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Towards an Alignment-Free, Impedance-Matched Cavity Quantum Memory in a Thulium-Doped Crystal

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Abstract: Here, we discuss our experimental efforts toward building an alignment-free, long-lived, and efficient cavity-enhanced quantum memory in a thulium-doped crystal. A significant step forward for creating efficient quantum memories with long optical storage times.

1. Introduction

Long-lived and highly efficient photonic quantum memories [1] are key constituents of quantum repeaters for long-distance quantum communications [2–4]. Rare earth ion-doped crystals [5, 6] are arguably ideally suited candidates for building such optical quantum memories as they offer excellent coherence properties. Towards this end, we investigate a thulium-doped garnet crystal (Tm^{3+}:$Y_3Ga_5O_{12}$ or Tm: YGG), a crystal whose promising spectroscopic properties [7, 8] and potential for storing optical data has already been established [9]. But for all of these experiments, the storage efficiency was a few percent, which was mainly limited by the low absorption of the crystal. To overcome this problem, we implement an atomic frequency comb (AFC) quantum memory protocol [10] inside an impedance-matched asymmetric cavity-crystal [11] of Tm^{3+}:YGG. In this work, we will discuss the developments toward building highly-efficient memories that can be realized in a weakly absorbing crystal, by using the impedance matching condition [12, 13].

2. Storage efficiency in an impedance-matched cavity quantum memory

For a single pass crystal, the AFC memory efficiency can be expressed as

$$\eta^{AFC}_{\text{single-pass}} = \tilde{d}^2 \exp(-\tilde{d}) \exp(-d_0) \eta_{\text{deph}} \tag{1}$$

where $\tilde{d} = d_1/F$ is the optical depth, averaged over the input photon bandwidth, where F is the comb finesse $F = \frac{\Delta(\text{AFC peak separation})}{\gamma(\text{AFC peak width})}$, d_0 is the background (or residual) optical depth (see Fig. 1(c)). The factor η_{deph} accounts for the dephasing due to the finite width of the AFC peaks. For square absorption peaks it can be written as $\eta_{\text{deph}} = \text{sinc}^2(\pi/F)$ and for gaussian AFC peaks $\eta_{\text{deph}} = e^{-\frac{7}{F^2}}$. The efficiency of a single-pass memory, where the output echo is emitted in the same mode as the input is bounded by 54% due to the re-absorption of the echo.

To overcome the weak absorption of the crystal, it was proposed to use an optical cavity around the crystal and operate it in the impedance-matched regime [11]. The impedance-matching condition is satisfied when $R_1 = R_2 \exp(-2\tilde{d}) \exp(-2d_0)$, where R_1 and R_2 are the front and back mirror reflectivites. Hence, in the presence of an impedance-matched cavity, the enhanced AFC memory efficiency is given by

$$\eta_{\text{cavity}}^{AFC} = \left[\frac{2(1-R_1)\sqrt{R_2}}{\left(1-\sqrt{R_1 R_2} e^{-(\frac{d_1}{F}+d_0)}\right)^2} \right]^2 \left(\frac{d_1}{F}\right)^2 e^{-2(\frac{d_1}{F}+d_0)} \eta_{\text{deph}}$$

3. Results

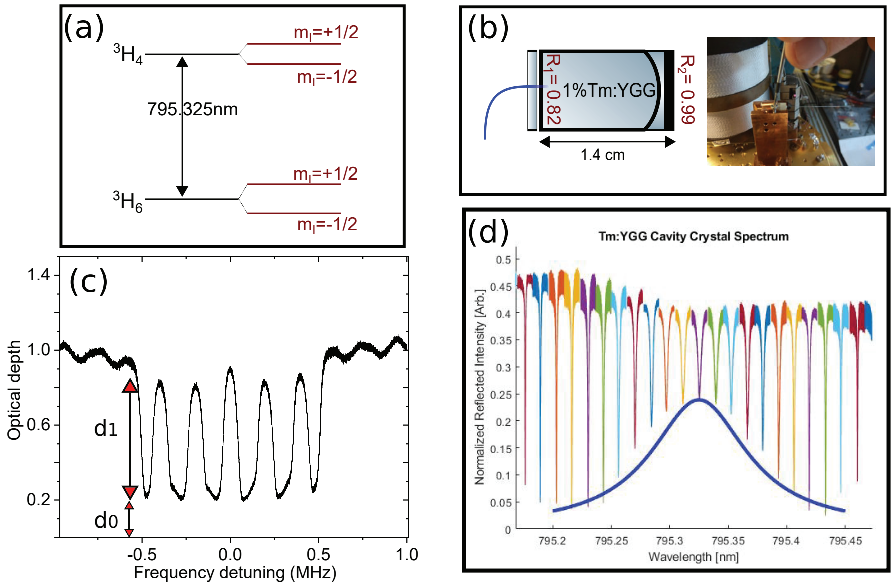

Fig. 1. **(a)** Simplified energy level diagram of the $^3H_6 \rightarrow {}^3H_4$ optical transition of Tm^{3+} in $\text{Y}_3\text{Ga}_5\text{O}_{12}$ (YGG). Only the lowest crystal field levels of each electronic manifold are shown. **(b)** A schematic of our novel fiber-pigtailed cavity-crystal and a picture of the real device. **(c)** An example of a 1 MHz wide AFC of finesse 2 tailored for 5μs storage time, crafted in a Tm:YGG bulk crystal. **(d)** The measured reflection spectra (different resonances of the cavity are depicted in different colors) of the Tm:YGG cavity-crystal system. A simulated Lorentzian (blue) represents the absorption of the Tm:YGG.

The cavity memory is made of a 1.4 cm long 1% Tm: $\text{Y}_3\text{Ga}_5\text{O}_{12}$ (Tm:YGG) crystal. The end facets of the crystal are reflection coated, with reflectivities R_2 = 99% on the rear and R_1 = 82% on the front side (see Fig. 1(b)). The reflectivity value for the front facet is chosen to allow for impedance matching at the peak absorption wavelength of 795.32 nm of Tm:YGG by meeting the impedance-matching condition $\text{R}_1 = \text{R}_2 \exp(-2\tilde{d})$, with $\tilde{d}$ the average optical depth across the cavity resonance bandwidth. To facilitate the use of the cavity-crystal quantum memory in a practical quantum repeater setting, its input is pigtailed to a single-mode fiber for 795 nm wavelength (see Fig. 1(b)). The in-out coupling efficiency of the cavity-crystal system is only 22-24%, which is the only major limitation of our novel design. The reflected spectra from the cavity-crystal are shown in Fig. 1(d), where different colors represent different cavity resonances. The free spectral range of the cavity-crystal is measured to be around 6.2 GHz, which is in accordance with the theoretical prediction. The cavity resonances are convoluted with the 55 GHz inhomogeneously broadened Lorentzian absorption profile of the Tm:YGG, centered around 795.32 nm. We note that the reflected intensity at the cavity resonances decreases and reaches a minimum at the wing of the absorption profile of the Tm:YGG where the absorption by Tm^{3+} ions is low. For the highly-efficient storage of light pulses, we need to craft AFCs with different finesse at different cavity resonances to satisfy the impedance-matching criteria.

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