Review article

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Low-dimensional saturable absorbers for ultrafast photonics in solid-state bulk lasers: status and prospects

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Abstract: Low-dimensional (LD) materials have originated a range of innovative applications in photonics and optoelectronics owing to their advantages of ultrafast carrier response and distinct nonlinear saturable absorption properties. In particular, these emerging LD materials including zero-, one-, and two-dimensional materials have recently been utilized for short and ultrashort pulse laser

generation in the visible, near infrared, and mid-infrared wavelength regions. Here, we review recent progress demonstrating the application of LD materials as versatile, wideband saturable absorbers for Q-switching and mode-locking in all-solid-state lasers. The laser performance in operating wavelength, output power, pulse width, repetition rate, and pulse energy is reviewed. Finally, the challenges and future perspectives are suggested.

Keywords: solid-state lasers; low-dimensional materials; saturable absorber; mode-locking; Q-switching.

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1 Introduction

All-solid-state pulsed lasers play an important role in scientific research, industry, medical, information, and military fields due to its narrow pulse width, high peak power, and large pulse energy [1–6]. Especially in recent years, the demand for ultrashort pulses with high average power has increased rapidly in many areas such as precision micro-nano processing, biomedicine, scientific research, and ultrahigh-speed optical communication [7–12]. With the gradual maturity of semiconductor laser technology, laser diode pumped solid-state lasers (LDPSSLs) are developing into excellent laser sources with compact structure, high efficiency, long life, and good beam quality [13, 14]. Especially with bulk crystals as the gain medium, LDPSSLs are suitable for generating high energy and high peak power ultrashort pulses, owing to the large mode area and low nonlinear effects of bulk gain medium. Q-switching and mode-locking laser technologies are the main means of generating pulse lasers, which can be divided into active and passive operation regimes [15–17]. Compared with active operation regimes, the passive operation regimes, in which a nonlinear optical device, termed as *saturable absorber* (SA), was inserted directly into the laser cavity, have the main advantages of simple and compact structure, low price, and reliable performance [18–20]. In the field of commercial systems, the most commonly used SA is the

semiconductor SA mirror (SESAM) [21, 22], which has been rapidly developed and commercialized over the past few decades and has been used in fiber lasers, solid-state lasers, and thin slice lasers [23–25]. However, the development of SESAM is limited by the fact that it requires a special design for specific wavelength mode-locking and is not capable of broadband modulation, low damage threshold, high cost, and complex preparation process [26]. Therefore, it is still a hot topic to explore novel SA materials that have the advantages of broadband modulation wavelength range, fast dynamic response time, the proper modulation depth and saturation intensity or fluency, low nonsaturable loss, and easy fabrication.

In recent years, the emergence of low-dimensional (LD) materials, including two-dimensional (2D), one-dimensional (1D), and zero-dimensional (0D) materials, provides a new opportunity for the development of pulsed lasers [27–29]. The 2D material refers to the atomic layer material, which can be a single layer or several layers thick. It has strong covalent bond within the layer and weak interlaminar van der Waals force. Without the interference of interlayer interaction, the movement of electrons is limited in 2D system, which results in the 2D materials having many new electrical and optical properties [30, 31]. Graphene is the first monatomic layer material discovered, with extraordinary mechanical, thermal, electrical, and optical properties [32]. Then, topological insulators (TIs), transition metal sulfides (TMDs), black phosphorus (BP), MXene, and perovskite materials were reported [33–35]. In addition, the emergence of 1D materials such as carbon nanotubes (CNTs) and 0D materials such as quantum dots (QDs) has also made many outstanding achievements in the development of pulsed solid-state lasers (Figure 1) [36, 37]. The emerging LD materials open a

door to develop novel nonlinear photonics devices with high performance.

Here, in this review, we first briefly review the unique structure, fundamental optoelectronic properties of the most widely studied LD materials, fabrication methods, common methods for characterization of nonlinear optical properties, and coupling methods. Then, we mainly focus on the application of LD-SAs in passively Q-switched and mode-locked solid-state bulk lasers operating in visible, near-infrared, and mid-infrared (MIR) wavelength band. And finally, we give some predictions about potential developments and perspectives of LD materials-based all-solid-state pulse lasers.

2 Material fabrication and characterization

2.1 Photoelectric characteristics of LD materials

Carbon nanotubes, a seamless cylindrical, 1D nanocrystalline graphite material with a fairly high aspect ratio, ranging from a few to several hundred nanometers in diameter and up to centimeters in length. According to the number of tube walls, CNTs can be divided into many types: single-walled CNTs (SWCNTs), double-walled CNTs, and multiwalled CNTs. The chiral properties of carbon tubes lead to the different application of metallic and semiconducting carbon tubes. The carbon tube of semiconductor type has obvious bandgap, while the band of metal type is continuous. In the electrical applications, the semiconductor-type

Figure 1: The development of SA ranged from SESAM to LD materials.

carbon tube can be used in the classical semiconductor devices, such as field effect tube. And the carbon tube of metallic type can be applied into touch screen. Unlike classical metals, CNTs rely on phonons instead of electrons for heat transfer, resulting in the conductivity of CNTs being weaker than that of classical metals; they have an obvious advantage in thermal conductivity ($3500 \text{ W/m} \cdot \text{K}$).

Graphene, an allotrope of carbon that is hexagonally arrayed by sp^2 -bonded carbon atoms [38], is the first 2D material to be discovered [32] (Figure 2A). Single-layer graphene has a small signal absorption rate of 2.3%, with electron mobility of up to $15,000 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$ at room temperature [40]. With a zero-bandgap structure, graphene can achieve broadband light response in visible to infrared bands. In 2004, graphene was successfully made by mechanical stripping and quickly became one of the most promising optoelectronic materials [32]. In the energy band structure of graphene, there are two different carrier relaxation dynamics: fast relaxation time (10–170 fs) and slow response time (about 1 ps) after photoexcitation. The fast response drives a rapid modulation on cavity loss, thus stabilizing femtosecond laser. The slow response is important for generating picosecond pulses and activating femtosecond laser [41]. Due to its broadband absorption, ultrafast response, and saturation absorption characteristics, graphene was first applied to mode-locked lasers in 2009, opening the door for the combination of 2D materials and ultrafast lasers [42].

Topological insulators, as phases peculiar to quantum matter, are special materials with a unique bandgap structure. On the one hand, like graphene, their surface state presents a Dirac-like linear band dispersion [43]. Besides, TIs also behave as intrinsic insulators with a narrow bandgap (0.16–0.3 eV) for the underlying bulk states. Such a narrow bandgap is exactly what is needed to construct SAs with wide-band absorption. The TIs structures of Bi_2Te_3 , Bi_2Se_3 , and Sb_2Te_3 have been predicted and calculated. In 2012, mode-locked laser operation based on Bi_2Te_3 and Bi_2Se_3 SAs was first reported [44, 45]. In 2013 and 2014, Lu et al. conducted a detailed study on the third-order nonlinearity of TIs using the Z-scan method [46]. Since then, other TIs have been discovered and used in pulsed lasers at various wavelengths.

Transition metal sulfides, Layered TMDs are atomically thin semiconductors with the general formula of MX_2 , where M denotes a transition metal atom (Mo, W, Nb, etc.), and X is a chalcogen atom (S, Se, Te, etc.) (Figure 2B). Currently, MoS_2 , WS_2 , MoSe_2 , WSe_2 , MoTe_2 , WTe_2 , and so on, have been reported. The layers of TMDs can be seen as sandwich structures interacting with van der Waals forces. Two layers of X elements are sandwiched with one layer of M element. Figure 2B shows the atomic structure and band structure of MoS_2 . In the bulk state, they are semiconductors with an indirect bandgap, which changes to a direct bandgap when the material is in the monolayer state. At present, it has

Figure 2: The atom structure and spectral region of 2D materials.

The atom structure and spectral region of 2D materials such as graphene (A), TMDs (B), phosphorene (C), arsenene (D), antimonene (E), bismuthene (F), MXene (G), and BN (H). Copyright 2019, Wiley-VCH. Reproduced with permission [39].

Figure 3: Fabrication methods of 2D materials.

(A) Fabrication methods of 2D materials. Fabrication process and experimental instrument photograph of the chemical vapor deposition method (B), the mechanical exfoliation method (C), and LPE (D). (B) Reproduced with permission [62]. Copyright 2009, American Chemical Society. Reproduced with permission [63]. Copyright 2010, Macmillan Publishers Ltd. (C) Reproduced with permission [64]. Copyright 2015, RSC. (D) Reproduced with permission [65] Copyright 2019, Wiley-VCH, and reproduced with permission [66]. Copyright 2019, IOP Publishing.

been proved experimentally that the bandgap of TMDs can be adjusted by controlling the number of layers of materials, which broadens the application field of TMDs in optoelectronics. In 2013, TMD MoS_2 was first used in ultrafast lasers.

Black phosphorus, an allotrope of phosphorus with a layered structure (Figure 2C), was first synthesized in 1960s [47]. In recent years, single-layer BP has been successfully prepared [48]. As a direct bandgap semiconductor,

bandgap controllability is one of the most promising features of BP. The bandgap decreases as the number of layers increases (1.73 eV in monolayer, 1.15 eV in bilayer, and 0.83 eV in trilayer phosphorene) [49]. This unique bandgap structure fills the gap between zero bandgap graphene and large bandgap TMDs. In addition, combined with its characteristics of high electron mobility and in-plane anisotropy, black scale has become an ideal material for a variety of optoelectronic devices [50–52]. In 2015, BP was first applied to mode-locked lasers as an SA [53]. In

Figure 4: Z-scan and double-arm methods; Coupling methods of LD materials.

Schematic of the Z-scan measurement setup (A) and of the two-arm measurement setup (B). Coupling methods between nanomaterials and devices including quartz (C), high-reflection mirror (D), microfiber (E), and D-shaped fiber (F).

Table 1: Pulsed solid-state lasers based on 0D materials.

Material	Incorporation method	Integration substrate	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
			α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
CsPbBr ₃ QDs	SPS	Glass	—	~11 MW/cm ²	Pr: LiYF ₄	522 nm	653 ns	96.2 kHz	9.11 mW	[73]	2017
C-QDs	SM	HRM	4%	15.34 W/mm ²	Nd:GdVO ₄	1063.03 nm	66.8 ns	1.13 MHz	179 mW	[74]	2017
Fe ₃ O ₄ NPs	CS	Quartz cell	2.49%	11.57 KW/cm ²	Nd:YVO ₄	1064.34 nm	53 ns	576.4 kHz	104 mW	[75]	2017
Fe ₃ O ₄ NPs	LPE	Quartz	6.9%	592.6 W/cm ²	Tm:LuAG	2 μ m	600 ns	96 kHz	472 mW	[76]	2018
Gold	LPE	Quartz	6.27%	32 W/cm ²	Tm:YAP	2 μ m	1 μ s	99 kHz	0.601 W	[77]	2018
GNPs			13.77%	66.6 W/cm ²			580 ns	129 kHz	0.564 W		
SINPs	LPE	Quartz	10.5%	34.7 μ J/cm ²	Nd:LuAG	1064.34 nm	490 ns	200 kHz	129 mW	[78]	2018
			18.5%	12 μ J/cm ²	Tm:YAP	1985.25 nm	453 ns	115 kHz	127 mW		
Bi-QDs	LPE	Sapphire	8.7%	17.6 μ J/cm ²	Nd:GdVO ₄	1341 nm	510 ns	135 kHz	125 mW	[79]	2019
Gold nanostars	CAR	Sapphire	3%	0.3 GW/cm ²	Pr:YLF	639 nm	168 ns	272 kHz	256 mW	[80]	2019
						721 nm	198 ns	240 kHz	238 mW		

SPS, Solution-phase synthesis; SM, solvothermal method; NPs, nanoparticles; CS, colloidal suspensions; CAR, chloroauric acid reduction. α_s , Modulation depth; I_{sat} , saturation intensity; λ , central wavelength; τ , pulse width; f_{rep} , repetition rate; P_{ave} , average output power.

addition, 2D group-VA monoelemental materials including arsenene (Figure 2D) [54], antimonene (Figure 2E) [55–57], and bismuthene (Figure 2F) [58, 59] have attracted abundant attention due to their intriguing structure and remarkable electronic properties.

MXene, chemical formula can be expressed as $M_{n+1}X_nT_x$ ($n=1, 2$, or 3), where M stands for transition metals, such as Sc, Ti, Zr, Hf, V, and Nb; X is C or N; and T is surface functional group. MXenes can be obtained by specific atom layer acid etching of the precursor MAX phase. MXene $Ti_3C_2T_x$ is the first 2D material successfully prepared in MXenes (Figure 2G). The energy band structure of $Ti_3C_2T_x$ is similar to that of a typical semimetal and has amorphous density in the Fermi energy level. Theoretical studies have shown that the electrical properties of MXene, from metals to semiconductors, depend on the properties of M, X elements, and surface functional groups. The carrier mobility and electrical conductivity of $Ti_3C_2T_x$ are up to 2.6 cm²/V/s and 6500 S/cm, respectively. Apart from the excellent electrical properties, the optical properties of MXene are also worth studying. The linear absorption loss of MXene is ~1%/nm, the nonlinear absorption coefficient is ~10⁻²¹ m²/V², and the negative nonlinear refractive index is (~10⁻²¹ m²/W) [60]. MXene has a high absorption coefficient of about 15–40 L/(g·cm) and photothermal conversion efficiency [61]. MXene exhibits broadband absorption from ultraviolet to far-infrared. For boron nitride (BN) with a narrow optical response in the ultraviolet wavelength region, has a bandgap of ~5 to 6 eV (Figure 2H).

2.2 Fabrication method

The fabrication process of 2D materials has a significant influence on the performance of the devices. Up to now, top-down method and bottom-up method are the main two ways to obtain 2D layered materials (Figure 3A). For top-down method including mechanical exfoliation and liquid-phase exfoliation (LPE), the van der Waals between layers is broken by the physical means to fabrication monolayer or few-layer 2D materials. This method is an effective method to obtain high-quality materials, but low yield, which is suitable for the field of basic research. For bottom-up method, such as chemical vapor deposition and pulsed laser deposition, the materials film is synthesized by the chemical means.

Here, we emphatically introduce three methods (mechanical exfoliation, LPE, and chemical vapor deposition) widely used to fabrication nanomaterials. Chemical vapor deposition is a significant way to synthesize

Figure 5: C-QD, C-QD, and FONPs Q-switched lasers.

(A) Output power vs. incident pump power, (B) dependence of the pulse repetition rate and pulse duration on the incident pump power of the C-QD Q-switched laser. Reproduced with permission [74]. Copyright 2017, Optical Society of America. (C) Pulse trains and (D) single pulse waveform of CsPbBr₃ perovskite QDs Q-switched laser. Reproduced with permission [73]. Copyright 2017, Optical Society of America. (E) The pulse trains and (F) single pulse profiles of the FONPs Q-switched Nd:YVO₄ laser. (G) Experimental setup of FONPs-SA Q-switched Tm:LuAG laser, and (H) pulse duration, repetition rate, pulse energy, and peak power vs. incident pump power. Reproduced with permission [76]. Copyright 2018, IEEE Photonics Society.

large-scale materials. When the raw materials and suitable substrate are placed in the reaction chamber, 2D materials can be produced on the substrate under appropriate conditions (Figure 3B). Mechanical exfoliation method is known for the fabrication way of graphene, which adopts scotch tapes to exfoliate bulk materials repeatedly to obtain layered materials (Figure 3C). This method has excellent advantages such as high qualities, low cost, and the ability of monolayer fabrication. Liquid-phase exfoliation, as a physical process, produces microbubbles through high-intensity ultrasound and destroys the van der Waals forces between the layers of the material and then removes the unstripped parts by centrifugation to obtain a single or few layers of 2D materials (Figure 3D).

As a low-cost and simple preparation method, it is difficult to accurately prepare large-size nanomaterials with a certain number of layers. Compared to mechanical exfoliation method, the chemical vapor deposition method can improve the yield and size of high-quality nanomaterials and control the layer numbers, which is a powerful mean to achieve realistic industry application of nanomaterials.

2.3 Nonlinear optical properties

The nonlinear optical properties of LD materials have great potential in photonics and optoelectronics, especially in the use of the saturated absorption characteristics

Figure 6: BiQDs, GNSs, and SiNPs Q-switched lasers.

(A) Pulse duration and repetition rate vs. absorbed pump power, (B) pulses trains of BiQDs Q-switched laser. Reproduced with permission [79]. Copyright 2019, Optical Society of America. Pulse width and repetition rate vs. absorbed pump power of the GNSs Q-switched lasers at (C) 721-nm and (D) 639-nm region. Reproduced with permission [80]. Copyright 2019, Optical Society of America. Pulse durations and repetition rates for SiNPs Q-switched (E) Nd:LuAG laser and (F) Tm:YAP laser. Reproduced with permission [78]. Copyright 2018, Optical Society of America. The dependence of (G) pulse duration and (H) repetition rate on absorbed pump power, (I) pulses trains of GNPs Q-switched laser. Reproduced with permission [77]. Copyright 2018, Elsevier.

of materials to achieve ultrashort pulse lasers. Currently, more and more LD materials are used as saturated absorbers to realize mode-locking lasers, such as QDs, CNT, graphene, TIs, TMDs, BP, and others. There are three important parameters of SA, namely, modulation depth (α_s), saturation intensity (I_s), and unsaturated loss (α_{ns}). The relationship among the three parameters is described by the following formula:

$$T = 1 - \frac{\alpha_s}{1 + I/I_s} - \alpha_{ns} \quad (1)$$

where I and T are input optical intensity and optical transmittance.

Z-scan method and double-arm measurement are two main methods to measure nonlinear optical properties of

LD materials. A Z-scan measurement setup is shown in Figure 4A. A picosecond/femtosecond laser pulse is split between two arms by a splitter: a measurement arm (high power) and a reference arm (low power). In the reference arm, the light is collected by detector 2. In the measurement arm, the pulse is focused on a translation stage sample. The stage is adjusted to alter the laser spot size and cause a variation in energy density. The light after the sample is collected by detector 1. If there is no aperture before detector 1, the method is called open aperture. Otherwise, it is called closed aperture. Two-arm measurement setup is shown in Figure 4B. The entire beam path is contained within the fiber, known as a fiber-typed open-aperture Z-scan. Pulsed laser propagates through a variable optical attenuator (VOA) and is divided into two paths by a splitter. One path with high power is injected into the

Table 2: Passively and mode-locked solid-state lasers based on 1D materials.

