Nonlinear Optics at Ultra Low Power in a High-Finesse Optical Cavity with Metastable Xenon

G. T. Hickman, T. B. Pittman, and J. D. Franson
Physics Department, University of Maryland Baltimore County, Baltimore, MD 21250 USA
garrett.hickman@umbc.edu

Abstract: We propose metastable xenon gas as a medium for realizing room temperature nonlinear optics experiments in cavity QED. We demonstrate the viability of this scheme by saturating the $6s[3/2]_2$ to $6p[3/2]_2$ transition with nanowatt powers.
OCIS codes: (270.5565), Quantum communications; (230.4320) Nonlinear optical devices

1. Introduction

Recent proposals for performing optical quantum computation and quantum communication make use of Kerr-type optical nonlinearities, such that a control field at single photon power levels induces an appreciable cross phase shift (XPS) on interaction with a classical coherent light beam [1,2]. Much effort has been spent on experimentally demonstrating large nonlinear phase shifts, with a number of recent results reporting a single-photon XPS as large as 0.5 radian or more [3,4].

Some proposed applications only require a small XPS of the order 10 mrad [1,2]. It would be beneficial to have a relatively simple, robust method for producing single-photon phase shifts in this regime that could avoid the complexity and technical challenge of most approaches [3,4]. A hot atomic vapor placed in an optical cavity would provide an excellent candidate medium, but the finesse of such a cavity is typically relatively low because of alkali atoms adsorbed onto the optical surfaces.

We propose the use of room temperature metastable xenon gas as an intra-cavity medium for performing ultra low power nonlinear optics experiments. Metastable Xe possesses nonlinear properties comparable to those of Rb, is simple to introduce into the system, and even when excited with an RF plasma discharge causes no noticeable degradation in the quality of precision optical surfaces. As a preliminary test we have performed an initial measurement of absorption saturation in such a system, clearly showing nonlinear effects at nanowatt power levels. Our results demonstrate the viability and the advantage of using Xe as a nonlinear intra-cavity medium.

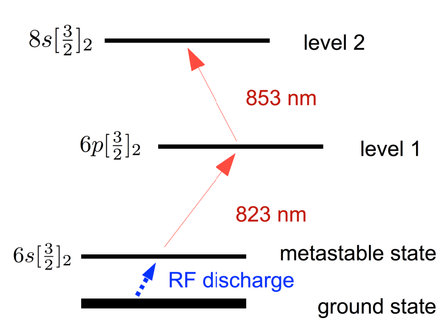

Figure 1: Xe energy level diagram. Xe atoms can be excited into the metastable state by means of an RF discharge. Transitions at 823 nm and 853 nm are then available in a ladder-type configuration for nonlinear optics experiments.

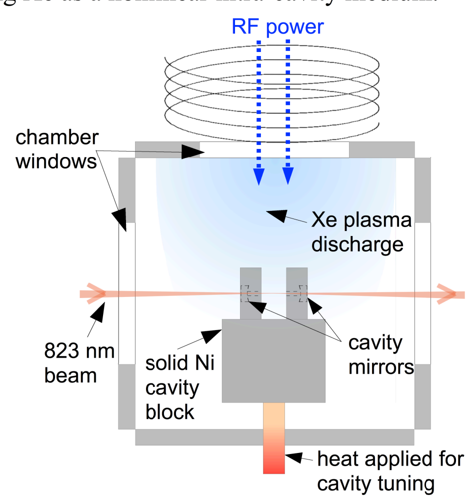

Figure 2: Overview of cavity construction within the vacuum chamber. Xenon was excited into the metastable state via an RF glow discharge. Cavity mirrors were supported in a solid nickel housing, exposed to the discharge through a 2mm diameter hole. The cavity was frequency tuned by adjusting the temperature of the nickel housing.

2. Metastable Xe in an optical cavity

Once excited to the $6s[3/2]_2$ metastable state, which has a long lifetime of about 43 s [5], the $6s[3/2]_2$ to $6p[3/2]_2$ transition at 823 nm becomes available. A further transition from $6p[3/2]_2$ to $8s[3/2]_2$ at 853 nm may be used for performing nonlinear optics experiments in a ladder type configuration, though we do not make use of it in the present work. Both transitions have dipole matrix elements similar to those of Rb. Figure 1 summarizes the Xe energy levels and transitions of interest.

