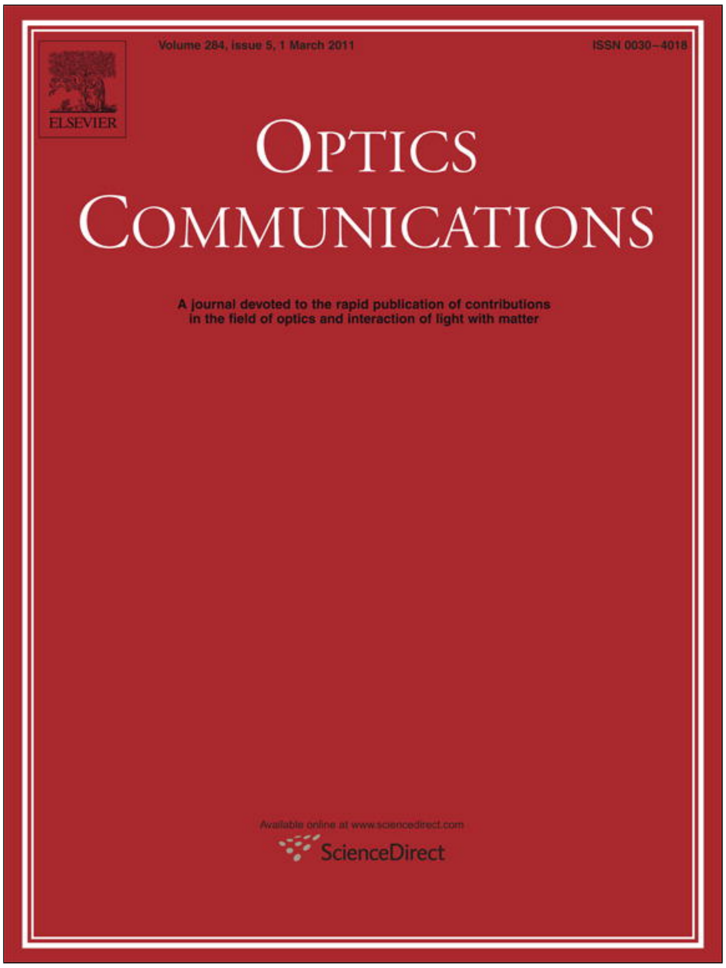
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Ultrafast laser pulses generated from the chromium-doped cunyite laser

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ABSTRACT

Femtosecond pulses were generated from a Cr^{4+}: Cunyite laser using a combination of a broadband semiconductor saturable absorber mirror (SESAM), chirped mirrors, and passive mode locking. The astigmatically compensated asymmetric X-cavity with a 4.5-mm-long Cr^{4+}:Ca_2GeO_4 sample was operated with a 2.5% output coupler. Dispersion compensation was achieved using chirped mirrors. During self-starting mode-locked operation, pulses as short as 365 fs were generated at a pulse repetition rate of 100 MHz with output power of 70 mW and a spectral bandwidth of 5.2 nm at the center wavelength of 1432 nm.

1. Introduction

Kerr-lens mode locking has become a standard method to produce ultra-short pulses for Ti^{3+}: Sapphire [1] and other tunable NIR solid-state lasers [2]. A major enabling technology is the development of semiconductor saturable absorber mirrors (SESAMs) as intra-cavity laser elements to passively initiate and maintain the pulse generation process with a higher degree of stability than apply in Kerr-lens mode locking [3,4]. Lasers in the mid-infrared region such as Forsterite at 1250 nm generating ultra-short pulses with less than 100 fs duration are promising tools for biomedicine and communications applications. Cr: Ca_2GeO_4 (Cunyite) is an important solid-state laser which produces broad laser radiation in the NIR around 1400 nm [5]. Most importantly, the broad emission band extending from 1300 to1500 nm can potentially be used to generate femtosecond pulses as short as 20 fs. Femtosecond Cr^{4+}: Ca_2GeO_4 Cunyite lasers are applicable in many research areas including spectroscopy, multiphoton imaging, material processing, microscopy, biophotonics imaging and telecommunications. To date, different methods of operation have been demonstrated with Cr^{4+}: Ca_2GeO_4 lasers. These include gain-switching, continuous-wave (CW) tunability [6], mode-locked operation [7] with milliwatt CW output powers. In mode-locking experiments, acousto-optic modulation was first employed to generate 80 ps at 1400 nm. This was followed by self-starting passively mode-locking experiments by several groups, which resulted in the generation of 60 ps pulses with semiconductor saturable absorber mirrors, being the shortest pulses at the time [8].

