ISSN 1054-660X, Laser Physics, 2012, Vol. 22, No. 4, pp. 635–647.

Research on 2-μm Solid-State Lasers[1]

C. T. Wu[a, b, *], Y. L. Ju[b], F. Chen[c], and G. Y. Jin[a]

[a] *School of Science, Changchun University of Science and Technology, Changchun 130022, China*

[b] *National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150001, China*

[c] *State Key Laboratory of Laser Interaction with Matter, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China*

*e-mail: bigsnow1@126.com

Received October 18, 2011; in final form, November 17, 2011; published online March 6, 2012

Abstract—Diode-pumped solid-state 2 μm lasers have rapid development for their efficient, compact and stable performance. In this paper, we will introduce and discuss the work on 2 μm solid-state-lasers. The advantages and disadvantages of four ways to realize 2 μm laser output are generalized and discussed.

DOI: 10.1134/S1054660X12040275

1. INTRODUCTION

2 μm lasers operating in the eye-safe spectral region are acknowledged for many applications, such as medicine, the pumping source of OPO, especially as the source of LIDAR systems. In recent years, diode-pumped solid-state 2 μm lasers have rapid development for their efficient, compact and stable performance. There're mainly four methods to achieve 2 μm laser output. Firstly, the 1.06 μm laser pumped OPO crystals to realize 2 μm laser output. Secondly, Tm, Ho codoped crystals are pumped by laser diode at around 800 nm, such as Tm, Ho:YLF and Tm, Ho:YAG. Thirdly, some Tm doped crystals are pumped by 800nm laser diode to achieve 1.9 μm laser output and then pumped Ho doped crystals to realize 2 μm laser output. Fourthly, some Tm doped crystals can realize 2 μm laser output directly pumped by laser diode at around 790 nm. In this paper, four ways to realize 2 μm laser output are generalized and discussed.

2. 1 μm LASER PUMPED OPO CRYSTAL

The schematic of 1 μm laser pumping OPO crystal to realize 2 μm laser output is shown in Fig. 1. The 1 μm lasers were mainly obtained by *Q*-switched Nd:YAG laser. Table 1 lists the various research results, including laser parameters and laser properties, about 2 μm laser using method of 1 μm laser pumping OPO crystal.

From the research results mentioned above, there're mainly two OPO crystals were used to be pumped by 1 μm laser source, KTP and MgO:PPLN whose damage threshold was high. By using this method, high average power, high energy 2 μm laser can be obtained. And the output wavelength can be turned in the 2 μm band. However, the linewidth of 2 μm lasers was too wide (about 5 nm) which would lower the mid-infrared OPO conversion efficiency, when the 2 μm lasers were used as the pumping source of mid-infrared OPO.

3. Tm, Ho CODOPED 2 μm LASERS

2 μm laser output can be realized by Tm, Ho codoped crystals pumped with 800 nm laser diode, as shown in Fig. 2.

Table 2 lists the various researches on the Tm, Ho codoped crystal as the laser materials to achieve 2 μm laser output. The results show that at low temperature, Tm, Ho codoped crystals had good laser characteristics, such as high output power and high slope efficiency. However, at room temperature, because of the seriously up-conversion of Ho ions, the output power was limited, especially for Tm, Ho codoped oxide. While because of the negative lens effect of Tm, Ho doped fluoride, it own the advantage on working at room temperature.

4. Tm DOPED LASER PUMPING Ho DOPED LASER

Tm-doped laser was pumped by laser diode at around 800 nm to achieve 1.9 μm lasers, and then make use of it pumping Ho doped crystal to realize 2 μm laser output. Tm-pumped Ho lasers mainly include two ways, Tm laser pump Ho laser in and outside cavity, as shown in Fig. 3. Various research groups take attention on this method to realize high power 2 μm outputs at room temperature, as listed in Table 3.

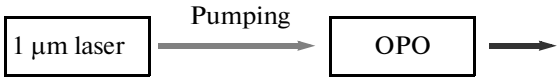

Fig. 1. schematic of 1 μm laser pumping OPO crystal.

[1] The article is published in the original.

Table 1. 2 μm laser output by 1 μm laser pumped OPO crystal

Researcher year Nation	Pumping source	OPO crystals Cavity parameters	Wavelength Power Slope efficiency
R. Burnham, 1989, USA [1]	Nd:YAG 1.06 μm 50 mJ, 30 ns	KTP 6 mm in length Plane-plane $L = 2.5$ cm, $T = 5\%$	2.12 μm
E. Cheung, 2000, USA [2]	Nd:YAG 1.06 μm MOPA	KTP (6 pieces) $3 \times 3 \times 6$ mm^3 Concave-plane, $T = 70\%$	2.13 μm 53 W 48%
Y. Hirano, 2001, Japan [3]	Nd:YAG 1.06 μm $P_{ave} = 160$ W	MgO:PPLN $1 \times 1.5 \times 30$ mm^3 $L = 60$ mm, $T = 70\%$	2 μm 57 W 82.2%
S. Haidar, 2004, Japan [4]	Nd:YAG 1.06 μm 640 mJ, 8 ns	KTP $10 \times 10 \times 20$ mm^3 $L = 27$ mm, $T = 20\%$	2.02 μm 43 mJ 22% (slope)
H. Ishizuki, 2006, Japan [5]	Nd:YAG 1.06 μm 30 Hz, 12 ns	MgO:PPLN $5 \times 5 \times 38$ mm^3 $L = 80$ mm, $T = 60\%$	1.94–2.30 μm (turning) 100 mJ 75%
R. Bhushan, 2008, Japan [6]	Nd:YAG 1.06 μm 5 J, 10 ns, 10 Hz	MgO:PPLN $5 \times 5 \times 36$ mm^3 $L = 75$ mm, $T = 60\%$	1.90–2.36 μm (turning) 186 mJ 58%

Due to the absence of sensitization ions, the up-conversion loss and the re-absorption loss of Tm laser pumped Ho laser structure reduce greatly. The quantum loss from 1.9 to 2.0 μm is quite small. Then the accumulation of heat inside the laser crystal was significantly reduced, which ensured the high efficiency operation of 2 laser. The research results show that Tm laser pumped Ho laser was one excellent method of achieving 2 μm laser output at room temperature, especially for short pulse width of 2 μm Q-switched laser output, although the laser system was complexity.

5. Tm DOPED 2 μm LASERS

Some Tm-doped crystals can realize 2 μm laser output directly pumped by laser diode at around 790 nm, as shown in Fig. 4. Table 4 summarizes the research on making Tm doped crystal to realize 2 μm laser output.

There're mainly two Tm doped crystals could realize 2 μm laser output, Tm:YAG and Tm:LuAG. Under continue wave operation, the laser characteristics were good and achieve high power output easily. However,

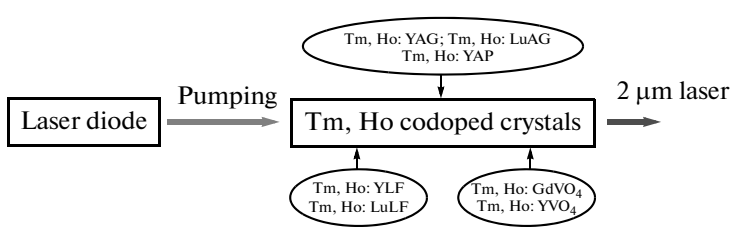

Fig. 2. Tm, Ho codoped crystals as the 2 μm laser materials.

