INTERACTION OF TRANSIENT TEMPORALLY MODULATED LASER RADIATION WITH SIMPLE ATOMIC SYSTEMS

Y. S. Bai, W. R. Babbitt, A. G. Yodh, and T. W. Mossberg
Dept. of Physics, Harvard University, Cambridge, Mass. 02138

ABSTRACT

We point out that the frequency-selective nature of the light-matter interaction can be utilized to effect the storage of a spectral image (Fourier transform) of a temporally structured light pulse in the absorption profile of an inhomogeneously broadened atomic ensemble, and that the stored information can be subsequently recalled in the form of a free-induction-decay signal. Applications of this process to optical data storage are discussed. We also consider the interaction of a phase-controlled, amplitude-gated, resonant laser field with the atoms in a collimated atomic beam. We describe experiments wherein suitably prepared atoms are placed in pure stationary-states (dressed states) of the atom + laser-field system, and note that atoms in pure dressed states should have interesting spectral and dynamical properties.

INHOMOGENEOUSLY BROADENED MATERIALS AS SPECTRUM ANALYZERS

Inhomogeneously broadened ensembles of atoms exhibit absorption profiles that are spectrally wider,often by orders of magnitude, than the absorption profiles of their individual constituent atoms. The possibility thus exists, in such materials, of selectively addressing various sets of spatially coincident absorber atoms on the basis of frequency. This fact has been incorporated into proposed optical-data-storage schemes which employ tunable, narrow-band lasers to write a multitude of data bits at each spatial location of a storage material.[1] We point out that the frequency domain can be equivalently exploited by inducing the material to remember the temporal shape of a data pulse and later on to reproduce it.

Consider a temporally structured data pulse of duration, τ_d, which is resonant with the inhomogeneously broadened absorption line of a sample material. Provided that $\tau_d \ll T_2$, where T_2 is the homogeneous dephasing time of the sample material, and that the modulation bandwidth of the pulse is less than the inhomogeneous absorption bandwidth of the excited transition, the data pulse will excite an optical polarization in the material which to first order in perturbation theory is proportional to its own Fourier transform. It follows that the temporal structure of the data pulse can be recreated from the information stored in the polarization. This fact has been demonstrated in various spin and photon echo experiments.[2] On the other hand, the ground- and excited-state populations, which are generally much more stable than the polarization, reflect only the power spectrum of the data pulse; consequently, the shape of the data pulse cannot be deduced from them.

It has been pointed out that the Fourier information available in the polarization can be transferred to populations or Zeeman coherences by means of an interference effect.[3] When two laser

0094-243X/86/1460421-4$3.00

pulses (a data pulse and a suitable reference pulse) both occurring within a time T_2 resonantly excite the sample, the ground- and excited-state population densities or Zeeman coherences within a given state contain a modulation in frequency that is proportional to the product of the Fourier spectra of the two pulses.

If a third laser pulse resonantly excites the material in an appropriate fashion, a free-induction-decay signal of the form

$$E_{fid}(t) \propto \int_{-\infty}^{\infty} E_r^*(\omega)\, E_d(\omega)\, E_3(\omega) e^{i\omega t}\, d\omega \qquad (1)$$

will be emitted. Here $E_d(\omega)$, $E_r(\omega)$, and $E_3(\omega)$ represent the Fourier spectra of the data, reference, and third pulses, respectively. In writing Eq. 1, it is assumed that the third pulse occurs delayed from the first two excitation pulses by an interval shorter than the spectral relaxation time of the relevant level population(s) or Zeeman coherences, and for convenience that the reference pulse occurs before the data pulse. If the product $E_r^* E_3$ can be factored outside the integral, $E_{fid}(t)$, has a temporal shape identical to that of the data pulse. $E_r(\omega)$ and $E_3(\omega)$ will be individually constant if the corresponding pulses are sufficiently brief, or their product will be constant if the corresponding pulses are frequency chirped at the same rate over the bandwidth of the data pulse.

