Experimental investigation of the transient dynamics of slow light in ruby

2014 New J. Phys. 16 123054

(http://iopscience.iop.org/1367-2630/16/12/123054)

New Journal of Physics
The open access journal at the forefront of physics
Deutsche Physikalische Gesellschaft DPG | IOP Institute of Physics

Experimental investigation of the transient dynamics of slow light in ruby

Emma Wisniewski-Barker[1], Graham M Gibson[1], Sonja Franke-Arnold[1], Zhimin Shi[2], Paul Narum[3], Robert W Boyd[1,4,5] and Miles J Padgett[1]

[1] University of Glasgow, School of Physics and Astronomy, SUPA, Glasgow, UK
[2] Department of Physics, University of South Florida, Tampa, FL 33620, USA
[3] The Norwegian Institute for Defence Studies, Oslo, Norway
[4] University of Rochester, The Institute of Optics and Department of Physics and Astronomy, Rochester, NY 14627, USA
[5] University of Ottawa, Department of Physics, Ottawa, Ontario, Canada
E-mail: e.wisniewski-barker.1@research.gla.ac.uk

Received 11 November 2014
Accepted for publication 20 November 2014
Published 19 December 2014

New Journal of Physics **16** (2014) 123054
doi:10.1088/1367-2630/16/12/123054

Abstract

When a pulsed light beam propagates through ruby, it is delayed by a slow-light mechanism. This mechanism has been the subject of debate (Wisniewski-Barker *et al* 2013 *New J. Phys.* **15** 083020; Kozlov *et al* 2014 *New J. Phys.* **16** 038001; Wisniewski-Barker *et al* 2014 *New J. Phys.* **16** 038002). To distinguish between the two main proposed mechanisms, we investigate the trailing edge of a square-wave pulsed laser beam propagating through ruby. Our observation of a pronounced tail on the trailing edge of the transmitted pulse cannot be explained solely by the effects of a time-varying absorber acting upon the incident pulse. Therefore, our observation of the creation of a tail at the trailing edge of the pulse provides evidence for a complicated model of slow light in ruby that requires more than pulse reshaping. The different delays of individual Fourier components of the pulse signal explain the pulse distortion that occurs upon transmission through the ruby and must be accounted for by any model that attempts to describe the effects of slow light in ruby.

Keywords: slow light, ruby, coherent population oscillations, energy delay

Slow light is the term applied to systems through which light propagates with a group velocity significantly smaller than the speed of light in a vacuum [1]. There are many mechanisms that cause slow light, and these vary from optical delay lines to material or structural optical resonances [2–6]. One mechanism for creating slow light that has lead to some debate is coherent population oscillation (CPO). One example of CPO occurs when intense green laser light propagates through ruby, causing the atoms in the ruby to be excited coherently. The CPO method requires only a single laser beam [7], as opposed to more complicated methods with co- or counter-propagating pump and probe lasers.

A debate has grown around different proposed mechanisms by which light is slowed in ruby [8–14]. Following the initial claims of CPO in ruby in 2003 [7], an alternative explanation for the observations in [7] was proposed in 2006 [8, 9], where the apparent slowing of an intense pulse of laser light was explained by the pulse reshaping brought about by a saturable absorber. Early demonstrations of slow light in ruby (see [7, 11]) could not differentiate between the two proposed mechanisms. Further work was done in the spatial domain in an attempt to differentiate between the two mechanisms. That work introduced a line of darkness into a bright image that was slowed, and hence azimuthally displaced, in its propagation through a rotating ruby rod [12]. As was recognized by Kozlov *et al* [13], the region of darkness could also be produced cleanly in the time domain through the use of a chopper to completely modulate the intensity of the pulse. We base our experiment on their experimental setup, although slight differences in our setup allowed us to achieve different results from those presented by Kozlov *et al*.

Our current work demonstrates that the delaying of transmitted laser intensity into the trailing edge of a pulse (tail) could only be caused by a temporal slowing of light, not by a time-varying (saturable) absorption. In the absence of fluorescence, an absorber can only decrease the intensity of light present at a given moment in time. Therefore, detecting more intensity in the tail, as compared to the tail of a reference pulse, provides strong evidence that the pulse delay in ruby is caused by a mechanism more complicated than that of time-varying (saturable) absorption alone.

