RESEARCH Revista Mexicana de Física **60** (2014) 366–370 SEPTEMBER-OCTOBER 2014

Enhancement of vectorial nonlinearity in rubidium vapor by using an additional pump beam

N. Korneev, Y.M. Torres and Y. Ortega
Instituto Nacional de Astrofísica, Óptica y Electrónica,
Luis Enrique Erro # 1, 72840, Apartado Postal 51 y 216, Tonantzintla, Puebla, México.

Received 14 March 2014; accepted 4 July 2014

We report the enhancement of nonlinearity to absorption ratio in rubidium vapor for a signal beam in ^{87}Rb transition D2 line with $F_g = 1$ by means of an additional pump beam. Experimental results for a pump beam in co- and counter-propagation configurations are reported. The ratio increment of approximately 2 times is obtained for the co-propagating case when the pump beam is tuned at $F_g = 1$.

Keywords: Rubidium vapor; polarization self-rotation; nonlinear phase shift.

Reportamos el incremento de la razón entre la no-linealidad y la absorción en vapor de rubidio para un haz señal en la línea de transición D2 del ^{87}Ru con $F_g = 1$ utilizando un haz de bombeo adicional. Se reportan resultados experimentales cuando el haz de bombeo se propaga en la misma dirección del haz señal y en dirección opuesta a éste. Un incremento de aproximadamente 2 veces se obtiene cuando los haces de bombeo y señal se propagan en la misma dirección y el láser de bombeo se encuentra sintonizado en la línea de transición $F_g = 1$.

Descriptores: Vapor de rubidio; autorotación del plano de polarización; fase no lineal.

PACS: 42.65.Hw; 42.70.Nq

1. Introduction

The self-rotation of elliptically polarized light when it interacts with near-resonant atomic vapors is a well known phenomenon [1-4]. The two initially unbalanced components of circularly polarized light in the elliptically polarized laser beam experiment different refractive index values. As a consequence, the change in the angle of the major axis of the polarization ellipse occurs upon propagation [1]. In rubidium vapor, a complete model of nonlinearity requires solving the full density matrix evolution equation. The resulting vectorial interaction shows that nonlinearity is maximal when the light intensity has some optimal value which is typically lower, than the maximal intensity of laser, and the nonlinearity can be enhanced by a combination of elliptic polarization and a weak longitudinal magnetic field [5]. Recently, the rubidium vapor nonlinearity has been used for applications such as dynamic interferometry and electromagnetic vacuum squeezing [6-10]. In these applications the figure of merit is the nonlinearity η to absorption α ratio (R $= \eta/\alpha$), which gives an estimate of the achievable nonlinear phase shift. Thus, increasing the value of R is important. In this work we show that it is possible to enhance the value of R by using an additional pump laser at resonance with $F_g = 1$ of D2 Rb line (780 nm) for a signal beam at $F_g = 1$. An improvement at R was found when the pump and signal beams are co-propagating in the rubidium vapor and the pump beam is resonant at $F_g = 1$, $F_e = 0$.

The improvement of R is also possible when the pump beam is at resonance with $F_g = 2$, $F_e = 2$ [11]. The enhancement of R in both cases is similar (∼2 times in relation to case without pump). However, our numerical model is valid only when the pump and the signal beams are resonant with different Doppler-broadened ground state sublevels. Thus we report here only the experimental results for both pump and signal beams within $F_g = 1$ line, though qualitatively the effects are close to those obtained for signal at $F_g = 1$ and pump at $F_g = 2$, which are reported in Ref. 11.