2. Experimental setup

In this letter, the generation of ultra-short NIR pulses from a self-cstarting passively mode-locked femtosecond Cr^{4+}: Ca_2GeO_4 laser at room-temperature operating at 1432 nm is reported for the first time. A standard astigmatically compensated asymmetric X-fold cavity was used in the experiments. When the focusing in the gain medium was optimized, self-starting passively mode locking could be initiated to generate an autocorrelation trace of 550 fs pulses at a pulse repetition rate of 100 MHz with an output power as high as 70 mW. The center wavelength of the pulses was 1432 nm. The pulses had a spectral bandwidth of 5.2 nm with a corresponding time-bandwidth product of approximately 0.28.

Fig. 1 shows a schematic of the experimental setup. The pump source was a 10 W continuous-wave Nd:YAG laser operating at 1064 nm .A 38.5 mm focal length was used to focus the pump beam in the crystal. The astigmatically compensated X-fold resonator had two curved mirrors M1 and M2 with radii (R = 50 mm), a SESAM (M7) instead of a flat end mirror, and a flat output coupler (M6) in combination with a pair of chirped flat dielectric mirrors (M4 and M5) used for dispersion compensation. Arm lengths of 40 cm (OC arm) and 60 cm (HR arm) were used to obtain a laser mode size of ~24 μm inside the Cr^{4+}: Ca_2GeO_4 (Cunyite) crystal in the continuous-wave regime. The gain medium was a 4.5 mm long, Brewster cut, 5.0 wt.%Cr^{4+}: Ca_2GeO_4 (highly doped Cunyite) crystal with a net absorption of 63% at

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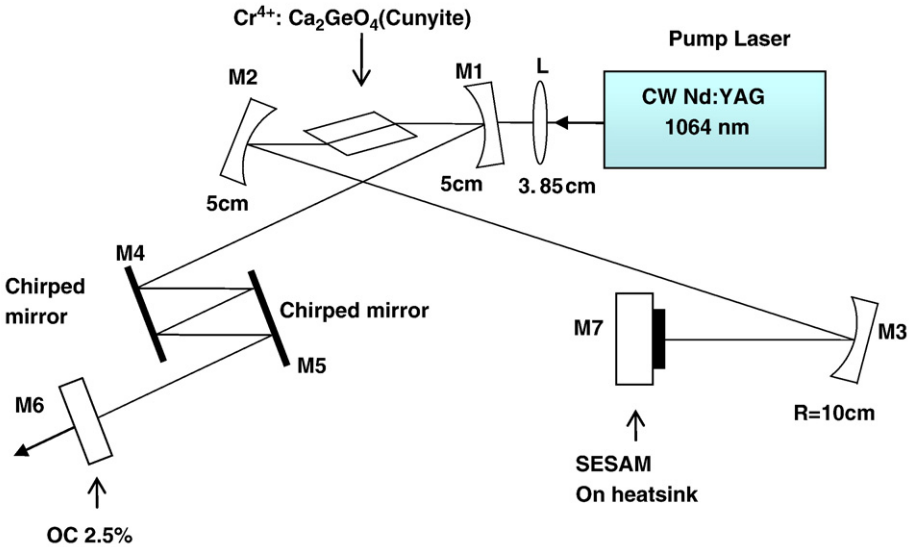

Fig. 1. Schematic of the Nd-YAG: pumped mode-locked Cr^{4+}: Ca_2GeO_4 (Cunyite) laser. The pump beam is focused onto a 4.5 mm-thick highly doped Cr^{4+}: Ca_2GeO_4 (Cunyite) crystal (absorption coefficient of 1 cm^{-1} at 1064 nm). M1 and M2: Dichroic, curved high reflectance mirrors with R = 5 cm; M4 andM5: Chirped dispersive mirrors; M6: 2.5% broadband output coupler. M3: curved high reflectance mirror focusing the beam onto the SESAM; M7: SESAM mirror glued at the center of a copper heatsink with 12.7 mm diameter.