As shown in figure 1, we produce 4 W of intense 532 nm light with a single longitudinal mode laser. This collimated laser beam is focussed onto a mechanical chopper by a 160 mm focal-length lens. Rotation of this mechanical chopper causes a square wave intensity modulation of the laser beam with a 50% duty cycle. The modulated laser beam is recollimated with a second 160 mm focal-length lens before passing through a beamsplitter. Half of the incident light is reflected onto a 60 mm focal-length lens that focusses the light through a dichroic bandpass filter onto a photodiode. The signal measured with this photodiode is designated as the reference signal. The remaining laser light is transmitted through the beamsplitter and a spherical lens with a focal length of 50 mm, which focuses the beam onto the front face of a 90 mm long standard laser ruby crystal rod. The optical axis is collinear to the rod's z axis. A 60 mm focal-length lens focuses the light through a dichroic bandpass filter and a 400 μm pinhole onto a second photodiode. The bandpass filter and pinhole ensure that only 532 nm light is measured, eliminating virtually all incoherent fluorescent light from the ruby. The intensity signals from both photodiodes are collected using a high speed data acquisition device that is controlled by a National Instruments LabVIEW Virtual Instrument, allowing for easy measurement of the intensities of the two signals.

Figure 2 shows the reference and transmitted signals for measurements taken without (a) or with (b) the ruby rod in place. Both (a) and (b) are plotted on semi-log scales with the same

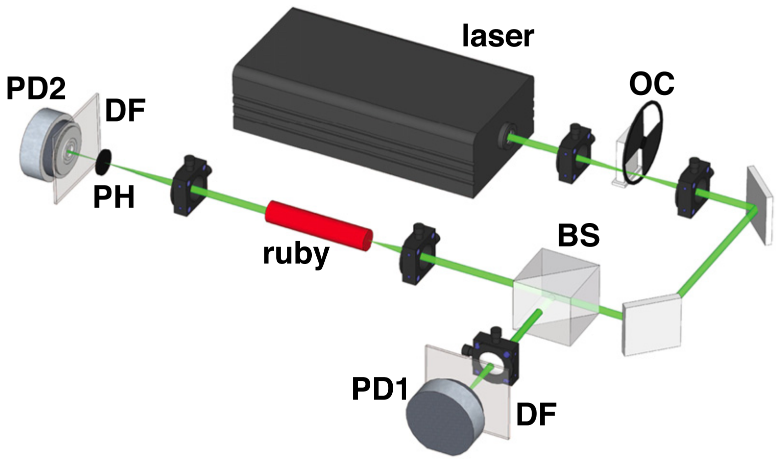

Figure 1. Intense 532 nm laser light is focussed onto an optical chopper (OC) and then recollimated by 160 mm focal-length lenses. The light is then split by a beamsplitter (BS), sending some of the light to be focussed by a 60 mm focal-length lens onto photodiode (PD1). The remaining light is focused onto the front surface of a 90 mm long ruby rod with a 50 mm focal-length spherical lens. The light transmitted through the ruby is measured by a second photodiode (PD2) after a spatial filter comprised of a 60 mm focal-length lens and a 400 μm pinhole (PH). Dichroic bandpass filters (DF) are placed before both photodiodes.

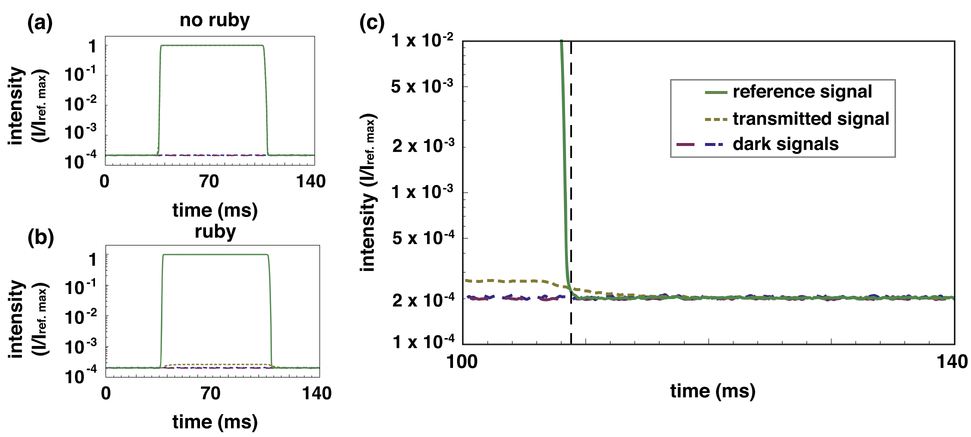

Figure 2. Time evolution of the reference and transmitted signals shown on semi-log plots. (a) When the ruby has been removed, the transmitted (beige, dotted) and reference (green, solid) signals have the same intensity profiles. (b) When the ruby is added, the overall intensity of the transmitted signal (beige, dotted) decreases, although the intensity at the trailing edge of the pulse increases above that of the reference signal (green, solid). The region of interest in (b) is shown in detail in (c). For times greater than that marked by the dashed vertical line in (c), the intensity of the transmitted signal is greater than that of the reference pulse. Dark signals taken with the laser off are shown for the reference (pink, large dashes) and transmitted (blue, dash dots) arms in (a)–(c).

