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Ultralow-power nonlinear optics using tapered optical fibers in noble gases

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Abstract: We demonstrate ultralow-power optical nonlinearities using a sub-wavelength diameter tapered optical fiber in a gas of metastable xenon atoms. The use of inert noble gases offers advantages over reactive alkali vapors such as rubidium.
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1. Introduction

The interest in nonlinear optics with ultralow-power fields is driven by applications such as all-optical switching. One promising system for the realization of these strong nonlinearities is the use of sub-wavelength diameter tapered optical fibers (TOF's) suspended in atomic vapors [1]. As shown in Figure 1, the TOF enables low-loss propagation of an evanescent field with a very small mode-area over a very long distance through the surrounding vapor. Current state-of-the art experiments using TOF's with waist diameters of ~300 nm produce evanescent fields with diameters of D ~1 μm propagating over an effective interaction length of L_{eff} ~ 1 cm. This gives a factor of $\sim 10^4$ enhancement of the relevant nonlinearities compared to typical free-space focusing of laser beams into an atomic vapor cell. For suitable atomic vapors, the high field intensities in the TOF system allow the observation of significant nonlinear optical interactions at nanoWatt- and even "few-photon"- power levels [2,3].

Virtually all previous TOF work in this area has used rubidium as the atomic vapor. Rb has a number of desirable properties, including a convenient (and strong) two-photon ladder transition allowing nonlinear optics with a "control beam" at 780 nm and a "signal beam" at 776 nm (see Figure 2(a)). Unfortunately, at the relatively high atomic densities needed in these experiments, the tendency of Rb to accumulate on silica surfaces causes a dramatic loss of transmission through the system [4]. Although this effect can be mitigated to some extent by heating the TOF [4], the scattering loss due to Rb accumulation on the TOF surface is currently one of the main limiting factors in the performance of this system.

2. Xenon vs. Rubidium

The problems associated with surface accumulation suggest the use of inert noble gases as a replacement for reactive Rb vapor in these systems. Here we specifically investigate the use of Xe [5]. As shown in Figure 2(b), a weak electric discharge is used to excite Xe to a long-lived metastable state [6] that serves as an "effective ground state" for a subsequent ladder transition at 823 nm and 853 nm. The transition rates of these lines are comparable to those shown for Rb. Consequently, using Xe metastable state densities comparable to typically used Rb vapor densities ($\sim 10^{12}$ cm^{-3}) should allow comparable overall nonlinearities, without the problem of surface accumulation.

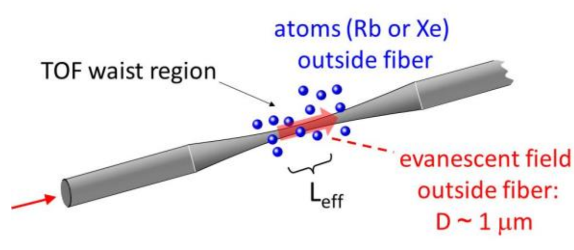

Figure 1: Conceptual illustration of a sub-wavelength diameter TOF suspended in an atomic vapor. The high intensity of the small mode-area evanescent field (D ~ 1 μm) interacting with the surrounding atoms allows the observation of nonlinear effects with ultralow-power fields. In this work, we demonstrate the use of xenon (an inert noble gas) as a replacement for traditionally used Rb (a reactive alkali vapor). This use of inert noble gases overcomes the problems associated with Rb atoms adhering to the surface of the TOF [5].

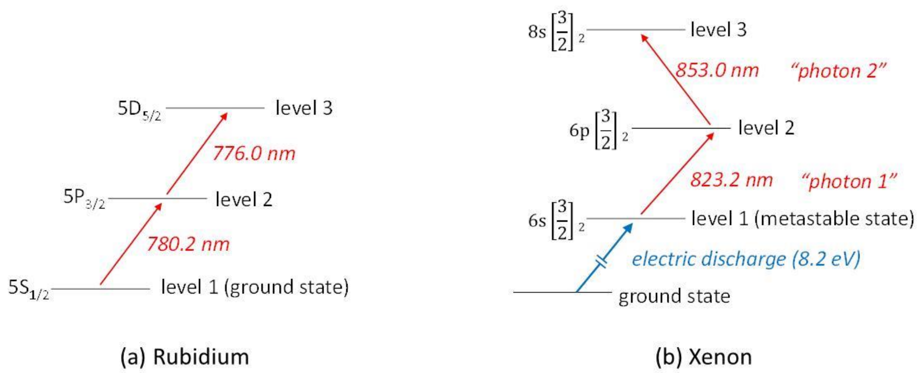

Figure 2: A comparison of the relevant energy level diagrams for a variety of nonlinear optics experiments in (a) Rubidium and (b) Xenon. Xe has a long-lived metastable state that serves as an effective ground state for the two-photon ladder transition at 823 nm and 853 nm.

3. Preliminary results using TOFs in Xe

Figure 3 summarizes the results of our initial work demonstrating the ability to saturate the 823 nm Xe transition at nanoWatt power levels [5]. This ultralow saturation power (~126 nW) is comparable to that typically observed in previous "TOF in Rb" systems [1,2,4], and indicates the suitability of the "TOF in Xe" system for various two-beam nonlinear interactions using the ladder transition of Figure 2(b). The data shown in Figure 3 was obtained using a relatively low density of Xe metastable states produced by a low intensity DC discharge system. The next challenge will be to achieve much higher densities (comparable to Rb experiments; ~10^{12} cm^{-3}) without damaging the TOF. We also expect noble gases to be of use as replacement for Rb in closely related experiments using hollow-core photonic bandgap fibers [3].

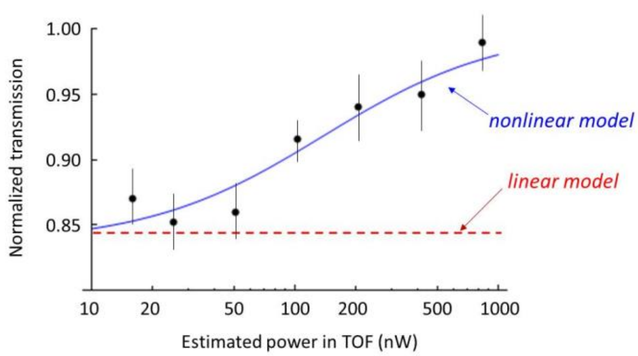

Figure 2: Experimental results showing ultralow-power saturated absorption using the "TOF in Xe" system [5]. The data shows the transmission of a TOF probe beam tuned to one of the Xe hyperfine resonances at 823 nm as the power is increased. The data is fit to a simple nonlinear absorption model with a saturation power comparable to those seen in typical "TOF in Rb" systems [1,2,4]. This data is taken from [5].

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