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Actively Q-switched tunable single-longitudinal-mode 2 µm Tm:YAP laser using a transversally chirped volume Bragg grating

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Abstract: A pulsed, single longitudinal mode, wavelength-tunable Tm:YAP laser is reported. We demonstrate 1 kHz stable operation with 230 µJ, 50 ns pulses and a spectrum linewidth narrowed below 4 pm (FWHM) close to the Fourier transform limit by use of a volume Bragg grating and a YAG etalon. The output wavelength was tuned from 1940 to 1960 nm owing to a transverse chirp of the period of the Bragg grating.

1. Introduction

Tunable coherent sources emitting between 8 and 12 µm can be used for remote gas sensing thanks to the very distinctive absorption spectra of molecules and to the high transmission of atmosphere in this wavelength range. In Ref. [1] we showed that this spectral range could be covered using a nested cavity optical parametric oscillator (NesCOPO), based on an orientation-patterned GaAs crystal (OP-GaAs). To control the spectral output of the NesCOPO, in which single frequency operation relies on Vernier spectral filtering in doubly resonant cavities [1], a single longitudinal mode (SLM) pumping laser is needed. A SLM Tm:YAP laser passively Q-switched with a Cr:ZnSe saturable absorber and operating in the nanosecond regime was specially designed to pump the OP-GaAs NesCOPO [2]. This laser delivers 170 µJ per pulse at 1938.46 nm with a pulse duration of 36 ns at a repetition rate of 100 Hz. Despite this achievement, several improvements still appeared to be necessary. Firstly, as the oscillation threshold of the NesCOPO is very low (owing to the double resonance and the use of small beam diameters), the output energy is also rather low. Energy upscaling could then be achieved using a separate optical parametric amplifier, which preserves the spatial and spectral properties of the NesCOPO output beam. However, to pump this amplifier, a more powerful SLM laser is required. For an amplification factor of 10, a laser energy of 200 to 250 µJ per pulse at 2 µm with a pulse duration between 10 and 100 ns is targeted. Besides, a higher average power and a higher pulse repetition rate are desirable for both facilitating wavelength using commercial spectrometers, as well as for using the NesCOPO as a source for stand-off detection of fast-moving gas plumes or in the presence of atmospheric fluctuations [3]. We built a second version of the laser operating at 300 Hz and successfully used it to pump an OP-GaAs NesCOPO. However, the energy per pulse was reduced to 80 µJ because of the use of passive Q-switching which required a modification of saturable absorber to maintain single longitudinal mode operation. Thus, active Q-switching of the laser would bring an increase of the repetition rate while maintaining SLM operation and would enable testing several configurations without needing to design a new saturable absorber

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in each case. Finally, large-scale wavelength tunability of the NesCOPO was previously achieved by temperature tuning of the index of refraction of the nonlinear crystal of the OPO, which is too slow for practical differential absorption measurements. It is well known that OPO wavelength tuning could be done faster by tuning the pump wavelength rather than the crystal temperature [4]. Simple calculations showed that tuning of the 2 µm pump over 20 nm is enough to address a similar tuning range as in [1], i.e. over 500 nm in the longwave infrared.

