激光与光电子学进展

# 2 μm 波段单掺铥脉冲固体激光器研究进展

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**摘要** 2 μm 波段激光用途广泛，既可以应用于激光雷达、激光测距和医疗手术等领域，又可以作为中长波红外波段激光器的泵浦源。采用激光二极管直接泵浦掺铥晶体获得 2 μm 波段激光，是一种直接高效的技术手段，受到了广泛关注。本文介绍了 Tm:YAG、Tm:YAP 和 Tm:YLF 脉冲激光器的研究进展，并进行了总结与展望。

**关键词** 激光器；固体激光器；脉冲激光器；激光二极管泵浦激光器；激光材料；2 μm 波段
**中图分类号** TN248.1 **文献标志码** A **DOI:** 10.3788/LOP220654

# Research Progress of Tm-Doped Pulsed Solid-State Lasers in 2 μm Band

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**Abstract** 2 μm band laser has a wide range of applications, not only in the fields of lidar, laser ranging, and medical surgery, but also as a pump source for mid and long wavelength infrared lasers. Using laser diodes to directly pump thulium-doped crystals to obtain lasers in the 2 μm band is a direct and efficient technical means, which has attracted wide attention. This paper introduces the research progress of Tm : YAG, Tm : YAP, and Tm : YLF pulsed lasers, and makes a summary and prospect.

**Key words** lasers; solid-state lasers; pulsed lasers; diode-pumped lasers; laser materials; 2 μm band

## 1 引 言

2 μm 波段激光位于大气窗口，并且水分子对此波段的吸收十分强烈，由于具有这些特性，因此 2 μm 波段激光在激光雷达、激光测距和医疗手术等领域有着广泛的应用前景，并且 2 μm 波段激光还可作为光学参量振荡器的泵浦源，从而实现更长波段的红外激光输出[1-5]。固体激光器在大能量、高峰值功率激光输出方面具有明显的优势，受到各国科研人员的广泛关注并取得了长足的发展。

目前，固体激光器实现 2 μm 波段大能量激光输出有以下四种常用技术手段：1)采用 1 μm 激光泵浦光学参量振荡器[6]；2)采用 LD 泵浦铥钬共掺增益介质[7]；3)采用 LD 泵浦单掺铥增益介质[8]；4)采用 1.9 μm 激光级联泵浦单掺钬增益介质[9]。其中，采用 LD 泵浦掺铥增益介质输出 2 μm 波段激光有以下优势：1)掺铥晶体的吸收峰大都在 790 nm 附近，此波段已有非常成熟的商用激光二极管可供使用；2)铥离子($Tm^{3+}$)的交叉弛豫现象，有利于提高量子效率。

铥属镧系元素，1878 年由瑞典科学家克莱夫从铒土中分离出来，典型准三能级结构。在波长为 800 nm 附近泵浦光的作用下，粒子从基态能级 $^3H_6$ 受激吸收跃迁到激发态能级 $^3H_4$，然后从激发态能级 $^3H_4$ 向下无辐射跃迁(NR)至上能级 $^3F_4$，最后由上能级 $^3F_4$ 向下跃迁

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**收稿日期**：2022-01-28；**修回日期**：2022-03-05；**录用日期**：2022-03-29；**网络首发日期**：2022-04-10

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至基态能级$^3H_6$产生激光。同时，掺铥基质材料还存在交叉弛豫（CR）现象，处于激发态能级$^3H_4$上的粒子将部分能量传递给基态能级$^3H_6$上的粒子，然后无辐射跃迁到$^3F_4$能级，基态能级$^3H_6$上的粒子吸收能量后也跃迁至上能级$^3F_4$，即在一个泵浦光的作用下可产生两个光子，理论上量子效率接近于2，其能级结构和能级跃迁过程如图1[10]所示。

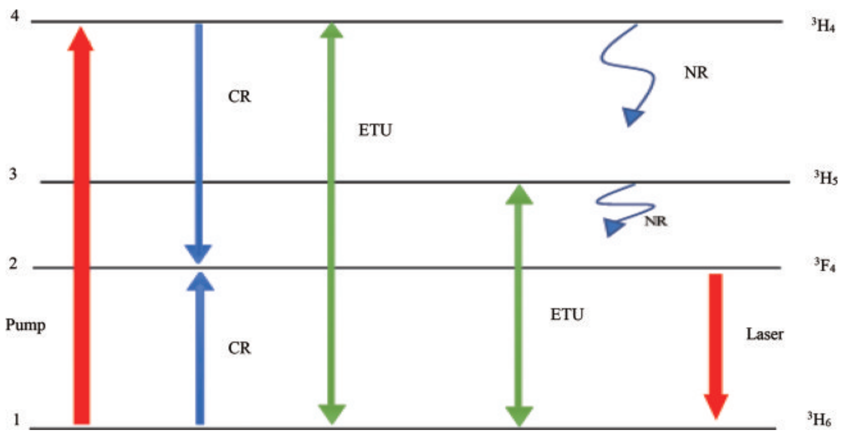

图1　Tm$^{3+}$能级结构图[10]

