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GRAPHENE Q-SWITCHED WAVEGUIDE LASER AT 1.83 µm

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Lasers emitting at around ~2 µm has gained interest for potential applications in atmospheric sensing, range-finding (LIDAR systems), wind mapping and medical surgeries [1]. Such ~2 µm lasers having a waveguide geometry are also useful in integrated optics, e.g., for various gas and bio-molecule on-chip sensors. Trivalent Thulium (Tm^{3+}) ions, efficiency pumped at ~0.8 µm ($^3H_6 \rightarrow {}^3H_4$ absorption band), are commonly used to generate ~2 µm laser emission from the $^3F_4 \rightarrow {}^3H_6$ transition. Monoclinic double tungstates, $KRE(WO_4)_2$ or shortly KREW where RE = Gd, Y or Lu, are very suitable hosts for Tm^{3+} doping [2]. In the present work, continuous-wave (CW) and graphene passively Q-switched (PQS) laser operation of Tm:KYW planar waveguide is reported.

The studied sample has symmetrical structure with an undoped KYW substrate, a Tm^{3+}-doped lattice-matched active layer and an undoped KYW cladding. The KYW bulk sample was grown by the Top-Seeded Solution Growth (TSSG) slow-cooling method. It was cut parallel to the (010) natural face and polished to laser quality. The Liquid Phase Epitaxy (LPE) method was used to grow the active layer with a composition of $KY_{0.58}Gd_{0.22}Lu_{0.17}Tm_{0.03}W$. The as-grown active layer was polished down to 12.4 µm and later an undoped KYW was grown as a cladding which was polished down to a final thickness of 58 µm. The fabricated waveguide sample was oriented for light propagation along the N_g-dielectric axis.

The laser cavity consisted of a flat pump mirror (PM) that was antireflection (AR) coated for 0.7–1 µm and high-reflection (HR) coated for 1.8–2.1 µm and a flat output coupler (OC) providing a transmission of T_{OC} = 5% at 1.8–2.1 µm. A transmission-type graphene-SA was inserted between the waveguide and OC. The graphene-SA was a commercial single-layer graphene fabricated by the chemical vapour deposition (CVD) method and deposited on a 1.05 mm-thick uncoated fused silica substrate. The presence of a graphene (single layer of C atoms) was confirmed by Raman spectroscopy and it has a small-signal transmission of 97.7% at ~2.06 µm [3].

A Ti:Sapphire laser beam, tuned to 802 nm and polarized along the N_m-optical axis of the active layer, was used as a pump source. The pump light was coupled into the waveguide with a 10X microscope objective lens (NA: 0.28, focal length: 20 mm). The incident pump power was varied with a gradient neutral density (ND) filter placed before the objective. The measured small-signal pump absorption was ~70% and the absorption dropped to ~60% for the highest pump power. The efficiency of the pump light coupling into the waveguide was estimated from the geometrical overlap of the pump beam and the active layer cross-section to be ~24%. The laser signal from the waveguide was filtered with a cut-off filter and coupled out with a 40 mm aspheric lens. The scheme of the laser set-up is shown in Fig. 1. The emission wavelength was detected with an optical spectrum analyzer (Yokogawa AQ6375). The far-field profile of the guided mode was detected using a FIND-R-SCOPE Near IR Camera. A fast InGaAs photodiode (rise time: 200 ps) and a 2 GHz digital oscilloscope were used for detection of the Q-switched pulses.

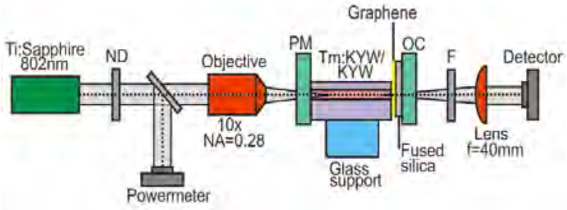

Figure 1 - Experimental set-up: ND – neutral density filter, PM - pump mirror, OC - output coupler, F - cut-off filter

CW Tm:KYW waveguide laser generated an output power of 14.4 mW at 1835.4 nm with a slope efficiency η of 18% with respect to the absorbed pump power. The laser threshold was at P_{abs} = 38 mW. Stable passive Q-switching was achieved when inserting the graphene-SA. The maximum average output power reached 6.5 mW at wavelength 1831.8 nm corresponding to η = 9% and a laser threshold at P_{abs} =51 mW, Fig. 2. The conversion efficiency with respect to the CW operation mode η_{conv} reached 45%. For both CW and PQS regimes the laser output was linearly polarized ($E \parallel N_m$). The output beam of the laser was multimode and strongly elliptic, see inset in figure 2(a).