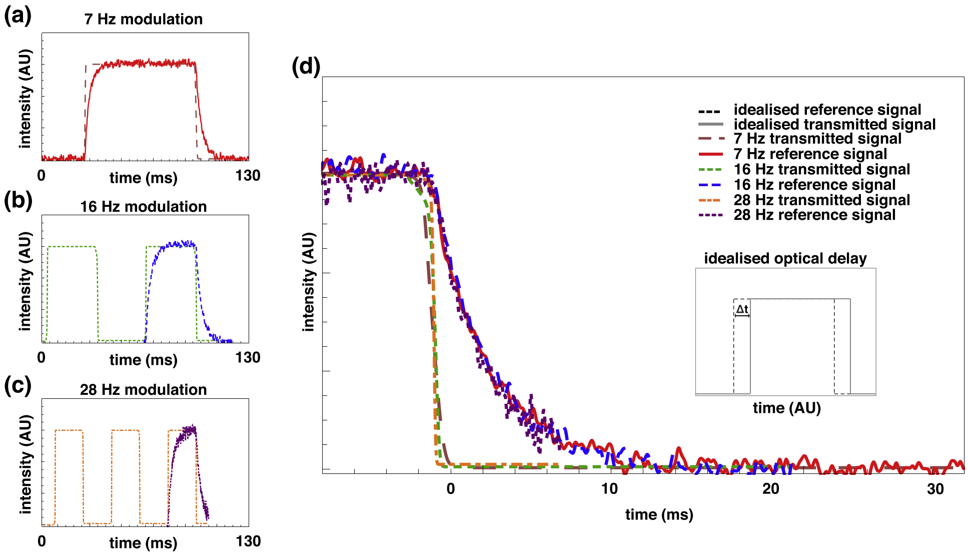

Figure 3. In an ideal slow-light medium, a square-top pulse would simply be delayed (shifted) in time, as shown in the insert in (d). In contrast, we show the observed square-wave reference signal with a modulation of (a) 7 Hz, (b) 16 Hz, and (c) 28 Hz along with the trace of an averaged corresponding transmitted ruby pulse. Unlike figure 2, all pulse shapes in this figure have been normalized to have the same peak intensity, to illustrate the difference in pulse shapes between the reference and transmitted signals. Part (d) shows all three traces overlaid temporally, where the falling edge of each reference pulse is aligned.

maxima and minima. The change in intensity of the transmitted signal (beige) from (a) to (b) is solely due to the addition of the ruby. The region of particular interest is immediately following the bright to dark transition and is shown enlarged in (c). When the ruby is added into the system, some of the energy is delayed, increasing the intensity of the trailing edge of the pulse (tail) of the transmitted signal, as highlighted by figure 2(c). This increase in the intensity in, and hence delay of optical energy into, the tail of the pulse, indicates that the slow-light mechanism in ruby is more complicated than described by a simple time-dependent (saturable) absorber.

We investigated various potential systematic errors. We use identical equipment in both the reference and ruby arms, including detectors, amplifiers, and gain settings. We tested all equipment in both data collection arms, and two data acquisition devices were used, with multiple channels tested on each. For all of these variables, we observed the same trend; adding the ruby delays energy from the pulse, causing an increase in intensity in the tail of the pulse. Other experimental parameters were also investigated. We replaced the 90 mm long ruby with a 6 mm long ruby, which also showed an increase in the energy in the tail of the ruby pulse, albeit to a smaller degree. The existence of a pronounced tail of the ruby pulse is observable for both linearly and circularly polarized light.

One might expect the delayed pulse to look exactly like the reference pulse with a simple shift in time, Δt, as illustrated by the insert in figure 3(d). However, the time delay of a signal depends on the Fourier components of which the intensity signal is comprised. It was reported by Bigelow *et al* [7] that laser beams modulated with sine waves of different frequencies have different time delays through ruby. More specifically, the higher the frequency of the sine wave,

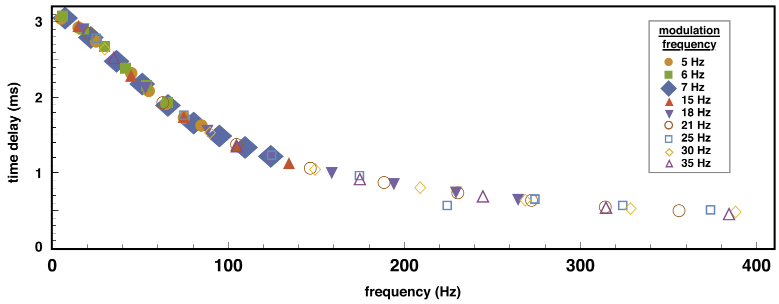

Figure 4. Time delay plotted against the frequency of the Fourier component for square-wave signals of different modulation frequencies. The delays of the Fourier components from the 7 Hz modulated square wave are marked with large filled diamonds. The trace of a corresponding 7 Hz modulated pulse is shown in figure 3(a). Delays of Fourier components from square waves modulated at different frequencies all follow the same curve. Because different frequency components experience different time delays, the square wave is distorted upon transmission through ruby, resulting in the transmitted traces in figure 3.