Regarding tunable Tm:YAP lasers, Jelinkova *et al.* demonstrated tunability from 1860 to 2040nm with a gain switched Tm:YAP laser using a Lyot filter. They obtained up to 42 mJ with 10 ms pulse duration and 55% slope efficiency for a repetition rate of 10 Hz [5]. Jin *et al.* studied a passively Q-switched Tm:YAP laser with a graphene saturable absorber. They obtained 2 to 9 µs pulses with repetition rates between 35 and 90 kHz depending on the output wavelength [6]. Cole *et al.* demonstrated 46% slope efficiency with a Tm:YAP laser passively Q-switched with a Cr:ZnS saturable absorber. They obtained pulses with energies between 0.5 to 0.7 mJ and pulse duration between 25 and 53 ns depending on selected wavelength. A Lyot filter was used to select 1.89, 1.94 and 1.99 nm as output wavelength, however, no information is given concerning the spectral width or the properties at intermediate wavelengths [7]. Passively Q-switched Tm:YLF lasers using a Cr:ZnS saturable absorber have been studied [8,9]. These lasers have an output wavelength close to 1.89 µm or 1.90 µm depending on cavity losses. They can emit pulse energies of several hundreds of microjoules but with repetition rates limited to a few hundreds of hertz. A Q-switched Tm:$LiLuF_4$ laser passively Q-switched by a Cr:ZnS saturable absorber with 26.2% slope efficiency at a 1.33 kHz repetition rate with 340 µJ and 51.6 ns pulses tunable from 1914.1 to 1965.2 nm was demonstrated by Yu *et al.*[10]. Thulium doped [11,12] or thulium, holmium co-doped [13] fiber lasers exhibit high repetition rate from several tens of kHz [11,12] to several hundred of kHz [13] using acousto-optic modulators, and near diffraction limited beams. A tunability of 100 nm with a linewidth of 0.8 nm using an acousto-optic tunable filter has been demonstrated [11] while a larger tunability of 180 nm and a narrower linewidth of 0.2 nm were achieved using a diffraction grating as of the end cavity mirror [12,13]. However, these lasers are rather complex due to the combination of free space optical components and a fiber gain medium. They also suffer from strong amplified spontaneous emission. As they involve high output and pump powers, they often require water cooling. Holmium bulk lasers also provide efficient pumping of LWIR OPO systems. They can deliver millijoule class pulses in the nanosecond regime near 2.1 µm [14,15]. However, they require thulium doped laser pumps.

Besides diffraction gratings, Volume Bragg Gratings (VBGs) are attractive components for spectral selection inside laser cavities, as they combine a narrow bandwidth and a very high diffraction efficiency. Tunability with these components can then be done by temperature tuning or rotation but is more preferably achieved with a chirp of the grating period. So far, VBGs have been extensively used in 1 µm lasers, while their use in 2 µm lasers has been more limited. We note that Duan *et al.* developed a continuous wave Tm:YLF laser with a volume Bragg grating and a 0.5 mm thick YAG etalon to narrow the output spectrum down to 0.1 nm (FWHM) [16]. In [6], the wavelength was tuned from 1965 to 2000nm with a rotating volume Bragg grating used as folding mirror in the cavity. Seger *et al* exhibited single longitudinal mode operation in a passively Q-switched, Nd:YVO_4 microlaser tuned between 1063 and 1065 nm with a transversally chirped volume Bragg grating (TC-VBG) [17]. Table 1 sums up the characteristics of the lasers developed in the aforementioned works.

Therefore, in order to achieve higher and easily controllable repetition rates of our Tm:YAP laser, we used active Q-switching with an acousto-optic modulator (AOM). We also investigated wavelength tuning and spectral narrowing of the laser output with a TC-VBG as an output coupler.

Table 1. Summary of laser characteristics reported in literature and in this work

