Direct Observation of Optical Precursors in a Region of Anomalous Dispersion

Heejeong Jeong, Andrew M. Dawes and Daniel J. Gauthier
Duke University, Department of Physics, Box 90305, Durham, North Carolina 27708 USA
hjjeong@phy.duke.edu

Abstract: We observe the creation of optical precursors when a step-modulated optical pulse propagates through a linear resonant absorber. The precursors are the dominant part of the transmitted field, displaying 100% transmission at their maximum amplitude.

OCIS codes: (190.5530) Pulse propagation and solitons; (270.1670) Coherent optical effects

1. Introduction

In a series of paper written in the early 1900's, Sommerfeld and Brillouin investigated the behavior of a step-modulated optical pulse propagating through a Lorentz dielectric [1]. The purpose of their study was to demonstrate that signals cannot travel faster than the speed of light in vacuum *c* even in regions of anomalous dispersion for which the group velocity of light $\upsilon_g > c$ [2]. Indeed, Sommerfeld demonstrated that the front (the moment when the field first takes on a non-zero value) of the step-modulated field travels precisely at *c*, regardless of the details of the dielectric, thereby demonstrating theoretically that a fast group velocity is consistent with the special theory of relativity. The first experimental test of luminal information transmission in a fast-light medium was reported recently [3].

Brillouin extended Sommerfeld's analysis to investigate the temporal evolution of the pulse beyond the front. For off-resonance propagation, he found that the pulse breaks up and, after some time, can be treated as two separate components: A series of two small wavepackets, which travel at *c* or slower, and a large-amplitude wavepacket, the leading edge of which travels at a velocity Brillouin defined as the "signal" velocity. The first (second) wavepacket, now known as the Sommerfeld (Brillouin) precursor, arises from spectral components of the pulse above (below) the resonance and is predicted to have a maximum strength of 10^{-7} (10^{-4}) of the eventual signal intensity. Precursors generally occur anytime a wave propagates through a dispersive media and have been observed in microwave waveguides near cut-off [4] and in fluid surface waves [5].

2. Optical Precursors and Narrow Resonances

The primary purpose of this paper is to describe our observation of optical precursors that are created when a step-modulated field propagates through a narrow-resonance absorber. In our experiment, the precursors persist for 10's of nanoseconds and hence it is possible to measure their temporal evolution directly. For resonant pulse propagation, we find that: the Sommerfeld and Brillouin precursors overlap; they are the dominant part of the signal emerging from the absorber; take on their maximum value immediately following the pulse front; and the peak of the precursors experience no absorption. These results demonstrate that precursors are a much more important part of field propagating through a dispersive medium that believed previously.

Our results are consistent with the theoretical analyses of Oughstun and Sherman [6] who have extended and corrected some errors in Brillouin's work using modern asymptotic analysis. For the case when the carrier frequency of the pulse is set to an atomic resonance where the dispersion is anomalous, they predict that the largest pulse amplitude occurs immediately after the pulse front, which propagates precisely at *c*, and that Brillouin's "signal" corresponds to the point where the pulse intensity begins to decay (see Fig. 9.18 of Ref [6]). When the carrier frequency is tuned away from the resonance, they predict that the amplitude of the Sommerfeld (Brillouin) precursor decays with propagation distance *z* as $\sim z^{-1}$ ($\sim z^{-1/2}$) and hence precursors may be useful for imaging through scattering media, such as biological tissue [7].

In contradistinction with our experiments, most theoretical studies of optical precursors consider pulse propagation though an absorber with a very broad resonance (on the order of 1 THz), where they find that the precursors persist for only a few optical cycles. Thus, it is often though that precursors are an ultra-fast phenomena. Many of the experiments have also used an absorber with a broad resonance and, because of the ultra-fast time scale, have to infer the creation of precursors using indirect measurements. For example, Choi and Österberg [8] have recently observed a slow drop in transmission as a function of distance of a 540-fs-long pulse propagating through a tube of pure water, consistent with the predictions of Oughstun and Sherman [6]. Other optical experiments have investigated pulse propagation through semiconductors [9,10], although a simple comparison to theoretical models is made difficult because of the greater complexity of the semiconductor resonances.

