Chapter

Q-Switched 2 Micron Solid-State Lasers and Their Applications

Kejian Yang, Yaling Yang, Jingliang He and Shengzhi Zhao

Abstract

In this chapter, we overview the Q-switched 2 μm solid-state laser development achieved in recent years, including flash- and diode-pumped solid-state lasers based on active and passive modulators. In summary, active Q-switching is still the first choice for obtaining large pulse energy at 2 μm currently, while passive Q-switching based on saturable absorbers (SAs), especially the newly emerging broadband low-dimension nanomaterial, is becoming promising approach in generating Q-switched 2 μm lasers specially with high repetition rate, although the output power, pulse duration, and pulse energy needs further enhancement. Besides, some important applications of 2 μm lasers, such as medicine, laser radar, and infrared directional interference, have also been introduced in brief.

Keywords: 2 μm, solid-state laser, Q-switched, flash-pumped, diode-pumped

1. Introduction

In 1916, Einstein proposed the theory of stimulated radiation, which laid a theoretical foundation for the emerging of lasers. Till 1960, the world's first laser was invented by Mehman. Since then, flash-pumping has been widely employed for laser technology to generate beams with good monochromaticity, excellent coherence and promising directivity. Moreover, with the advent of laser diodes (LD), diode-pumped solid-state lasers have achieved rapid development for many advantages such as high efficiency, small size, and high beam quality compared with flash-pumped lasers. However, free-running lasers have relaxation oscillations, which deliver series of disordered small pulse spikes that do not possess high or stable peak powers. With the directional stored energy further modulated temporally, the laser operation regime would gradually evolve from continuous wave (CW) to Q-switching. It is well known that Q-switching is always an efficient method for generating pulsed lasers for any wavelength, since it provides an efficient way to obtain short laser pulses with high peak power, which is much beneficial for scientific or practical applications in terms of light-matter interactions. By using the Q-switching technology, the pulse peak power can reach KW or even MW level, and the pulse energy reaches mJ or even J level, which are very suitable for medical and industrial fields.

In recent years, 2 μm lasers located in the eye-safe spectral range have gained much attention because of their wide applications in the fields of environmental monitoring [1], laser medicine [2], laser radar [3, 4], micro-machining, material processing [5], and so on. In addition, the 2 μm lasers can also be used as pump sources for producing the mid- and far-infrared lasers. For example, they can be used as high-efficiency pumping sources for optical parametric oscillators (OPOs) and optical parametric amplifiers (OPAs) to achieve broadband tunable lasers in the mid-infrared spectral range of 3–5 and 8–12 μm [6–8]. However, it should be noticed that in practical applications, such as laser surgery, industrial processing, and nonlinear optics, laser pulses with high peak powers are required. Therefore, nanosecond 2 μm laser source with high peak power, large pulse energy and excellent stability is of great significance and has become an important topic of current research on 2 μm lasers.

As mentioned above, Q-switching technology is not an exceptional choice for obtaining nanosecond 2 μm solid-state lasers with high peak power. According to the different operation regimes, Q-switching technology can be divided into active and passive Q-switching (PQS). The basic principle of active Q-switching is regularly modulating the intracavity losses by a voltage controlled modulator, including electro-optic (EO) and acousto-optic (AO) modulators. Although actively Q-switched lasers are frequency adjustable, stable and reliable, they have the disadvantages of large size and expensive cost. Passive Q-switching technology is a good choice to overcome them. In passively Q-switched lasers, the saturable absorber (SA) is the key element and thus the output laser characteristics strongly depend on the nature of the SA materials. Up to now, semiconductor saturable absorber mirrors (SESAMs), chromium doped II-VI semiconductor materials (Cr^{2+}: ZnSe/S), and low-dimensional nanomaterials have been widely studied and regarded as reliable SAs for 2 μm lasers. However, the utilization of SESAMs is restricted by the complicated and expensive fabrication process as well as narrow absorption bandwidth. At present, the low dimensional nanomaterials with advantages of broadband absorption and low cost have been attractive candidates as SAs for PQS.

2. Flash-pumped 2 micron solid-state pulsed lasers

Up to now, flash-pumped solid-state lasers are still widely used in industry and medical science, because of the advantage of high energy output. In general, the flash-pumping way can support larger mode area than that of diode-pumping regime, which is critical for high energy laser output. To increase the absorption efficiency, Cr^{3+} ions are usually co-doped as sensitizer/activator for Tm or Tm-Ho host materials when flash-pumped. Under this situation, the energy level diagram for Cr,Tm,Ho: YAG crystal is illustrated in **Figure 1**. The flash pump light is absorbed by the broadband Cr^{3+} ions. After a nonradiative decay to and within the $^4T_2$ and ^2E states, the excitation is transferred from the Cr^{3+} ion to the $^3F_3$ and $^3H_4$ states of the Tm^{3+} ion, via dipole–dipole interactions. Nonradiative decay of the $^3F_3$ places virtually all the excited ions in the $^3H_4$ state. Each excited Tm^{3+} ion then interacts with a ground state of Tm^{3+} ion in a cross-relaxation process which gives rise to two Tm^{3+} ions in the $^3F_4$ state. Finally, these Tm^{3+} ions transfer their energy to two Ho^{3+} ions to populate the $^5I_7$ upper laser level, and lasing occurs between the $^5I_7$ and $^5I_8$ transition at 2.097 μm [9].

In 1962, Johnson et al. in Bell Labs, USA achieved the firstly 2.06 μm laser emission, but this laser was typically cooled by liquid-N_2 at 77 K and the output power was very low. Lately, it was found that some rare earth ions can sensitize Ho^{3+}, thus a Er,Tm,Ho:YAG laser was realized with a slope efficiency of 5% with aid of liquid-N_2 cooling. In 1985, Antipenko et al. increased the flash-pumping efficiency and achieved the first 2 μm laser output at room temperature by replacing Er^{3+} with Cr^{3+}. But CW operation cannot satisfy the requirements of high peak power and narrow

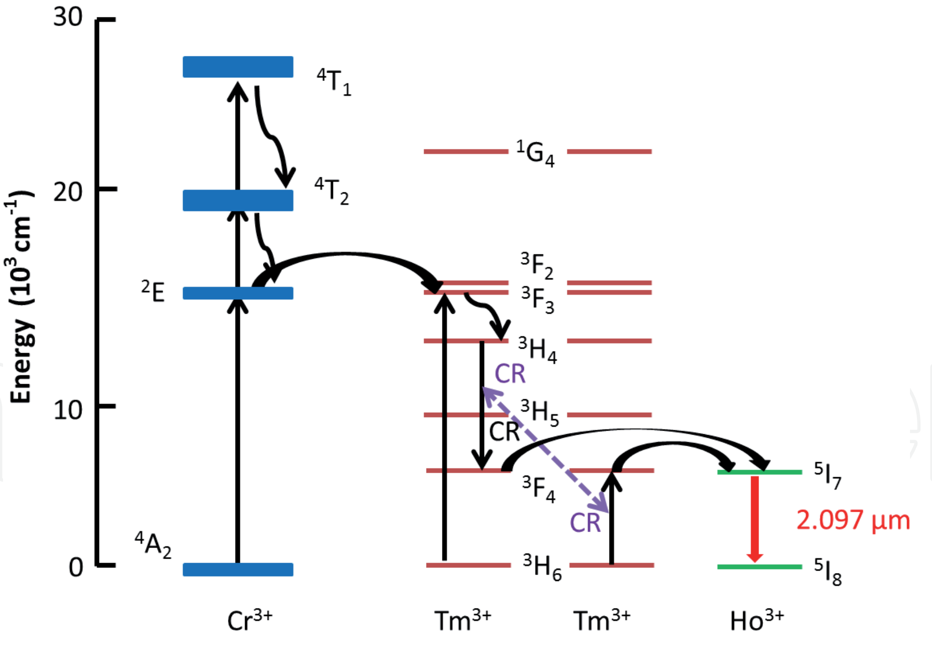

Figure 1.
Energy level diagram for Cr,Tm,Ho:YAG, CR: cross relaxation.

pulse width in many applications. Then Q-switching technology was utilized including passive and active Q-switching methods.

