One of our main objectives was to overcome the pulse-to-pulse fluctuations that occur in supercontinuum-seeded systems, which would be detrimental for nonlinear spectroscopy experiments. Our measurements are displayed in Fig. 4(a) and taken with a setup of the type as presented in [10]. Hence, a supercontinuum-seeded OPA shows strong pulse-to-pulse fluctuations due to the limited coherence of such supercontinua [20]. Since the soliton number in our system is, depending on the launch power, on the order of 3 to 6, the coherence is maintained and excellent short term stability is observed after both conversion stages, as shown in Figs. 4(b) and (c).

On longer timescales a temporal jitter lowers the stability of the first conversion stage. While Fig. 4(d) demonstrates that the short term fluctuations of the supercontinuum seeded OPA average out on a timescale of seconds, the soliton-seeded OPA shows fluctuations and slight drifts. This is due to a timing-jitter that solitons experience as a consequence of varying launch power. The effect can be understood by investigating the soliton dynamics in the tapered fiber and will be described in the following paragraph.

The soliton red shift, which is due to stimulated Raman-scattering, is intensity dependent. Therefore, less launch power leads to a weaker red shift. On the one hand, this changes the soliton center wavelength very slightly, but on the other hand it also influences the time that the soliton needs for the propagation through the fiber due to its GVD. According to simulations, the delay of the soliton is on the order of $250\frac{\mathrm{fs}}{\mathrm{mW}}$, which means that very small fiber output power fluctuations on the order of a fraction of a milliwatt significantly influence the temporal overlap of the soliton (pulse duration < 60 fs) with the pump pulse (425 fs). Hence, this timing-jitter leads to large fluctuations in the signal output, where distortions in the operation show up as dips in the output power. The concept of a two-stage setup eliminates this timing-jitter to a certain degree, since the first and the second conversion stage are passively synchronized by the pump beam. Since the conversion in the second stage is strongly saturated, it depends only very weakly on the seed power that is generated by the first stage. Hence, the signal of the second stage is very stable (cf. Fig. 4(f)). The largest share of remaining fluctuations is due to the first stage. However, a strong drift in the soliton may lead to a complete breakdown of the signal power of the first and hence also the second stage. For stable long term operation of more than one hour, slight readjustments of delay or fiber launch power are required. Also, due to the chirped nature of the seed, timing instabilities translate into spectral instabilities which were observed at high signal wavelengths.

4. Conclusion

A high-power femtosecond OPA at 41.7 MHz repetition rate has been demonstrated with a signal tuning range from 1.35 to 1.95 μm and up to 1.8 W average power. The corresponding idler ranges from 2.2 to 4.5 μm, where up to 650 mW average power were obtained. The combination of a coherent soliton seed and two passively synchronized conversion stages lead to power fluctuations of only 0.6% rms over half an hour and excellent short term stability with pulse-to-pulse fluctuations as low as 0.8% rms. Apart from spectroscopic applications, the high output power of this system is well suitable for subsequent nonlinear experiments such as difference frequency generation to extend the spectral range further into the mid-infrared or pumping of nonlinear fibers for mid-infrared supercontinuum generation.

Acknowledgments

We acknowledge financial support from Baden-Württemberg-Stiftung (PROTEINSENS), Deutsche Forschungsgemeinschaft (SPP1391), European Research Council (COMPLEXPLAS), Zeiss-Stiftung, and Alexander von Humboldt Stiftung. This work was supported by the German Research Foundation (DFG) within the funding program Open Access Publishing.