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The comb waveguide: a new tool for strong interaction between atoms and light

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Abstract. Coupling quantum emitters and nanostructures, in particular cold atoms and waveguides, has recently raised a large interest due to unprecedented possibilities of engineering light-matter interactions. However, the implementation of these promising concepts has been hampered by various theoretical and experimental issues. In this work, we propose a new type of periodic dielectric waveguide that provides strong interactions between atoms and guided photons with an unusual dispersion. We design an asymmetric comb waveguide that supports a slow mode with a quartic (instead of quadratic) dispersion and an electric field that extends far into the air cladding for an optimal interaction with atoms. We compute the optical trapping potential formed with two guided modes at frequencies detuned from the atomic transition. We show that cold Rubidium atoms can be trapped as close as 100 nm from the structure in a 1.3-mK-deep potential well. For atoms trapped at this position, the emission into guided photons is largely favored, with a beta factor as high as 0.88 and a radiative decay rate into the slow mode 10 times larger than the free-space decay rate.

1 Introduction

Recently, the coupling of cold atoms with nanofibers or nanostructured waveguides has triggered the emergence of a new field of research known as waveguide QED. Photons travelling in the waveguide carry the information through long distances while atoms trapped in its vicinity can store it for long times.

These systems are a promising building block for quantum networks as shown recently by the experimental demonstrations of the heralded creation of a single collective excitation of atomic arrays [1], or a correlated photon transport. When the decay rate of the atoms inside the waveguide mode Γ_{1D} exceeds greatly the decay into every other mode Γ', we reach the strong coupling of waveguide QED where new phenomena in many-body physics appear such as the emergence of solitons dynamics or many-body localization.

A promising route to increase Γ_{1D} (or the beta factor $\beta = \frac{\Gamma_{1D}}{\Gamma_{1D}+\Gamma'}$) is to use periodic dielectric waveguides, i.e., waveguides with a periodic modulation of the refractive index along the propagation direction. Indeed, the radiative decay rate of a single atom in a guided mode is given by $\Gamma_{1D}/\Gamma_0 = n_g\sigma/(2A_{\text{eff}})$, where Γ_0 is the atomic decay rate in free space, σ is the absorption cross-section, n_g and A_{eff} are the group index of the mode and the effective area at the atom position [2, 3]. In periodic waveguides, the coupling between contrapropagating modes results in the opening of bandgaps in the dispersion relation and in the apparition of band edges where the group velocity $v_g = c/n_g$ goes to zero. Close to these peculiar points, periodic waveguides support slow guided modes with large n_g's, which, in turn, lead to increased values of Γ_{1D} and β.

The so called Alligator waveguide [3, 4], which is the most studied periodic waveguide up to now, was built upon this idea. However, it has two major flaws: a lack of accessibility of the trapping region (where the evanescent tail of the slow mode is large), and a very curved dispersion of the slow mode not robust enough against disorder in fabrication. Thus, only $N = 3$ atoms have been trapped close to this structure, with a moderate coupling to the slow mode $\Gamma_{1D} \sim \Gamma'$ ($\beta = 0.5$).

2 The comb waveguide

To improve those figures of merits, we designed an asymetric comb waveguide [5] with the following assets:

- first, it can be suspended in air to provide easy access to the trapping region. As shown in Fig 1, the atoms can be trapped in the back of the structure
- second, the transverse asymmetry of the structure provides additional degrees of freedom to engineer the dispersion curve. We designed a completely new quartic dispersion $\omega \sim \Delta k^4$, that provides more resilience to our

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structure against fabrication imperfections and enlarges its operation bandwidth.

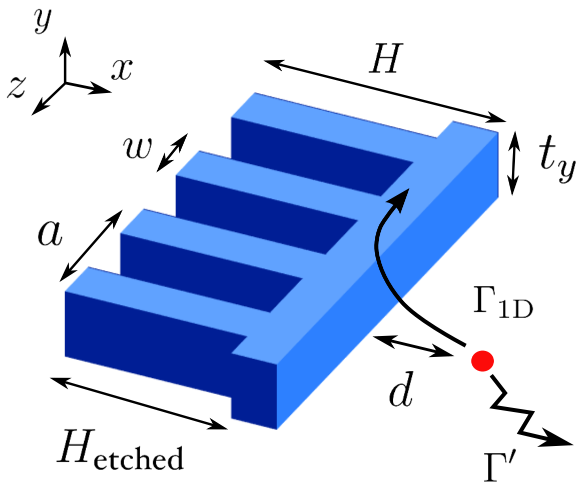

Figure 1. Scheme of the comb waveguide we designed to improve the experimental figures of merit of waveguide QED. We optimized the structure so that Rubidium atoms can be trapped in the back of the structure, in a deep potential well ($U_{trap} \sim 1$mK) and at a distance of $d = 100$nm from the waveguide.

We optimized the structure so that two additional fields, blue and red detuned with respect to the atomic transition frequency, can propagate through the waveguide. We computed rigorously the trapping potential produced by these fields using the recently-introduced open-source package Nanotrappy [6]. The calculation includes the Casimir Polder interaction that arises when an atoms is very close to a dielectric surface. We showed that Rubidium atoms can be trapped efficiently ($U_{trap} \sim 1$mK) as close as $d = 100$nm from the back of the structure, where the slow mode has a strong evanescent tail.

At this distance, the atoms emit preferentially into the slow mode. Using a rigorous modal method, we computed exactly the decay rate inside the slow mode and in all the other modes and showed that $\Gamma_{1D} = 10\Gamma_0 = 8.8\Gamma'$ for an atom inside the trap leading to a value of $\beta = 0.88$.

3 Conclusion and outlook

The fabrication of the comb waveguide is now in progress at c2n. We believe that the trapping of $N \sim 10 - 20$ atoms with a strong coupling to the comb waveguide can be seriously considered. Such high figures of merit would lead to the emergence of new physical phenomena.

First, the quartic dispersion of the slow mode can drastically modify the collective effets that emerges when many atoms are strongly coupled to the structure.

Second, thanks to the unprecedented value of $\beta = 0.88$ accessible with the comb waveguide, new quantum-non linear effects could be observed, such as soliton dynamics [7, 8] , or many-body localization [9] .

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