Appl Phys B
DOI 10.1007/s00340-011-4843-2

Applied Physics B
Lasers and Optics

OPCPA pump laser based on a regenerative amplifier with volume Bragg grating spectral filtering

M. Hemmer · A. Vaupel · M. Wohlmuth ·
M. Richardson

Received: 7 August 2010 / Revised version: 3 August 2011

Abstract A novel Nd:YVO_4−based regenerative amplifier system operating in the picosecond regime featuring a volume Bragg grating (VBG) as an intracavity spectral narrowing element is described. This compact amplifier provides pulses with duration of ∼85 ps operating at repetition rates ranging from single shot to 10 kHz. The VBG is used to passively tailor the pulse duration and achieve transform-limited pulses with 50 pm FWHM of spectral linewidth. A Gaussian output beam profile is obtained from the amplifier at all repetition rates. The intracavity VBG also guarantees a high spectral purity by efficiently preventing the build-up of out-of-band ASE. The spectral, spatial and temporal properties of this amplifier make it highly suitable for OPCPA pumping applications.

1 Introduction

Picosecond, low divergence Gaussian mode pulses in the near IR with energies reaching the multi-millijoule level at multi-kHz repetition rate are of particular interest for pumping broadband Ti:sapphire-based OPCPAs. Optimal parametric amplification imposes severe requirements on the pump beam parameters of these systems such as excellent beam quality and high pulse stability. Several pathways have been investigated for the generation of high-energy picosecond pulses in various repetition rate regimes. A regenerative amplifier producing up to 3 mJ of output energy at 10 Hz has been reported by Ishii et al. [1] and an Yb:YAG thin disk regenerative amplifier was reported by the same group yielding up to 25 mJ at 3 kHz [2]. Another approach involving an Yb:YAG thin disk regenerative amplifier operating at 140 kHz with 40 μJ output energy has been reported [3]. A cryogenically cooled Yb:YAG regenerative amplifier providing picosecond pulses with energy up to 40 mJ at 2 kHz repetition rate was also reported [4]. Several recent investigations have been carried out involving Nd:YVO_4-based regenerative amplifiers operating at repetition rates from 40 kHz to 200 kHz without spectral control [5, 6]. On the other hand, fiber-based amplifier schemes allow scaling of the repetition up to MHz; however, output energies are currently limited to the hundreds of microjoules [7, 8].

In this paper, we present a picosecond Nd:YVO_4-based regenerative amplifier featuring for the first time in this type of system a volume Bragg grating [9, 10] used as a spectral filter and pulse broadening element. This design also features a diode side-pumped amplifier module enabling extra flexibility and compactness compared to previously reported systems employing end-pumped geometry [4, 5]. This amplifier, seeded by pulses from a fiber-amplified Ti:sapphire laser-based source, produces 85 ps transform-limited pulses with energies up to 880 μJ at 1 kHz and 500 μJ at 10 kHz without requiring additional stretcher and compressor assemblies [2]. Numerical optimization of the cavity [11] allowed for compensation of the thermal lensing in the required output energy range enabling the propagation of a perfect Gaussian beam profile at all pump powers. The VBG ensures an in-band energy (defined as the power falling

---

M. Hemmer · A. Vaupel · M. Richardson (✉)
Townes Laser Institute, CREOL, The College of Optics
and Photonics, University of Central Florida, 4000 Central
Florida Blvd., Orlando, FL 32816, USA
e-mail: mcr@creol.ucf.edu
Fax: +1-407-8236880

M. Wohlmuth
Department of Computer Science and Erlangen Graduate School
in Advanced Optical Technologies (SAOT), Friedrich-Alexander
University Erlangen-Nürnberg, Cauerstr. 6, 91058 Erlangen,
Germany

within the reflectivity bandwidth of the VBG) to out-of-band energy (defined as the power falling outside the reflectivity bandwidth of the VBG) ratio maintained to greater than 10^5 at all repetition rates, a hundred-fold improvement over previously reported work [5]. The stable, clean and tailored pulses generated by this regenerative amplifier currently seed subsequent amplifiers providing up to 2.2 mJ at multi-kHz repetition rate and in the near future up to 15 mJ in the same repetition rate range [12].

