Femtosecond laser writing in rare earth-doped crystals for quantum memory applications

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Abstract: Photonic quantum memories allow coherent storage and retrieval of quantum states of light. Here we optimize the fabrication of femtosecond laser written waveguide memories and propose a hybrid glass-crystal memory to store path-encoded photonic qubits.

In quantum information processing, quantum memories (QMs) are synchronization devices, allowing the coherent and on-demand storage and retrieval of quantum states of light [1]. Rare earth ion doped crystals operated at cryogenic temperatures have great potential for the realization of scalable QMs to be integrated with other photonic components. These are based on the absorption and re-emission of quantum light by the rare earth ion ensemble, in which the light-matter interaction is further boosted by realizing waveguides in the substrate. Waveguide memories fabricated by femtosecond laser micromachining (FLM) have shown increased memory efficiency and reduced losses, while preserving the coherence properties of the rare earth ions [2,3].

In this work, we first focused on the optimization of the waveguide fabrication process by FLM in Praseodymium-doped YSO (Pr:YSO) crystals. Tuning the laser parameters, we were able to obtain a smooth positive index modification in the crystal matrix, acting as the waveguide core. Such waveguides show high transmission with propagation losses around 0.1 dB/cm and negligible coupling losses to single mode optical fibres, while maintaining single mode guidance for both light polarization modes. A post-irradiation thermal annealing process further boosts the polarization insensitivity of the waveguides. The cross section of the final waveguide is shown in Fig. 1. Such guiding performances represent a significant leap forward with respect to previous experiments both in terms of polarization guidance and overall losses.

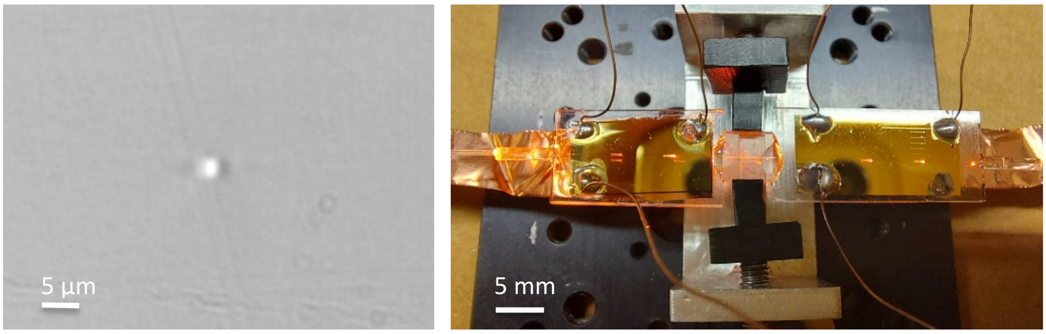

Fig. 1. Left: confocal microscope image of cross section of the optimized waveguide inscribed in Pr:YSO. Right: hybrid glass-crystal quantum memory for storage of path encoded qubits, connectorized with copper wires for the control of the surface microheaters.

Next, we realized a hybrid glass-crystal memory for the storage of path-encoded qubits. First, a pair of fully reconfigurable Mach-Zehnder interferometers (MZI) were realized in borosilicate glass using FLM, used for the state encoding and tomography. Reconfigurability of the MZI is achieved by means of thermo-optic phase shifting, implemented with a pair of microheaters patterned on gold thin film deposited on the MZI. Then, a pair of identical waveguide QMs are realized in a Pr:YSO crystal. The MZIs are glued to the crystal waveguides, and the device is fiber-pigtailed on both ends. The final device is shown in Fig. 1. The direct interface between glass-based photonic circuits and YSO waveguides is peculiar to our fabrication process, allowing to achieve a compact device with low coupling losses. Our storage platform represents the first hybrid integrated platform that joins together reconfigurable optical processors and quantum memories.

References

[1] Lvovsky, Alexander I., Barry C. Sanders, and Wolfgang Tittel. "Optical quantum memory." *Nature photonics* **3.12,** 706-714 (2009).

[2] Zhou, Zong-Quan, et al. "Photonic Integrated Quantum Memory in Rare-Earth Doped Solids." *Laser & Photonics Reviews* **17.10,** 2300257 (2023).

[3] Rakonjac, Jelena V., et al. "Storage and analysis of light-matter entanglement in a fiber-integrated system." *Science Advances* **8.27,** eabn3919 (2022).

[4] Ceccarelli, Francesco, et al. "Low power reconfigurability and reduced crosstalk in integrated photonic circuits fabricated by femtosecond laser micromachining." *Laser & Photonics Reviews* **14.10**, 2000024 (2020).