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Analysis of the coherent properties of ultrashort pulses inside embedded cavities of mode-locked fiber laser and Raman oscillator

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ABSTRACT

Synchronously pumped Raman oscillators provide efficient nonlinear spectral conversion of ultrashort pulses. Designing of Raman oscillators is a highly dimensional optimization task requiring extensive computations. Here, we implement novel numerical model of stimulated Raman scattering to design a specific laser system with embedded cavities of mode-locked fiber laser and Raman oscillator. Following system allows taking the advantages of high intracavity powers of mode-locked laser during Raman spectral conversion. We analyze the regions of stable coexistence of mode-locked and Raman pulses, their spectral-temporal and coherent properties.

Keywords: fiber mode-locked laser, nonlinear spectral conversion, stimulated Raman scattering, coherence spike

1. INTRODUCTION

Synchronously pumped Raman fiber oscillators provide efficient nonlinear spectral conversion of ultrashort pulses[1,2]. In conventional schemes pulses from a seed laser are launched into Raman oscillator cavity[3]. Seed pulses are pre-amplified by several cascades of fiber amplifiers in order to achieve high conversion efficiency. However, optical amplification and stimulated Raman scattering introduce additional power and phase noises into converted pulse comb.

In this work we investigate spectral conversion of the ultrashort pulses inside fiber laser system with embedded cavities of mode-locked fiber laser and Raman oscillator. Proposed scheme exploits high intracavity powers of mode-locked laser for efficient resonant Raman conversion and intracavity mode-locking mechanism. Numerical modeling of such complex nonlinear system is highly computationally demanding, especially, in case of pulses with durations longer than several tens of picoseconds, e.g. high energy dissipative solitons. To overcome this issue, we implement novel numerical model of stimulated Raman scattering to design Raman oscillator.

In this paper we demonstrate evolution of the height of coherence spike depending on cavity parameters such as: saturation power of saturable absorbers, bandwidth of spectral filters, power ratio of output couplers. It was found that Raman pulses may act in controversial manner: they may destabilize or stabilize mode-locked pulses. Only re-injection of Raman pulses is not enough to achieve fully mode-locked two-color pulses. Mode-locking for both pulses requires addition of mode-locking elements inside Raman oscillator.

2. NUMERICAL SCHEME

The principle scheme of the laser setup is depicted on Figure 1. Right (Signal) and left (Stokes) parts of the laser setup are fiber mode-locked cavity with fast saturable absorber and spectral filtration. Signal and Stokes waves interacting with each other only inside Raman fiber after which are separated by wavelength demultiplexer.

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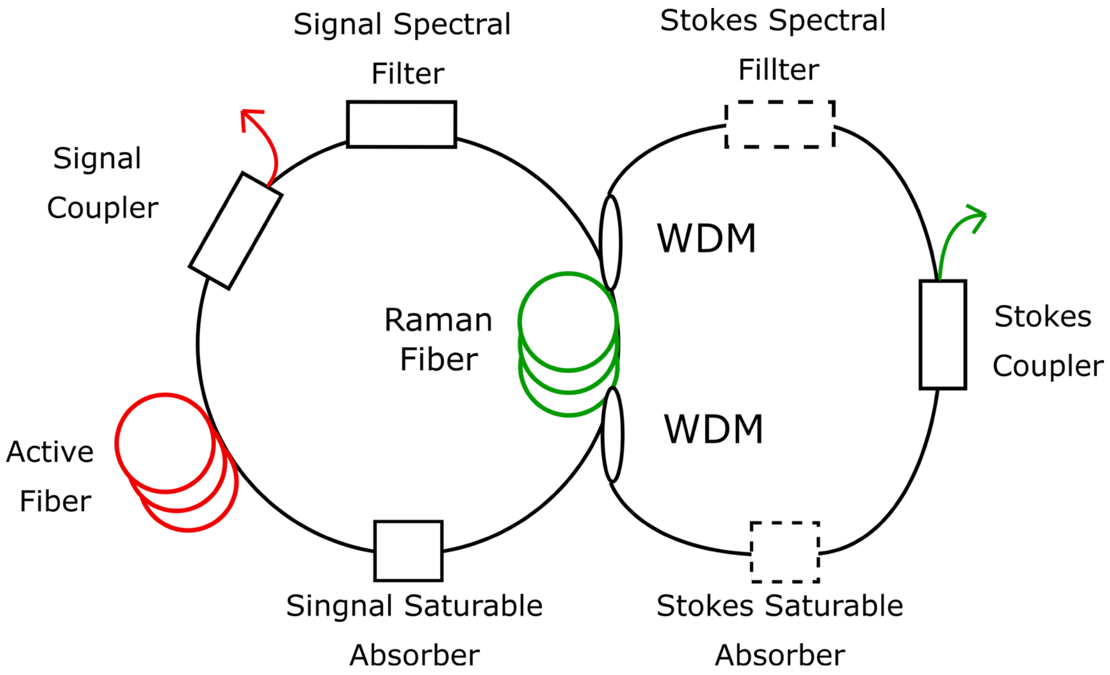

