Soliton frequency comb at microwave rates in a high-Q silica micro-resonator

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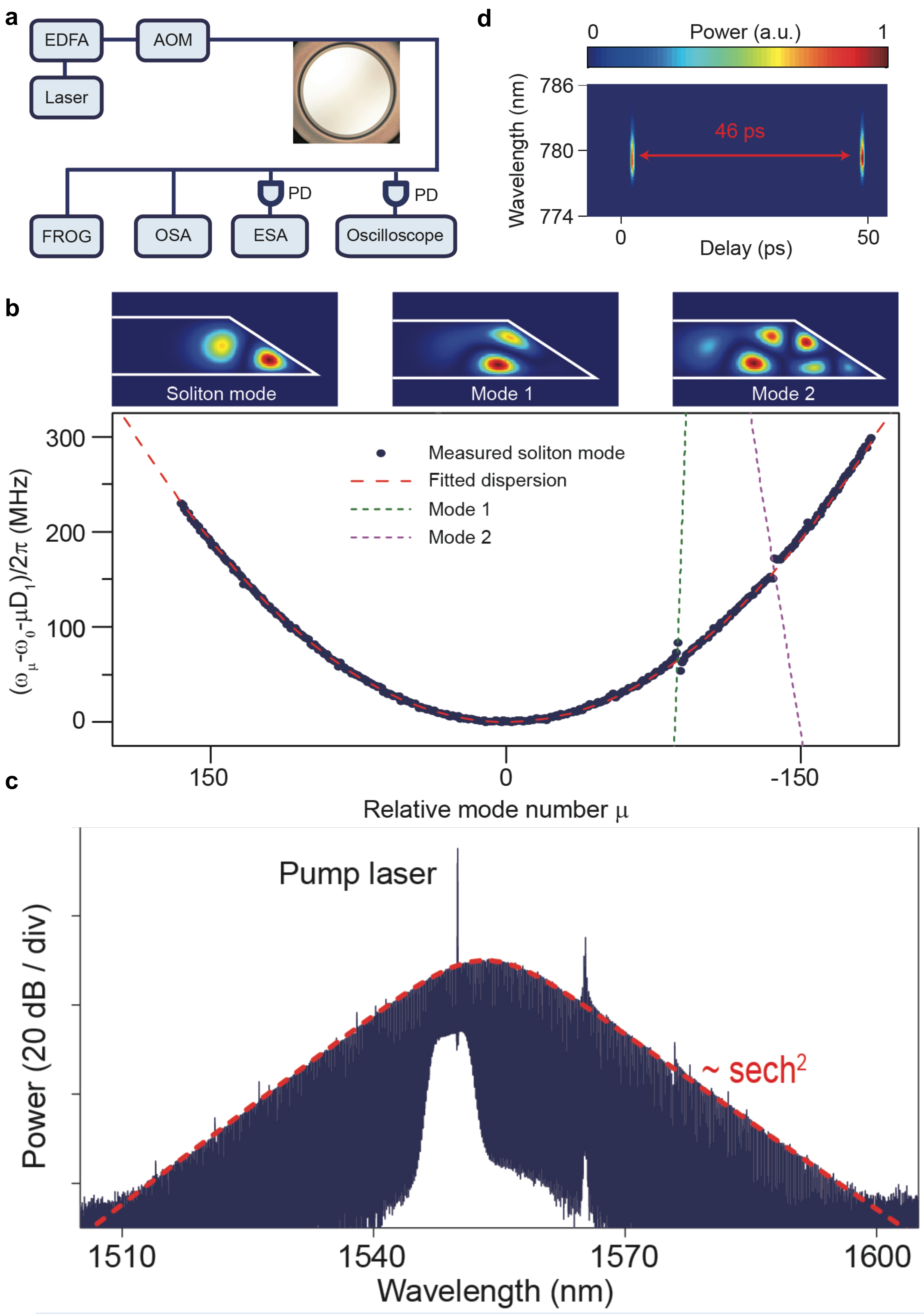
Frequency combs are having a broad impact on science and technology because they provide a way to coherently link radio/microwave-rate electrical signals with optical-rate signals derived from lasers and atomic transitions. Integrating these systems on a photonic chip would revolutionize instrumentation, time keeping, spectroscopy, navigation, and potentially create new mass-market applications. Here, we demonstrated a mode lock soliton frequency comb in high-Q silica micro-resonator on a silicon chip. The resonators produce low-phase-noise soliton pulse trains at readily detectable pulse rates - two essential properties for operation of self-referenced frequency combs. The theoretical dependence of comb power, efficiency, and soliton existence power on pulse width are also tested. The influence of the Raman process on the soliton existence power and efficiency is also observed. The resonators are microfabricated on silicon chips and feature reproducible modal properties required for soliton formation.

