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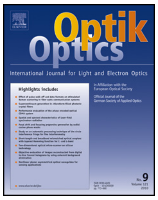

Research on all-solid-state blue lasers

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ABSTRACT

Blue lasers have many important applications such as high-density optical data storage, biological and medical diagnostics, color displays, and submarine laser imaging and communication. High efficiency, high brightness and compactness all-solid-state blue lasers have attracted much attention for their merits. In this paper, four main ways for achieving all-solid-state blue lasers are reviewed and compared in detail, such as the semiconductor laser, the frequency-doubling of the semiconductor laser, the up-conversion blue laser, the nonlinear optical frequency conversion of Nd^{3+}-doped or optical parametric oscillating lasers and so on. Results show that the nonlinear optical frequency conversion of the Nd^{3+}-doped lasers is a potential way to realize a high power, high efficiency cw or pulsed blue laser output.

1. Introduction

Continuous-wave (cw) blue lasers have many important applications such as high-density optical data storage, biological and medical diagnostics, and color displays. And pulsed blue lasers are also needed in some special cases such as submarine laser imaging and communication [1–4]. In these applications, high efficiency, high brightness and compact blue lasers are in demand urgently. Therefore, all-solid-state blue lasers have attracted much attention for their merits. By now, four main ways are used to achieve all-solid-state blue lasers output. First of all, the blue laser is emitted by semiconductor directly. Secondly, the blue laser is generated by frequency-doubling of the near-infrared semiconductor laser. Thirdly, the blue laser is obtained by using some up-conversion materials. Fourthly, the blue laser is achieved by using the nonlinear optical frequency conversion of the Nd^{3+}-doped or optical parametric oscillating lasers, such as frequency-doubling, third harmonic effect and so on.

In this paper, the development of all-solid-state blue lasers in recent years is reviewed and their characteristics are compared in detail, including semiconductor lasers, up-conversion lasers, nonlinear optical frequency conversion lasers and so on. Results show that the nonlinear optical frequency conversion of the Nd^{3+}-doped lasers is a potential way to realize a high power, high efficiency cw or pulsed blue laser output.

2. Semiconductor blue lasers

In 1991, Haase reported a blue laser which was obtained by using a semiconductor material of ZnCdSe/ZnSe [5]. In this laser, the temperature of the semiconductor material should be kept at 77 K for pulsed laser operation. In 1995, Okuyam achieved the 471 nm blue laser by using a semiconductor material of ZnSe/ZnMgSSe [6]. Compared with the materials of SiC and ZnSe, GaN in III–V group has a larger direct band gap, higher thermal conductivity and higher electron saturation velocity. Also, the stability of the physical and chemical characteristics is quite well. Therefore, it is easier to obtain blue laser output by using GaN, but the wavelength is located in blue-violet band [7,8].

3. Blue lasers by frequency-doubling of near-infrared semiconductor lasers

With the development of laser diode in infrared band, the blue laser is researched by using frequency-doubling of the semiconductor laser. In 1994, the Coherent Inc. presented a 430 nm blue laser with output power of 10 mW by using frequency-doubling of an 860 nm laser diode. However, the output power is too low and the beam quality is not well by this way.

4. Blue lasers produced by some up-conversion materials

According to the up-conversion mechanism, some materials doped with rare earth ions can emit blue lasers with the wavelengths shorter than that of the excited light. Up-conversion

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mechanism is usually divided into three processes, which are excited state absorption, energy transfer, and photon avalanche. Tm^{3+} or Pr^{3+} doped oxides and fluorides are mostly used as gain medium for generating blue lasers. To improve the absorption efficiency of the pump light and the up-conversion luminescence efficiency, Yb^{3+} ions as a sensitizer is usually co-doped with Tm^{3+} or Pr^{3+} doped oxides and fluorides according to the multi-phonon absorption principle. Fiber is always used due to the waveguide structure, which can ensure a higher energy density of the pump light in the entire length of the medium. Thereby, the efficiency of the up-conversion is improved obviously. Also, the long length of the medium can compensate the disadvantage of low absorption resulted from the low concentration of the active ions [9–13]. Usually, the absorption band of up-conversion materials is much wider and the absorption of the pump laser is insignificant to the polarization. Due to these two reasons, the efficiency of the up-conversion blue laser is quite high. However, the up-conversion mechanism is sensitive to the temperature and the output spectrum is becoming wider with the increase of the temperature. Thus the absorption efficiency will be reduced by this way. Furthermore, the metastable state lifetime of the gain medium is reduced by the adverse effect of the heat induced cross-relaxation, leading to an unstable operation of the output laser. Moreover, the output laser is not reproducible, which limits its practical application.

