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JTh2A.32
Experimental Analysis of the Influence of the Spectral Width of Out-coupling Fiber Bragg Gratings to the amount of Stimulated Raman Scattering in a cw kW fiber laser oscillator, Andreas Liem1, Erik Freier2, Christian Matzdorff2, Volker Reichel1, Thomas Schreiber1, Ramona Eberhardt1, Andreas Tünnermann1; 1Fraunhofer Institute for Applied Optics and Precision Engineering, Germany; 2Friedrich-Schiller-University Jena, Institute of Applied Physics, Germany. The spectral behavior of a LMA cw kW fiber laser oscillator was measured depending on the spectral width of the output FBGs (0.04 nm, 0.5 and 1.5 nm (FWHM)). The SRS thresholds were compared.

JTh2A.33
Driving Current Induced Spectral Effect in RSOA-based Mode-Locked Fiber Laser, Chunshu Zhang1, Nicolas Godbout2, Bryan Burgoyne1, Youngjae Kim3, Peicheng Liao1, Alain Villeneuve1, Odile Liboiron-Ladouceur1; 1Dept. of Electrical and Computer Eng., McGill University, Canada; 2Dept. of Eng. Physics, Polytechnique Montréal, Canada; 3Genia Photonics, Canada. A directly modulated mode-locked fiber laser is studied based on dispersion tuning technique by using an RSOA and a CFBG. The impact of the electrical pump current on the laser performance is studied.

JTh2A.34
Limits of the Energy Scalability for Chirped-Pulse Fiber and Solid-State Laser Oscillators, Vladimir L. Kalashnikov1, Alexander Apolonski2; 1Technische Universität Wien, Austria; 2Ludwig-Maximilians-Universität and Max-Planck-Institut für Quantenoptik, Germany. It is shown, that the quantum noise and the stimulated Raman scattering impose fundamental constraints on the energy scalability of femtosecond laser oscillators operating in normal dispersion regime.

JTh2A.35
Spatio-spectral Phase-matching in Broadband Soliton Mode-locked Lasers, Shih-Huan Chia1,2, Li-Jin Chen2, Franz X. Kaertner1,3; 1IDES, Germany; 2IEECS, MIT, USA; 3Physics, Hamburg University, Germany. A spatio-spectral phase-matching theory is introduced. It is used to improve broadband mode-locking of a Ti:sapphire laser with a tunable enhancement of >15dB at long wavelengths while maintaining a good beam profile.

JTh2A.36
Amplification of Burst Mode Picosecond Pulses to High Peak Powers in Chirally Coupled Core (3C) Fibers, Timothy S. McComb1, Dennis McCall1, Roger Farrow2, David Logan1, Tyson L. Lowder1, Changpeng Ye1, Thomas Sosnowski1; 1University of Idaho, USA; 2Physics, Hamburg University, Germany. The spectral behavior of a LMA cw kW fiber oscillator was measured depending on the spectral width of the output FBGs (0.04 nm, 0.5 and 1.5 nm (FWHM)). The SRS thresholds were compared.

JTh2A.37
Laser-Induced Efficiency Improvement for Thulium-doped Fiber Laser Systems, Cesar Jauregui1, Fabian Stutzki1, Florian Jansen1, Jens Limpert1, Andreas Tünnermann1; 1Friedrich-Schiller-Universität Jena, Germany; 2Fraunhofer Institute for Applied Optics and Precision Engineering, Germany. In this paper it is shown that pumping at the excited state of Thulium high-power fibers leads to a significant cooling and efficiency improvement. Nearly a factor 2 higher efficiency is expected with this technique.

JTh2A.38
Power Scaling of Raman Fiber Amplifier based Source for Laser Guide Star, Lei Zhang1, Shuzhen Cai1, Jinmeng Hu1, Lingxia Chen1, Yan Feng1; 1Shanghai Institute of Optics and Fine Mechanics, China. Quasi-CW 1178 nm single frequency Raman fiber amplifier with peak power up to 118 W is generated and frequency doubled to 589 nm with peak power up to 68 W.