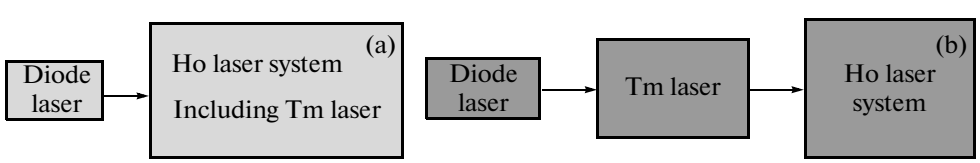

Fig. 3. Tm laser pumped Ho laser (a) Tm laser pumped Ho laser in the cavity (b) Tm laser pumped Ho laser out the cavity.

Table 2. 2 μm laser output by Tm,Ho codoped crystals as laser materials

Researcher, Year, Nation	Laser Material, Dimensions, mm^3, Doped, at %, Temperature, K	Cavity structure	Laser characteristics	Special introduction
T.Y. Fan, 1988, USA [7]	Cr, Tm, Ho:YAG Cr: 2.5×10^{20} cm^{-3} Tm: 8×10^{20} cm^{-3} Ho: 5×10^{19} cm^{-3}	Concave-concave $R = 250$, 500 mm $T = 0.5\%$	19% (slope)	Spectrum at RT was measured. Threshold was calculated
B.T. Mcguckin, 1991, USA [8]	Tm, Ho:YLF Tm:6%, Ho:0.4% 275 K	–	84 mW (CW) 220 μJ 150 Hz 22 ns	–
P. A. Budni, 1992, USA [9]	Tm, Ho:YLF 5 × 5 × 7 Tm: 5.7%, Ho: 1.25% 77 K	Plane-concave $R = 300$ mm $T = 40\%$	1.75 mJ 1 kHz 10 ns	The cavity loss was 7%
M.G. Jani, 1995, USA [10]	Tm, Ho:YLF Tm: 4%, Ho: 0.5% 4 × 4 × (11 + 20 + 11) 289 K	Concave-plane $L = 500$ mm $T = 2, 6, 10, 18\%$	130 mJ 5.2% (slope)	Pulse pumping
V. Kushawaha, 1996, USA [11]	Tm, Ho:LuAG Tm: 6%, Ho: 0.36% Φ6.35 × 7.5 77 K	Plane–plane $L = 80$ mm $T = 5\%$	1.38 W 2.1 μm 35.6% (o–o)	The spectrum of LuAG is wider than YLF and YAG at RT
P. A. Budni, 1998, USA [12]	Tm, Ho:YLF	–	$P_{ave} = 23$ W 10 kHz	–
V. Sudesh, 2001, Japan [13]	Tm, Ho:$LuLF_4$ Tm: 5%, Ho: 0.5% 4 × 3 × 4.8	Plane-concave $R = 300$ mm $T = 5\%$	11.3 mJ (20 Hz) 5.6% (slope) 24.5 mJ (10Hz) 10.7% (slope)	A novel quasi-end pumping source
V. Sudesh, 2003, Japan [14]	Tm, Ho:LuLF Tm: 5%, Ho: 0.5% 4 × 3 × 2.8 273 K	Plane-concave $R = 300$ mm $T = 5\%$	24.4 mJ (10 Hz) 11.6% (slope)	A novel quasi-end pumping source
M. Petros, 2003, USA [15]	Tm, Ho:LuLF Tm: 6%, Ho: 0.5% 3 × 3 × (15 + 20 + 15) 288 K	Ring laser $R = 3.5$ m $T = 28\%$ $L = 3$ m	100 mJ 150 ns 2053 nm 10 Hz	The σ_{emi} at 2053 nm was larger than 2067 nm
V. Sudesh, 2004, Japan [16]	Tm, Ho:LuLF Tm: 5%, Ho: 0.5% 4 × 3 × 2.7	Plane-concave $R = 100$ mm $T = 0.5\%$	285 mW 32% (slope)	The crystal was Brewster cut
A. Sato, 2004, Japan [17]	Tm, Ho:$GdVO_4$ Tm: 3%, Ho: 0.3% 1.5 × 2.7 × 4 (c × a × a)	Plane-concave $R = 100$ mm $T = 1.5,3\%$ $L = 93$ mm	31.2 mJ 14.5% (slope)	The crystal was Brewster cut
B.Q. Yao, 2004, China [18]	Tm, Ho:$GdVO_4$ Tm: 5%, Ho: 0.5% 5 × 5 × 10 77 K	Plane-concave $R = 300$ mm $T = 20, 30, 40\%$ $L = 150$ mm	3.5 W 25% (o–o) 2048 nm	One end of the crystal was a reflected mirror
Y. Urata, 2005, Japan [19]	Tm, Ho:$GdVO_4$ Tm:3%, Ho:0.5% 3 × 3 × 1.5	Concave-plane $T = 1$~2%	7.1% (slope) 2046 nm	Pulse pumping
M.W. Phillips, 2005, USA [20]	Tm, Ho:YLF 200 K	Folded cavity	400 mJ 8% (o–o) 900 ns 2051 nm	Pulse pumping; Side pumping
S. S. Chen, 2005, USA [21]	Tm, Ho:LuLF Tm: 6%, Ho: 0.5% 4 × 4 × (15 + 20 + 15) 286 K	Ring laser $R1 = R2 = 0.5$ m $L = 2.7$ m	0.63 J 4.1% (o–o) 1.05 J 6.9% (o–o)	Injection-seede *d* and MOPA

Table 2. (Contd.)

Researcher, Year Nation	Laser Material, Dimensions, mm^3, Doped, at %, Temperature, K	Cavity structure	Laser characteristics	Special introduction
X. L. Zhang, 2005, China [22]	Tm, Ho:LuLF Tm: 6%, Ho: 0.4% 5 × 5 × 2.5 293 K	Plane-concave R = 100 mm T = 2%	393 mW 14% (o–o) 45 μJ 142 ns	113 mW SLM laser output
B.Q. Yao, 2005, China [23]	Tm, Ho:$GdVO_4$ Tm:5%, Ho:0.5% 4 × 4 × 7 77 K	Concave-plane R = 400 mm T = 40% L = 110 mm	P_{ave} = 3.9 W 29% (o–o) 35% (slope) 1.1 mJ (3 kHz) 23 ns (3 kHz)	The wavelength of the pumping source was 794 nm
W.J. He, 2006, China [24]	Tm, Ho:$GdVO_4$ Tm:5%, Ho:0.5% 4 × 4 × 7 77 K	L-cavity R = 400 mm T = 60% L = 172 mm	P_{ave} = 10.1 W 10 kHz 50% (slope) M2 < 1.1	Double ends pumping
X.B. Zhang, 2007, China [25]	Tm, Ho:$GdVO_4$ Tm: 5%, Ho: 0.5% 5 × 5 × 10 77 K	Concave-plane	25 ns (10 kHz) 3 W 2048 nm	195 mW laser output at 3.88 μm
A. Sato, 2008, Japan [26]	Tm, Ho:$GdVO_4$ Tm: 7%, Ho: 0.4% 0.7 mm in length	Plane–plane L = 0.7 mm	550 mW 23.7% (o–o)	The crystal was side cooled
Y. X. Bai, 2008, USA [27]	Tm, Ho:LuLiF Tm: 6%, Ho: 0.5% 288 K	Concave-plane R = 1 m T = 40% L = 0.56 m	10 Hz 1.6 J 30% (slope) 20% (o–o)	Making use of He–Ne laser at 543.5 nm to measure Ho ions population-inversion
Z.G. Wang, 2009, China [28]	Tm, Ho:$GdVO_4$ Tm: 5%, Ho: 0.5% 4 × 4 × 7 77 K	Ring laser R = 1 m T = 18% L = 1 m	20 Hz 2 mJ 170 ns	Injection seeded laser
X.M. Duan, 2008, China [29]	Tm, Ho:YAP Tm: 5%, Ho: 0.3% 4 × 4 × 2 274 K	Plane-concave R = 50 mm T = 2% L = 17 mm	163 mW 7.1% (o–o) 11.1% (slope) 2102 nm	–
B.Q. Yao, 2008, China [30]	Tm, Ho:YAP Tm: 5%, Ho: 0.3% 4 × 4 × 8 77 K	L-cavity R = 0.4 m T = 30% L = 55 mm (CW) L = 125 mm (Q)	5 W 2.13 μm 29% (slope) 1–10 kHz 3.3 mJ 40 ns	Double ends pumping. 160 mW output was obtained at RT with slope efficiency of 11%
L.J. Li, 2009, China [31]	Tm, Ho:YAP Tm: 5%, Ho: 0.3% 4 × 4 × 8 77 K	L-cavity R = 0.3 m T = 30%	2.28 W 2.044 μm 15.7% (o–o) 19.3% (slope)	Double ends pumping. c-cut Tm, Ho:YAP crystal
L.J. Li, 2009, China [32]	Tm, Ho:YAP Tm: 5%, Ho: 0.3% 4 × 4 × 8 77 K	L-cavity R = 0.3 m T = 30%	P_{ave} = 2.17 W 2.044 μm 15.0% (o–o) 10 kHz	Double ends pumping. c-cut Tm, Ho:YAP crystal
L.J. Li, 2009, China [33]	Tm, Ho:YAP Tm: 5%, Ho: 0.3% 4 × 4 × 8 77 K	L-cavity T = 30% L = 150 mm	4.45 W 2.13 μm P_{ave} = 4.21 W 15 kHz	Double ends pumping and laser diode is 798 nm
B.Q. Yao, 2010, China [34]	Tm, Ho:YVO_4 Tm: 4%, Ho: 0.4% 3 × 3 × 8 77 K	Folding-cavity R = 0.5 m T = 40% L = 255 mm	20.2 W (CW) 2054.7 nm P_{ave} = 19.4 W 24 ns (15 kHz)	Double ends pumping double crystals