In 1996, Kuo et al. used Ho:YVO_4 and Ho:CaF_2 crystals as SAs for Tm,Cr:YAG lasers, and the corresponding pulse energies and pulse widths were 3.5 mJ, 45 ns and 5.1 mJ, 60 ns at 2.017 μm, respectively [10, 11]. In 2001, flash-lamp-pumped Ho:YAG (2090 nm) and Tm:YAG (2017 nm) lasers were passively Q-switched based on a Cr^{2+}:ZnSe SA for the first time, from which a Q-switched Ho laser with 1.3 mJ pulse energy and ~90 ns pulse duration and a Q-switched Tm laser with ~3.2 mJ pulse energy and 90 ns pulse duration were demonstrated [12]. In 2005, Gaponenko et al. realized passively Q-switched Cr,Tm,Ho:$Y_3Sc_2Al_3O_{12}$ and Cr,Tm,Ho:YAG lasers using PbS SAs, where the pulse energies and pulse widths were 2.4 mJ, 50 ns and 4.5 mJ, 70 ns at about 2.09 μm, respectively [13]. However, because the pulse energies were too low to satisfy the demands of practical application, active Q-switching technology was applied in flash-lamp-pumped 2 μm lasers.

In 1991, Bowman et al. designed an AO Q-switched Cr,Tm,Ho:YAG laser using a quartz crystal with Brewster angle placed in the cavity. At temperature of 20°C, the pulse energy of 110 mJ with the pulse width of 40 ns was obtained at the repetition rate of 1 Hz [14]. Two years late, they achieved AO Q-switched Cr,Tm,Ho:YAG laser with pulse energy of 24 mJ and duration of 90 ns at a repetition rate of 29 Hz [15]. In 2000, using flash-lamp-pumping, an AO Q-switched Cr,Tm:YAG laser was realized with a maximum pulse energy exceeding 0.8 J and a pulse width of 135 ns [16]. In 2005, Zheng et al. reported a AO Q-switched Cr,Tm,Ho:YAG laser delivering a pulse energy of 120 mJ and a pulse width of 90 ns at the repetition rate of 10 Hz [17].

Besides AO modulator, EO modulator is also a common method to modulate flash-lamp-pumped 2 μm lasers, which could further shorten the pulse duration. In 1981, Gettermy et al. reported a $LiNbO_3$ (LN) crystal based EO Q-switched Ho:YAG laser, which had to be cooled down to 77 K to obtain high energy and short pulses. A pulse energy of 80 mJ with a pulse width of 30 ns at the repetition rate of 5 Hz was obtained [18]. In 1990, Henderson et al. reported a EO Q-switched Cr,Tm,Ho:YAG laser using a LN crystal as modulator. At the repetition rate of 3 Hz, the pulse energy of 50 mJ with a corresponding pulse width of 150 ns was obtained

[19]. In 1993, Kim et al. also achieved a pulse energy of 50 mJ from a LN based EO Q-switched Cr,Tm,Ho:YAG laser at 170 K [20]. In 2008, Nieuwenhuis et al. utilized $RbTiOPO_4$ (RTP) crystal as EO modulator in a lamp-pumped Cr,Tm,Ho:YAG laser, and obtained a pulse width of 100 ns with a pulse energy of 42 mJ [21]. In 2012, a flash-lamp-pumped 2.09 μm Cr,Tm,Ho:YAG laser utilizing a $La_3Ga_5SiO_{14}$ (LGS) crystal as the EO modulator is proposed and demonstrated for the first time, which results are shown in **Figure 2**. Operated at a repetition rate of 3 Hz, a pulse energy as high as 520 mJ with a 35 ns pulse width was achieved by optimizing the delay time of EO modulator and compensating for the thermal depolarization with a quarter-wave plate. The corresponding pulse peak power was 14.86 MW, and the energy extraction efficiency was 66.3% [22].

In conclusion, as shown in **Table 1**, flash-pumped 2 μm solid-state lasers have been well developed for generating high pulse energy, especially in combination with active Q-switching methods. To now, the highest single pulse energy obtained at 2 μm was 800 mJ, with corresponding pulse duration of 135 ns by using an AO modulator. As for flash-pumped EO Q-switched 2 μm solid-state lasers, the highest single pulse energy of 520 mJ was achieved with a corresponding pulse width of 35 ns, which delivered the highest pulse peak power from the flash-pumped 2 μm

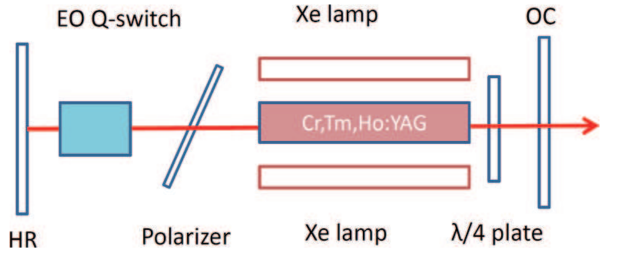

Figure 2.
Schematic setup of flash-lamp-pumped EO Q-switched Cr,Tm, Ho:YAG laser. [Reprinted/Adapted] With permission from Ref. [22] © The Optical Society.

Modulator	Gain media	Durations (ns)	Energy (mJ)	Time	Ref.
$Ho:YVO_4$	Tm,Cr:YAG	45	3.5	1966	[10]
$Ho:CaF_2$	Tm,Cr:YAG	30	5.1	1966	[11]
Cr:ZnSe	Ho:YAG	90	1.3	2001	[12]
Cr:ZnSe	Tm:YAG	90	3.2	2001	[12]
PbS	Cr,Tm,Ho:YSAG	50	2.4	2005	[13]
PbS	Cr,Tm,Ho:YAG	70	4.5	2005	[13]
AO	Cr,Tm,Ho:YAG	40	110	1991	[14]
AO	Cr,Tm,Ho:YAG	90	24	1993	[15]
AO	Cr,Tm:YAG	135	800	2000	[16]
AO	Cr,Tm,Ho:YAG	90	120	2005	[17]
LN	Ho:YAG	30	80	1981	[18]
LN	Cr,Tm,Ho:YAG	150	50	1990	[19]
LN	Cr,Tm,Ho:YAG	—	50	1993	[20]
RTP	Cr,Tm,Ho:YAG	100	42	2008	[21]
LGS	Cr,Tm,Ho:YAG	35	520	2012	[22]

Table 1.
Overview of flash-pumped Q-switched 2 micron solid-state lasers.

solid-state laser, to the best our knowledge. In the future, flash-pumped 2 μm solid-state lasers still have great potential for various applications demanding high energy.

3. Diode-pumped actively modulated 2 micron solid-state lasers

3.1 AO modulated 2 micron solid-state lasers

The AO modulator has the advantages of high damage threshold, easy operation, and low insertion loss. It is capable of generating peak power as high as several hundred kilowatts, high repetition frequency, and short pulse width with several tens of nanoseconds. Thus, AO Q-switching has attracted a lot in generating 2 μm laser pulses based on Tm^{3+} or Ho^{3+} ions doped crystals.

