Non-Reciprocal Amplification of Light Using Cold Atoms Coupled to an Optical Nanofiber

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Abstract. Optical nanofibers realized as the waist of tapered silica fibers can be used to trap and optically interface laser-cooled atoms. Building on this system, we experimentally show a novel scheme for the non-reciprocal Raman amplification of light. While typically either the magneto-optical effect, a temporal modulation or an optical nonlinearity is employed to break reciprocity, in our approach, this results from the spin of the atoms forming the gain medium. By taking advantage of the inherent spin-momentum locking present in optical nanofibers, we perform an experiment in which we set the amplification direction by a suitable preparation of the atomic spin state. Our approach is general and, suitable quantum emitters provided, could also be implemented beyond the optical domain of the electromagnetic spectrum.

1 Introduction

Typically, non-reciprocal optical devices are realized by employing either the magneto-optical effect, time modulation or an optical nonlinearity in order to break Lorentz reciprocity [1]. In recent years, a new class of such devices based on spin-polarized quantum emitters have attracted increasing interest, and respective isolators and circulators have been demonstrated experimentally [2]. Recently, we have demonstrated non-reciprocal Raman amplification of light using spin-polarized atoms with directional coupling to a tapered optical fiber with a nanofiber waist [3]. We show that we can switch the operation direction of the amplifier by flipping the atomic spin.

2 Experimental Setup

Figure 1 a) shows a schematic of the experimental setup. We couple a 1D array of laser-cooled, optically trapped cesium atoms to the evanescent field surrounding an optical nanofiber of 500 nm diameter [4]. We then launch a probe laser field into either port 1 or port 2 of the nanofiber. We choose the polarization such that, due to the strong transverse confinement of the light, the local polarization at the position of the atoms is either σ^-- or σ^+-polarized, depending on the propagation direction [5]. This inherent link between polarization and propagation direction is also known as spin-momentum locking. In addition to the probe light, we illuminate the atoms with a free-space π-polarized coupling laser field that propagates in the x-direction. In Fig. 1 b), we show the energy levels relevant to our experiment. Initially, we prepare the atoms in state $|6S_{1/2}, F = 4, m_F = -4\rangle$. In order to stabilize this spin-polarization, we apply a magnetic offset field of $\sim$ 7 G along z. The coupling field is detuned by Δ=82 MHz from the excited state, and the probe laser is tuned to the respective light shifted two-photon resonance.

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3 Experimental demonstration of non-reciprocal Raman amplification

First, we switch on the probe laser field, which does not couple to the atoms in their initial state, and measure a transmission of 9 pW. We then switch on the coupling laser field at time $t = 0$ μs and measure the probe transmission dynamics, see Fig. 2 a). We observe an increase of the probe transmission by up to $\sim$ 130 % when launching the probe field into port 1 of the waveguide (red diamonds). However, if the probe laser is launched into port 2, the transmission is almost unchanged, since the atoms do not couple to σ^+-polarized probe light (blue circles). The data is in good agreement with the predictions of our model, which consists of solving the Master equation for a three-level system for each atom and consecutively calculating the transmission coefficient along an array of $N = 1400$ atoms, see solid lines in Fig. 2. By preparing the atoms in $|F = 4, m_F = +4\rangle$, we are able to switch the operation direction of the amplifier, and the probe laser field is amplified only when propagating from port 2 to port 1, see Fig. 2 b). These results demonstrate non-reciprocal amplification of the probe light field and that we are able to set the direction of amplification via the atomic spin state.

4 Outlook

Our results provide a new element to the novel class of spin-controlled, non-reciprocal optical devices. Our scheme could be extended to continuous-wave operation by the addition of a repump laser field and thus enable

