Kues, M., Reimer, C., Wetzel, B., Roztocki, P., Little, B. E., Chu, S. T., Hansson, T., Viktorov, E. A., Moss, D. J. and Morandotti, R. (2017) A Passively Mode-locked Nanosecond Laser with an Ultra-narrow Spectral Width. In: Conference on Lasers and Electro-Optics Europe & European Quantum Electronics Conference (CLEO/Europe-EQEC 2017), Munich, Germany, 25-29 Jun 2017, ISBN 9781509067367 (doi:10.1109/CLEOE-EQEC.2017.8086991)

A Passively Mode-locked Nanosecond Laser With An Ultra-narrow Spectral Width

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Many different mode-locking techniques have been realized in the past [1,2], but mainly focused on increasing the spectral bandwidth to achieve ultra-short coherent light pulses with well below picosecond duration. In contrast, no mode-locked laser scheme has managed to generate Fourier-limited nanosecond long pulses, which feature narrow spectral bandwidths (~MHz regime) instrumental to applications in spectroscopy, efficient excitation of molecules, sensing, and quantum optics. The related limitations are mainly caused by the adverse operation timescales of saturable absorbers, as well as by the low strength of the nonlinear effects typically reachable through nanosecond pulses with manageable energies.

Here, we demonstrate a technique for passive mode-locking based on an integrated nonlinear microring resonator embedded in a nonlinear amplifying loop mirror (NALM) architecture, acting as an artificial saturable absorber (Fig. 1a). Using this new approach, we realize the first Fourier-transform-limited nanosecond mode-locked laser pulses [3]. Specifically, the high-Q integrated microring resonator simultaneously limits the spectral bandwidth of the oscillating laser field, while increases the nonlinear interactions through field cavity enhancement, ultimately resulting in the appropriate nonlinear phase shift for nanosecond mode-locking by the NALM. The laser characteristics are summarized in Fig. 1b-e. The laser produced optical pulses in the nanosecond regime (4.3 ns in duration), with an overall spectral bandwidth of 104.9 MHz—more than two orders of magnitude smaller than previous realizations. The very narrow bandwidth of the laser made it possible to fully characterize its spectral properties in the radiofrequency domain using a beating technique exploiting a continuous wave laser in combination with widely available GHz-bandwidth optoelectronic components. In turn, this characterization reveals the strong coherence of the generated pulse train.

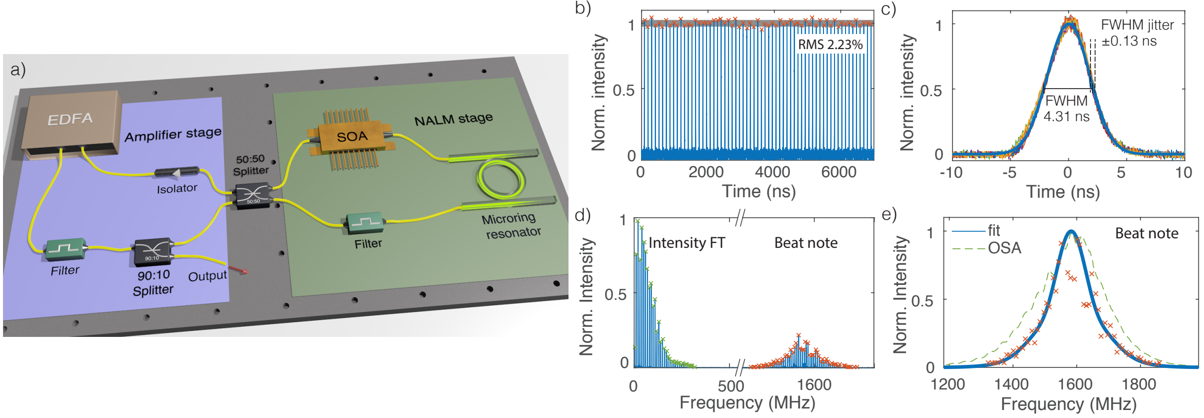

Fig. 1: a) Experimental setup of the mode-locked laser. b) Real-time time trace of 44 pulses, with RMS noise below 2.3%. c) Temporal profile of the emitted pulses (10 pulses superimposed) with a 4.31 ns FWHM Gaussian pulse fit (blue solid line) and a low FWHM jitter of 0.13 ns. d) Radiofrequency spectrum of the mode-locked laser beating with a CW laser. Lower frequency part (intensity FT): clear and narrow peaks at the repetition rate of the laser (9.565 MHz). High frequency part (beat note): related to the optical spectrum of the mode-locked laser. e) Optical spectrum of the laser, retrieved with a high-resolution optical spectrum analyzer (dashed green line) and from the beat note (red crosses). The blue line corresponds to the spectrum of the fitted pulse (Fig. 1c) with an additional temporal phase induced by the Kerr nonlinearity.

The compact architecture, and modest requirements in terms of power, readily allow for stable and portable operation, while opening up a route towards the full integration of the laser system. Together with the possibility to resolve the full laser spectrum in the RF domain, such characteristics can pave the way towards novel sensing and spectroscopy implementations. From a fundamental perspective, the low and tractable number of modes (11 within the spectral FWHM), may enable further studies of both nonlinear mode coupling and complex mode-locking regimes.

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