To test these results, we performed an experiment on the 555.6 nm $^1S_0$-$^3P_1$ intercombination line of atomic ^{174}Yb vapor. This system does not provide the very long storage times that are characteristic of cryogenic solids, but because of its simplicity allows for detailed comparison of theory and experiment. Pulses were generated by acousto-optically gating the output of a cw ring dye laser. Shown in Figure 1a is a data pulse representing an ASCII encoding of the letters JG. When this data pulse (preceded by a reference pulse and followed by a third pulse, both of approximately the same width as the subpulses shown) is used to excite the Yb sample, the signal shown in Figure 1b is observed. The single-event traces shown in Figure 1 are nearly identical. A slight broadening of the subpeaks in Figure 1b

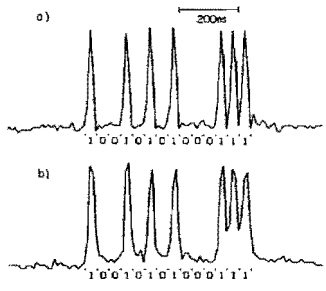

Fig. 1. Short pulse storage and recall.

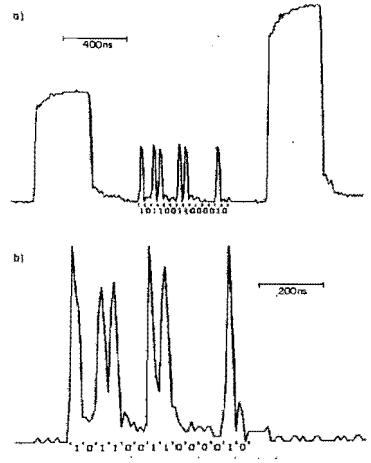

Fig. 2. Chirped pulse storage/recall.

arises from the use of insufficiently brief reference and third pulses. An excitation sequence in which the brief reference and third pulses are replaced by frequency chirped ones is shown in Figure 2a. The single-event putput signal produced, which accurately represents the ASCII encoding of the letters YB, is shown in Figure 2b. Shape reproduction using long chirped pulses is technically important because of difficulties associated with producing short pulses of sufficient power. We note that despite the perturbative nature of Eq. 1, the results presented here were obtained with fairly large area ($\approx \pi/4$) input pulses. As a result, the output signals observed in this strongly relaxing system were roughly 0.05 percent as intense as the original data pulse. In the absence of material relaxation, output signals should be approximately 30 times larger. We note that in certain cases introducing phase noise onto an amplitude encoded data pulse opens the possibility of generating output signals larger in absolute intensity.

Optical memories based on this frequency-selective storage means could operate at multi-gigahertz bit rates (limited by the material's inhomogeneous absorption bandwidth) and achieve ultra-high-storage densities (each bit requires only about 10^6 absorber atoms). In solids, storage times of perhaps years are expected.

INTERACTION OF A TRANSIENT PHASE-CONTROLLED LASER WITH TWO-LEVEL ATOMS

In the semiclassical approximation, the interaction of a two-level atom with an applied laser field is easily visualized using the vector model. In this model, the observables of the atom, i.e. level populations and coherences, are represented in terms of a three-dimensional atomic-state vector which precesses about a driving field vector, where the driving-field vector represents the strength, phase, and detuning of the laser field. The simple atomic behavior predicted by the vector model is quite difficult to observe experimentally because various atoms in the ensembles studied typically possess different detunings and/or have experienced different excitation histories. As a result, elemental two-level atom results must be ensemble averaged to describe actual measurements. We have undertaken an experimental program to study the response of ensembles of essentially identical atoms to transient laser excitation.[4] Such ensembles are realized by right-angle excitation of a collimated ^{174}Yb atomic beam. The ^{174}Yb atom constitutes an ideal two-level atom when excited by circularly polarized light, and its excited $^3P_1$ state decays sufficiently slowly (875 nsec lifetime) to facilitate detailed experimental observation before atom-field phase randomization occurs.