Material	Incorporation method	Integration substrate	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
			α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
CNT	LA	HRM	—	—	Er/Yb:glass	1570 nm	68 fs	85 MHz	80 mW	[86]	2005
SWNT	deposition	Bragg reflectors	0.3%	40 $\mu\text{J}/\text{cm}^2$	Er:Yb:glass	1561.7 nm	261 fs	74.539 MHz	63 mW	[87]	2007
SWCNT	HiPCO	Quartz	<0.4%	6.0 $\mu\text{J}/\text{cm}^2$	Cr:forsterite	1.25 μm	120 fs	79 MHz	202 mW	[88]	2008
SWCNT	LPE	Quartz	0.25%	10 $\mu\text{J}/\text{cm}^2$	Yb:KLuW	1048 nm	115 fs	89 MHz	30 mW	[89]	2008
SWCNT	EAD	Quartz	—	—	Tm:KLu(WO ₄) ₂	1944 nm	9.7 ps	126.03 MHz	240 mW	[90]	2009
SWCNT	HiPCO	Quartz	<0.5%	<10 $\mu\text{J}/\text{cm}^2$	Cr:YAG	1.5 μm	100 fs	85 MHz	110 mW	[91]	2010
SWCNT	HiPCO	Quartz	0.3%	10 mJ/cm ²	Yb:KY(WO ₄) ₂	1.04 μm	133 fs	79 MHz	—	[92]	2010
SWCNT	HiPCO	Quartz	—	—	Cr:forsterite	1.24 μm	100 fs	—	—	—	—
SWCNT	HiPCO	Quartz	—	—	Cr:YAG	1.5 μm	92 fs	—	—	—	—
SWCNT	HiPCO	Quartz	0.15%	29 $\mu\text{J}/\text{cm}^2$	Ti:sapphire	near 800 nm	62 fs	99.4 MHz	600 mW	[93]	2011
DWCNT	CVD	Quartz	—	—	Yb:Sc ₂ SiO ₅	1062.6 nm	15 ps	89 MHz	818 mW	[94]	2011
DWCNT	CVD	Quartz	—	—	Yb:Sc ₂ SiO ₅	1061.7 nm	1.6 ps	—	377 mW	[94]	2011
DWCNT	CVD	Quartz	—	—	Yb:LuYSiO ₅	1045.5/1059 nm	8.0 ps	103.5 MHz	1.27 W	[95]	2011
SWCNT	HiPCO	Quartz	0.15%	<29 $\mu\text{J}/\text{cm}^2$	Cr:LiSAF	868/882 nm	106 fs	—	24 mW	[96]	2012
SWCNT	HiPCO	Quartz	0.5%	10 $\mu\text{J}/\text{cm}^2$	Cr:forsterite	1247 nm	121 fs	4.51 MHz	46 mW	[97]	2012
SWCNT	VE	Glass	2%	100 $\mu\text{J}/\text{cm}^2$	Yb:Sc ₂ SiO ₅	1061 nm	880 fs	96 MHz	712 mW	[98]	2012
SWCNT	EAD	Quartz	—	—	Tm:YAP	1.97 μm	690 ps	158 MHz	432 mW	[99]	2012
SWCNT	EAD	Quartz	1.5%	—	Nd:GdVO ₄	1063.28 nm	8 ps	81 MHz	1.22 W	[100]	2012
DWCNT	CVD	Quartz	—	—	Tm:YAP	2023 nm	41 ps	72.26 MHz	375 mW	[101]	2012
SWCNT	—	Quartz	<1%	<10 $\mu\text{J}/\text{cm}^2$	Tm:Lu ₂ O ₃	2070 nm	175 fs	88 MHz	36 mW	[102]	2012
SWCNT	EAD	Quartz	—	—	Yb:Sc ₂ SiO ₅	1062.6 nm	1.8 ps	94 MHz	349 mW	[103]	2012
SWCNT	EAD	Quartz	—	—	Yb:LuYSiO ₅	1038.3 nm	4.0 ps	103 MHz	157 mW	[104]	2012
SWCNT	HiPCO	Quartz	<0.5%	<10 $\mu\text{J}/\text{cm}^2$	Cr:YAG	near 1.5 μm	49 fs	85 MHz	67 mW	[105]	2013
DWCNT	CVD	Quartz	—	—	Yb:CaF ₂ -SrF ₂	1045.5 nm	5 ps	87 MHz	292 mW	[106]	2013
SWCNT	EAD	Quartz	—	—	Tm:Sc ₂ SiO ₅	1967.4 nm	<100 ps	92.6 MHz	195 mW	[107]	2013
SWCNT	VE	Quartz	2–3%	—	Nd:YVO ₄ /KTP	532 nm	7.1 ps	87.14 MHz	456 mW	[108]	2014
SWCNT	VE	Quartz	2–3%	—	Nd:YVO ₄	1064 nm	12 ps	83.7 MHz	1.78 W	[109]	2014
CNT	TD	Silver mirror	—	40 $\mu\text{J}/\text{cm}^2$	Cr:ZnS	2.35 μm	61 fs	—	955 mW	[110]	2014
DWCNT	CVD	Quartz	—	—	Yb:LSO	1058.7 nm	7 ps	78 MHz	700 mW	[111]	2016
SWCNT	VE	Quartz	2%–3%	—	Nd:Y:SrF ₂	1056 nm	1.7 ps	107.8 MHz	319 mW	[112]	2016
SWCNT	CVD	CaF ₂	—	—	Cr:ZnS	2.4 μm	49 fs	76 MHz	186 mW	[113]	2019
SWCNT	HiPCO	Quartz	0.3%	45 $\mu\text{J}/\text{cm}^2$	Cr:LiSAF	850 nm	21 fs	47.9 MHz	8.6 mW	[114]	2019

LA, Laser ablation; HiPCO, high-pressure carbon monoxide decomposition; EAD, electric arc discharge; CVD, chemical vapor deposition; VE, vertical evaporation; TD, thermally decomposing. α_s , Modulation depth; I_{sat} , saturation intensity; λ , central wavelength; τ , pulse width; f_{rep} , repetition rate; P_{ave} , average output power.

Figure 7: Performance of CNTs mode-locked lasers.

(A) Experimental setup, (B) optical spectrum, and (C) autocorrelation trace of the CNTs mode-locked Er/Yb:glass laser. Reproduced with permission [86]. Copyright 2005, Optical Society of America. (D) Experimental setup, (E) autocorrelation trace, and (F) mode-locked pulse trains of the SWCNTs mode-locked Cr: LiSAF laser. Reproduced with permission [114]. Copyright 2019, Optical Society of America. (G) Average output power vs. incident pump power, (H) autocorrelation trace and (I) wide-span RF spectrum of the SWCNT Mode-locked Tm:KLuW laser. Reproduced with permission [90]. Copyright 2009, Optical Society of America.

sample. The powers of two paths are measured by a dual-channel power meter. The power of light interacted with the sample can be adjusted by the VOA.

2.4 Coupling methods

As we know, all-solid-state lasers are composed of free space resonators. As saturated absorbers of solid-state lasers, LD materials need to be coupled to the laser resonator in a proper way to realize optical modulation. In general, LD materials can be made into transmissive and reflective saturable absorbers. It is called *transmissive coupling* transferring an LD material to a substrate by means of spin coating, dropping, or chemical vapor deposition on specific substrate and allowing light to pass through the material and substrate (Figure 4C). Substrate materials include quartz, sapphire, BK7, CaF_2 , YAG, SiC, and silica, and sometimes the output mirrors (OMs)

are also used as the substrate. When the LD materials are placed on the high-reflection mirrors, the saturable absorption mirrors will reflect the incident light, called *reflection mode* (Figure 4D). In fiber lasers, the micro-fiber and D-shaped fiber are common methods to achieve ultrafast laser by taking advantage of evanescent field of fiber.

3 Pulsed lasers using LD materials as SAs

A solid-state laser is usually composed of a free-space cavity, which is mainly composed of mirrors and solid-state gain medium. Solid-state lasers cover a wide range of wavelengths, from visible to MIR range. Different bands of lasers can be realized by different activation ions, such as Pr^{3+} , Dy^{3+} , Sm^{3+} , and other ions for visible

Table 3: Passively Q-switched solid-state lasers based on 1D materials.

Material	Incorporation method	Integration substrate	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
			α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
SWCNT	EAD	Quartz	—	—	Tm:KLu(WO ₄) ₂	—	10 μ s	~33 kHz	170 mW	[90]	2009
SWCNT	EAD	Quartz	—	—	Tm:YAP	2.01 μ m	255.1 ns	21.76 kHz	295 mW	[115]	2012
DWCNT	VE	Quartz	~7%	~80 μ J/cm ²	Nd:YAG	1064 nm	90 ns	316 kHz	640 mW	[116]	2013
SWCNT	EAD	Quartz	—	—	Tm ³⁺ :Sc ₂ SiO ₅	1970 nm	442 ns	55.6 kHz	189 mW	[117]	2014
SWCNT	EAD	Quartz	4%	70 μ J/cm ²	Nd:GGG	—	49.8 ns	292 kHz	1.24 W	[118]	2015
SWCNT	VE	—	—	—	Tm,Mg:LiNbO ₃	1963 nm	640 ns	44.6 kHz	0.93 W	[119]	2015
SWCNT	EAD	Quartz	17.6%	4.2 kW/cm ²	Tm,La:CaF ₂	1904.6 nm	1.1 μ s	31.49 kHz	367 mW	[120]	2019
Ag-NRs	SMG	Quartz	41.1%	—	Nd,Gd:CaF ₂	1066.5 nm	1046 ns	53.93 kHz	116 mW	[121]	2018
Ag-NRs	SMG	Quartz	41.1%	—	Nd:YAG	1064.3 nm	197 ns	223.7 kHz	114 mW	[122]	2017
Ag-NRs	SMG	Quartz	27.8%	5.74 MW/cm ²	Tm:CaF ₂	1935.4 nm	3100 ns	9.3 kHz	385 mW	[123]	2018
Au-NBPs	SMG	Quartz	13%	1 μ J/cm ²	Nd,La:SiF ₆	1060.0 nm	1.15 μ s	41 kHz	—	[124]	2017
Au-NBPs	SMG	Quartz	10%	—	Nd:GdVO ₄	1342 nm	342 ns	141.8 kHz	175 mW	[125]	2018
Au-NBPs	SMG	Quartz	10%	—	Nd:GdVO ₄	1340 nm	862 ns	74.5 kHz	160 mW	[126]	2019
Bi ₂ Te ₃ nanowire	LPE	Quartz	12.64%	1.12 MW/cm ²	Yb:GAB	1.0 μ m	303 ns	178.2 kHz	213 mW	[127]	2018
			9.9%	1.0 MW/cm ²	Er:YSGG	2.79 μ m	444 ns	69.3 kHz	344 mW		

EAD, Electric arc discharge; VE, vertical evaporation; SMG, seed-mediate growth method.

 α_s , Modulation depth; I_{sat} , saturation intensity; λ , central wavelength; τ , pulse width; f_{rep} , repetition rate; P_{ave} , average output power.

Table 4: Passively Q-switched and mode-locked solid-state visible lasers based on 2D materials.

Material	Incorporation method	Integration substrate	Layers	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
				α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
Graphene	CVD	ARM	7	28%	1.6 $\mu\text{J}/\text{cm}^2$	Nd:YVO ₄	531.7 nm	374 fs	71.4 MHz	117 mW	[128]	2013
Graphene	CVD	Infrasil	–	–	–	Cr ³⁺ :BeAl ₂ O ₄	750 nm	65 fs	5.56 MHz	8 mW	[129]	2018
Graphene	CVD	Quartz	–	–	–	Pr:LuLiF ₄	639 nm	45 ps	~100 MHz	20 mW	[130]	2018
Graphene	CVD	Flat mirror	–	–	–	Pr: LiYF ₄	721 nm	73.4 ps	140 MHz	75 mW	[131]	2019
MoS ₂	PLD	Quartz	1–3	~1%	~80 nJ/cm ²	Pr:GdLiF ₄	522 nm	46 ps	101.4 MHz	10 mW	[67]	2017
							607.6 nm	30 ps	90.2 MHz	18 mW		
							639.2 nm	55 ps	104.4 MHz	22 mW		
							639 nm	25 ps	94.7 MHz	46 mW		
Graphene	CVD	Sapphire	–	54%	–	Pr:LiYF ₄	721 nm	709 ns	225 kHz	17 mW	[132]	2019
MoS ₂	PLD	Quartz	–	7.7%	837 kW/cm ²	Pr:GdLiF ₄	522 nm	579 ns	69.6 kHz	154 mW	[68]	2016
MoS ₂	PLD	Quartz	–	~1%	136–280 GW/cm ²	Pr:GdLiF ₄	605 nm	278 ns	246 kHz	327 mW	[133]	2015
							639 nm	403 ns	210 kHz	127 mW		
WS ₂	LPE	BK7	–	7.2%	5.17 MW/cm ²	Pr:LiYF ₄	640 nm	382 ns	177 kHz	120 mW		
ReS ₂	LPE	Sapphire	–	3.0%	58.2 $\mu\text{J}/\text{cm}^2$	Pr:LiYF ₄	640 nm	630 ns	88 kHz	21.5 mW	[134]	2016
PtSe ₂	MS/CVD	YAG	13	39.9%	256.6 GW/cm ²	Pr:LiYF ₄	639 nm	160 ns	520 kHz	52 mW	[135]	2018
Bi ₂ Se ₃	LPE	BK7	5	–	–	Pr:LiYF ₄	639 nm	91.8 ns	297.6 kHz	17 mW	[136]	2019
						Pr:LiYF ₄	604/607 nm	238 ns	192.3 kHz	35.7 mW	[137]	2018
							640 nm	210 ns	263.1 kHz	40.2 mW		
							721 nm	368 ns	185.2 kHz	30.9 mW		
Bi ₂ Se ₃	LPE	BK7	3	3.8%	53 MW/cm ²	Pr:LiYF ₄	604 nm	802 ns	130 kHz	26 mW	[138]	2017
BP	ME	Quartz	–	7.57%	9.87 GW/cm ²	Pr:GdLiF ₄	639 nm	189 ns	172 kHz	18 mW	[139]	2015
γ -Graphyne	LPE	Sapphire	–	3.1%	215 MW/cm ²	Pr:LiYF ₄	639 nm	210 ns	164 kHz	80 mW	[140]	2019
Ti ₃ C ₂ X	LPE	Quartz	–	13.5%	43 MW/cm ²	Pr: LiYF ₄	607 nm	426 ns	153 kHz	111 mW	[141]	2019
							639 nm	264 ns	163 kHz	150 mW		
							721 nm	328 ns	140 kHz	115 mW		

CVD, Chemical vapor deposition; PLD, pulsed laser deposition; MS, magnetron sputtering; ME, mechanical exfoliation. α_s , Modulation depth; I_{sat} , saturation intensity; λ , central wavelength; τ , pulse width; f_{rep} , repetition rate; P_{ave} , average output power.

Figure 8: Performance of graphene and MoS₂ mode-locked lasers in visible region.

(A) Raman spectrum and photograph of the graphene SA mirror; (B) setup of the passively mode-locked visible laser. Reproduced with permission [128]. Copyright 2013, IOP Publishing. (D) Nonlinear curve of MoS₂ sample; (E) schematic, (F) Autocorrelation curve of the MoS₂ mode-locked visible laser. Reproduced with permission [67]. Copyright 2017, Optical Society of America. (G) Power efficiency curves of the cavity; (H) setup and (I) autocorrelation trace of graphene mode-locked Alexandrite laser. Reproduced with permission [129]. Copyright 2018, Optical Society of America.

range (400–700 nm), Nd³⁺, Yb³⁺, Er³⁺, Cr⁴⁺, and other ions for near-infrared range (800–1600 nm); and Tm³⁺, Ho³⁺, Cr²⁺, Er³⁺, and other ions for MIR range (1900–3000 nm). GdVO₄, YVO₄, GGG, GYSGG, CLGGG, YAG, LuYAG, YAlO₃, LuYAG, KGW, KYW, KLuW, LuPO₄, GAB, YCOB, ScBO₃, BGSO, LiTaO₃, GdYTao₄, YLF, CaF₂, SrF₂, and others are common substrates for laser gain medium. Applying LD materials as SAs, pulse lasers from short wavelength as 522 nm [67, 68] to long wavelength as 2.95 μ m have been obtained [69–72].

3.1 0D materials as SAs in solid-state pulse lasers

The uniform size of 0D materials makes them excellent optical modulators, especially for solid-state lasers with large oscillating mode. Significant efforts have been made to exploit SAs based on novel 0D materials. Table 1 lists pulsed solid-state lasers based on 0D materials. As

promising carbon nanomaterial, carbon QDs (C-QDs) have been widely researched and used in various optoelectronic devices [81, 82]. In 2017, the C-QDs Q-switched laser was first achieved using Nd:GdVO₄ crystal as a gain medium [74]. The shortest pulse duration was 66.8 ns with the repetition rate of 1.13 MHz, as shown in Figure 5A and B. CsPbBr₃ perovskite QDs exhibit unique photoelectronic properties [83, 84]. In 2017, Li et al. [73] demonstrated CsPbBr₃ QDs Q-switched Pr:LiYF₄ laser operating at 522 nm. It generated 653 ns pulses with the repetition rate and average output power of 96.2 kHz and 9.11 mW, respectively, as shown in Figure 5C and D. These results indicate that perovskite QDs have the potential to be excellent SAs. The same year, Fe₃O₄ nanoparticles (FONPs) were successfully employed as SAs to achieve 53 ns pulses with the repetition rate of 576.4 kHz operating at 1064 nm, as shown in Figure 5E and F [75]. Subsequently, in 2018, with FONPs as modulator, Liu et al. [76] demonstrated passive Q-switching in a Tm:LuAG bulk laser capable of generating 600-ns pulses with a repetition of 96 kHz in

Table 5: Performance summary of mode-locked solid-state lasers operating in near-infrared range with 2D material.

Material	Incorporation method	Integration substrate	Layers	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
				α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
G	CVD	HR mirror	M	1.2% 4.3%	71 $\mu\text{J}/\text{cm}^2$ 15 $\mu\text{J}/\text{cm}^2$	Nd:YVO ₄	1342 nm	20 ps 7.4 ps	44.7 MHz 44.7 MHz	748 mW 220 mW	[142]	2019
G	CVD	Sapphire	–	–	–	Nd:YVO ₄	1064 nm	52 ps	6.5 GHz	375 mW	[143]	2018
G	CVD	Infrasil	M	0.62%	28 $\mu\text{J}/\text{cm}^2$	Cr:LISAF	850 nm	19 fs	107 MHz	8.5 mW	[144]	2017
G	CVD	HRM	M	0.6–0.7%	~50 $\mu\text{J}/\text{cm}^2$	Yb:CaYAlO ₄	1068 nm	68 fs	132 MHz	11.5 mW	[145]	2015
G	CVD	Glass	M	–	–	Yb:Y ₂ SiO ₅	1042.6 nm	30 fs	113.5 MHz	26.2 mW	[146]	2016
G	CVD	Glass	M	–	–	Yb:Y ₂ SiO ₅	1042.6 nm	883 fs	87 MHz	1.013 W	[147]	2015
G	CVD	Glass	M	–	–	Yb:Y ₂ CaF ₂	1051 nm	4.8 ps	60 MHz	370 mW	[148]	2015
G	VE	Quartz	–	–	–	Yb:LSO	1058 nm	9.8 ps	87 MHz	0.95 W	[149]	2013
G	CVD	K9	M	–	–	Yb:Sc ₂ SiO ₅	1063 nm	7 ps	97 MHz	351 mW	[150]	2014
G	CVD	K9	4–5	7%	–	Nd:YAG	1064 nm	15.6 ps	112 MHz	2 W	[151]	2013
G	CVD	Gold	2	–	–	Yb:YCOB	1037 nm	152 fs	~100 MHz	–	[152]	2014
G	LPE	Quartz	–	–	–	Nd:GYSGG	1057.28 nm 1060.23 nm	441 ps	100 MHz	0.189 W	[153]	2015
G	CVD	Quartz	1,2,3	–	–	YVO ₄ /Nd:YVO ₄	1064 nm	330 ps	140 MHz	1.6 W	[154]	2014
G	CVD	Quartz	M	–	–	Yb:Sc ₂ SiO ₅	1062.8 nm	14 ps	90.7 MHz	480 mW	[155]	2015
G	CVD	Sapphire	M	2.1%	0.51 MW/cm ²	Yb:KGW	1032 nm	325 fs	66.3 MHz	1.78 W	[156]	2014
G	CVD	Quartz	M	53%	0.75 MW/cm ²	Yb:YAG	1048 nm	367 fs	105.7 MHz	1.93 W	[157]	2014
G	CVD	Quartz	M	0.75%	50 $\mu\text{J}/\text{cm}^2$	Yb:KLuW	1047 nm	160 fs	92.5 MHz	47 mW	[158]	2012
G	LPE	DM	2–10	–	–	Nd:GdVO ₄	1064 nm	203 fs	92.5 MHz	160 mW	[159]	2011
G	CVD	Quartz	M	0.54%	14.5 $\mu\text{J}/\text{cm}^2$	Cr:forsterite	1.25 μm	16 ps	43 MHz	360 mW	[160]	2011
G	CVD	Quartz	M	~0.4%	14 $\mu\text{J}/\text{cm}^2$	Cr:YAG	1516 nm	94 fs	75 MHz	230 mW	[161]	2011
G	CVD	Quartz	M	1.8%	66.5 $\mu\text{J}/\text{cm}^2$	Ti:sapphire	800 nm	91 fs	85.1 MHz	100 mW	[161]	2013
G	CVD	Quartz	M	–	–	Yb:KGW	1031.1 nm	63 fs	99.4 MHz	480 mW	[162]	2012
G	LPE	DM	1–10	–	–	Yb:KGW	1031.1 nm	428 fs	86 MHz	504 mW	[163]	2011
G	LPE	Quartz	–	17.4%	0.87 MW/cm ²	Nd:YAG	1064 nm	4 ps	88 MHz	100 mW	[164]	2010
G	LPE	DM	2–10	1.6%–4.5%	~49.6–62.2 $\mu\text{J}/\text{cm}^2$	Nd,GdVO ₄	1.34 μm	11 ps	100 MHz	1.29 W	[165]	2012
GO	VE	Quartz	1–3	12%	80 $\mu\text{J}/\text{cm}^2$	Nd:GdVO ₄	1064 nm	4.5 ps	70 MHz	1.1 W	[166]	2012
GO	VE	Quartz	1–3	12%	80 $\mu\text{J}/\text{cm}^2$	Yb:Y ₂ SiO ₅	1059 nm	763 fs	94 MHz	700 mW	[167]	2015
GO	VE	Quartz	1–3	12%	80 $\mu\text{J}/\text{cm}^2$	Yb:Sc ₂ SiO ₅	1062.6 nm	1.7 ps	94 MHz	355 mW	[168]	2015
GO	VE	Quartz	–	–	–	Nd:YVO ₄	1064 nm	8.8 ps	84 MHz	3.06 W	[169]	2013
GO	LPE	HRM	1–3 nm	13%	–	Yb:GAGG	1041.1 nm	643 fs	45 MHz	0.8 W	[170]	2013
G-gold	VC	–	–	–	–	Ti ³⁺ :sapphire	830 nm	48 fs	131.7 MHz	76 mW	[171]	2017
G-gold	CVD	Infrasil	–	–	–	Cr:forsterite	1240 nm	80 fs	4.51 MHz	16 mW	[172]	2016
MoS ₂	CVD	Sapphire	–	–	–	Nd:YVO ₄	1064 nm	43 ps	6.5 GHz	424 mW	[143]	2018
PtSe ₂	selenization	Quartz	–	–	–	Nd:LuVO ₄	1066 nm	15.8 ps	61.3 MHz	180 mW	[173]	2018
ReS ₂	LPE	Sapphire	~6	12.6%	17.1 $\mu\text{J}/\text{cm}^2$	Yb:CALGO	1060 nm	323 fs	50.7 MHz	350 mW	[135]	2018
WS ₂	LPE	SiO ₂	0.5 nm	5.2%	21.5 $\mu\text{J}/\text{cm}^2$	Yb:YAG	1057.5 nm	736 fs	86.7 MHz	270 mW	[174]	2015
WS ₂ + EOM	VE	Quartz	8–9	4.3%	87 $\mu\text{J}/\text{cm}^2$	Nd:LuYVO ₄	1064 nm	467 ps	1 kHz	341 mW	[175]	2017
3R-NbS ₂	LPE	HRM	6	5.1% 10%	179.4 $\mu\text{J}/\text{cm}^2$ 33 MW/cm ²	Yb:KYW	1050.6 nm	302 fs	41.55 MHz	530 mW	[176]	2019