Ref.	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]
Gain medium	Tm:YAP	Tm:YAP	Tm:YAP	Tm:YLF	Tm:YLF	Tm:YLF	Tm:fiber	Tm:fiber
Q-switch method	Gain switch	PQS graphene	PQS Cr:ZnS	PQS Cr:ZnS	PQS Cr:ZnS	PQS Cr:ZnS	AQS AOM	AQS AOM
E_p (µJ)	42 10^3	10	700	800	529	340	14	575
τ_p (ns)	10 10^6	2 10^3	25	15	59	51.6	35	65
PFR (kHz)	0.01	90	18	0.12	0.378	1.33	20	40
P_{peak} (kW)	4 10^{-3}	5 10^{-3}	28	53	8.8	6.7	0.4	8.8
λ range	1860–2040 nm	1965–2000 nm	1.89, 1.94, 1.99 µm	1886 nm	1885 nm	1914–1965 nm	1869–1962 nm	1875–2055 nm
Tuning	Lyot filter	Turning VBG	Lyot filter	_	_	T_{OC}	AOTF	Grating
Linewidth	NA	NA	NA	NA	37 nm	NA	0.8 nm	0.2 nm
Linewidth narrowing	_	_	_	_	_	_	AOTF	Grating
Ref.	[13]	[14]	[15]	[15]	[16]	[17]	[2]	This work
Gain medium	Tm,Ho:fiber	Ho:YAG	Ho:YLF	Ho:YLF	Tm:YLF	$Nd:YVO_4$	Tm:YAP	Tm:YAP
Q-switch method	AQS AOM	PQS Cr:ZnS	AQS AOM	AQS AOM	_	PQS Cr:YAG	PQS Cr:ZnS	AQS AOM
E_p (µJ)	275	600	11 10^3	28 10^3	_	5.7	170	270
τ_p (ns)	50	29	70	320	_	4	36	50
PFR (kHz)	200	24.4	1	0.01	_	140	0.1	1
P_{peak} (kW)	5.5	20.7	157	87	7 10^{-2}	1.4	4.7	5.4
λ range	2090 nm	2089 nm	2065 nm	2064 nm	1908 nm	1063–1065 nm	1938 nm	1939–1960 nm
Tuning	Grating	_	_	_	_	TC-VBG	_	TC-VBG
Linewidth	0.2 nm	NA	NA	SLM	0.1 nm	SLM	SLM	SLM < 4 pm
Linewidth narrowing	Grating	_	_	SLM seeded	VBG + etalon	TC-VBG	Etalon	TC-VBG + etalon

NA : not available in the referenced article

2. Set-up design

2.1. Laser set-up

Based on our previous passively Q-switched 2 µm laser [2], we designed a Tm:YAP laser with a TC-VBG as output coupler and an AOM to perform active Q-switching of the laser with repetition rates of a few kilohertz. The cavity, shown in Fig. 1, is composed of a highly reflective dielectric concave mirror around 2 µm with a radius of curvature of 50 mm, an AOM working at 2 µm, an uncoated 4 mm thick YAG etalon, a 4 mm long 3%at. thulium-doped a-cut YAP rod, and a TC-VBG provided by OptiGrate Corp. with 1940 nm to 1960 nm tuning range, 85% reflectivity and 1.2 nm bandwidth (FWHM). The AOM is used to switch the cavity losses and achieve pulsed operation.

The cavity is about 50 mm long. Its free spectral range is ~3 GHz which corresponds to ~40 pm. The cavity theoretical frequency comb is shown as the blue curve in Fig. 2. The gain medium is pumped with a continuous-wave 9 W laser diode emitting near 790 nm, which results in 7 W incident on the laser crystal due to Fresnel losses of VBG facets at 790 nm. The pumping laser is

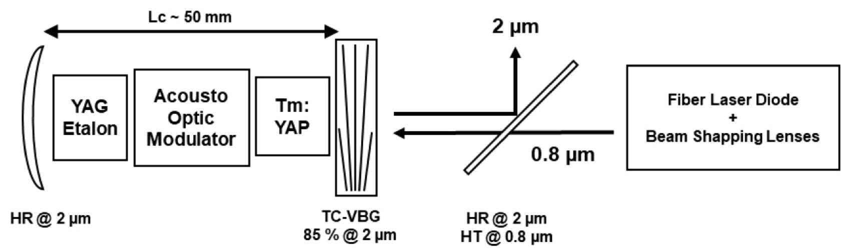

Fig. 1. Schematic diagram of the laser set-up

focused in the laser medium through the TC-VBG with a lens doublet to get a beam radius of 100 µm ($1/e^2$). A dichroic mirror is used to separate the 2 µm laser output from the input pump beam.

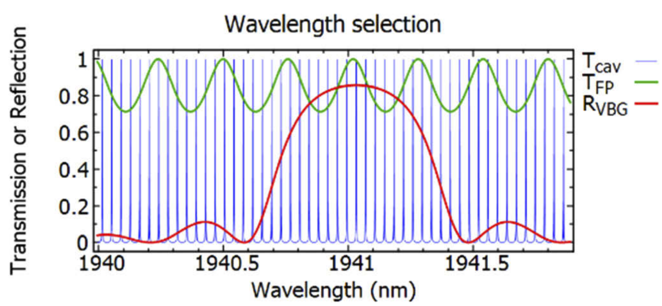

Fig. 2. Comparison between the cavity frequency comb (blue) the VBG reflection for a given transverse position (red) and the transmission curve of an uncoated 4 mm thick YAG etalon (green)

YAP ($YAlO_3$) was chosen because of the relatively high gain offered by cross relaxation of thulium in this host. In addition, YAP is an anisotropic crystal which enforces the laser to have a linear polarization. In order to stabilize thermal lensing in the YAP crystal, we implemented active temperature regulation.