JTh2A.39
High-power Three-level Neodymium Fiber Laser Sources Emitting near 910nm, Mathieu Laroche1, Baptiste Leconte1, Benoit Cadier1, Hervé Gilles1, Sylvain Girard1, Laurent Lablond1, Thierry Robin1; CMAP, France; IXFN, France. We present recent work on Nd-doped fiber laser operating on the three-level transition. Up to 20W was achieved at 910nm in CW regime. Wavelength tunability between 890nm and 925nm and pulse amplification were also demonstrated.

JTh2A.40
Diode-pumped Mode-locked Tm:YAG Ceramic Laser, Qingfeng Lin1, Yuwan Zou1, Qing Wang2, Zhaiyi Wei1, Jian Zhang1, Dingyuan Tang1; 1School of Technical Physics, Xi'an University, China; 2Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, China; 3School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. We realized a laser-diode pumped mode-locked Tm:YAG ceramic laser with a semiconductor saturable absorber for the first time to our knowledge. 60 ps laser pulse with 182mW power was obtained at 2007 nm.

JTh2A.41
Controlling the Phase-Locked States of the Array of Two Mutually-Injected Fiber Lasers, Jianqiu Cao1, Wei Zhen2, Bing Lei2, Shaofeng Guo1, Qisheng Lu1; National Univ of Defense Technology, China. The phase-locked states of the array of two mutually-injected fiber lasers are studied in experiment. Controlling of these phase-locked states is realized with a self-feedback loop.

JTh2A.42
Multiwavelength Programmable Er-doped Fiber Laser, Youngjae Kim1, Alain Villeneuve1, Nicolas Godbout2, Bryan Burgoyne1, Guido Perni; Genia Photonics Inc., Canada; École Polytechnique de Montréal, Canada. We present a multiwavelength programmable laser by simultaneously applying multiple electric pulse trains with different frequencies to the electro-optic modulator. We achieved a tunable two or three (or N) wavelengths Erbium fiber laser with 60 ps pulse width.

JTh2A.43
Amplification of Temporally Shaped Picosecond Pulses in Yb-doped Rod-type Fibers, Simonette Pierrot1, Francois Salin1; EOLIT Systems, France. A new technique to produce high power sub-picosecond pulses from a fiber amplifier starting from tenths of picoseconds Fourier transform pulses is presented. 63MW, 780fs pulses with 25W average power were obtained, and ways to scale the technique to higher peak powers were identified.
Limits of the Energy Scalability for Chirped-Pulse Fiber and Solid-State Laser Oscillators

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Abstract: It is shown, that the quantum noise and the stimulated Raman scattering impose fundamental constraints on the energy scalability of femtosecond laser oscillators operating in normal dispersion regime.

OCIS codes: (140.4050) Mode-locked lasers; (320.7090) Ultrafast lasers; (060.5530) Pulse propagation and temporal solitons.

1. Introduction

In the last decade, the concept of energy scalability of femtosecond laser oscillators was actively developing and become now well-established. Realization of this concept allowed a high-energy and high-power femtosecond pulse generation directly from both fiber and solid-state oscillators [1-3]. The pulse energy scalability is based on a capacity of chirped pulses to accumulate energy at the cost of chirp growth without a loss of stability and a spectrum narrowing. This phenomenon, called “dissipative soliton resonance” [4], was predicted on the basis of the “master diagram” representation of chirped-pulse parametric space [5].

As some recent achievements on the road of femtosecond pulse energy scalability, one can point at generation of 20 nJ pulses (compressible down to 200 fs) from an all-fiber-laser operating at 7 MHz pulse repetition rate [6]; 30 nJ pulses (compressible down to 80 fs) [7] and 280 nJ [8] pulses from fiber lasers with a free-space sector operating at 70 and 1.2 MHz repetition rates, respectively; 0.9 μJ pulses (compressible down to 90 fs) from a 76 MHz large-mode-area fiber laser [9]; 0.5 μJ (compressible down to 30 fs) [10] and 1.1 μJ (compressible down to 74 fs) [11] pulses from Ti:Sa solid-state oscillators operating at 2 and 1 MHz repetition rates, respectively; and, at least, 0.75 μJ pulses (compressible down to 190 fs) from a 40 MHz thin-disk Yb:YAG oscillator [12].

