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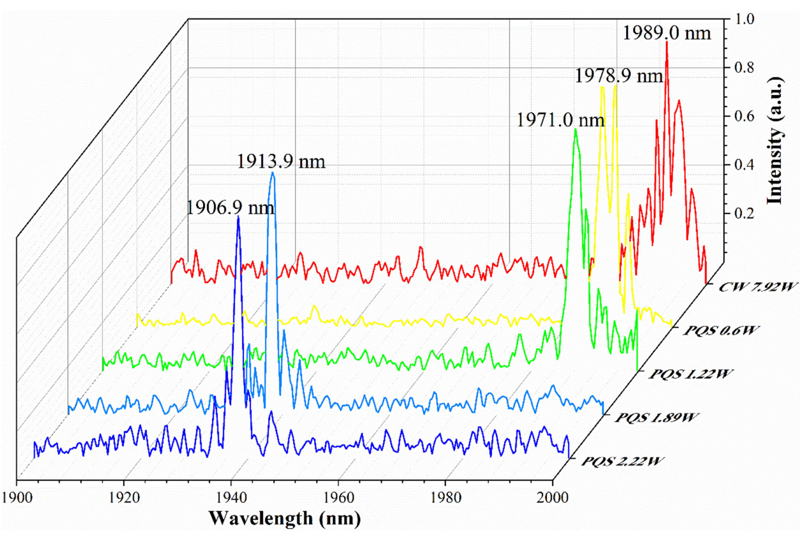

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A 2.22-W Passively Q-Switched Tm^{3+}-Doped Laser With a TiC_2 Saturable Absorber

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Abstract: A TiC_2 solution was prepared by using an ultrasonic decomposition and nonlinear saturable absorption characteristics at about 2 μm were evaluated. A passively Q-switched (PQS) Tm:YAP laser was developed using the TiC_2 material as a saturable absorber, and a 2220-mW average output power with a 579-ns pulse duration at 255 kHz was achieved in PQS mode, corresponding to 8.4% optical conversion efficiency. Also, an 8.7-μJ per pulse energy and a 15.0-W peak power were achieved from this PQS Tm:YAP laser. Furthermore, quality factors of vertical and horizontal beams from the Tm:YAP laser were less than 1.2 under two different modes of operation.

Index Terms: Passively Q-switched, beam quality factors, TiC_2 saturable absorber, lasers.

1. Introduction

Ultra-Short pulsed solid-state lasers operated at 2 μm wavelength coverage, offer strong absorption in human tissue and water, and have been applied in material processing, medical diagnostics, environmental protection surgery, and so on [1]–[4]. PQS technology based on SAs has been proved to be an inexpensive, compact-structured and efficient way in which to achieve microsecond (μs) or nanosecond (ns) pulsing in a laser, and the SAs play an important role in governing the pulse width therein [5], [6]. Compared with traditional SA materials (mainly ion-doped crystals and

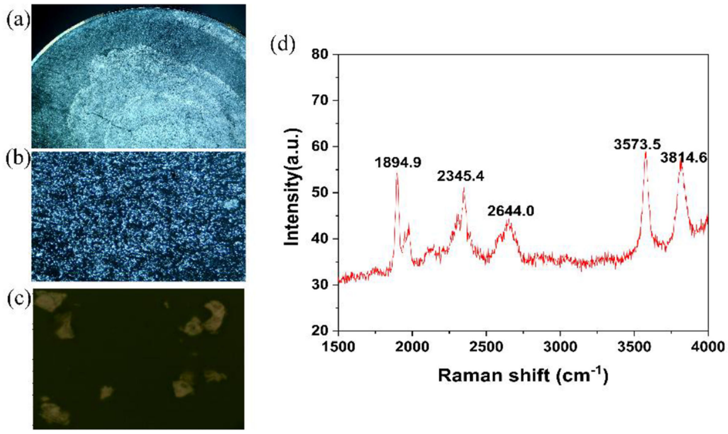

Fig. 1. The preparation and representation of TiC_2 SA. (a) A mirror with the TiC_2 layers. (b) A simple structure of TiC_2 layers and its effects on the appearance of the CaF_2 mirror. (c) The refined structure of TiC_2 layers. (d) The Raman spectra of the TiC_2 layers at 1500–4000 cm^{-1}.

semiconductor saturable absorber mirrors), many new type two-dimensional (2D) materials with wide bandwidth, involving simple processes, at low cost, have attracted significant attention because of their large modulation depth, highly non-linear effects, and broadband saturable absorption: these may be used as SAs for 1–3 μm ultrashort pulsed laser applications [5]–[8].