2.2. VBG design

The TC-VBG was designed to obtain a constant gain over its tuning range. We simulated the gain spectrum with the model proposed by Stoneman and Esterowitz [18] applied to the case of the VBG transmission. We determined that a diffraction efficiency between 80 and 90% is required to have a constant gain between 1.94 and 1.96 µm. We then used the thick hologram model [19] to determine the feasibility of the target VBG with realistic physical parameters. The tuning range is limited to 20 nm due to the technical limitations in the optical system used to write the chirped index grating inside the photorefractive glass. Theoretical diffraction efficiency of the VBG for a given selected wavelength is illustrated by the red curve in Fig. 2 in comparison with the cavity frequency comb. On this graph, it appears that the laser operating with the VBG as an output coupler is likely to be slightly multimode. Note that in [17], Seger *et al.* observed that their VBG should not have enabled SLM operation of their Nd:YVO_4 laser. They resolved this point assuming that the spectral reduction was linked to unpredicted beneficial Fabry-Perot effect. Moreover, neodymium emission cross section presents a rather sharp peak around 1064.4 nm and there is also a wavelength selection operated by chromium saturable absorber. In our case, the VBG was designed to obtain a gain curve without sharp structures in the tuning range and the AOM has a constant transmission over the tuning range. Therefore, to ensure single longitudinal mode operation, we chose to add a Fabry-Perot etalon in the cavity.

2.3. *Etalon design*

We used a YAG etalon to ensure SLM operation of the laser. YAG has a refractive index of 1.81 which leads to 8.3% Fresnel reflection per facet, and thus yields a decent finesse without coating. It also has a high damage threshold and a very good transparency. The thickness of the etalon was determined to be able to select only one longitudinal mode of the laser cavity therefore to induce sufficient losses to adjacent modes when the transmission is centred on one mode. The thickness was limited in order to have only one transmission of the etalon inside the spectral width of 0.2 nm measured during preliminary experiments on the laser without the AOM. Theoretical transmission of an uncoated 4 mm thick YAG etalon is given in Fig. 2 by the green curve. This illustrates the complementarity of the VBG and thick etalon to reach SLM operation.

3. Results

3.1. *Continuous wave results*

Without the etalon and with the AOM switched off, we obtained a 28% slope efficiency with a 4 W pump threshold in continuous wave (CW) operation, see the blue plot in Fig. 3(a). For a fixed pump power, the output power varies with the transverse position of the TC-VBG, as shown in Fig. 3(b). The polarization extinction ratio (PER) is measured to be over 19 dB.

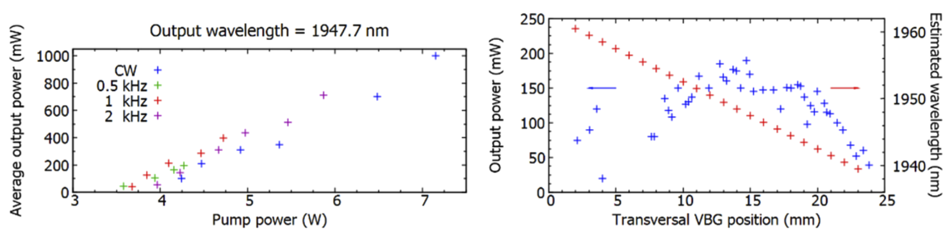

Fig. 3. (a) Average output power at different repetition rates for the cavity without the etalon for a given position of the TC-VBG (b) Output power and estimated wavelength depending on the TC-VBG transverse position for fixed pump power.