2 Amplifier layout and design

An ultrabroad band Ti:sapphire oscillator delivering an octave-spanning spectrum ranging from 550 nm to 1.2 µm (IdestaQE Inc.) seeds a fiber pre-amplifier that provides 5 ps pulses with ∼2 nJ of energy and ∼20 nm of spectral bandwidth centered at 1064 nm with 85 MHz repetition rate. An $RbTiOPO_4$ (RTP) pulse picker (Quantum Technology) reduces the repetition rate from 85 MHz to any repetition rate up to 25 kHz before seeding the regenerative amplifier (Fig. 1a).

The gain medium of the regenerative amplifier is a 4 cm long, 2 mm diameter $Nd:YVO_4$ crystal (0.3 at.%) radially pumped by up to 180 W of continuous optical power, provided by three sets of diode bar arrays in a side-pump arrangement (RBA module, Northrop Grumman CEO). Pulses are injected into and ejected from the cavity by a β-BaB_2O_4 (BBO) Pockels cell (Quantum Technology) operating at repetition rates of up to 25 kHz. The pulse duration and spectral purity are controlled in the regenerative amplifier. The latter is achieved by replacing one of the highly reflective cavity end mirrors by an AR-coated VBG (Optigrate Corp.). The VBG ($0.5 \times 0.5 \times 1$ cm^3) used for the experiment has a reflectivity linewidth of 50 pm FWHM centered at 1064.35 nm and a reflectivity of 70% set by the design. The volume Bragg grating is recorded at a slant angle with respect to its glass faces to prevent parasitic lasing due to Fresnel reflections.

The side-pumped rod geometry enables a large mode volume in the crystal with uniform gain, reducing thermal lensing and the risks of optical damage when operating in the picosecond regime. Employing an optimized mode volume is important to (i) simultaneously prevent the excitation of higher-order transverse modes, (ii) improve the signal-to-ASE ratio and (iii) efficiently extract the gain. The size of the mode volume and the cavity stability—both relying on the strong thermal lensing induced in the YVO_4 crystal—were numerically optimized by a commercially available software (LAS-CAD GmbH) using a method described in [11]. The simulation indicates that a thermal lens increasing with the pump power leads to a larger mode volume in the rod but also to a smaller beam size on the end mirror and the VBG (Fig. 1b). The design predicts that the maximum pump power that can be used, limited by the damage threshold of the dielectric coating of the end mirror and the VBG, is ∼100 W. It was numerically found, and experimentally proven, that a 1 m long flat-flat cavity with a round-trip time of ∼7 ns, compatible with the switching time of the high voltage supply of the Pockels cell, offered the best compromise between energy extraction, beam quality, simplicity and stability of the design, and reduced risk of optical damage.

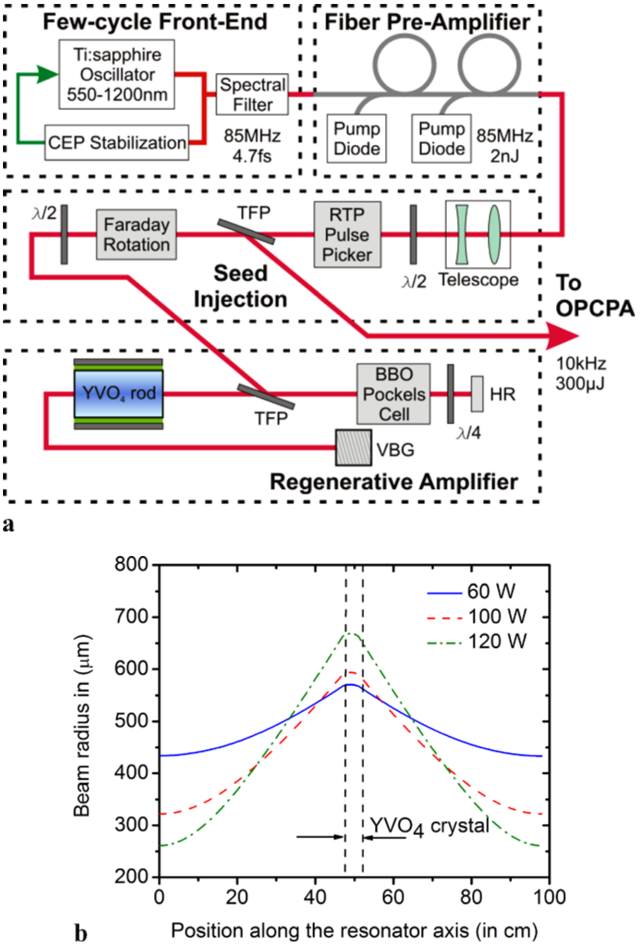

Fig. 1 **a** Compact layout of the regenerative amplifier (30×60 cm^2) and seed injection scheme; **b** numerical simulations of the evolution of the beam diameter through the cavity showing both an increased beam diameter in the crystal and reduced spot size on the end mirrors for increased pump powers. The positions at 0 cm and 100 cm correspond to each ends of the cavity