5. Blue lasers by using nonlinear optical frequency conversion

Diode-pumped solid-state laser (DPSSL) owns the merits of high efficiency, high output power, high beam quality and stable operation. Combined with the nonlinear optical frequency conversion technology, high performance laser can be achieved in the visible region. In accordance with the nonlinear optical frequency conversion technology, four ways for generating the blue lasers are listed as follows.

5.1. Frequency-doubling

Nd^{3+} doped laser materials, such as Nd:YAG, Nd:YVO_4, Nd:$GdVO_4$, Nd:$LuVO_4$ and Nd^{3+} fiber, can emit 0.9 μm laser by using the quasi-three-level transition between $^4F_{3/2} \rightarrow {}^4I_{9/2}$. Therefore, high power and high beam quality blue laser around 0.45 μm can be obtained by frequency-doubling technology [14–23].

Ti:Al_2O_3 and Cr:LiSAF can emit laser at near infrared region and their wavelengths can be tuned around 0.8 μm, so cw or pulsed blue laser can be also achieved by frequency-doubling [24,25].

In addition, blue laser at 490 nm is generated by frequency-doubling of the optics pumping semiconductor vertical external cavity surface emitting laser (OPS Laser) at 980 nm [26]. The OPS laser owns the characteristics of high output power, high beam quality and compact structure. The sheet-type gain medium is used to avoid thermal lens effect. The stimulated emission cross section of the multi-quantum well is increased by the periodical structure of the resonant gain. The resonant cavity loss is reduced by the distributed Bragg reflector. Compared with the rod gain medium, this structure provides a better beam quality near diffraction limit and a wide-ranging wavelength choice [27].

5.2. Sum-frequency

Blue laser at the wavelength of 455–475 nm is achieved by extra-cavity sum-frequency of the 1.06 μm Nd^{3+} laser ($^4F_{3/2} \rightarrow {}^4I_{11/2}$) and the diode laser around 800–860 nm [28]. It should be noted that the beam quality of the diode laser should be quite well in this way. In addition, to improve the efficiency of sum-frequency, both the mode of 1.06 μm laser and diode laser should be single-longitudinal-mode. But the mode requirement will increase the complexity of the structure, and the output power is usually quite low.

Furthermore, blue laser at 491 nm is also obtained by sum-frequency of the1.06 μm Nd^{3+} laser ($^4F_{3/2} \rightarrow {}^4I_{11/2}$) and the 0.9 μm Nd^{3+} laser ($^4F_{3/2} \rightarrow {}^4I_{9/2}$) [29–32].

5.3. Optical parametric oscillator combining with frequency-doubling

Blue laser can be achieved by optical parametric oscillator (OPO) combining with frequency-doubling. For example, the nonlinear crystal, such as KTP or LBO, can be pumped by high power green laser to obtain 0.9 μm laser. Then, the blue laser can be realized by combining the frequency-doubling technology [33]. Generally, the blue laser by this method owns the merits of high output power, good beam quality and tunable wavelength. However, the efficiency is quite low, and the structure is complex and the volume is much larger.

5.4. Frequency-tripling

440 nm blue laser is realized by frequency-tripling from the Nd^{3+} laser generated 1.3 μm laser ($^4F_{3/2} \rightarrow {}^4I_{13/2}$) [34–36]. It is relatively easy to obtain high power 1.3 μm laser for a larger stimulated emission cross-section at 1.3 μm in Nd^{3+} ions. Two main ways are usually used to obtain the frequency-tripling blue laser. One way is achieving red laser by frequency-doubling of 1.3 μm laser firstly, then generating the blue laser by sum-frequency of the red laser and the residual 1.3 μm laser. The other way is frequency-tripling of the 1.3 μm laser directly by using some nonlinear crystals to improve the efficiency.

6. Development of all-solid-state blue lasers

The research development of all-solid-state cw and pulsed blue lasers in recent years is listed in Tables 1 and 2, respectively. As the classification of semiconductor blue lasers, up-conversion blue lasers, and nonlinear optical frequency conversion blue lasers, the technical solutions and the laser characteristics are reviewed and compared in detail.

