Design of nonlinear pulse shaper for flexible repetition rate ultrashort pulse generation

Mikko Närhi[1,*], *Katariina* Ranne[1], and *Regina* Gumenyuk[1]

[1]Photonics laboratory, Tampere University, 33014 , Tampere, Finland

Abstract. Nonlinear pulse shaping based on Mamyshev regenerator is a powerful approach for ultrashort pulse generation. The performance strongly depends on the initial seed parameters. We investigate and design a nonlinear pulse shaper seeded by a long pulsed gain-switched laser diode for generation of high quality ultrashort pulses with flexible repetition rate. The shaper architecture provides more flexibility on the input diode requirements and can yield shorter pulses with the improved laser relative intensity noise. The system optimization is based on numerical simulations mapping the favourable parameters at each stage of the system and enabling identification of limiting factors.

1 Introduction

Ultrashort laser pulses have found widespread use in sciences and recently even in more commercial applications, such as laser materials processing and optical measurement technology. Pulse durations in the picosecond range and below are generated typically by mode-locked lasers. While mode-locked lasers have impressive performance in many aspects, they are fixed in repetition rate, that typically lie in the MHz range. External modulators can be used to divide the fundamental repetition rate, but flexibility is limited otherwise.

Using modulated laser diodes allows for more flexible repetition rate control as there is no laser cavity to set the fundamental repetition rate and they offer other operating modalities such as burst mode pulsing. The limitations arise in minimum achievable pulse durations, pulse shape and higher relative intensity noise (RIN).

In 2017 Fu et al. demonstrated 140 fs pulse generation from a gain-switched laser diode (GSLD) followed by nonlinear shaping [1]. This was achieved by a so-called Mamyshev regenerator (MR) system, seeded by a state-of-the-art GSLD providing 10 ps pulses. Use of cheaper, commercially available diodes with longer pulse durations in the 20-80 ps range has been studied numerically and experimentally by using a single or double stage MR system [2,3]. Here we study in detail the architecture of MR system and limiting factors for nonlinear pulse shaping. We utilize experiments and numerical simulations to explore the vast parameter space to refine pulse shapes in two-stage MR system and obtain improved RIN performance.

2 Schematic of a two-stage MR system

The GSLD provides ~40 ps pulses at 1062.4 nm, that are amplified to 15 mW at 1 MHz repetition rate. We use 200 m of single-mode polarization maintaining fiber to broaden the GSLD pulses spectrally, which is followed by a second amplifier stage to maintain a sufficient peak power after the tuneable bandpass filter (TBPF). This part consists of the 1st MR stage. To reduce the number of components, we utilize the same fiber for the 2nd broadening stage by reflecting the filtered light by a fiber-optical loop mirror. The returning light is then picked up by a circulator, separating the input and output lights to different ports. At the output of the circulator a second TBPF is used to complete the 2nd MR stage. This is illustrated in Figure 1. The optical spectra and temporal profile of pulses are measured at the output of each stage.

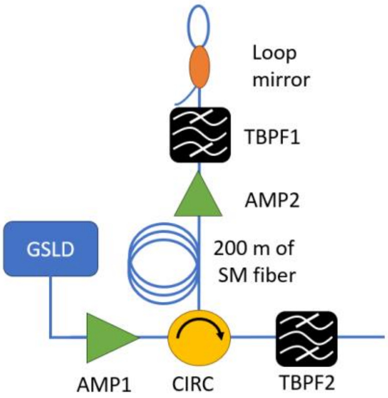

Figure 1: Experimental schematic of 2-stage MR system.

A Treacy type grating compressor with 1250 l/mm gratings separated by 30 cm is used to verify compressibility of the output pulses measured by an autocorrelator.

---

[*] Corresponding author: mikko.narhi@tuni.fi

2.1 Optical performance of the first MR stage

Figure 2 (i) shows the four optical spectra after the first MR stage filtering with different TBPF settings. The broadened spectrum spans approximately a 5 nm bandwidth (-10 dB level) compared to the 0.2 nm input bandwidth (black). Corresponding autocorrelation traces to the filtered spectra are shown below in Fig 2 (ii)-(v).

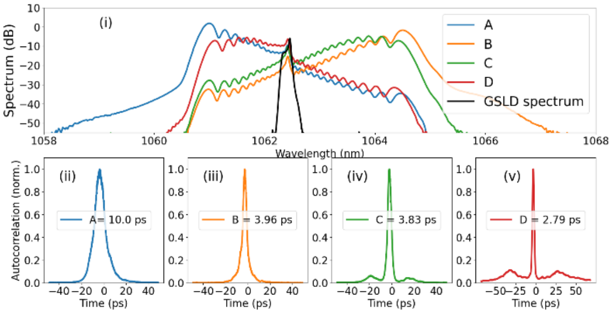

Figure 2: Performance of single-stage MR system. (i) Optical spectra after 1st broadening & filtering stages for four different filter settings. (ii)-(v) Corresponding autocorrelation functions.

