Optimization of Mamyshev Regenerator for ultrafast pulse generation

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ABSTRACT

Fiber based Mamyshev regenerators provide potentially a low cost, pulse-on-demand source with pulse durations down to the hundred femtosecond scale. Based on nonlinear broadening of gain switched diode laser pulses in fiber and consequent pulse shaping methods, these sources could provide an alternative for mode-locked systems. Here we study numerically the properties and limitations of such sources in terms of input pulse duration and power. We show that an optimum operating region can be found for each input parameter combination, that is limited mainly by the onset of stimulated Raman scattering and optical wave breaking.

Keywords: Mamyshev regenerator, Ultrashort pulse laser, Fiber laser, Tunable repetition rate

1. INTRODUCTION

Interest in nonlinear oscillators and pulse generation by nonlinear effects has attracted attention as an alternative to the traditional mode-locked laser design. The so-called Mamyshev regenerator[1,2] or Mamyshev oscillator,[3–5] designs have reported pulse durations down to 135 fs and 40 fs. In particular, the Mamyshev regenerator has the attractive trait of providing pulse-on-demand operation as the pulses are seeded by a gain-switched laser diode (GSD). The system operates by injecting pulses with durations of tens of picoseconds from the GSD to optical fibers, where spectral broadening due to self-phase modulation (SPM) occurs. Filtering part of the broadened spectrum combined with further pulse shaping by similariton amplification can provide coherence improvement and spectral bandwidths with linear chirp profiles compressible down to the hundred femtosecond regime.[1]

In order to reduce the cost of these systems, it would be beneficial to use GSDs with longer pulse durations. However, longer pulses tend to provide less spectral broadening that is insufficient for filtering. Increasing pulse peak power and/or increasing fiber length are straightforward ways to circumvent this problem. Nevertheless, this approach has its limitations, as stimulated Raman scattering (SRS) arising from noise and optical wave breaking (OWB) start affecting the pulse properties in degrading manner.

Here we study these limitations of such a pulse regeneration scheme by numerical simulations using the generalized nonlinear Schrödinger equation (GNLSE). We inject Gaussian input pulses with various pulse durations and peak powers into single-mode and polarization maintaining fibers at 1064 nm. We use the -6dB bandwidth of the pulse spectral bandwidth at the output as a metric, as larger bandwidth allows for efficient coherence improvement by spectral filtering and easier pulse shaping with additional components after the regenerator.

2. SYSTEM SCHEMATIC AND THEORETICAL DESCRIPTION

The schematic for pulse cleaning by a Mamyshev regenerator is illustrated in figure 1

Noisy pulses from a GSD (Fig. 1 a1 & a2) will broaden spectrally in the passive fiber due to SPM caused by the third order nonlinearity (Fig. 1 b1 & b2). These broadened pulses are then bandpass filtered slightly offset from the center wavelength of the GSD, allowing one to potentially decrease the pulse-to-pulse fluctuations of the system (Fig. 1 c1 & c2).[6] These filtered pulses generally have cleaner pulse shapes than the GSD pulses