1064 nm. The crystal was wrapped with thermal paste and held between aluminum plates that were water cooled at 16 °C.

3. Results and discussion

The performance of the laser with the available output couplers was evaluated. Fig. 2 shows the CW laser performance using a 1%, 2.5%, and 5% transmission output couplers. The CW output wavelength was ~1430 nm for all output couplers. The corresponding threshold pump power and the slope efficiency with respect to pump power were 0.5 W, 1 W, 1.5 W and 3.125%, 4.58%, 3.75% respectively. The best laser performance was obtained with the 2.5% OC. Using this output coupler, the laser produced 240 mW of output power with 5 W pump power. The CW operation was very stable and repeatable over a long period scale.

By performing a Fourier transform of the white-light interferometric cross correlation [10,11], we measured the group velocity dispersion (GVD) of the Cunyite crystal (Cr^{4+}: Ca_2GeO_4 over the wavelengths from 1200 nm to 1600 nm which is positive and decreases slightly with increasing wavelength. Fig. 3 shows the measured group velocity dispersion. The data should be useful for the dispersion compensation and for further short pulse generation in femtosecond Cr^{4+}:Ca_2GeO_4 lasers.

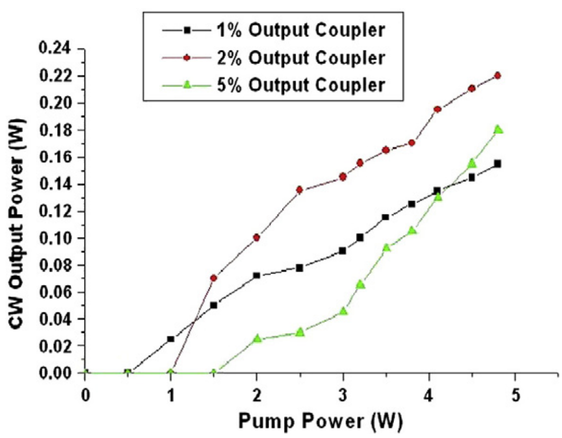

Fig. 2. CW efficiency curves for the Nd:YAG pumped Cr: Ca_2GeO_4 (Cunyite) laser taken with the 1%, 2.5%, 5% OCs.

In self-starting mode-locked operation, a pair of chirped mirrors (M4 and M5), with GVD of approximately −100 fs^2/mm per bounce, were used to provide negative dispersion. The estimated total round-trip cavity dispersion was approximately −800 fs^2. A SESAM (M7) was used to initiate and sustain mode locking. The SESAM had a low level of non-saturable loss (~0.5%), a 2% saturable absorption at 1064 nm, a 1% depth of modulation, a reflectivity of 99%, a bandwidth of 100 nm, an intra-cavity saturation fluence of 100 μJ/cm^2, and a carrier lifetime of 20 ps. The laser beam was focused onto the SESAM by a concave mirror (M3, ROC = 100 mm). The incident angle on the SESAM-focusing mirror was as small enough for optimized operation. The beam size was approximately 170 μm, upon the SESAM. The separation between the mirror (M3) and the SESAM was 6.5 cm. To obtain sufficient bleaching of the saturable absorber for pulse formation, a 100-mm radius of curvature curved mirror (M3) determines the spot size of the laser beam on the saturable absorber. With the SESAM in the cavity, the mode locking became self-starting when the separation between the SESAM (M7) and the curved mirror (M3) was optimized. The total cavity length was 150 cm, with asymmetric HR and OC arm lengths of 50 cm and 100 cm respectively. The SESAM was made of a thin narrow bandgap absorption region, which was sandwiched between a cap layer and a spacer layer placed on the top of a high reflectivity Bragg reflector. The SESAM was prepared by stacking pairs of quarter-wavelength layers that are composed of semiconductors with alternating high and low refractive indices [9]. It consists of 24.5 periods of 123 nm AlAs low-index-104.9 nm

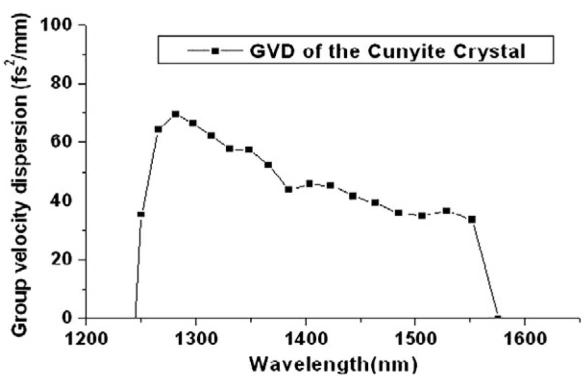

Fig. 3. Group delay dispersion (GDD) of a 3-mm Brewster cut Cr:Cunyite sample . Points represent measured values.