Table 5 (continued)

Material	Incorporation method	Integration substrate	Layers	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
				α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
BP	LPE	HRM	~8	7.5%	1.35 MW/cm ²	Nd:YVO ₄	1064 nm	6.1 ps	140 MHz	460 mW	[177]	2015
	LPE	HRM	8	10.95%	1.7 μJ/cm ²	Yb:Lu:CALGO	1053.4 nm	272 fs	63.3 MHz	820 mW	[178]	2016
	LPE	Quartz	~7	16%	1.3 μJ/cm ²	Nd:GdVO ₄	1.34 μm	9.24 ps	58.14 MHz	350 mW	[179]	2017
	LPE	YAG	~15–20	19.6%	1.27 MW/cm ²	Nd:LuYVO ₄	1064 nm	220 ps	1 kHz	389 mW	[180]	2017
								119 ps		462 mW		
Bi ₂ Se ₃ Bi ₂ Te ₃ G/MoS ₂	CVD	Sapphire	–	–	–	Nd:YVO ₄	1064 nm	26 ps	6.5 GHz	277 mW	[143]	2018
	SCCA	Sapphire	8–10	8%	210 W/cm ²	Nd:YVO ₄	1064 nm	7.9 ps	948.9 MHz	180 mW	[181]	2018
	CVD/PLD	HRM	1G/10 MoS ₂	16.7%	72 MW/cm ²	Yb:KYW	1037.2 nm	236 fs	41.84 MHz	550 mW	[182]	2018
MoS ₂ /GO	LPE	OM	12 nm	–	–	Nd:YVO ₄	1064 nm	17.15 ps	1.02 GHz	508 mW	[183]	2015
MoS ₂ /G								16.83 ps	0.94 GHz	404 mW		
Ti ₃ C ₂ T _x	LPE	HRM	3–4 nm	2.9%	134 μJ/cm ²	Yb:KYW	1053.2 nm	316 fs	64.06 MHz	770 mW	[184]	2018
α-In ₂ Se ₃	LPE	HRM	4–5	5.4%	80 MW/cm ²	Yb:KYW	1050.4 nm	352 fs	42.4 MHz	0.56 W	[185]	2019

CVD, Chemical vapor deposition; VE, vertical evaporation; VC, voltage controlled; SCCA, spin coating-co-reduction approach.

α_s , Modulation depth; I_{sat} , saturation intensity; λ , central wavelength; τ , pulse width; f_{rep} , repetition rate; P_{ave} , average output power.

2- μ m spectral band, as shown in Figure 5G and H. Using gold nanoparticles (GNPs) and silicon nanoparticles (SiNPs) as SA, passively Q-switched lasers in 1- and 2- μ m regions were obtained, as shown in Figure 6E–I [77, 78]. In early 2019, uniform bismuth QDs (BiQDs) SA were successfully fabricated and first used as a Q-switcher at 1.3 μ m [79]. The stable nanosecond Nd:GdVO₄ bulk laser was realized with the maximum repetition rate of 135 kHz, as shown in Figure 6A and B. Very recently, Wang et al. [80] first reported passively Q-switched solid-state bulk lasers employing the gold nanostars (GNSs) as SA at the visible range. Using Pr:YLF as gain medium, 639- and 721-nm pulse lasers were achieved with the shortest pulse duration of 168 and 198 ns, respectively, as shown in Figure 6C and D.

3.2 1D materials as SAs in solid-state pulse lasers

Since the first application of SWCNTs in solid-state lasers to obtain Q-switched mode-locked pulses [85], significant efforts have been made to explore varieties of excellent pulse lasers with CNTs as SAs. Table 2 lists the passively mode-locked solid-state lasers based on 1D materials. In 2005, Schibli et al. [86] presented the first CW mode-locking operation of solid-state laser using CNTs-SA. With Er/Yb:glass as gain medium, stable 68-fs pulses were achieved with repetition rate of 85 MHz at 1570-nm wavelength, as shown in Figure 7A–C. The shortest femtosecond pulses of 21 fs were obtained from a laser diode directly pumped Cr:LiSAF laser using an SWCNT-SA [114]. The laser operated at 850 nm with a repetition rate of 47.9 MHz, as shown in Figure 7D–F. Note here that the first self-starting mode-locking operation of solid-state laser in MIR regime was demonstrated with the 1D materials of SWCNTs as SAs [90]. Transform-limited pulses with duration of 10 ps were delivered from a Tm:KLu(WO₄)₂ bulk laser with the maximum average output power and repetition rate of 240 mW and 126 MHz, respectively, as shown in Figure 7G–I. After that, ultrashort pulses with durations from tens of picoseconds to tens of femtoseconds were obtained in various CNTs-SAs mode-locked solid-state lasers, illustrating the excellent optical modulation performances of CNTs from 800-nm to 2- μ m region. Compared with the mode-locking operation, more diverse 1D materials are used as SAs to realize passively Q-switched solid-state lasers, as listed in Table 3. Using CNTs, silver nanorods (Ag-NRs), gold nanobipyramids (Au-NBPs), and Bi₂Te₃ nanowires as SAs, Q-switching operations were achieved in solid-state lasers from 1 μ m to around 2.8

Figure 9: Performance of the first graphene mode-locked solid-state laser.

(A) Raman spectrum of graphene. (B) Transmission of graphene vs. pump intensity. Inset: CW mode-locked pulse train. (C) Autocorrelation trace and (D) corresponding output spectrum of the graphene mode-locked laser. Reproduced with permission [164]. Copyright 2010, AIP Publishing.

Figure 10: Performance of graphene and MoS₂ mode-locked near-infrared lasers.

(A) Transmission vs. the incident fluence of the graphene SA. Reproduced with permission [145]. Copyright 2015, Optical Society of America. (B) Schematic and (C) autocorrelation trace of the graphene mode-locked Cr:LiSAF laser. Reproduced with permission [144]. Copyright 2017, Optical Society of America. (D) Average output power of the graphene mode-locked Ti:sapphire laser; (E) schematic and (F) radiofrequency spectrum. Reproduced with permission [162]. Copyright 2016, Wiley Publishing. (G) Pulse trains; (H) schematic and (I) radiofrequency spectrum of the MoS₂/GO mode-locked laser. Reproduced with permission [183]. Copyright 2012, IOP Publishing.

Table 6: Performance summary of passively mode-locked solid-state MIR lasers based on 2D materials.

Material	Fabrication method	Integration substrate	Layers	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
				α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
GO	LPE	quartz	—	—	—	Tm:YAP	2023 nm	<10 ps	71.8 MHz	268 mW	[189]	2011
G	CVD	HRM	1–2	~1%	—	Tm:CLNGG	2018 nm	729 fs	98.7 MHz	60.2 mW	[190]	2012
G	CVD	CaF ₂	M	<0.4%	<14 $\mu\text{l}/\text{cm}^2$	Cr:ZnSe	2500 nm	226 fs	77 MHz	80 mW	[191]	2013
G	CVD	quartz	M	—	—	Tm: Lu ₂ O ₃	2067 nm	410 fs	110 MHz	270 mW	[192]	2013
G	CVD	HRM	1–2	—	—	Tm:CLNGG	2013.5 nm	9 μs	5.8 kHz	40 mW	[193]	2012
							2014.4 nm	882 fs	95 MHz	60 mW		
G	CVD	CaF ₂	1–2	—	—	Tm:MgWO ₄	2017 nm	86 fs	76 MHz	39 mW	[194]	2017
G	CVD	CaF ₂	M	0.4%	14 $\mu\text{l}/\text{cm}^2$	Cr:ZnS	2330 nm	220 fs	112 MHz	880 mW	[195]	2016
G	CVD	GM	2	—	—	Tm:CLNGG	2.0 μm	354 fs	—	—	[152]	2014
							2.4 μm	116 fs				
G	CVD	HRM	1–3	—	—	Cr:ZnSe	2.4 μm	41 fs	108 MHz	—	[196]	2014
G	CVD	HRM	2	—	—	Cr:ZnS	2.4 μm	0.87 ps	46 MHz	700 mW	[197]	2014
							2.4 μm	189 fs		—		
G	CVD	quartz	M	—	—	Tm:YAP	1988 nm	100 ps	62.4 MHz	256 mW	[198]	2016
MoS ₂	LPE	CaF ₂	—	2.9%	37.94 ml/cm ²	Tm:YAG	2011.0 nm	280 ps	232.2 MHz	0.2 W	[199]	2019
							2017.3 nm					

CVD, Chemical vapor deposition.

 α_s , Modulation depth; I_{sat} , saturation intensity; λ , central wavelength; τ , pulse width; f_{rep} , repetition rate; P_{ave} , average output power.

Figure 11: Performance of the first GO mode-locked Tm-doped laser.

(A) Raman spectrum of graphene. Inset is the photo of graphene oxide aqueous dispersion. (B) Schematic of the graphene oxide absorber mode-locked Tm:YAG laser. (C) Output power vs. incident pump power. (D) Mode-locked pulse trains with graphene oxide as absorber. Reproduced with permission [189]. Copyright 2011, IOP Publishing.

μm, delivering nanosecond pulses with pulse durations of 90 ns [116], 197 ns [122], 342 ns [125], and 444 ns [127], respectively.

3.3 2D materials as SAs in solid-state pulse lasers

3.3.1 Mode-locking operation

As SAs for mode-locked lasers, 2D materials generally have the advantages of broadband absorption, fast relaxation time, low saturation fluency, and simple fabrication methods. These characteristics make them potential replacements for SESAMs in ultrashort pulse generation.

In visible region, mode-locked solid-state lasers using layered materials such as graphene and MoS₂ have been achieved. Table 4 lists recent years' progress in pulsed solid-state lasers based on 2D materials as SAs in visible regime. Due to the limitation of visible optical modulator, solid-state ultrafast visible lasers are difficult to realize. For a long time, the frequency doubling method has been used to obtain ultrashort pulses in the visible range. Figure 8A–C show a femtosecond green laser based on

graphene SA, which use an 808-nm laser diode pumped Nd:YVO₄ crystal and an LBO intracavity frequency doubling [128]. Femtosecond pulses with a duration of 374 fs and a repetition rate of 71.4 MHz were achieved at 531.7 nm. Until 2017, by employing the few-layer MoS₂ as SA in the laser diode directly pumped praseodymium bulk lasers, broadband ultrafast visible lasers are originally realized [67]. The ultrafast visible lasers with the wavelengths of 522, 607, and 639 nm were achieved with the pulse width of 46, 30, and 25 ps, respectively, as shown in Figure 8D–F. This work largely provides confidence for the development of visible ultrafast photonics and the application of 2D photoelectric materials. Since then, using graphene as an SA, the visible band ultrashort pulse lasers are successfully obtained [129–131]. And it is worth mentioning that a femtosecond Alexandrite red laser was first reported by applying graphene as an optical modulator, in 2018 [129]. The pulse duration is as short as 65 fs with a repetition rate of 5.56 MHz, as shown in Figure 8G–I.

Near-infrared lasers are the most widely studied and applied laser sources. Table 5 lists recent years' progress in mode-locked solid-state lasers based on 2D materials as SAs in near-infrared region. As early as 2010, the first all-solid-state mode-locked lasers with 2D materials as SAs

Figure 12: Grapheme mode-locked and MXene QML mid-infrared lasers.

(A) Raman spectra with different layered graphene. (B) Schematic and (C) interferometric autocorrelation of the graphene mode-locked Cr:ZnS laser. Reproduced with permission [196]. Copyright 2014, Optical Society of America. (D) Degenerate pump-probe data; (E) tunable laser spectra and (F) frequency spectra of the graphene mode-locked Cr:ZnS laser. Reproduced with permission [195]. Copyright 2016, Optical Society of America. (G) Nonlinear transmittance of MXene $\text{Ti}_3\text{C}_2\text{T}_x$; (H) output spectra and (I) pulse trace of $\text{Ti}_3\text{C}_2\text{T}_x$ Q-switched mode-locked Er:Ca_{0.8}Sr_{0.2}F₂ laser. Reproduced with permission [202]. Copyright 2019, IOP Publishing.

were reported [164]. Using solution processed graphene as mode-locker, Tan et al. [164] demonstrate an Nd:YAG laser at 1064 nm with pulse width of 4 ps, as shown in Figure 9. These transform-limited results reveal the potential of applying graphene as a mode-locker for solid-state lasers operating in the visible to the MIR and greatly encourage the development and application of other 2D materials in all-solid-state lasers. Subsequently, a large number of ultrashort pulse results passively mode-locked by various layered 2D materials, such as TMDs, BP, TIs, and others have been reported. Among them, an almost transform-limited 19-fs pulses were obtained from a graphene mode-locked Cr:LiSAF laser operating at 850 nm, as shown in Figure 10A–C [144]. These were the shortest pulses directly generated from solid-state lasers using a

layered graphene as mode-locker. End pumped by two single-mode diode lasers, the maximum average output power was 8.5 mW, with the repetition rate of 107 MHz. In addition, the maximum peak power of 76.65 kW (Figure 10D–F) [162] and the maximum single pulse energy of 36 nJ [169] were reported. In recent years, by superimposing different layers of materials on top of each other and combining the advantages of these materials, heterostructures have been novel optical modulators with excellent photoelectric characteristics [186–188]. In 2015, Zhao et al. [183] first reported ultrashort pulse lasers employing heterostructures of MoS₂/graphene oxide (MoS₂/GO) and MoS₂/G in solid-state bulk lasers. The repetition rate of 1.02 GHz was demonstrated, using a V-shaped resonator, as shown in Figure 10G–I. This is the highest repetition

Figure 13: Performance of ReS₂ and MoS₂ Q-switched visible lasers.

(A) AFM image of the ReS₂ SA and the typical height profiles; (B) average output power, peak power, (C) pulse duration and repetition rate vs. the absorbed pump power of ReS₂ Q-switched 640 nm laser. Reproduced with permission [135]. Copyright 2018, Optical Society of America. (D) Absorbance of the MoS₂/quartz sample and quartz glass substrate. (Inset) Atomic-layer MoS₂/quartz sample. (E) Trend of normalized transmittance with input peak intensity of the MoS₂ SA at wavelength of 522 nm. (F) The repetition rate and pulse width vs. absorbed pump power of MoS₂ Q-switched 522 nm laser. Reproduced with permission [68]. Copyright 2016, IEEE Photonics Society.

rate acquired from LD materials mode-locked solid-state lasers, so far. By using the dual-loss modulation mechanism, with BP SAs and electro-optic modulator (EOM), Tang et al. [180] demonstrate a mode-locked Nd:LuYVO₄ laser with a high peak power of 3.89 MW. This dual-loss modulation mechanism, which combines passive modulation with active modulation, provides an effective method to improve the peak power of pulsed lasers. Additionally, some emerging 2D materials as SAs often obtain mode-locked lasers first in near-infrared bands. In 2018, the first generation of Ti₃C₂T_x mode-locked pulses was first demonstrated in the Yb:KYW bulk lasers [184]. Pulses with a duration of 363 fs and maximum average output power of 0.77 W were obtained. Very recently, α-In₂Se₃ as SA was applied in the ultrashort solid-state lasers [185]. Passively mode-locked Yb:KYW laser was achieved, with the pulse width and maximum output power of 352 fs and 560 mW, respectively.

Table 6 lists recent years' progress in mode-locked solid-state lasers based on 2D materials as SAs in MIR region. In 2011, Liu et al. [189] presented the first graphene oxide passively mode-locked Tm-doped laser. Sub-10 ps Tm:YAP pulsed laser near 2 μm was obtained, with average output power and pulse repetition rate of

268 mW and 71.8 MHz, respectively, as shown in Figure 11 [189]. In 2012, Ma et al. [190] demonstrate the first graphene mode-locked femtosecond Tm:CLNGG laser, with a short pulse width of 729 fs operating at 2018 nm. The first femtosecond pulse generation from a monolayer graphene mode-locked Cr:ZnSe laser at 2.5 μm was first reported in 2013 [191]. Later, graphene mode-locked Tm:Lu₂O₃ laser [192], Cr:ZnS laser [197], Tm:LiYF₄ laser [200], and a Tm:YAG ceramic laser [201] were also achieved. It is worth mentioning that Tolstik et al. [196] demonstrate the shortest reported MIR pulse of 41 fs, applying the combination of a chirped mirror and nitrogen purging technique, as shown in Figure 12A–C. The corresponding average output power, repetition rate, and single pulse energy were 250 mW, 108 MHz, and 2.3 nJ, respectively. In 2016, Cho et al. [195] reported a transmission-type monolayer graphene mode-locked Cr:ZnS laser with near 300-nm tuning range from 2120 to 2408 nm, as shown in Figure 12D–F. For a long time, in the MIR range, no other 2D material has been reported as a continuous mode-locker other than graphene.

Until very recently, the first MoS₂-SA mode-locked solid-state laser was reported at the wavelength of 2 μm. Using a "Z"-shaped folded resonator, the bulk Tm:YAP

Table 7: Performance summary of Q-switched solid-state lasers operating in near-infrared range with 2D materials.