Such and quite reachable higher pulse powers would allow bringing the high-field physics on tabletop scales of a mid-level university lab. High energy pulses at MHz repetition rates are required for various applications (e.g. coherent high harmonics and ultra-broad frequency comb supercontinuum generation, lithography and modification of transparent materials, seeding parametric amplifiers, ultra-sensitive spectroscopy, etc.) need a further pulse energy scaling up to mJ level. Therefore, an understanding of fundamental limits of the energy scalability is a critical issue for further development of all-normal (chirped pulse) oscillators.

2. Concept of the pulse energy scalability

Evident constraints on the pulse energy scalability are imposed by instabilities due to both dissipative and non-dissipative nonlinearities in a laser. This means that a pulse peak power $P_0$ has to be kept below some critical value. Such a confinement can be provided by dissipative factors in a laser: saturation of self-amplitude modulation (SAM) for a soft-aperture Kerr-lens mode locking or mode-locking due to nonlinear polarization evolution (with the corresponding inverse power of saturation $\zeta$), as well as spectral dissipation provided by perfectly saturable absorber (with the squared inverse bandwidth of a spectral filter $\alpha$). The energy scaling can be then provided by only pulse stretching. If $\zeta$ is the parameter limiting the pulse peak power, then one has an approximated energy scaling law $E = 2\sqrt{2}|\beta|/\zeta\gamma$ for a chirp-free soliton from the soliton area theorem. Here $\beta$ is a net-group-delay dispersion (GDD) coefficient and $\gamma$ is the net-self-amplitude (SPM) modulation coefficient for a defined laser setup. Such an energy scaling causes a growth of the pulse duration and squeezing of its spectrum $\propto 1/\sqrt{|\beta|}$, which can be compensated by only nonlinear external pulse broadening and subsequent compression. A chirped pulse provides an alternative mechanism of energy scaling due to pulse stretching (Fig. 1, right; black solid line) caused by chirp (Q): $E \propto Q$ [2,3]. Such a pulse with a linear chirp can be easily compressed outside a resonator. The spectrum width in this case tends to some constant value $\Omega = 2\sqrt{2/3}\alpha$ defined by only spectral filter/gain bandwidth so that the pulse duration $T$ after linear compression $\propto \sqrt{\alpha}$. The phenomenon of perfect energy scalability was called a “dissipative soliton resonance” (DSR) [4] and corresponds to the asymptotic $\lim_{c=\rightarrow 2/3} (E c^{3/2} \zeta / \gamma \sqrt{\alpha}) = \infty$, which can be obtained from the adiabatic theory of chirped dissipative soliton [5] (see Fig. 1, left; black curves. $\kappa$ is the inverse...
power of the nonlinear loss saturation in a laser, \( C \equiv \alpha \gamma / \beta \kappa \). It is obvious, that an existence of such asymptotic provides perfect energy scalability by laser cavity lengthening or pump power scaling, for instance.

\[
\frac{\partial a(z,t)}{\partial z} = i \beta \frac{\partial^2}{\partial t^2} - (1 - f_R) \alpha |a|^2 \right) a + \left( -\alpha + \beta \frac{\partial^2}{\partial t^2} + \kappa (1 - \zeta |a|^2) |a|^2 \right) \right) a - \left( -i f_R \gamma a(z,t) \int_{-\infty}^{t} dt' h(t-t') |a(z,t')|^2 + s(z,t), \right)
\]

where \( a(z,t) \) is a slowly varying amplitude of the laser field depending on a propagation distance \( z \), which is periodical so that \( z = z + nL \) (\( n \) is a laser cavity round-trip number, \( L \) is a length of a ring cavity or doubled length of a linear cavity), \( t \) is the local time, \( \sigma \) is the energy-dependent saturated net-loss coefficient. For the first time to our knowledge, a complex quantum noise term \( s(z,t) \) and a stimulated Raman scattering (SRS) in its full form are included in Eq. (1). The noise correlation properties are defined by \( \langle s(z',t)s^*(z,t) \rangle = \Gamma \delta(z' - z) \delta(t' - t) \). The parameter \( f_R \) defines a fraction of SRS in SPM, and the Raman response function is defined as \( h(t) = \frac{T^2}{T_1 T_2} e^{t/T_1} \sin \left( \frac{T_2}{T_1} \right) \) [15].