The actively Q-switched Tm^{3+} doped laser can be traced back to 1991, when Suni et al. realized a LD-pumped AO Q-switched Tm:YAG laser with the pulse width of 330 ns and the single pulse energy of 1 mJ at the repetition frequency of 100 Hz [23]. In 2004, Sullivan et al. realized a high-power Q-switched Tm:YAP laser with a maximum output power of 50 W at 1940 nm. At the repetition rate of 5 kHz, the maximum pulse energy was 7 mJ with a corresponding pulse width of 75 ns [24]. But it was low temperature of −10°C. In 2008, Cai et al. realized a diode-pumped AO Q-switched Tm:YAP laser with a maximum single pulse energy of 1.57 mJ and the minimum pulse width of 80 ns at a repetition rate of 1 kHz under room temperature [25]. In 2010, Li et al. showed another double-diode end-pumped AO Q-switched c-cut Tm:YAP laser, which delivered a maximum average output power of 12.5 W at a repetition rate of 10 kHz with a pulse width of 126 ns [26]. In 2015, Yumoto et al. realized AO Q-switched Tm:YAG laser at a center wavelength of 2.013 μm. The maximum pulse energy of 128 mJ was obtained at a repetition rate of 10 Hz, corresponding to a minimum pulse width of 160 ns [27], which was the largest pulse energy for AO Q-switched 2 μm laser. In 2015, Luan et al. realized a 790 nm diode-pumped doubly Q-switched Tm:LuAG laser simultaneously with AO modulator and multilayered graphene as Q-switches, from which a minimum pulse width of 170 ns with a corresponding pulse energy of 0.53 mJ was obtained at a repetition rate of 1 kHz [28]. The results well indicated that doubly Q-switching technique could efficiently shorten the pulse duration.

Efforts are not stopped being paid on exploring diode-pumped solid-state AO Q-switched lasers based on novel kinds of Tm^{3+} and Ho^{3+} doped crystals. In 2017, Liu et al. demonstrated an AO Q-switched Tm,Y:CaF_2 laser in a V-type cavity as shown in **Figure 3**, which could run at high repetition rates from 1 to 10 kHz [29]. Under the modulation frequency of 1 kHz, pulses with the shortest duration of 280 ns and the maximum pulse energy of 0.335 mJ were delivered, corresponding to a maximum peak power of 1.19 kW. In 2019, Zagumennyi et al. reported a novel AO Q-switched Tm:$Yb_3Al_5O_{12}$ (Tm:YbAG) laser pumped by the 1.678 μm laser. The pulse energy was 100 μJ with a pulse duration of 45 ns at the repetition rate of 6.7 kHz [30].

In addition to the Tm lasers emitting around 1.9–2.0 μm, Ho^{3+} ions can emit laser radiations at around 2.0–2.1 μm due to the transition $^5I_7$–$^5I_8$, which can keep away from the water vapor absorption and is helpful for the applications requiring free space transmission. Moreover, Ho^{3+} ion with long upper laser level lifetime are attractive for Q-switched operation. Since Tm^{3+} ions have absorption bands around 800 nm where commercial GaAs/AlGaAs diodes are available, a Tm sensitized Ho laser is an ideal way to achieve a ~ 2.1 μm laser. In 2005, Yao et al. realized the AO Q-switched Tm,Ho:$GdVO_4$ laser under liquid nitrogen refrigeration. And the maximum pulse energy of 1.1 mJ and minimum pulse duration of 23 ns were obtained at a repetition rate of 3 kHz [31]. In 2010, Yao et al. investigated the characteristics of AO Q-switched Tm,Ho:YVO_4 laser under low temperature conditions. A maximum output power of 19.4 W was achieved with a pulse width of 24.2 ns at a repetition rate of 15 kHz [32]. In 2017, Li et al. achieved a stable AO Q-switched Tm,Ho:YAP laser with a pulse width of 66.85 ns and a single pulse energy of 0.97 mJ at the repetition rate of 7.5 kHz and temperature of 77 K cooled by the liquid nitrogen in Dewar bottle [33]. However, the above Tm,Ho co-doped laser were operated under low temperature conditions, which limited their applications.

As for Ho laser emitting around 2 μm, another way is resonantly pumping Ho laser by an extracavity Tm laser, which has high conversion efficiency and low thermal load. Thus, Ho-doped laser is also a vital approach to obtain high output power and pulse energy laser at wavelength over 2 μm. In 2012, Lamrini et al. realized an actively Q-switched Ho:YAG laser based on an AO modulator at 2.09 μm by using a 1.9 μm LD as the pump source, which schematic setup is shown in **Figure 4**. At the repetition rate of 100 Hz, the obtained maximum pulse energy and minimum pulse width were 30 mJ and 100 ns, respectively [34]. In 2014, an AO Q-switched Ho:$GdVO_4$ was realized end-pumped by a 1942 nm Tm-fiber laser, delivering a pulse width of 4.7 ns and an output pulse energy of 0.9 mJ at the repetition frequency of 5 kHz, corresponding to a peak power of 187.2 kW [35]. In 2014, Wang et al. used a 1.908 μm Tm:YLF solid-state laser as the pump source to realize an actively Q-switched Ho:YAG ceramic laser at 2.097 μm based on an AO Q-switch. The maximum pulse energy and minimum pulse width were 10.2 mJ and 83 ns at the repetition rate of 100 Hz [36]. In 2016, Ji et al. used a 1.94 μm LD as the pump source to realize an actively Q-switched Ho:YLF solid-state laser based on an AO Q-switch at 2.06 μm. The maximum pulse energy of 1.1 mJ was achieved with a corresponding minimum pulse duration was 43 ns at the repetition rate of 100 Hz [37]. Up to present, many Ho lasers based on various hosts have been demonstrated. However, there is rare report on the Ho laser with more than 100 W output power.

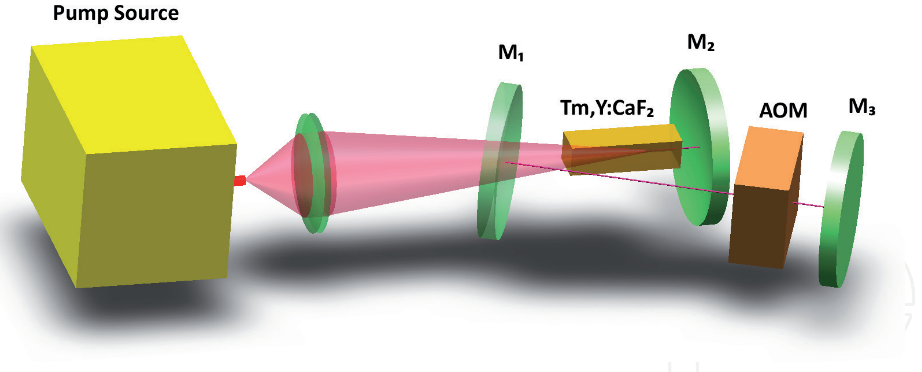

Figure 3.
Experimental setup of the actively Q-switched Tm,Y:CaF_2 laser. [Reprinted/Adapted] With permission from Ref. [29] © The Optical Society.

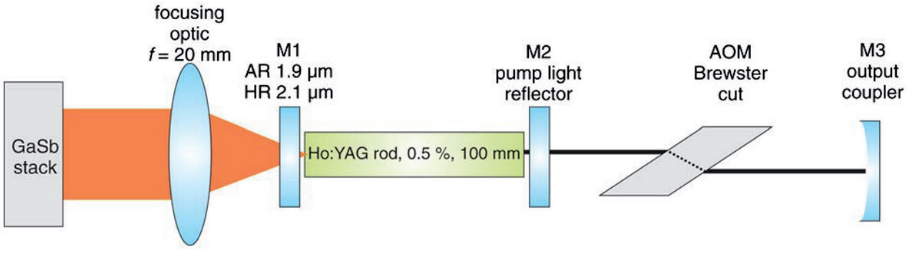

Figure 4.
Resonator of the AO Q-switched Ho(0.5%):YAG laser formed by mirror M1 and mirror M3 (output coupler). [Reprinted/Adapted] With permission from Ref. [34] © The Optical Society.