In most cases, an applied laser field causes atomic populations and coherences to undergo amplitude oscillations as the atomic-state vector precesses about the driving-field vector. There are two exceptions to this general result. When the atomic-state vector and the driving-field vector are aligned either parallel or anti-parallel, explicit motion of the atomic-state vector vanishes. These atom-field conditions are special, and in fact, correspond to eigenstates (i.e. dressed-states) of the atom + field system.[4,5] We have resonantly excited atoms into pure dressed states, by suddenly shifting the phase of an excitation field by 90° after the atoms, initially in their

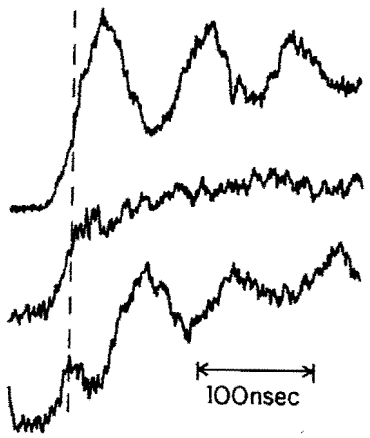

Fig. 3. Fluorescence vs. time. Top down: 0°, 90°, and 180° phase changes at vert. line.

ground state, are excited by a net pulse area of $\pi/2$. The atoms' behavior during this excitation sequence is monitored by detecting (see Figure 3) their resonance fluorescence. When placed in a pure dressed state (middle trace) oscillations in the fluorescence disappear.

One of the most important reasons for studying atoms under controlled excitation conditions is to test existing treatments of natural radiative decay. Steady-state resonance fluorescence from atoms driven by a strong, resonant, driving field is known to display a three-peaked spectrum.[6] Atoms excited to a pure dressed state, however, should initially display a double-peaked spectra. A test of this prediction[7] is planned.

Another aspect of natural decay which has apparently not been subjected to detailed experimental study is its rate in the presence of a strong, resonant, driving field. Despite this fact, it is widely assumed that the rate of natural decay is unaffected by applied optical fields of moderate (Rabi frequency small compared to the optical frequency) strength. Preliminary studies of the decay of atoms prepared in pure dressed states reveal that driving fields with Rabi frequencies up to 10 times the natural decay linewidth do not induce decay rate changes of more than about 25%. Higher precision studies are planned.

We thank the National Science Foundation (PHY-85-04260), the Army Research Office (DAAG29-83-K0040), and the Joint Services Electronics Program (N00014-85-K0724) for financial support of this work.

REFERENCES

1. W. E. Moerner and M. D. Levenson, J. Opt. Soc. Am. B 2, 915 (1985).
2. S. Fernbach and W. G. Proctor, J. Appl. Phys. 26, 170 (1955); V. A. Zuikov and V. V. Samartsev, Phys. Status Solidi A 73, 683 (1982); N. W. Carlson, L. J. Rothberg, A. G. Yodh, W. R. Babbitt, and T. W. Mossberg, Opt. Lett. 8, 483 (1983).
3. N. W. Carlson, W. R. Babbitt, Y. S. Bai, and T. W. Mossberg, J. Opt. Soc. Am. B 2, 909 (1985).
4. Y. S. Bai, A. G. Yodh, and T. W. Mossberg, Phys. Rev. Lett. 55, 1277 (1985.
5. E. Courtens and A. Szoke, Phys. Rev. A 15, 1588 (1977); D. Grischkowsky, Phys. Rev. A 14, 802 (1976).
6. For a review see: P. L. Knight and P. W. Milonni, Phys. Rep. 66, 21 (1980).
7. N. Lu, P. R. Berman, Y. S. Bai, J. E. Golub, and T. W. Mossberg, (submitted to Phys. Rev. A).