2. Experimental results

The experimental setup is shown in Fig. 1. We used two independent tuneable diode external cavity lasers near 780 nm, with 50 mW (signal) and 60 mW (pump). The initial polarizations of both beams are linear and mutually perpendicular. The measurement rubidium cell, 75 mm long, was magnetically isolated with a double μ-metal shield. The resistive heater was located between the two shells. The first polarizing beamsplitter cube gives a well defined initial vertical polarization in the signal beam. A quarter-wave plate pro-

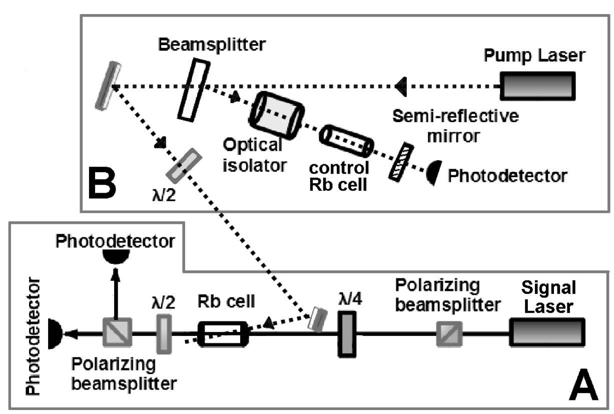

FIGURE 1. The experimental setup. The scheme marked with letter A represents the measurement arm. The scheme marked with letter B represents the pump and control arm.

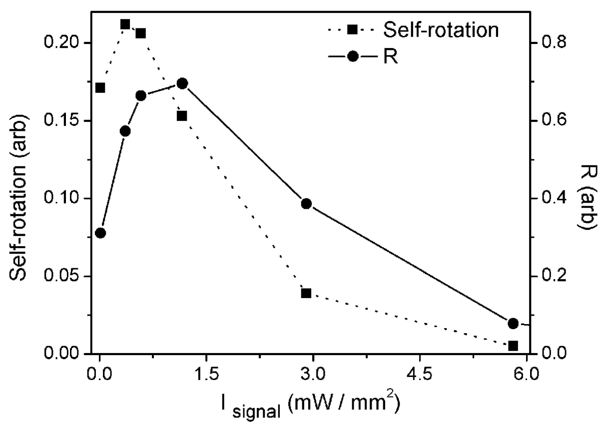

FIGURE 2. The self-rotation and rotation to absorption ratio R without pump beam when the signal intensity is changed.

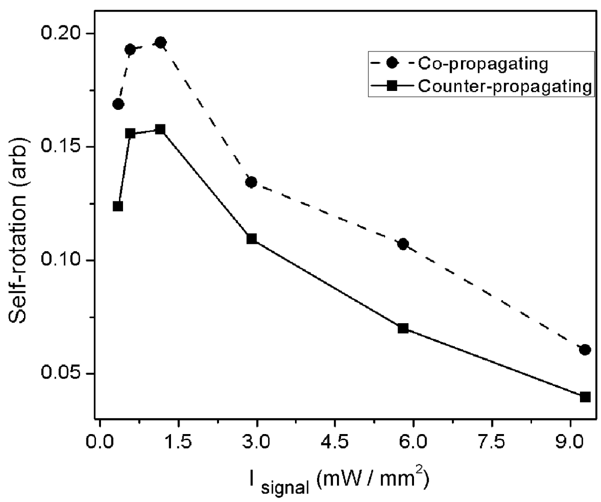

FIGURE 3. Comparative curves of self-rotation as a function of signal intensity for co- and counter-propagating pump laser in the transition $F_g = 1$, $F_e = 0$. The intensity of pump beam is at maximum (2.22 mW/mm^2).

duces a beam with controlled elliptic polarization ($\pm 5^\circ$ plate rotation angle). The output half-wave plate is followed by a polarizing beamsplitter and a differential photodetector. The signal beam is frequency scanned, and the half-wave plate is rotated until signals of two photodetectors are equal far from the absorption line. The difference signal from photodetector pair is proportional to polarization ellipse rotation angle [1,7]. The sum of these two signals gives a measure of absorption (measurement arm in Fig. 1).