In 2018, Duan et al. reported a Ho:YAG laser with the output power of up to 108 W in CW mode and 106 W in Q-switching mode, respectively [38]. As far as we know, this is the highest output power of CW and Q-switched Ho lasers ever reported. A pulse energy of 5.3 mJ and a pulse duration of 21 ns were obtained, corresponding to a pulse peak power of approximately 252 kW.

In conclusion, AO Q-switching is an effective method to obtain pulsed 2 μm lasers. **Table 2** shows the summaries of diode-pumped AO Q-switched 2 micron solid-state lasers reported in recent years. From it, we can see that the maximum single pulse energy ever achieved based on AO Q-switching method is 128 mJ. However, for high-energy or high-power lasers, the turn-off capacity of AO switching is poor. In practical, most applications demand pulsed 2 μm lasers with large power, high pulse energy and repetition rate, which sets an important challenge for AO modulators to overcome.

3.2 EO modulated 2 micron solid-state lasers

EO Q-switching is an important way of obtaining high peak power and narrow pulse width which has the advantages of fast switching speed, high extinction ratio and small volume. The peak power of this kind of laser can easily reach hundreds of megawatts. The most important component in EO Q-switch is EO crystal, many EO crystals including $LiNbO_3$ (LN), $RbTiOPO_4$ (RTP) and $La_3Ga_5SiO_{14}$ (LGS) have been successfully applied in the 2 μm EO Q-switched lasers.

From 1970s on, LN crystals have been used as the EO crystal to generate laser pulses, which is exceptional for its no deliquescence, low half-wave voltage, and lateral modulation, etc. In 2015, based on LN crystal Liu et al. reported a diode-pumped EO Q-switched Tm:LuAG laser generating a pulse energy of 2.51 mJ with a pulse width of 88 ns at a repetition rate of 50 Hz [39]. In 2016, with Tm,Ho:YAP

Gain media	Durations (ns)	Frequency (kHz)	Energy (mJ)	Wavelength (μm)	Time	Ref.
Tm:YAG	330	0.1	1	2.015	1991	[23]
Tm:YAP	75	5	7	1.94	2004	[24]
Tm:YAP	80	1	1.57	1.99	2008	[25]
Tm:YAP	126	6	1.6	1.99	2010	[26]
Tm:YAG	160	0.01	128	2.015	2015	[27]
Tm:LuAG	170	1	0.53	2.023	2015	[28]
Tm,Y:CaF_2	280	1	0.335	1.912	2017	[29]
Tm:YbAG	45	6.7	0.1	2.02	2019	[30]
Tm,Ho:$GdVO_4$	23	3	1.1	2.05	2005	[31]
Tm,Ho:YVO_4	24.2	15	1.3	2.055	2010	[32]
Tm,Ho:YAP	66.85	7.5	0.97	2.119	2017	[33]
Ho:YAG	100	0.1	30	2.09	2012	[34]
Ho:$GdVO_4$	4.7	5	0.9	2.05	2014	[35]
Ho:YAG	83	0.1	10.2	2.097	2014	[36]
Ho:YLF	43	0.1	1.1	2.06	2016	[37]
Ho:YAG	21	20	5.3	2.09	2018	[38]

Table 2.
Overview of AO Q-switched 2 μm solid-state lasers.

crystal as gain material and EO Q-switch based on LN crystal, a maximum pulse energy of 1.65 mJ and a shortest pulse duration of 107.4 ns were obtained at a repetition rate of 200 Hz [40]. In 2018, to lower down the thermal effect of gain medium, Guo et al. incorporated diode-wing-pumping technique into a LN EO Q-switched Tm:LuAG laser. A maximum pulse energy of 10.8 mJ and a minimum pulse width of 52 ns at a repetition rate of 100 Hz was delivered, as shown in **Figure 5** [41]. However, further increase of pule energy is limited by the relatively low damage threshold of LN crystal.

RTP crystal belongs to orthorhombic crystal system and has large EO coefficient, high damage threshold and broad transmission range. In 2013, using a 1.94 μm Tm^{3+} fiber laser as the pump source, Fonnum et al. realized a RTP EO Q-switched Ho:YLF laser utilizing the setup shown in **Figure 6**. A maximum pulse energy of 550 mJ and a minimum pulse width of 14 ns at a repetition rate of 1 Hz were obtained [43]. In 2016, a diode-pumped RTP EO Q-switched Tm:YAG slab laser delivered a maximum pulsed energy of 7.5 mJ with a pulse width of 58 ns [44]. However, since RTP crystal is biaxial, two crystals with the same size and direction are required to combine with each other to offset natural birefringence, which greatly increases the difficulty of crystal processing. Moreover, under high-power operation regime, thermal induced birefringence can deteriorate switching performance of the RTP EO Q-switch, which subsequently limits the obtained pulse energy and output power.

In 2003, LGS crystal was firstly grown and studied in Institute of Crystal Materials of Shandong University. LGS crystal is uniaxial and thus free of birefringence induced problems. Compared with LN, the LGS crystal has a 9.5-times-higher anti-photo-damage threshold. Additionally, LGS crystal has a broadband transparency from 190 to 2400 nm, good physical and chemical stability, small thermal expansion coefficient and considerable electro-optic coefficient ($\gamma_{11} = 2.3 \times 10^{-12}$ m/V). Kong et al. firstly employed LGS crystal as EO Q-switch in a Nd:YAG laser and achieved pulsed operation at 1 μm [45]. Very recently, Ma et al. realized a LGS EO Q-switched Tm:YAP laser with a maximum repetition rate of 200 kHz, a maximum average output power of 2.79 W and a minimum pulse width of 5.5 ns [46].

In conclusion, EO Q-switch plays a crucial role in generating high-energy laser pulses and suitable choice of EO crystal can determine the performance of EO Q-switch. At present, LN, RTP, and LGS are the most successful EO crystals. For LD pumped 2 μm solid lasers, 550-mJ single pulse energy set a record, to the best of our knowledge. However, exploring excellent EO crystals with high damage threshold, low driven voltage, high repetition rate and the small volume are still on the way (**Table 3**).

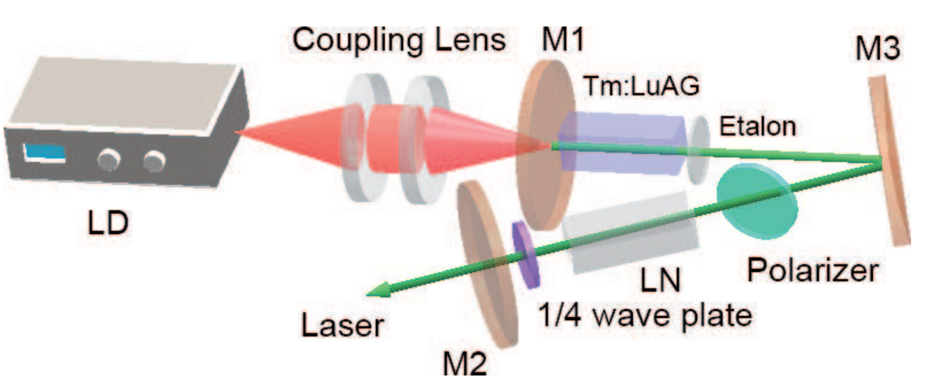

Figure 5.
Schematic of EO Q-switched Tm:LuAG laser. [Reprinted/Adapted] With permission from Ref. [41] © The Optical Society.