Fig. 1　Energy level structure diagram of Tm$^{3+}$[10]

铥掺杂的基质材料按成分划分主要包括石榴石类晶体、铝酸物晶体、氟化物晶体、钒酸物晶体、钨酸盐晶体和硅酸盐晶体6类[11]。其中：钇铝石榴石晶体（$Y_3AI_5O_{12}$，YAG）具有优良的物理性能和激活粒子承载能力，光学上各向同性，生长制备技术成熟，热导率高，有利于实现大平均功率激光运转；铝酸钇晶体（$YAlO_3$，YAP）物理性能近似于YAG，由于YAP具有各向异性的光谱特性，因此可以选择晶体的结晶取向从而获得最佳性能输出[12]；氟化钇锂晶体（$YLiF_4$，YLF）具有较小的声子能量和较大的上能级寿命，负折射率特性有效减轻了晶体热透镜效应，有利于实现大脉冲能量激光运转。三种具有代表性的掺铥基质材料，其各自的物理化学特性如表1所示。本文将介绍基于这三种基质材料的2 μm波段单掺铥脉冲固体激光器的研究进展及未来发展前景。

表1　常见掺Tm$^{3+}$晶体特性[12-14]

Table 1　Commonly doped Tm$^{3+}$ crystal characteristics[12-14]

| Gain medium | Tm∶YAG | Tm∶YAP | Tm∶YLF |
|---|---|---|---|
| Crystal structure | Cubic system | Orthorhombic system | Tetragonal system |
| Density $\rho$ /(g. cm$^{-3}$) | 4. 56 | 5. 35 | 3. 99 |
| Melting temperature /K | 2220 | 1870 | 1098 |
| Hardness by Moos | 8. 25–8. 5 | 8. 5–9 | 4–5 |
| Refractive index $n$ | 1. 8123 | a：1. 9048<br>b：1. 9185<br>c：1. 9270 | 1. 44 |
| Thermal conductivity /(W·cm$^{-1}$·K$^{-1}$) | 0. 13 | 0. 11 | a：0. 072<br>c：0. 058 |
| Upper level lifetime $\tau_2$ /ms | 11 | 4. 4–4. 9 | 14 |
| Pump wavelength $\lambda_p$ /nm | 785 | 795 | 792 |
| Absorption cross-section $\sigma_a$ /(10$^{-20}$cm$^2$) | 0. 65 | 0. 91 | 0. 35 |
| Emission cross-section $\sigma_e$ /(10$^{-20}$cm$^2$) | 0. 22 | 0. 5 | 0. 23 |
| Laser wavelength $\lambda_L$ /nm | 2. 01 | 1. 94，1. 99 | 1. 89，1. 91，1. 94 |

## 2 单掺铥2 μm波段脉冲固体激光器

### 2.1 Tm∶YAG脉冲激光器

1965年，美国贝尔实验室Johnson等[15]首次报道了Tm∶YAG激光器，通过氙灯和钨灯泵浦，在液氮冷却（77 K）下，最终获得了波长为2.01 μm的脉冲和连续激光输出。

1992年，Pinto等[16]首次报道了Tm∶YAG主动锁模激光器，当重复频率为300 MHz时，实现了脉宽35 ps、输出功率70 mW的2 μm脉冲输出。

2009年，中国科学院物理研究所Ma等[17]首次采用输出波长为1064 nm的Nd∶YAG激光器泵浦Tm∶YAG，在室温下实现了Tm∶YAG激光器脉冲输出。波长为1064 nm的激光对应能级$^3H_6$至$^3H_5$的跃迁，量子亏损小，采用腔内泵浦的方式，可增加Tm∶YAG晶体对1064 nm激光的吸收率。Tm∶YAG晶体设计成键合式结构以便于散热，声光调Q运转下，当重复频率30 kHz时，成功获得了平均功率5.1 W、脉宽300 ns的2 μm激光输出。

2011年，哈尔滨工业大学Wu等[18]报道了一台室温工作的Tm∶YAG单频激光器。通过插入两个标准具，获得了平均功率为60 mW、波长为2013 nm的单频种子光输出。把种子光注入蝶形腔结构的激光振荡器中，当重复频率为15 Hz时，获得了单脉冲能量为2.0 mJ、脉冲宽度为356.2 ns的2 μm单频激光输出。