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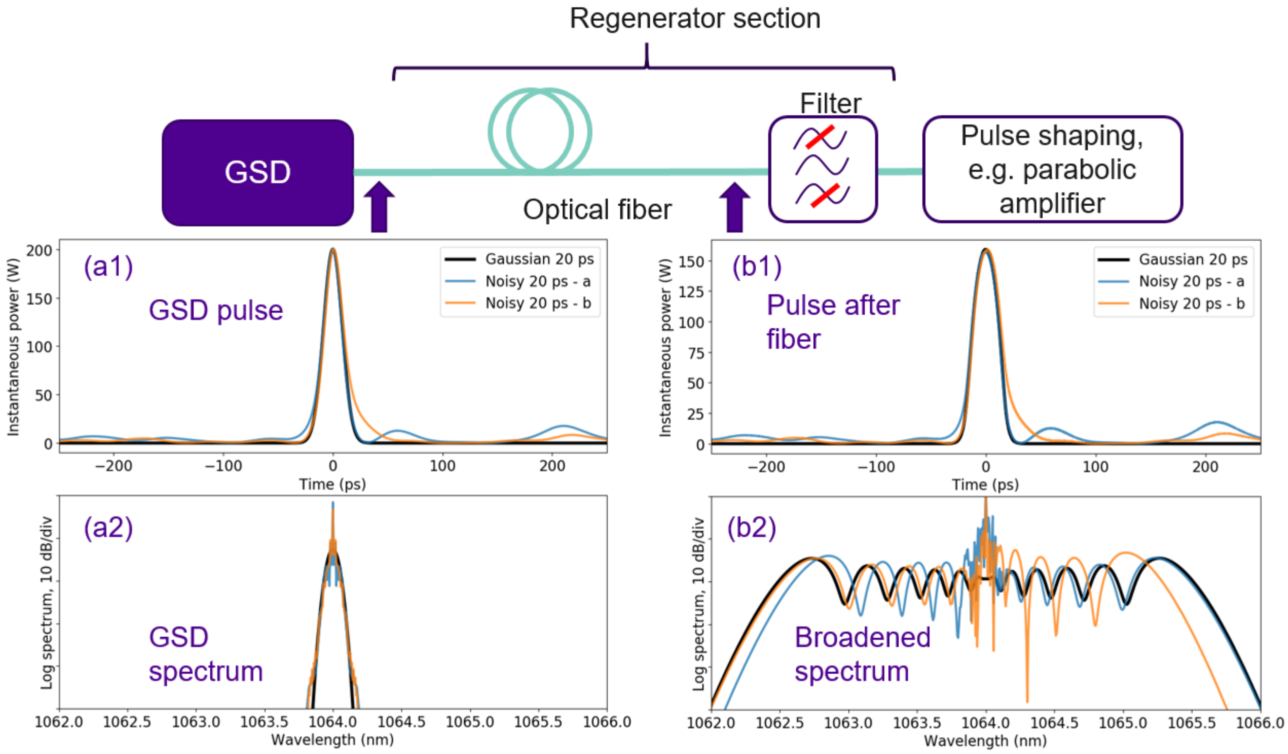

Figure 1. High-level experimental schematic of a single Mamyshev Regenerator stage consisting of a noisy Gain Switched Diode Laser, long piece of passive fiber and subsequent bandpass filter. Subfigures demonstrate pulse temporal and spectral evolution inside the regenerator starting at the GSD pulses (a), after propagation in fiber (b). We have compared a Gaussian pulse shape (black) to two noisy GSD pulse shapes (orange and blue) with the same peak power & duration but additional random noise. Further pulse shaping stages can be used after the regenerator to achieve even shorter pulse durations than shown here.

and are more applicable for further pulse shaping and amplification by for example parabolic amplification[1,7] or direct compression by gratings.

For the simulations in this manuscript, we have used transform limited Gaussian pulses for reasons of clarity. This way various nonlinear effects are easier to isolate in the pulse evolution and the results are more straightforward to analyze. Practical GSD pulses are generally not Gaussian shaped and contain a lot of fluctuations in amplitude, phase and possible subpulses or pulse tails. However, using only Gaussian pulses is a reasonable simplification, as can be seen in the example simulations in Fig. 1, where we have compared a Gaussian pulse (black curve) evolution with two simulated noisy GSD pulses (red & blue) in the same system. While noisy pulses will cause fluctuations in the broadened spectra, the average spectral width will be comparable to a Gaussian pulse of the same duration. Indeed, we have also performed experiments based on 80 ps GSD laser and verified that the average spectral broadening is of similar magnitude than the simulated 80 ps Gaussian pulses. Furthermore, the aim of the study is to optimize the spectral broadening for various pulse durations and to find general trends for Mamyshev regenerator systems justifying this simplification.

Getting sufficient spectral broadening with typical low-cost GSDs with pulse durations in the 40-100 ps range can be practically difficult. This difficulty is because of simultaneous SRS occurring in the fiber with SPM. In particular, longer pulses will have larger walk-off lengths for the amplified Raman signal arising from noise, increasing the effective gain.[8] Thus the SRS level can reach values comparable to the signal with long pulses which will distort the pulse shape and reduce the pulse energy, mitigating the benefits of the filtering stage in the regenerator.