A small portion of the pump laser is deviated by a beam-splitter through the control and pump arm (B in Fig. 1), where the saturated-absorption spectroscopy lines for the pump beam are obtained by using an additional control cell and are used for frequency fixing of the pump laser light. The other part of pump beam is directed towards the measurement rubidium cell. A half-wave plate is used to change the polarization direction of the pump beam to parallel or perpendicular with respect to that of the signal beam. The experiments

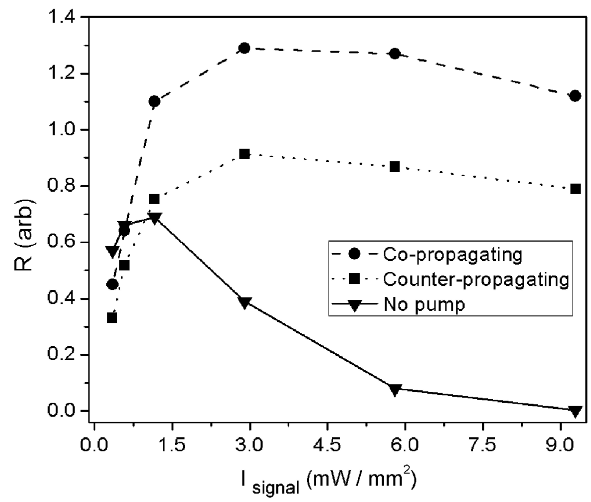

FIGURE 4. Comparative curves of R as a function of signal intensity without and with the pump beam in the transition $F_g = 1$, $F_e = 0$. The intensity of pump laser is at maximum (2.22 mW/mm^2).

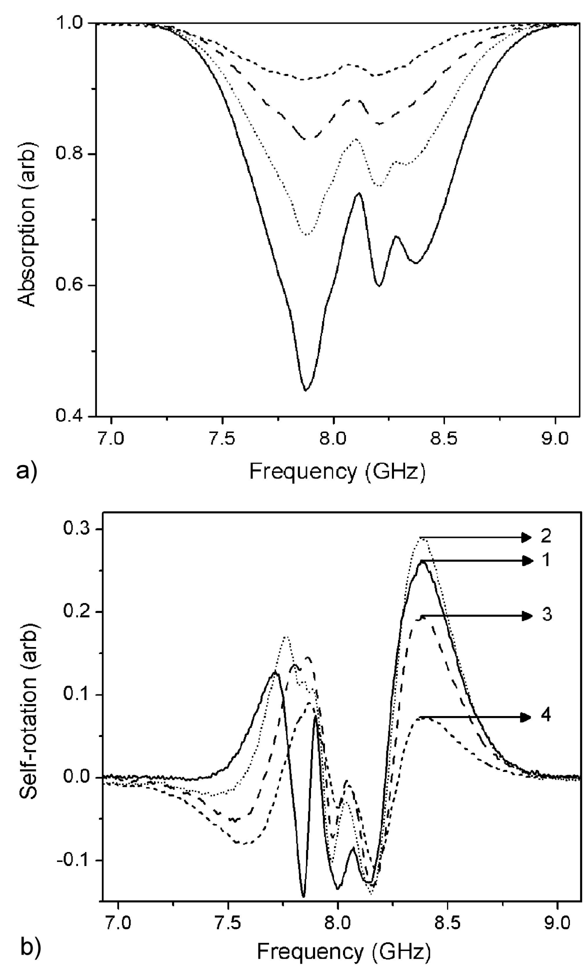

FIGURE 5. Absorption and self-rotation curves for a parallel polarization of the pump beam impinging in a counter-propagating direction. The pump laser intensity is 2.22 mW/mm^2 and the signal intensity is: Curve 1: 0.35 mW/mm^2, curve 2: 1.16 mW/mm^2, curve 3: 2.9 mW/mm^2 and curve 4: 9.3 mW/mm^2.