Figure 1. Principle scheme of the laser setup with two embedded cavities for signal and Stokes radiation.

In order to simulate nonlinear propagation of laser pulses along optical fibres, while taking into account Raman scattering, the generalised nonlinear Schrödinger equation (GNLSE) is widely used[4]:

$$\partial_z A = -\frac{i\beta_2}{2}\partial_t^2 A + i\gamma\left(1+\frac{i\partial_t}{\omega_0}\right)\left(A\int_0^\infty R(t')|A(z,t,-t')|^2\,dt'\right),$$

where $A(z,t)$ stands for the complex field envelope; z and t are the longitudinal coordinate and time in the retarded frame of reference; ω_0 stands for the carrier frequency; β_2 and γ are the dispersion and nonlinear coefficients, c denotes the light speed in vacuum; $i^2 = -1$. We used following values of nonlinear and dispersion coefficients in our simulations: $\gamma = 4.7$ (W km)$^{-1}$ and $\beta_2 = 1.4 \times 10^{-26}$ sec^2/m. The kernel $R(t)$ of the integral operator includes both electronic (instantaneous) and nuclear contributions: $R(t) = (1 - f_R)\delta(t) + f_R h_R(t)$. Delayed (Raman) response of silica $h_R(t)$ in the first approximation can be taken in the form of a damped oscillator[5]. Due to a short length of the Raman oscillator we neglected the linear losses of the optical fibre. In order to speed-up numerical simulations, we also used approximation of slowly varied amplitudes[5] for Eq. (3).

3. RESULTS

We chose the height of a coherence spike of autocorrelation function of the pulses as a merit of mode-locking quality. (Figure 2). For normalized autocorrelation function the height of coherence spike equal to 0.5 corresponds to fully incoherent radiation. The height of coherence spike equal to 0 corresponds to fully mode-locked pulse as depicted at (Figure 3).

