Chirped dissipative Raman soliton and the problem of soliton energy scalability

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Abstract: For the first time, the chirped dissipative Raman soliton is demonstrated. Its dynamical properties and impact on the dissipative soliton resonance are analyzed numerically. The limits of dissipative soliton energy scalability and stability are determined.

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.

References:
Dissipative Solitons: N.N. Akhmediev, A. Ankiewicz (Eds.), 2005. Springer


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):

\[
\frac{\partial a(z,t)}{\partial z} = i \beta + \frac{\partial^2}{\partial t^2} (1-f_n) |a(z,t)|^2 a(z,t) + \gamma |(1-\delta |a(z,t)|^2) a(z,t)|^3 a(z,t) - \gamma \Delta a(z,t) + \gamma |(1-\delta |a(z,t)|^2) a(z,t)|^3 a(z,t) -
\]

where \( a(z,t) \) is the slowly-varying field amplitude depending on the propagation distance \( z \) and the local time \( t \); \( \beta \) is the group-delay dispersion (GDD) coefficient; \( \gamma \) is the self-phase modulation (SPM) coefficient; \( \alpha \) is the saturable net-loss coefficient depending on the energy \( E \); \( \alpha \) is the coefficient of saturable nonlinear gain (the coefficient of saturation is \( \gamma \)). An important extension of traditional model is the inclusion of the SRS with the response function \( n(t) = \frac{1}{\sqrt{2\pi}} \frac{e^{t/\gamma}}{\gamma} \sin (\frac{f}{\gamma} t) \), and \( f \) is the corresponding response frequency, \( f_n \) is the fraction of SRS in SPM) and of the complex white noise with the correlation function \( \langle e^{i(x', t')^2} e^{i(x, t)} \rangle = \delta (x-x') \delta (t-t') \).

For \( \beta > 0 \) (normal GDD), NGCLE 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 DSR: \( \lim_{f \to \infty} E_i = \infty \). Such a resonance corresponds to the width \( W \) scaling of CDS with both peak power \( P \) and spectral width \( W \). The CDS growth causes an appearance of two CDS with overlapping spectra. Such a regime is analog of multipulsing for ordinary dissipative solitons and results from growth of spectral losses due to CDS spectral broadening and growing Stokes shift. The latter factor enhances a tendency to multipulsing and impedes the CDS energy scalability.

Different types of chirped dissipative Raman solitons (CDRS)

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

The energy growth results in a merging of the CDS and CDRS spectra so that a sole CDRS develops. As opposed to the previous case, which can be interpreted as multipulsing and, thereby, is unstable, this regime belongs to the stability region of the master diagram. However, the evolution of peak and spectral powers are chaotic.

Multipulsing can be suppressed by an appropriate growth of GDD. Then, a sole CDRS with visible Stokes-shift develops. Nevertheless, all types of CDRS 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.

Master diagram of CDS

CDS widths corresponding to master diagram

Contour plot of spectral power

- Both CDS at central wavelength and Stokes-shifted CDRS coexist and chaotically interact via SRS. SRS acts as a nonlinear spectral and temporal filter for CDS.
- As a result, the CDS energy is confined by energy transfer to CDRS and its width is reduced. Simultaneously, the CDRS loses energy due to spectral filtering.