2012年中国科学院理化技术研究所Cao等[19]报道了基于声光调Q的Tm∶YAG激光器。实验装置如图2所示，$M_1$、$M_2$为前后腔镜，三个激光模块和声光Q开关放置在直腔中。在泵浦功率为1300 W、水冷温度8 ℃、重复频率为10 kHz时，实现了平均输出功率为171.4 W、脉冲宽度为1 μs、单脉冲能量为17.14 mJ、峰值功率为17.14 kW、波长为2020 nm的激光输出，对应的光-光转换效率为13.3%，斜率效率为18.9%，这是目前报道的Tm∶YAG脉冲固体激光器获得的最大平均功率输出。

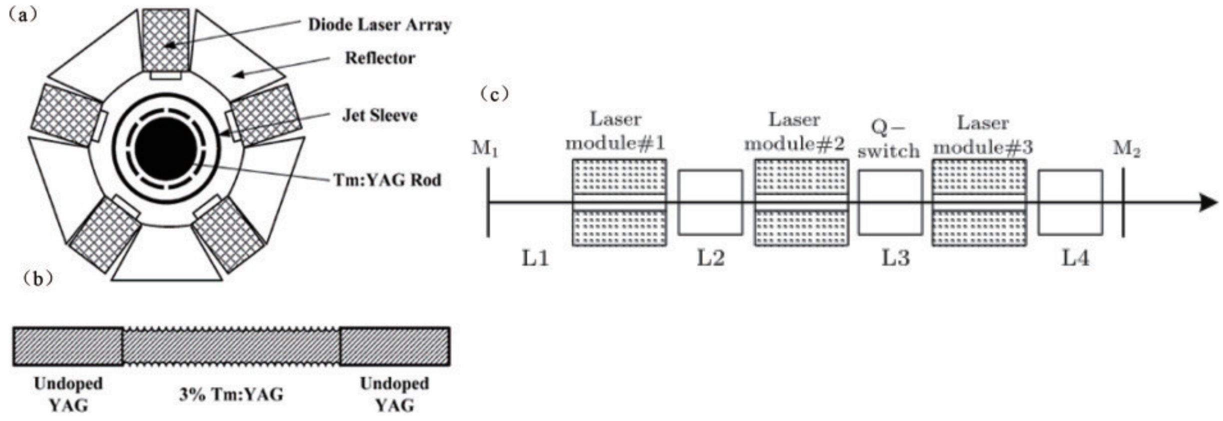

图2 Tm∶YAG激光装置。(a)单个激光模块；(b)键合式Tm∶YAG晶体；(c)Tm∶YAG激光器结构[19]

Fig. 2 Tm∶YAG laser device. (a) Single laser module; (b) bonded Tm∶YAG crystal; (c) Tm∶YAG laser structure[19]

2014年，哈尔滨工业大学Cai等[20]首次将声光腔倒空技术应用在Tm∶YAG激光器中，获得了纳秒量级的脉冲输出。以中心波长为785 nm的LD作为泵浦源，当重复频率为200 kHz时，获得了平均功率595 mW、脉宽54 ns、波长为2013 nm的激光输出。

2015年，Ma等[21]首次报道了采用石墨烯作为锁模材料，在Tm∶YAG陶瓷激光器中实现被动锁模。采用中心波长为790 nm的LD泵浦，在重复频率为98.7 MHz时，获得了脉宽为2.8 ps，平均输出功率为158 mW的2 μm激光输出。

2015年，Yumoto等[22]报道了纳秒级大能量Tm∶YAG脉冲固体激光器。采用中心波长为785 nm的LD阵列侧面泵浦Tm∶YAG晶体，声光调Q运转下，重复频率为10 Hz时，成功获得了单脉冲能量为128 mJ、脉冲宽度为160 ns、波长为2.01 μm的激光输出，斜效率为14 %。

2020年，哈尔滨理工大学Li等[23]首次报道了采用硫化物$MoS_2$作为可饱和吸收体的Tm∶YAG被动锁模激光器。采用中心波长为792 nm的LD泵浦，当重复频率为232.2 MHz时，成功实现了脉宽为280 ps、平均功率为200 mW、波长为2013.8 nm的激光输出。

2021年，Körner等[24]首次报道了Tm∶YAG激光器在低温状态下成功输出中心波长为1.88 μm的激光。泵浦源为重复频率为1 Hz、峰值功率为28 W的脉冲LD，晶体温度保持在120 K，在调Q状态下获得了单脉冲能量为2.55 mJ、脉冲宽度为650 ns、中心波长为1.88 μm的激光输出，在腔倒空状态下脉冲宽度被压缩至15 ns，对应单脉冲能量为2.22 mJ。