To date, many 2D materials with good optical performance, for example, graphene, black phosphorus (BP), boron nitride (BN), tungsten disulfide (WS_2), molybdenum disulfide (MoS_2), and so on, have been demonstrated in PQS or passively mode-locked laser in the 2 μm waveband range [7]–[10]. Also, some new and conventional 2D materials, have yet to be proved in PQS or passively mode-locked laser applications, which raised concern about their ability to achieve higher non-linear and other optical effects. 2D TiC_2 is found to be stable (both dynamically and thermally), and this has given rise to a new type of 2D metal carbides with exceptional properties [11]. The optical properties of TiC_2, including its absorption spectra, and reflectivity and energy-loss spectra, have been calculated, and the energy level of the material was acquired from 0 to 5 eV [12], however, TiC_2 materials have never been applied as SAs in PQS and passively mode-locked lasers at 2 μm.

In this work, we have prepared a new SA at about 2 μm which was based on TiC_2 and demonstrated a PQS *b*-cut Tm:YAP laser with output wavelengths from 1906.9 to 1978.9 nm. In PQS mode, a 2.22-W average output power and a 579-ns pulse duration at 255 kHz were achieved, corresponding to an 8.4% optical conversion efficiency, and an 8.7-μJ per pulse energy output and 15.0-W peak power were also realized. In addition, M^2 for a Tm:YAP laser in both horizontal and vertical directions was less than 1.2 under continuous wave (CW) and PQS modes.

2. Preparation and Characterization of a TiC_2 SA Mirror

A TiC_2 solution was synthesized by ultrasonic pyrolysis method, and an ultrasonic instrument (JY92-IIN) was used to achieve cell-level particles. The TiC_2 solution was coated onto one face of a CaF_2 mirror using a rubber equalizing set-up (KW-4A). The TiC_2 -based SA mirror is illustrated in Fig. 1(a). The layers and simple structure in this TiC_2 SA mirror were realized by use of a homemade device [see Fig. 1(b). Fig. 1(c) illustrates the refined structure of the TiC_2 layers as evinced by Raman spectrometer (LabRAM HR800). Fig. 1(d) shows the Raman spectra of TiC_2 layers at 1500–4000 cm^{-1}, and five feature peaks of the sample were detected at 1894.9, 2345.4, 2644.0, 3573.5, and 3814.6 cm^{-1}, respectively, corresponding to the familiar Raman shift of the 2D material layers [13], [14].

Fig. 2 illustrates the experimental results and the equipment used to measure the optical nonlinearity of the TiC_2 layers. A Q-switched Tm^{3+}-Ho^{3+} co-doped laser at 2119.3 nm was selected

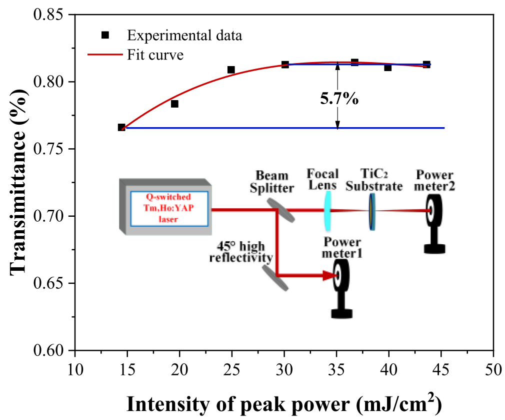

Fig. 2. Non-linear performance of a TiC_2 SA. The insert shows the laboratory equipment used for TiC_2 SA measurement.Blue lines from top to bottom were used to illustrate the positions of saturation absorption transmittance and original transmittance.

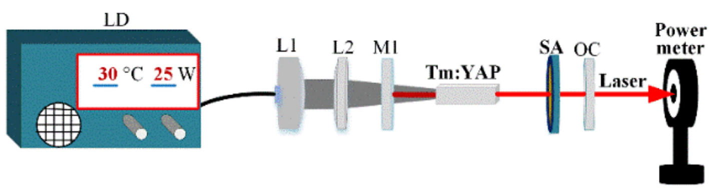

Fig. 3. Experimental equipment of the Tm:YAP laser.

as the light source with which to test the non-linear absorption of TiC_2 layers. A test-spot radius on the appearance of TiC_2 layers was computed to be 312 μm by the ABCD matrix, and saturation absorption intensity, modulation depth, and original transmittance were 30.10 mJ/cm^2, 5.7% and 76.6%, respectively.