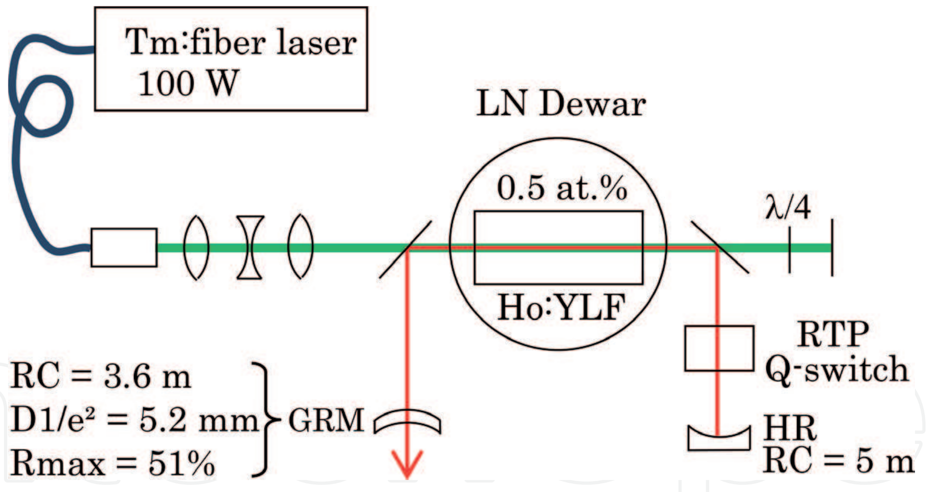

Figure 6.
Schematic setup of the Tm:fiber pumped RTP EO Q-Switched Ho:YLF laser. [Reprinted/Adapted] With permission from Ref. [43] © The Optical Society.

EO crystal	Gain media	Duration (ns)	Frequency (kHz)	Energy (mJ)	Wavelength (μm)	Time	Ref.
LN	Tm:LuAG	88	0.05	2.51	2.023	2015	[39]
LN	Tm,Ho:YAP	107	0.2	1.65	2.13	2016	[40]
LN	Tm:LuAG	52	0.1	10.8	2.023	2018	[41]
RTP	Tm:LuAG	3	100	0.0122	2.013	2016	[42]
RTP	Ho:YLF	14	0.001	550	2.051	2013	[43]
RTP	Tm:YAG	58	1	7.5	2.015	2016	[44]
LGS	Tm:YAP	5.5	200	0.0139	1.99	2019	[46]

Table 3.
Overview of EO Q-switched 2 μm solid-state lasers.

4. Diode-pumped SAs modulated 2 micron solid-state lasers

4.1 Two-dimensional nanomaterial modulated 2 micron solid-state lasers

In recent years, two-dimensional (2D) material based SAs have been widely used in generating laser pulses. The family of 2D materials includes graphene, black phosphorus (BP), transition metal dichalcogenides (TMDs) and topological insulators (TIs), and so on [47]. There are several methods available for fabricating 2D materials, including micromechanical exfoliation, chemical synthesis, pulsed laser deposition (PLD) and liquid phase exfoliation (LPE) [48, 49]. To fabricate 2D material, LPE is widely used because of its simplicity and effectiveness. Layered materials can be directly exfoliated from their bulk counterparts by this method.

Graphene, a single atomic layer of carbon atom, has attracted particular interest due to its broadband absorption, controllable modulation depth and low non-saturable loss. However, low absorption in graphene limits its applications. In 2012, graphene was firstly used as SAs at 2 μm region [50]. The obtained maximum average output power, pulse repetition rate, and single pulse energy were 38 mW, 27.9 kHz, and 1.74 μJ, respectively. Since then, graphene has been widely applied in many kinds of Tm¯doped crystals based 2 μm lasers, such as Tm:LSO, Tm:YAP, Tm:LuAG, Tm,Y:CaF_2, and et al. [28, 51–53].

Another kind of 2D material, TMDs, has also been widely studied in recent years. Properties of few-layered TMDs depend on the number of layers. For instance, bulk MoS_2 has an indirect 1.29 eV (961 mm) bandgap, while monolayer MoS_2 has a direct 1.8 eV (689 nm) bandgap. However, many reports show the saturable absorption property of few-layered TMDs at near-infrared wavelength region, which corresponds to photon energies smaller than material bandgap for most of TMDs. In a perfect crystalline semiconductor, incident photons with energy lower than the bandgap cannot be absorbed. However, crystallographic defects, including edges and vacancies, enable such absorption [54]. In 2014, Wang et al. concluded that by introducing defects with a suitable quantity range, the bandgap of MoS_2 could be reduced from 1.08 (R = 1:2) to 0.08 eV (R = 1:2.09), corresponding to an absorption wavelength from 1.1 to 15.4 μm, which showed that MoS_2 with S defects could be used as a kind of broad SA. Passively Q-switched lasers based on MoS_2 SA in the range of 1–2 μm have been demonstrated [48].

BP, a layered allotrope of phosphorus, also exhibits a layer-dependent direct bandgap, which is tunable from 0.3 eV (bulk) to 2.0 eV (monolayer), corresponding to an absorption band from 620 nm to 4.13 μm. However, different from MoS_2, which owns indirect band-gap at multilayer format, BP always has the direct transition for all thickness. But it has an intrinsic disadvantage of easy oxidation. In 2015, Lu et al. reported the broadband and enhanced SA property of multi-layered BP (with a thickness of ~10 nm) by wide-band Z-scan method [49]. At the same year, Jiang et al. demonstrated passively Q-switched operation of Tm¯doped fiber laser based on BP SAs [55]. In 2016, Xie et al. achieved a BP Q-switched Tm:YAG ceramic laser generating pulses with a maximum average output power of 38.5 mW, pulse energy of 3.32 μJ, and pulse width of 3.12 μs [56]. Zhang et al. demonstrated a compact Q-switched Tm:YAP laser based on multi-layered BP nanoplatelets, which delivered an average output power of 3.1 W and a pulse duration of 181 ns at a repetition rate of 81 kHz [57].

Another group of 2D materials, TIs such as Bi_2Te_3 and Sb_2Te_3, have also been proposed and investigated in recent years. In general, bulk TIs materials have a small bandgap but a gapless metallic surface state is generated in layered 2D TIs, which is caused by strong spin-orbit coupling and time-reversal symmetry [58]. With such typical band structure, 2D TIs materials show broadband absorption like CNTs and graphene and have become one of promising optical modulator candidates in generating 2 μm laser pulses.

In conclusion, 2D material based SAs have attracted much attention in generating laser pulses due to its advantage of easy fabrication, compact setup, and broadband optical absorption. Related reports on passively Q-switched 2 μm solid-state lasers based on 2D material SAs are summarized in **Table 4**. However, the obtained output powers are in the order of several hundred mW and the pulse widths are in the order of several hundred ns, especially the pulse energies are only with tens of microjoules, which limits the pulse peak power and their applications furthermore. In the future, the damage thresholds of the 2D material based SAs should be greatly increased, which would benefit the increase of the output power and pulse energy as well as the long-term stabilities of the Q-switched lasers.

4.2 Cr^{2+}-doped crystal modulated 2 micron solid-state lasers

Since Podlipensky et al. demonstrated that Cr^{2+}:ZnSe crystals can be used as SAs for 1.54 μm Er:glass lasers [67], Cr^{2+} doped II-VI compounds like Cr^{2+}:ZnS and Cr^{2+}:ZnS have been widely used in the spectral range of 1.5–2.1 μm. **Figure 7** shows that Cr:ZnS and Cr:ZnSe have broadband absorption spectra form 1.5 to 2.2 μm [68].

