Adaptive liquid-core optical fibers for advanced soliton control

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Nonlinear optical functionalities in optical fibers are key for many applications in laser engineering, optical signal processing, and telecommunications. It appears to be a particularity of fibers that their linear and nonlinear optical properties are permanent after fabrication. Ultimately, this invariability inhibits to explore the manifold of operational regimes of all-fiber systems. Current advances in novel hybrid-material fibers may offer a solution to those limitations while opening the field of adaptive optics for the fiber technology community.

Here, we review our recent advances in both, (i) leveraging the fabrication particularities of liquid-core optical fibers (LCF) towards fiber-system integration and telecom compatibility, and (ii) utilizing the reconfigurable optical properties of such fibers via local temperature control, core composition, and higher-order mode excitation.

With their special optical properties, LCF unify the unprecedented nonlinear efficiency of soft-glass fibers and the extraordinary tunability and reconfigurability of gas-filled fibers (see Figure 1a). In particular liquids of low molecular complexity feature extraordinary, broadband transmission from the visible to the mid-IR, high nonlinearities, and outstanding coherence features of nonlinear processes such as supercontinuum generation [1]. Moreover, the large variety of liquids (e.g. carbon disulfide, chlorides, fluorides) and liquid compositions give access to vast dispersion landscapes based on simple, commercially available capillaries or micro-structured fiber types, providing an ideal testbed for dispersion-sensitive nonlinear experiments without the need for expensive waveguide fabrication. Yet, typical operation challenges, such as the use of external optofluidic mounts and free-space coupling, have long time prohibited LCFs to emerge outside the lab.

Here, we introduce the design principles and fabrication details of fiber-interconnectable, dispersion-optimized, step-index LCFs. We showcase the adaptive tuning potential of LCFs in three key applications: (1) controlling the soliton fission point [2], (2) wideband detuning of the soliton self-frequency shift at picojoule energy level (see Figure 1b) [3], and (3) tunable generation of femtosecond dispersive waves simultaneously at near- and short-wave infrared wavelengths [4].

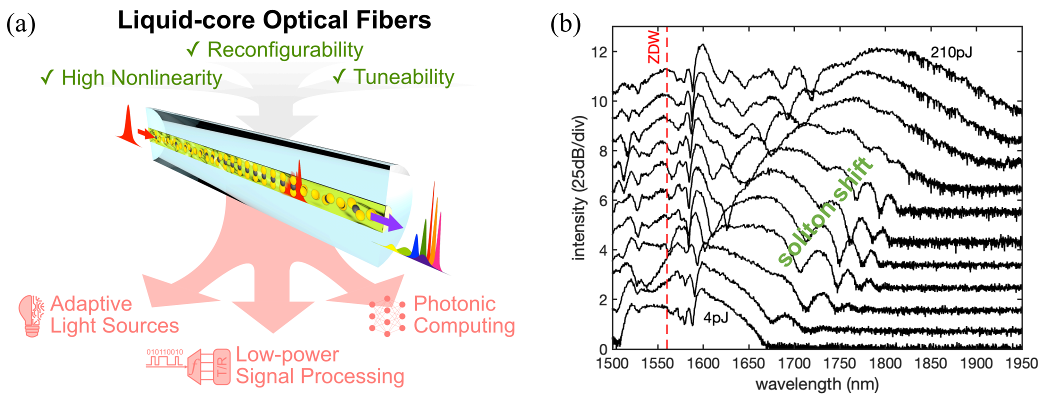

Fig. 1 (a) Advantages and application potential of liquid-core optical fibers. (b) Experimental showcase of pico-Joule-level soliton self-frequency shifting enabled by accurate design of the linear and nonlinear optical properties of straight-forward-to-fabricate step-index liquid-core fibers.

Our results emphasize liquid-core optical fibers as a promising platform featuring low coupling losses, low pump requirements, flexible dispersion landscapes, and hence, the ability to boost adaptive operation control and nonlinear functionalities in all-fiber-integrated systems. Those advanced may pave the way for next generation fiber technologies involving low-power, broadband signal processing, autonomous system optimization, as well as photonic machine learning.

References

[1] M. Chemnitz, M. Gebhardt., C. Gaida, F. Stutzki, J. Kobelke, J. Limpert, A. Tünnermann, & M.A. Schmidt, “Hybrid soliton dynamics in liquid-core fibres. *Nature Communications* ***8***, 42 (2017).
[2] M. Chemnitz, R. Scheibinger, C. Gaida, M. Gebhardt, F. Stutzki, S. Pumpe, J. Kobelke, A. Tünnermann, J. Limpert, and M. A. Schmidt, "Thermodynamic control of soliton dynamics in liquid-core fibers," Optica **5**, 695 (2018).
[3] M. Chemnitz, S. Junaid, N. Walther, R. Scheibinger, K. Schaarschmidt, J. Kobelke, and M. A. Schmidt, "Tailoring soliton fission at telecom wavelengths using composite-liquid-core fibers," Opt Lett **45**, 2985 (2020).
[4] R. Scheibinger, N. M. Lüpken, M. Chemnitz, K. Schaarschmidt, J. Kobelke, C. Fallnich, and M. A. Schmidt, "Higher-order mode supercontinuum generation in dispersion-engineered liquid-core fibers," Sci. Rep. **11**, 5270 (2021).