An atomic frequency comb memory in rare-earth doped thin-film lithium niobate

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Abstract: We demonstrate compact chip-integrated atomic frequency comb storage in rare-earth doped thin-film lithium niobate. Our optical memory exhibits a broad storage bandwidth exceeding 100 MHz, and optical storage time of over 250 ns. © 2022 The Author(s)

1. Introduction

Integrated atomic frequency combs memories that coherently store optical signals are essential for scalable quantum technology [1]. Lithium niobate is an ideal photonic platform for developing integrated optical memories based on rare earth ions. Rare-earth ion diffused waveguides patterned in bulk lithium niobate have been previously used to demonstrate optical quantum memory [2–4]. However, these devices have a large mode cross section and require high optical powers for coherent control and storage using atomic frequency combs. Here we utilize a thin-film lithium niobate waveguide doped with thulium rare-earth ions. By patterning an atomic frequency comb [1,2] on the absorption spectrum of the thulium ion ensemble by spectral hole burning, we achieve optical memory with bandwidth exceeding 100MHz and storage times over 250 ns. The tight confinement of the thin-film lithium niobate waveguide led to a three orders of magnitude improvement in the Rabi frequency as compared to the large ion-diffused waveguides.

2. Device structure

Fig. 1a shows a schematic of the device structure, which consists of a ridge waveguide patterned in thin-film lithium niobate doped with thulium ions density of 0.1%. Fig. 1b shows a scanning electron microscope image of a fabricated waveguide with grating coupler to couple light in and out of the chip. Fig. 1c shows the calculated cross-sectional mode profile of the simulated TE mode in the thin film waveguide, which is aligned along the x axis of the crystal which achieves maximal rare-earth ion absorption. The optical mode has a transverse area of 0.07 μm², which is three orders of magnitude smaller than ion-diffused waveguides [3] and results in a strong light confinement within the waveguide.

Figure 1. (A) Schematic of the device structure, composed of a thin-film lithium niobate waveguide doped with thulium rare-earth ions. (B) Scanning electron microscopy image of the waveguide with grating coupler. (C) Finite difference time domain simulation showing the x component of the electric field of the waveguide mode, which is maximally aligned with the rare-earth ion absorption.

3. Coherence time measurement

In order to characterize the coherence time of the atomic ensemble, which puts a fundamental limit on the storage time of the medium, we perform a photon echo measurement using two pulses with an area of π/2 and π, respectively, separated by time τ (Fig. 2a.) By measuring the strength of the generated photon echo as a function of τ we can determine the coherence time of the rare-earth ensemble. In Fig. 2b, we first determine the duration of a π pulse to be 70 ns, by plotting the power of the output photon echo as a function of second pulse duration while keeping the first pulse duration fixed. The Rabi frequency of the dipole transition is determined to be 44.9 MHz (π/2) for a driving power of 1 μW in the waveguide, which is three orders of magnitude smaller than the power require in to achieve the same Rabi frequency in ion diffused waveguides [3]. Fig. 2c shows the photon echo
amplitude decays with an exponential time constant of $350 \pm 48$ ns as a function of the delay $\tau$, which determines the coherence time $T_2 = 2\tau$ to be $700 \pm 96$ ns. This value is comparable to previous measurements for thulium ions in bulk lithium niobate at 4 K [5], indicating that thin-film processing does not significantly degrade the coherence properties of the rare-earth ions.

4. Light storage in an atomic frequency comb memory

We create an atomic frequency comb by burning a series of spectral holes with a periodic pulse train of 150 pulses with 10 ns duration and variable period $T = 2\pi/\Delta$ (Fig. 3a). As an example, the absorption spectrum of the atomic ensemble burnt with a period of $T=130$ ns is shown in Fig. 3b. When a pulse enters the prepared atomic ensemble, it excites the individual comb teeth which rapidly dephase, and then rephase at a time $T = 2\pi/\Delta$ and re-emit the photon. Fig. 3c shows that waveguide output for several different frequency combs corresponding to storage time ranging from 90 ns to 250 ns. Each comb results in an output pulse that is delayed by the correct time programmed into the frequency comb memory. We can further improve the storage efficiency by taking advantage of the thin film platform and designing impedance matched cavities [6,7]. The ability to integrate active modulation on chip could further enable electro-optically tunable [8,9] integrated photonic memory. Such a versatile platform is therefore a critical step towards scalable, highly efficient, electro-optically tunable quantum photonic systems where one can store and manipulate light on chip with high bandwidth and low powers.

5. References

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