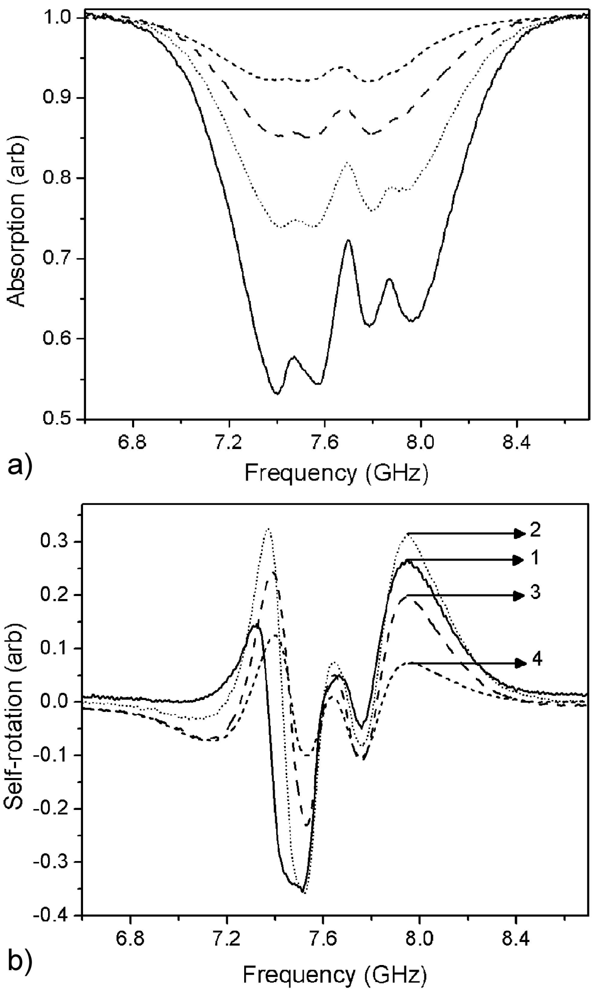

FIGURE 6. The same, as in Fig. 5, but for a perpendicular polarization of the pump beam.

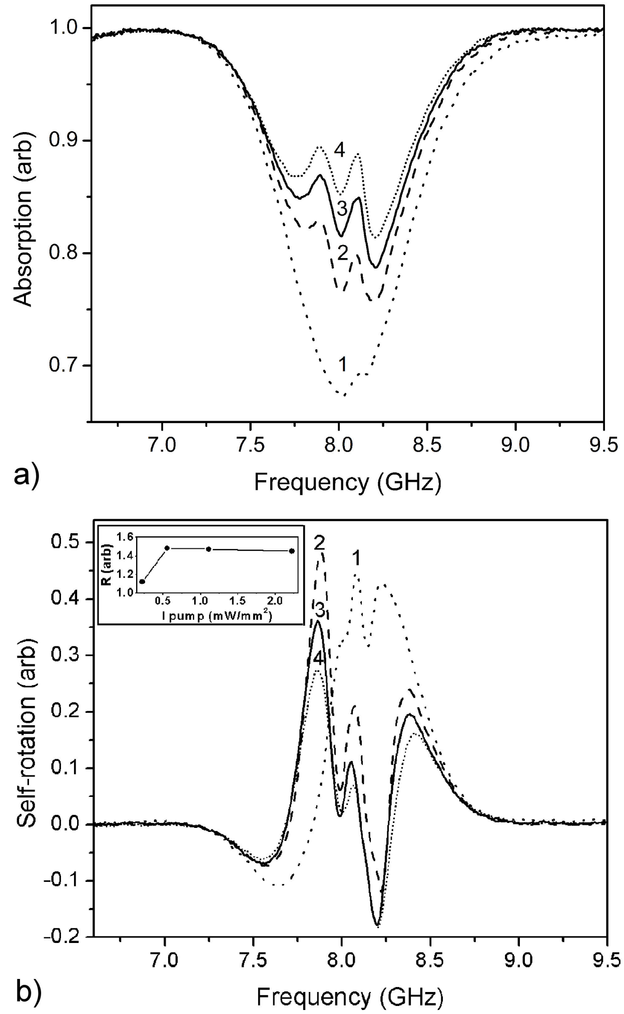

FIGURE 7. Absorption (a) and self-rotation (b) curves for a co-propagating beam in transition $F_g = 1$, $F_e = 0$. The pump laser intensity is: Curve 1:0 mW/mm^2, curve 2: 0.55 mW/mm^2, curve 3: 1.11 mW/mm^2 and curve 4: 2.22 mW/mm^2. The signal intensity is 2.9 mW/mm^2. The variation of R with the pump beam intensity is also shown.

were performed impinging the pump beam in the direction of signal beam (co-propagating scheme, Fig. 1), and also in the counter-propagating direction (not shown).

