

A report on

Slow Light and Nonlinear Optics

For

ECE-568

Nonlinear Optics

Fall 2011

By

Hemashilpa Kalagara

University of New Mexico

Introduction: Slow light is the propagation of an optical pulse or other modulation of an optical carrier at a very low group velocity. Slow light occurs when a propagating pulse is substantially slowed down by the interaction with the medium in which the propagation takes place. This phenomenon is observed in various media, especially semiconductors which have a high degree of nonlinearity. The group index of the light propagating in a nonlinear medium can be modified using a high intensity wave (laser beam), thus producing slow and fast lights. In this report, we discuss about the slowing of light in semiconductor materials. The concept of slowing of light has arisen several decades ago. Slow light is produced by decreasing the group velocity of light propagating in a medium. Slow light can have potential applications in telecommunications, optical computing, optical buffers etc. Several experimental demonstrations of slow light have been done. Slow light is demonstrated using various physical phenomenon such as electromagnetically induced transparency (EIT) [2,3] and coherent population oscillations (CPO) [4, 5]. The most impressive results using electromagnetically induced transparency-reduction of the light group velocity by more than seven orders of magnitude have been obtained using ultracold sodium atoms (in the vicinity of the Bose-Einstein condensation temperature) [6, 7]. We shall discuss the above mentioned phenomena to produce slow light.

Electromagnetically induced transparency (EIT): is a coherent optical nonlinearity which makes a medium transparent over narrow spectral range within an absorption line. Extreme dispersion is also created within this transparency "window" which leads to "slow light", described below. Observation of EIT involves two optical fields (highly coherent light sources, such as lasers) which are tuned to interact with three quantum states of a material. The "probe" field is tuned near resonance between two of the states and measures the absorption spectrum of the transition. A much stronger "coupling" field or the "control/pump" is tuned near resonance at a different transition. If the states are selected properly, the presence of the coupling field will create a spectral "window" of transparency which will be detected by the probe. EIT is based on the destructive interference of the transition probability between atomic states.

The Kramers–Kronig relations dictate that a change in absorption (or gain) over a narrow spectral range must be accompanied by a change in refractive index over a similarly narrow region. This rapid and negative change in refractive index produces an extremely low group velocity.

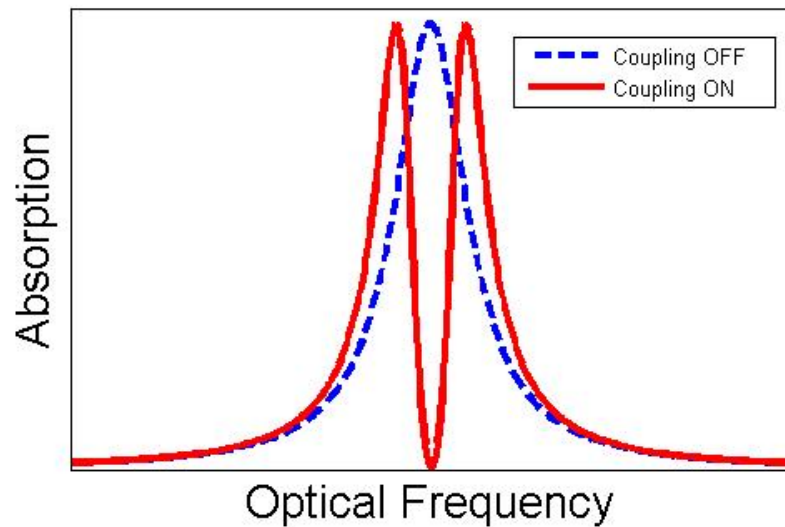


Figure 1: The effect of EIT on a typical absorption line. A weak probe normally experiences absorption shown in blue. A second coupling beam induces EIT and creates a "window" in the absorption region (red). This plot is a computer simulation of EIT in an InAs/GaAs quantum dot.

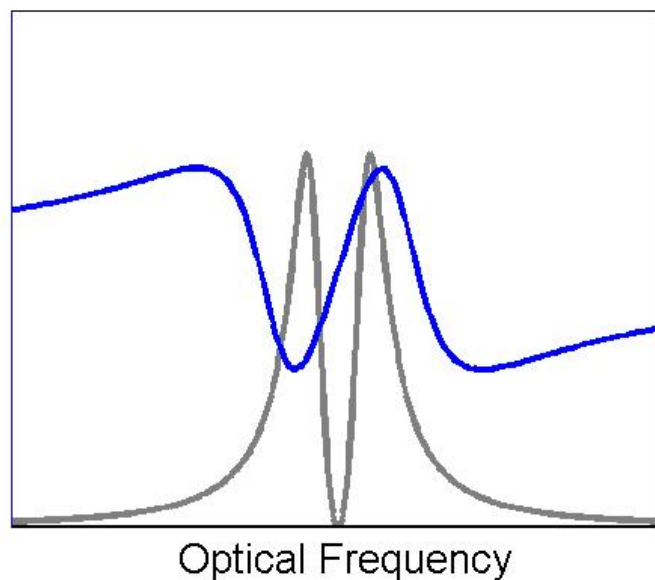


Figure 2: Rapid change of index of refraction (blue) in a region of rapidly changing absorption (gray) associated with EIT. The steep and positive linear region of the refractive index in the center of the transparency window gives rise to slow light.