Table 2. (Contd.)

Researcher, Year, Nation	Laser Material, Dimensions, mm^3, Doped, at %, Temperature, K	Cavity structure	Laser characteristics	Special introduction
F. G. Yang, 2010, China [35]	Tm, Ho, Ce:NaY-$(WO_4)_2$ Tm: 5%, Ho: 1%, Ce: 30% 3 × 3 × 8 77 K	Plane-concave $R = 0.1$ m $T = 7\%$ $L = 30$ mm	0.2 W 2.07 μm	–
X.L. Zhang, 2010, China [36]	Tm, Ho:YLF Tm: 6%, Ho: 0.4% 5 × 5 × 2.5 293 K	Plane-concave $R = 51.88$ mm $T = 2\%$ $L = 45$ mm	118 mW Single frequency	792 nm LD pumping
B. Richards, 2010, UK [37]	$Tm^{3+}/Ho^{3+}/Yb^{3+}$-codoped telluride fiber	$T = 50, 30, 10\%$ Fiber length 24.7 cm	67 mW	Pumping with 1.088 μm and 1.61 μm silica fiber laser
X.L. Zhang, 2010, China [38]	Tm, Ho:YLF Tm: 6%, Ho: 0.4% 5 × 5 × 2.5 293 K	Plane-concave $R = 51.88$ mm $T = 2\%$ $L = 45$ mm	106 mW Single frequency	792 nm LD pumping
G. Li, 2011, China [39]	Tm, Ho:YVO_4 Tm: 4%, Ho: 0.4% 8 mm-long 77 K	Folding-cavity $R = 400$ mm $T = 3.5\%$ $L = 1.97$ m	210 mW 2.05 μm 16.32 kHz	Double ends pumping and laser diode is 798–802 nm.
X.L. Zhang, 2011, China [40]	Tm, Ho:YLF Tm: 6%, Ho: 0.4% 5 × 5 × 2.5 293 K	Plane-concave $R = 51.88$ mm $T = 2\%$ $L = 45$ mm	2053 nm 4 μJ 1.3–2.6 kHz	792 nm LD pumping
V. Jambunathan, 2011, Spain [41]	Ho, Tm:KLuW Tm: 5.0%, Ho: 0.5% 3 × 3 × 3 289 K	*Z*-type cavity $R = 100$ mm $T = 9\%$	1919 and 2061 nm 244 mW	Ti:sapphire 802 nm pumping
B.Q. Yao, 2011, China [42]	Tm, Ho:YVO_4 Tm, Ho:$GdVO_4$ Tm: 5.0%, Ho: 0.5% 4 × 4 × 0.25 283 K	Plane cavity $T = 1\%$	2052.3 nm 16.5 mW 2048.5 nm 8 mW	802 nm LD pumping
P.B. Meng, 2011, China [43]	Tm, Ho:$GdVO_4$ Tm: 5.0%, Ho: 0.5% 4 × 4 × 7 77 K	*L*-shape cavity $T = 40\%$ $L = 195$ mm	10 kHz 85 ns 2.6 kW	802 nm LD pumping, pump waist 800 μm
B.Q. Yao, 2011, China [44]	Tm, Ho:YVO_4 Tm: 5.0%, Ho: 0.5% 4 × 4 × 0.25 283 K	Plane cavity $T = 1\%$	2052.3 nm 16.5 mW Single frequency	802 nm LD pumping
P.B. Meng, 2011, China [45]	Tm, Ho:YLF Tm: 6.0%, Ho: 0.4% 3 × 3 × 0.5 291 K	Plane cavity $T = 2\%$	2050.5 nm 17 mW Single frequency	–
L.J. Li, 2011, China [46]	*c*-cut Tm, Ho:$YAlO_3$ Tm: 5.0%, Ho: 0.3% 3 × 3 × 8 77 K	Plane cavity $T = 30\%$	2044 nm 3.45 mJ 47 ns 2.5 kHz	794.8 nm LD double ends pumping
Y.L. Ju, 2011, China [47]	Tm, Ho:YAP Tm: 5.0%, Ho: 0.3% 4 × 4 × 0.8 Room temperature	Plano–plano $T = 2\%$	2012.6 nm 42 mW Single frequency	791.7 nm LD pumping

Table 2. (Contd.)

Researcher, Year, Nation	Laser Material, Dimensions, mm^3, Doped, at %, Temperature, K	Cavity structure	Laser characteristics	Special introduction
F. Chen, 2011, China [48]	Tm, Ho:YAP Tm: 5.0%, Ho: 0.3% 4 × 4 × 3 285 K	Plano–plano $T = 2\%$	2030.8 nm 31 mW Single frequency	792 nm LD pumping
X.L. Zhang, 2011, China [49]	Tm, Ho:YLF Tm: 6%, Ho: 0.4% 5 × 5 × 2.5 293 K	Plane-concave $R = 51.88$ mm $T = 2\%$ $L = 48$ mm	2053 nm 0.8–4.0 kHz 1.7 μs 3.7 μJ	792 nm LD pumping
L.J. Li, 2011, China [50]	*b*-cut Tm, Ho:$YAlO_3$ Tm: 5.0%, Ho: 0.3% 4 × 4 × 10 77 K	Plane cavity $T = 30\%$	2120 nm 8.14 W 10 kHz	794.2 nm LD double ends pumping
P.B. Meng, 2011, China [51]	Tm, Ho:$GdVO_4$ Tm: 5.0%, Ho: 0.5% 4 × 4 × 7 77 K	Plane cavity $R = 500$ mm $T = 40\%$ $L = 195$ mm	1.7 mJ 28 ns 300 kHz	802 nm LD pumping

there're less reports on Q-switched operation. The main problem is the serious thermal effect of Tm doped laser, which would take in difficulties about resonator design. And because of the limit of the coating, the output energy of Q-switched laser could not be too high.

