will generate depolarization loss due to thermal birefringence effect when the laser operates under a high power, which will affect laser output power, and this is an important defect of this crystal. Rothacher et al. obtained laser output of output power of 370mW and slope efficiency of 3.7% at 2μm wavelength through LD pumping Yb, Ho:YAG under indoor temperature in 1998[15]. It’s reported that in YAG, energy transfer efficiency between Yb and Ho can reach as high as 92%[16]. Therefore, Yb, Ho:YAG is a kind of laser gain medium with great development potentials.

②Yb,Ho:YAP

YAP, the abbreviation of yttrium aluminum perovskite crystals with orthorhombic crystal system and birefringence characteristics, can inhibit thermally-induced birefringence effect with features such as wide absorption spectrum, large absorption cross section, anisotropy, short growth period and uneasy saturation of output power. Meanwhile, laser rays of this crystal have a high linear polarization, this linear polarization has advantages in aspects of obtaining polarized oscillation and laser modulation with small harmful depolarization under high-power pumping, and laser output power produced by the crystal will be high [17]. Its shortcoming is that it is of relative instability under high temperature with anisotropic thermal expansion coefficients, which will easily cause crystal cracking. There has been no report on 2μm laser output by Yb, Ho:YAP laser crystals. Nevertheless, the author believes that this crystal also has a good development prospect by virtue of its advantages.

2)Borate laser crystals

①Yb,Ho:YAB

Yb,Ho:YAB, the abbreviation of Yb,Ho:$YAl_3(BO_3)_4$, has a great nonlinear optics coefficient (deff>1.3pm/V), favorable thermal conductivity and chemical stability, and it is a superior matrix crystal. As shown in Fig. 2, as early as 2003, it's verified through an experiment that fluorescence of 2μm wavelength of Yb,Ho:YAB could be stimulated by 976nm laser, and integral emission cross section in the 1966nm channel was larger than 10^{-18}cm [18]. It's reported that this crystal is expected to realize laser output at 2μm wavelength[19]. Even though no other related experiments have verified luminous power or efficiency of this work material so far, it's undeniable that this crystal has a good development potential.

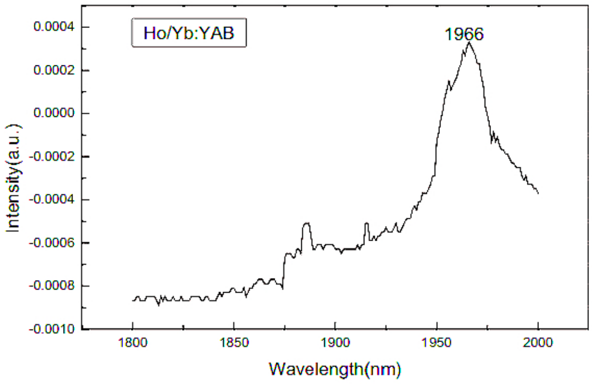

Fig 2. Fluorescence emission spectrum of Yb,Ho:YAB pumped at 976nm

3)Tungstate laser crystals

①Yb,Ho:$KLu(WO_4)_2$

Yb,Ho:$KLu(WO_4)_2$, abbreviated as Yb,Ho:KLuW, belongs to a monoclinic system with C2/c space group and superior high-temperature resistance, large emission cross section, small quantum defect and natural birefringence, so it is superior laser crystal. As shown in Fig. 3, Venkatesan Jambunathan et al., conducted an experimental study and analysis of this crystal in 2010, it could realize laser output at 2μm wavelength under laser pumping with output wavelength of 980nm[20], and they proposed that this crystal would be a potential work material for solid lasers at 2μm wavelength.

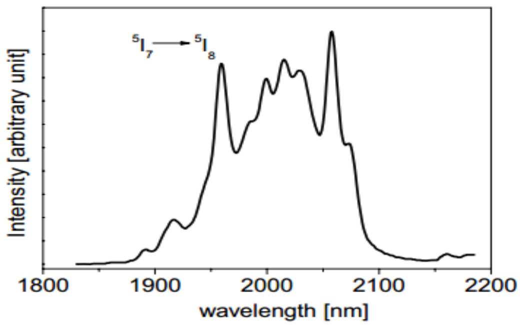

Fig 3. Laser emission spectrum of Yb,Ho:KLu(WO4)2 pumped at 980nm

②Yb,Ho:KGW

Low-temperature phase of $KGd(WO_4)_2$ crystal (abbreviated as KGW) belongs to a monoclinic system with space group of C2/c. It is an outstanding laser matrix material [21-22]. Zhu ZL et al. from Changchun University of Science and Technology proved through an experiment that in this crystal, Yb^{3+} had absorption peaks at both 935nm and 981nm, the absorption peak at 981nm was the strongest, and it's suitable for LD pumping. As shown in Fig. 4, this crystal has a strong emission peak nearby 1985nm[23], and it is one of ideal work materials generating 2μm laser. There has been no experimental report on this crystal generating a high-power 2μm laser.

