An example of the broadest spectra that we have observed is shown in Fig. 5. A 1.6-m segment of the PCF was used to obtain this result. Significant energy extends over nearly 200 nm at the base of the spectrum. The pulse energy is 1 nJ. The production of spectra with $\sim$ 20% of the energy below the pump wavelength (where there is no gain) and the excellent agreement between calculated and measured spectra demonstrate that the Yb gain bandwidth does not limit the output spectrum. The FWHM pulse duration is 21 fs, which corresponds to 6 cycles of the field. The pulse does have significant structure in the wings, with energy extending beyond 100 fs from the peak. Nevertheless, these pulses were used to produce high-resolution images by third-harmonic generation microscopy [20].

The pulse evolution in this laser exhibits some remarkable aspects. The spectrum broadens from 4 to 30 nm in the gain fiber, and then to 110 nm in the passive fiber, for an overall spectral breathing ratio of 27. The intracavity pulse duration varies between 1 and 10 ps, yet the pulse can be dechirped outside the cavity to $\sim$20 fs. With respect to that pulse duration, the laser is equivalent to 300 dispersion lengths of propagation. For comparison, in a 5-fs Ti:sapphire laser the spectrum exceeds the gain bandwidth by $\sim$ 30%, the spectral breathing is less than a factor of 2, and the intracavity pulse duration varies from 10 to 50 fs [21].

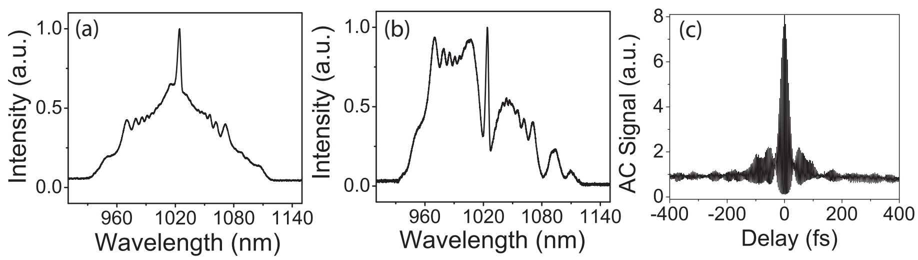

Fig. 5. Experimental (a) spectrum after the PCF, (b) output spectrum, and (c) output autocorrelation signal after phase correction by MIIPS for a 21-fs pulse.

4. Discussion

The results presented here show that substantial bandwidth enhancement by nonlinear pulse propagation can be stabilized in a self-similar laser. Systematic studies of the behavior of the laser with varying parameters should be performed. We have not identified the factors that limit the operation or performance of this kind of laser. We do observe indications of wave-breaking (as in Fig. 3) near the boundaries of convergence of the simulations. The simulations neglect higher-order dispersion, so this suggests that the higher-order dispersion does not limit the stability of the laser. The influence of higher-order dispersion of the nonlinear segment on the generated pulse should be studied, however. It should be possible to produce pulses with more-linear chirp by better design of the nonlinear segment. The existence of the CW component, and its influence on the mode-locked state, also need further investigation. We conjecture that the CW solution of the average cavity model can co-exist with the desired self-similar solution. The PCF has a cut-off wavelength around 300 nm, so extremely broad spectra can be accommodated without risk of multimode propagation. With broader spectra, the loss from filtering will present a challenge.

This work can be extended by continuing the ideal self-similar evolution from the gain segment in a section without bandwidth limitations. This is theoretically possible with a dispersion-decreasing fiber, where the resulting system is formally equivalent to a gain fiber [22]. In addition to the potential of unbounded bandwidth, we expect the pulse to be closer to a parabola and therefore have a nearly-linear chirp. Indeed, initial numerical simulations show that the use of a dispersion-decreasing fiber should allow the generation of broader and less-structured spectra, with smaller higher-order phase to be corrected. The generation of parabolic pulses in dispersion-decreasing fiber has been reported [23,24], but the dispersion varies over kilometers. If such a fiber can be fabricated with the dispersion varying on the scale of meters, this will be another promising way to extend the work presented here.

Finally, the laser described here is designed to illustrate the pulse evolution. To construct a version that would be a long-term stable instrument, one would remove the sampling beam-splitters and replace the free-space coupling into the PCF with a spliced connection. Ultimately, an all-fiber version will be desired.

5. Conclusion

In conclusion, we have shown that the gain bandwidth does not present a fundamental limitation to the minimum pulse duration in an amplifier-similariton laser. The spectrum can be broadened in a separate nonlinear segment, and filtering produces the seed pulse to the amplifier that allows a self-consistent solution. This opens a promising route to the development of few-cycle fiber lasers.

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