To observe the effect of pump laser tuned in ^{87}Rb D2 line, the frequency of the pump beam was fixed and the signal laser was scanned across a transition. The pump and the signal beams intersect inside the cell with a small angle ($\sim$13 mrad in a vertical plane). The pump laser frequency can be fixed at resonance with $F_g = 1$, $F_e = 0$, 1 and 2, as well as for intermediate values, but the better increment of R was found when the pump was fixed at resonance with $F_g = 1$, $F_e = 0$. The value of R is calculated for the frequency that corresponds to the maximum value of self-rotation for each data set. In Fig. 2, the dependence of self-rotation and rotation to absorption ratio R on the signal beam intensity is shown when the pump beam is absent [11]. The self-rotation in this case is maximal, when the signal intensity is 0.36 mW/mm^2, and R is maximal when this value is 1.16 mW/mm^2.

When the pump beam is present, the value of self-rotation and R increases related to the case without pump in both co- and counter-propagating cases (Figs. 3 and 4). The intensity of signal beam for the maximal value of self-rotation is 1.16 mW/mm^2 in both cases. The maximum value of R is obtained for signal intensity 2.9 mW/mm^2. The enhancement in the value of R is better for the co-propagating case, where the value of R is $\sim$2 times the value obtained when there is not pump beam.

The shapes of the absorption and rotation curves present some differences if the direction of polarization of the pump beam is parallel or perpendicular with respect to the signal beam polarization in the counter-propagating case (Figs. 5 and 6). Some additional oscillations in the rotation curves are observed for low signal intensity when the polarizations of the pump and signal beams are parallel (Fig. 5). In both cases, when the pump beam has a polarization perpendicular (Fig. 6) or parallel to that of the signal, the asymmetry in the curves is evident in a vicinity of the pump beam frequency.

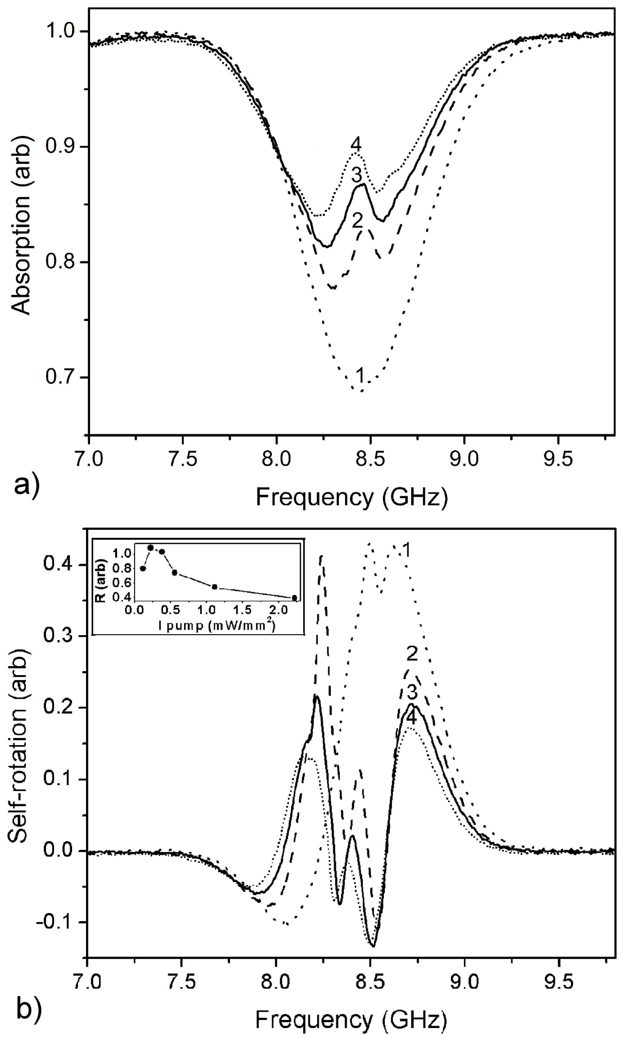

FIGURE 8. The same, as in Fig. 10, but for counter-propagating pump. The signal intensity is 2.9 mW/mm^2.