3. Step-Modulated Pulse Propagation through a Resonant Absorber

In our experiment, we propagate a step-modulated optical pulse through an absorbing resonance and measure the temporal evolution of the transmitted intensity. The resonant absorber consists of a cloud of cooled and trapped potassium atoms generated in a vapor-cell magneto-optic trap [9]. The atoms are captured in the trap using trapping and repumping lasers tuned to the $4S_{1/2} \leftrightarrow 4P_{3/2}$ transition (transition wavelength 767 nm), resulting in a cloud that has a temperature of ~400 μK, a diameter of ~2 mm, and an atomic number density of $\sim 6 \times 10^{10}$ atoms/cm^3. The trapping and cooling beams are switched on and off repetitively in the following sequence. The repumping beam is first switched off and the repumping beam is switched off 1 μs later, which causes the potassium atoms to be optically pumped into the $4S_{1/2}$ (F=1) hyperfine level. The beams are left off for 20 μs while the optical precursor experiment is conducted, turned back on for 80 μs, and the cycle repeated. The gradient magnetic field is left on for the entire experiment.

The optical precursor experiment is conducted on the $4S_{1/2}$ (F=1) $\leftrightarrow$ $4P_{1/2}$ (F=2) transition (transition wavelength 770 nm), which is well separated from the other potassium optical transitions so that we are interacting essentially with a single resonance. When the frequency of a very weak probe laser beam is scanned through the resonance, we observe a Lorentzian-like resonance with a width (full width at half maximum) of ~9.6 MHz and maximum single-pass absorption of ~64%.

The step-modulated field is created by passing a weak continuous-wave laser through a 20-GHz bandwidth Mach-Zehnder modulator (EOSpace, Inc.) driven by an electronic edge generator (Data Dynamics, Model 5113) whose edge is steepened using a back recovery diode (Stanford Research Systems, Model DG535). The maximum intensity of the pulse is ~64 μW/cm^2, which is much less than the saturation intensity of the transition (~3 mW/cm^2). The pulse is detected with a fast-rise-time photomultiplier tube (Hamamatsu, Model H6780-20) and the resulting electrical signal is measured with a 1-GHz analog bandwidth transient digitizer (Tektronix, Model TDS 680B). In the absence of the atoms, we measure an edge rise time (10%-90%) of 1.7 ns, which includes the bandwidth-limiting effects of all components. This time is short in comparison to the expected duration of the optical precursors.

Figure 1 shows the measured temporal evolution of the step-modulated field after passing through the cloud of atoms. The optical carrier frequency of the pulse is set equal to the resonance frequency, where the dispersion is anomalous. It is seen that the pulse intensity increases rapidly immediately following the turn on of the pulse, attaining a maximum value corresponding to ~95% transmission. The intensity then decays approximately exponentially until it reaches a constant value corresponding to the measured steady-state transmission of the line.

Based on the theoretical predictions of Oughstun and Sherman [6], we attribute this peak in the transmitted intensity to both the Sommerfeld and Brillouin precursors, which overlap temporally for the resonant conditions used in our experiment. We stress that the observed temporal evolution of the transmitted pulse is due to the linear optical response of the atoms because we keep the pulse intensity nearly 50 times weaker than the saturation intensity of the transition. This data demonstrates that optical precursors can be the dominant feature of the transmitted field and that they can be readily observed in narrow-resonance-width absorbers. We speculate that they can also be readily observed in other systems containing narrow resonances, such as those created in electromagnetically-induced-transparency experiments.

4. References

[1] L. Brillouin, *Wave Propagation and Group Velocity* (Academic Press, New York, 1960).