Each way to realize all-solid-state blue laser owns its advantages and disadvantages, the comparison results are listed in Table 3.

Blue diode laser and frequency-doubling of the OPS laser are ideal cw blue lasers. The characteristics of compactness and small size make the blue laser useful in the areas of laser display and high density optical storage. However, the expensive equipment and substrate material restrict the development of blue diode lasers. The output power is relatively too low, and the beam quality of the blue laser should be improved to meet the requirements in applications.

The up-conversion blue laser owns the merits of wide absorption bandwidth and high efficiency. However, the low output power and poor stability make it difficult to meet the requirements in applications.

Tunable blue laser can be obtained by the frequency-doubling of the OPO laser or the Ti:Al_2O_3 laser, but the structure is too complex and the efficiency is quite low.

High power of cw and pulsed blue laser can be realized by the sum-frequency of the 0.9 μm and 1.3 μm Nd^{3+} doped lasers or the frequency-tripling of the 1.3 μm laser. However, the efficiency is usually too low, and the wavelength deviates from the window of deep seawater seriously.

Table 1
Research development of all-solid-state cw blue lasers.

Year	Researcher	Technical solutions	Laser characteristics
1995	N.G. Basov	ZnCdSe/ZnSe semiconductor laser	1.6 W, 484 nm, single-frequency [37]
1998	S. Nakamura	GaN semiconductor laser	5 mW, 482 nm [38]
1998	H. Zellmer	Tm:ZBLAN up-conversion laser	375 mW, 482 nm [39]
2004	J. Chilla	OPS laser + LBO intracavity frequency-doubling	15 W, 488 nm, and 5 W, 460 nm [40]
2005	E. Herault	Sum-frequency from 1063 nm and 912 nm $Nd:GdVO_4$ laser + BiBO	0.5 W, 491 nm [29]
2005	X.C. Lin	OPO + BiBO frequency-doubling	1.3 W, 450–495 nm tunable blue laser [33]
2006	Y. Chen	946 nm Nd:YAG laser + LBO intracavity frequency-doubling	3.8 W, 473 nm, $M^2 = 2.3$ [15]
2007	A. Jechow	976 nm LD + PPLN outer cavity frequency-doubling	159 mW, 488 nm, $M^2 = 1.05$ [41]
2008	X. Ding	$Ti:Al_2O_3$ tunable laser + BBO intracavity frequency-doubling	3.5 W, 400 nm, $M^2 = 2.15$ [24]
2009	Q. Zheng	912 nm $Nd:GdVO_4$ laser + LBO intracavity frequency-doubling	14.8 W, 456 nm [17]
2009	Q. Zheng	914 nm $Nd:YVO_4$ laser + LBO intracavity frequency-doubling	13.2 W, 457 nm, $M^2 = 2.13$ [19]
2010	Y.F. Lü	880 nm $Nd:YVO_4$ laser + BiBO intracavity frequency-doubling	233 mW, 440 nm [42]
2010	Y.F. Lü	908 nm $Nd:YLiF_4$ laser + LBO intracavity frequency-doubling	4.33 W, 454 nm [43]
2010	Y.T. Wang	946 nm Nd:YAG laser + PPKTP intracavity frequency-doubling	1 W (SLM), 473 nm [44]
2010	Y.F. Lü	Sum-frequency from 1047 nm Nd:YLF laser and 916 nm $Nd:LuVO_4$ laser + LBO	425 mW, 489 nm [45]
2010	Y.F. Lü	899 nm Nd:YAG laser + BiBO intracavity frequency-doubling	284 mW, 449.5 nm [46]
2011	Y.L. Li	942 nm Nd:GSAG laser + LBO intracavity frequency-doubling	572 mW, 471 nm [47]
2011	K. Li	976 nm LD + PPLN outer cavity frequency-doubling	1.2 W, 456 nm [48]
2011	K.P. Sφrensen	Sum-frequency from 808 nm LD and 1064 nm $Nd:YVO_4$ laser + PP-KTP	100 mW, $M^2 = 1.2\&1.7$ [49]
2011	Y.F. Lü	935 nm Nd:CNGG laser + BiBO intracavity frequency-doubling	490 mW, 468 nm [50]

Table 2
Research development of all-solid-state pulsed blue lasers.