3 Amplifier performance

The cavity design described above was extensively characterized in performance using the fiber-amplified Ti:sapphire seed source. When injected with 2 nJ pulses, the 1 m long flat-flat cavity regenerative amplifier provides output pulses

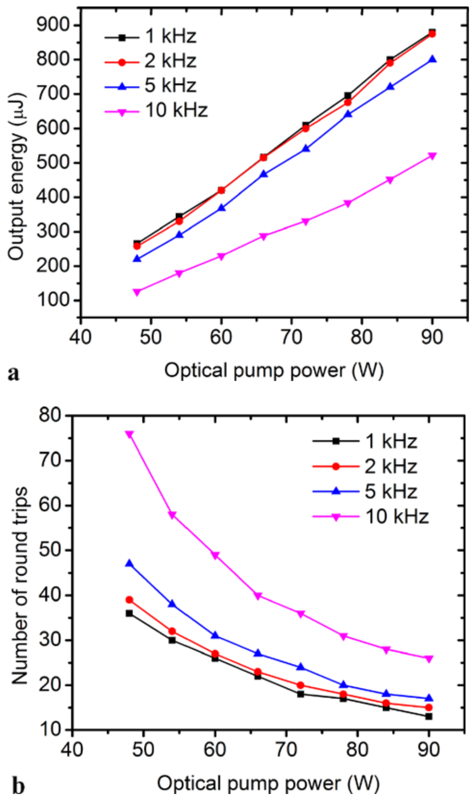

Fig. 2 **a** Output energy versus optical pump power at 1 kHz (*black squares*), 2 kHz (*red circles*), 5 kHz (*blue upward triangles*) and 10 kHz (*pink downward triangles*) repetition rate; **b** Number of round trips required to reach saturation versus optical pump power at 1 kHz (*black squares*), 2 kHz (*red circles*), 5 kHz (*blue upward triangles*) and 10 kHz (*pink downward triangles*) repetition rate

with up to 880 µJ pulses, corresponding to an optical gain of 4.4×10^5. Figure 2a shows the output energy as a function of pump power for repetition rates ranging from 1 kHz to 10 kHz. For operation at repetition rates up to 5 kHz, the output energy remains essentially constant, while operation beyond 5 kHz resulted in decreased output energy. The 40% decrease in output energy between operation at 5 kHz and 10 kHz is due to gain reduction attributed to the insufficient pumping rate. Operation at higher repetition rates beyond 10 kHz resulted in chaotic behavior and bifurcation [5, 6, 13, 14].

The 4 cm active length and large emission cross-section ($\sigma = 1.14 \times 10^{-22}$ m^2) of the Nd:YVO$_4$ rod produces a high single-pass small-signal gain ($g \approx 3$ at 100 W pump power) reducing the number of round trips required to reach saturation. Figure 2b shows the evolution of the number of round trips required to reach saturation as a function of pump power. Similar to the output energy, no major change was observed for repetition rates up to 5 kHz. An increased number of round trips is required for repetition rates beyond 5 kHz, confirming that the gain is reduced and saturation is harder to achieve. The VBG used in this experiment has a reflectivity of only 70% to safely investigate the behavior of a VBG in a picosecond regenerative amplifier cavity. Ultimately, a VBG with 99.9% reflectivity can be inserted in the cavity, resulting in insertion losses lower than etalons (typically 5%) while providing comparable spectral filtering power and ease the cavity alignment process.

For regenerative amplifiers to maintain a high temporal pulse fidelity, it is necessary to limit the amount of ASE between pulses. In our design this is performed spatially and spectrally. Spatially, the cavity design ensures a maximized overlap between the pumped volume of the rod and the mode beam size preventing unseeded regions of the rod to spontaneously emit. Simultaneously dramatic spectral narrowing is achieved via the insertion of an intracavity VBG ensuring that amplification occurs in a limited spectral bandwidth.

