Study of all-solid-state, high-power continuous-wave tunable blue laser

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ABSTRACT

During the past few years, study of the all-solid-state blue laser has been focused on laser field applications in many fields and potential value of commerce. There has been much work done in order to obtain an efficient and simple solid-state blue laser source, this device being of interest for applications such as display technologies, production of high-density optical disk systems, high-resolution printing, or medical diagnostics. This paper discusses three means to realize all-solid-state blue lasers, including blue-emitting diode laser, direct frequency doubling of infrared laser diode (LD), diode-laser pumped all-solid-state blue lasers, respectively. However, direct emitters based on II – VI semiconductors are limited by the lifetime of laser diode. A practical and the most used way is the frequency-doubling of the 946-nm in Nd:YAG. In the field of nonlinear frequency conversion, we compare some different frequency-doubling crystals with improved optical characteristics, including higher nonlinear coefficient, wider transmission range, and more flexible phase-matching (PM) properties. Some nonlinear optical crystals usually used in solid-state laser are analyzed and compared, including $KNbO_3$, LBO, BBO, BiBO, CBO (CsB_3O_5), KBBF ($KBe_2BO_3F_2$). The recent progress on solid-state blue laser has resulted research in from gain media, frequency-doubled crystals, and configurations of the cavities. Two difficulties which are the coating techniques and the blue noise problem (the fluctuation of the laser output power) in the development of solid-state lasers are pointed out, and the techniques of solving blue noise problem that have been usually used in the past research are presented.

Keywords: All-solid-state, Blue laser, Diode-laser, frequency doubling

1. INTRODUCTION

All-solid-state blue emission is a new visible laser source after green laser. Three means of generating blue emission are often used: 1) blue-emitting diode laser, 2) directly frequency-doubled diode-laser radiation, 3) diode-pumped all-solid-state blue lasers. The frequency-doubling of the 946nm in Nd:YAG to 473nm is a practical and the most used way. Fan and Byer first introduced Nd:YAG laser end-pumped by diode laser at 808nm and realized infrared output at 946nm, and built up the theoretical model of the diode-pumped quasi-three-level laser[1]. In previous work, Czeranowsky[2] used BiB_3O_6 (BiBO) for intracavity frequency doubling of Nd:YAG, achieved up to 2.8W at 473nm, it was the highest output power in the blue spectral region so far. In 1999, Changchun Institute of Optics, Fine mechanics and Physics of Chinese Academy of Sciences (CAS) reported firstly in china the output of 473nm by LBO intracavity frequency doubling of Nd:YAG[3]. Through optimization, 120mW of blue light was obtained pumped by a 2W single-stripe diode laser, low-noise and single-longitudinal-mode operation was realized if an all-wave plate was inserted into the cavity[4]. There was a great development on high-power tunable blue laser output in 2003 done by Institute of Physics of CAS, the output power achieved up to 1.3W, and the blue wavelength could be tuned between 455nm and 492nm. In this paper,

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the recent progress on all-solid-state blue laser has been summarized from gain media, frequency-doubled crystals, and configurations of the cavities, and the techniques of solving blue noise problem that has been usually used in the past research are presented.

2. EXPERIMENTAL RESEARCH

2.1 Blue-emitting diode laser

In 1996, Sony realized 515nm blue-green radiation, which output power reached 1mW and worked continuously for 100h[5]. In 2001, Nagahama reported InGaN multi-quantum-well-structure laser diodes, which emission wavelengths are in the pure blue region. Its lifetime was approximately 3000h under 50 °C with 5 mW output power at 460nm[6]. Skierbiszewski reported the InGaN multi-quantum LD made by rf plasma-assisted molecular beam epitaxy (PAMBE) which operated at 408-nm at room temperature[7]. It's believed that with the continuing improvements on the quality of GaN substrates and further optimization of the PAMBE growth conditions the technique is well positioned to become an alternative to the MOCVD technology in the production of high performance GaN-based optoelectronic devices.

2.2 Direct frequency doubling of LD to obtain blue generation

Direct frequency doubling can realize considerable high optical-to-optical conversion efficiency. Coldkey[8] et al. reported 24mW, 421nm blue radiation generated by direct frequency doubled 842nm LD with $KNbO_3$ crystal, its optical conversion efficiency was 17%. Kozlovsky[9] et al. reported using electronic servo technique to lock the frequency of 856nm diode laser, and obtained stable generation of 41mW of 428nm blue output with an optical conversion efficiency of 39%. Xiaofan Cao[10] et al. reported generation of 0.3mW blue radiation from a 852nm diode laser with a conversion efficiency of 22% using quasi-phase-matching (QPM) in a $LiNbO_3$ waveguide. Bier et al. reported 403nm blue-violet laser output by frequency doubling 806nm diode laser by an external resonant cavity with critically phase matched LBO and BBO. 98mW blue-violet output could generate with a 16-mm-long LBO crystal at 387mW pump power, or a 12-mm-long BBO crystal at 417mW pump power. The measured conversion efficiencies were in good agreement with the values calculated[11]. Woll et al. obtained 1W blue radiation at 465nm, using LBO crystal for direct frequency doubling 4W 930nm LD[12]. At the same year, Tomoya et al. demonstrated new type periodic poled $MgO:LiNbO_3$ waveguide and obtained blue generation of 17.3mW at 426nm with 31% optical conversion efficiency [13].