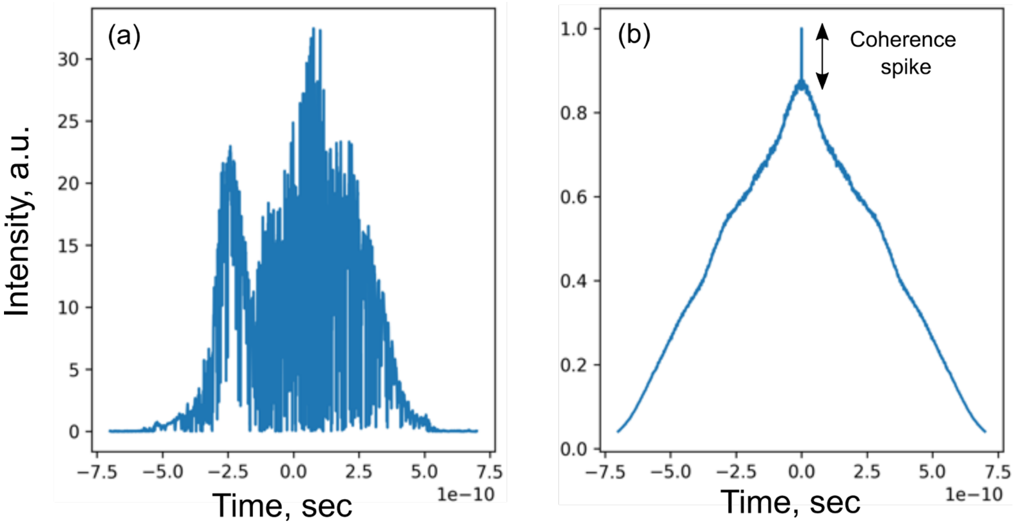

Figure 2. Time distribution of a noise-like pulse (a) and its autocorrelation function (b)

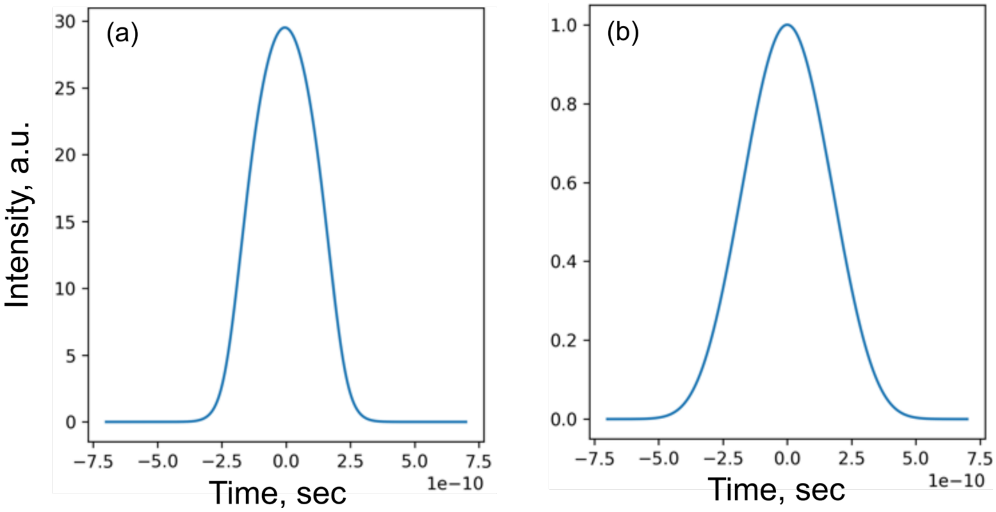

Figure 3. Time distribution of the mode-locked pulse (a) and its autocorrelation function (b)

We applied extensive grid search of the cavity parameters in order to find stable mode-locked regimes. The space of parameters was following: Signal and Stokes coupler coefficients 0.1 – 0.9, Signal and Stokes spectral filters bandwidth 1 – 15 nm, Raman fiber length 1 – 50 m, Signal and Stokes energy saturation of saturable absorbers 10 – 150 W, Saturation energy of the active fiber 0.1 – 2 nJ, small signal gain. Linear losses of saturable absorbers were fixed at 10% level.

Almost all regimes in the space of element parameters were corresponding to noisy pulses. However, we have found that coupler ratios of the output Signal and Stokes couplers play the key role in mode-locked mechanism. Increasing the fraction of output Stokes wave, it is possible to reach the case when Stokes wave is experiencing large losses in comparison with the gain inside Raman fiber. At this case, the influence of a Stokes wave to Signal wave either its power is negligible and the Right part of laser system may be considered as a separate mode-locked laser with a presence of Raman scattering effect.

More interesting result corresponds to the case when the output fraction of a Signal wave is high. We have reached co-existed stable mode-locked regimes for both pulses in the case when 90% of Signal wave was launched out the cavity. Other cavity parameters were used as follows: Signal spectral width = 8 nm, Length of Raman fiber = 50 m, Stokes spectral width = 4 nm, both saturation power of saturable absorbers = 100 W, output for Stocks wave = 0.1.