In the co-propagation case, no evident feature is seen when the pump beam polarization changes even with a low power signal beam. We suppose that this dependence of the pump beam polarization is a characteristic of the cross-phase modulation interaction between the pump and signal beams when the pump intensity is stronger than the signal intensity as *e.g.*, occurs at the curve 1 in Fig. 5 where the intensity ratio pump/signal is ∼6 times.

We verify the dependence of self-rotation and R values with the signal beam intensity for both cases, when the pump beam polarization is parallel and perpendicular to that of the signal beam. An enhancement in the value of R was observed when the polarization of the pump and signal beams is parallel. For this reason, the Figs. 3 and 4 described before were done for a parallel polarizations of the pump and signal beams.

The dependence of absorption and rotation curves on the pump beam intensity is shown in Figs. 7 and 8. In the co-propagating case, although the self-rotation value reaches a maximum for a pump beam intensity of 0.55 mW/mm^2 and then decreases, the value of R does not change significantly from this value until the pump intensity is maximal (Fig. 7(b)). In the counter-propagating case, R is maximal when the pump beam is 0.22 mW/mm^2 and then decreases if this intensity grows (until 40% when intensity is maximal), as it is shown in Fig. 8(b). However, the co-propagating case continues to be the scheme with the better value of R as can be seen in Figs. 7(b) and 8(b).

3. Discussion and conclusions

We have demonstrated experimentally that is possible to enhance the polarization self-rotation and rotation to absorption ratio in ^{87}Rb D2 line for a signal beam tuned at $F_g = 1$ line by using an additional pump beam. An increment of ∼2 times in the value of the figure of merit was obtained for a pump laser tuned at $F_g = 1$, $F_e = 0$. In the counter-propagating case we found a saturation pump beam intensity from which the figure of merit decreases (0.22 mW/mm^2). The saturation was predicted by the theory in a previous work but had not been evident when the pump beam was at resonance with $F_g = 2$ [11]. In the co-propagating scheme, the maximal value of R was obtained when the pump beam intensity was 0.55 mW/mm^2 and remained fixed until the pump intensity is maximal. In this case the better increase of R was obtained, so the enhancement of R is possible with a low-power pump beam (∼2 mW).

We also found some characteristic asymmetries in self-rotation curves for low intensities of the signal beam when the pump laser is counter-propagating with respect to the signal. The enhancement of R was better when the polarization of the pump and signal beams is parallel that when the beams are mutually perpendicular.

Acknowledgments

This research was performed in the framework of Consejo Nacional de Ciencia Tecnología project 156891.

1. S. M. Rochester, D. S. Hsiung, D. Budker, R. Y. Chiao, D. F. Kimball, and V. V. Yashchuk, *Phys. Rev. A* **63** (2001) 043814.
2. V. M. Arutyunyan, T. A. Papazyan, G. G. Adonts, A.V. Karmanyan, S. P. Ishkhanyan, and L. Khol'ts, *Sov. Phys. JETP* **41** (1975) 22.
3. W. V. Davis, A. L. Gaeta, and R. W. Boyd, *Opt. Lett.* **17** (1992) 1304.
4. S. Qiu *et al.*, *Chinese Optics Letters* **10** (2012) 052701.

5. N. Korneev, and C. Gutiérrez Parra, *J. Opt. Soc. Am. B* **29** (2012) 2588.
6. A. B. Matsko, I. Novikova, G. R. Welch, D. Budker, D. F. Kimball, and S. M. Rochester, *Phys. Rev. A* **66** (2002) 043815.
7. J. Ries, B. Brezger, and A. I. Lvovsky, *Phys. Rev. A* **68** (2003) 025801.
8. E. E. Mikhailov, A. Lezama, T. W. Noel, and I. Novikova, *J. Mod. Opt.* **56** (2009) 1985.
9. I. H. Agha, Messin G., and P. Grangier, *Opt. Exp.* **18** (2010) 4198.
10. T. Horrom, G. Romanov, I. Novikova, and E. Mikhailov, *J. Mod. Opt.* **60** (2013) 43.
11. N. Korneev, Y.M. Torres, C. Gutiérrez-Parra and Y. Ortega, *J. Mod. Opt.* **61** (2014) 12.