1. Background

The optical frequency comb is revolutionizing a wide range of subjects spanning spectroscopy to time standards. Since their invention, a miniaturized approach to the formation of a comb of optical frequencies has been proposed in high-Q micro-resonators. These "microcombs" were initially realized through a process of cascaded four-wave mixing driven by parametric oscillation. However, a recent advance has been the demonstration of mode locking through formation of dissipative Kerr solitons in micro-resonators [1]. Solitons balance dispersion with the Kerr nonlinearity while also balancing optical loss with Kerr parametric gain, which can be characterized by Lugatio-Lefever equation (LLE equation). In this work, low-noise and detectable pulse rate soliton generation is demonstrated on a chip, representing a significant step towards a fully integrated frequency comb system [2].

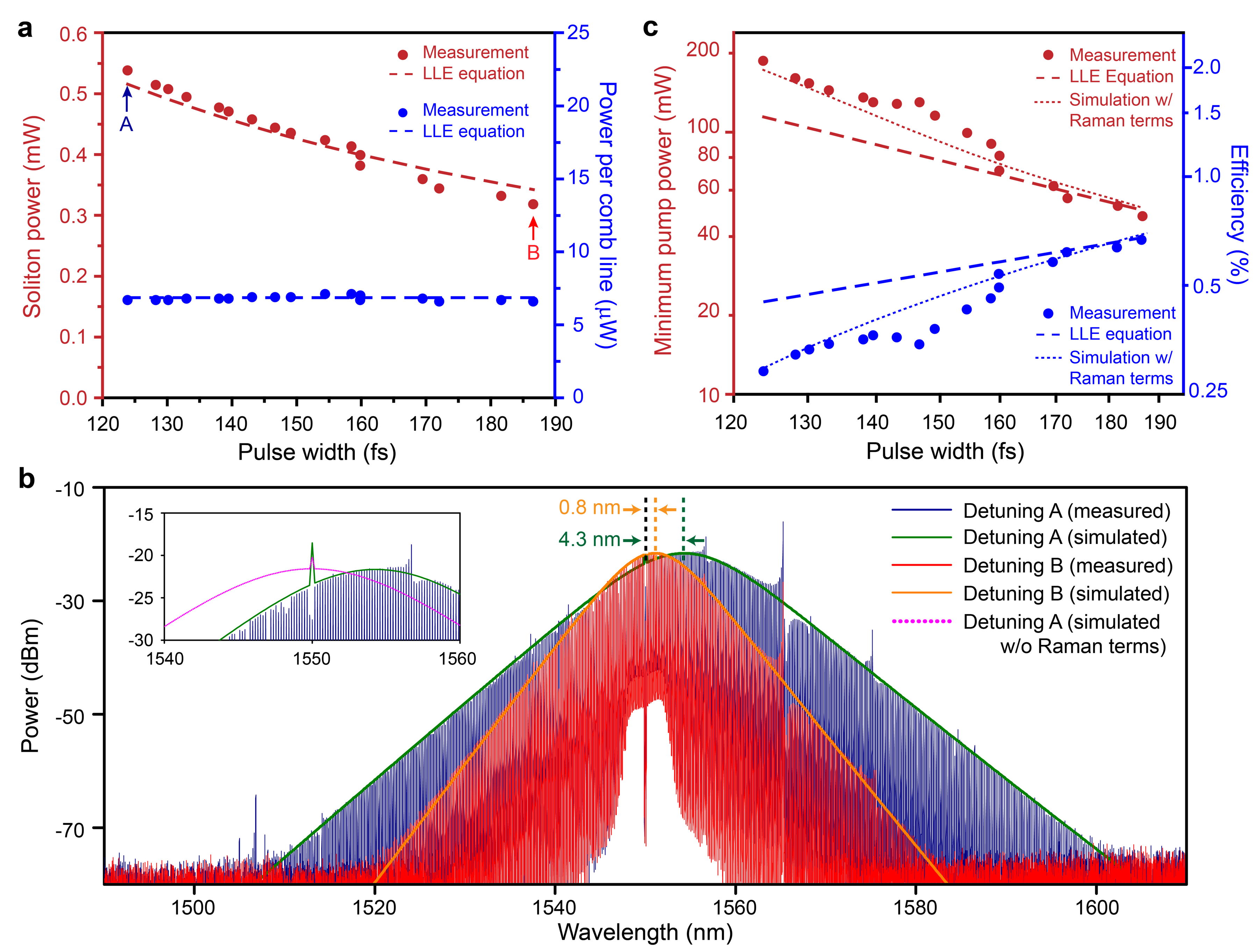
2. Soliton frequency comb generation

(a) Conceptual schematic of the setup for soliton generation and characterization. (b) Mode spectrum of the soliton mode. Two minor avoided mode crossings are identified with numerical simulation, including spatial profiles of the soliton and non-soliton mode families. (c) Soliton optical spectrum: a hyperbolic sech^2 envelope is measured and 130 fs pulse width can be inferred. (d) Temporal characterization of soliton with 46 ps pulse spacing (22 GHz repetition rate) using a FROG system. The soliton pulses can be spectral broadened to > 400 nm with commercial HNLF.