The Signal pulse had the energy equal to 0.742 nJ and time duration equal to 101.6 ps; The Stockes pulse had the energy equal to 0.03 nJ and time duration equal to 40.3 ps.

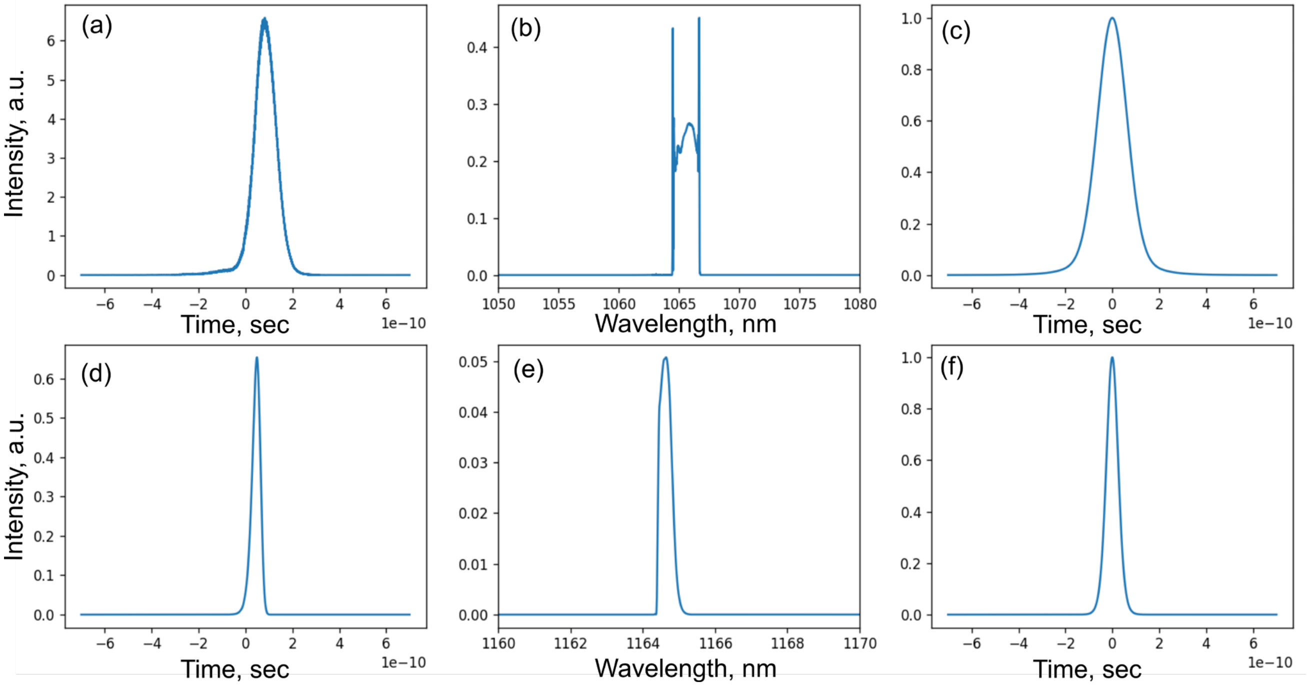

Figure 4. Time distribution (a), optical spectrum(b), autocorrelation function of a Signal pulse; Time distribution (d), optical spectrum(e), autocorrelation function (f) of a Stockes pulse

4. DISCUSSION

Here we show the possibility to reach co-existence of mode-locked regimes inside complex laser system consisted with two embedded laser cavities. The interaction between two spectrally separated pulses was implemented through stimulated Raman scattering effect. We have found that the ratio of output coupling for Stokes and Signal pulses plays major role in stabilizing mode-locking regimes. Future investigations will focuses on increasing the intracavity energies of the pulses.

5. ACKNOWLEDGMENT

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