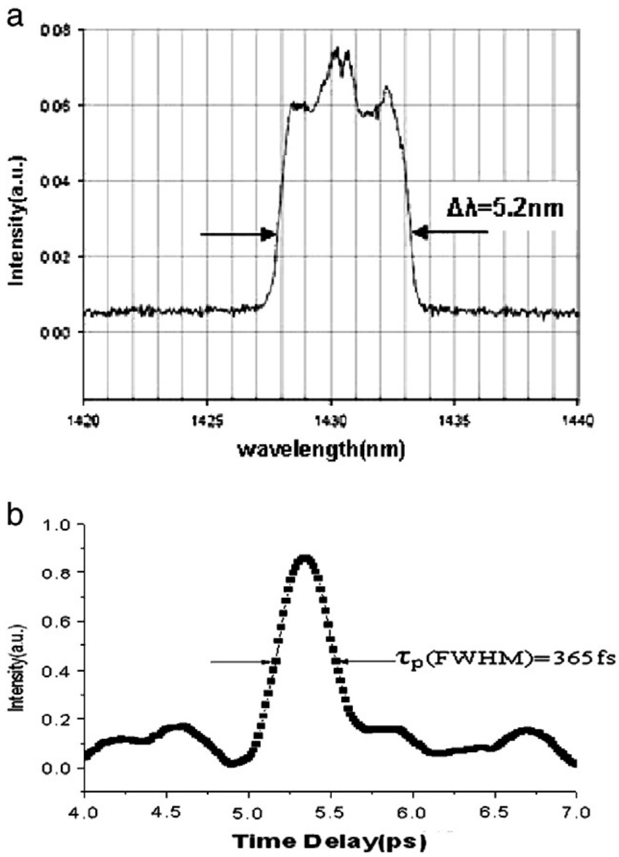

Fig. 4. (a) Measured autocorrelation trace of the mode-locked Cunyite laser Spectrum of the mode-locked pulses; (b) Central wavelength $\lambda_c = 1430$ nm, bandwidth $\Delta\lambda = 5.2$ nm, and pulse width $\Delta\tau = 365$ fs. Circles represent experimental data and the solid line is the best fit corresponding to sech^2 pulse shape. FWHMs are shown by arrows.

GaAs high-index quarter-wave layers for 1.43 μm. A 21.9 nm thick $Al_{0.48}In_{0.52}As$ buffer layer was grown between the partial Bragg stack and a double quantum well. The double quantum well in the saturable absorber region follows the buffer layer and has the following structure: 6.5 nm $Ga_{0.47}In_{0.53}$ well-8-nm $Al_{0.48}In_{0.52}$ barrier- 6.5-nm $Ga_{0.47}In_{0.53}$ well. The entire structure was capped by a 65.8-nm-thick $Al_{0.48}In_{0.52}As$ layer, so that the total thickness of the buffer -double quantum well-cap layer was 1.43-μm quarter-wave layer completing the SESAM.

Fig. 4(a) and (b) shows the intensity autocorrelation trace and spectrum of the mode-locked pulses at the maximum power of 70 mW. The *FWHM sech*^{2}-fit pulse duration is 365 fs and the spectral width is 5.2 nm centered at 1430 nm.

4. Conclusions

In summary, a self-starting mode-locked Cr:Cunyite laser at 1450 nm was achieved with an $In_{0.47}Al_{0.53}As$ buffer layer, which was inserted between the GaAs/AlAs mirror and the $In_{0.48}Ga_{0.52}As$ quantum well generating FWMM of 365 fs pulses with 70 mW output power. With the implementation of intra-cavity group-dispersion compensation, shorter pulses will be pursued in the near future. Work is in progress to directly amplify these femtosecond pulses which may lead to a reliable high-energy light source.

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