the smaller the time delay the signal experienced. By taking the Fourier transform of our square-wave intensity signal, we see the sinusoidal waves of many different frequencies that form the Fourier components of our signal. Measuring the difference in phase of the Fourier components of the reference and ruby signals allows us to observe that the time delays as a function of frequency of the Fourier components all follow the same trend, regardless of the modulation frequency of the square wave (see figure 4). Lower frequencies are delayed more than higher frequencies, which makes it evident that the square wave will be distorted when delayed by a slow-light medium. Figure 3 depicts the observed shape of the delayed square wave, as measured under the same conditions as the data presented in figures 2 and 4.

Figure 4 shows that the delays of individual Fourier components are independent of the modulation frequency of the signal. In other words, the shape of the tail should be independent of the modulation frequency of the pulse. Representative pulse traces taken at 7, 16, and 28 Hz modulations are shown in figures 3(a)–(c). Figure 3(d) overlays the three traces so that the end of the traces coincide temporally. As can be seen in figure 3(d), although the three pulses have different modulation frequencies, the traces have tails with the same shape, which is consistent with the delays of Fourier components all following the same trend in figure 4.

We fit the tail of both the ruby and the reference pulses to exponential decays to find the decay time of each. The reference tail has a decay time of approximately $\tau = 0.10$ ms, probably arising from the finite bandwidth of the detector and the associated electronics. By contrast, when the ruby is in place, the tail has a decay time of approximately $\tau = 3.0$ ms. This increased decay time resembles the upper state lifetime of the trap level in ruby, which is approximately 3.4 ms at room temperature [15].

Through careful control of the experimental parameters, we have shown the existence of a pronounced tail on the trailing edge of the transmitted signal, due to the light pulse being slowed as it propagates through the ruby, which is not compatible with a simple model of pulse delay in a time-varying (saturable) absorber. Instead, our experimental evidence supports a more complicated model of slow light in ruby that results in a delay of the transmitted optical energy and a distortion of the pulse shape, as individual Fourier components of the signals are delayed by different amounts.

Acknowledgments

The authors acknowledge fruitful discussions with Ebrahim Karimi regarding the interpretation of these experimental results and would like to thank the reviewers for their careful reading and deep understanding of this work. This work was supported by the Engineering and Physical Sciences Research Council (grant number EP/I012451/1). ELW-B is supported by the Scottish Universities Physics Alliance, and MJP is supported by the Royal Society. RWB gratefully acknowledges support by the US Defense Threat Reduction Agency and the Canadian Excellence Research Chairs programme.

References

[1] Boyd R W 2009 *J. Mod. Opt.* **56** 1908
[2] Boyd R W 2011 *J. Opt. Soc. Am.* B **28** A38
[3] Hau L V, Harris S E, Dutton Z and Behroozi C H 1999 *Nature* **397** 594
[4] Baba T 2008 *Nat. Photonics* **2** 465
[5] Thévenaz L 2008 *Nat. Photonics* **2** 474
[6] Boyd R W and Gauthier D J 2009 *Science* **326** 1074
[7] Bigelow M S, Lepeshkin N N and Boyd R W 2003 *Phys. Rev. Lett.* **90** 113903
[8] Aleksandrov E B and Zapasskii V S 2006 *Phys.—Usp.* **49** 1067
[9] Zapasskii V S and Kozlov G G 2006 *Opt. Spectrosc.* **100** 419
[10] Piredda G and Boyd R W 2007 *J. Eur. Opt. Soc.* **2** 07004
[11] Franke-Arnold S, Gibson G, Boyd R W and Padgett M J 2011 *Science* **333** 65
[12] Wisniewski-Barker E, Gibson G, Franke-Arnold S, Shi Z, Boyd R W and Padgett M J 2013 *New J. Phys.* **15** 083020
[13] Kozlov G G, Poltavtsev S V, Ryzhov I I and Zapasskii V S 2014 *New J. Phys.* **16** 038001
[14] Wisniewski-Barker E, Gibson G, Franke-Arnold S, Shi Z, Boyd R W and Padgett M J 2014 *New J. Phys.* **16** 038002
[15] Nelson D F and Sturge M D 1965 *Phys. Rev.* **137** 1117