同年，长春理工大学Fu等[25]报道了一种双脉冲Tm∶YAG激光器。基于声光调Q技术，当泵浦功率为10 W、重复频率为100 Hz时，获得了单脉冲能量为3.6 mJ、中心波长为2014.16 nm的双脉冲激光输出，前后两个脉冲的脉宽分别为416 ns和407 ns。

表2 Tm:YAG脉冲固体激光器发展概况

Table 2 Development of Tm:YAG pulsed solid-state laser

| Year | Operation mode | Repetition frequency | Output power | Peak power | Pulse energy | Pulse width |
|---|---|---|---|---|---|---|
| 1992[16] | Actively mode-locked | 300 MHz | 70 mW | 6.7 W | 0.23 nJ | 35 ps |
| 2009[17] | AO *Q*-switched | 30 kHz | 5.1 W | 566.7 W | 0.17 mJ | 300 ns |
| 2011[18] | AO *Q*-switched | 15 Hz | 30 mW | 5.6 kW | 2.0 mJ | 356.2 ns |
| 2012[19] | AO *Q*-switched | 10 kHz | 171.4 W | 17.1 kW | 20 mJ | 1 μs |
| 2013[26] | — | 100 Hz | 18 W | 900 W | 180 mJ | 200 μs |
| 2014[20] | Acousto optically cavity dumped | 200 kHz | 598 mW | 54.6 W | 2.95 μJ | 54 ns |
| 2015[21] | Passively mode-locked | 98.7 MHz | 158 mW | 571.7 W | 1.6 nJ | 2.8 ps |
| 2015[22] | AO *Q*-switched | 10 Hz | 1.3 W | 800 kW | 128 mJ | 160 ns |
| 2015[27] | Passively mode-locked | 89 MHz | 150 mW | 561.8 W | 1.7 nJ | 3 ps |
| 2017[28] | AO *Q*-switched | 1 kHz | 20.7 W | 246.4 kW | 20.7 mJ | 84 ns |
| 2017[29] | Self-mode locked | 3.376 GHz | 1.2 W | 120.1 W | 0.36 nJ | 3 ps |
| 2018[30] | Passively *Q*-switched | 49.36 kHz | 421 mW | 20.2 W | 8.53 μJ | 423 ns |
| 2018[31] | Passively *Q*-switched | 57.67 kHz | 272 mW | 12.6 W | 4.8 μJ | 382 ns |
| 2019[32] | AO *Q*-switched | 200 Hz | 1.37 W | 18.6 kW | 6.83 mJ | 367.7 ns |
| 2020[33] | Passively *Q*-switched | 124.5 kHz | 842 mW | 19 W | 6.76 μJ | 355 ns |
| 2020[23] | Passively mode-locked | 232.2 MHz | 200 mW | 3.1 W | 0.86 nJ | 280 ps |
| 2020[34] | Passively mode-locked | 97.7 MHz | 117 mW | 25.1 W | 1.2 nJ | 47.9 ps |
| 2021[35] | Passively mode-locked | 203.1 MHz | 320mW | 2.7 W | 1.58 nJ | 580.5 ps |
| 2021[36] | Passively *Q*-switched | 101.8 kHz | 263 mW | 5.8 W | 2.3 μJ | 398 ns |
| 2021[24] | EO *Q*-switched | 1 Hz | 2.53 mW | 3.9 kW | 2.53 mJ | 650 ns |
| 2021[37] | Passively *Q*-switched | 119.3 kHz | 251 mW | 6.5 W | 2.1 μJ | 322.6 ns |
| 2021[25] | AO *Q*-switched | 100 Hz | 0.36 W | — | 3.6 mJ | — |
| 2021[38] | Passively mode-locked | 208.5 MHz | 102 mW | 2.19 W | 0.49 nJ | 224 ps |

### 2.2 Tm:YAP脉冲激光器

1997年，Elder等[39]以Tm:YAP为增益介质，首次在室温下采用LD泵浦的方式，获得了1.965~2.020 μm的可调谐光输出。

2004年，Sullivan等[40]报道了声光调*Q*的高功率Tm:YAP激光器。当重复频率为5 kHz时，获得了平均功率为35 W、单脉冲能量为7 mJ、脉冲宽度为75 ns、波长为1940 nm的激光输出。

2011年，哈尔滨工业大学Yao等[41]报道了一台双波长高光束质量的Tm:YAP锁模激光器，基于半导体饱和吸收体（SESAM）获得了锁模脉冲输出，在重复频率为26.47 kHz时，得到平均功率为480 mW，1936.9 nm和1938.9 nm双波长激光输出，光束质量$M^2$为1.2±0.2。