As shown in Fig. 4(a), with a dielectric mirror as an output coupler instead of the VBG, the spectrum of the laser cavity, which is then unconstrained, is almost 4 nm wide. This corresponds to tens of longitudinal modes. In addition, the lasing longitudinal modes vary over time as the laser is emitting. The spectrum with the VBG is given in Fig. 4(b) for various output powers. The spectrum broadens with increasing output power: it is single longitudinal mode near the laser threshold, and becomes slightly multimode when the power rises. Nevertheless, this shows that the VBG narrows a 4 nm wide spectrum down to 0.2 nm. The VBG also enforces the operating wavelength which can be outside the unconstrained spectrum. In addition, translation of the TC-VBG over more than 20 mm corresponds to a tuning range of more than 20 nm, which is confirmed with an optical spectrum analyser.

3.2. *Active Q-switching results*

In pulsed operation, without the etalon, the threshold was around 3.5 W and the slope efficiency was 31.6% at a pulse repetition rate of 1 kHz, see the red plot in Fig. 3(a). A typical temporal pulse profile is shown on Fig. 5(a). Repetition rates of 0.5, 1 and 2 kHz have been tested. Pulse trains are shown on Fig. 5(b). Pulse duration depends on AOM alignment in the cavity, on beam size inside the AOM and on pulse energy. With an optimized AOM alignment, a pulse duration as short as 40 ns with 300 µJ per pulse was obtained. Pulse energies over 300 µJ were not investigated to avoid damaging optical components. However, pulses with higher energies could easily be obtained with this set-up. PER is measured to be over 19 dB also for pulsed operation.

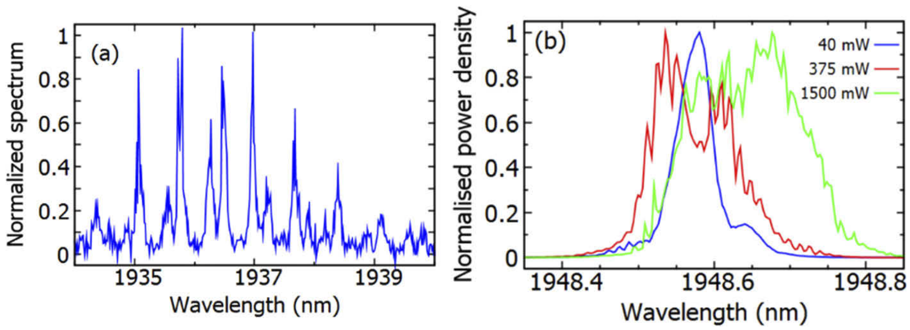

Fig. 4. Output spectrum of the laser (a) with a dielectric output coupler with 300 mW output power and (b) with a TC-VBG at different output powers for a given transversal position.

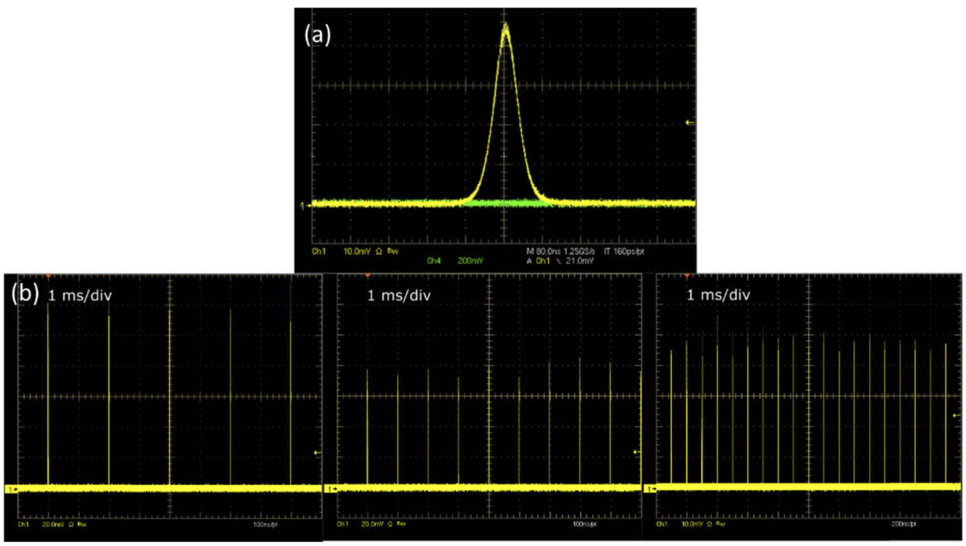

Fig. 5. (a) Typical temporal pulse profile (b) Oscillograms of the pulse trains at 500 Hz (left), 1 kHz (middle) and 2 kHz (right).