Black solid curves in Fig. 1 demonstrate the pulse stability threshold, or a master diagram (left) and the normalized pulse duration in dependence on the normalized energy in the absence of noise (\( \Gamma = 0 \)). Horizontal asymptotic of the threshold for \( E \kappa \sqrt{\kappa z} / \gamma \sqrt{\alpha} > 100 \) (left), as well as the power law scaling of the pulse duration (right) demonstrate the DSR, i.e. a perfect scalability of the pulse, in agreement with the adiabatic theory of the chirped dissipative soliton [5]. Blue reference point in Fig. 1, left, corresponds to a real-world fiber laser configuration with the parameters like those in [13].

In the presence of noise (\( \Gamma = 10^{-10} / \gamma L \) if \( z \) is normalized to \( L \)), the DSR disappears (dashed red curve in Fig. 1, left). This means that a decrease of the control parameter \( C \equiv \alpha \gamma / \beta \kappa \) is required to stabilize the pulse at higher energies. In other words, one has to increase i) GDD or/and ii) self-amplitude modulation or/and iii) spectral filter bandwidth, or/and to reduce SPM. As a result of the \( C \)-decrease along the stability border, the pulse becomes longer in the presence of noise (dashed red curve in Fig. 1, right). The most critical manifestation of the noise influence is that a stable pulse generation becomes impossible at all, if the parameter \( E \kappa \sqrt{\kappa z} / \gamma \sqrt{\alpha} \) exceeds some critical value. Above this value, only strongly chaotic regimes exist.

For a high-energy mode-locked fiber laser, where the SRS plays an important role [6], the issue of the stability loss is aggravated. Since the SRS causes the spectrum red-shift, the spectral loss increases, reducing the pulse...
energy $E$ and, as a consequence, the gain saturation. As a result, the net-loss coefficient $\sigma$ in Eq. (1) becomes negative and multiple pulse generation develops. Hence, the pulse stabilization requires a further decrease of the $C$-parameter. The pulse stabilized in this way represents a new type of a dissipative soliton, notably a chirped dissipative Raman soliton (CDRS) (Fig. 2). Such a CDRS has a red-shifted spectrum ($\approx 0.02 \text{ fs}^{-1}$ for the pulse in Fig. 2) with a strongly perturbed leading edge. As a result of this perturbation, the peak power of a self-sustained CDRS evolves chaotically with preservation of mean soliton characteristics. A further decrease of the $C$-parameter (e.g., by increasing the GDD) stabilizes the pulse and reduces its spectral shift so that a CDRS becomes a usual chirped dissipative soliton having narrower spectrum and consequently increased pulse duration.

4. Conclusion

Energy scalability of femtosecond laser oscillators is a sensitive issue of modern laser technology. The phenomenon of the DSR promised perfect energy scalability via the pump or resonator length scaling. Nevertheless, our analysis based on the nonlinear complex Ginzburg-Landau equation demonstrates that the DSR disappears in the presence of quantum noise and SRS so that an essential adjustment of laser parameters is required for the pulse stabilization. Unfortunately, even such an adjustment does not allow further scaling if the energy exceeds some critical value. Only strongly chaotic regimes exist above this critical energy. If the SRS contributes to the laser dynamics, as it takes place in a fiber laser, a tendency to multiple pulsing intensifies due to higher spectral dissipation. To suppress multipulsing, a higher GDD is necessary that narrows the spectrum and stretches the pulse. A new type of dissipative soliton appears in the vicinity of the stability border, namely a chirped dissipative Raman soliton. It has a red-shifted spectrum and a chaotically evolved peak power. One should think that further progress in generating high-energy femtosecond pulses in laser oscillators will require a modification of basic paradigms exploited so far.

This work was supported by the Austrian Fund FWF, Project P24916.

5. References


Figure 2. Self-sustained evolution of the chirped dissipative Raman soliton. $E \sqrt{\kappa}/\gamma \alpha = 110$, $C = 0.04$, $T_1 = 12 \text{ fs}$, $T_2 = 32 \text{ fs}$, $f_s = 0.22$. 
Abstract: It is shown, that the quantum noise and the stimulated Raman scattering impose fundamental constraints on the energy scalability of femtosecond laser oscillators operating in a normal dispersion regime.