2015年，哈尔滨工业大学Yao等[42]首次报道了采用电光腔倒空方式获得脉冲输出的Tm:YAP激光器，实验装置如图3所示。泵浦源采用中心波长为792 nm的LD，电光晶体RTP上周期性地加载四分之一电压，最终成功获得了脉宽为7.1 ns、平均功率为3.02 W的脉冲激光输出，对应重复频率为100 kHz。

2018年，济南大学张海鹍等[43]基于SESAM，实现了LD泵浦Tm:YAP晶体的大功率连续锁模运转输出。当最大抽运功率为7.96 W时，获得锁模激光的最大平均输出功率为730 mW、脉宽为1.7 ps，对应的重复频率为88.7 MHz，中心波长为1982.4 nm。

2019年，长春理工大学Wen等[44]采用双端泵浦技术实现了Tm:YAP激光器高峰值功率输出。泵浦源采用中心波长为795 nm的LD，当泵浦功率为79.2 W、重复频率为1 kHz时，获得了单脉冲能量为16.36 mJ、峰值功率为430.07 kW、脉宽38.04 ns、波长1.99 μm的激光输出，对应的光光转换效率为20.66%。这是目前Tm:YAP脉冲激光器所获得的最大峰值功率。

同年，山东大学Niu等[45]通过声光调*Q*和被动调*Q*相结合的方式实现了Tm:YAP激光器的脉冲输出。与单调*Q*手段相比，双调*Q*技术在获得窄脉宽、高峰值功率的激光输出有独特的优势。当吸收泵浦功率为5.34 W、重复频率为1 kHz时，最终获得了脉冲宽度为239 ns、峰值功率为1146 W的2 μm的激光输出。

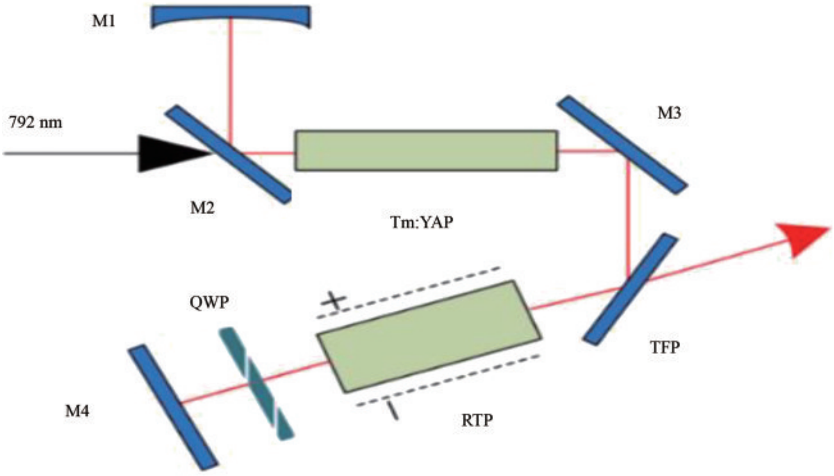

图3　基于电光腔倒空的Tm:YAP激光器[42]

Fig. 3　Tm:YAP laser with electro-optical cavity-dumped[42]