The effects of both these measures to reduce ASE have been experimentally verified: first the cavity was purposely modified to feature an increased pump-to-signal mode area mismatch. The behavior of the amplifier in such configuration was investigated with both a VBG and a dielectric $R = 60\%$ output coupler to decouple the spatial and spectral properties (Fig. 3a). Second, the output spectrum of these two seeded cavities was measured to provide some insight on the out-of-band ASE (defined as the ASE produced outside the reflection bandwidth of the VBG) reduction capabilities of the VBG in a configuration prone to ASE generation (Fig. 3b). Finally a measure of the time domain SNR has been performed to confirm the lack of in-band ASE (defined as the ASE falling within the reflectivity bandwidth of the VBG and potentially leading to a nanosecond pulse pedestal around the amplified pulse) by efficiently frequency-doubling the output of the regenerative amplifier.

In order to intentionally generate excess ASE, the amplifier was modified such that the mode beam size in the gain medium was reduced from 1.2 mm to 600 µm diameter for the TEM$_{00}$ mode. Pumping the entire volume of the rod while partially seeding the pumped volume resulted in a large pumped and unseeded volume prone to ASE. The modification of the mode beam size was achieved by inserting two identical AR-coated 17.5 cm focal length lenses on each side of the rod. Adjusting the position of the lenses in the cavity enabled controlling the mode beam size in the rod as the thermal lens power increased with increased pump power. The mode beam size was estimated via LAS-CAD computations. To demonstrate the importance of the cavity design in limiting ASE, particularly in the case of a side pumped gain media, the VBG was replaced by a $R = 60\%$ dielectric output coupler. Competition between ASE and pulse energy results in limited pulse amplification beyond 100 W of pump power. If the pump power is further increased, instabilities start to appear in the time domain while the output energy stops increasing linearly. This behavior is

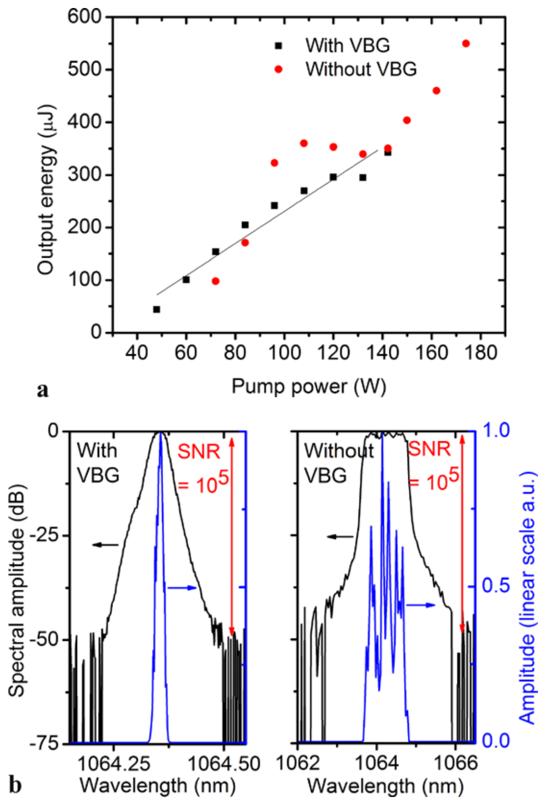

Fig. 3 **a** Measured output energy versus pump power with the amplifier operated with the VBG in the cavity (*black squares*) and without the VBG (*red circles*) at 1 kHz repetition rate; **b** Spectra recorded for a pump power of 80 W with the amplifier operated with the VBG as the end of the cavity on a log scale (*black line*, *left plot*) and linear scale (*blue line*, *left plot*) and with an HR mirror replacing the VBG on a log scale (*black line*, *right plot*) and linear scale (*blue line*, *right plot*). The wavelength scale is dramatically different due to the spectral narrowing effect of the intracavity VBG. **a** and **b** have been obtained with the detuned cavity featuring a mismatch between pump and seed volumes

attributed to competition between gain saturation in the reduced seeded volume of the rod limiting the pulse amplification, and increasing gain in the non-seeded region of the crystal, leading to increased ASE levels. This interpretation was confirmed by replacing the dielectric output coupler by the VBG: in this case, the relationship between pump power and output energy remains linear for pump powers up to 140 W (Fig. 3a). The broad ASE spectrum is still generated from the gain medium and the cavity layout being identical, the generated photons have the same chances of resonating throughout the cavity but the VBG enables only a small spectral fraction of these photons to resonate, therefore limiting the overall ASE and providing stable operation.