The dependence of the pulse characteristics (pulse duration, $\Delta\tau$, determined as full width at half maximum, FWHM, pulse repetition frequency, PRF, pulse energy, $E_{out} = P_{out}$/PRF, and peak power, $P_{peak} = E_{out}/\Delta\tau$), are shown in figure 3. When the absorbed pump power was increased from 75 to 126 mW, the pulse duration shortened from 312 to 195 ns and the pulse energy increased from 2.3 to 5.8 nJ. This was accompanied by a nearly linear increase of the PRF, in the 0.73-1.13 MHz range. The maximum peak power reached ~30 mW. These results have shown a significant improvement as compared to [4] where Cr^{2+}:ZnS was used as a SA with a similar waveguide structure.

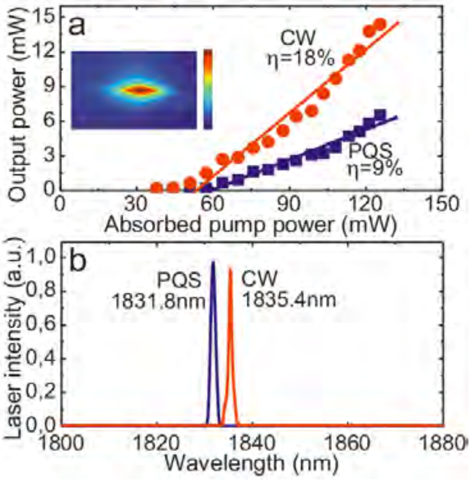

Figure 2 - CW and graphene PQS Tm:KYW waveguide lasers: (a) input-output dependences, *η* - slope efficiency, *inset* - spatial profile of the laser beam; (b) typical laser emission spectra measured at P_{abs} = 126 mW

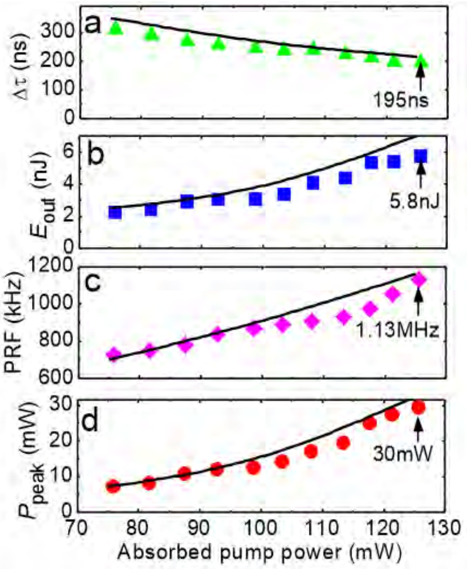

Figure 3 - Graphene PQS Tm:KYW waveguide laser: (a) pulse duration $\Delta\tau$ (FWHM), (b) pulse energy E_{out}, (c) pulse repetition frequency (PRF) and (d) peak power P_{peak} versus the absorbed pump power

The oscilloscope trace of the shortest single Q-switched pulse and the corresponding pulse train are shown in Fig. 4. The intensity instabilities in the pulse train are <10% and the rms pulse-to-pulse timing jitter is <15%. The Q-switching instabilities in the studied laser are caused mainly by the temporal instabilities of the output of the Ti:Sapphire laser and to less extend – to the heating of the graphene-SA with the non-absorbed pump.

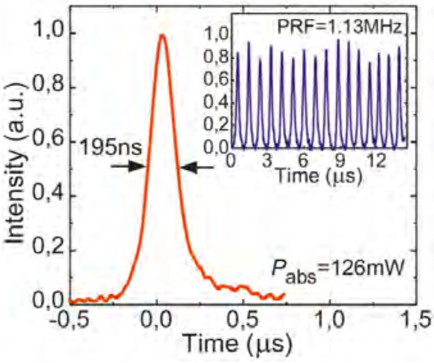

Figure 4 - Oscilloscope traces of a single Q-switched pulse and the corresponding pulse train (*inset*) for graphene PQS Tm:KYW waveguide laser, P_{abs} = 126 mW

In conclusion, the first ~2 μm double tungstate waveguide laser passively Q-switched by a graphene-SA was demonstrated. The laser is based on a buried 3 at.% Tm^{3+}:KYW planar waveguide and delivered 5.8 nJ / 195 ns pulses at 1831.8 nm at a high pulse repetition frequency of 1.13 MHz. The Q-switching conversion efficiency reached 45%. Future work will focus on implementing higher Tm^{3+}-doping as well as channel waveguide lasers for improving the pulse duration and repetition frequencies.

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