2.3 All-solid-state blue laser

In order to obtain higher output power and better beam quality, it's usually to double frequency of all-solid-state laser to generate blue light. Risk et al. developed the first 946-nm Nd:YAG laser in the world intracavity frequency-doubled by $LiIO_3$ crystal, resulting $100\mu W$ of blue light[14]. The best result to date at 473nm is 2.8W[1], with a passive Q-switch, the peak power of the blue laser pulse reached up to 26W[15].

2.3.1 Laser crystal

There are many laser crystals that can generate blue radiation through intracavity frequency doubling, such as Cr:LiSAF, Nd:YAG, $Nd:YVO_4$, $Nd:YAlO_3$, $Nd:GdVO_4$, Yb:YAG, and so on. The crystals doped with Nd^{3+} are the most used materials than the others.

Comparison of Nd^{3+} laser characteristics, as shown in fig.1 and fig.2[16]

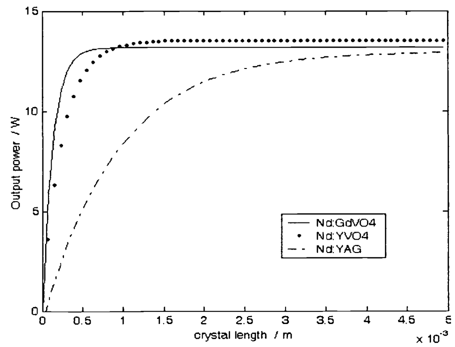

Fig.1 Output power vs crystal length

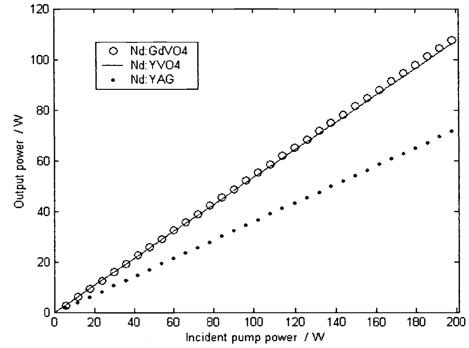

Fig.2 Output power vs incident pump power

Three Nd^{3+}-doped crystals have different physical property, so they have different characteristics in laser output. Comparison with Nd:YAG, the most advantage of Nd:YVO_4 exist in wide absorption band, high absorption efficiency, and the peak pump wavelength at 808nm, but due to its short upper level life time and low thermal conductivity, it is the ideal gain medium for low power lasers, especially for microchip laser. Nd:$GdVO_4$ is also an efficient crystal, the thermal conductivity of which is comparable with that of Nd:YAG crystals, and is almost two times greater than Nd:YVO_4[17]. It has a larger absorption cross section and an emission cross section at 1064nm. Therefore Nd:$GdVO_4$ is the promising substitute for Nd:YVO_4 and Nd:YAG in diode-pumped laser products.

2.3.2 Nonlinear crystals of all-solid-state lasers

There are many NOL crystals, such as $KNbO_3$, $LiNbO_3$, BBO, LBO, BiBO, CBO, KBBF. The $KNbO_3$ crystal has a high value of nonlinear coefficient (d_{31}=15.8pm/v, d_{32}=18.3pm/v)[18], small walk-off, but it has a small temperature and spectral acceptance bandwidths, photo-refractivity, and its domain structure is easily disturbed. Compared with usually used BBO and LBO, CBO has a considerable nonlinear coefficient with LBO, exhibits transparent far in the ultraviolet range and much higher damage threshold than BBO, but it is easy deliquescence[19]. KBBF, has a high optical damage threshold nearly the same as LBO, no photo-refractive phenomenon, could be an excellent crystal for the fourth harmonic generation of Nd:YAG laser compared with BBO and CLBO, and it may realize sixth harmonic generation of Nd:YAG laser output. But due to it decomposes at a relatively low temperature and exhibits a strong layering tendency, it very difficult to grow samples thicker than a millimeter[20].

