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DOI
10.1109/PN62551.2024.10621752

Publication date
2024

Document Version
Final published version

Published in
2024 Photonics North (PN)

Citation (APA)
Taherizadegan, S., Davidson, J. H., Kumar, S., Oblak, D., & Simon, C. (2024). Towards a Realistic Model for Cavity-Enhanced Atomic Frequency Comb Quantum Memories. In *2024 Photonics North (PN)* (Photonics North). IEEE. https://doi.org/10.1109/PN62551.2024.10621752

Towards a Realistic Model for Cavity-Enhanced Atomic Frequency Comb Quantum Memories

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Abstract—**We develop a theoretical model for cavity-enhanced atomic frequency comb (AFC) quantum memory that includes the effects of dispersion and show a close alignment of the model with our own experimental results. Our model is a step forward to accurately estimating the created comb properties, such as the optical depth inside the cavity, and so being able to make precise predictions of the performance of the prepared cavity-enhanced AFC quantum memory.**

Keywords—quantum communication, quantum memory, optics, quantum networks

2024 Photonics North (PN) | 979-8-3503-6636-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/PN62551.2024.10621752

I. INTRODUCTION

Optical quantum memory with the ability to store and recall on-demand quantum states of light with high efficiency and fidelity is one of the essential elements for long-distance quantum communication based on quantum repeaters. Atomic frequency comb (AFC) quantum memory [1] is a favorable candidate in quantum repeater applications because of the capability to simultaneously store and read out multiple temporal and spectral modes leading to enhancement in the performance of the quantum repeater. Cryogenically cooled rare-earth-ion-doped crystals are favorable candidates for implementation of AFC quantum memory due to the long coherence times of their optical 4f-4f transitions. To obtain high efficiency in quantum memories, a large optical depth in the storage material is needed. However, in practice, simultaneously achieving high optical depth and long coherence times is difficult. To overcome this, it was proposed to put the storage medium in an asymmetric impedance matched optical cavity [2]. While putting the AFC in a cavity improve the efficiency significantly, it has been experimentally difficult to measure the AFC properties, e.g., optical depth within the impedance matched cavity. The fact that no detailed general theoretical model for cavity-enhanced AFC quantum memory exists, makes it difficult to compare experiments to theory, and hence also to infer the system parameters from experiments.

We develop a general model for cavity-enhanced AFC quantum memory and extend the impedance-matched model beyond the resonance condition by including the round-trip phase shifts of light as travelling inside the cavity in the initial proposal making it valid for any AFC bandwidth with a background absorption, and created at any detuning with respect to the cavity resonance. We show that, including dispersion, our developed model closely agrees with our own experimental results, and enables prediction of the experimental memory efficiency at any detuning with respect to the cavity resonance.

II. THEORETICAL MODEL

We consider an AFC quantum memory with a background absorption inside a general asymmetric cavity with reflectivites R_1 and R_2 where $\mathrm{R}_1 < \mathrm{R}_2 \approx 1$ (see Fig. 1(a)), and apply the "sum over all round-trips" approach of a Fabry-Perot cavity. The reflected amplitude ($\mathrm{E}_{\mathrm{out}}/\mathrm{E}_{\mathrm{in}}$) from the cavity can be written as

$$\frac{E_{out}}{E_{in}} = \frac{-\sqrt{R_1} + \sqrt{R_2} e^{-d(\nu)} e^{-i\Phi(\nu)}}{1 - \sqrt{R_1 R_2} e^{-d(\nu)} e^{-i\Phi(\nu)}} \ , \qquad (1)$$

where L is the length of the crystal, $d(\nu) = \alpha(\nu)L$ is the optical depth, and $\alpha(\nu)$ is the absorption coefficient. In addition, the total round-trip phase is $\Phi = 2KL$, where $K = 2\pi\, n(\nu)/\lambda$ is the wavenumber, and $n(\nu)$ is the real refractive index of the matter inside the cavity. $\alpha(\nu)$ and $n(\nu)$ are connected as a result of the Kramers-Kronig relations, that relate the real $\chi_r(\nu)$ and imaginary $\chi_i(\nu)$ parts of the susceptibility of a medium (see (2)). Equation (1) is a general version of (11) in [2] and can be applied to both on-resonance and off-resonance conditions. We assume an AFC with an engineered optical depth $d(\nu)$ of a series of Gaussian peaks with identical amplitudes (d_c), spacing (Δ), width (γ), and a constant d_0 which is the optical depth associated with the background absorption.