Year	Researcher	Technical solutions	Laser characteristics
2000	Y. Lutz	Pulsed pumped 946 nm Nd:YAG laser + $KNbO_3$ outer cavity frequency-doubling	22.5 mW, 473 nm, 2.5 Hz, 25 ns [51]
2005	A. Chakraborty	GaN semiconductor laser	23.5 mW, 452 nm [52]
2005	O. Casel	Passive mode-locking OPS laser + LBO intracavity frequency-doubling	6 mW, 489 nm, 5.8 ps [53]
2005	Y. F. Chen	Acousto-optic Q-switched $Nd:YVO_4$ 1342 nm laser + LBO/KTP frequency-tripling	0.28 W, 447 nm, 25 kHz,15 ns [34]
2006	H. B. Peng	Acousto-optic Q-switched 1319 nm Nd:YAG laser + LBO intracavity frequency-tripling	7.6 W, 439.7 nm, 5 kHz, 170 ns [35]
2007	S. K. Rong	Pulsed pumped $Ti:Al_2O_3$ tunable laser + LBO outer cavity frequency-doubling	1.0 W, 455 nm, 10 Hz, 17 ns [54]
2008	E. Herault	1063 nm and 912 nm $Nd:GdVO_4$ laser cavity dumper + BiBO intracavity sum-frequency	279 mW, 491 nm, 10 kHz, 3 ns [32]
2008	H. Y. Zhu	Acousto-optic Q-switched 1341.4 nm Nd:YAP laser + LBO/KTP frequency-tripling	4.76 W, 447 nm, 4.6 kHz, 190 ns [36]
2010	F. Chen	946 nm Nd:YAG laser + BiBO outer cavity frequency-doubling	1.5 W, 473 nm, 10 kHz, 9 ns [55]
2010	F. Chen	912 nm $Nd:GdVO_4$ laser + BiBO intracavity frequency-doubling	1.2 W, 456 nm, 42.7 kHz [56]

Table 3
Comparison of the all-solid-state blue lasers.

Technical solution	Operation mode	Best laser characteristics	Advantages	Disadvantages
Semiconductor blue lasers	cw	1.6 W, SLM	Small volume, compact structure, high efficiency	Low power
	Pulsed	23.5 mW		
Frequency-doubling of semiconductor	cw	1.0 W	Simple structure	Low power and poor beam quality
Up-conversion laser	cw	375 mW	Wide absorption bandwidth, high efficiency	Low power and poor stability
Frequency-doubling of Nd^{3+} laser	cw	14.8 W	High power, high efficiency, good beam quality	Gain competition, severely thermal effect
	Pulsed	1.5 W, 9 ns		
Frequency-doubling of tunable $Ti:Al_2O_3$ laser	cw	3.5 W, $M^2 = 2.15$	Tunable	Complex structure, wide linewidth
	Pulsed	1.0 W, 17 ns		
Frequency-doubling of OPS laser	cw	24 W	High power, slight thermal effect	Uneven absorption, poor beam quality
	Pulsed	6 mW, 5.8 ps		
Sum-frequency of 900 nm laser and 1.3 µm laser	cw	0.5 W	High repetition, narrow pulse width	Low efficiency, complex structure
	Pulsed	279 mW, 3 ns		
Sum-frequency of OPO laser	cw	1.3 W	Tunable	Low efficiency, complex structure
Frequency-tripling of 1.3 µm laser	Pulsed	7.6 W, 170 ns W, 15 ns	High repetition, narrow pulse width, high power	Low efficiency, severely thermal effect

Results show that the best way for generating blue laser by now is the frequency-doubling of the 0.9 µm Nd^{3+}-doped quasi-three-level lasers, which own the advantages of simple structure, high efficiency and good beam quality. If the coating quality of the laser medium and the mirrors is improved, the problem of gain competition between the quasi-three-level laser and four-level laser can be solved, and the laser output power will be increased further.

7. Conclusion

This paper reviews the development of all-solid-state blue lasers in detail, and compares the technical solutions and the laser characteristics of semiconductor blue lasers, up-conversion blue lasers, and nonlinear optical frequency conversion blue lasers. Results show that the nonlinear optical frequency conversion of the Nd^{3+}-doped lasers is a potential way to realize a high power, high efficiency cw or pulsed blue laser output.

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