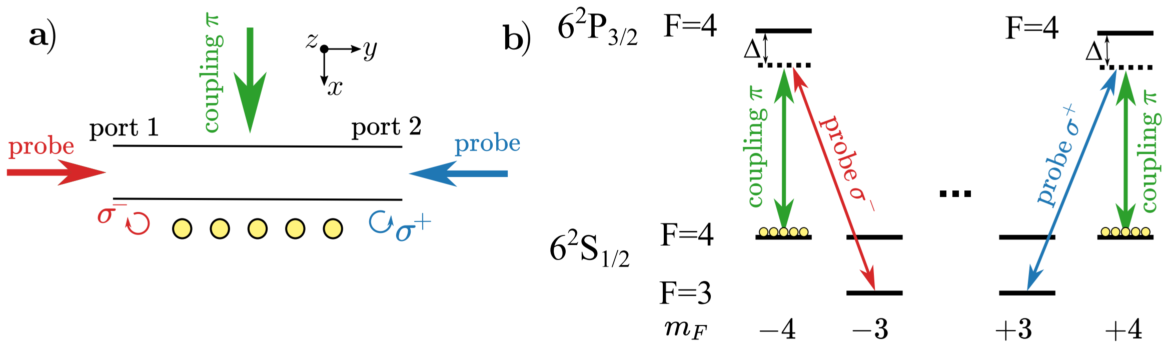

Figure 1. a) We trap cesium atoms (yellow circles) in a 1D array of trapping sites, close to an optical nanofiber. A probe laser field is launched either into port 1 or port 2 of the waveguide and interacts with the atoms via the evanescent part of the nanofiber-guided mode. The probe field is either predominantly σ^-- or σ^+- polarized at the position of the atoms. A π-polarized coupling laser field illuminates the atoms from the side. b) Energy levels relevant to our scheme. The atoms are initially prepared in $|6^2S_{1/2}, F = 4, m_F = -4\rangle$. The probe and coupling laser fields couple to different Λ-system, depending on the probe polarization and initial atomic state.

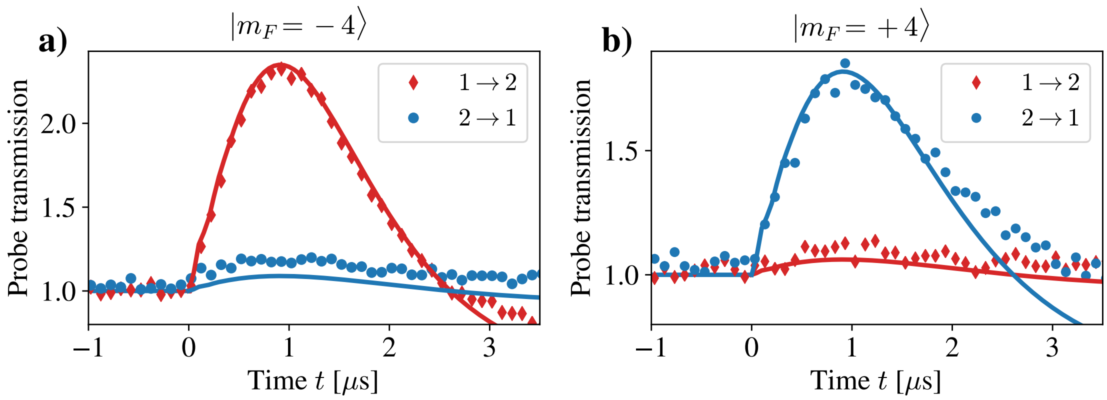

Figure 2. Non-reciprocal gain. Measured probe transmissions when launching the probe laser into port 1 or port 2 of the waveguide, see red diamonds and blue circles, respectively. a) We prepare the atoms in $|F = 4, m_F = -4\rangle$. At $t = 0\,\mu$s, we switch on the coupling field and the probe transmission increases by $\sim 130\,\%$ in the $1 \rightarrow 2$ direction, while it is almost unchanged in the $2 \rightarrow 1$ direction. b) Here, we prepare the atoms in $|F = 4, m_F = +4\rangle$ and observe that the direction in which there is gain is now switched, showcasing non-reciprocal amplification and that the gain directionality can be controlled by suitably preparing the atomic spin state. The data is in good agreement with the theory prediction, see solid lines.

fundamental studies of lasing with spin-controlled gain directionality. Moreover, our scheme could be implemented using other quantum emitters and nanophotonic structures, allowing the extension of our method to other domains of the electromagnetic spectrum.

References

[1] V. S. Asadchy *et al.*, "Tutorial on electromagnetic nonreciprocity and its origins," Proc. IEEE **108**, 1684 (2020).

[2] P. Lodahl *et al.*, "Chiral quantum optics," Nature **541**, 473 (2017).

[3] S. Pucher *et al.*, "Atomic spin-controlled non-reciprocal Raman amplification of fibre-guided light," Nature Photonics **16**, 380 (2022).

[4] E. Vetsch *et al.*, "Optical interface created by laser-cooled atoms trapped in the evanescent field surrounding an optical nanofiber," Phys. Rev. Lett. **104**, 203603 (2010).

[5] R. Mitsch *et al.*, "Quantum state-controlled directional spontaneous emission of photons into a nanophotonic waveguide," Nature Communications **5**, 1 (2014).