To illustrate these effects, we present a GNLSE simulation[8,9] of a 20 ps pulse propagating over 250 m length in a typical single mode PM fiber at 1064 nm in figure 2. The simulations used a 300 photons per bin noise as a seed for the SRS signal. This noise level was set to agree with experimental observations in the laboratory with the 80 ps GSD seed amplified with a low power pre-amplifier. We also utilize the experimentally measured Raman gain spectrum to model SRS growth[10]

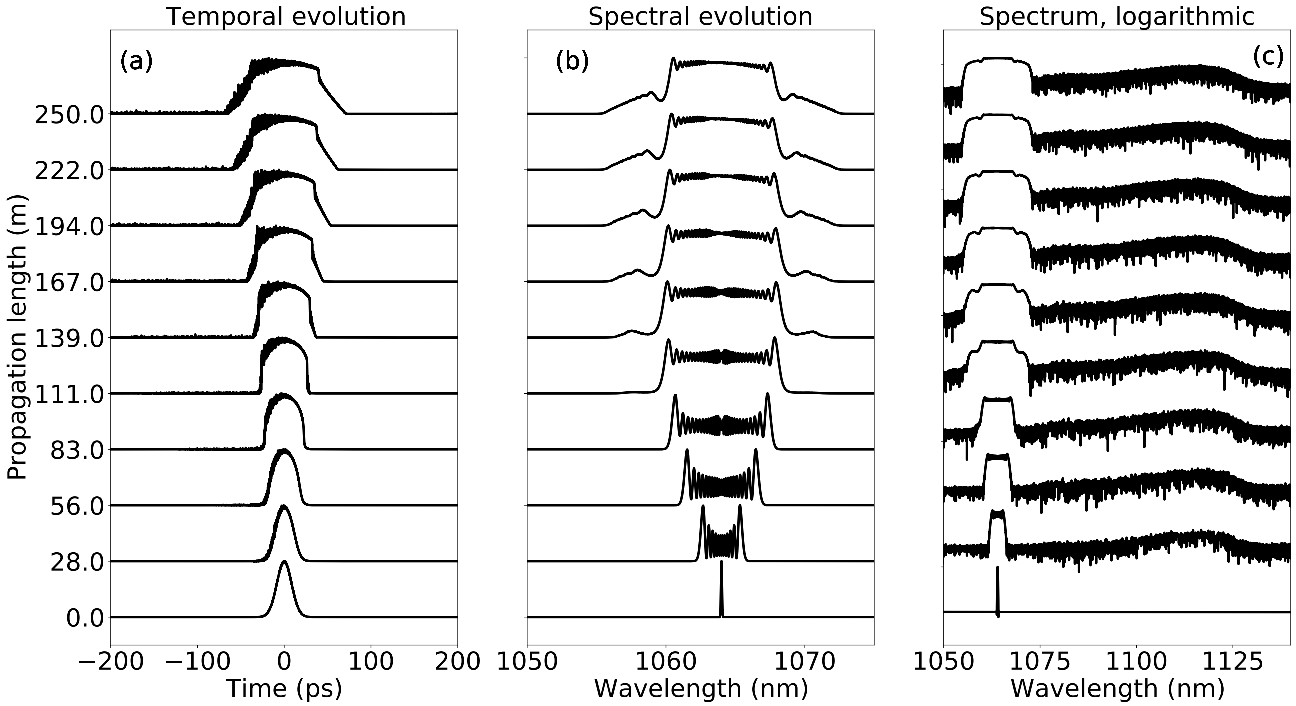
Temporal evolution
Spectral evolution
Spectrum, logarithmic

Figure 2. Numerical simulation of 20 ps gaussian pulse propagation in single mode PM fiber. a) Pulse evolution in time domain, b) Pulse evolution in spectral domain, c) Pulse evolution in spectral domain with logarithmic y-axis.