Material	Incorporation method	Integration substrate	Layers	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
				α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
G	CVD	Quartz	M	0.6%	12 $\mu\text{J}/\text{cm}^2$	Nd,Mg:LiTaO ₃	1082 nm	176 ns	133 kHz	365 mW	[203]	2015
GO	LPE	Quartz	–	–	–	Nd:GYSGG	1092 nm	115 ns	338 kHz	521 mW	[204]	2015
G	CVD	BK7	3	–	–	Nd:GGG	1057.3 nm	556 ns	166.7 kHz	0.69 W	[205]	2015
G	CVD	Fused silica	M	–	–	Yb:YAG	1032 nm	228 ns	285 kHz	185 mW	[206]	2015
G	CVD	OC	2	–	–	Nd:YAG	–	192 ns	167 kHz	2.7 W	[207]	2014
G	CVD	Quartz	M	10.7%	7.8 mJ/cm ²	Er:YAG	1645 nm	6.64 μs	35.09 kHz	474 mW	[208]	2014
G	CVD	DM	M	–	–	Nd:YLF	1047 nm	2.5 μs	90 kHz	472 mW	[209]	2013
G	CVD	SiC	–	–	–	Er:LuYAG	1648 nm	2.05 μs	78.9 kHz	460 mW	[210]	2013
G	EG	SiC	5–7	35%	–	Nd:YAG	1123 nm	875.7 ns	46.8 kHz	332 mW	[211]	2013
G	LPE	K9	5–7	35%	–	Nd:LYSO	1076 nm	96 ns	159 kHz	1.8 W	[212]	2013
G	EG	SiC	M	–	–	Er:YAG	1079 nm	2.34 μs	35.6 kHz	251 mW	[213]	2012
G	LPE	BK7	2–10	1.6%–4.5%	49.6–62.2 $\mu\text{J}/\text{cm}^2$	Nd,GdVO ₄	1.34 μm	450 ns	43 kHz	260 mW	[165]	2012
G	LPE	BK7	2–10	–	–	Nd:GdVO ₄	1063 nm	105 ns	704 kHz	2.3 W	[214]	2011
G	LPE	Quartz	–	–	–	Nd:GdVO ₄	1064 nm	104 ns	600 kHz	1.22 W	[215]	2011
G	CVD	Fused-silica	M	–	–	Yb:glass	1057 nm	140 ns	833 kHz	21 mW	[216]	2015
g-C ₃ N ₄	Nano-casting	YAG	12 nm	13.6%	5.2 mJ/cm ²	Er,Yb:glass	1535 nm	–	526 kHz	27 mW	[217]	2017
			1–2 nm	11.1%,	3.9 mJ/cm ²	Nd:LLF	1.3 μm	275 ns	112 kHz	1.07 W		
			–	11.6%,	4.3 mJ/cm ²	–	–	>400 ns	154 kHz	0.96 W		
MoS ₂ /G	LPE	Quartz	–	9.12%	20.86 kW/cm ²	Yb:GAB	1047.2 nm	370 ns	138.9 kHz	102 mW	[218]	2017
MoS ₂	CVD	Sapphire	2.5 nm	3.1%	1.08 kW/cm ²	Yb:LuPO ₄	1049.6 nm	83 ns	429 kHz	2.06 W	[219]	2018
MoS ₂	CVD	Sapphire OC	–	3.1%	1.1 KW/cm ²	Yb:LuPO ₄	1020.8 nm	61 ns	870 kHz	1.53 W	[220]	2018
MoS ₂	LB	Quartz	6–7 nm	4.9%	104 KW/cm ²	Nd:GdVO ₄	1010.5 nm	39 ns	1.27 kHz	1.57 W		
MoS ₂	LPE	BK7	–	–	–	Nd:YAG	1002.3–1009.5 nm	269.2 ns	1.03 MHz	1.39 W	[221]	2018
MoS ₂	LPE	YAG	–	20.2%	2.856 mJ/cm ²	Er:YAG	946 nm	280 ns	609 kHz	210 mW	[222]	2017
MoS ₂	LPE	Quartz	–	8.71%	195.14 MW/cm ²	Nd:YVO ₄	1.6 μm	1.138 μs	46.6 kHz	1.08 W	[223]	2017
MoS ₂	LPE	Quartz	2–3	7.9%	11.6 mJ/cm ²	Nd:YVO ₄	1064.4 nm	5.4 ns	1 kHz	–	[224]	2017
MoS ₂	LPE	BK7	4–5	20%,	0.32 MW/cm ²	Nd:LuAG	1064 nm	70.6 ns	435 kHz	1.15 W	[225]	2017
MoS ₂	PLD	Quartz	30	27%	2.45 GW/cm ²	Nd:GdVO ₄	1.3 μm	188 ns	78 kHz	525 mW	[226]	2014
MoS ₂	LPE	DM	15	9.7%	–	Yb:CLGGG	1.06 μm	970 ns	732 kHz	227 mW		
MoS ₂	PLD	Quartz	30	0.2%	0.8 MW/cm ²	Yb:KLuW	1025.2 nm	182 ns	333 kHz	600 mW	[227]	2015
MoS ₂	CVD	Glass	1–3	–	–	Nd:YAG	1028.1 nm	220 ns	300 kHz	147 mW	[228]	2016
MoS ₂	PLD	Quartz	30	27%	2.45 GW/cm ²	Nd:YGG	1030 nm	203 ns	1.10 MHz	85.2 mW	[229]	2016
							1.42 μm	729 ns	77 kHz	52 mW	[226]	2014

Table 7 (continued)

Material	Incorporation method	Integration substrate	Layers	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
				α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
MoS ₂	LPE	BK7	3	—	13 MW/cm ²	Nd:YAlO ₃	1079.5 nm	227 ns	232.5 kHz	0.26 W	[230]	2014
MoSe ₂	LPE	K9	—	10.8%	51 kW/cm ²	Nd:GdVO ₄	1064 nm	217 ns	487 kHz	175 mW	[231]	2019
MoSe ₂	LPE	BK7	10	16.5%	0.84 MW/cm ²	Nd:GdVO ₄	1.34 μ m	420 ns	238 kHz	52.6 mW	[232]	2019
WS ₂	CVD	Sapphire	~5 nm	—	—	Nd:GdYTaO ₄	1066 nm	640 ns	231 kHz	101.2 mW	[233]	2019
WS ₂	CVD	Sapphire OC	—	4.4%	8.73 MW/cm ²	Yb:LuPO ₄	1001.8 nm	34 ns	1.43 kHz	2.34 W	[220]	2018
WS ₂	LPE	Quartz	—	6.94%	297.81 MW/cm ²	Nd:YVO ₄	1010.1 nm	3.99 ns	1 kHz	—	[224]	2017
WS ₂	LPE	Quartz	<10	3.6%	136.4 μ J/cm ²	YVO ₄ /Nd:YVO ₄	1064.4 nm	56 ns	1.03 MHz	1.36 W	[234]	2017
WS ₂	CVD	Sapphire	—	4.4%	8.73 MW/cm ²	Yb:LuPO ₄	1.01 μ m	28.6 ns	1.33 MHz	4.35 W	[235]	2018
WS ₂	VE	Quartz	11–12	4.9%	143.4 mJ/cm ²	Nd:YVO ₄	1.06 μ m	53 ns	—	1.18 W	[236]	2017
WS ₂	MS	Quartz	11.05 nm	—	—	Nd:YVO ₄	1064 nm	2.3 μ s	135 kHz	19.6 mW	[237]	2017
WS ₂	LPE	Quartz	—	—	—	Nd:YAG	1064 nm	1.28 μ s	45.25 kHz	54 mW	[238]	2016
WS ₂	VacE	Quartz	—	—	—	Nd:GYSGG	1057 nm	0.922 μ s	52.48 kHz	42.5 mW	[239]	2016
WSe ₂	CVD	Sapphire	—	0.2%	0.014 GW/cm ²	Nd:YAG	946 nm	591 ns	70.7 kHz	367 mW	[240]	2017
ReS ₂	LPE	Sapphire	~4 nm	15%	15.6 μ J/cm ²	Nd:YAG	1329 nm	10.8 ns	500 Hz	—	[241]	2019
ReS ₂	LPE	Sapphire	~6	5.2%	21.5 μ J/cm ²	Nd:YAG	1.064 μ m	403 ns	214 kHz	78 mW	[244]	2019
SnSe ₂	LPE	Sapphire	—	6.9%	0.67 GW/cm ²	Nd:YAG	1.3 μ m	139 ns	644 kHz	120 mW	[135]	2018
MoTe ₂	CVD	Sapphire	12–15	0.9%	1.71 MW/cm ²	Yb:YCOB	1035.5 nm	323 ns	223 kHz	136 mW	[242]	2019
BP	ME	Quartz	60–80	13.8%	277.34 mJ/cm ²	Yb:ScBO ₃	1063.6 nm	52 ns	704 kHz	1.58 W	[243]	2018
BP	LPE	Glass	~7	—	—	Er:YAG	1.6 μ m	495.5 ns	30.6 kHz	43 mW	[244]	2016
BP	LPE	HRM	5–15	—	—	Yb:CYA	1046 nm	2.3 μ s	40 kHz	86 mW	[245]	2016
BP	ME	Quartz	40–50	35.48%	6.14 GW/cm ²	Nd:GdVO ₄	1.06 μ m	2.55 μ s	36.3 kHz	87 mW	[246]	2015
BP	LPE	HRM	—	6.3%	107 MW/cm ²	Nd:YVO ₄	1064 nm	620 ns	113.6 kHz	37 mW	[246]	2015
BP	LPE	Quartz	~40	8.88%	640.1 MW/cm ²	Nd:YVO ₄	1064.4 nm	495 ns	312 kHz	22 mW	[139]	2015
BP	LPE	GM	25–33	7.8%	1.15 μ J/cm ²	Yb:LuYAG	1.03 μ m	119 ns	722 kHz	1.23 W	[247]	2017
BP	LPE	K9	—	—	—	Nd:GGG	0.9 μ m	2.86 ns	1 kHz	—	[224]	2017
BP	LPE	OM	17	15.5%	1.03 μ J/cm ²	Nd:GdVO ₄	1.3 μ m	1.73 μ s	63.9 kHz	6 mW	[248]	2016
BP	LPE	YAG	7–11	16%	2 mJ/cm ²	Er:YAG	1.3 μ m	219 ns	8 kHz	52 mW	[249]	2017
Bi ₂ Se ₃	LPE	Quartz	—	30%	4.3 GW/cm ²	Nd:GdVO ₄	1064 nm	321 ns	220 kHz	135 mW		
Bi ₂ Se ₃	LPE	HRM	—	—	—	Yb:KGW	1030 nm	363 ns	175 kHz	157 mW		
Bi ₂ Se ₃	LPE	Quartz	50 nm	—	—	Nd:Lu ₂ O ₃	1081 nm	72 ns	625 kHz	452 mW	[250]	2018
Bi ₂ Se ₃	LPE	BK7	3	—	—	Nd:YLF	1313 nm	2.8 μ s	34 kHz	330 mW	[251]	2018
Bi ₂ Se ₃	LPE	OC	3–5	0.87%	7 MW/cm ²	Nd:YVO ₄	1066.6 nm	666 ns	547 kHz	32 mW	[252]	2013
								1.6 μ s	166.7 kHz	439.4 mW	[253]	2014
								720 ns	94.7 kHz	79 mW	[254]	2014
								433 ns	161.3 kHz	200 mW	[255]	2015
								250 ns	135 kHz	32 mW	[256]	2015

Table 7 (continued)

Material	Incorporation method	Integration substrate	Layers	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
				α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
1T-TiSe ₂	LPE	Sapphire	10	14.3%	2.38 $\mu\text{J}/\text{cm}^2$	Nd:YVO ₄	1066.8 nm	483 ns	152 kHz	410 mW	[257]	2018
Bi ₂ Te ₃	CVD	Sapphire	–	10.1%	4.02 $\mu\text{J}/\text{cm}^2$	Nd:GdVO ₄	1064.4 nm	344 ns	224 kHz	360 mW	[258]	2018
				1.1%	2.42 MW/cm ²	Yb:LuPO ₄	1341 nm	55 ns	1.67 MHz	5.02 W		
Bi ₂ Te ₃	SM	Quartz	30–50 nm	10.11%, 10.95%, 13.96%	1.26 kW/cm ² 4.96 kW/cm ² 19.61 kW/cm ²	Yb:GdAl ₃ (BO ₃)	1014.5 nm	34 ns	1.38 MHz	3.94 W	[259]	2015
							1004.9 nm	860 ns	54.7 kHz	24 mW		
							1012.7 nm	760 ns	64.3 kHz	37 mW		
Bi ₂ Te ₃	ME	Quartz	10–60 nm	12.2%–19.4%, 12.8%–14.7%	1.1 W/cm ²	Nd:YVO ₄	1045.3 nm	415 ns	111.4 kHz	57 mW	[260]	2015
							1046.2 nm	370 ns	110 kHz	40 mW		
Bi ₂ Te ₃	ME	Quartz	30–50 nm	14.7%	4.6 kW/cm ²	Nd:YAG	1.0 μm	97 ns	47 kHz	26.1 mW	[261]	2016
Bi ₂ Te ₃	HE	–	18.5 nm	–	0.45 mJ/cm ²	Er:YAG	1.3 μm	93 ns	75 kHz	37 mW	[262]	2013
Bi ₂ Te ₃	SM	HRM	–	8.8%	0.64 MW/cm ²	Er:YAG	1.06 μm	576 ns	28.57 kHz	150 mW	[263]	2017
Bi ₂ Te ₃	HE	GM	–	~17.5%	–	Nd:YVO ₄	1.34 μm	6.3 μs	11.6 kHz	210 mW	[264]	2014
Bi ₂ Te ₃	SM	Quartz	–	14.29%	16.62 kW/cm ²	Yb:CYB	1645 nm	~2 μs	63.5 MHz	247 mW	[265]	2016
							1617 nm	416 ns	151.5 kHz	183 mW		
Bi ₂ Te ₃	CVD	Sapphire	12–15	1.1%	2.42 MW/cm ²	Yb:YCOB	1027.9 nm	96 ns	400 kHz	3.85 W	[266]	2018
Bi-NSs	LPE	Quartz	–	22.1%	21.5 $\mu\text{J}/\text{cm}^2$	Nd:BGSO	1040.3 nm	376.5 ns	136.6 kHz	1.038 W	[267]	2019
ITO	Sputter	Glass	–	8.5%, 22.9%	0.5 kW/cm ² 24.1 kW/cm ²	Nd:YVO ₄	1065.2 nm	144 ns	1112 kHz	150 mW	[268]	2019
							1063 nm	808 ns	201 kHz	19 mW		
Sb ₂ Te ₃ /GO	LPE	Quartz	–	7.5%	1.08 MW/cm ²	Nd:YGG	1340 nm	551 ns	60 kHz	83 mW	[269]	2018
WS ₂ /G	CVD	–	1.1 nm	2%	2.6 GW/cm ²	Nd:GGG	1410 nm	237 ns	72 kHz	408 mW	[270]	2017
Ti ₃ C ₂ T _x	LPE	Quartz	–	~16%	~256 $\mu\text{J}/\text{cm}^2$	Nd:YAG	1066 nm	43.4 ns	–	0.69 W	[271]	2018
Ti ₃ C ₂ T _x	LPE	Quartz	–	36.7%	107 $\mu\text{J}/\text{cm}^2$	YVO ₄ /Nd:YVO ₄ /YVO ₄	1.3 μm	454 ns	162 kHz	406 mW	[272]	2018
InSe	LPE	Quartz	8–9	3.06%	1.98 MW/cm ²	Nd:YAG	1034 nm	359 ns	186 kHz	94.8 mW	[273]	2019
				3.78%	1.21 MW/cm ²	Nd:YVO ₄	1064 nm	599 ns	130 kHz	175 mW		
							1340 nm	520 ns	150 kHz	420 mW		

CVD, Chemical vapor deposition; EG, epitaxially grown; LB, Langmuir-Blodgett; PLD, pulsed laser deposition; VE, vertical evaporation; MS, magnetron sputtering; VacE, vacuum evaporative; ME, mechanical exfoliation; HE, hydrothermal intercalation/exfoliation; SM, solvothermal method.

α_s , Modulation depth; I_{sat} , saturation intensity; λ , central wavelength; τ , pulse width; f_{rep} , repetition rate; P_{ave} , average output power.

Figure 14: Performance of the first graphene Q-switched near-infrared laser.

(A) Absorbance of graphene SA. Inset shows its photograph; (B) Raman spectra of graphene SA; (C) AFM image of the graphene SA; (D) typical height variation of graphene. (E) Experimental setup of graphene Q-switched Nd:YAG pulsed lasers. (F) The output power varies with the incident pump power. (G) Repetition rate and pulse width via the increase of incident pump power. Reproduced with permission [274]. Copyright 2010, American Chemical Society.

laser generated a 280-ps pulse duration with a repetition rate of 232.2 MHz [199]. In addition, no LD materials have been reported to obtain continuous mode-locked lasers near 3 μm or even longer bands. Encouragingly, with a novel 2D material of MXene ($\text{Ti}_3\text{C}_2\text{T}_x$) as an SA, Liu et al. [202] demonstrated a passively Q-switched mode-locked Er:CaF₂-SrF₂ laser operating at 2796.7 nm. The pulse width was calculated as approximately 2.4 ns with a repetition rate of 103.2 MHz, as shown in Figure 12G–I.

3.3.2 Q-switching operation

Besides mode-locking, Q-switching is another technology to generate a pulse with short pulse width and high peak power. Compared with mode-locking, Q-switching can obtain a laser with much larger pulse energy (generally, 2 or 3 orders of magnitude).

In visible regime, compared with mode-locked pulse lasers, there are more study results of Q-switched pulse lasers, as shown in Table 4. It can be seen that lasers have excellent pulse performance using graphene [132], TMDs [68, 133–135], TIs [137, 138], and BP [139] as SA. Among them, the minimum pulse duration of 160 ns [135], maximum repetition rate of 520 kHz (Figure 13A–C) [135], and the maximum single pulse energy of 2.21 μJ [68] are recorded, as shown in Figure 13D–F. Very recently, the novel 2D MXene $\text{Ti}_3\text{C}_2\text{T}_x$ [141] and γ -graphyne [140] were applied as SAs to realize passive Q-switched visible bulk lasers.

Table 7 lists recent years' progress in Q-switched solid-state lasers based on 2D materials as SAs in near-infrared region. The first 2D material Q-switched laser is demonstrated in 2010. Employing graphene as SA, Q-switched Nd:YAG laser has a maximum frequency of 660 kHz with the shortest pulse width of 161 ns, as shown in Figure 14 [274]. Up to now, a large number of near-infrared Q-switched pulse lasers have been achieved with layered materials, such as graphene, TIs, TMDs, BP, and others. Among them, the maximum repetition rate of 1.67 MHz [258], the minimum pulse duration of 2.86 ns, the maximum single pulse energy of 365 μJ , and maximum peak power of 67.6 kW [224] have been reported. The details are shown in Figure 15.

In MIR regime, compared with the application in the mode-locking operation, the LD materials are more fruitful in the Q-switching operation. Table 8 lists recent years' progress in Q-switched solid-state lasers based on 2D materials as SAs in MIR region. Significant development has been made with various LD materials in the generation of pulse lasers, since the first instance of graphene as Q-switcher for Tm:YAG laser at 2.01 μm [275]. As shown in Figure 16, the maximum average output power, repetition rate, and minimum pulse duration were 32 mW, 279 kHz, and 2.08 μs , respectively. Subsequently, TIs, TMDs, and BP Q-switched pulse lasers were also demonstrated. Among them, the maximum pulse energy and peak power of 81 kHz and 39.5 μJ , respectively, were obtained with BP SA, as shown in Figure 17A–C [310]. Additionally, pulse width of 157 nm (Figure 17D) [277], repetition rate of

Figure 15: Performance of BP, WS₂ and MoS₂ Q-switched near-infrared lasers.

(A) Schematic of WS₂, MoS₂, and BP SAs Q-switched lasers. Inset shows their dispersion solutions. (B) Saturable absorption properties of BP, WS₂, and MoS₂ solutions. (C) The output pulse energy vs. absorbed pump pulse energy. (D) Pulse durations corresponding to BP, WS₂ and MoS₂, respectively. Reproduced with permission [224]. Copyright 2017, Optical Society of America.

260 kHz (Figure 17E) [228], and average peak power of 3.3 W (Figure 17F) [285] were reported.

3.4 LD materials as SAs in fiber lasers

Besides solid-state lasers, LD materials have also been widely used in fiber lasers. Recent years, mode-locked fiber lasers using layered materials, including graphene, TIs, TMDs, and BP have developed rapidly [12, 33, 324]. For these mode-locked lasers, the minimum pulse width is 29 fs [325], 195 fs [326], 67 fs [327], and 102 fs [328], respectively.

Soon after implementing the graphene mode-locked fiber lasers, the researchers realized the Q-switching operations of fiber lasers based on graphene, TIs, TMDs, and BP, respectively. Among them, the maximum pulse energy is 877 μJ [329], and minimum pulse width is 155 ns [330], respectively [35].

4 Conclusion and future work

Low-dimensional materials, especially 2D materials, are a booming and hot field, growing in variety and quantity,

Table 8: Performance summary of passively Q-switched solid-state MIR lasers based on 2D materials.