表3　Tm:YAP脉冲固体激光器发展概况

Table 3　Development of Tm:YAP pulsed solid-state laser

| Year | Operation mode | Repetition frequency | Output power | Peak power | Pulse energy | Pulse width |
|---|---|---|---|---|---|---|
| 2004[40] | AO *Q*-switched | 5 kHz | 35 W | 93.3 kW | 7 mJ | 75 ns |
| 2011[41] | Passively mode-locked | 26.47 kHz | 480 mW | — | 18.1 μJ | — |
| 2014[48] | Acousto optically cavity dumped | 200 kHz | 1.28 W | 148.8 W | 6.4 μJ | 43 ns |
| 2015[42] | Electro-optic cavity dumped | 100 kHz | 3.02 W | 4.3 kW | 30.2 μJ | 7.1 ns |
| 2018[43] | Passively mode-locked | 88.7 MHz | 730 mW | 4.8 kW | 8.2 nJ | 1.7 ps |
| 2019[44] | AO *Q*-switched | 1 kHz | 16.4 W | 430.1 kW | 16.4 mJ | 38.04 ns |
| 2019[49] | Passively mode-locked | 96.55 MHz | 880 mW | 19.03 W | 9.11 nJ | 478.83 ps |
| 2019[50] | Passively *Q*-switched | 255 kHz | 2.2 W | 15 W | 8.7 μJ | 579 ns |
| 2019[51] | Passively *Q*-switched | 101 kHz | 542 mW | 10.1 W | 5.4 μJ | 533 ns |
| 2019[45] | Doubly *Q*-switched | 1 kHz | 274 mW | 1.1 kW | 274 μJ | 239 ns |
| 2019[52] | Doubly *Q*-switched | 62.7 kHz | 350 mW | 22.4 W | 5.6 μJ | 249.4 ns |
| 2020[53] | Passively *Q*-switched | 95 kHz | 957 mW | 11.5 W | 10.1 μJ | 857.5 ns |
| 2020[54] | AO *Q*-switched | 1 kHz | 230 mW | 4.6 kW | 230 μJ | 50 ns |
| 2020[46] | EO *Q*-switched | 10 kHz | 21.96 W | 107.3 kW | 2.20 mJ | 20.64 ns |
| 2020[47] | EO *Q*-switched | 200 Hz | 630 mW | 185.3 kW | 3.15 mJ | 17 ns |
| 2020[55] | Passively *Q*-switched | 113.7 kHz | 1.29 W | 28.9 W | 11.3 μJ | 392.7 ns |
| 2020[56] | Passively *Q*-switched | 24 kHz | 100 mW | 1.55 W | 3.8 μJ | 2.5 μs |
| 2020[57] | EO *Q*-switched | 1 kHz | 2 W | 33.3 kW | 2 mJ | 60 ns |
| 2020[58] | Passively *Q*-switched | 71 kHz | 451 mW | 8.58 W | 6.35 μJ | 740 ns |
| 2021[59] | AO *Q*-switched | 10 kHz | 33.2 W | 16.6 kW | 3.3 mJ | 200 ns |
| 2021[60] | Passively *Q*-switched | 88.28 kHz | 0.97 W | 24.4 W | 11.2 μJ | 459.0 ns |
| 2021[61] | AO *Q*-switched | 1 kHz | 2.3 W | 80 kW | 2.3 mJ | 29.5 ns |
| 2021[62] | Passively *Q*-switched | 105.1 kHz | 2.05 W | 21.2 W | 19.5 μJ | 916 ns |
| 2021[63] | Doubly *Q*-switched | 100 Hz | 420 mW | 111.8 kW | 4.2 mJ | 38 ns |
| 2021[64] | Passively *Q*-switched | 98.59 kHz | 1.37 W | 6.4 W | 13.85 μJ | 2.16 μs |
| 2021[65] | Passively *Q*-switched | 175 kHz | 0.81 W | 2.7W | 4.6 μJ | 1.69 μs |
| 2021[66] | Passively mode-locked | 70.2 MHz | 630 mW | 57 W | 8.9 nJ | 156 ps |
| 2021[67] | Doubly *Q*-switched | 200 Hz | 151 mW | 34.3 kW | 755 μJ | 22 ns |
| 2021[68] | Passively *Q*-switched | 70.08 kHz | 153 mW | 2.67 W | 2.18 μJ | 821 ns |
| 2022[69] | EO *Q*-switched | 1 kHz | 1.76 W | 88 kW | 1.76 mJ | 20 ns |
| 2022[70] | Passively *Q*-switched | 49 kHz | 280 mW | 6.6 W | 5.7 μJ | 0.86 μs |
| 2022[71] | Passively *Q*-switched | 95 kHz | 220 mW | 10.5 W | 2.3 μJ | 220 ns |

2020年，长春理工大学Wen等[46]报道了基于电光调$Q$的Tm∶YAP高重复频率板条激光器，采用中心波长为795 nm的LD进行双端泵浦，当泵浦功率为79.2 W、重复频率为10 kHz时，成功获得了平均功率为21.96 W、脉冲宽度为20.64 ns、单脉冲能量为2.20 mJ、峰值功率为107.3 kW、中心波长为1937.87 nm的脉冲激光输出。

同年，山东大学Yang等[47]报道了一台基于电光调$Q$的Tm∶YAP窄脉宽激光器，当重复频率为200 Hz、泵浦功率为10.1 W时，获得了脉冲宽度为17 ns、峰值功率为185.3 kW、中心波长为1988 nm的脉冲激光输出。

## 2.3　Tm∶YLF脉冲激光器

1997年，Ketteridge等[72]报道了一种在低温下(77 K)运行、光纤耦合LD双端泵浦的连续可调的Tm∶YLF激光器，波长连续调谐范围1.85~1.92 μm。

2002年，Petros等[73]报道了高脉冲能量的Tm∶YLF激光器。谐振腔设计成V型结构，通过LD阵列脉冲泵浦，输出脉宽为450 μs时，获得脉冲激光的能量为310 mJ、波长为1.91 μm，对应的斜效率为29%。

2007年，Jabczyński等[74]采用中心波长为792 nm的LD泵浦Tm∶YLF晶体，声光调$Q$运转下，当重复频率为几Hz时，获得了峰值功率为300 kW、脉宽为15 ns、波长为1900 nm的激光输出。