Table 2 Properties of NLO crystals for frequency-doubling at 946nm

	BBO	LBO	$LiIO_3$	$BiB0_3$	KN
Phase matching type	I	I	I	I	I
Phase matching angle	θ=24.9°	θ=19.5° ϕ=90°	θ=34.3	θ=161.7 ϕ=90	θ=90^0 ϕ=59.2°
$d_{eff}(pm/v)$	2.08	0.81	4.0	3.3	16.4
Walk-off (mrad)	60.3	11.3	80.3	40.7	17.4
Deliquescence	Easy	Not easy	Easy	Not easy	easy

2.3.3 Configuration of cavity

The basic pump method is end-pumping, as shown in fig4。When end-pumping power is low, due to pump beam can match well with cavity mode, gain medium can absorb the pump light completely, and it's easy to output TEM_{00} mode, therefore the laser can be readily be operated on low threshold pump power, high slope efficiency.

Besides plane-cavity, folded cavity designed to achieve efficient laser operation and minimize the thermal lens effects in the crystal, includes V-type cavity (fig.3) and Z-type cavity (fig.4). Compared with plane-cavity, folded cavity which has a wider permitted variable range of the focal length of thermal lens, can improve the output power of frequency doubling. However, compared with Z-type cavity, V-type cavity has a narrow stable range, and its mode parameter is easy varied with the focal length of the thermal lens, but due to less components and light transition in the cavity, its cavity loss will be much lower than Z-type[21]。

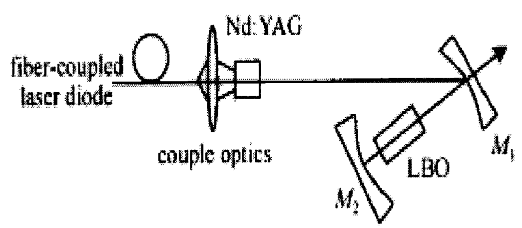

Fig.3 V-type cavity[22]

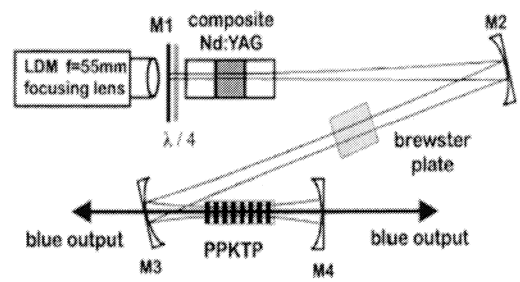

Fig.4 Z-type cavity[23]

3. DIFFICULTIES IN THE DEVELOPMENT OF ALL-SOLID-STATE BLUE LASER

Although there have been great improved on all-solid-state blue lasers, there still exists problem that limit the development of blue laser.

One factor that restrains the development of blue laser is optical coating. In order to obtain 946-nm or 914-nm infrared output, the parasitic oscillation at 1064nm must be suppressed, so the surfaces of crystals should be anti-reflection coated at the pumping wavelength of 808-nm and high-transmission coated at 1064-nm. But due to optical coating is complex and not easy to succeed, it limits the development of the blue laser to a certain extent.

"Blue problem". The principle of the blue problem is the same as green problem. The noises result from coupling of the longitudinal modes in the nonlinear optical crystal. Baer presented a rate-equation model of a multi-longitudinal mode in an intracavity frequency doubling crystal, which predicts accurately the dependence of these fluctuations on the pump level, the nonlinear coupling constant, and the number of oscillating modes[24]. Since Nd:YAG is an isotropic material and emits un-polarized radiation, the incident beam consisted of two orthogonal linearly polarized modes, and when the polarization eigenvectors were parallel to the E and O axes of the crystal, a large amplitude fluctuation was observed. Oka et al. explained it by analyzing the coupling of the two orthogonal linearly polarized modes through a sum-frequency-generation process[25]. Blue noise influence the stability of the output and the beam quality, and limit the application of blue light. A direct method to eliminate or reduce the noise is to force the laser operation on single longitudinal mode. By inserting a quarter-wave plate into cavity with its azimuthal angle at 45° with respect to the E axes of the crystal, the instability caused by the coupling of two polarization modes was effectively suppressed. Using silicon crystal all-wave plate can also realize low noise and single longitudinal mode operation[4]. Low-noise stable output can also realizd by using two identically crossed placed doubler and one polarized plate which could successively eliminate the coupling between different modes [26].

4 CONCLUSIONS

In this paper, we have introduced three means to realize all-solid-state blue lasers and its recent progresses on solid-state blue laser have been summarized from gain media, frequency-doubled crystals, and configurations of the cavities, and compared some nonlinear crystals usually used. We also pointed out the two difficulties including the coating techniques and the blue noise problem (the fluctuation of the laser output power), and presented the techniques of solving blue noise problem that has been usually used in the past research.

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