[2] R.W. Boyd and D.J. Gauthier, " 'Slow' and 'Fast' Light," in *Progress in Optics, Vol. 43*, E. Wolf, ed. (Elsevier, Amsterdam, 2002), Ch. 6, pp. 497-530.

[3] M.D. Stenner, D.J. Gauthier, and M.A. Neifeld, "The speed of information in a 'fast light' optical medium," Nature **425**, 695-698 (2003).

[4] P. Pleshko and I. Palócz, "Experimental observation of Sommerfeld and Brillouin precursors in the microwave domain," Phys. Rev. Lett. **22**, 1201 - 1204 (1969).

[5] É. Falcon, C. Laroche, and S. Fauve, "Observation of Sommerfeld precursors on a fluid surface," Phys. Rev. Lett. **91**, 064502-1 - 064501-4 (2003).

[4] K.E. Oughstun and G.C. Sherman, *Electromagnetic Pulse Propagation in Causal Dielectrics* (Springer-Verlag, Berlin, 1994).

[5] R. Albanese, J. Penn, and R. Medina, "Sort-rise-time microwave pulse propagation through dispersive biological media," J. Opt. Soc. Am. B **6**, 1441-1446 (1989).

[6] S.-H. Choi and U. Österberg, "Observation of optical precursors in water," Phys. Rev. Lett. **92**, 193903-1 - 193903-4 (2004).

[7] J. Aaviksoo, J. Kuhl, and K. Ploog, “Observation of optical precursors at pulse propagation in GaAs,” Phys. Rev. A **44**, R5353 - R5356 (1991).
[8] M. Sakai, R. Nakahara, J. Kawase, H. Kunugita, K. Ema, M. Nagai, and M. Kuwata-Gonokami “Polariton pulse propagation at exciton resonance in CuCl: Polariton beat and optical precursor,” Phys. Rev. B **66**, 033302-1 - 033302-4 (2002).
[9] R.S. Williamson III, and T. Walker, “Magneto-optical trapping and ultracold collisions of potassium atoms,” J. Opt. Soc. Am. B **12**, 1393 - 1397 (1995).

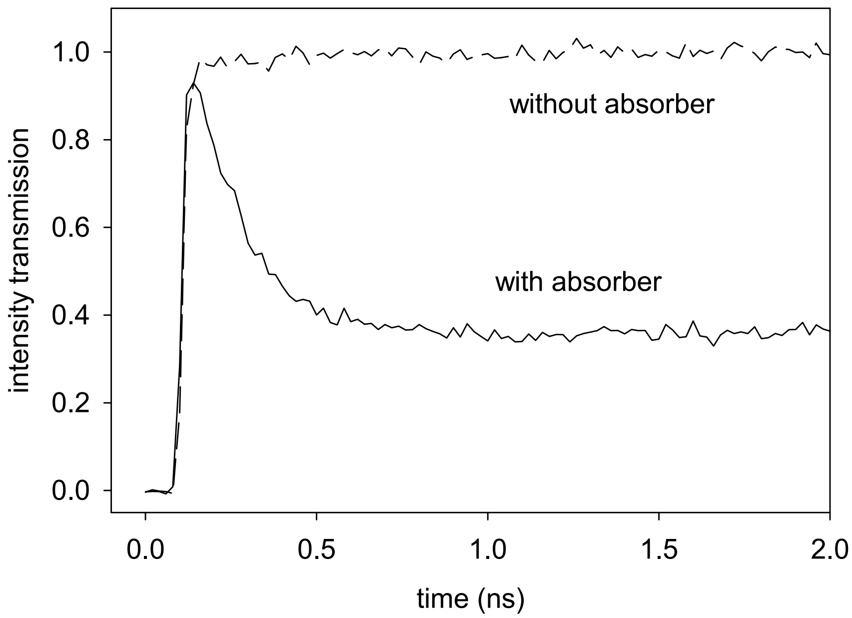

Fig. 1. Temporal evolution of a step modulated optical field propagating through a resonant absorber.