2017年，诺曼底大学Soulard等[75]采用SESAM，展示了一种2.3 μm连续被动锁模Tm∶YLF激光器。采用中心波长780 nm激光泵浦Tm∶YLF晶体，重复频率100 MHz下，获得平均功率165 mW、脉宽为94 ps的锁模激光输出，这是第一次报道2.3 μm波长的SESAM锁模Tm∶YLF激光器。

同年，Canbaz等[76]基于克尔透镜，在采用780 nm泵浦的Tm∶YLF激光器中实现了被动锁模，获得了飞秒量级的脉冲输出。当泵浦功率为880 mW、重复频率为41.5 MHz时，获得了平均功率14.4 mW、脉宽514 fs、波长2303 nm的激光输出。

2020年，Goldberg等[77]报道了大能量、高峰值功率的Tm∶YLF被动调$Q$激光器。该激光装置将Cr∶ZnS作为可饱和吸收体：当Cr∶ZnS的透过率为92%、泵浦功率为30.5 W、重复频率为1 kHz时，获得了峰值功率为280 kW、单脉冲能量为10.8 mJ、脉冲宽度为38 ns的1.9 μm激光输出；当Cr∶ZnS的透过率为89%、泵浦功率为14.7 W、重复频率约为300 Hz时，获得了峰值功率为350 kW、单脉冲能量为10.2 mJ、脉冲宽度为29 ns的1.9 μm激光输出，分别是目前已知Tm∶YLF被动调$Q$脉冲激光器所获得的最大单脉冲能量和最高峰值功率。

2021年，Tamer等[78]基于如图4所示Tm∶YLF激光装置，获得了焦耳量级的脉冲输出，实现了单掺铥大能量激光器的重大突破。该激光装置由振荡器和放大器两部分组成。振荡器部分采用中心波长为793 nm、峰值功率为1 kW的脉冲LD进行侧面泵浦，基于电光腔倒空技术，在重复频率为1 Hz时，获得了脉冲能量为18 mJ、脉宽为20 ns、波长为1.88 μm的脉冲激光输出。放大器部分采用双端脉冲泵浦的方式，2 min发射一个脉冲，经过四通放大，当LD输出脉冲宽度为30 ms、峰值功率为12.2 kW时，成功获得单脉冲能量为3.88 J、脉宽为20 ns、中心波长为1.88 μm的激光输出。在振荡器自由运转的状态下，当LD输出脉冲宽度为40 ms、峰值功率为16.9 kW时，获得了脉冲能量为38.1 J，脉宽为毫秒量级的激光输出。这项工作不仅打破了Tm∶YLF激光器所获得的最高单脉冲能量纪录[73]，也是2 μm波段激光装置所获得的最高单脉冲能量[79]，展示了大能量Tm∶YLF激光器的广阔前景。