This behavior has been confirmed by investigating the effects of the VBG on out-of-band ASE generation. The output spectrum of the cavity with poor pump-to-signal mode matching was measured with the VBG and with the $R = 60\%$ output coupler (Fig. 3b). The seed spectrum was identical in both cases and covered the entire emission bandwidth of the Nd:YVO$_4$ gain medium. Measurements were performed at a pump power of 80 W, lower than the power at which the cavity equipped with the dielectric output coupler became unstable (Fig. 3a). Replacing the amplifier cavity end mirror by a VBG results in dramatic spectral narrowing of the pulse spectrum from 1.2 nm FWHM with the dielectric mirror output coupler down to ~50 pm FWHM spectral linewidth once the VBG was inserted in the cavity. Figure 3b compares the output spectra measured when the amplifier was operated with the VBG as an end-mirror versus an output coupler with 40% reflectivity. The in-band to out-of-band ratio in the case featuring the VBG is as high as 10^5 despite the poor signal-to-pump volume matching and the emission bandwidth is as narrow as 300 pm at -50 dB. When the VBG was replaced by the dielectric output coupler, amplification over the entire emission bandwidth (3.5 nm at -50 dB) was observed. In addition to providing a higher spectral purity and prevent mode hopping, the VBG allows temporal tailoring of the pulse as discussed further in this paper.

A measure of the temporal SNR (defined as the ratio between the energy contained in the pulse versus the energy in the background) has been performed by frequency doubling the output of the regenerative amplifier with the intracavity VBG and featuring the optimized pump-to-signal overlap. The pulse cleanliness was investigated using the optimum cavity design with maximum filling of the pump volume (in the conditions used to record data from Fig. 2) by frequency-doubling of the amplifier output in a non-critically phase-matched 2 cm long LiB$_3$O$_5$ (LBO) crystal. The beam was loosely focused into the crystal to a measured beam diameter of 1.4 mm resulting in peak intensity of 1 GW·cm^{-2}. The resulting conversion efficiency was ~ 60%, confirming the negligible influence of the in-band ASE.

The effects of the VBG on the pulse duration were also investigated in the optimal cavity design configuration enabling maximum overlap between pumped and seeded volumes. When operated with the dielectric output coupler, the 1.2 nm wide output spectrum (similar to Fig. 3b) resulted in a transform-limited pulse duration of 1.4 ps significantly shorter than the measured 25 ps duration (Fig. 4). This confirms the presence of chirp in the seed pulse attributed to its propagation in the fiber pre-amplifier. Once the VBG was inserted in the cavity, the spectrum narrowed to 50 pm linewidth FWHM thereby reducing the influence of initial chirp and producing a close to transform-limited pulse width of 85 ps duration The choice of an 85 ps target pulse duration is chosen to minimize effects of jitter in OPCPA pumping applications and mitigate B-integral effects in subsequent amplifiers. Nonetheless, shorter pulse durations could be achieved by simply replacing the intracavity VBG. The corresponding spectrum is that shown in Fig. 3b-left at 80 W pump power since the pumped to seeded volume had little

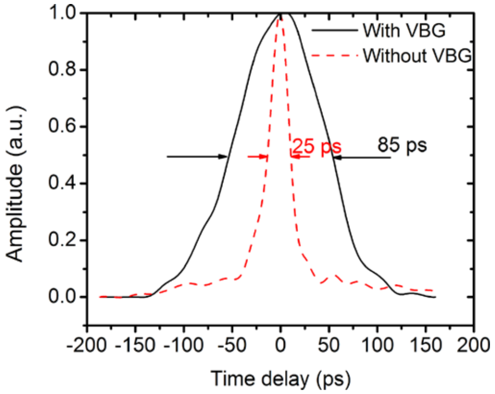

Fig. 4 Intensity autocorrelation trace of the output pulse with the VBG in the cavity (*black solid line*) and without the VBG (*red dashed line*) for an optimized cavity with maximum pumped to seeded volume overlap at 80 W pump power

influence on the spectral shape. Figure 4 shows intensity autocorrelation signals of the output pulses when the regenerative amplifier was operated with and without VBG.

Another critical requirement for OPCPA pump sources is excellent spatial profile. The seed of the regenerative amplifier is pre-amplified in a single-mode ytterbium fiber, therefore ensuring a perfect TEM_{00} spatial seed profile. The choice of $Nd{:}YVO_4$ as a gain medium allows high single-pass gain, allowing a reduced number of passes in the crystal to reach saturation, hence limiting the amount of B-integral (B ∼0.1 in the last pass) acquired primarily during propagation through the gain medium [14]. As a consequence, the output beam profile suffers no degradation in beam shape compared to the Gaussian input spatial profile. Figure 5 shows typical beam profiles obtained at maximum output energy for the cavity designed for maximum overlap between pump and seed volumes.