5. CONCLUSIONS

In summary, four methods of realizing 2 μm laser output were summarized and discussed. To achieve high power, high energy 2 μm laser output, and many innovative and interesting ways were used, such as new quasi-end-pumping source, pulse pumping source and so on. The crystal length and doping concentration were optimized. To relieve the heat of the laser crystal, thin-disk and composite structure was used. Side cooling, water cooling, thermoelectric cooling and other ways were used to enhance laser output power. In resonator design, the thermal lens focal length was fully estimated which was helpful to obtain high energy Q-switched laser output. The advantages and disadvantages of four methods have been described clearly above. Due to low conversion efficiency, 1 μm laser pumped OPO to obtain 2 μm laser output has not been widely adopted. Because of the intense up-conversion and re-absorption loss in Tm, Ho codoped laser, it is difficult to achieve high output power at room temperature. Laser diode-pumped Tm-doped laser, and then pumped Ho crystal was mainly used to obtain short pulse width of 2 μm laser output. And the laser system was quite complexity. Tm doped crystals pumped by laser diode to produce laser output wavelength of 2 μm can ensure the high power, high efficiency and high beam quality output. Especially, the small emission cross section of the laser materials meets the requirement of the radar system for parameter of long pulse laser source.

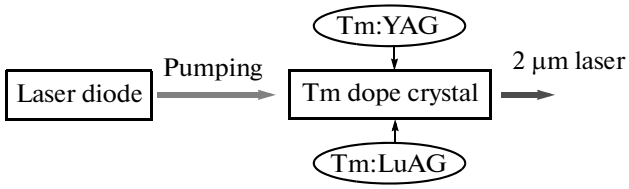

Fig. 4. Tm codoped crystals as the 2 μm laser materials.

Table 3. Tm laser pumped Ho laser to realize 2 μm laser output

Researcher, Year, Nation	Cavity structure	Tm laser	Ho laser	Laser characteristics
R.C. Stoneman, 1992, USA [52]	Plane-concave $T = 1.5\%$ Ti sapphire laser pumping source	Tm:YAG 2.5 mm in length Tm: 12% RT	Ho:YAG 2.5 mm in length Ho: 0.6% RT	>120 mW 2.1 μm – 48% (785–2000)
C. Bolling, 1998, England [53]	Convex-concave $R1 = -100$ mm $R2 = 50$, $T = 10\%$ $L = 45$ mm	Tm:YAG 5 mm in length Tm: 7% 283 K	Ho:YAG 10 mm in length Ho: 0.6% 283 K	2.1 W 2.097 μm M2 = 1.6 75%
P.A. Budni, 2003, USA [54]	Plane-concave $R = 5$ m, $T = 70\%$ $L = 330$ mm	Tm:YLF $M^2 = 3$ Outside pumping source (outside)	Ho:YAG 2.5 mm in length Ho: 0.5% 258–293 K	>50 mJ (60 Hz) 14 ns 2.09 μm $M^2 = 1.2$ 64%
A. Dergachev, 2003, USA [55]	*U*-cavity	Tm:YLF slab Tm: 3.5% 1940 nm Outside	Ho:YLF 20 mm in length	21 W (CW) 37 mJ (Q) 77%
D. Y. Shen, 2004, USA [56]	Plane-concave $R = 100$ mm $T = 10\%$ $L = 23$ mm	Tm fiber laser 1907 nm 9.6 W Outside	Ho:YAG 20 mm in length Ho: 1%	6.4 W 2.1 μm 80%
D. Y. Shen, 2004, USA [57]	Plane-concave $R = 25$ mm $T = 3\%$ $L = 18$ mm	Tm fiber laser 1942 nm 9.4 W Outside	Ho:YLF 15 mm in length Ho: 1.5%	4.8 W 51% (o–o)
A. Dergachev, 2005, USA [58]	Double-*Z*-type cavity	Tm fiber laser 1940 nm 100 W Outside	Ho:YLF	43 W (CW) 42% 45 mJ (Q)
C. Kieleck, 2005, France [59]	Plane-concave $L = 70$ mm	Tm:YLF 20 W Outside	Ho:YAG Ho: 0.5% 40 mm in length	11.5 W 2.09 μm 53.8% (o–o)
M. Schellhorn, 2006, France [60]	Thin-disk laser $T = 2.1\%$	Tm:YLF 1906.5–1908.3 Outside	Ho:YAG 0.4 mm in length Ho: 2%	9.4 W 40%
E. Lippert, 2006, Norway [61]	*L*-cavity	Tm fiber laser 1907.5 nm Outside	Ho:YAG 20 mm in length Ho: 1%	9.6 W 2096 nm 20 kHz 74%
S. So, 2006, U.K. [62]	Plane-concave $R = 50$ mm $T = 5\%$ $L = 23$ mm	Tm:YLF slab $2 \times 9 \times 20$ mm^3 $L = 67$ mm	Ho:YAG $2 \times 4 \times 10$ mm^3 Ho: 1%	13 W 2.09 μm 16%
I. Elder, 2007, [63]	*L*-cavity	Tm fiber laser 41.6 W Outside	Ho:YAG (5 + 20 + 5) mm Ho: 1%	27.3 W 2.09 μm 69%
Y.X. Bai, 2007, USA [64]	*Z*-type cavity	Tm fiber laser 1941 nm 30 W Outside	Ho:YLF	30 mJ 2051 nm

Table 3. (Contd.)

Researcher, Year, Nation	Cavity structure	Tm laser	Ho laser	Laser characteristics
G. Renz, 2007, Germany [65]	Concave-plane $R = 5$ m $T = 60\%$ $L = 400$ mm	Tm fiber laser 1908 nm Outside	Ho:YAG	90 mJ 2.09 μm 20 ns 100 Hz
S. So, 2008, U.K. [66]	Plane-concave $R = 100$ mm $T = 11\%$ $L = 100$ mm	Tm:YLF slab 73 W Outside	Ho:YAG 80 mm in length Ho: 0.25%	38 W 2.09 μm 73%
X.M. Duan, 2008, China [67]	Plane-concave $R = 100$ mm $T = 51\%$ $L = 93$ mm	Tm:YLF 18.1 W 1.91 μm Outside	Ho:YAG $\Phi 4 \times 25$ mm^3 Ho: 0.8%	10.5 W 2090 nm 65.7% 1 mJ/25 ns/10 kHz
J. Kwiatkowski, 2009, Poland [68]	Plane-concave $R = 150$ mm $T = 5\%$ $L = 115$ mm	Tm fiber laser 1908 nm Outside	Ho:YAG $\Phi 4 \times 10$ mm^3 Ho: 1%	2132.8 nm 1130 mW 53%
B.Q. Yao, 2009, China [69]	Plane-concave $R = 150$ mm $T = 30\%$ $L = 80$ mm	Tm fiber laser 10.6 W Outside	Ho:YAP $4 \times 4 \times 20$ mm^3 Ho: 1%	2.54 W 2117.9 nm 49%
X.N. Duan, 2009, China [70]	Plane-concave $R = 100$ mm $T = 7\%$ $L = 57$ mm	Tm:YLF 1.91 μm 7.26 W Outside	Ho:YAP $4 \times 4 \times 20$ mm^3 Ho: 1%	2105 nm 3.5 W 46.9%
X.N. Duan, 2009, China [71]	Plane-concave $R = 120$ mm $T = 52\%$ $L = 70$ mm	Tm:YLF 1.91 μm 7.26 W Outside	Ho:YAP $\Phi 5 \times 35$ mm^3 Ho: 0.5%	2118 nm 10.2 W 64%
X.N. Duan, 2009, China [72]	Plane-concave $R = 120$ mm $T = 29\%$ $L = 80$ mm	Tm:YLF 1.91 μm 18.4 W Outside	Ho:LuAG $\Phi 5 \times 25$ mm^3 Ho: 0.8%	2100 nm 18.4 W 51.3%
X.J. Cheng, 2010, China [73]	Plane-concave $T = 5\%$	Tm:YLF 1.91 μm 7.26 W Outside	Ho:YAG (ceramic slab) $1.5 \times 10 \times 18$ mm^3 Ho: 1%	1.2 W 2.09 μm 42.6%
A.S. Kurkov, 2010, Russia [74]	Self-pulsing in an all-fiber laser	GTW Yb-fiber 1.125 μm 10 W	Ho fiber laser Ho: 1.9×10^{20}/cm^3 Ho fiber: 0.8 m	$P_{ave} = 2.8$ W 30% $P_{peak} = 25$ W
A.S. Kurkov, 2010, Russia [75]	All fiber laser	GTW Yb-fiber 1.125 μm 13 W	Ho fiber laser Ho: ~10^{19}/cm^3	4.2 W 2.1 μm 34%
Y.L. Tang, 2011, China [76]	Plano–plano $T = 8\%$ $L = 20$ mm	Tm:YLF 1.91 μm 18.5 W	Ho:LuAG $3 \times 3 \times 20$ Ho: 1% 289 K	2130 and 2101 nm 4 mJ 2 kHz 20 ns