SAs	Gain media	Output power (mw)	Duration (ns)	Frequency (kHz)	Energy (μJ)	Time	Ref.
Graphene	Tm:YAG	38	2250	27.9	3.8	2012	[50]
	Tm:LSO	106	7800	7.6	14	2013	[51]
	Tm:YAP	362	735	42.4	8.5	2014	[52]
	Ho:LuAG	370	752.2	48.8	7.5	2016	[28]
	Tm,Y:CaF_2	400	1316	20.22	20.4	2018	[53]
MoS_2	Tm,Ho:YGG	205.62	410	149	1.38	2014	[48]
	Tm:CLNGG	79.2	4840	110	0.72	2015	[59]
	Tm:$GaVO_4$	100	800	48.09	2.08	2015	[60]
	Tm,Ho:YAP	275	435	55	5	2017	[61]
	Tm:CYA	490	480	102.6	4.87	2017	[62]
BP	Tm:YAP	3199.5	181	81	39.5	2016	[57]
	Tm:YAP	150.92	1780	19.25	7.84	2016	[63]
	Tm:CaYA	12	3100	17.7	0.68	2016	[64]
	Tm:YAG	38.512	3120	11.6	3.32	2016	[56]
Bi_2Te_3	Tm:LuAG	2030	620	118	18.4	2017	[65]
Sb_2Te_3	Tm:$GdVO_4$	700	223	200	3.5	2018	[66]

Table 4.
Overview of 2D nanomaterials modulated 2 μm solid-state lasers.

Up to now, Cr:ZnSe/ZnS have been applied in many 2 μm pulsed lasers, as shown in **Table 5**. In 2015, Sebbag realized a Cr:ZnSe Q-switched Tm:YAP solid-state laser at 1935 nm, which delivered a pulse energy of 1.55 mJ and a pulse duration of 42.2 ns, corresponding to a peak power of 36.7 kW [71]. In 2017, Lan reported a Cr:ZnSe Q-switched Tm:CYA laser with a maximum repetition rate of 21.9 kHz, a minimum pulse width of 42.6 ns and a maximum pulse energy of 60.2 μJ [73]. In 2017, a Cr^{2+}:ZnSe passively Q-switched Nm–cut Tm:KLu$(WO_4)_2$ mini-slab laser was reported, where the obtained shortest pulse duration was 35 ns and maximum pulse energy was 0.3 mJ [76]. Due to the low absorption cross-section of Cr:ZnSe crystal around 2 μm, it was mainly used in Tm-doped crystal based lasers. In 2013, A Cr^{2+}:ZnS passively Q-switched Ho:YAG laser pumped by a Tm:YLF laser was demonstrated with a maximum pulse energy of 2.47 mJ, a minimum pulse duration of 36.6 ns at a repetition rate of 10.4 kHz [82]. In 2015, a diode-pumped Cr:ZnS passively Q-switched Tm:KLu$(WO_4)_2$ microchip laser generated sub-nanosecond (780 ps) pulses with a pulse repetition frequency of 5.6 kHz, which was the shortest pulse duration among the passively Q-switched 2 μm lasers ever achieved [86]. Besides, in 2017, another novel Cr^{2+} ions doped Cr:CdSe crystal was firstly demonstrated in a Ho: YAG laser at 2.09 μm. A maximum output pulse energy of 1.766 mJ at a repetition frequency of 685 Hz was obtained with a pulse duration of 15.4 ns, which indicated that a Cr:CdSe crystal could be a promising SA in passively Q-switched 2 μm lasers [90].

In conclusion, Cr^{2+} doped II-VI compounds have been successfully used as SAs in passively Q-switched 2 μm lasers. In this way, the obtained pulse energies and the pulse widths can reach hundreds of μJ and ns or even sub-ns level. The maximum pulse energy of 2.47 mJ, and the shortest pulses with sub-nanosecond (780 ps) duration were both realized with a kind of Cr:ZnS SA. Therefore, Cr^{2+} doped II-VI

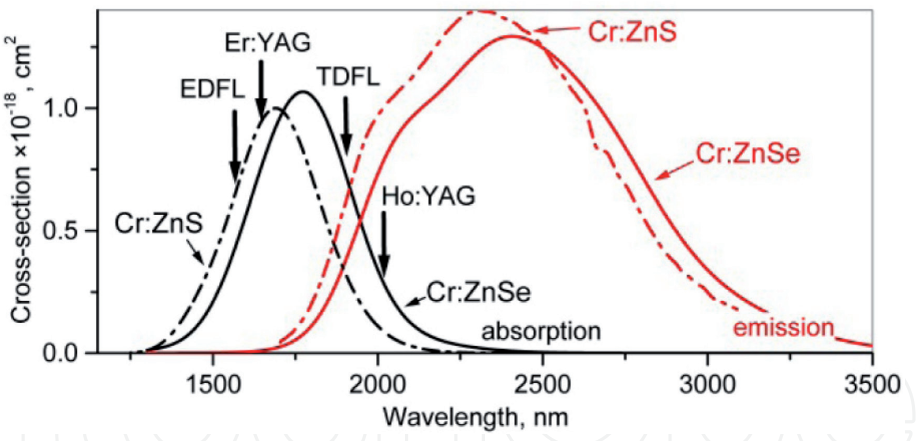

Figure 7.
Absorption (black) and emission (red) cross-sections of ZnS and ZnSe doped with Cr^{2+} ions. [Reprinted/Adapted] With permission from Ref. [68] © The Optical Society.

SAs	Gain media	Output power (W)	Duration (ns)	Frequency (kHz)	Energy (μJ)	Time	Ref.
Cr:ZnSe	Tm:YAG	1.6	300	4	400	2003	[69]
	Tm,Ho:YLF	0.1	40	4	25.6	2014	[70]
	Tm:YAP	0.87	42.2	0.561	1550	2015	[71]
	Tm:YLF	0.027	1200	2.1	13	2014	[72]
	Tm:CYA	1.32	42.6	21.9	60.2	2017	[73]
	Tm:CYA	0.25	107	5.85	48.2	2017	[74]
	Tm:CGA	0.64	44	13.9	46	2017	[75]
	Tm:KLuW	3.2	35	6.3	300	2017	[75]
	Ho:SSO	2.4	73.5	2.65	900	2017	[77]
Cr:ZnS	Tm:KLW	0.39	25	2.7	145	2012	[78]
	Tm:YLF	0.098	14	0.12	850	2012	[79]
	Tm,Ho:YLF	0.016	1250	1.3~2.6	4	2012	[80]
	Tm:LLF	0.2	7.6	0.161	1260	2012	[81]
	Ho:YAG	16.6	36.6	10.4	2470	2013	[82]
	Tm,Ho:$LuLiF_4$	0.074	1200	5.8	13	2013	[83]
	Tm,Ho:$GdVO_4$	3.2	354	52	70.5	2013	[84]
	Tm,Ho:YVO_4	0.3	500	65	3.5	2014	[85]
	Tm:KLW	0.146	0.78	5.6	25.6	2015	[86]
	Ho:YAG	14.8	29	24.4	600	2015	[87]
	Ho:LuAG	1.14	36	0.79	1540	2015	[88]
	Ho:YAP	6.1	93.6	7.5	830	2015	[89]
	Tm:YAP	0.89	35.8	0.481	1850	2015	[71]
	Tm,Ho:KLuW	0.131	14	8.2	10.4	2016	[78]
Cr:CdSe	Ho:YAG	1.2	15.4	0.685	1766	2017	[90]

Table 5.
Overview of Cr^{2+}-doped crystal modulated 2 μm solid-state lasers.

crystals are still irreplaceable SAs in generating passively Q-switched 2 μm lasers with pulse energies over mJ level and pulse width in order of several nanoseconds to sub-nanoseconds.

4.3 Gain crystal modulated 2 micron solid-state lasers

As mentioned above, the popular SAs used in the 2 μm Q-switched solid-state lasers are mainly low-dimensional nanomaterials and Cr-doped crystals. In addition, the absorption effect of Ho^{3+} doped gain crystals can also be used for SAs, which can be classified as a slow-relaxing solid-state SA due to possessing a long emission lifetime. However, the study of passively Q-switched solid-state lasers based on gain crystals is relatively rare. In 1994, Kuo et al. reported a flash-lamp pumped $Tm,Cr:Y_3Al_5O_{12}$ laser using a $Ho:YLiF_4$ as SA at room temperature [91]. A maximum single pulse energy of 11 mJ and a shortest pulse duration of 45 ns were obtained. It paved the way for Ho-doped crystals as SAs for passively Q-switched 2 μm lasers. Additionally, Ho:SSO has also been employed as an efficient SA. In 2018, a Ho:SSO crystal was used as SA for the Ho:YAG laser [92]. At a repetition rate of 42.1 kHz, a minimum pulsed duration of 48 ns and a maximum pulse energy of 2 mJ were obtained.