Coherent population oscillations (CPO): We have to utilize cold atomic vapors [6] or solid-state material [8] at low temperature to demonstrate slow light via electromagnetically induced transparency (EIT). Slow light based on this type of pump-probe scheme can usually provide huge slowdown factors. However, there are also restrictions for EIT, e.g., the difficulty of room temperature operation, susceptibility to the inhomogeneous broadening of the material systems,

and the low bandwidth for signal transmission. On the other hand, slow light based on coherent population oscillation (CPO) is less limited by these problems. When a pump and probe signal with a small frequency detuning are incident onto a two-level system, they induce a population beating with a frequency determined by the detuning frequency. This population beating is significant when the detuning frequency is smaller than the inverse carrier lifetime and leads to an absorption dip on the absorption spectrum. From Kramers–Kronig relation, a positive-slope variation of the refractive index within a bandwidth determined by the population lifetime and pump intensity is present near the pump frequency and can be used to demonstrate slow light. The room-temperature operation of slow light has been demonstrated via CPO in a ruby crystal [9] and semiconductor quantum dots [10]. CPO based on semiconductor quantum wells (QWs) [5] and quantum dots (QDs) [11] can provide gigahertz bandwidth, which is much higher than those schemes based on other coherent processes in different materials.

Calculation of nonlinear perturbation in semiconductor lasers applying coherent population oscillation (CPO): The perturbation of light propagation occurs in semiconductor amplifying medium due to parametric interaction of waves (modes) at sufficiently high intensity of one of the interacting waves called the driving wave. As these perturbations are located in a narrow vicinity of the driving wave frequency, a small change of the real refractive index, n leads to a significant variation of the frequency dispersion of the refractive index ($dn/d\omega$). The nonlinear (induced) part of the refractive dispersion of probe wave can provide a decrease of the group index ($n_g = c/u$) to zero value and even to a conversion of its sign (the case of nonlinear reflection of probe wave).

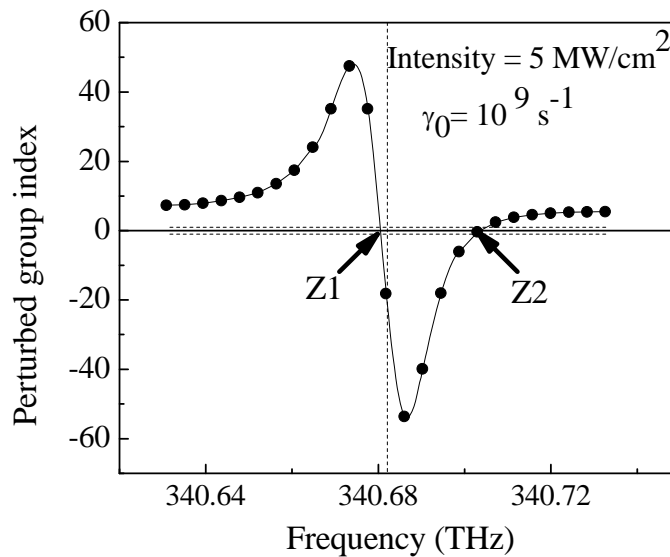


Figure 3: Variations of perturbed group index around the frequency of a driving wave. The case of RW semiconductor laser based on GaAs/AlGaAs, γ_0 is initial relaxation rate, Z1 and Z2 are points of *critically-anomalous dispersion*

References:

- [1]. Experimental demonstration of slow and superluminal light in semiconductor optical amplifiers. Bala Pesala, Zhangyuan Chen, Alexander V. Uskov, and Connie Chang-Hasnain. *Optics Express*, Vol. 14, Issue 26, pp. 12968-12975 (2006)
- [2]. C. J. Chang-Hasnain, P. C. Ku, J. Kim, and S. L. Chuang, "Variable optical buffer using slow light in semiconductor nanostructures," *Proc. of IEEE* **91**, 1884-1897 (2003).
- [3]. C. Liu, Z. Dutton, C. H. Behroozi, L. V. Hau, "Observation of coherent optical information storage in an atomic medium using halted light pulses," *Nature* **409**, 490-493 (2001).
- [4]. M. S. Bigelow, N. N. Lepeshkin, and R.W. Boyd, "Observation of ultraslow light propagation in ruby crystal at room temperature," *Phys Rev. Lett.* **90**, 113903 (2003).
- [5]. P. C. Ku, F. Sedgwick, C. J. Chang-Hasnain, P. Palinginis, T. Li, H. Wang, S. W. Chang and S. L. Chuang, "Slow light in semiconductor quantum wells," *Optics Lett.* **29**, 2291-2293 (2004).
- [6]. Light speed reduction to 17 metres per second in an ultracold atomic gas. Lene Vestergaard Hau^{1,2}, S. E. Harris³, Zachary Dutton^{1,2} & Cyrus H. Behroozi^{1,4}
- [7]. Observation of coherent optical information storage in an atomic medium using halted light pulses. Chien Liu^{1,2}, Zachary Dutton^{1,3}, Cyrus H. Behroozi^{1,2} & Lene Vestergaard Hau^{1,2,3}
- [8] A. V. Turukhin, V. S. Sudarshanam, M. S. Shahriar, J. A. Musser, B.S. Ham, and P. R. Hemmer, "Observation of ultraslow and stored light pulses in a solid," *Phys. Rev. Lett.*, vol. 88, no. 2, p. 023602, Jan. 2002.
- [9] M. S. Bigelow, N. N. Lepeshkin, and R. W. Boyd, "Observation of ultraslow light propagation in a ruby crystal at room temperature," *Phys. Rev. Lett.*, vol. 90, no. 11, p. 113903, Mar. 2003.
- [10] S. W. Chang and S. L. Chuang, "Slow light based on population oscillation in quantum dots with inhomogeneous broadening," *Phys. Rev. B*, vol. 72, no. 23, p. 235330, Dec. 2005.
- [11] H. Su and S. L. Chuang, "Room-temperature slow light with semiconductor quantum-dot devices," *Opt. Lett.*, vol. 31, no. 2, pp. 271-273, 2006.