Table 4. Tm codoped 2 μm lasers

Researcher, Year, Nation	Laser Material, Size, mm^3, Doped, at %, Temperature, K	Cavity structure	Laser characteristics	Special introduction
R.C. Stoneman, 1990, USA [77]	Tm:YAG/YSGG 2.6 mm in length, 3.2 mm in length Tm: 12%	Plane-concave $R = 100$ mm $T = 0.5, 1.0, 2.5, 5\%$	YAG: 870 mW 1.87–2.16 μm YSGG: 740 mW 1.85–2.14 μm	Birefringent filter in the cavity
P.J.M. Sun, 1991, USA [78]	Tm:YAG 6 mm in length Tm: 4%	Plane-concave $R = 100$ mm $T = 2\%, 5\%$ $L = 800$ mm	0.5 W CW 49% 1 mJ (100 Hz) 330 ns	Electro-optic Q-switch
J.F. Pinto, 1992, USA [79]	Tm:YAG Φ3.15 × 3 Tm: 12% Brewster cut	Plane-plane $T = 1.5\%$	300 MHz (Ref) 35 ps $P_{ave} = 70$ mW	Mode-locking laser, double bire-fringent filter in the cavity
J.M. Fukumoto, 1992, USA [80]	Tm:YAG 10 mm in length Tm: 2.6% 308–313 K	Plane-concave $R = 150$ mm $T = 2\%$	6 W 15%	Side-pumping source
D.C. Shannon, 1993, Poland [81]	Tm:YAG 5 mm in length Tm: 4% 248–298 K	Plane-concave $R = 100$ mm $T = 2.6, 4.5\%$ $L = 50$ mm	5.5 W 28.312% (273 K)	Suddenly no laser out-put when pump power reached to 22 W
N.P. Barnes, 1995, USA [82]	Tm:LuAG Φ4 × 7 Tm: 2%, 4%, 7%	Concave-plane $R = 800$ mm $T = 2\%$ $L = 500$ mm	<80 mJ 23.6% 2.0238 μm	Pulse pumping source with Ref of 1 Hz and width of 1 ms
D.D. Lowenthal, 1995, USA [83]	Tm:YAG 5 × 5 × ? Tm: 4%, 6% 258–293 K	Plane-plane $L = 50$–70 mm $T = 2\%$	2.9 W 28.1% (258 K)	Low gain and high saturation intensity (50 J/cm^2)
C. Borel, 1995, England [84]	Tm:YAG waveguide 4 mm in length, thickness 14.6 μm Tm: 6.6%	$T = 2\%, 12\%$	102 mW 48% ($T = 12\%$) Six oscillating modes.	Threshold is lower for Ti sapphire laser as pump-ing source
R. Beach, 1996, USA [85]	Tm:YAG Tm: 4% Φ5 × (3 + 5 + 3)	Plane-concave	51 W 24% (o–o)	A special wing pumping structure at 805 nm
T. Yokozawa, 1996, Japan [86]	Tm:YAG Tm: 3%, 4 mm Tm: 6%, 1.8 mm Tm: 12%, 1 mm	Plane-concave $R = 100$ mm $L = 100$ mm $T = 3\%, 1\%, 0.7\%$	124 mW 36% Threshold of 77 mW	The temperature of the crystal infects laser char-acteristics obviously
G. Rustad, 1997, Norway [87]	Tm:YAG Tm: 2, 3.3% Side-pumping	Plane-concave $R = 150$~1000 mm $T = 0.9\%, 2.5\%$	Ref: 0~10 Hz 2 mJ	The Ref infects the heat of laser crystal
E.C. Honea, 1997, The USA [88]	Tm:YAG Φ3 × (5 + 45 + 5) Tm: 2%	Plane-plane Plane-concave $L = 60$ mm	115 W $M^2 \sim 23$ $\eta = 1.99$	Complex coupling sys-tem of pumping source
C. Bollig, 1998, England [89]	Tm:YAG 8 mm in length Tm: 7%	Convex-concave $R1 = -150$ mm $R2 = 50$ mm $T = 3\%$ $L = 32$ mm	4.1 W (293 K 2.013 μm $M^2 \sim 1.4, 1.2$	–
Cheng Li, 1999, Japan [90]	Tm:YAG 3 mm in length Tm: 5.2% 248~293 K	V-cavity $R = 200$ mm $T = 3\%$ $L = 300$ mm	760 mW 44% 1.2 mJ (120 Hz) 380 ns	Double passes pumping
M. Tsunekane, 1999, Japan [91]	Tm:YAG Φ3 × (1 + 2 + 1) Tm: 6%, 297 K	Plane-concave $R = 100$ mm $T = 2\%$		Composite crystal was used

Table 4. (Contd.)