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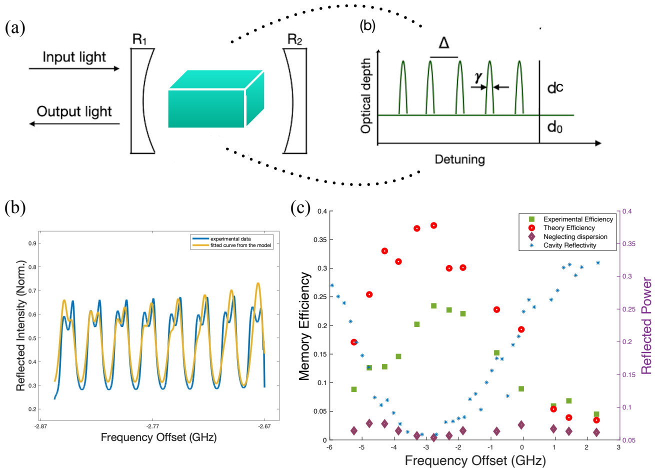

Fig. 1. (a) Tm:YAG crystal cavity and the comb shaped absorption profile of Tm:YAG (b) The fitted curve from our model to the experimental data for one of the combs close to the cavity resonance. (c) Comparison of the experimental and obtained theoretical memory efficiencies.

$$\chi_r(\nu) = \frac{2}{\pi}\mathscr{P}\int_0^\infty \frac{\nu'\chi_i(\nu')}{\nu'^2-\nu^2}d\nu' \qquad\qquad \chi_i(\nu) = \frac{2}{\pi}\mathscr{P}\int_0^\infty \frac{\nu\chi_r(\nu')}{\nu^2-\nu'^2}d\nu' \tag{2}$$

Thus, frequency engineering of the absorption coefficient and creating AFC affects the real refractive index n(ν). To obtain the real refractive index n(ν) we need to take into account the absorption coefficient over the whole frequency range.

III. EXPERIMENT

The sample used in the experiment is an approximately 4mm long 0.1% thulium-doped $Y_3Al_5O_{12}$ (Tm:YAG) crystal at the cryogenic temperature of 1.5 K. The two ends of the crystal surface are reflection coated with reflectivities R_1 on the front end and R_2 on the back end. We prepare several combs at different frequencies across the cavity features (see Fig. 1(b)). The obtained experimental memory efficiencies for the created combs are shown in Fig. 1(c). In [3] the reflected power of the crystal cavity with no engineered comb is measured. The measurements show almost perfect impedance matching for the reflected power of the cavity occurs near −4 GHz frequency offset.

IV. RESULTS

To compare the experimental data with our theoretical model we fit (1) in our model to the experimental data for the cavity with no comb reflectivity and obtain the exact values for the crystal cavity properties as the fitting parameters. Then, we consider the crystal cavity with a spectral shaped AFC. By fitting the model to the measurement results of the reflected intensity of the AFC cavity, we extract the comb shape and optical depth of the created combs. Finally, we use the obtained comb parameters from the fitting to predict the efficiencies of the created cavity-enhanced AFC quantum memories at different frequency offsets across the cavity features. We also investigate the effect of neglecting dispersion due to the atomic absorption in the model. The reflected power from the cavity for one of the created combs near the impedance-matched frequency and the memory efficiencies for AFC cavity quantum memories created at different detunings with respect to the cavity resonance are shown in Fig. 1.

V. CONCLUSION

In summary, we have developed a model for cavity-enhanced AFC quantum memory, which helps to address the challenges of the measurement of comb properties inside the cavity. Employing the experimental cavity reflectivity, our model allows us to estimate the comb properties and the efficiency of the cavity-enhanced AFC quantum memory with a background absorption and arbitrary bandwidth created at any frequency offset with respect to the cavity resonance which can further inform the next generation of cavity-enhanced quantum memories leading to more rapid progress towards their application in quantum networks.

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