As our TBPF minimum bandwidth is about 1 nm and the sideband rejection is limited, there is always some residual GSLD peak remaining on the pulse spectrum. As can be observed in the autocorrelations, a stronger contribution of the GSLD peak results in appearance of sub-pulses in the temporal profile of the compressed pulse. Compressed autocorrelation durations vary from 3-10 ps.

2.2 Optical performance of the second MR stage

Figure 3 (a-d, solid lines) illustrate the broadened and filtered (dashed lines) spectra after the second MR stage for each of the four TBPF positions after the 1st stage.

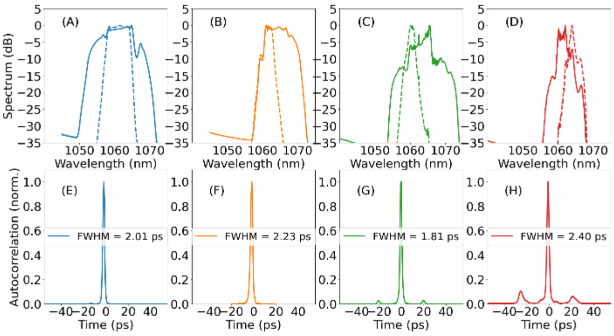

Figure 3: Optical spectra (A-D) and autocorrelations (E-H) after the second MR stage.

The reduced pulse duration after the first stage results in an enhanced spectral broadening to the backward direction with spectral bandwidths varying between 10-20 nm (-10 dB). This allows for a stronger offset filtering from the residual GSLD light, that improves the output pulse shapes. Figure 3 (e-h) demonstrates the corresponding autocorrelations to the filtered spectra after the second MR stage. Autocorrelation durations have decreased to 2-3 ps, indicating fundamental pulse durations of around 1 ps. Furthermore, side pulses have vanished for large offset filtering and decreased near the center of the spectrum.

3 RIN performance

The data analysis of different filter position in two stage of MT system shows that the nonlinear pulse shaping can either emphasize or depress input pulse fluctuations, depending on the filter parameters. To explore the RIN properties of the MR system in the vast operating parameter space set by the two TBPFs, we performed numerical simulations based on the Generalized Nonlinear Schrödinger Equation (see [3] for details). The input in simulations had 7% RIN over a 200-pulse ensemble. Figure 4 illustrates the RIN performance with varying TBPF center wavelength and bandwidth after the first MR stage.

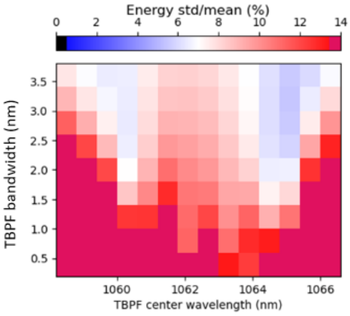

Figure 4: RIN performance of first MR stage with varying TBPF settings. Blue colors indicate lower than input RIN.

We observe a decrease in RIN with broad filter bandwidths that are slightly offset from the center wavelength of 1062.4 nm. This is understood by some basic considerations: (i) filtering at seed wavelength cannot improve RIN as it will include seed RIN, (ii) edges of the spectrum increase RIN due to the nonlinear broadening being sensitive to power fluctuations, (iii) narrow bandwidths will cause increased RIN due to the modulated spectral structure changing from shot-to-shot and only partially filling the narrow bandwidth. Behaviour of the second stage is qualitatively similar. For a single-stage MR system the lowest RIN achievable is 5.5%, which decreases to 3.7% after the second stage, demonstrating further the benefit of a two-stage design.

4 Conclusions

We have demonstrated 1 ps pulses from a GSLD in a two-stage MR system with improved noise performance. Due to the nonlinear design, the pulse shapes and RIN performance can vary largely depending on the filter settings. A two-stage system generally can outperform a single-stage system, but filter parameters need to be designed with care.

References

1. W. Fu, L. G. Wright, and F. W. Wise, Optica 4, 831-834 (2017)
2. M. Marš, V. Agrež, R. Petkovšek, Optics & Laser Technology, 163, (2023)
3. M. Närhi, et. al, Opt. Express 29, 15699-15710 (2021)