3. Experimental Set-up

Fig. 3 illustrates the experimental equipment used with the PQS Tm:YAP laser with a TiC_2 SA. A two-mirror linear cavity was used in the experiment: the cavity was composed of a plane highly-reflective (HR) mirror and a plane output coupler (OC). The $^3F_4 \rightarrow ^3H_6$ laser transition of Tm^{3+} ions in a Tm:YAP crystal was selected to emit 2-μm laser radiation. A laser crystal containing 3 at. % Tm (0.6×10^{21} ions /cm^3), was grown by a Czochralski method, and this was cut along its *b*-axis to form a 3 mm $\times$ 3 mm cross-section with an 8-mm length. The double-head faces of the laser crystal were covered to over 99.5% transmission at 790–800 nm and 1890–2100 nm. A laser water cooler (DIC004ASL-LA2) with a cooling temperature range of from 281.1 to 303.1 K was used to relief the heating effect of the laser crystal by cycler water. The HR mirror was coated to over 99.95% reflectivity at 1.9–2.2 μm on one face and covered at 790–798 nm with an over 98.0% transmission coating on its dual surfaces. The OC was covered at 1900–2200 nm with high reflectivity material. A laser diode (LD) with a 792-nm centre output wavelength and a 40-W output power (DL-SYSTEM, MINI, Dilas Corp.,USA) was selected as the pumping supply for this Tm:YAP laser, and formed a coupled output via a 200-μm core-diameter fiber with a 0.22 numerical aperture. Under stable operating conditions, the LD temperature was set at 303.1 K to produce a red-shifted output wavelength of 793.3 nm to improve the absorption efficiency of the Tm:YAP crystal. A pump beam from the LD was refocused onto the Tm:YAP crystal by an alignment mirror (L1) with a 35-mm focal length and a focusing mirror (L2) with a 35-mm focal distance. A 100-μm pump facula (radius)

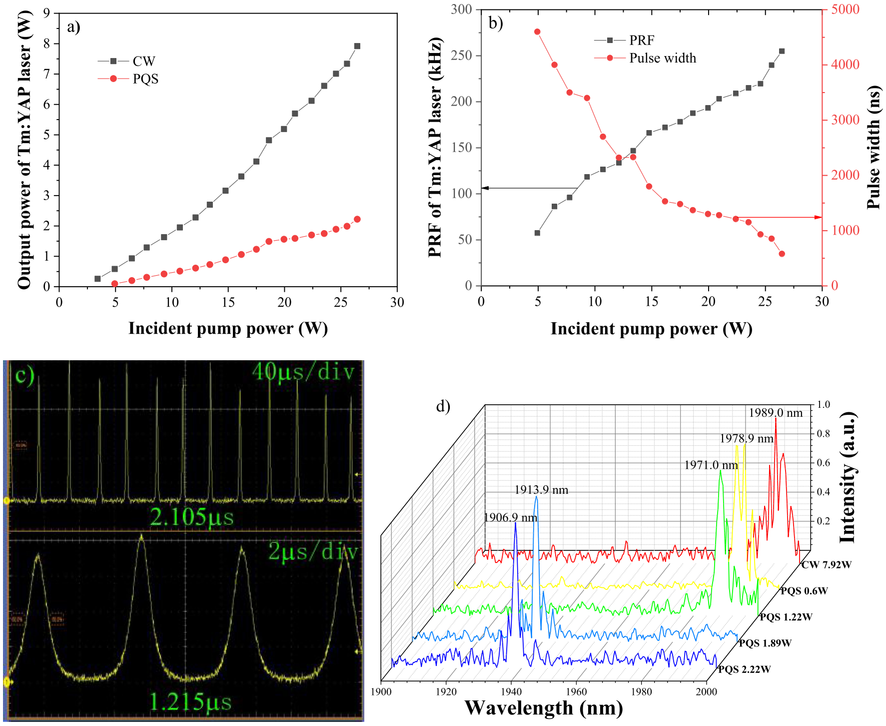

Fig. 4. Output characteristics of Tm:YAP laser. (a) Output powers from the Tm:YAP laser in two modes of operation. (b) The pulse widths and PRFs of the PQS Tm:YAP laser. (c) Typical Q-switched pulse trains in 40 and 2 μs time scales. (d) Output wavelengths of the Tm:YAP laser.

was located at one input end face of laser crystal. A prepared TiC_2 SA mirror was positioned within the laser cavity between the Tm:YAP crystal and the OC (nearer the OC). The physical cavity length of this PQS Tm:YAP laser was 27 mm. Laser beam diameters at the surface of the OC and HR were about 331 and 388 μm as found by using the ABCD matrix.

4. Results and Discussion

An OC with a transmittance of 2.5% was selected for a *b*-cut Tm:YAP laser in two modes of operation. Under 26.5-W available pump power, the output performance of Tm:YAP laser is illustrated in Fig. 4.