Initial propagation up to 83 m is largely dominated by SPM spectral broadening coupled with dispersion causing the pulse duration to simultaneously stretch in the time domain close to 50 ps. Looking at the logarithmic spectrum one can also notice the immediate growth of SRS from background noise at the wavelength of 1120 nm. While initially over 60 dB below the signal level, it reaches a level of 15 dB relative to the signal at 111 m. At this stage one can observe clearly the modulation in the temporal pulse shape caused by the strong Raman contribution and with further propagation it will start to deplete the pump pulse and consequently carve out a portion of signal pulse. Furthermore, as the Raman pulse intensity increases it will begin to contribute to the phase and amplitude profile of the signal pulse via cross-phase modulation.

Additionally, OWB starts to manifest itself in the spectral and temporal domains similarly at 111 m. This is observed by the spectral sidelobes appearing in the SPM broadened spectrum as well as in the steep edges of the temporal pulse shape with modulation caused by the OWB. The spectral sidelobes actually arise from four-wave mixing of the edges of the already broadened spectrum resulting in a small reduction of bandwidth. This will be detrimental for the regenerator purposes as no clean pulse with a clear phase profile can be achieved after this point.

Considering the above, the regenerator system is limited by the maximum acquirable bandwidth, while keeping the SRS and OWB effects minimal for a given pulse duration and peak power. Our simulations target to find this optimum operating point for various pulse durations. Our approach is as follows: we inject transform limited pulses with various durations and peak powers into PM fiber with a mode-field diameter of 6.92 μm and $\beta_2 = 0.0024 ps^2$. The GNLSE pulse propagation code is run until either:

1. SRS level arises above -15 dB level relative to maximum,

2. OWB starts to decrease the bandwidth of the pulse,
3. fiber length exceeds 500 m.

The last condition is set by practical constraints - fiber lengths of hundreds of meters are not very practical in real life systems and the pulse broadening slows down after the initial broadening.

3. SIMULATION RESULTS

We consider three pulse durations in the simulations, 20 ps corresponding to high performance GSD and 50 ps and 80 ps to typical off-the shelf GSDs. The fiber parameters stated above correspond to commercial PM980 fiber values. We run the simulation until one of the stop conditions listed above is met and note down the 6 dB spectral bandwidth and fiber length for the simulation. We choose 6 dB bandwidth as it is less sensitive to the numerous spectral features arising from the nonlinear interactions. Figure 3 a) shows the 6 dB bandwidths at a given pulse duration & peak power and b) corresponding fiber lengths.