The laser spectrum was slightly broader in pulsed operation compared to continuous wave operation. With the VBG, the output spectrum is 0.25 nm wide (FWHM) for corresponding energy per pulse in the 250 to 300 µJ range. This spectral width reveals multi longitudinal mode operation of the laser as the cavity FSR is ~40 pm. The tuning range was ~20 nm wide as for the continuous wave case (see Fig. 6).

3.3. Complete cavity results

The efficiency and the threshold were similar with the etalon added to the cavity, but the alignment of the cavity was much more delicate. We selected a working point with 1 kHz repetition rate and ~250 µJ/pulse. The pulse duration was then measured to be between 40 and 60 ns. As shown in Fig. 7, stable operation with 230 µJ/pulse over half an hour with a standard deviation of 1.5% was demonstrated. Stable working points with up to 270 µJ/pulse were found but exhibit lesser stability. PER was still over 19 dB. The laser beam has a TEM_{00} spatial mode with beam quality (M^2) measured to 1.16 horizontally and 1.17 vertically.

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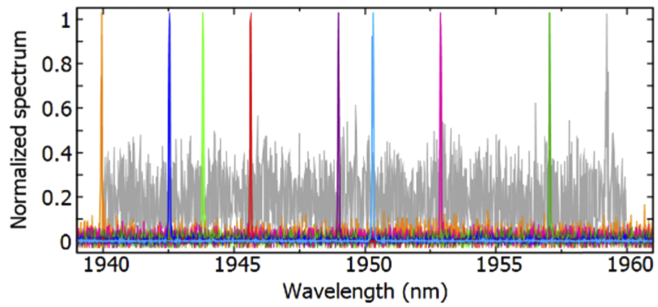

Fig. 6. Normalized spectra for different transversal position of the VBG.

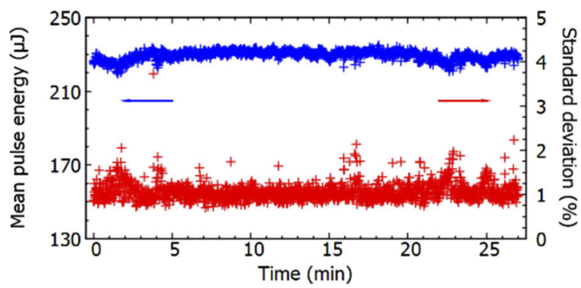

Fig. 7. Mean energy per pulse and standard deviation over half an hour

As Fig. 8(a) shows, the spectral width of the laser with the etalon is measured to be below 4 pm which is the resolution of the measurement set-up. Therefore, since the cavity FSR is ~40 pm, the laser is single longitudinal mode with the etalon. Assuming a nearly Fourier-transform-limited linewidth, one could expect a pulse spectral width of ~0.1 pm for the 50 ns duration.

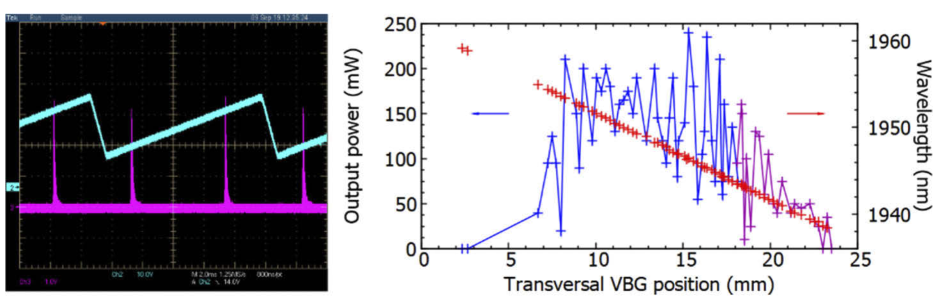

Fig. 8. (a) Output spectrum at working point with the etalon measured with a scanning Fabry-Perot with a free spectral range of 10 GHz (b) Output power and wavelength depending on the TC-VBG transverse position