Researcher year Nation	Laser Material Size, mm^3 Doped, at % Temperature, K	Cavity structure	Laser characteristics	Special introduction
K. S. Lai, 2000, Singapore [92]	Tm:YAG Φ3 × (20 + 65 + 20) Tm: 3%	Plane-plane $L = 180$ mm $T = 25\%, 30\%$	120 W 31.2% 25.2% (o–o) $M^2 \sim 21, 14$	Side pumping
V. Sudesh, 2000, Australia [93]	Tm:LuAG Tm: 2%	Plane-concave $R = 150$ mm $T = 2\%$	1 mJ 13% 2.3 μm	Ti sapphire laser as the pumping source
S.W. Henderson, 2001, USA [94]	Tm:LuAG	Plane-concave	50 mW (SLM) 2020–2030 nm 1–5 kHz/ms	F–P etalons and birefringent filter were inserted
S. Goidring, 2002, Israeli [95]	Tm:YAG Tm: 6% (5 + 10 + 5) RT	*U*-cavity $L = 95$ mm $T = 15\%$	Ref 20 Hz 2.4 mJ 57 ns	Electric-optic Q-switch
K. Scholle, 2004, German [96]	Tm:LuAG 435 μm in length Tm: 10%	Plane-concave $L = 50$ mm	51 mW (SLM) 7.3% (Slope)	Four passes pumping, 125 μm F–P in the cavity
S.W. Henderson, 2005, USA [97]	Tm:LuAG	–	2022.5 nm 500 Hz 400 ns $P_{ave} = 1$ W	No parameter was mentioned in the paper.
H. Kalaycioglu, 2007, Turkey [98]	Tm:LuAG Tm: 5/0.5%	No mention about laser characteristics.	17.7 ± 3.4 ms $1.2 \pm 0.2 \times 10^{-21}$ cm^2 (at 2023 nm)	Introduce some spectrum of Tm:LuAG crystal
M. Eichhorn, 2008, France [99]	Tm:YAG 15 mm in length Tm: 2%	Convex-concave $R1 = -200$ mm $R2 = 200$ mm $T = 20\%$	4 mJ 80 ns 12% TEM_{00}	Pulse pumping, Ref of 100 Hz, width of 4 ms, electric-optic Q-switch
M. Eichhorn, 2009, France [100]	Tm:YAG Φ3 × (5 + 80 + 5) Tm: 2%	Planc-concave $L = 810$ mm $R = 50$ mm $T = 20\%$	5.6 mJ 100 Hz 216 ns 25.9 kW (Peak)	Double ends pumping at 804 nm, electric-optic Q-switch
M. Eichhorn, 2009, France [101]	Tm:YAG Φ1.5 × (5 + 70 + 5) Tm: 2%	Covex-concave $L = 180$ mm $R = -300$ mm $T = 20\%$	2.53 mJ (bad) 100 Hz 170 ns 14.9 kW (Peak)	Double ends pumping at 804 nm, acousto-optic Q-switch
J. Li, 2010, China [102]	Tm:YAP 3 × 3 × 5 Tm: 5%	Planc-concave $L = 30$ mm $R = 50, 100, 200$ mm	1988 nm 344 mW Single frequency	793 nm LD pumping
M.S. Gaponenko, 2010, Belarus [103]	Tm:KYW 2.5 mm-thick Tm: 5%	*Z*-fold cavity $T = 1\%$ $L = 80$ cm	1936 nm 20 mW	802 nm LD pumping, mode-locking operation
F. Chen, 2011, China [104]	Tm:YAG Φ3.0 × 2.5 Tm: 3.5%	Plane-concave $R = 100$ mm $T = 2\%$ $L = 40$ mm	2013.91 nm 60 mW Single frequency	792 nm LD pumping
C.Q. Gao, 2011, China [105]	Diffusion-bonded Tm:YAG Φ4.0 × (16.5 + 12 + 16.5) Tm: 3.5%	Plane-concave $R = 1000$ mm $T = 1.6\%, 3.6\%$ 6.4%, 8.0% $L = 450$ mm	Free-running: 102.5 mJ@1 Hz 94.6 mJ@10 Hz Q-switched: 21.2 mJ, 330 ns	785 nm pulsed LD side-pumping
Z. Zhang, 2011, China [106]	Tm:YAP 3 × 3 × 8 Tm: 3%	*L*-shape cavity $R = 200$ mm $T = 15\%$ $L = 30$ mm	1936 nm FWHM = 3.8 nm 12.3 W	795 nm LD double ends pumping

Table 4. (Contd.)

Researcher, Year, Nation	Laser Material, Size, mm^3, Doped, at %, Temperature, K	Cavity structure	Laser characteristics	Special introduction
F. Chen, 2011, China [107]	Tm:YLF 3 × 3 × 10 Tm: 4%	Plane-concave R = 100 mm T = 10% L = 67 mm	1907.3 nm 1.92 W FWHM = 60 pm	792 nm LD pumping
C. T. Wu, 2011, China [108]	Tm:LuAG 3 × 3 × 2 Tm: 4%	Plane-concave	2026 nm 148 mW Single frequency	–
C. T. Wu, 2011, China [109]	Tm:YAG Φ3.0 × 2.5 Tm: 3.5%	Plane-concave R = 100 mm T = 2% L = 40 mm	2013.91 nm single frequency Long-term frequency stability 1.16×10^{-7}–1.75×10^{-7} Song-term frequency stability 97 Hz/μs	792 nm LD pumping
P. Zhou, 2011, China [110]	Tm fiber 1 m-length	Plane cavity using Bragg gratings	Dual wavelength	1580 nm Er-fiber laser pumping

ACKNOWLEDGMENTS

This work is supported by School of Science in Changchun University of Science and Technology and the program of Excellent Team in Harbin Institute of Technology.

REFERENCES

1. R. Burnham, R. A. Stolzenberger, and A. Pinto, IEEE Photonics Tech. Lett. **1**, 27 (1989).
2. E. Cheung, S. Palese, H. Injeyan, C. Hoefer, R. Hilyard, H. Komine, J. Gish, and W. Borenberg, IEEE Aerospace Conf. Proc. **3**, 55 (2000).
3. Y. Hirano and S. Yamamoto, H. Taniguchi, in *Proceedings of the Conf. on Lasers and Electro-Optics* (2001), p. 579.
4. S. Haidar, K. Miyamoto, and H. Ito, Opt. Commun. **241**, 173 (2004).
5. H. Ishizuki, J. Saikawa, and T. Taira, in *Proceedings of the Conference Advanced Solid-State Photonics* (2006), p. TuC3.
6. R. Bhushan, H. Yoshida, K. Tsubakimoto, H. Fujita, M. Nakatsuka, N. Miyanaga, Y. Izawa, H. Ishizuki, and T. Taira, Opt. Commun. **281**, 3902 (2008).
7. T. Y. Fan, G. Huber, L. R. Byer, and P. Mitzscherlich, IEEE J. Quantum Electron. **24**, 924 (1988).
8. B. T. McGuckin, R. T. Menziesn, and H. Hemmati. Appl. Phys. Lett. **59**, 2926 (1991).
9. P. A. Budni, M. G. Knights, E. P. Chicklis, and H. P. Jenssen, IEEE J. Quantum Electron. **28**, 1029 (1992).
10. M. G. Jani, F. L. Naranjo, N. P. Barnes, K. E. Murray, and G. E. Lockard, Opt. Lett. **20**, 872 (1995).
11. V. Kushawaha, Y. Chen, Y. Yan, and L. Major, Appl. Phys. B **62**, 109 (1996).
12. P. A. Budni, L. A. Pomeranz, M. L. Lemons, P. G. Schunemann, T. M. Pollak, and E. P. Chicklis, in *Proceedings of the Conference Advanced Solid-State Lasers* (1998), vol. 19, p. 90.
13. V. Sudesh, K. Asai, K. Shimamura, and T. Fukuda, Opt. Lett. **26**, 1675 (2001).
14. V. Sudesh and K. Asai, Opt. Soc. Am. B **20**, 1829 (2003).
15. Mulugeta Petros, Jirong Yu, Songsheng Chen, Upendra N. Singh, Brian M. Walsh, Yingxin Bai, and Norman P. Barnes, in *Proceedings of the Conference Advanced Solid-State Photonics* (2003), p. 1.
16. V. Sudesh, K. Asai, A. Sato, U. N. Singh, B. M. Walsh, and N. P. Barnes, in *Proceedings of the Conference Advanced Solid-State Photonics* (2004), p. WB19.
17. A. Sato, K. Asai, and K. Mizutani, Opt. Lett. **2**, 836 (2004).
18. B. Q. Yao, X. B. Zhang, Y. Z. Wang, W. J. He, Y. F. Li, and Y. L. Ju, Chin. Opt. Lett. **2**, 595 (2004).
19. Y. Urata, H. Machida, M. Higuchi, K. Kodaira, and S. Wada, in *Proceedings of the Conference Advanced Solid-State Photonics* (2005), p. MF13.
20. M. W. Phillips, J. P. Tucker, Proceeding of SPIE **5653**, 146 (2005).
21. S. S. Chen, J. R. Yu, M. Petros, Y. X. Bai, U. N. Singh, and M. J. Kavaya, Proceeding of SPIE **5653**, 175 (2005).
22. X. L. Zhang, Y. L. Ju, and Y. Z. Wang, Opt. Express. **13**, 4056 (2005).
23. B. Q. Yao, Y. Z. Wang, Y. L. Ju, and W. J. He, Opt. Express. **13**, 5157 (2005).
24. W. J. He, B. Q. Yao, Y. L. Ju, and Y. Z. Wang, Opt. Express. **14**, 11653 (2006).
25. X. B. Zhang, B. Q. Yao, Y. L. Ju, and Y. Z. Wang, Chin. Phys. Lett. **24**, 1953 (2007).
26. A. Sato, K. Asai, S. Ishii, K. Mizutani, and T. Itabe, in *Proceedings of the Conference Advanced Solid-State Photonics* (2008), p. WE39.

