Femtosecond Pulse Generation from an Extended Cavity Cr^{4+}:forsterite Laser using Graphene on YAG

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Abstract: A room temperature, multipass-cavity, femtosecond Cr^{4+}:forsterite laser was mode-locked with a single-layer graphene saturable absorber on a YAG substrate. The resonator produced nearly transform-limited 92 fs pulses near 1250 nm with 53 kW of peak power.

OCIS codes: (140.3580) Lasers, solid state; (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers.

1. Introduction

Recently, graphene saturable absorbers (GSAs) have emerged as alternatives to semiconductor saturable absorber mirrors (SESAMs) [1] for initiating mode-locked operation of lasers because of their favorable properties, such as simpler fabrication, lower cost, and extremely broad operating range. It has been shown that GSAs can be used in lasers with different operation wavelengths ranging from 800 to 2500nm [2-6]. In this study, a single-layer graphene saturable absorber transferred onto a 2mm long YAG substrate (GSA-YAG) was used to initiate mode-locked operation of a room temperature, multipass-cavity (MPC), femtosecond Cr^{4+}:forsterite laser. When mode-locked with GSA-YAG, the resonator produced 92fs, nearly transform-limited pulses with a spectral bandwidth of 19nm and a time-bandwidth product of 0.33. The corresponding pulse peak power was 53kW and the pulse energy was 4.9 nJ. Mode-locking results were similar to our previously reported values using a GSA on a quartz substrate [7]. Furthermore, the cavity nonlinearities that limit further power-scaling were investigated during the mode-locking experiments by using output couplers with different transmission levels.

2. Experimental Setup

The layout of the Cr^{4+}:forsterite laser is shown in Fig. 1. Initially, a short x-cavity was constructed with two curved dispersion compensation mirrors (DCMs) (M1, & M2), each with 10cm radius of curvature (ROC), two flat DCM mirrors (M3 and M4) to adjust the inclination angle of the beam entering the MPC, and two flat end mirrors (M5, a high reflector DCM and M10, an output coupler (OC) with 4.7% or 2.4% transmission). A 20mm long, Brewster-cut Cr^{4+}:forsterite crystal with 70% absorption at the pump wavelength of 1064 nm was placed between M1 and M2, and was end-pumped with a continuous-wave (CW) Yb:fiber laser operating at 1064nm. By using a lens with 20cm focal length (L1), the pump beam was focused to an estimated waist of 30μm inside the crystal. The Cr^{4+}:forsterite crystal was mounted on a copper holder and kept at room temperature (20^0C) by water cooling . With this short x-cavity configuration, an average CW output power of 815mW was obtained using a 4.7% OC at the pump power of 8W.

In order to reduce the repetition rate of the pulses and increase the energy per pulse, a q-preserving MPC extension was added to the short x-cavity by removing the mirror M5. As seen in Fig. 1, the MPC consists of a curved mirror (M6, ROC=4m) and a flat mirror (M7). Both of these mirrors have notches, in order to allow beam injection and extraction. The MPC extension added an effective optical path length of 59.4m to the original cavity.

To overcome the positive dispersion coming from the Cr^{4+}:forsterite gain medium (+800fs^2), MPC (+360fs^2), and air (+794fs^2), four flat Gires-Tournois interferometer (GTI) mirrors (M11, M12, M17, and M18) each having a group delay dispersion (GDD) of -250fs^2 per bounce, and three flat DCM mirrors (M13, M14, and M19) each with -150fs^2 GDD per bounce were introduced into the cavity. To increase the amount of negative intracavity GDD, the circulating beam reflected off four times from the GTI mirrors in each roundtrip. Including GDD originating from other intracavity dispersive mirrors (-1500fs^2), a net intracavity GDD of around -4440fs^2 was obtained.

Two curved mirrors M15 and M16 (ROC=500 mm) were used to focus the circulating beam on the GSA-YAG sample to an estimated waist of 97µm. The overall optical path length of the composite cavity was 66.5m, corresponding to a pulse repetition rate of 4.51MHz.