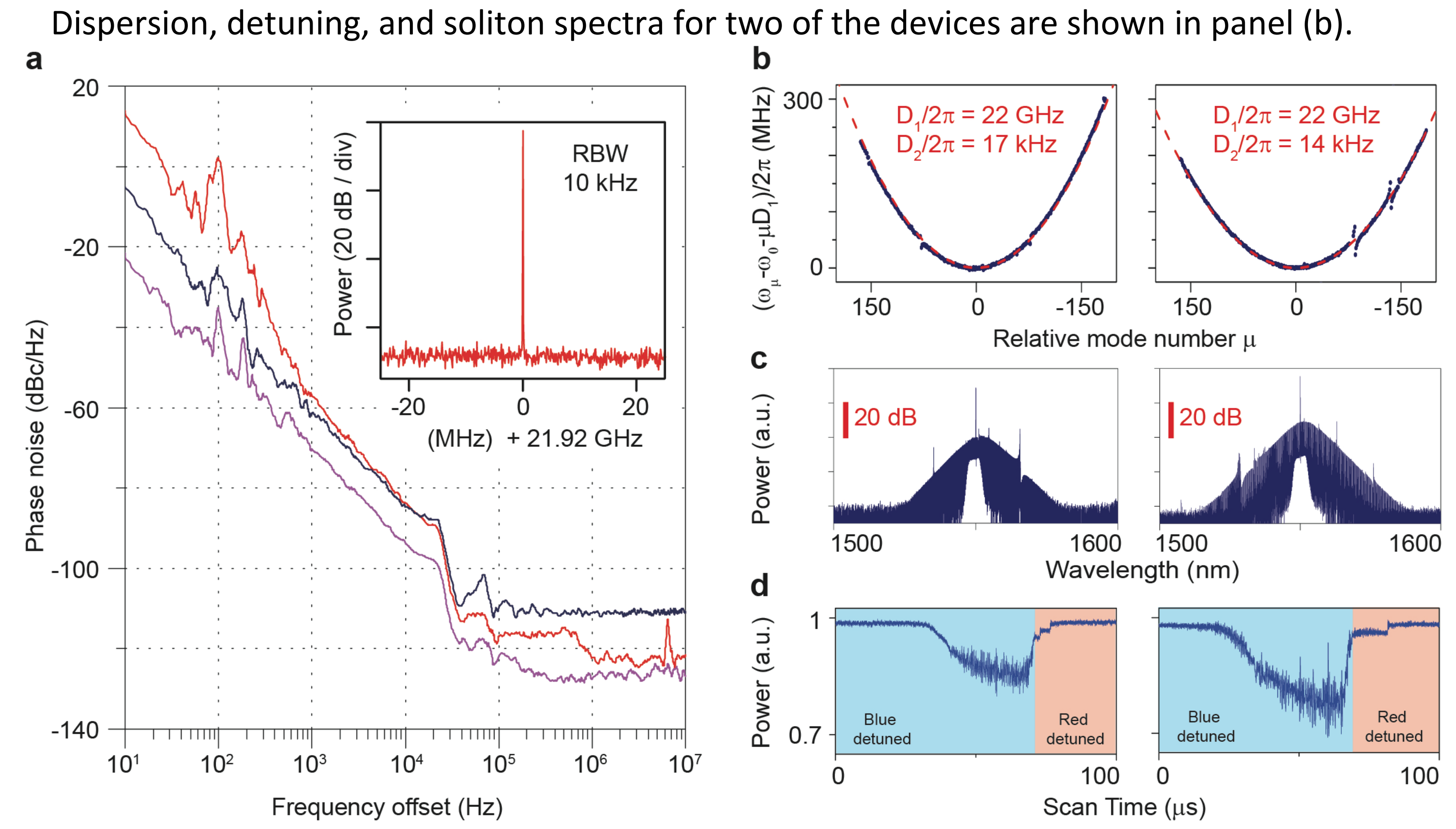
3. Soliton characterization

Solitons are formed when the pump laser frequency is tuned tens of cavity linewidths to the red relative to the resonator mode frequency. Interestingly, most soliton properties such as average power and pulse width are determined by the relative detuning of pump laser and resonator. In the plots below, soliton power, central comb tooth power, minimum pump power for existence and efficiency are measured vs. soliton pulse width. For these measurements all quantities are measured at a series of detuning values. Detuning is thus used as a parameter in the plots. The measured plots are then compared with modeling of the soliton characteristics. Modeling and measurement are shown to be in good agreement. In certain cases (see panel c), the LLE equation is augmented to include the Raman interaction in order to explain slight discrepancies between measurements with the simplified soliton model that omits Raman interactions.



4. Detectable repetition rate and reproducible solitons

The solitons demonstrated in this work feature readily detectable repetition rate using commercial photo-detectors. They also exhibit a free-running phase noise comparable to a good K-band signal source. This is a key advantage towards self-referencing of the frequency comb. The silica resonator in this work is fabricated on a silicon chip which enables reproducible avoided mode-crossing control through micro-lithographic control of resonator geometry. Phase noise measurement on three devices is shown in panel (a). Dispersion, detuning, and soliton spectra for two of the devices are shown in panel (b).



[1] T. Herr, V. Brasch, J. Jost, C. Wang, N. Kondratiev, M. Gorodetsky, and T. Kippenberg, "Temporal solitons in optical microresonators," Nature Photon. 8, 145–152 (2014).
[2] X Yi, QF Yang, KY Yang, MG Suh, K Vahala, "Generation of high-stability solitons at microwave rates on a silicon chip", arXiv preprint arXiv:1508.00170.

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