Motivation:
- Chirped dissipative solitons (CDSs) are energy-scalable. This phenomenon can be interpreted as existence of dissipative soliton resonance (DSR), which is of interest for a lot of applications.
- Experiments with a CDS high-energy (>20 nJ) all-fiber laser revealed the suppression of DSR due to stimulated Raman scattering (SRS).
- There is no a theory of CDS taking into account a noise and SRS in corporate.

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Acknowledgments:
The work was supported by the Austrian FWF project P24916-N27.

Concept of CDS energy scalability and impact of noise and SRS
A well-established test bed for study of mode-locked lasers is the generalized cubic-quintic nonlinear complex Ginzburg-Landau equation (NGCLE):
\[
\frac{\partial a(x,t)}{\partial t} = i \beta \frac{\partial^2}{\partial x^2} - (1 - f_0) |a(x,t)|^2 a(x,t) + \gamma |a(x,t)|^4 a(x,t) + \sigma |a(x,t)|^2 a(x,t) + \eta \frac{\partial}{\partial x} \frac{\partial}{\partial t} a(x,t) + \xi \frac{\partial}{\partial x} \frac{\partial}{\partial t} a(x,t) + s(x,t),
\]
where \(a(x,t)\) is the slowly-varying field amplitude depending on the propagation distance \(x\) and the local time \(t\); \(\beta\) is the group-delay dispersion (GDD) coefficient; \(\gamma\) is the self-phase modulation (SPM) coefficient; \(\sigma\) is the saturable net-loss coefficient depending on the energy \(E\); \(\alpha\) is the squared inverse bandwidth of a spectral filter; \(\eta\) is the coefficient of saturable nonlinear gain (the coefficient of saturation is \(\xi\)). An important extension of traditional model is the inclusion of the SRS with the response function \(h(t) = \frac{h^2}{\sqrt{2\pi}} e^{-(t/T_1)^2} \sin \left( \frac{\pi}{T_2} t \right)\) and the corresponding response function, \(\frac{\partial}{\partial t} a(x,t)\) and \(\frac{\partial}{\partial x} a(x,t)\) are the fraction of SRS in SPM and of the complex white noise with the correlation function \(\langle e^{(x_1,t_1)} e^{(x_2,t_2)} \rangle = T_1 \langle (x_1-t_1)^2/(x_2-t_2)^2 \rangle\).

For \(\beta > 0\) (normal GDD), NCGLE has solution in the form of CDS, which can be characterized by two-dimensional master diagram. The CDS stability border \(\alpha = 0\) is of particular interest (see Fig. below). In the absence of noise and SRS, the master diagram demonstrate existence of CDS: \(\lim_{\beta \to \infty} E_{\alpha=0} \approx 0\). Such a resonance corresponds to the width (\(T\)) scaling of CDS with fixed both peak power \(P = 1/\Gamma\) and spectral width \(\Delta \lambda = \sqrt{8 T/\pi}\). Noise and SRS impede pulse energy scalability: 1) substantial decrease of \(\alpha\) parameter (i.e. GDD spectral broadening and growing Stokes shift. The latter factor enhances a tendency to multiplexing and impede the CDS energy scalability.

Different types of chirped dissipative Raman solitons (CDRSs)

- Chaotic complex of CDS+CDRS
- CDS spectrum merges with CDRS one. Sole CDRS appears
- Two CDRSs with coinciding spectra
- Sole CDRS

The energy growth causes an appearance of two CDRSs with coinciding spectra. Such a regime is analog of multiplexing for ordinary dissipative solitons and results from growth of spectral losses due to CDRS spectral broadening and growing Stokes shift. The latter factor enhances a tendency to multiplexing and impede the CDS energy scalability.

Multiplexing can be suppressed by an appropriate growth of GDD. Then, a sole CDRS with visible Stokes-shift develops. Nevertheless, all types of CDRSs behaves chaotically: 1) peak power (both temporal and spectral) evolves chaotically; 2) such an evolution is closely connected with strong disturbance of CDRS trailing edge, where blue spectral components are located; 3) respectively, short-wavelength edge of spectrum is disturbed as well.