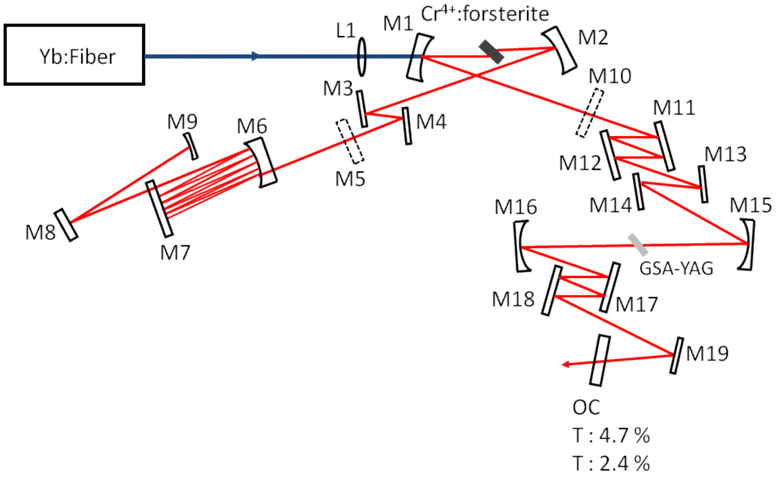

Fig. 1. Experimental setup of the multipass-cavity femtosecond Cr^{4+}:forsterite laser containing the dispersion control optics and the single-layer graphene saturable absorber on YAG (GSA-YAG).

3. Results and Discussion

The graphene samples used in this study were synthesized on copper foils by using the technique of chemical vapor deposition. After the growth, the graphene layers were transfer printed on a 2 mm long YAG substrate. Details of the fabrication process can be found in Ref [8]. To investigate the saturation characteristics, ultrafast relaxation dynamics, and quality of the GSA-YAG samples, pump-probe and Raman spectrum measurements were made. In the Raman measurements, the D/G ratio was determined to be 0.18, and the FWHM of the 2D band was measured to be 35 cm^{-1}. In the pump-probe measurements, the fast and slow decay times were determined to be 383 fs and 1.7 ps respectively. The saturation fluence and the modulation depth of the GSA-YAG sample were further determined to be 70 $\mu J/cm^2$ and 0.8 %. Fig. 2 shows the power efficiency curves for the complete laser resonator (containing the MPC and dispersion control optics) with two different OCs and different GSA substrates. By using the laser threshold data, the single pass optical loss of the GSA-YAG sample was estimated to be 4%.

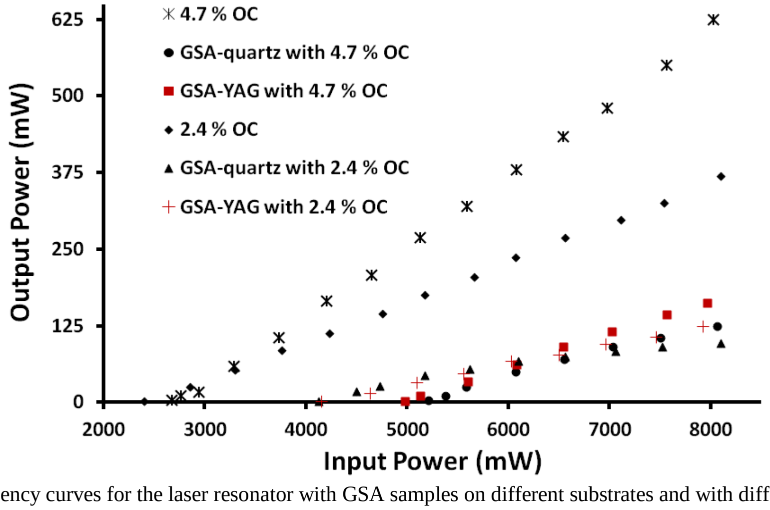

Fig. 2. Power efficiency curves for the laser resonator with GSA samples on different substrates and with different output couplers (OC).