Xenon gas was introduced into a vacuum chamber, at a pressure of about 0.1 Torr in this experiment with an additional 0.9 Torr of buffer gas. A resonant RF circuit consisting of a coil and capacitors was housed in a solid aluminum casing and placed against a window flange near to the experiment. RF power was applied to the coils, driving a glow discharge that diffused through the chamber.

The interaction in our experiment took place inside a confocal cavity with finesse of about 4,000, composed of two super-polished dielectric mirrors with radii of curvature 2.5 cm. A pair of rectangular wings were machined into a cylindrical block of solid nickel to house the mirrors. A 2mm diameter hole drilled though the wings and centered on the mirror insets left space for a laser beam to couple into the cavity fundamental transverse mode. The cavity resonant frequency could be temperature tuned by a full free spectral range with a temperature change of only a fraction of a degree C. The setup is illustrated in Figure 2.

3. Measured Saturation of 6s[3/2]$_2$ to 6p[3/2]$_2$ Transition

We have demonstrated the possibility of achieving nonlinear optical effects at low power levels in this system by measuring the saturation power of the first transition. We locked a frequency tunable diode laser to the cavity resonance using a LabView routine interfaced with the external optics and scanned the cavity resonance across the absorption spectrum of the first transition. Hyperfine splitting and the presence of multiple isotopes divide the transition here into four distinguishable dips, as seen in Figure 3. The spectrum was scanned with beam powers of 0.5, 2, and 19 nW, showing significant saturation effects at nanowatt powers. Noise in the signal came from a number of Fabry Perot-type interference effects along the beam path, which was contained almost entirely in fiber. These will be suppressed or eliminated in future experiments. This work was funded by DARPA grant W31P4Q-12-1-0015.

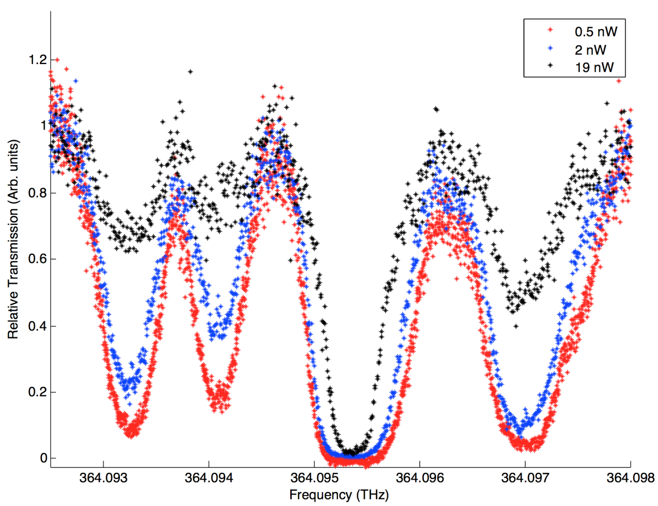

Figure 3: Transmission versus frequency for the Xe 6s[3/2]$_2$ to 6p[3/2]$_2$ transition with varying input optical power. The spectrum shows significant saturation effects at nanowatt power levels.

4. References

[1] W. J. Munro, Kae Nemoto, and T. P. Spiller, “Weak nonlinearities: a new route to optical quantum computation,” New J. Phys. 7 137, (2005) .

[2] B. T. Kirby and J. D. Franson, “Nonlocal Interferometry Using Macroscopic Coherent States and Weak Nonlinearities,” Phys. Rev. A **87**, 053822 (2013).

[3] Ofer Firstenberg, Thibault Peyronel, Qi-Yu Liang, Alexey V. Gorshkov, Mikhail D. Lukin, and Vladan Vuletić, “Attractive photons in a quantum nonlinear medium,” Nature **502**, 71–75 (2013).

[4] Ilya Fushman, Dirk Englund, Andrei Faraon, Nick Stoltz, Pierre Petroff, and Jelena Vučković, “Controlled phase shifts with a single quantum dot,” Science **320**, 5877, 769-772 (2008).

[5] M. Walhout, A. Witte, and S. L. Rolston, “Precision measurement of the metastable 6s[3/2]$_2$ lifetime in xenon,” Phys. Rev. Lett. **72**, 2843-2846 (1994).