5. Applications of pulsed 2 micron solid-state lasers

2 μm laser is an ideal light source for the medical application, which has less damage to the rest of the tissue, and less bleeding during the operation. 2 μm lasers used in laser medical treatment are mainly YAG-based two pulsed lasers [93–96]. Ho:YAG has been successfully used in urology and orthopedics [96]. However, little is known about hard dental tissue ablation with Ho:YAG laser. For example, non-contact laser surgery offers several potential advantages in dental treatment, such as reduced pain and vibration, more precise control by electronic device and haemostatic effect. **Figure 8** shows cross-sectional images of ablation crater created on the urinary calculi surface by pulsed Ho:YAG laser (Wuhan National Laboratory for Optoelectronics) in air (dry condition) and underwater with various thickness [93]. The pulsed Ho:YAG laser emitted at 2.12 μm with the pulse energy of 2000 mJ and the pulse duration of 300/450 μs at the repetition rate of 20 Hz.

Lidar technology is an optical remote sensing technology that acquires the physical information of a target object by detecting the scattered light characteristics of a distant target object. Compared with the traditional radar technology, the laser radar technology realizes the information loading by modulating the amplitude and frequency of the laser beam, thereby having the advantages of high resolution and good anti-interference. In recent years, laser radar technology with 2 μm band laser as coherent light source has been proposed and made some progress. In 2006, the NICT agency in Japan reported on the airborne coherent wind lidar system. The system used a Tm:YAG laser with a center wavelength of 2.01 μm as the coherent light source, and the maximum single pulse energy was 7 mJ, and it was successfully applied to the test of atmospheric wind profile [97]. In 2007, NASA agencies in the United States reported on the vehicle's coherent wind Lidar system. The system utilized $Tm,Ho:LuLiF_4$ laser at 2.05 μm and a pulse energy of 100 mJ as the coherent light source, and successfully detected the wind field information of the boundary layer and the troposphere [98]. In 2013, the NICT facility in Japan used a differential absorption Lidar system to successfully measure CO_2 concentrations and mountain targets in the 7 km range. The system used a Ho:YLF laser as the light source with

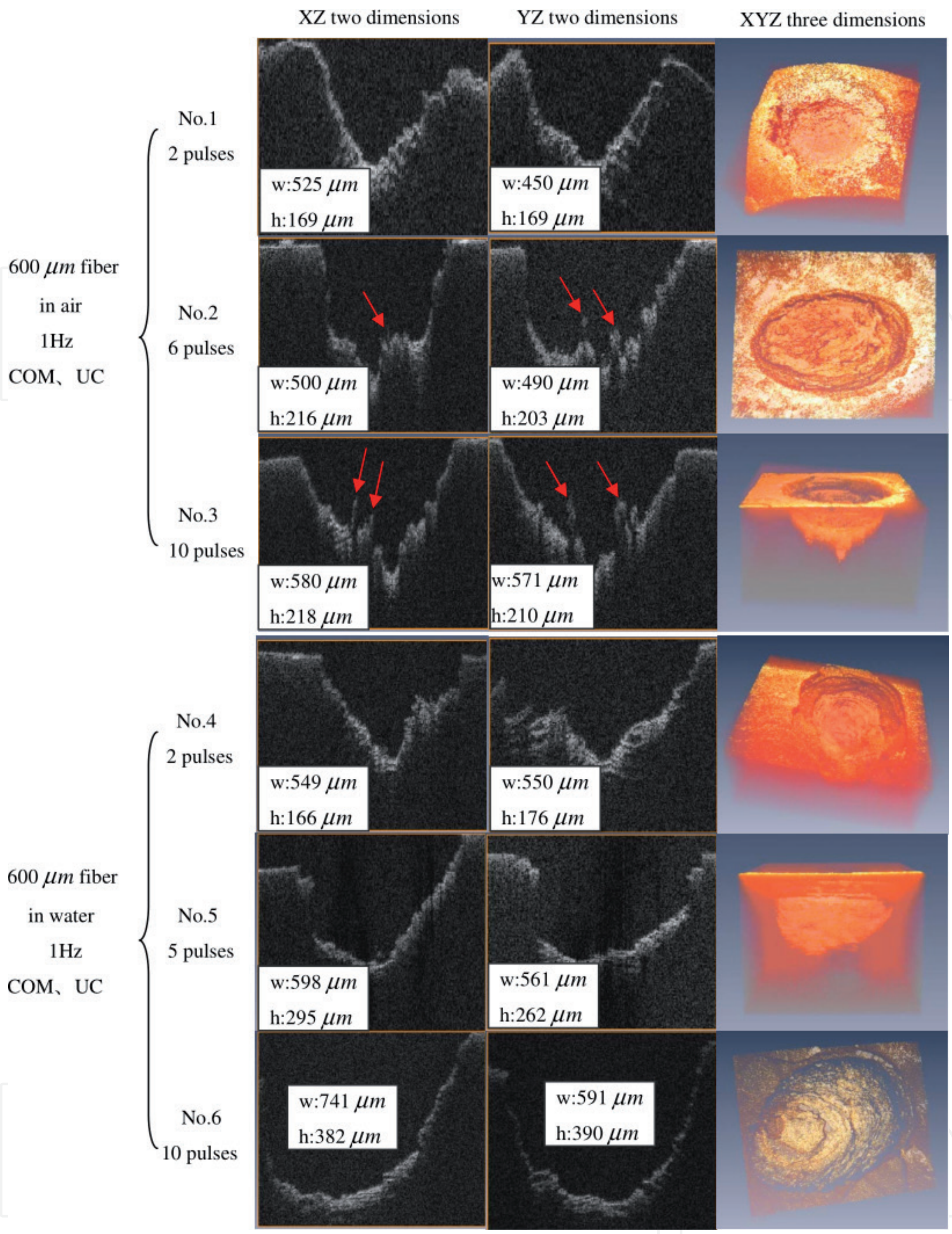

Figure 8.
(Color online) Cross-sectional topography of holmium laser-induced (300 μs, 300 mJ, 1 Hz) craters acquired with OCM system in air and in water. The 600 μm fiber is vertically in contact with the urinary calculi surface. w = width; h = height. [Reprinted/Adapted] With permission from Ref. [93] © The Optical Society.

a pulse energy of 50–80 mJ and a pulse width of 150 ns at the repetition frequency of 30 Hz [99]. In 2014, the French Polytechnic University reported a Ho:YLF multi-frequency single longitudinal mode laser with a center wavelength of 2.051 μm. The laser operated at a repetition rate of 2 kHz with a pulse energy of 13 mJ and a pulse width of 42 ns. The laser could be used as a source of differential absorption Lidar for the measurement of atmospheric CO_2 concentrations, as shown in **Figure 9** [100].