Material	Fabrication method	Integration substrate	Layers	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
				α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
G	EG	SiC	2	–	–	Tm:YAG	2.01 μm	2.08 μs	18.1 kHz	38 mW	[275]	2012
G	–	Quartz	–	–	–	Ho:YAG	2097 nm	2.6 μs	64 kHz	264 mW	[276]	2014
G	CVD	Fused silica	2–3	0.23%	0.6 MW/cm ²	Tm:KLuW	1926 nm	190 ns	260 kHz	1.03 W	[228]	2016
G	EG	SiC	3–4	–	–	Cr:ZnSe	2.4 μm	157 ns	169 kHz	256 mW	[277]	2015
G	CVD	Sapphire	M	–	–	Ho,Pr:LLF	2.95 μm	937.5 ns	55.7 kHz	88 mW	[72]	2017
G	CVD	Quartz	M	–	–	Er:CaF ₂	2.8 μm	1.324 μs	62.7 kHz	172 mW	[278]	2016
G	CVD	Fused silica	M	1.2%	0.61 MW/cm ²	Tm:KLuW	1948 nm	285 ns	190 kHz	310 mW	[279]	2015
G	–	–	M	0.3%	–	Er:Lu ₂ O ₃	2845 nm	247 ns	174 kHz	~1.4 W	[280]	2019
GO	LPE	Au-glass	–	–	–	Tm:YAP	1973 nm	2 ns	156.25 MHz	464 mW	[281]	2012
GO	LPE	Quartz	–	23.1%	–	Tm:Y:CaF ₂	1969 nm	1.316 μs	20.22 kHz	400 mW	[282]	2018
GO	LPE	Quartz	–	23.1%	–	Tm:YLF	1928.23 nm	1.038 μs	38.33 kHz	379 mW	[283]	2018
g-C ₃ N ₄	TC	YAG	7–15	3.3%	7.5 MW/cm ²	Er:Lu ₂ O ₃	2.84 μm	351 ns	99 kHz	1.09 W	[284]	2017
MoS ₂	LPE	CaF ₂	–	5.1%	0.091 MW/cm ²	Tm, Ho:YAP	2000.4 nm	2.61 μs	133.6 kHz	550 mW	[285]	2018
								1.64 μs	110 kHz	688 mW		
								2.37 μs	133.2 kHz	3300 mW		
MoS ₂	PLD	Quartz	30	27%	2.45 GW/cm ²	Tm:Ho:YGG	2.1 μm	410 ns	149 kHz	206 mW	[226]	2014
MoS ₂	PLD	GM	–	7.2%	–	Tm:CLNGG	1979 nm	4.84 μs	110 kHz	62 mW	[286]	2015
MoS ₂	PLD	Quartz	30	0.32%	0.5 MW/cm ²	Tm:KLuW	1929 nm	175 ns	170 kHz	1.27 W	[228]	2016
MoS ₂	LPE	OC	65 nm	–	–	Tm:CYAO	1850 nm	0.48 μs	84.9 kHz	490 mW	[287]	2017
MoS ₂	LPE	Glass	4–5	21%	0.8 MW/cm ²	Tm, Ho:YAP	2129 nm	435 ns	55 kHz	270 mW	[288]	2017
MoS ₂	LPE	YAG	4–10	20.7%	3.7 mJ/cm ²	Er:Lu ₂ O ₃	2.84 μm	335 ns	121 kHz	1.03 W	[289]	2016
MoS ₂	CVD	YAG	46	4.2%	–	Ho,Pr:LLF	2.95 μm	621 ns	85.8 kHz	70 mW	[70]	2017
MoS ₂	PLD	Quartz	30	0.32%	0.5 MW/cm ²	Tm:KLuW	1929 nm	175 ns	170 kHz	1.27 W	[228]	2016
MoS ₂	TD	Mica	3–4	–	–	Tm:GdVO ₄	1902 nm	0.8 μs	48.09 kHz	100 mW	[290]	2015
ReS ₂	LPE	Sapphire	~5	9.7%	22.6 $\mu\text{J}/\text{cm}^2$	Er:YSGG	2.8 μm	324 ns	126 kHz	104 mW	[291]	2017
ReS ₂	LPE	YAG	3–10	3.8%	–	Er:SrF ₂	2.79 μm	508 ns	49 kHz	580 mW	[292]	2018
ReS ₂	LPE	Sapphire	~6	2.9%	2.7 $\mu\text{J}/\text{cm}^2$	Tm:YAP	1.991 μm	415 ns	67.7 kHz	245 mW	[135]	2018
ReSe ₂	LPE	OM	~11	7.5%	14.5 $\mu\text{J}/\text{cm}^2$	Er:YAP	2.73 μm	202.8 ns	244.6 kHz	526 mW	[293]	2019
							2.80 μm					
SnSe ₂	LPE	Sapphire	–	12.6%	0.76 GW/cm ²	Tm:YLF	1.9 μm	716 ns	54.6 kHz	113 mW	[242]	2019
WS ₂	LPE	CaF ₂	5	6.7%	10.6 MW/cm ²	Er:Y ₂ O ₃	2716.3 nm	0.72 μs	29.4 kHz	233.5 mW	[294]	2018
WS ₂	TD	SiO ₂	5–6	6%	150 $\mu\text{J}/\text{cm}^2$	Tm:LuAG	2012.9 nm	660 ns	63 kHz	1.08 W	[295]	2016
WS ₂	LPE	YAG	7–14	3.5%	–	Ho,Pr:LLF	2.95 μm	654 ns	90.4 kHz	82 mW	[71]	2017
MoSe ₂	LPE	YAG	22–30	~7.4%	3.6 mJ/cm ²	Ho,Pr:LLF	2954.87 nm	818.8 ns	71.05 kHz	58 mW	[296]	2017
MoSe ₂	LPE	SiO ₂	~30	4.7%	–	Tm:LuAG	2.0 μm	520 ns	58 kHz	1.19 W	[297]	2017
1T-TiSe ₂	LPE	Sapphire	10	8.9%	10.12 $\mu\text{J}/\text{cm}^2$	Tm:YAP	1978 nm	350 ns	84 kHz	0.99 W	[257]	2018
1T-TiSe ₂	LPE	Sapphire	10	6.1%	15.59 $\mu\text{J}/\text{cm}^2$	Er:YSGG	2790 nm	160 ns	78 kHz	0.25 W		
TiSe ₂	LPE	Sapphire	~7	9.2%	4.6 $\mu\text{J}/\text{cm}^2$	Ho,Pr:LLF	2.92 μm	160.5 ns	98.8 kHz	130 mW	[298]	2018
WSe ₂	LPE	YAG	5–8	5.3%	–	Er:Lu ₂ O ₃	2.85	280 ns	121 kHz	776 mW	[299]	2018

Table 8 (continued)

Material	Fabrication method	Integration substrate	Layers	Saturable absorption properties		Laser gain medium	Laser output characteristics				Reference	Year
				α_s	I_{sat}		λ	τ	f_{rep}	P_{ave}		
WSe ₂	LPE	YAG	24–33	9.2%	2.3 mJ/cm ²	Ho,Pr:LLF	2.95 μm	571 ns	89.3 kHz	147 mW	[300]	2018
PtSe ₂	CVD	Sapphire	2	6.6%	3.2 $\mu\text{J}/\text{cm}^2$	Tm:YAP	1987 nm	244 ns	58 kHz	1.41 W	[301]	2018
MoTe ₂	LPE	YAG	8–15	22%	0.14 mJ/cm ²	Ho,Pr:LLF	2.95 μm	670 ns	76.46 kHz	73 mW	[302]	2017
MoTe ₂	LPE	CaF ₂	18	6%	2.26 $\mu\text{J}/\text{cm}^2$	Tm:YAP	2.0 μm	380 ns	144 kHz	1.21 W	[303]	2018
MoTe ₂	LPE	BK7	–	4%	18 MW/cm ²	Tm:CYA	1.9 μm	690 ns	70.9 kHz	750 mW	[304]	2018
WTe ₂	LPE	CaF ₂	9	7.2%	5.1 $\mu\text{J}/\text{cm}^2$	Tm:YAP	2.0 μm	368 ns	78 kHz	640 mW	[305]	2018
WTe ₂	LPE	YAG	20	20.9%	1.97 mJ/cm ²	Ho,Pr:LLF	2.95 μm	366 ns	92 kHz	128 mW	[306]	2018
Bi ₂ Te ₃	LPE	Quartz	~50 nm	7.5%	786 W/cm ²	Tm:LuAG	2023.6 nm	620 ns	118 kHz	2.03 W	[307]	2017
Bi ₂ Te ₃	LPE	Sapphire	28	15%	0.7 kW/cm ²	Tm:LuAG	2021.7 nm	233.3 ns	145.5 kHz	1.74 W	[308]	2018
BP	ME	Quartz	40–50	35.48%	6.14 GW/cm ²	Tm:Ho:YAG	2.1 μm	636 ns	122 kHz	27 mW	[139]	2015
BP	LPE	Quartz	5–13	–	–	Tm:YAP	1988 nm	1.78 μs	19.25 kHz	151 mW	[309]	2016
BP	LPE	OC	~17	19.6%	3.1 $\mu\text{J}/\text{cm}^2$	Tm:YAP	1969 nm	181 ns	81 kHz	3.1 W	[310]	2016
BP	ME	GM	–	5%	20 $\mu\text{J}/\text{cm}^2$	Tm:YAG	2009 nm	3.12 μs	11.6 kHz	38.5 mW	[311]	2016
BP	LPE	OC	~10	10.7%	0.96 MW/cm ²	Cr:ZnSe	2.4 μm	189 ns	176 kHz	36 mW	[312]	2016
BP	LPE	GM	~40	7.8%	1.15 $\mu\text{J}/\text{cm}^2$	Tm:CaYAlO ₄	1.93 μm	3.1 μs	17.7 kHz	12 mW	[248]	2016
BP	LPE	YAG	28–52	8%	–	Er:Y ₂ O ₃	2.72 μm	4.47 μs	12.6 kHz	6 mW	[313]	2016
BP	LPE	Silicon	3–9 nm	–	–	Er:Lu ₂ O ₃	2.84 μm	359 ns	107 kHz	755 mW	[314]	2016
BP	LPE	Quartz	3–9 nm	–	–	Er:SrF ₂	2.79 μm	702 ns	77.03 kHz	180 mW	[315]	2018
BP	LPE	CaF ₂	~80	18.4%	3.37 $\mu\text{J}/\text{cm}^2$	Er:CaF ₂	2.8 μm	954.8 ns	41.93 kHz	178 mW	[69]	2018
Bi-NSs	LPE	Quartz	<2.5 nm	1.82%	3.59 kW/cm ²	Ho,Pr:LLF	2.95 μm	194.3 ns	158.7 kHz	385 mW	[316]	2018
Bi ₂ Te ₃ /G	LPE	OC	–	6.6%	0.44 MW/cm ²	Er:SrF ₂	2730.5 nm	980 ns	56.20 kHz	0.226 W	[317]	2017
Ti ₃ C ₂ T _x	LPE	Quartz	1 nm	26.6%	–	Tm:YAP	2.0 μm	238 ns	108 kHz	2.34 W	[318]	2019
Ti ₃ C ₂ T _x	LPE	Quartz	–	1.86%	241 kW/cm ²	Ho:YLF	2062.22 nm	837 ns	35.5 kHz	110 mW	[202]	2019
Ti ₃ C ₂ T _x	LPE	Quartz	1 nm	1.75%	45.5 kW/cm ²	Er:Ca _{0.8} Sr _{0.2} F ₂	2796.7 nm	400 ps	103.2 MHz	83 mW	[319]	2019
Ti ₃ C ₂ T _x	LPE	Quartz	–	34.7%	5.0 kW/cm ²	Er:CaF ₂ -SrF ₂	2728.8 nm	814 ns	45.3 kHz	286 mW	[320]	2018
TiC ₂	LPE	CaF ₂	–	5.7%	30.1 mJ/cm ²	Tm:YAP	1929.7 nm	2.390 μs	19.61 kHz	–	[321]	2019
Ta ₂ NiS ₅	LPE	Sapphire	22	12.2%	15.4 $\mu\text{J}/\text{cm}^2$	Tm:BYF	1906.9 nm	579 ns	255 kHz	2220 mW	[322]	2019
Sb ₂ Te ₃	PVD	Glass	3–15 nm	7.5%	0.17 MW/cm ²	Tm:GdVO ₄	1910 nm	313 ns	50 kHz	1.1 W	[323]	2018
InSe	LPE	Quartz	8–9	7.94%	0.31 MW/cm ²	Tm:YLF	1913 nm	223 ns	200 kHz	0.7 W	[273]	2019

EG, Epitaxially grown; CVD, chemical vapor deposition; TC, thermal condensation; TD, thermally decomposing; ME, mechanical exfoliation; PVD, physical vapor deposition. α_s , Modulation depth; I_{sat} , saturation intensity; λ , central wavelength; τ , pulse width; f_{rep} , repetition rate; P_{ave} , average output power.

Figure 16: Performance of the first graphene Q-switched Tm:YAG laser.

(A) Schematic of the graphene Q-switched Tm:YAG laser. (B) Raman spectrum of graphene sample. (C) Output power vs. incident pump power of the graphene Q-switched laser, with its spectrum inserted. (D) Pulse traces in different time scales. (E) Pulse width and repetition rate vs. incident pump power. Reproduced with permission [275]. Copyright 2012, Optical Society of America.

as well as in quality. Over the past decade, LD materials-based pulsed lasers have experienced rapid development, and a series of important results have been achieved. This is mainly due to the maturity of LD material preparation and coupling technology, as well as the continuous progress of pulsed laser technology over the past decades. However, several challenges and scientific problems remain to be conquered.

1. How to select the best candidate material from a large number of LD materials. Theoretical method for

various LD materials can quickly make predictions, but cannot guarantee accuracy, in the actual study. The interactions of photons and materials are very complex and uncertain, and the relationship between light and material is poorly understood. All factors are needed to be planned as a whole between materials scientists, physicists, and engineers.

2. How to prepare LD materials with large size, high quality, and controllable layers. There are two main strategies for the preparation of LD layered materials:

Figure 17: Performance of BP, graphene, and MoS₂ Q-switched mid-infrared lasers.

(A) AFM image and typical height profile and (B) saturable absorption behavior of BP SA mirror. (C) The single pulse energy and peak power vs. absorbed pump power of the BP Q-switched laser. Reproduced with permission [310]. Copyright 2014, Optical Society of America. (D) The typical pulse trains of graphene Q-switched Cr:ZnSe laser with the minimum pulse width of 157 ns. Reproduced with permission [277]. Copyright 2015, IEEE Photonics Society. (E) Pulse repetition frequency of graphene and MoS₂ Q-switched Tm:KLuW lasers. Reproduced with permission [228]. Copyright 2016, Optical Society of America. (F) Average output powers of the layered MoS₂ Q-switched Tm,Ho:YAP lasers. Reproduced with permission [285]. Copyright 2018, Optical Society of America.

top-down method and bottom-up method. Among them, the more typical is the chemical vapor deposition method; this method is directly conducted on basal atomic deposition, because the process of crystal growth will be affected by the influence of the substrate, causing material defects and, in turn, which will affect the photoelectric properties of materials. Therefore, the growing quality of LD material is an important step to promote the LD material nonlinear devices.

- How to achieve controllable nonlinear optical parameters for LD materials and high-performance ultrafast laser. The modulation depth and saturable influence of LD material are significant parameters in the process of achieving ultrafast laser. It is necessary to explore the influence of the nonlinear effect of LD materials on the resonator. In addition, the bandgap of LD materials can be modulated by the external electrical field, resulting in the changing of nonlinear characteristics, which have the potential to obtain active Q-switching and mode-locking.

In conclusion, we hope that LD materials with good reliability, low defects, high stability, excellent thermal performance, and broadband optical response and suitable for solid-state laser high-energy operation will be fabricated, and ultrafast lasers based on LD materials SAs will get out of the laboratory and achieve the industrial application.

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References

- [1] Lagatsky AA, Koopmann P, Fuhrberg P, Huber G, Brown CTA, Sibbett W. Passively mode locked femtosecond Tm:Sc₂O₃ laser at 2.1 μm. *Opt Lett* 2012;37:437–9.
- [2] Ma J, Xie GQ, Gao WL, et al. Diode-pumped mode-locked femtosecond Tm:CLNGG disordered crystal laser. *Opt Lett* 2012;37:1376–8.
- [3] Yao B, Wang W, Yu K, Li G, Wang Y. Passively mode-locked Tm:Ho:YVO₄ laser based on a semiconductor saturable absorber mirror. *Chin Opt Lett* 2012;10:071402.
- [4] Tyazhev A, Soulard R, Godin T, et al. Passively mode-locked diode-pumped Tm³⁺:YLF laser emitting at 1.91 μm using a GaAs-based SESAM. *Laser Phys Lett* 2018;15:045807.
- [5] Zhao Y, Wang Y, Zhang X, et al. 87 fs mode-locked Tm:Ho:CaYAlO₄ laser at ~2043 nm. *Opt Lett* 2018;43:915–8.
- [6] Uemura S, Torizuka K. Generation of 10 fs pulses from a diode-pumped Kerr-lens mode-locked Cr:LiSAF laser. *Jpn J Appl Phys* 2000;39:3472–3.
- [7] Yang K, Heinecke D, Paajaste J, et al. Mode-locking of 2 μm Tm:Ho:YAG laser with GaInAs and GaSb-based SESAMs. *Opt Express* 2013;21:4311–8.
- [8] Zou X, Leng Y, Li Y, et al. Passively Q-switched mode-locked Tm:LLF laser with a MoS₂ saturable absorber. *Chin Opt Lett* 2015;13:081405.
- [9] Cho CY, Chen YF, Zhang G, Chen WD, Liang HC. Exploring the self-mode locking of the 2 μm Tm:YAG laser with suppression of the self-pulsing dynamic. *Opt Lett* 2017;42:5226–9.
- [10] Zhou W, Xu X, Xu R, et al. Watt-level broadly wavelength tunable mode-locked solid-state laser in the 2 μm water absorption region. *Photonics Res* 2017;5:583–7.
- [11] Ling W, Xia T, Dong Z, et al. 1.91 μm Passively continuous-wave mode-locked Tm:LiLuF₄ laser. *Opt Laser Technol* 2018;108:364–7.
- [12] Ma J, Qin Z, Xie G, Qian L, Tang D. Review of mid-infrared mode-locked laser sources in the 2.0 μm–3.5 μm spectral region. *Appl Phys Rev* 2019;6:021317.
- [13] Zhou Z, Guan X, Huang X, et al. Tm³⁺-doped LuYO₃ mixed sesquioxide ceramic laser: effective 2.05 μm source operating in continuous-wave and passive Q-switching regimes. *Opt Lett* 2017;42:3781–4.
- [14] Stevenson NK, Brown CTA, Hopkins JM, Dawson MD, Kränkel C, Lagatsky AA. Diode-pumped femtosecond Tm³⁺-doped LuScO₃ laser near 2.1 μm. *Opt Lett* 2018;43:1287–90.
- [15] Lan J, Zhou Z, Guan X, et al. Passively Q-Switched Tm:CaGdAlO₄ laser using a Cr²⁺:ZnSe saturable absorber. *Opt Mater Express* 2017;7:1725–31.
- [16] Luan C, Yang K, Zhao J, et al. Diode-pumped mode-locked Tm:LuAG laser at 2 μm based on GaSb-SESAM. *Opt Lett* 2017;42:839–42.
- [17] Wang Y, Jing W, Loiko P, et al. Sub-10 optical-cycle passively mode-locked Tm:(Lu_{2/3}Sc_{1/3})₂O₃ ceramic laser at 2 μm. *Opt Express* 2018;26:10299–304.
- [18] Feng T, Yang K, Zhao J, et al. 1.21 W passively mode-locked Tm:LuAG laser. *Opt Express* 2015;23:11819–25.
- [19] Lan J, Xu B, Zhou Z, et al. High-power CW and Q-switched Tm:CaYAlO₄ lasers at 1.94 μm for shallow water absorption. *IEEE Photonics Tech L* 2017;29:2127–30.
- [20] Zhang Y, Xu B, Tian Q, et al. Sub-15-ns passively Q-switched Er:YSGG laser at 2.8 μm with Fe:ZnSe saturable absorber. *IEEE Photonics Tech L* 2019;31:565–8.
- [21] Keller U, Miller DAB, Boyd GD, Chiu TH, Ferguson JF, Asom MT. Solid-state low-loss intracavity saturable absorber for Nd:YLF lasers: an antiresonant semiconductor Fabry–Perot saturable absorber. *Opt Lett* 1992;17:505–7.
- [22] Gluth A, Wang Y, Petrov V, et al. GaSb-based SESAM mode-locked Tm:YAG ceramic laser at 2 μm. *Opt Express* 2015;23:1361–9.
- [23] Mashiko Y, Fujita E, Tokurakawa M. Tunable noise-like pulse generation in mode-locked Tm fiber laser with a SESAM. *Opt Express* 2016;24:26515–20.
- [24] Soulard R, Tyazhev A, Doualan J-L, et al. 2.3 μm Tm³⁺:YLF mode-locked laser. *Opt Lett* 2017;42:3534–6.
- [25] Mateos X, Loiko P, Lamrini S, et al. Ho:KY(WO₄)₂ thin-disk laser passively Q-switched by a GaSb-based SESAM. *Opt Express* 2018;26:9011–6.
- [26] Lin C, Grau M, Dier O, Amann MC. Low threshold room-temperature continuous-wave operation of 2.24–3.04 μm GaInAsSb/AlGaAsSb quantum-well lasers. *Appl Phys Lett* 2004;84:5088–90.
- [27] Sobon G. Mode-locking of fiber lasers using novel two-dimensional nanomaterials: graphene and topological insulators [invited]. *Photonics Res* 2015;3:A56–63.
- [28] Hu Q, Zhang X, Liu Z, et al. High-order harmonic mode-locked Yb-doped fiber laser based on a SnSe₂ saturable absorber. *Opt Laser Technol* 2019;119:105639.
- [29] Luo ZC, Liu M, Luo AP, Xu WC. Two-dimensional materials-decorated microfiber devices for pulse generation and shaping in fiber lasers. *Chin Phys B* 2018;27:094215.
- [30] Wu K, Chen B, Zhang X, et al. High-performance mode-locked and Q-switched fiber lasers based on novel 2D materials of topological insulators, transition metal dichalcogenides and black phosphorus: review and perspective (invited). *Opt Commun* 2018;406:214–29.
- [31] Zhang Y, Wang H, Li F, et al. The emerging ferroic orderings in two dimensions. *Sci China Inform Sci* 2019;62:220402.
- [32] Novoselov KS, Geim AK, Morozov SV, et al. Electric field effect in atomically thin carbon films. *Science* 2004;306:666.
- [33] He J, Tao L, Zhang H, Zhou B, Li J. Emerging 2D materials beyond graphene for ultrashort pulse generation in fiber lasers. *Nanoscale* 2019;11:2577–93.
- [34] Li J, Zhang Z, Du L, et al. Highly stable femtosecond pulse generation from a MXene Ti₃C₂T_x (T=F, O, or OH) mode-locked fiber laser. *Photonics Res* 2019;7:260–4.
- [35] Guo B, Xiao Q, Wang S, Zhang H. 2D layered materials: synthesis, nonlinear optical properties, and device applications. *Laser Photonics Rev* 2019;13:1800327.
- [36] Woodward R, Kelleher E. 2D saturable absorbers for fibre lasers. *Appl Sci* 2015;5:1440–56.
- [37] Liu X, Guo Q, Qiu J. Emerging low-dimensional materials for nonlinear optics and ultrafast photonics. *Adv Mater* 2017;29:1605886.
- [38] Xia F, Wang H, Xiao D, Dubey M, Ramasubramaniam A. Two-dimensional material nanophotonics. *Nat Photonics* 2014;8:899.
- [39] Wang G, Baker-Murray AA, Blau WJ. Saturable absorption in 2D nanomaterials and related photonic devices. *Laser Photonics Rev* 2019;13:1800282.