27. Y. X. Bai, J. Yu, B. Trieu, M. Petros, P. Petzar, H. Lee, and U. Singh, in *Proceedings of the Conference Advanced Solid-State Photonics* (2008), p. WE34.
28. Z. G. Wang, Y. L. Ju, C. T. Wu, C. W. Song, and Y. Z. Wang, Laser Phys. Lett. **6**, 98 (2009).
29. X. M. Duan, B. Q. Yao, L. L. Zheng, C. T. Wu, L. J. Zhang, Y. J. Zhang, Y. L. Ju, and Y. Z. Wang, Laser Phys. **18**, 951 (2008).
30. B. Q. Yao, L. J. Li, L. L. Zheng, Y. Z. Wang, G. J. Zhao, and J. Xu, Opt. Express. **16**, 5075 (2008).
31. L. J. Li, B. Q. Yao, Z. G. Wang, Y. L. Ju, Y. J. Zhang, and Y. Z. Wang, Laser Phys. Lett. **6**, 359 (2009).
32. L. J. Li, B. Q. Yao, Y. L. Ju, Y. J. Zhang, and Y. Z. Wang, Laser Phys. Lett. **6**, 367 (2009).
33. L. J. Li, B. Q. Yao, C. W. Song, Y. Z. Wang, and Z. G. Wang, Laser Phys. Lett. **6**, 102 (2009).
34. B. Q. Yao, G. Li, P. B. Meng, G. L. Zhu, Y. L. Ju, and Y. Z. Wang, Laser Phys. Lett. **7**, 857 (2010).
35. F. G. Yang, F. P. Yan, Z. Y. You, C. Y. Tu, C. L. Sun, Y. Wang, Z. J. Zhu, and J. F. Li, Laser Phys. Lett. **7**, 867 (2010).
36. X. L. Zhang, L. Li, J. H. Cui, Y. L. Ju, and Y. Z. Wang, Laser Phys. Lett. **7**, 194 (2010).
37. B. Richards, A. Jha, Y. Tsang, D. Binks, J. Lousteau, F. Fusari, A. Lagatsky, C. Brown, and W. Sibbett, Laser Phys. Lett. **7**, 177 (2010).
38. X. L. Zhang, L. Li, B. Jiang, J. H. Cui, Y. L. Ju, and Y. Z. Wang, Laser Phys. Lett. **7**, 108 (2010).
39. G. Li, B. Q. Yao, P. B. Meng, W. Wang, Y. L. Ju, and Y. Z. Wang, Laser Phys. Lett. **8**, 42 (2011).
40. X. L. Zhang, L. Li, Y. F. Liu, Y. F. Peng, J. H. Cui, and Y. L. Ju, Laser Phys. Lett. **8**, 277 (2011).
41. V. Jambunathan, A. Schmidt, X. Mateos, M. C. Pujol, J. J. Carvajal, M. Aguiló, F. Díaz, U. Griebner, and V. Petrov, Laser Phys. Lett. **8**, 799 (2011).
42. B. Q. Yao, F. Chen, C. T. Wu, Q. Wang, G. Li, C. H. Zhang, Y. Z. Wang, and Y. L. Ju, Laser Phys. **21**, 468 (2011).
43. P. B. Meng, B. Q. Yao, G. Li, Y. L. Ju, and Y. Z. Wang, Laser Phys. **21**, 348 (2011).
44. B. Q. Yao, F. Chen, C. T. Wu, Q. Wang, G. Li, C. H. Zhang, Y. Z. Wang, and Y. L. Ju, Laser Phys. **21**, 663 (2011).
45. P. B. Meng, B. Q. Yao, R. L. Zhou, F. Chen, Y. L. Ju, and Y. Z. Wang, Laser Phys. **21**, 643 (2011).
46. L. J. Li, B. Q. Yao, J. P. Qin, D. Y. Wu, Y. M. Wang, J. Wang, Z. L. He, W. Y. Liu, J. J. Chen, Y. Z. Wang, Z. G. Zhang, and A. H. Li, Laser Phys. **21**, 489 (2011).
47. Y. L. Ju, C. H. Zhang, F. Chen, G. Li, B. Q. Yao, L. X. Tian, and Y. Z. Wang, Laser Phys. **21**, 97 (2011).
48. F. Chen, B. Q. Yao, X. D. He, C. H. Zhang, G. Li, and Y. Z. Wang, Laser Phys. **21**, 1566 (2011).
49. X. L. Zhang, L. Li, J. H. Cui, and Y. L. Ju, Laser Phys. **21**, 1581 (2011).
50. L. J. Li, B. Q. Yao, D. Y. Wu, J. Wang, L. Gang, Y. Z. Wang, and Z. G. Zhang, Laser Phys. **21**, 446 (2011).
51. P. B. Meng, B. Q. Yao, G. L. Zhu, Y. L. Ju, and Y. Z. Wang, Laser Phys. **21**, 94 (2011).
52. R. C. Stoneman and L. Esterowitz, Opt. Lett. **17**, 736 (1992).
53. C. Bollig, R. A. Hayward, W. A. Clarkson, and D. C. Hanna, Opt. Lett. **23**, 1757 (1998).
54. P. A. Budni, C. R. Ibach, S. D. Setzler, E. J. Gustafson, R. T. Castro, and E. P. Chicklis, Opt. Lett. **28**, 1016 (2003).
55. A. Dergachev and P. F. Moulton, in *Proceedings of the Conference Advanced Solid-State Photonics* (2003) **83**, p. 137.
56. D. Y. Shen, J. Sahu, and W. A. Clarkson, Proceeding of SPIE **5620**, 46 (2004).
57. D. Y. Shen, W. A. Clarkson, L. J. Cooper, and R. B. Williams, Opt. Lett. **29**, 2396 (2004).
58. A. Dergachev, P. F. Moulton, and T. E. Drake, in *Proceedings of the Conference Advanced Solid-State Photonics* (2005) **98**, p. 608.
59. C. Kieleck, A. Hirth, and M. Schellhorn, Proceeding of SPIE **5989**, 598905 (2005).
60. M. Schellhorn, Appl. Phys. B **85**, 549 (2006).
61. E. Lippert, S. Nicolas, G. Arisholm, K. Stenersen, and G. Rustad, Appl. Opt. **45**, 3839 (2006).
62. S. So, J. I. Mackenzie, D. P. Shepherd, W. A. Clarkson, J. G. Betterton, E. K. Gorton, and J. A. C. Terry, Opt. Express **14**, 10481 (2006).
63. I. Elder, Proceeding of SPIE **6378**, 673804 (2007).
64. Y. X. Bai, J. R. Yu, M. Petros, P. J. Petzar, B. C. Trieu, H. R. Lee, and U. Singh, in *Proceedings of the Conf. on Lasers and Electro-Optics* (2007), p. CTuN5.
65. G. Renz, M. Klose, C. Reiter, F. Massmann, and H. Voss, in *Proceedings of the Conference Advanced Solid-State Photonics* (2006), p. WD3.
66. S. So, J. I. Mackenzie, D. P. Shepherd, and W. A. Clarkson, Proceeding of SPIE **6871**, 68710R (2008).
67. X. M. Duan, B. Q. Yao, C. W. Song, J. Gao, and Y. Z. Wang, Laser Phys. Lett. **5**, 800 (2008).
68. J. Kwiatkowski, J. K. Jabczynski, L. Gorajek, W. Zendzian, H. Jelínková, J. Šulc, M. Němec, and P. Koranda, Laser Phys. Lett. **6**, 531 (2009).
69. B. Q. Yao, X. T. Yang, X. M. Duan, T. H. Wang, Y. L. Ju, and Y. Z. Wang, Laser Phys. Lett. **6**, 509 (2009).
70. X. M. Duan, B. Q. Yao, L. Ke, Y. L. Ju, and Y. Z. Wang, Laser Phys. Lett. **6**, 715 (2009).
71. X. M. Duan, B. Q. Yao, G. Li, T. H. Wang, X. T. Yang, Y. Z. Wang, G. J. Zhao, and Q. Dong, Laser Phys. Lett. **6**, 279 (2009).
72. X. M. Duan, B. Q. Yao, Y. L. Ju, Y. Z. Wang, and G. J. Zhao, Laser Phys. Lett. **6**, 847 (2009).
73. X. J. Cheng, J. Q. Xu, M. J. Wang, B. X. Jiang, W. X. Zhang, and Y. B. Pan, Laser Phys. Lett. **7**, 351 (2010).
74. A. S. Kurkov, E. M. Sholokhov, A. V. Marakulin, and L. A. Minashina, Laser Phys. Lett. **7**, 587 (2010).
75. Y. L. Tang, L. Xu, M. J. Wang, Y. Yang, X. D. Xu, and J. Q. Xu, Laser Phys. Lett. **8**, 120 (2011).
76. A. S. Kurkov, E. M. Sholokhov, O. I. Medvedkov, V. V. Dvoyrin, Y. N. Pyrkov, V. B. Tsvetkov, A. V. Marakulin, and L. A. Minashina, Laser Phys. Lett. **6**, 661 (2009).