A pulsed 2 μm laser with high peak power is also a promising pump source for OPOs in the wavebands such as 3~5 and 8~12 μm. The laser in this waveband plays a key role in the directed infrared countermeasures. Compared with other mid-far

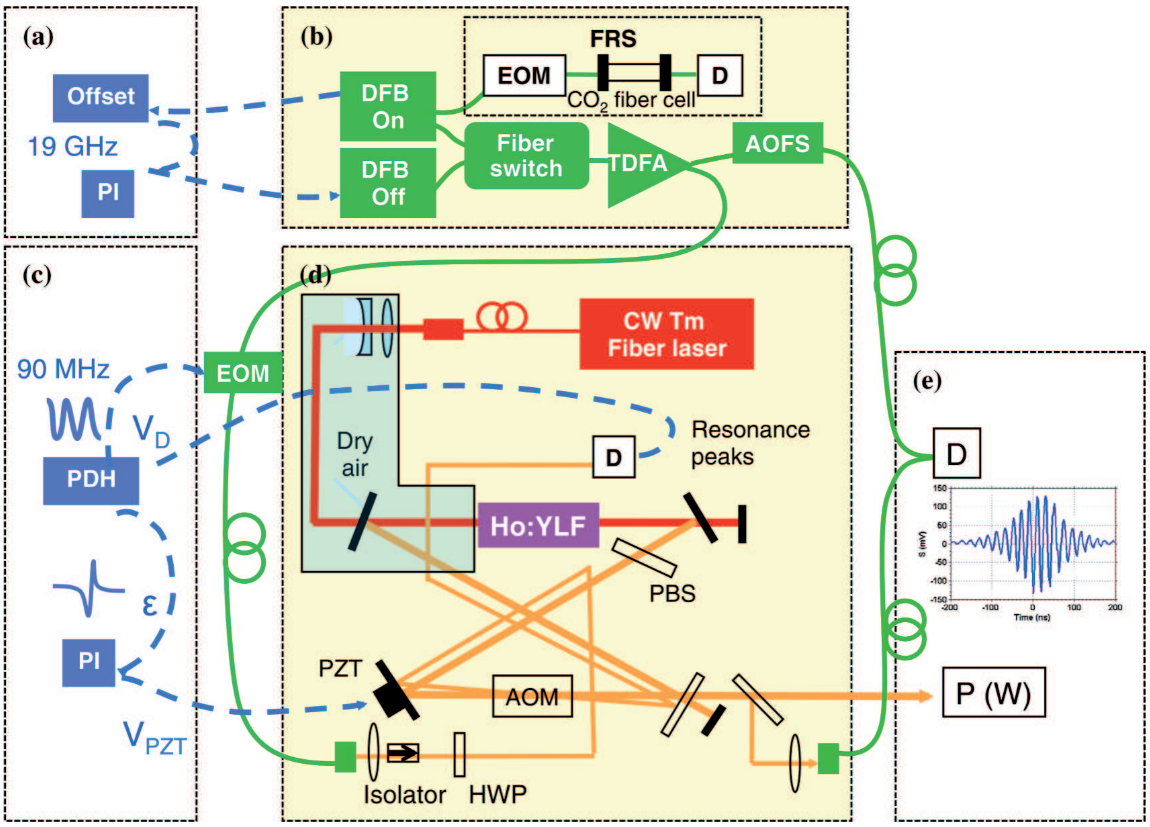

Figure 9.
Experimental setup diagram of differential absorption Lidar for the measurement of atmospheric CO_2 concentrations based on 2 μm laser. (a) Offset locking between On and Off distributed-feedback laser diode (DFB), (b) seeding architecture, (c) cavity length locking using Pound-Drever-Hall technique (PDH), (d) 2-μm pulsed oscillator, and (e) characterization: power meter, beam profiler, heterodyne detection [100].
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infrared lasers (such as CO lasers [101, 102], quantum cascade lasers [103, 104]), OPOs have the advantages of wideband tunability of output spectrum and narrow laser line width. The typical system is Directed Infrared Countermeasures (DIRCM) system, which can protect airborne platforms from infrared guided missile threats. The layout of the Ho:YAG master oscillator power amplifier (MOPA) in DIRCM system [105]. A Tm:YLF fiber laser pumped Ho:YAG laser system with pulse energies up to 90 mJ and the pulse width of 20 ns at 100 Hz. Then, the wavelength was converted into the 3 to 5-micron region using a zinc germanium phosphide (ZGP) crystal in a linear or ring resonator.

In conclusion, 2 μm wave is located in the weak absorption band of the atmosphere and the safe region of the human eye. Therefore, it is of great significance to study 2 μm Q-switched lasers in the areas such as laser medicine and laser lidar. Moreover, the 2 μm pulse laser with high peak power can also be used as an efficient pump source for OPOs and OPA to obtain the output of mid- and far- infrared laser. With the development of 2 μm pulsed laser, it will have more broad applying foreground in industrial processing, medicine, and military field.

6. Summary and outlook

2 μm pulsed laser with stable, compact and cost-effective characteristics has been a hot topic in recent years. To achieve pulsed laser sources with large pulse energy and high peak power, the traditional method is based on actively AO or EO Q-switching technology. For the flash-pumping operation regime, it has great advantages in generating high energy laser output with hundreds of mJ level due

to the larger mode area than that of diode-pumping case. However, diode-pumped solid-state 2 μm lasers have achieved rapid development because of the advantages such as high efficiency, small size, and high beam quality. Furthermore, in cased of the AO Q-switching, many excellent works have been done and the maximum single pulse energy ever achieved is 128 mJ. For diode-pumped EO Q-switched solid lasers, 550-mJ single pulse energy has set a record in the case of using a RTP crystal as EO modulator, to the best of our knowledge. Although the EO modulator has relatively good switching effect, suitable EO crystal with low driven voltage and high repetition rate is rare. Recently, a LGS crystal based EO Q-switched Tm:YAP laser with a maximum repetition rate of 200 kHz was reported, which indicated that the LGS crystal with high damage threshold could be a promising EO Q-switch. Compared with active Q-switching method, passive Q-switching technology has shown promising advantages, such as simplicity, compactness, and high repetition rate, although it usually works in low-energy regime. The most mature SAs are Cr^{2+} doped II-VI crystals which are still irreplaceable in generating passively Q-switched 2 μm laser with pulse energy over mJ level and pulse width in an order of several nanoseconds to sub-nanoseconds. Besides, the Ho^{3+} doped gain crystals can also be used as SAs for 2 μm solid-state lasers, however, this rarely employed method can only deliver tens of nanoseconds pulses with tens of kHz repetition rate. At present, the 2D nanomaterials based SAs have become hot spots in generating pulsed lasers due to its advantages of easy fabrication, compact setup, and broadband optical absorptions. However, the pulse energy was limited to μJ level determined by the low damage thresholds of the 2D material. At the same time, there is also a problem in fabricating high quality thin films with large area and uniform thickness. In the near future, active Q-switching technology would still be the main method in obtaining high pulse energy or short pulse width with excellent stability and controllability. Of course, more suitable EO crystals would be further explored. For SAs suitable for passively Q-switched lasers, novel kinds of 2D nanomaterials are emerging endlessly, and the preparation method for growing high quality 2D-SAs are coming to maturity.

As for the applications of Q-switched 2 μm lasers, the application fields are becoming broader and broader. When the 2 μm pulsed laser is applied on the tissue, it can generate the effects such as the vaporization, cutting, solidification, hemostasis and so on, so it plays an important role in medical surgery. Q-switched 2 μm lasers can also be effectively used in environmental monitoring and measurement of carbon dioxide, aerosol concentration, cloud layer and water vapor distribution in the atmosphere. Besides, it should be particularly stated that 2 μm pulsed laser with high peak power is an efficient pump source for OPOs or OPA to realize mid- and far- infrared laser sources, which have important applications in the fields such as Lidar, optoelectronic countermeasures, laser ranging and infrared guidance technology. With the continuous enhancement of Q-switched 2 μm laser performance, more complicated application fields would be further explored and developed in the future.

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Author details

Kejian Yang[1,3]*, Yaling Yang[2,3], Jingliang He[1] and Shengzhi Zhao[2]

1 Institute of Crystal Materials, Shandong University, Jinan, China

2 School of Information Science and Engineering, Shandong University, Qingdao, China

3 Shenzhen Research Institute of Shandong University, Shenzhen, China

*Address all correspondence to: k.j.yang@sdu.edu.cn

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