The mode-locked spectra, collinear autocorrelation traces, and the RF spectra for the 2.4% and 4.7% OCs are shown in Fig.3. The resonator produced 4.9nJ (3.1nJ), 92fs (112fs) nearly transform-limited pulses (assuming a $sech^2$ temporal profile) with a spectral bandwidth of 19nm (17nm), and time-bandwidth product of 0.33 (0.36) using the 4.7% (2.4%) OC. Similar mode-locking results were previously obtained with GSA on quartz substrate [7]. To investigate the cavity nonlinearities that limit further power scaling, the nonlinear refractive index of the Cr^{4+}:forsterite medium was estimated by using the experimental mode-locking data and the soliton-area theorem [9].

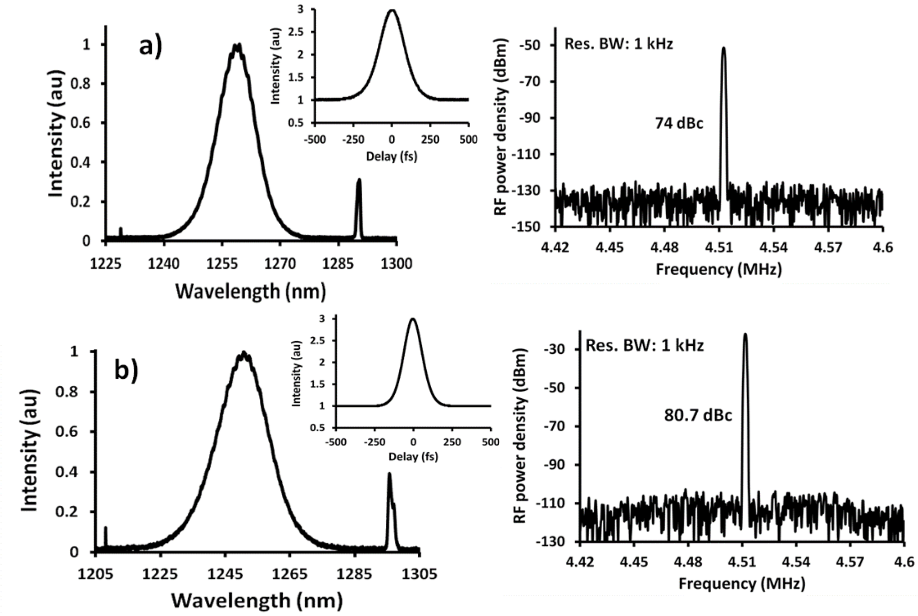

Fig. 3.Mode-locked spectrum, collinear autocorrelation trace (inset), and RF spectrum for the (a) 2.4% OC and(b) 4.7% OC.

The estimated nonlinear refractive index of the Cr^{4+}:forsterite gain medium was determined to be $10.38 \pm 2 \times 10^{-20} m^2/W$ in good agreement with our previously reported values obtained by using a single walled carbon nanotube saturable absorber (SWCNT-SA) [10], GSA on quartz substrate [7], and the value reported by Chassagne et al. [11]. By using this nonlinear refractive index value, the critical power for self-focusing was determined to be 1.45MW, in good reasonable agreement with the experimentally observed limiting intracavity peak power of 1.13MW.

In conclusion, we have successfully demonstrated a GSA-YAG mode-locked femtosecond Cr^{4+}:forsterite laser. To scale the peak power at low average powers, a q-preserving MPC was introduced and the pulse repetition rate was reduced to 4.51MHz. We have obtained 4.9nJ, 92fs, nearly transform-limited pulses with 53kW peak power which is the highest peak power obtained from a Cr^{4+}:forsterite laser mode-locked with GSA.

4. References

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