77. R. C. Stoneman and L. Esterowitz, Opt. Lett. **15**, 486 (1990).
78. P. J. M. Suni and S. W. Henderson, Opt. Lett. **16**, 817 (1991).
79. J. F. Pinto and L. Esterowitz, Opt. Lett. **17**, 731 (1992).
80. J. M. Fukumoto, W. H. Long, and E. A. Stappaerts, Proceeding of SPIE **1627**, 151 (1992).
81. D. C. Shannon, D. L. Vecht, S. Re, J. Alonis, and R. W. Wallace, Proceeding of SPIE **1865**, 164 (1993).
82. N. P. Barnes, M. G. Jani, and R. L. Hutcheson, Appl. Opt. **34**, 4290 (1995).
83. D. D. Lowenthal, C. E. Hamilton, S. C. Tidwell, M. S. Bowers, and J. J. Ewing, Proceeding of SPIE **2502**, 483 (1995).
84. C. Borel, A. Rameix, P. Thony, and B. Ferrand, Proceeding of SPIE **2380**, 14 (1995).
85. R. Beach, S. B. Sutton, E. C. Honea, J. A. Skidmore, and M. A. Emanuel, Proceeding of SPIE **2698**, 168 (1996).
86. T. Yokozawa and H. Hara, Appl. Opt. **35**, 1424 (1996).
87. G. Rustad and K. Stenersen, IEEE J. Sel. Topics Quantum Electron, **3**, 82 (1997).
88. E. C. Honea, R. J. Beach, S. B. Sutton, J. A. Speth, S. C. Mitchell, J. A. Skidmore, M. A. Emanuel, and S. A. Payne, IEEE J. Quantum Electron. **33**, 1592 (1997).
89. C. Bollig, W. A. Clarkson, R. A. Hayward, and D. C. Hanna, Opt. Commun. **154**, 35 (1998).
90. C. Li, J. Song, D. Y. Shen, N. S. Kim, and K. Ueda, Opt. Express. **4**, 12 (1999).
91. M. Tsunekane, N. Taguchi, and H. Inaba, Appl. Opt. **38**, 1788 (1999).
92. K. S. Lai, P. B. Phua, R. F. Wu, Y. L. Lim, E. Lau, S. W. Toh, and A. Chng, Opt. Lett. **25**, 1591 (2000).
93. V. Sudesh and J. A. Piper, IEEE J. Quantum Electron. **36**, 879 (2000).
94. S. W. Henderson, C. P. Hale, J. W. Hobbs, P. Gatt, and J. R. Magee, Proceeding of SPIE **4153**, 93 (2001).
95. S. Goidring, E. Lebiush, and R. Lavi, Proceeding of SPIE **4630**, 13 (2002).
96. K. Scholle, E. Heumann, and G. Huber, Laser Phys. Lett. **1**, 285 (2004).
97. S. W. Henderson and S. M. Hannon, Proceeding of SPIE **5887**, 1 (2005).
98. H. Kalaycioglu, A. Sennaroglu, A. Kurt, and G. Ozen, J. Phys. **19**, 1 (2007).
99. Z. F. Lin, M. W. Gao, and C. Q. Gao, Chin. J. Lasers. **34**, 181 (2007) [in Chinese].
100. M. Eichhorn and A. Hirth, in *Proceedings of the Conf. on Lasers and Electro-Optics* (2008), p. CTuII3.
101. M. Eichhorn, C. Kieleck, and A. Hirth, in *Proceedings of the Conf. on Lasers and Electro-Optics* (2009), p. CWH2.
102. J. Li, S. H. Yang, H. Y. Zhang, D. X. Hu, and C. M. Zhao, Laser Phys. Lett. **7**, 203 (2010).
103. M. S. Gaponenko, V. E. Kisel, N. V. Kuleshov, A. M. Malyarevich, K. V. Yumashev, and A. A. Onushchenko, Laser Phys. Lett. **7**, 286 (2010).
104. F. Chen, B. Q. Yao, C. Yuan, C. T. Wu, X. M. Duan, and Y. Z. Wang, Laser Phys. **21**, 851 (2011).
105. C. Q. Gao, Z. F. Lin, R. Wang, Y. S. Zhang, M. W. Gao, and Y. Zheng, Laser Phys. **21**, 70 (2011).
106. Z. Zhang, N. J. Ruan, F. Zhou, Z. J. Liu, and L. J. Xu, Laser Phys. **21**, 1078 (2011).
107. F. Chen, B. Q. Yao, X. M. Duan, C. H. Zhang, and Y. Z. Wang, Laser Phys. **21**, 439 (2011).
108. C. T. Wu, Y. L. Ju, Q. Wang, B. Q. Yao, and Y. Z. Wang, Laser Phys. **21**, 312 (2011).
109. C. T. Wu, Y. L. Ju, B. Q. Yao, L. Ke, and Y. Z. Wang, Laser Phys. **21**, 356 (2011).
110. P. Zhou, X. L. Wang, Y. X. Ma, K. Han, and Z. J. Liu, Laser Phys. **21**, 184 (2011).