Fig. 4(a) illustrates the output power of the Tm:YAP laser. In CW mode, a 7.92-W output power was achieved with a 29.1% optical-optical conversion efficiency. Under PQS mode operation, a 2220-mW average output power was achieved with an 8.4% optical-optical conversion efficiency. A detector (ET-5000) with a 28-ps rise time and an oscilloscope (DPO71254C) with a 33-ps rise time and a 12.5-GHz bandwidth were used to test the pulse trains of the PQS Tm:YAP laser, as shown in Fig. 4(b). When increasing the incident pump power from 5.0 to 26.5 W, the pulse repetition frequency (PRF) increased from 57.3 to 255 kHz, and the pulse duration decreased from 4.6 μs to 579 ns. Typical PQS pulse trains were recorded over 40 and 2.0 μs time scales, as illustrated in Fig. 4(c). A wavemeter (721A IR, Bristol Instruments Inc.), whose measurement range was 1.3–5 μm, was chosen to test the output spectra of the Tm:YAP laser, as shown in Fig. 4(d). A 1989.0-nm output wavelength was acquired at a 7.92-W output power from the CW Tm:YAP laser. Under PQS mode, the output wavelengths of 1906.9, 1913.9, 1971.0, and 1978.9 nm were achieved from the Tm:YAP laser with the average output power increasing from 0.6 to 2.22 W. The output wavelength of the CW Tm:YAP was longer than that of the PQS Tm:YAP laser, which was due to the stimulated-emission cross-section in CW mode becoming a critical factor because the energy kept in the crystal was much less than the threshold for a PQS mode of operation.

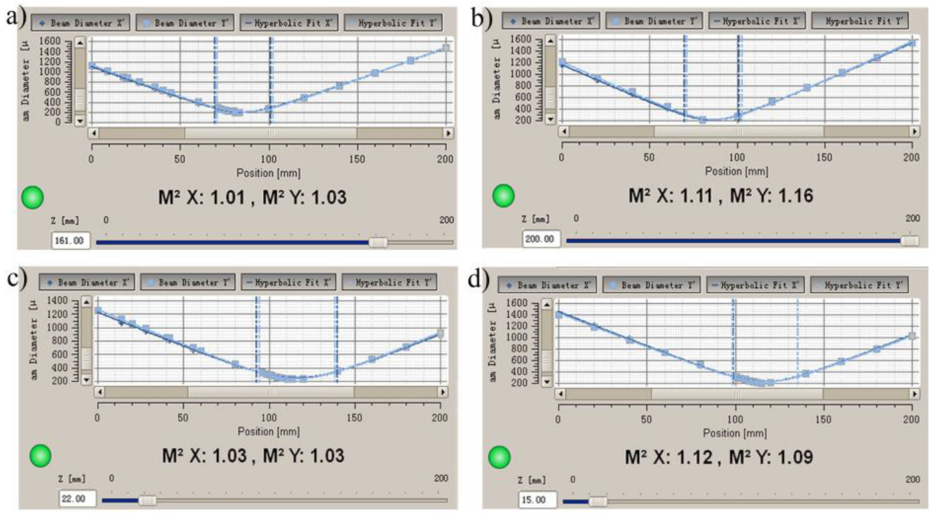

Fig. 5. M^2 measurement for the Tm:YAP laser. (a) M^2 factor of the CW Tm:YAP laser at the output power of 1.0 W. (b) M^2 factor of the CW Tm:YAP laser at the output power of 2.0 W. (c) M^2 factor of the PQS Tm:YAP laser at the average output power of 0.5 W. (d) M^2 factor of the PQS Tm:YAP laser at the average output power of 1.0 W.