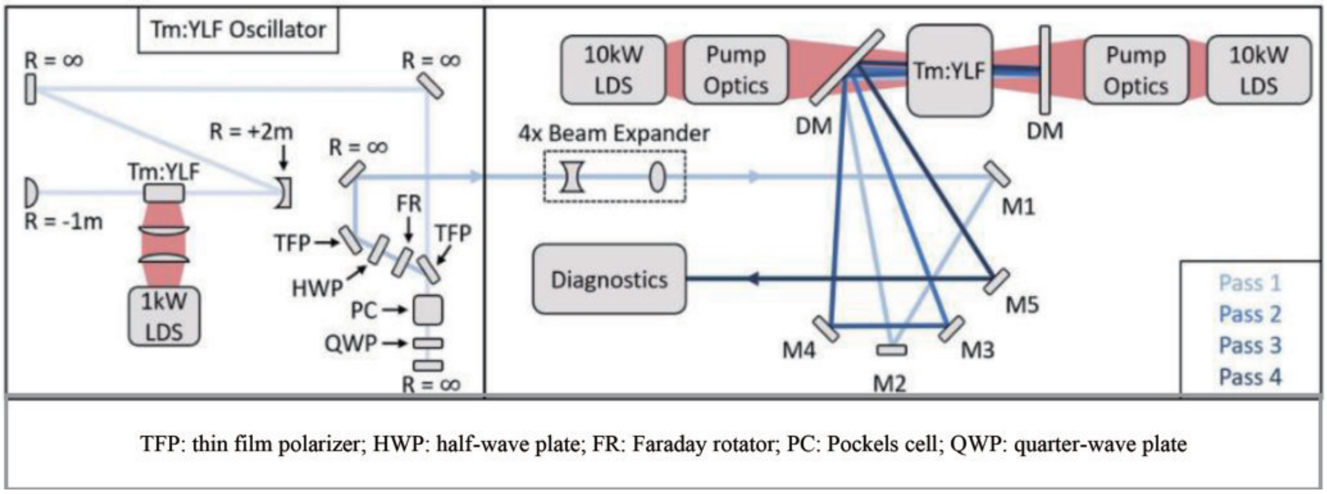

图4　大能量Tm∶YLF实验装置

Fig. 4　Large energy Tm: YLF experimental device

表4　Tm:YLF脉冲固体激光器发展概况

Table 4　Development of Tm : YLF pulsed solid-state laser

| Year | Operation mode | Repetition frequency | Output power | Peak power | Pulse energy | Pulse width |
|---|---|---|---|---|---|---|
| 2002[73] | Free-running operation | — | — | — | 310 mJ | — |
| 2007[74] | AO *Q*-switched | — | — | 300 kW | 4.5 mJ | 15 ns |
| 2017[75] | Passively mode-locked | 100 MHz | 165 mW | 17.6 W | 1.65 nJ | 94 ps |
| 2017[76] | Passively mode-locked | 41.5 MHz | 14.4 mW | 675.1 W | 0.35 nJ | 514 fs |
| 2018[80] | Passively mode-locked | 94 MHz | 95 mW | 32.6 W | 1.01 nJ | 31 ps |
| 2019[81] | AO *Q*-switched | 1 kHz | 1.97 W | 53.2 kW | 1.97 mJ | 37 ns |
| 2019[82] | Passively *Q*-switched | 76 kHz | 6.3 W | 27.5 W | 85.2 μJ | 3.1 μs |
| 2019[83] | Passively *Q*-switched | 82 kHz | 1.05 W | 30 W | 12.8 μJ | 427 ns |
| 2019[84] | Passively mode-locked | 54.1 MHz | 1.04 W | 179.7 W | 19 nJ | 107 ps |
| 2020[85] | AO *Q*-switched | 9 kHz | 25 W | 2.7 kW | 2 mJ | 740 ns |
| 2020[86] | EO *Q*-switched | 1 kHz | 1.4 W | 82.4 kW | 1.4 mJ | 17 ns |
| 2020[77] | Passively *Q*-switched | 1 kHz | 10.8 W | 280 kW | 10.8 mJ | 38 ns |
|  |  | — | — | 350 kW | 10.2 mJ | 29 ns |
| 2020[87] | Passively *Q*-switched | 6.67 kHz | 320 mW | 57 W | 48 μJ | 843 ns |
| 2021[88] | EO *Q*-switched | 500 Hz | 625 mW | 65.8 kW | 1.25 mJ | 19 ns |
| 2021[78] | Electro-optic cavity dumped | — | — | — | 3.88 J | — |
| 2021[78] | free-running operation | — | — | — | 38.1 J | — |
| 2021[89] | AO *Q*-switched | 5 kHz | 7.32 W | 21.5 kW | 1.4 mJ | 68 ns |

## 3　结束语

近年来，基于Tm:YAG、Tm:YAP和Tm:YLF晶体的2 μm波段固体激光器取得了一定的进展，激光输出功率、脉冲宽度、单脉冲能量等关键技术指标不断提升。就各自激光输出特性而言，目前，基于Tm:YAG晶体的2 μm波段固体激光器实现了平均输出功率大于150 W的2 μm波段激光输出。Tm:YAG具有激光基质材料所要求的很多特性，性能稳定，在未来随着技术的发展，Tm:YAG作为增益介质输出2 μm波段激光的潜力会得到进一步释放。

基于Tm:YAP晶体的2 μm波段固体激光器经过多年的发展，输出峰值功率可达百千瓦量级，脉冲宽度可达皮秒量级。由于Tm:YAP晶体可直接获得线偏振光输出，与Tm:YLF晶体相比具有更优良的物理与热性能，因此在一些领域也有着广泛用途。

Tm:YLF晶体具有较长的上能级寿命和较小的声子能量，有利于实现大能量运转。最新报道中，Tm:YLF激光装置基于电光腔倒空获得了单脉冲能量为3.88 J的纳秒级激光输出，在长脉冲泵浦时获得了脉冲能量为38.1 J的毫秒级激光输出，这不仅是Tm:YLF激光器所获得的最大单脉冲能量输出，也是2 μm波段固体激光器实现的最大能量输出，印证了Tm:YLF晶体作为大能量2 μm波段固体激光器增益介质的优越性。

由于铥为准三能级结构，因此存在激光输出性能受温度影响大的问题，在未来，可通过改善热管理、优化泵浦结构及激光谐振腔、寻找新的激光基质材料等方式，进一步提升单掺铥脉冲激光器输出性能，满足相关应用。

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