- [40] Novoselov KS, Geim AK, Morozov S, et al. Two-dimensional gas of massless Dirac fermions in graphene. *Nature* 2005;438:197.
- [41] Xu JL, Li XL, He JL, et al. Performance of large-area few-layer graphene saturable absorber in femtosecond bulk laser. *Appl Phys Lett* 2011;99:261107.
- [42] Bao Q, Zhang H, Wang Y, et al. Atomic-layer graphene as a saturable absorber for ultrafast pulsed lasers. *Adv Funct Mater* 2009;19:3077–83.
- [43] Zhang H, Liu C, Qi X, Dai X, Fang Z, Zhang S. Topological insulators in Bi_2Se_3 , Bi_2Te_3 and Sb_2Te_3 with a single Dirac cone on the surface. *Nat Phys* 2009;5:438–42.
- [44] Zhao C, Zhang H, Qi X, et al. Ultra-short pulse generation by a topological insulator based saturable absorber. *Appl Phys Lett* 2012;101:211106.
- [45] Zhao C, Zou Y, Chen Y, et al. Wavelength-tunable picosecond soliton fiber laser with topological insulator: Bi_2Se_3 as a mode locker. *Opt Express* 2012;20:27888–95.
- [46] Lu S, Zhao C, Zou Y, et al. Third order nonlinear optical property of Bi_2Se_3 . *Opt Express* 2013;21:2072–82.
- [47] Brown A, Rundqvist S. Refinement of the crystal structure of black phosphorus. *Acta Crystallogr* 1965;19:684–5.
- [48] Wang X, Lan S. Optical properties of black phosphorus. *Adv Opt Photonics* 2016;8:618–55.
- [49] Li L, Kim J, Jin C, et al. Direct observation of the layer-dependent electronic structure in phosphorene. *Nat Nanotechnology* 2017;12:21–25.
- [50] Wang Y, Zhang F, Tang X, et al. All-optical phosphorene phase modulator with enhanced stability under ambient conditions. *Laser Photonics Rev* 2018;12:1800016.
- [51] Zheng J, Tang X, Yang Z, et al. Few-layer phosphorene-decorated microfiber for all-optical thresholding and optical modulation. *Adv Opt Mater* 2017;5:1700026.
- [52] Zheng J, Yang Z, Si C, et al. Black phosphorus based all-optical-signal-processing: toward high performances and enhanced stability. *ACS Photonics* 2017;4:1466–76.
- [53] Chen Y, Jiang G, Chen S, et al. Mechanically exfoliated black phosphorus as a new saturable absorber for both Q-switching and mode-locking laser operation. *Opt Express* 2015;23:12823–33.
- [54] Guo S, Zhang Y, Ge Y, Zhang S, Zeng H, Zhang H. 2D V-V binary materials: status and challenges. *Adv Mater* 2019;31:1902352.
- [55] Lu L, Tang X, Cao R, et al. Broadband nonlinear optical response in few-layer antimonene and antimonene quantum dots: a promising optical Kerr media with enhanced stability. *Adv Opt Mater* 2017;5:1700301.
- [56] Wang Y, Huang W, Wang C, et al. An all-optical, actively Q-switched fiber laser by an antimonene-based optical modulator. *Laser Photonics Rev* 2019;13:1800313.
- [57] Tao W, Ji X, Zhu X, et al. Two-dimensional antimonene-based photonic nanomedicine for cancer theranostics. *Adv Mater* 2018;30:e1802061.
- [58] Wang Y, Huang W, Zhao J, et al. A bismuthene-based multifunctional all-optical phase and intensity modulator enabled by photothermal effect. *J Mater Chem C* 2019;7:871–8.
- [59] Guo B, Wang SH, Wu ZX, et al. Sub-200 fs soliton mode-locked fiber laser based on bismuthene saturable absorber. *Optics Express* 2018;26:22750.
- [60] Jiang X, Liu S, Liang W, et al. Broadband nonlinear photonics in few-layer MXene $\text{Ti}_3\text{C}_2\text{T}_x$ ($T=\text{F}, \text{O}, \text{or OH}$). *Laser Photonics Rev* 2018;12:1700229–39.
- [61] Wang C, Wang Y, Jiang X, et al. MXene $\text{Ti}_3\text{C}_2\text{T}_x$: a promising photothermal conversion material and application in all-optical modulation and all-optical information loading. *Adv Opt Mater* 2019;7:1900060.
- [62] Li X, Cai W, Colombo L, Ruoff RS. Evolution of graphene growth on Ni and Cu by carbon isotope labeling. *Nano Lett* 2009;9:4268–72.
- [63] Bae S, Kim H, Lee Y, et al. Roll-to-roll production of 30-inch graphene films for transparent electrodes. *Nat Nanotechnol* 2010;5:574–8.
- [64] Yi M, Shen Z. A review on mechanical exfoliation for the scalable production of graphene. *J Mater Chem A* 2015;3:11700–15.
- [65] Guo J, Huang D, Zhang Y, et al. 2D GeP as a novel broadband nonlinear optical material for ultrafast photonics. *Laser Photonics Rev* 2019;13:1900123.
- [66] Wang C, Wang YZ, Jiang XT, et al. Thermal stress-induced all-optical modulation in MXene-coated polarization maintaining fiber. *Laser Phys Lett* 2019;16:065107.
- [67] Zhang Y, Yu H, Zhang R, et al. Broadband atomic-layer MoS_2 optical modulators for ultrafast pulse generations in the visible range. *Opt Lett* 2017;42:547–50.
- [68] Zhang Y, Wang S, Wang D, et al. Atomic-layer molybdenum sulfide passively modulated green laser pulses. *IEEE Photonics Tech L* 2016;28:197–200.
- [69] Nie H, Zhang P, Zhang B, et al. Watt-level continuous-wave and black phosphorus passive Q-switching operation of $\text{Ho}^{3+}, \text{Pr}^{3+}:\text{LiLuF}_4$ bulk laser at 2.95 μm . *IEEE J Sel Top Quant* 2018;24:1–5.
- [70] Zhang S, Liu X, Guo L, et al. Passively Q-Switched $\text{Ho}, \text{Pr}:\text{LLF}$ Bulk slab laser at 2.95 μm based on MoS_2 saturable absorber. *IEEE Photonics Tech L* 2017;29:2258–61.
- [71] Guo L, Li T, Zhang S, et al. Passively Q-switched $\text{Ho}, \text{Pr}:\text{LiLuF}_4$ bulk laser at 2.95 μm using WS_2 saturable absorbers. *Opt Mater Express* 2017;7:2090–5.
- [72] Nie H, Zhang P, Zhang B, et al. Diode-end-pumped $\text{Ho}, \text{Pr}:\text{LiLuF}_4$ bulk laser at 2.95 μm . *Opt Lett* 2017;42:699–702.
- [73] Li J, Dong H, Xu B, et al. CsPbBr_3 perovskite quantum dots: saturable absorption properties and passively Q-switched visible lasers. *Photonics Res* 2017;5:457–60.
- [74] Liu S, Wang Q, Wang K, et al. Two-photon saturable absorption properties and laser Q-switch application of carbon quantum dots. *Opt Lett* 2017;42:3972–5.
- [75] Wang X, Wang Y, Mao D, Li L, Chen Z. Passively Q-switched $\text{Nd}:\text{YVO}_4$ laser based on Fe_3O_4 nanoparticles saturable absorber. *Opt Mater Express* 2017;7:2913–21.
- [76] Liu X, Yang K, Zhao S, et al. Ferroferric-oxide nanoparticle based optical modulator for 2 μm spectral region. *IEEE Photonics Tech L* 2018;30:777–80.
- [77] Zhang X, Liu X, Xu X, et al. Self-assembled gold nanoparticles as saturable absorber for low-threshold all-solid-state pulsed 2 μm laser. *Opt Mater* 2018;83:82–6.
- [78] Liu X, Yang K, Zhao S, et al. Silicon-nanoparticle-based broadband optical modulators for solid-state lasers. *Opt Lett* 2018;43:5957–60.
- [79] Su X, Wang Y, Zhang B, et al. Bismuth quantum dots as an optical saturable absorber for a 1.3 μm Q-switched solid-state laser. *Appl Opt* 2019;58:1621–5.
- [80] Wang P, Yang Q, Wang X. Gold nanostars as the saturable absorber for a Q-switched visible solid-state laser. *Appl Opt* 2019;58:6733–6.

- [81] Dhanabalan SC, Dhanabalan B, Ponraj JS, Bao Q, Zhang H. 2D-materials-based quantum dots: gateway towards next-generation optical devices. *Adv Opt Mater* 2017;5:1700257.
- [82] Dong Y, Wang R, Li H, et al. Polyamine-functionalized carbon quantum dots for chemical sensing. *Carbon* 2012;50:2810–5.
- [83] Wu K, Liang G, Shang Q, Ren Y, Kong D, Lian T. Ultrafast interfacial electron and hole transfer from CsPbBr₃ perovskite quantum dots. *J Am Chem Soc* 2015;137:12792–5.
- [84] Zhou Y, Hu Z, Li Y, Xu J, Tang X, Tang Y. CsPbBr₃ nanocrystal saturable absorber for mode-locking ytterbium fiber laser. *Appl Phys Lett* 2016;108:261108.
- [85] Il'ichev NN, Obratsova ED, Garnov SV, Mosaleva SE. Nonlinear transmission of single-wall carbon nanotubes in heavy water at a wavelength of 1.54 μm and self-mode locking in a Er³⁺:glass laser obtained using a passive nanotube switch. *Quantum Electronics* 2004;34:572.
- [86] Schibli TR, Minoshima K, Kataura H, et al. Ultrashort pulse-generation by saturable absorber mirrors based on polymer-embedded carbon nanotubes. *Opt Express* 2005;13:8025–31.
- [87] Fong KH, Kikuchi K, Goh CS, et al. Solid-state Er:Yb:glass laser mode-locked by using single-wall carbon nanotube thin film. *Opt Lett* 2007;32:38–40.
- [88] Cho WB, Yim JH, Choi SY, et al. Mode-locked self-starting Cr:forsterite laser using a single-walled carbon nanotube saturable absorber. *Opt Lett* 2008;33:2449–51.
- [89] Schmidt A, Rivier S, Steinmeyer G, et al. Passive mode locking of Yb:KLuW using a single-walled carbon nanotube saturable absorber. *Opt Lett* 2008;33:729–31.
- [90] Cho WB, Schmidt A, Yim JH, et al. Passive mode-locking of a Tm-doped bulk laser near 2 μm using a carbon nanotube saturable absorber. *Opt Express* 2009;17:11007–12.
- [91] Cho WB, Schmidt A, Choi SY, et al. Mode locking of a Cr:YAG laser with carbon nanotubes. *Opt Lett* 2010;35:2669–71.
- [92] Cho WB, Yim JH, Choi SY, et al. Boosting the non linear optical response of carbon nanotube saturable absorbers for broadband mode-locking of bulk lasers. *Adv Funct Mater* 2010;20:1937–43.
- [93] Baek IH, Choi SY, Lee HW, et al. Single-walled carbon nanotube saturable absorber assisted high-power mode-locking of a Ti:sapphire laser. *Opt Express* 2011;19:7833–38.
- [94] Su LM, Wang YG, Liu J, Zheng LH, Su LB, Xu J. Double-wall carbon nanotube absorber for passively mode-locked Yb³⁺:Sc₂SiO₅ laser. *Laser Phys Lett* 2011;9:120–5.
- [95] Yang Q, Wang YG, Liu DH, et al. Dual-wavelength mode-locked Yb:LuYSiO₅ laser with a double-walled carbon nanotube saturable absorber. *Laser Phys Lett* 2012;9:135–40.
- [96] Agnesi A, Pirzio F, Ugoletti E, Choi SY, Yeom D-II, Rothermund F. Femtosecond single-mode diode-pumped Cr:LiSAF laser mode-locked with single-walled carbon nanotubes. *Opt Commun* 2012;285:742–5.
- [97] Baylam I, Ozharar S, Cankaya H, et al. Energy scaling of a carbon nanotube saturable absorber mode-locked femtosecond bulk laser. *Opt Lett* 2012;37:3555–7.
- [98] Liu C, Wang Y, Liu J, Zheng L, Su L, Xu J. Ultrafast laser performance of Yb³⁺: Sc₂SiO₅ crystal with a single-walled carbon nanotube absorber. *Opt Commun* 2012;285:1352–5.
- [99] Qu ZS, Ma BM, Fan XW, Liu J, Wang YG. Broad spectral pulse operation of 2 μm Tm:YAP laser based on reflection-type carbon nanotube absorber. *Laser Phys* 2012;22:509–12.
- [100] Qu ZS, Wang YG, Liu J. Passive mode-locking of diode-pumped Nd:GdVO₄ laser with carbon nanotube intracavity absorber. *J Mod Optic* 2012;59:789–93.
- [101] Qu Z, Wang Y, Liu J, Zheng L, Su L, Xu J. Passively mode-locked 2- μm Tm:YAP laser with a double-wall carbon nanotube absorber. *Chin Phys B* 2012;21:064211.
- [102] Schmidt A, Koopmann P, Huber G, et al. 175 fs Tm:Lu₂O₃ laser at 2.07 μm mode-locked using single-walled carbon nanotubes. *Opt Express* 2012;20:5313–8.
- [103] Su L, Wang Y, Liu J, et al. Passively mode-locked Yb³⁺:Sc₂SiO₅ laser with reflection-type single-walled carbon nanotube absorber. *Appl Opt* 2012;51:1283–6.
- [104] Yang Q, Liu J, Fan XW, et al. Passively mode-locked Yb:LYSO laser with a reflection type single-walled carbon absorber. *Laser Phys* 2012;22:896–9.
- [105] Cafiso SDDD, Ugoletti E, Schmidt A, et al. Sub-50 fs mode-locking of a Cr:YAG laser using an SWCNT-SA. *Laser Phys Lett* 2013;10:085801.
- [106] Liu J, Feng C, Su LB, et al. Characteristics of a diode-pumped Yb:CaF₂–SrF₂ mode-locked laser using a carbon nanotube absorber. *Laser Phys Lett* 2013;10:105806.
- [107] Liu J, Li YQ, Zheng LH, Su LB, Xu J, Wang YG. Passive Q-switched mode locking of a diode-pumped Tm:SSO laser near 2 μm . *Laser Phys Lett* 2013;10:105812.
- [108] Cai W, Peng Q, Hou W, Liu J, Wang Y. Picosecond passively mode-locked laser of 532 nm by reflective carbon nanotube. *Opt Laser Technol* 2014;58:194–6.
- [109] Fan M, Ma B, Liu J, Wang Y. Reflective carbon nanotube as the saturable absorber for mode-locked 1064 nm laser. *Optik* 2014;125:5666–8.
- [110] Tolstik N, Okhotnikov O, Sorokin E, Sorokina IT. Femtosecond Cr:ZnS laser at 2.35 μm mode-locked by carbon nanotubes. *Proc SPIE* 2014;8959:89591A–1A-6.
- [111] Feng C, Hou W, Yang J, et al. Dual-wavelength synchronous mode-locked Yb:LSO laser using a double-walled carbon nanotube saturable absorber. *Appl Opt* 2016;55:3639–44.
- [112] Li C, Cai W, Liu J, et al. Single-walled carbon nanotube saturable absorber for a diode-pumped passively mode-locked Nd:Y:Yb:Yb₂SiO₅ laser. *Opt Commun* 2016;372:76–9.
- [113] Okazaki D, Arai H, Anisimov A, et al. Self-starting mode-locked Cr:ZnS laser using single-walled carbon nanotubes with resonant absorption at 2.4 μm . *Opt Lett* 2019;44:1750–3.
- [114] Tanisalı G, Baylam I, Tascı M, et al. 21 fs Cr:LiSAF laser mode locked with a single-walled carbon nanotube saturable absorber. *Opt Lett* 2019;44:4662–5.
- [115] Qu Z, Wang Y, Liu J, Zheng L, Su L, Xu J. Performance of 2 μm Tm:YAP pulse laser based on a carbon nanotube absorber. *Appl Phys B* 2012;109:143–7.
- [116] Yu H, Zhang L, Wang Y, et al. Sub-100 ns solid-state laser Q-switched with double wall carbon nanotubes. *Opt Commun* 2013;306:128–30.
- [117] Li Y, Liu J, Zhu H, et al. Performance of diode-pumped Tm³⁺:Sc₂SiO₅ crystal passively Q-switched 2 μm laser. *Opt Commun* 2014;330:151–4.
- [118] Chu H, Zhao S, Yang K, et al. Passively Q-switched Nd:GGG laser with a SWCNT as saturable absorber. *Opt Quantum Electron* 2015;47:697–703.
- [119] Zhang S, Li H, Zhao Q, et al. Integratable pulsed 2- μm laser with Tm,Mg:LiNbO₃ crystal and single-walled carbon nanotube saturable absorber. *Opt Laser Technol* 2015;65:36–8.