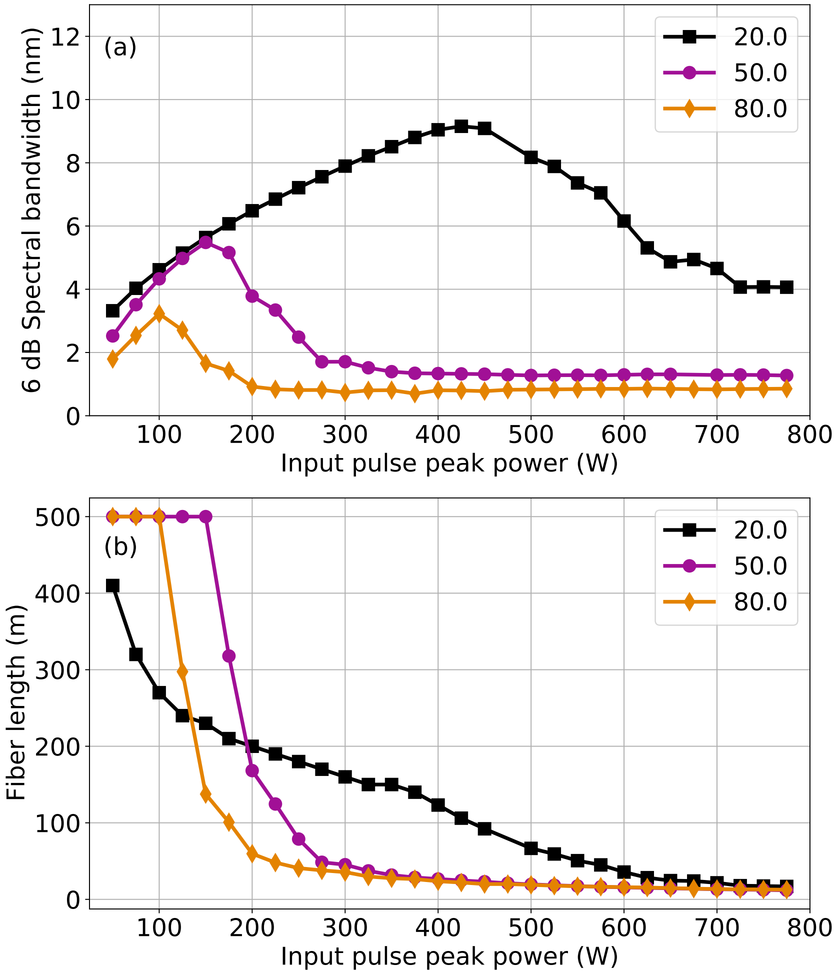

Figure 3. a) 6 dB bandwidths of measured pulses at the output of the fiber b) fiber length at where the simulation was stopped.

We first concentrate on the results for the 20 ps pulse shown in black. We see an increase in spectral bandwidth with increasing peak power up to 425 W in Fig. 3 (a), as one would expect due to increased nonlinear effects. For the simulated fiber lengths in Fig. 3 (b) illustrating the simulation stop condition (i.e. SRS, OWB or 500 m length) we see a decrease from 400 m to 120 m at a peak power of 425 W. Up to this point, the simulations are limited by the OWB condition, but beyond this point SRS is starting to limit the fiber length. This is clearly not observable in the fiber length figure, but we have verified this separately by looking at the simulated results. As SRS becomes the limiting factor, fiber lengths decrease even faster with increasing peak power. This is observed as a reduced bandwidth of the pulses that continues to decline rapidly.

For 50 ps (purple curves in Fig. 3) and 80 ps (orange curves in Fig. 3) pulses the behavior is slightly different. Here in Fig. 3 (b) we notice that both cases end up with 500 m fiber length with low peak powers, meaning that OWB and SRS are not yet playing a significant role in the dynamics. At 100 W of peak power for 80 ps pulses and 150 W of peak power for 50 ps pulses we notice a very rapid decline in the simulated fiber lengths. For the long pulses SRS becomes immediately the limiting factor due to the longer walk-off lengths between the Raman and signal pulses. Fiber lengths fall rapidly below the corresponding lengths for 20 ps pulse at the same peak power and consequently we observe the maximum obtainable bandwidth for both cases at this point. Thus, obtainable bandwidths for longer pulses also are significantly reduced and practical realization of a regenerator can become difficult without additional means.

4. SUMMARY AND DISCUSSION

We have simulated pulse propagation in passive optical fibers with various lengths and pulse durations & peak powers corresponding to typical gain switched diode lasers. We have determined stimulated Raman scattering and optical wave breaking to be limiting factors for practical realization of Mamyshev regenerator schemes based on gain switched diodes. The results point out that shorter pulse durations will be practically more realizable as sufficient spectral broadening is obtained by a wide range of parameters. However, we have also discovered that longer pulses can be utilized as long as attention is paid with the design of the rest of the system. In particular, the peak power of the pulses should not be increased audaciously in pursuit of spectral broadening of the pulses, but an optimum combination for a reduced peak power and fiber length will result in the best performance.

Even though some of the results point towards using fiber lengths in vicinity of 500 meters, it should be noted that in practice nearly similar broadening can be obtained with significantly reduced fiber lengths as spectral broadening slows down the fiber as dispersion stretches the pulse duration which consequently reduces peak power.

We also note that the -15 dB level limit of SRS here could also be slightly relaxed and exact effects on consequent pulse shaping would have to be verified depending on the total system design. We have chosen a conservative value in order to be well beyond any unwanted effects. Furthermore, we have not analyzed the effects of choosing different fiber types for spectral broadening, which could open up even more routes for optimization of the regenerator system.

ACKNOWLEDGMENTS

This work was supported by PULSE project, grant agreement number 824996, funded by the European Commission Horizon 2020 Program.
The work is part of the Academy of Finland Flagship Programme, Photonics Research and Innovation (PREIN), decision 320165.
The authors wish to acknowledge CSC – IT Center for Science, Finland, for computational resources.

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