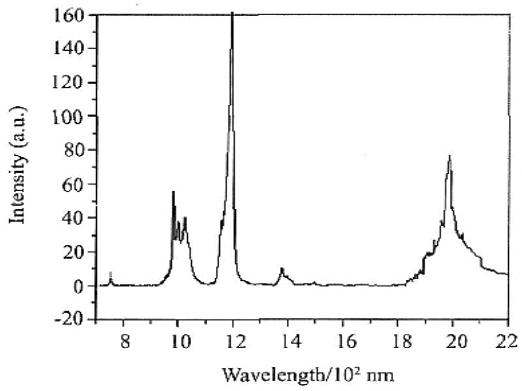

Fig 4. Fluorescence spectrum of Yb,Ho:KGW

4)Vanadate laser crystals

①Yb,Ho:$LuVO_4$

Although this crystal is a new crystal in vanadate, it has been extensively used as matrix material of Nd^{3+}, Tm^{3+} and Yb^{3+}. In 2006, Liu JH and Valentin Petrov et al. conducted single-end and double-end pumping experiences on Yb:$LuVO_4$ and obtained maximum power output of 4.5W, optical conversion efficiency of 33% and slope efficiency of 40%[24]. In 2014, Yao BQ and Cui Z et al. conducted double-end pumping of the Ho:$LuVO_4$ crystal under indoor temperature and obtained laser output at 2μm wavelength, but optical conversion efficiency was only 12.9% and slope efficiency was only 17.6% [25], so the effect was not that ideal. However, as Yb^{3+} has a high optical conversion efficiency in this crystal and high-efficiency energy transfer exists between Yb^{3+} and Ho^{3+}, Yb,Ho:$LuVO_4$ will generate laser at 2μm wavelength more easily with a higher output efficiency under the laser pumping at 980nm. So far, there has been no related report on 2μm laser output by Yb,Ho:$LuVO_4$ crystal, which is used as laser work material, but we have reason to believe that Yb,Ho:$LuVO_4$ will be one of ideal work materials of 2μm solid lasers through the analysis.

5)Other oxide laser crystals

①Yb,Ho:Y_2O_3

Sesquioxide Y_2O_3 belongs to a cubic crystal system with high thermal conductivity. Suitable for rare earth ion doping, it is one of ideal laser gain media. Lv L from Xidian University and Zou YW from Chinese Academy of Sciences et al. realized maximum output power of 138mW in 2012 by taking Yb,Ho:Y_2O_3 as the gain medium and 790nm semiconductor laser as pumping source, which corresponded to continuous operation of laser at 2μm wavelength with slope efficiency of 2.7% [26].

3.2 Fluoride crystals

①Yb,Ho:YLF

Yttrium lithium fluoride (YLF), a low-photon material, has many advantages over other matrix materials (YAP and YAG) such as small upconversion loss, favorable thermal stability and energy storage performance, high optical damage threshold, no thermally-induced birefringence effect, and moreover, as it has a uniaxial crystal structure and negative refraction rate coefficient, polarized oscillation can be easily obtained by taking it as the matrix, and its service life is relatively long [27-28]. However, an experiment has already verified that due to intense cross relaxation phenomenon between $Yb^{3+}$and in this work material, 940~970nm pumping light can't be used to stimulate this work material to generate laser at 2μm wavelength[29-30]. Therefore, from existing research progresses, this work material is not suitable to be used as work material generating 2μm laser.

4. Conclusions and expectations

Based on the analysis of luminescence mechanism of Yb^{3+}-Ho^{3+} co-doped laser crystal, advantages and disadvantages of commonly seen Yb^{3+}-Ho^{3+} co-doped oxide laser crystals and fluoride laser crystals in the aspect of realizing laser output at 2μm wavelength were expounded in detail, where Yb^{3+}-Ho^{3+} co-doped oxide laser crystals have high hardness, high mechanical strength and good chemical stability, but this laser crystal can be of a certain instability under high temperature, which will affect laser output power. Fluoride laser crystals have advantages such as long service life of autofluorescence, small thermal lens effect and low photon energy, but they have poor chemical stability and mechanical strength, so they are not good for practical application. So far, Yb,Ho:YAG, Yb,Ho:KLu$(WO_4)_2$ and Yb,Ho:Y_2O_3 crystals have realized laser output at 2μm wavelength. According to domestic and foreign studies on laser performances of Yb^{3+}-Ho^{3+} co-doped laser crystals at 2μm wavelength, it can be obtained that Yb,Ho:YAG, Yb:Ho:YAP and Yb,Ho:$LuVO_4$ will have favorable laser output performances and have good research and application prospects as research hotspots in the field of laser at 2μm wavelength.

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