- [120] Zu Y, Guo X, Liu J, Liu J, Su L. Passively Q-switched operation of a novel Tm^{3+} , La^{3+} co-doped CaF_2 single crystal near 2 μm . *Infrared Phys Technol* 2019;102:103010.
- [121] Wu Y, Pang S, Zu Y, et al. Silver nanorods absorber for passively Q-switched Nd:Gd:CaF₂ laser. *Chin Opt Lett* 2018;16:020015.
- [122] Wu Y, Zhang C, Liu J, Zhang H, Yang J, Liu J. Silver nanorods absorbers for Q-switched Nd:YAG ceramic laser. *Opt Laser Technol* 2017;97:268–71.
- [123] Liu J, Zhang C, Zu Y, et al. Efficient continuous-wave, broadly tunable and passive Q-switching lasers based on a Tm^{3+} :CaF₂ crystal. *Laser Phys Lett* 2018;15:045803.
- [124] Zhang F, Zhang HN, Liu DH, et al. Tunable Nd, La:SrF₂ laser and passively Q-switched operation based on gold nanobipyramids saturable absorber. *Chin Phys B* 2017;26:024205.
- [125] Chu Z, Zhang H, Wu Y, Zhang C, Liu J, Yang J. Passively Q-switched laser based on gold nanobipyramids as saturable absorbers in the 1.3 μm region. *Opt Commun* 2018;406:209–13.
- [126] Wang C, Peng QQ, Xin LL, Liu J. Active–passive pulse laser based on gold nanobipyramids at 1.3 μm wavelength. *Chin Opt Lett* 2019;17:020003.
- [127] Sun Y, Tu C, You Z, Liao J, Wang Y, Xu J. One-dimensional Bi₂Te₃ nanowire based broadband saturable absorber for passively Q-switched Yb-doped and Er-doped solid state lasers. *Opt Mater Express* 2018;8:165–74.
- [128] Shi RP, Bai Y, Qi M, et al. A passively mode-locked intracavity frequency doubled Nd:YVO₄ femtosecond green laser based on graphene. *Laser Phys Lett* 2013;11:025001.
- [129] Cihan C, Kocabas C, Demirbas U, Sennaroglu A. Graphene mode-locked femtosecond Alexandrite laser. *Opt Lett* 2018;43:3969–72.
- [130] Zhang Y, Lu D, Yu H, Zhang H. Low-dimensional saturable absorbers in the visible spectral region. *Adv Opt Mater* 2018;7:1800886.
- [131] Li N, Huang J, Xu B, et al. Direct generation of an ultrafast vortex beam in a CVD-graphene-based passively mode-locked Pr:LiYF₄ visible laser. *Photonics Res* 2019;7:1209–13.
- [132] Zhang Y, Yang Y, Zhang L, et al. Watt-level continuous-wave and passively Q-switched red lasers pumped by a single blue laser diode. *Chin Opt Lett* 2019;17:071402.
- [133] Zhang Y, Wang S, Yu H, et al. Atomic-layer molybdenum sulfide optical modulator for visible coherent light. *Sci Rep* 2015;5:11342.
- [134] Cheng Y, Peng J, Xu B, et al. Passive Q-switching of a diode-pumped Pr:LiYF₄ visible laser using WS₂ as saturable absorber. *IEEE Photonics J* 2016;8:1–6.
- [135] Su X, Zhang B, Wang Y, et al. Broadband rhenium disulfide optical modulator for solid-state lasers. *Photonics Res* 2018;6:498–505.
- [136] Cui N, Zhang F, Zhao Y, et al. The visible nonlinear optical properties and passively Q-switched laser application of a layered PtSe₂ material. *Nanoscale* 2020;12:1061–6.
- [137] Luo S, Yan X, Xu B, et al. Few-layer Bi₂Se₃-based passively Q-switched Pr:YLF visible lasers. *Opt Commun* 2018;406:61–5.
- [138] Cheng Y, Peng J, Xu B, Xu H, Cai Z, Weng J. Passive Q-switching of Pr:LiYF₄ orange laser at 604 nm using topological insulators Bi₂Se₃ as saturable absorber. *Opt Laser Technol* 2017;88:275–9.
- [139] Zhang R, Zhang Y, Yu H, et al. Broadband black phosphorus optical modulator in the spectral range from visible to mid-infrared. *Adv Opt Mater* 2015;3:1787–92.
- [140] Yang Q, Zhang X, Yang Z, et al. Broadband γ -graphyne saturable absorber for Q-switched solid-state laser. *Appl Phys Express* 2019;12:122006.
- [141] Yang Q, Zhang F, Zhang N, Zhang H. Few-layer MXene Ti₃C₂T_x (T=F, O, or OH) saturable absorber for visible bulk laser. *Opt Mater Express* 2019;9:1795–1802.
- [142] Wang Y, Zhang B, Yang H, et al. Passively mode-locked solid-state laser with absorption tunable graphene saturable absorber mirror. *J Lightwave Technol* 2019;37:2927–31.
- [143] Li Z, Zhang Y, Cheng C, Yu H, Chen F. 6.5 GHz Q-switched mode-locked waveguide lasers based on two-dimensional materials as saturable absorbers. *Opt Express* 2018;26:11321–30.
- [144] Canbaz F, Kakenov N, Kocabas C, Demirbas U, Sennaroglu A. Generation of sub-20-fs pulses from a graphene mode-locked laser. *Opt Express* 2017;25:2834–9.
- [145] Canbaz F, Kakenov N, Kocabas C, Demirbas U, Sennaroglu A. Graphene mode-locked Cr:LiSAF laser at 850 nm. *Opt Lett* 2015;40:4110–3.
- [146] Ma J, Huang H, Ning K, et al. Generation of 30 fs pulses from a diode-pumped graphene mode-locked Yb:CaAlO₄ laser. *Opt Lett* 2016;41:890–3.
- [147] Zhu H, Zhao L, Liu J, et al. Monolayer graphene saturable absorber with sandwich structure for ultrafast solid-state laser. *Opt Eng* 2015;55:081304.
- [148] Zhu H, Liu J, Jiang S, et al. Diode-pumped Yb,Y:CaF₂ laser mode-locked by monolayer graphene. *Opt Laser Technol* 2015;75:83–6.
- [149] Feng C, Liu J, Wang Y, Zheng L, Su L, Xu J. An Yb³⁺-doped Lu₂SiO₅ mode-locked laser using a reflective graphene oxide absorber. *Laser Phys* 2013;23:065802.
- [150] Cai W, Li Y, Zhu H, et al. Performance of chemical vapor deposition fabricated graphene absorber mirror in Yb³⁺:Sc₂SiO₅ mode-locked laser. *Opt Eng* 2014;53:126103.
- [151] Li L, Ren Z, Chen X, et al. Passively mode-locked radially polarized Nd-doped yttrium aluminum garnet laser based on graphene-based saturable absorber. *Appl Phys Express* 2013;6:082701.
- [152] Ma J, Xie G, Lv P, et al. Wavelength-versatile graphene-gold film saturable absorber mirror for ultra-broadband mode-locking of bulk lasers. *Sci Rep* 2014;4:5016.
- [153] Song Q, Wang G, Zhang B, et al. Passively Q-switched mode-locked dual-wavelength Nd:GYSGG laser using graphene oxide saturable absorber. *Opt Commun* 2015;347:64–7.
- [154] Xu SC, Man BY, Jiang SZ, et al. Watt-level passively Q-switched mode-locked YVO₄/Nd:YVO₄ laser operating at 1.06 μm using graphene as a saturable absorber. *Opt Laser Technol* 2014;56:393–7.
- [155] Cai W, Jiang S, Xu S, et al. Graphene saturable absorber for diode pumped Yb:Sc₂SiO₅ mode-locked laser. *Opt Laser Technol* 2015;65:1–4.
- [156] Xu SC, Man BY, Jiang SZ, et al. Sapphire-based graphene saturable absorber for long-time working femtosecond lasers. *Opt Lett* 2014;39:2707–10.
- [157] Xu SC, Man BY, Jiang SZ, et al. Direct growth of graphene on quartz substrate as saturable absorber for femtosecond solid-state laser. *Laser Phys Lett* 2014;11:085801.

- [158] Ugolotti E, Schmidt A, Petrov V, et al. Graphene mode-locked femtosecond Yb:KLuW laser. *Appl Phys Lett* 2012;101:161112.
- [159] Xu J, Li X, Wu Y, Hao X, He J, Yang K. Graphene saturable absorber mirror for ultra-fast-pulse solid-state laser. *Opt Lett* 2011;36:1948–50.
- [160] Cho WB, Kim JW, Lee HW, et al. High-quality, large-area monolayer graphene for efficient bulk laser mode-locking near 1.25 μm . *Opt Lett* 2011;36:4089–91.
- [161] Cafiso SDDD, Ugolotti E, Schmidt A, et al. Sub-100-fs Cr:YAG laser mode-locked by monolayer graphene saturable absorber. *Opt Lett* 2013;38:1745–7.
- [162] Baek IH, Lee HW, Bae S, et al. Efficient mode-locking of sub-70-fs Ti:sapphire laser by graphene saturable absorber. *Appl Phys Express* 2012;5:032701.
- [163] Xu J, Li X, He J, et al. Performance of large-area few-layer graphene saturable absorber in femtosecond bulk laser. *Appl Phys Lett* 2011;99:261107.
- [164] Tan WD, Su CY, Knize RJ, Xie GQ, Li LJ, Tang DY. Mode locking of ceramic Nd:yttrium aluminum garnet with graphene as a saturable absorber. *Appl Phys Lett* 2010;96:031106.
- [165] Xu J, Li X, He J, et al. Efficient graphene Q switching and mode locking of 1.34 μm neodymium lasers. *Opt Lett* 2012;37:2652–4.
- [166] Wang Y, Qu Z, Liu J, Tsang YH. Graphene oxide absorbers for watt-level high-power passive mode-locked Nd:GdVO₄ laser operating at 1 μm . *J Lightwave Technol* 2012;30:3259–62.
- [167] Zhu H, Cai W, Wei J, et al. 763fs Passively mode-locked Yb:Y₂SiO₅ laser with a graphene oxide absorber mirror. *Opt Laser Technol* 2015;68:120–3.
- [168] Ge P, Su LM, Liu J, et al. A 1.7-ps pulse mode-locked Yb³⁺:Sc₂SiO₅ laser with a reflective graphene oxide saturable absorber. *Chin Phys B* 2015;24:014207.
- [169] Feng C, Wang Y, Liu J, Tsang YH, Song Y, Yu Z. 3 W high-power laser passively mode-locked by graphene oxide saturable absorber. *Opt Commun* 2013;298:168–170.
- [170] Lou F, Cui L, Li Y-B, et al. High-efficiency femtosecond Yb:Gd₃Al_{0.5}Ga_{4.5}O₁₂ mode-locked laser based on reduced graphene oxide. *Opt Lett* 2013;38:4189–92.
- [171] Baylam I, Ozharar S, Kakenov N, Kocabas C, Sennaroglu A. Femtosecond pulse generation from a Ti³⁺:sapphire laser near 800 nm with voltage reconfigurable graphene saturable absorbers. *Opt Lett* 2017;42:1404–7.
- [172] Baylam I, Balci O, Kakenov N, Kocabas C, Sennaroglu A. Graphene-gold supercapacitor as a voltage controlled saturable absorber for femtosecond pulse generation. *Opt Lett* 2016;41:910–3.
- [173] Tao L, Huang X, He J, et al. Vertically standing PtSe₂ film: a saturable absorber for a passively mode-locked Nd:LuVO₄ laser. *Photonics Res* 2018;6:750–5.
- [174] Hou J, Zhao G, Wu Y, He J, Hao X. Femtosecond solid-state laser based on tungsten disulfide saturable absorber. *Opt Express* 2015;23:27292–8.
- [175] Tang W, Zhao J, Yang K, et al. High peak power sub-nanosecond pulsed Nd:Lu_{0.15}Y_{0.85}VO₄ laser with WS₂ saturable absorber and EO modulator. *Opt Mater Express* 2017;7:1180–7.
- [176] Sun XL, Shi BN, Wang HY, et al. Optical properties of 2D 3R phase niobium disulfide and its applications as a saturable absorber. *Adv Opt Mater* 2019:1901181.
- [177] Zhang B, Lou F, Zhao R, et al. Exfoliated layers of black phosphorus as saturable absorber for ultrafast solid-state laser. *Opt Lett* 2015;40:3691–4.
- [178] Su X, Wang Y, Zhang B, et al. Femtosecond solid-state laser based on a few-layered black phosphorus saturable absorber. *Opt Lett* 2016;41:1945–8.
- [179] Sun X, Nie H, He J, et al. Passively mode-locked 1.34 μm bulk laser based on few-layer black phosphorus saturable absorber. *Opt Express* 2017;25:20025–32.
- [180] Tang W, Zhao J, Li T, et al. High-peak-power mode-locking pulse generation in a dual-loss-modulated laser with BP-SA and EOM. *Opt Lett* 2017;42:4820–3.
- [181] Wang Y, Sung W, Su X, et al. Ultralow saturation intensity topological insulator saturable absorber for gigahertz mode-locked solid-state lasers. *IEEE Photonics J* 2018;10:1–10.
- [182] Sun X, Zhang B, Li Y, et al. Tunable ultrafast nonlinear optical properties of graphene/MoS₂ van der Waals heterostructures and their application in solid-state bulk lasers. *ACS nano* 2018;12:11376–85.
- [183] Zhao G, Hou J, Wu Y, He J, Hao X. Preparation of 2D MoS₂/Graphene heterostructure through a monolayer intercalation method and its application as an optical modulator in pulsed laser generation. *Adv Opt Mater* 2015;3:937–42.
- [184] Sun X, Zhang B, Yan B, et al. Few-layer Ti₃C₂T_x (T=O, OH, or F) saturable absorber for a femtosecond bulk laser. *Opt Lett* 2018;43:3862–5.
- [185] Sun X, He J, Shi B, et al. Alpha-phase indium selenide saturable absorber for a femtosecond all-solid-state laser. *Opt Lett* 2019;44:699–702.
- [186] Geim AK, Grigorieva IV. Van der Waals heterostructures. *Nature* 2013;499:419–25.
- [187] Jiang Y, Miao L, Jiang G, et al. Broadband and enhanced nonlinear optical response of MoS₂/graphene nanocomposites for ultrafast photonics applications. *Sci Rep* 2015;5:16372.
- [188] Sun Z, Chu H, Li Y, Zhao S, Li G, Li D. Theoretical investigation on electronic and optical properties of the graphene–MoSe₂–graphene sandwich heterostructure. *Mater Design* 2019;183:108129.
- [189] Liu J, Wang YG, Qu ZS, Zheng LH, Su LB, Xu J. Graphene oxide absorber for 2 μm passive mode-locking Tm:YAlO₃ laser. *Laser Phys Lett* 2011;9:15–9.
- [190] Ma J, Xie GQ, Lv P, et al. Graphene mode-locked femtosecond laser at 2 μm wavelength. *Opt Lett* 2012;37:2085–7.
- [191] Cizmeciyan MN, Kim JW, Bae S, Hong BH, Rothermund F, Sennaroglu A. Graphene mode-locked femtosecond Cr:ZnSe laser at 2500 nm. *Opt Lett* 2013;38:341–3.
- [192] Lagatsky AA, Sun Z, Kulmala TS, et al. 2 μm solid-state laser mode-locked by single-layer graphene. *Appl Phys Lett* 2013;102:013113.
- [193] Xie GQ, Ma J, Lv P, et al. Graphene saturable absorber for Q-switching and mode locking at 2 μm wavelength [invited]. *Opt Mater Express* 2012;2:878–83.
- [194] Wang Y, Chen W, Mero M, et al. Sub-100 fs Tm:MgWO₄ laser at 2017 nm mode locked by a graphene saturable absorber. *Opt Lett* 2017;42:3076–9.
- [195] Cho WB, Choi SY, Zhu C, et al. Graphene mode-locked femtosecond Cr²⁺:ZnS laser with ~300 nm tuning range. *Opt Express* 2016;24:20774–80.
- [196] Tolstik N, Sorokin E, Sorokina IT. Graphene mode-locked Cr:ZnS laser with 41 fs pulse duration. *Opt Express* 2014;22:5564–71.
- [197] Tolstik N, Pospischil A, Sorokin E, Sorokina IT. Graphene mode-locked Cr:ZnS chirped-pulse oscillator. *Opt Express* 2014;22:7284–9.

- [198] Wan H, Cai W, Wang F, Jiang S, Xu S, Liu J. High-quality monolayer graphene for bulk laser mode-locking near 2 μm . *Opt Quantum Electron* 2016;48:11.
- [199] Li L, Zhou L, Li T, et al. Passive mode-locking operation of a diode-pumped Tm:YAG laser with a MoS_2 saturable absorber. *Opt Laser Technol* 2020;124:105986.
- [200] Bai Y, Qi M, Wang S, et al. CW mode-locked 1.908 μm Tm:LiYF₄ Slab laser based on an output-coupling graphene saturable absorber mirror. *Appl Phys Express* 2013;6:102701.
- [201] Ma J, Xie G, Zhang J, Yuan P, Tang D, Qian L. Passively mode-locked Tm:YAG ceramic laser based on graphene. *IEEE J Sel Top Quant* 2015;21:50–5.
- [202] Liu J, Zhang F, Zhang Z, Liu J, Zhang H, Su L. Watt-level continuous-wave and high-repetition-rate mid-infrared lasers based on a Er^{3+} -doped $\text{Ca}_{0.8}\text{Sr}_{0.2}\text{F}_2$ crystal. *Appl Phys Express* 2019;12:115505.
- [203] Chu H, Zhao S, Li T, et al. Dual-wavelength passively Q-switched Nd:Mg:LiTaO₃ laser with a monolayer graphene as saturable absorber. *IEEE J Sel Top Quant* 2015;21:343–7.
- [204] Song Q, Wang G, Zhang B, et al. Diode-pumped passively dual-wavelength Q-switched Nd:GSGG laser using graphene oxide as the saturable absorber. *Appl Opt* 2015;54:2688–92.
- [205] Xu B, Wang Y, Cheng Y, Yang H, Xu H, Cai Z. Nanosecond pulse generation in a passively Q-switched Nd:GGG laser at 1331 nm by CVD graphene saturable absorber. *J Optics* 2015;17:105501.
- [206] Serres JM, Jambunathan V, Mateos X, et al. Graphene Q-switched compact Yb:YAG laser. *IEEE Photonics J* 2015;7:1–7.
- [207] Li L, Zheng X, Jin C, et al. High repetition rate Q-switched radially polarized laser with a graphene-based output coupler. *Appl Phys Lett* 2014;105:221103.
- [208] Zhou R, Tang P, Chen Y, et al. Large-energy, narrow-bandwidth laser pulse at 1645 nm in a diode-pumped Er:YAG solid-state laser passively Q-switched by a monolayer graphene saturable absorber. *Appl Opt* 2014;53:254–8.
- [209] Matía-Hernando P, Guerra JM, Weigand R. An Nd:YLF laser Q-switched by a monolayer-graphene saturable-absorber mirror. *Laser Phys* 2013;23:025003.
- [210] Yang XF, Wang Y, Huang HT, et al. A passively Q-switched Er:LuYAG laser with a graphene saturable absorber. *Laser Phys Lett* 2013;10:105810.
- [211] Men S, Liu Z, Zhang X, et al. A graphene passively Q-switched Nd:YAG ceramic laser at 1123 nm. *Laser Phys Lett* 2013;10:035803.
- [212] Zhao Y, Li X, Xu M, et al. Dual-wavelength synchronously Q-switched solid-state laser with multi-layered graphene as saturable absorber. *Opt Express* 2013;21:3516–22.
- [213] Gao C, Wang R, Zhu L, et al. Resonantly pumped 1.645 μm high repetition rate Er:YAG laser Q-switched by a graphene as a saturable absorber. *Opt Lett* 2012;37:632–4.
- [214] Li X, Xu J, Wu Y, He J, Hao X. Large energy laser pulses with high repetition rate by graphene Q-switched solid-state laser. *Opt Express* 2011;19:9950–5.
- [215] Wang YG, Chen HR, Wen XM, Hsieh WF, Tang J. A highly efficient graphene oxide absorber for Q-switched Nd: GdVO₄ lasers. *Nanotechnology* 2011;22:455203.
- [216] Choudhary A, Dhingra S, D'Urso B, Kannan P, Shepherd DP. Graphene Q-switched mode-locked and Q-switched ion-exchanged waveguide lasers. *IEEE Photonics Tech L* 2015;27:646–9.
- [217] Gao X, Li S, Li T, Li G, Ma H. g-C₃N₄ as a saturable absorber for the passively Q-switched Nd:LLF laser at 1.3 μm . *Photonics Res* 2017;5:33–6.
- [218] Wang X, Xu J, Gao S, et al. Dual-wavelength passively Q-switched bulk laser using MoS_2 /graphene heterojunction. *Mater Res Bull* 2017;89:63–7.
- [219] Dou X, Yang J, Zhu M, et al. Watt-level passively Q-switched Yb:LuPO₄ miniature crystal laser with few-layer MoS_2 saturable absorber. *Opt Express* 2018;26:14232–40.
- [220] Dou X, Yang J, Zhu M, et al. High-gain Yb:LuPO₄ microchip laser passively Q-switched by MoS_2 or WS_2 deposited on a sapphire etalon output coupler. *Opt Mater Express* 2018;8:2542–9.
- [221] Zheng Q, Wang J, Wang Y, Chen Z. Novel molybdenum disulfide Langmuir Blodgett thin film as a saturable absorber for a passively Q-switched Nd:GdVO₄ laser. *Opt Mater Express* 2018;8:3176–83.
- [222] Lin H, Zhu W, Xiong F, Cai L. MoS_2 -based passively Q-switched diode-pumped Nd:YAG laser at 946 nm. *Opt Laser Technol* 2017;91:36–9.
- [223] Xia H, Li M, Li T, Zhao S, Li G, Yang K. Few-layered MoS_2 as a saturable absorber for a passively Q-switched Er:YAG laser at 1.6 μm . *Appl Opt* 2017;56:2766–70.
- [224] Liu H, Sun Z, Wang X, Wang Y, Cheng G. Several nanosecond Nd:YVO₄ lasers Q-switched by two dimensional materials: tungsten disulfide, molybdenum disulfide, and black phosphorous. *Opt Express* 2017;25:6244–52.
- [225] Qiao J, Zhao S, Yang K, et al. Hybrid Q-switched laser with MoS_2 saturable absorber and AOM driven sub-nanosecond KTP-OPO. *Opt Express* 2017;25:4227–38.
- [226] Wang S, Yu H, Zhang H, et al. Broadband few-layer MoS_2 saturable absorbers. *Adv Mater* 2014;26:3538–44.
- [227] Lou F, Zhao R, He J, et al. Nanosecond-pulsed, dual-wavelength, passively Q-switched ytterbium-doped bulk laser based on few-layer MoS_2 saturable absorber. *Photonics Res* 2015;3:A25–9.
- [228] Serres JM, Loiko P, Mateos X, et al. MoS_2 saturable absorber for passive Q-switching of Yb and Tm microchip lasers. *Opt Mater Express* 2016;6:3262–73.
- [229] Cheng C, Liu H, Shang Z, et al. Femtosecond laser written waveguides with MoS_2 as saturable absorber for passively Q-switched lasing. *Opt Mater Express* 2016;6:367–73.
- [230] Xu B, Cheng Y, Wang Y, et al. Passively Q-switched Nd:YAlO₃ nanosecond laser using MoS_2 as saturable absorber. *Opt Express* 2014;22:28934–40.
- [231] Sun Z, Chu H, Li Y, et al. Optical properties of MoSe_2 nanosheets: characterization, simulation and application for Q-switching. *Opt Mater Express* 2019;9:3494–503.
- [232] Dong L, Li D, Pan H, et al. Pulse characteristics from a MoSe_2 Q-switched Nd:GdVO₄ laser at 1.3 μm . *Appl Opt* 2019;58:8194–9.
- [233] Peng Z, Ma Y, Peng F, et al. Diode-pumped passively Q-switched Nd:GdYTaO₄ laser based on two-dimensional WS_2 nanosheet. *Opt Laser Technol* 2019;109:319–22.
- [234] Tang W, Wang Y, Yang K, et al. 1.36 W Passively Q-Switched YVO₄/Nd:YVO₄ Laser With a WS_2 Saturable Absorber. *IEEE Photonics Tech L* 2017;29:470–3.
- [235] Dou X, Ma Y, Zhu M, et al. Multi-watt sub-30 ns passively Q-switched Yb:LuPO₄/ WS_2 miniature laser operating under high output couplings. *Opt Lett* 2018;43:3666–9.