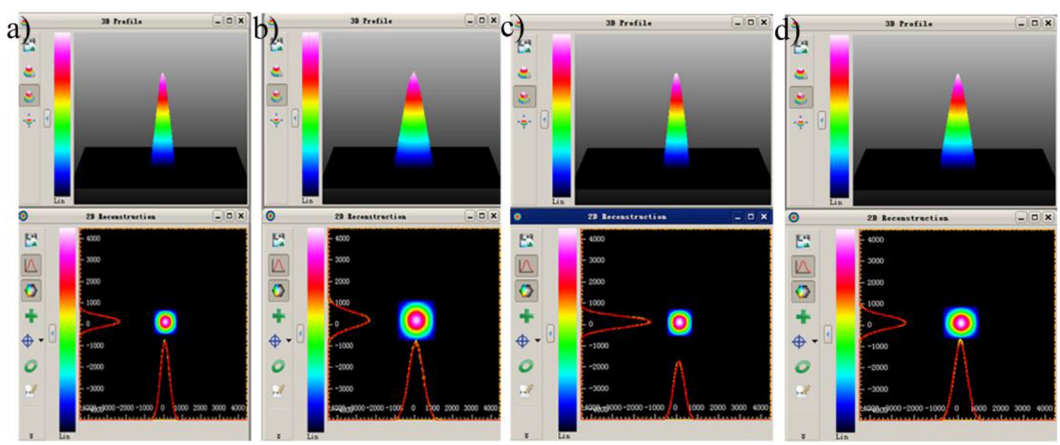

Fig. 6. The 2D and 3D spatial power distributions of the Tm:YAP laser. (a) The 2D and 3D spatial power distributions of the CW Tm:YAP laser at the output power of 1.0 W. (b) The 2D and 3D spatial power distributions of the CW Tm:YAP laser at the output power of 2.0 W. (c) The 2D and 3D spatial power distributions of the PQS Tm:YAP laser at the output power of 0.5 W. (d) The 2D and 3D spatial power distributions of the PQS Tm:YAP laser at the output power of 1.0 W.

To assess the beam quality of the Tm:YAP laser, M^2 factors were measured under different output power regimes by using an M^2 analytic system (BP109-IR2). Fig. 5 shows the M^2 factors of the Tm:YAP laser under different conditions. Fig. 5(a) and (b) show the M^2 factors of the CW Tm:YAP laser at output powers of 1.0 and 2.0 W, corresponding to M_x^2/M_y^2 factors of 1.01/1.03 and 1.11/1.16. Fig. 5(c) and (d) show the M^2 factors of the PQS Tm:YAP laser under average output powers of 0.5 and 1.0 W, corresponding to M_x^2/M_y^2 factors of 1.03/1.03 and 1.12/1.09. In CW and PQS modes, the M_x^2 and M_y^2 values of the Tm:YAP laser increase with increasing output power. Moreover, the 2D and three-dimensional (3D) spatial power distributions of the Tm:YAP laser are as shown in Fig. 6. Fig. 6(a) and (b) illustrate the 2D/3D spatial power distributions of the CW Tm:YAP laser at output powers of 1.0 and 2.0 W. Fig. 6(c) and (d) illustrate the 2D/3D spatial power

TABLE 1
Comparisons of PQS Laser Characteristics About 2000 nm: TiC_2, BP, WS_2, and MoS_2 SAs

SA	Laser crystal	Output spectra (nm)	Output power (mW)	Pulse duration (ns)	Peak power (W)	Optical conversion efficiency (%)	Ref.
TiC_2	Tm:YAP	1906.9	2220	579	15.0	8.4	This work
BP	Tm:YAP	1988	151	1780	4.40	5.1	[15]
WS_2	Tm:YAP	1942	488	430	12.6	9.2	[16]
MoS_2	Tm:$GdVO_4$	1902	100	800	2.6	3.2	[17]

distributions of the PQS Tm:YAP laser at average output powers of 0.5 and 1.0 W. These results indicated that the CW and PQS Tm:YAP laser has TEM_{00} mode preparation with high beam quality, but, as the pump power increasing, the M^2 factors of the CW Tm:YAP laser were changed more than that of the PQS Tm:YAP laser because TiC_2 SA suppressed the laser output in PQS mode.

PQS Tm^{3+}-doped lasers emit at about 2000 nm: Table 1 summarizes various output parameters achieved when using PQS solid-state Tm^{3+}-doped lasers with TiC_2, BP, WS_2, and MoS_2 SAs. The PQS Tm:YAP laser with a WS_2 SA could produce shorter pulses than those of other lasers, however, the average output power and peak power of WS_2-based systems were less than those of a TiC_2-based PQS Tm:YAP laser. Compared with the output performances of BP-based and MoS_2-based PQS Tm^{3+}-doped lasers, the output performances of a TiC_2-based PQS Tm:YAP laser offered significant advantages in terms of pulse width, average output power and peak power.

5. Conclusion

In conclusion, a new TiC_2 material as the SA to obtain a PQS Tm:YAP laser output at around 2.0 μm. In CW mode, a 7.92-W output power at 1989.0 nm was obtained from this Tm:YAP laser with a 29.1% optical-optical efficiency. Under PQS regime, a 2220-mW average output power at 1906.9 nm was achieved with a 579-ns pulse duration at 255 kHz. Furthermore, the M^2 factor of the Tm:YAP laser in both of its modes operation was estimated to be less than 1.2.

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