4 Conclusion

A novel picosecond regenerative amplifier featuring a VBG spectral filter as an output coupler is presented. The amplifier provides pulses with up to 880 µJ at repetition rates up to 2 kHz and 500 µJ at 10 kHz in 85 ps pulse duration. The use of a VBG results in dramatic spectral narrowing, optimum pulse tailoring and enhanced signal to ASE ratio while remaining user friendly. The pulses produced by the regenerative amplifier have been frequency-doubled with up to 60% efficiency in an LBO crystal and are therefore a suitable pump laser source for an optical parametric chirped pulse amplifier (OPCPA).

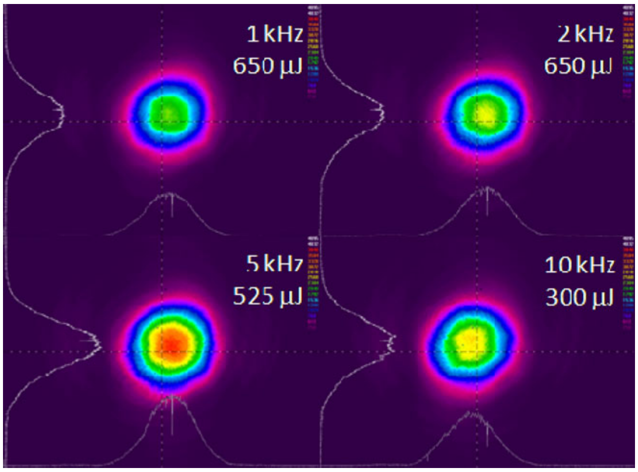

Fig. 5 Beam profile at the output of the oscillator recorded at 1 kHz (*upper left*), 2 kHz (*upper right*), 5 kHz (*lower left*) and 10 kHz (*lower right*). Measurements were performed at 80 W pump power for the optimized cavity

The authors would like to thank the Ultrafast Photonics Group at CREOL for the loan of the spectrum analyzer (Fig. 3b), Vadim Smirnov at Optigrate for the collaboration on the VBG and Tim McComb and Lawrence Shah for fruitful discussions. This work is funded by the DoE and the State of Florida.

References

1. N. Ishii, C.Y. Teisset, T. Fuji, S. Köhler, K. Schmid, L. Veisz, A. Baltuska, F. Krausz, IEEE J. Sel. Top. Quantum Electron. **12**, 173 (2006)
2. T. Metzger, A. Schwarz, C.Y. Teisset, D. Sutter, A. Killi, R. Kienberger, F. Krausz, Opt. Lett. **34**, 2123 (2009)
3. M. Schultze, T. Binhammer, A. Steinmann, G. Palmer, M. Emons, U. Morgner, Opt. Express **18**, 2836 (2010)
4. K. Hong, J. Gopinath, D. Rand, A.M. Siddiqui, S. Huang, E. Li, B.J. Eggleton, J.D. Hybl, T.Y. Fan, F.X. Kärtner, Opt. Lett. **35**, 1752 (2010)
5. M. Grishin, V. Gulbinas, A. Michailovas, Opt. Express **17**, 15700 (2009)
6. M. Lührmann, C. Theobald, R. Wallenstein, J.A. L'Huillier, Opt. Express **17**, 22761 (2009)
7. J. Rothhardt, S. Hädrich, T. Gottschall, T. Clausnitzer, J. Limpert, A. Tünnermann, Opt. Express **17**, 24130 (2009)
8. S. Hädrich, J. Rothhardt, F. Röser, T. Gottschall, J. Limpert, A. Tünnermann, Opt. Express **16**, 19812 (2008)
9. L. Glebov, in *Advanced Solid State Photonics* (OSA, Washington, 2008)
10. A.V. Okishev, C. Dorrer, V.I. Smirnov, L.B. Glebov, J.D. Zuegel, Opt. Express **15**, 8197 (2007)
11. M. Wohlmuth, C. Pflaum, L. Altmann, M. Paster, C. Hahn, Opt. Express **17**, 17303 (2009)
12. M. Hemmer, A. Vaupel, B. Webb, M. Richardson, in *Photonics West* (SPIE, San Francisco, 2010)
13. J. Dörring, A. Killi, U. Morgner, A. Lang, M. Lederer, D. Kopf, Opt. Express **12**, 1759 (2004)
14. M. Grishin, V. Gulbinas, A. Michailovas, Opt. Express **15**, 9434 (2007)