- [236] Qiao J, Zhao S, Yang K, et al. Sub-nanosecond KTP-OPO pumped by a hybrid Q-switched laser with WS_2 saturable absorber and AOM. *Opt Mater Express* 2017;7:3998–4009.
- [237] Tang CY, Cheng PK, Tao L, et al. Passively Q-switched Nd:YVO₄ laser using WS_2 saturable absorber fabricated by radio frequency magnetron sputtering deposition. *J Lightwave Technol* 2017;35:4120–4.
- [238] Wang X, Wang Y, Duan L, Li L, Sun H. Passively Q-switched Nd:YAG laser via a WS_2 saturable absorber. *Opt Commun* 2016;367:234–8.
- [239] Gao YJ, Zhang BY, Song Q, et al. Dual-wavelength passively Q-switched Nd:GSGG laser by tungsten disulfide saturable absorber. *Appl Opt* 2016;55:4929–32.
- [240] Sun Y, Bai Y, Li D, et al. 946 nm Nd:YAG double Q-switched laser based on monolayer WSe_2 saturable absorber. *Opt Express* 2017;25:21037–48.
- [241] Lin M, Peng Q, Hou W, Fan X, Liu J. 1.3 μm Q-switched solid-state laser based on few-layer ReS_2 saturable absorber. *Opt Laser Technol* 2019;109:90–3.
- [242] Wang M, Wang Z, Xu X, Duan S, Du C. Tin diselenide-based saturable absorbers for eye-safe pulse lasers. *Nanotechnology* 2019;30:265703.
- [243] Ma Y, Tian K, Dou X, et al. Passive Q-switching induced by few-layer MoTe_2 in an Yb:YCOB microchip laser. *Opt Express* 2018;26:25147–55.
- [244] Lu D, Pan Z, Zhang R, et al. Passively Q-switched ytterbium-doped ScBO_3 laser with black phosphorus saturable absorber. *Opt Eng* 2016;55:081312.
- [245] Liu Q, Zhang B, Qi S, et al. Integration of helicity-control and pulse-modulation for vortex laser based on a black phosphorus plate. *Opt Express* 2016;24:30031–7.
- [246] Ma J, Lu S, Guo Z, et al. Few-layer black phosphorus based saturable absorber mirror for pulsed solid-state lasers. *Opt Express* 2015;23:22643–8.
- [247] Wang X, Wang Z, Wang Y, Li L, Yang G, Li J. Watt-level high-power passively Q-switched laser based on a black phosphorus solution saturable absorber. *Chin Opt Lett* 2017;15:011402.
- [248] Kong L, Qin Z, Xie G, et al. Black phosphorus as broadband saturable absorber for pulsed lasers from 1 μm to 2.7 μm wavelength. *Laser Phys Lett* 2016;13:045801.
- [249] Han S, Zhang F, Wang M, et al. Black phosphorus based saturable absorber for Nd-ion doped pulsed solid state laser operation. *Indian J Phys* 2017;91:439–43.
- [250] Sun X, Nie H, He J, et al. Passively Q-switched Nd:GdVO₄ 1.3 μm laser with few-layered black phosphorus saturable absorber. *IEEE J Sel Top Quant* 2018;24:1–5.
- [251] Guo L, Li T, Zhang S, et al. Black phosphorus saturable absorber for Q-switched Er:YAG laser at 1645 nm. *Opt Laser Technol* 2018;100:225–9.
- [252] Yu H, Zhang H, Wang Y, et al. Topological insulator as an optical modulator for pulsed solid-state lasers. *Laser Photonics Rev* 2013;7:L77–83.
- [253] Hu M, Liu J, Tian J, Dou Z, Song Y. Generation of Q-switched pulse by Bi_2Se_3 topological insulator in Yb:KGW laser. *Laser Phys Lett* 2014;11:115806.
- [254] Wang B, Yu H, Zhang H, et al. Topological insulator simultaneously Q-switched dual-wavelength Nd:Lu₂O₃ Laser. *IEEE Photonics J* 2014;6:1–7.
- [255] Xu B, Wang Y, Peng J, et al. Topological insulator Bi_2Se_3 based Q-switched Nd:LiYF₄ nanosecond laser at 1313 nm. *Opt Express* 2015;23:7674–80.
- [256] Jia F, Chen H, Liu P, Huang Y, Luo Z. Nanosecond-pulsed, dual-wavelength passively Q-switched c-cut Nd:YVO₄ laser using a few-layer Bi_2Se_3 saturable absorber. *IEEE J Sel Top Quant* 2015;21:369–74.
- [257] Yan B, Zhang B, Nie H, et al. Broadband 1T-titanium selenide-based saturable absorbers for solid-state bulk lasers. *Nanoscale* 2018;10:20171–7.
- [258] Yang J, Tian K, Li Y, et al. Few-layer Bi_2Te_3 : an effective 2D saturable absorber for passive Q-switching of compact solid-state lasers in the 1- μm region. *Opt Express* 2018;26:21379–89.
- [259] Sun Y, Lee C, Xu J, et al. Passively Q-switched tri-wavelength $\text{Yb}^{3+}:\text{GdAl}_3(\text{BO}_3)_4$ solid-state laser with topological insulator Bi_2Te_3 as saturable absorber. *Photonics Res* 2015;3:A97–101.
- [260] Xu J, Sun Y, He J, et al. Ultrasensitive nonlinear absorption response of large-size topological insulator and application in low-threshold bulk pulsed lasers. *Sci Rep* 2015;5:14856.
- [261] Lin Y, Lee P, Xu J, et al. High-pulse-energy topological insulator Bi_2Te_3 -based passive Q-switched solid-state laser. *IEEE Photonics J* 2016;8:1–10.
- [262] Tang P, Zhang X, Zhao C, et al. Topological insulator Bi_2Te_3 saturable absorber for the passive Q-switching operation of an in-band pumped 1645-nm Er-YAG ceramic laser. *IEEE Photonics J* 2013;5:1500707.
- [263] Huang B, Tang P, Yi J, et al. Resonantly pumped Er:YAG laser Q-switched by topological insulator nanosheets at 1617 nm. *Opt Mater* 2017;71:74–7.
- [264] Li P, Zhang G, Zhang H, et al. Q-switched mode-locked Nd:YVO₄ laser by topological insulator Bi_2Te_3 saturable absorber. *IEEE Photonics Tech L* 2014;26:1912–5.
- [265] Sun Y, Lee C, Wang Y, et al. Passively Q-switched wavelength-tunable bulk laser using topological insulator at 1 μm . *IEEE Photonics Tech L* 2016;28:2764–7.
- [266] Yang J, Ma Y, Tian K, et al. High-power passive Q-switching performance of a Yb:YCa₄O(BO₃)₃ laser with a few-layer Bi_2Te_3 topological insulator as a saturable absorber. *Opt Mater Express* 2018;8:3146–54.
- [267] Feng X, Lin Y, Yu X, et al. Continuous-wave and Q-switched Nd:BGO lasers based on bismuth nanosheets absorber. *Appl Opt* 2019;58:6545–8.
- [268] Zhang Z, Liu J, Hao Q, Liu J. Sensitive saturable absorber and optical switch of epsilon-near-zero medium. *Appl Phys Express* 2019;12:065504.
- [269] Wang B, Song Q, Gao C, et al. Compact passively Q-switched Nd:GGG laser with antimony telluride-graphene oxide as saturable absorber. *Opt Laser Technol* 2018;105:41–4.
- [270] Tan Y, Liu X, He Z, et al. Tuning of interlayer coupling in large-area graphene/ WSe_2 van der Waals heterostructure via ion irradiation: optical evidences and photonic applications. *ACS Photonics* 2017;4:1531–8.
- [271] Wang C, Peng Q, Fan X, et al. MXene $\text{Ti}_3\text{C}_2\text{T}_x$ saturable absorber for pulsed laser at 1.3 μm . *Chin Phys B* 2018;27:094214.
- [272] Feng X, Ding B, Liang W, et al. MXene $\text{Ti}_3\text{C}_2\text{T}_x$ absorber for a 1.06 μm passively Q-switched ceramic laser. *Laser Phys Lett* 2018;15:085805.
- [273] Pan H, Cao L, Chu H, et al. Broadband nonlinear optical response of InSe nanosheets for the pulse generation from 1 to 2 μm . *ACS Appl Mater Inter* 2019;11:48281–9.

- [274] Yu H, Chen X, Zhang H, et al. Large energy pulse generation modulated by graphene epitaxially grown on silicon carbide. *ACS Nano* 2010;4:7582–6.
- [275] Wang Q, Teng H, Zou Y, et al. Graphene on SiC as a Q-switcher for a 2 μm laser. *Opt Lett* 2012;37:395–7.
- [276] Zhao T, Wang Y, Chen H, Shen D. Graphene passively Q-switched Ho:YAG ceramic laser. *Appl Phys B* 2014;116:947–50.
- [277] Wang Z, Chen X, He J, et al. Graphene Q-switched Cr:ZnSe laser. *IEEE J Quantum Electron* 2015;51:1–5.
- [278] Li C, Liu J, Jiang S, et al. 2.8 μm passively Q-switched Er:CaF₂ diode-pumped laser. *Opt Mater Express* 2016;6:1570–5.
- [279] Serres JM, Loiko P, Mateos X, et al. Tm:KLu(WO₄)₂ microchip laser Q-switched by a graphene-based saturable absorber. *Opt Express* 2015;23:14108–13.
- [280] Uehara H, Tokita S, Kawanaka J, Konishi D, Murakami M, Yasuhara R. A passively Q-switched compact Er:Lu₂O₃ ceramics laser at 2.8 μm with a graphene saturable absorber. *Appl Phys Express* 2019;12:022002.
- [281] Feng C, Liu D, Liu J. Graphene oxide saturable absorber on golden reflective film for Tm:YAP Q-switched mode-locking laser at 2 μm . *J Mod Optic* 2012;59:1825–8.
- [282] Zhang C, Liu J, Fan X, et al. Compact passive Q-switching of a diode-pumped Tm,Y:CaF₂ laser near 2 μm . *Opt Laser Technol* 2018;103:89–92.
- [283] Zu Y, Zhang C, Wu Y, Liu J, Wang Y, Liu J. Graphene oxide for diode-pumped Tm:YLF passively Q-switched laser at 2 μm . *Chin Opt Lett* 2018;16:020013.
- [284] Fan M, Li T, Li G, et al. Graphitic C₃N₄ as a new saturable absorber for the mid-infrared spectral range. *Opt Lett* 2017;42:286–9.
- [285] Li L, Yang X, Zhou L, et al. Active/passive Q-switching operation of 2 μm Tm, Ho:YAP laser with an acousto-optical Q-switch/MoS₂ saturable absorber mirror. *Photonics Res* 2018;6:614–9.
- [286] Kong LC, Xie GQ, Yuan P, et al. Passive Q-switching and Q-switched mode-locking operations of 2 μm Tm:CLNGG laser with MoS₂ saturable absorber mirror. *Photonics Res* 2015;3:A47–50.
- [287] Lan J, Zhang X, Zhou Z, et al. Passively Q-switched Tm:CaYAlO₄ laser using a MoS₂ saturable absorber. *IEEE Photonics Tech L* 2017;29:515–8.
- [288] Luan C, Zhang X, Yang K, et al. High-peak power passively Q-switched 2- μm laser with MoS₂ saturable absorber. *IEEE J Sel Top Quant* 2017;23:66–70.
- [289] Fan M, Li T, Zhao S, et al. Watt-level passively Q-switched Er:Lu₂O₃ laser at 2.84 μm using MoS₂. *Opt Lett* 2016;41:540–3.
- [290] Ge P, Liu J, Jiang S, Xu Y, Man B. Compact Q-switched 2 μm Tm:GdVO₄ laser with MoS₂ absorber. *Photonics Res* 2015;3:256–9.
- [291] Su X, Nie H, Wang Y, et al. Few-layered ReS₂ as saturable absorber for 2.8 μm solid state laser. *Opt Lett* 2017;42:3502–05.
- [292] Fan M, Li T, Zhao J, et al. Continuous wave and ReS₂ passively Q-switched Er:SrF₂ laser at ~3 μm . *Opt Lett* 2018;43:1726–9.
- [293] Yao Y, Cui N, Wang Q, et al. Highly efficient continuous-wave and ReSe₂ Q-switched ~3 μm dual-wavelength Er:YAP crystal lasers. *Opt Lett* 2019;44:2839–42.
- [294] Guan X, Wang J, Zhang Y, et al. Self-Q-switched and wavelength-tunable tungsten disulfide-based passively Q-switched Er:Y₂O₃ ceramic lasers. *Photonics Res* 2018;6:830–6.
- [295] Luan C, Yang K, Zhao J, et al. WS₂ as a saturable absorber for Q-switched 2 micron lasers. *Opt Lett* 2016;41:3783–6.
- [296] Yan Z, Li G, Li T, et al. Passively Q-switched Ho,Pr:LiLuF₄ laser at 2.95 μm using MoSe₂. *IEEE Photonics J* 2017;9:1–7.
- [297] Liu X, Yang K, Zhao S, et al. High repetition rate all-solid-state pulsed 2 μm laser based on selenide molybdenum saturable absorber. *IEEE J Sel Top Quant* 2017;24:1–6.
- [298] Nie H, Sun X, Zhang B, et al. Few-layer TiSe₂ as a saturable absorber for nanosecond pulse generation in 2.95 μm bulk laser. *Opt Lett* 2018;43:3349–52.
- [299] Yan Z, Li T, Zhao J, et al. Passively Q-switched 2.85 μm Er:Lu₂O₃ laser with WSe₂. *Laser Phys Lett* 2018;15:085802.
- [300] Liu X, Zhang S, Yan Z, et al. WSe₂ as a saturable absorber for a passively Q-switched Ho,Pr:LLF laser at 2.95 μm . *Opt Mater Express* 2018;8:1213–20.
- [301] Yan B, Zhang B, Nie H, et al. Bilayer platinum diselenide saturable absorber for 2.0 μm passively Q-switched bulk lasers. *Opt Express* 2018;26:31657–63.
- [302] Yan Z, Li T, Zhao S, et al. MoTe₂ saturable absorber for passively Q-switched Ho,Pr:LiLuF₄ laser at ~3 μm . *Opt Laser Technol* 2018;100:261–4.
- [303] Yan B, Zhang B, Nie H, et al. High-power passively Q-switched 2.0 μm all-solid-state laser based on a MoTe₂ saturable absorber. *Opt Express* 2018;26:18505–12.
- [304] Zhang Y, Wang J, Guan X, et al. MoTe₂-based broadband wavelength tunable eye-safe pulsed laser source at 1.9 μm . *IEEE Photonics Tech L* 2018;30:1890–3.
- [305] Chen L, Li X, Zhang H, Xia W. Passively Q-switched 1.989 μm all-solid-state laser based on a WTe₂ saturable absorber. *Appl Opt* 2018;57:10239–42.
- [306] Yan Z, Li T, Zhao J, et al. Tungsten ditelluride for a nanosecond Ho,Pr:LiLuF₄ laser at 2.95 μm . *Laser Phys Lett* 2018;15:045801.
- [307] Liu X, Yang K, Zhao S, et al. High-power passively Q-switched 2 μm all-solid-state laser based on a Bi₂Te₃ saturable absorber. *Photonics Res* 2017;5:461–6.
- [308] Qiao J, Zhao S, Yang K, et al. High-quality 2- μm Q-switched pulsed solid-state lasers using spin-coating-corededuction approach synthesized Bi₂Te₃ topological insulators. *Photonics Res* 2018;6:314–20.
- [309] Chu Z, Liu J, Guo Z, Zhang H. 2 μm passively Q-switched laser based on black phosphorus. *Opt Mater Express* 2016;6:2374–9.
- [310] Zhang H, He J, Wang Z, et al. Dual-wavelength, passively Q-switched Tm:YAP laser with black phosphorus saturable absorber. *Opt Mater Express* 2016;6:2328–35.
- [311] Xie Y, Kong L, Qin Z, Xie G, Zhang J. Black phosphorus-based saturable absorber for Q-switched Tm:YAG ceramic laser. *Opt Eng* 2016;55:081307.
- [312] Wang Z, Zhao R, He J, et al. Multi-layered black phosphorus as saturable absorber for pulsed Cr:ZnSe laser at 2.4 μm . *Opt Express* 2016;24:1598–1603.
- [313] Fan M, Li T, Zhao S, et al. Multilayer black phosphorus as saturable absorber for an Er:Lu₂O₃ laser at ~3 μm . *Photonics Res* 2016;4:181–6.
- [314] Liu J, Liu J, Guo Z, et al. Dual-wavelength Q-switched Er:SrF₂ laser with a black phosphorus absorber in the mid-infrared region. *Opt Express* 2016;24:30289–95.

- [315] Li C, Liu J, Guo Z, et al. Black phosphorus saturable absorber for a diode-pumped passively Q-switched Er:CaF₂ mid-infrared laser. *Opt Commun* 2018;406:158–62.
- [316] Liu J, Huang H, Zhang F, et al. Bismuth nanosheets as a Q-switcher for a mid-infrared erbium-doped SrF₂ laser. *Photonics Res* 2018;6:762–7.
- [317] You Z, Sun Y, Sun D, et al. High performance of a passively Q-switched mid-infrared laser with Bi₂Te₃/graphene composite SA. *Opt Lett* 2017;42:871–4.
- [318] Zhang C, Zhang F, Fan X, Yang J, Liu J, Zhang H. Passively Q-switched operation of in-band pumped Ho:YLF based on Ti₃C₂T_x MXene. *Infrared Phys Technol* 2019;103:103076.
- [319] Hao Q, Liu J, Zhang Z, et al. Mid-infrared Er:CaF₂-SrF₂ bulk laser Q-switched by MXene Ti₃C₂T_x absorber. *Appl Phys Express* 2019;12:085506.
- [320] Zu Y, Zhang C, Guo X, et al. A solid-state passively Q-switched Tm,Gd:CaF₂ laser with a Ti₃C₂T_x MXene absorber near 2 μm. *Laser Phys Lett* 2018;16:015803.
- [321] Li L, Zhou L, Yang X, et al. A 2.22-W passively Q-switched Tm³⁺-doped laser with a TiC₂ saturable absorber. *IEEE Photonics J* 2019;11:1–7.
- [322] Yan B, Zhang B, He J, et al. Ternary chalcogenide Ta₂NiS₅ as a saturable absorber for a 1.9 μm passively Q-switched bulk laser. *Opt Lett* 2019;44:451–4.
- [323] Loiko P, Bogusławski J, Serres JM, et al. Sb₂Te₃ thin film for the passive Q-switching of a Tm:GdVO₄ laser. *Opt Mater Express* 2018;8:1723–32.
- [324] Ma C, Wang C, Gao B, Adams J, Wu G, Zhang H. Recent progress in ultrafast lasers based on 2D materials as a saturable absorber. *Appl Phys Rev* 2019;6:041304.
- [325] Purdie DG, Popa D, Wittwer VJ, et al. Few-cycle pulses from a graphene mode-locked all-fiber laser. *Appl Phys Lett* 2015;106:253101.
- [326] Bogusławski J, Soboń G, Zybała R, et al. Investigation on pulse shaping in fiber laser hybrid mode-locked by Sb₂Te₃ saturable absorber. *Opt Express* 2015;23:29014–23.
- [327] Liu W, Pang L, Han H, et al. Tungsten disulfide saturable absorbers for 67 fs mode-locked erbium-doped fiber lasers. *Opt Express* 2017;25:2950–9.
- [328] Jin X, Hu G, Zhang M, et al. 102 fs pulse generation from a long-term stable, inkjet-printed black phosphorus-mode-locked fiber laser. *Opt Express* 2018;26:12506–13.
- [329] Zhao J, Zheng Z, Ouyang D, et al. 70-W graphene-oxide passively Q-switched thulium-doped double-clad fiber laser. *IEEE J Sel Top Quant* 2017;23:13–9.
- [330] Chen H, Chen Y, Yin J, Zhang X, Guo T, Yan P. High-damage-resistant tungsten disulfide saturable absorber mirror for passively Q-switched fiber laser. *Opt Express* 2016;24:16287–96.