The wavelength tuning range was measured in pulsed regime with both the AOM and the etalon to be slightly larger than 20 nm, as shown in Fig. 8(b). As in the continuous wave regime, power is not constant over the tuning range. These variations are mainly attributed to parasitic Fabry-Perot effects between the VBG and its substrate facets. The etalon transmission also adds additional variations. With an antireflective coated TC-VBG, we would expect to only observe the power variations due to the etalon free spectral range.

4. Discussion

The cavities without or with the etalon exhibit similar performances in terms of threshold, slope, pulse duration, PER, and tuning range. The laser without the etalon exhibits a few longitudinal modes which leads to an overall spectral width between 0.15 and 0.25 nm, whereas the laser with the etalon is single longitudinal mode and has a spectral width between 0.1 and 4 pm. In both cases, the laser meets the targeted pulse energy over 200 μJ and duration between 10 and 100 ns. The tuning range of 20 nm was shown to be imposed by the VBG only. However, the etalon was shown to be necessary to obtain single longitudinal mode operation.

In this work we obtained up to 270 μJ pulses with 50 ns pulse duration, providing 5.4 kW peak power on a single longitudinal mode. Most of the reported systems [9–13] present peak powers that also stand in the 1 to 10 kW range but are multi-longitudinal-mode. Reference [7,8,14,15] present much higher peak powers ranging from 20 to 160 kW, but, either they are multi-longitudinal-mode, or they use a much more complex laser design. Among the possible evolutions, we could generate higher peak powers investigating higher pulses energies using the extra pump power available. We could also decrease losses inside the cavity by adding antireflective coatings on the VBG, thus lowering the threshold and increasing the system overall efficiency. Increasing the pulse energy would also reduce the pulse duration providing an additional increase in the peak power. Instead of increasing the peak power, we could also increase the repetition rate to scale up the average power which would benefit to automatization of the tunable OP-GaAs NesCOPO pumped by this laser, by reducing the integration time of the different instruments used to control the system. However, since the obtained pulse energy and duration are already well-suited to pump both the NesCOPO and a parametric OP-GaAs amplifier, future work will mainly focus on the increase of the overall system efficiency and long-term stability while maintaining a similar working point. The 20 nm tuning range we demonstrated is smaller than what has already been demonstrated with thulium lasers [5–7,10–12]. In our case, the tuning range is restricted by the current technical limitation of the fabrication process of the TC-VBG. Therefore, increasing our tuning range would require some additional work from the supplier or using a different approach. After down conversion by the NesCOPO, this 20 nm tuning range translates to 360 nm around 8 μm and to 500 nm tuning around 10 μm, which is enough to scan different absorption bands of several hazardous chemicals [3]. The SLM operation we demonstrated with less than 4 pm linewidth is nearly Fourier transform limited and outperforms all that was already demonstrated with pulsed tunable 2 μm lasers.

5. Conclusion

We demonstrated, for the first time to our knowledge, an efficient actively Q-switched diode pumped single longitudinal mode Tm:YAP laser tunable from 1.94 μm to 1.96 μm, using a transversally chirped volume Bragg grating as output coupler and an acousto-optic modulator. We obtained a wavelength tunability of 20 nm than would translate to a 500 nm tunability near 10 μm after frequency down conversion. With the etalon added to the cavity, the output spectrum is nearly Fourier transform limited. Both features are of interest to pump single longitudinal mode optical parametric oscillators and record absorption spectra of gas molecules.

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Volume Bragg Grating" and at the ASSL congress in 2019, "Actively Q-switched Tunable Narrowband 2 µm Tm:YAP Laser Using a Transversally Chirped Volume Bragg Grating."

Disclosures

The authors declare no conflicts of interest.

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