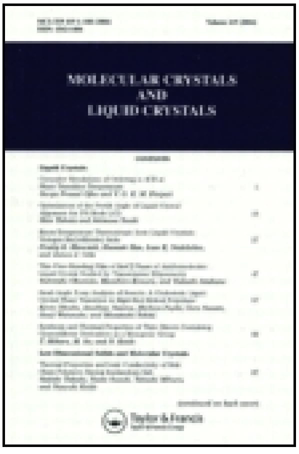
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Photon Echoes in Inverted Media

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PHOTON ECHOES IN INVERTED MEDIA

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ABSTRACT We present the results of simulations of two pulse and three pulse photon echoes both in absorbing and inverted media. It is found that under proper conditions the efficiency of the photon echo process may substantially be improved in an inverted medium.

I. INTRODUCTION

It is known that photon echoes have the potential to be used in a variety of information storage and processing applications with advantages over traditional electronic methods[1-4]. However, a serious problem in application of photon echoes in practical systems is the relatively low efficiency of the process. Photon echoes in an inverted medium were first observed in 1984[5]. Recent studies of photon echoes in amplifying media concluded that no substantial improvement may be gained by using an optically thin inverted medium compared with an optically thin absorber[6]. In this study we examine the case of photon echoes in an optically thick inverted medium by solving the coupled Maxwell-Bloch equations with appropriate initial and boundary conditions.

II. BASIC MODEL

The coherent interaction of light with a system of inhomogeneously broadened two level atoms is governed by Bloch's equations, where the electric field acts as a source for the atomic dipoles. If the pulse propagation effects are to be accounted for, Maxwell's wave equation should also be used, where the atomic dipoles act as a source for the electric field. The mutual interaction of light pulses and atomic dipoles is governed by the coupled Maxwell-Bloch equations[7]

$$\frac{dr_1(z,t,\omega)}{dt} = (\omega - \omega_0) r_2(z,t,\omega)$$

$$\frac{dr_2(z,t,\omega)}{dt} = (\omega_0 - \omega) r_1(z,t,\omega) + \Omega(z,t) r_3(z,t,\omega) \qquad (1)$$

$$\frac{dr_3(z,t,\omega)}{dt} = -\Omega(z,t) r_2(z,t,\omega)$$

$$\frac{\partial \Omega(z,t)}{\partial t} + \frac{n}{c}\frac{\partial \Omega(z,t)}{\partial z} = \frac{\alpha}{2\pi}\int_{-\infty}^{\infty} r_2(z,t,\omega) g(\omega) d\omega$$

where r_1, r_2, and r_3 are the in-phase, out-of-phase, and inversion components of polarization, $g(\omega)$ is the inhomogeneous line-shape, ω is the transition frequency of the two level atom, α is the absorption (amplification) coefficient, n is the index of refraction, c is the vacuum speed of light, and the laser electric field is assumed to be a plane wave with no phase modulation given by

$$E(z,t) = \frac{\hbar}{2\mu}\Omega(z,t)\cos(\omega_0 t - kz). \qquad (2)$$

Here ω_0 is the laser carrier frequency, Ω is the electric field in Rabi frequency, and μ is the dipole matrix element of transition.

These equations may not be solved analytically in their general form. However, if the area of the pulse is defined as

$$A(z) = \int_{-\infty}^{\infty} \Omega(z,t') dt' \qquad (3)$$

then $A(z)$ obeys the following area theorem[8]

$$\frac{dA(z)}{dz} = -\frac{1}{2}\alpha \sin(A(z)) \qquad (4)$$

The area theorem does not provide any information about the shape of the pulses. However, it can be used as a verification for results obtained by numerical methods. For example, in a two pulse echo process the sum of the two initial pulses and the echo pulse together must obey the area theorem[9].

III. NUMERICAL INTEGRATION OF MAXWELL-BLOCH EQUATIONS

We have used the finite differencing method to integrate the set of equations (1). A two dimensional grid is defined with one dimension representing time and the other representing space. A third dimension, frequency, is also used to model the inhomogeneous broadening which is responsible for the production of the photon echoes.

The boundary conditions are the input pulse sequence at the input plane and the absorbing boundary condition at the output plane. The absorbing boundary condition is necessary to minimize the numerical reflection of the fields from the output plane back into the grid. In effect, it simulates a 100% transmission from the output plane.

The initial conditions are the states of the dipoles in the medium at t=0. If all the dipoles are initially in the ground state ($r_1=r_2=0$, $r_3=-1$), the system represents an absorber. If the dipoles are initially in the excited state ($r_1=r_2=0$, $r_3=1$), the system represents an amplifier. A central differencing scheme (both in time and space) is used to integrate the equations to ensure accuracy.

IV. DEFINITIONS

In order to compare the results of the simulation in different cases, it is convenient to make a few definitions. A *data pulse* is a time-structured weak pulse, which itself may consist of some sub-pulses. A *brief pulse* is a short and usually strong pulse which might precede or follow a data pulse. We define the *Amplitude Efficiency* of a photon echo process as the ratio of the amplitude of the output data pulse to the amplitude of the input data pulse. The *Power Efficiency* is defined as the square of the amplitude efficiency.

Often times the efficiency of the echo process is limited by distortion, since we are interested not just in the size of the echo output, but it's fidelity to the input data pulse as well. Here we intend to define a distortion factor which roughly quantifies the distortion for the data pulses we have used. We define the *Amplitude Distortion* as the larger of the following two ratios: (I) The ratio of the minimum amplitude (the height of the valley between two positive sub-pulses) to the maximum amplitude within the output data pulse. (II) The ratio of the amplitude of the ripples to the maximum amplitude within the output data pulse. Case (I) assures that the sub-pulses within a data pulse remain distinguishable in the output. In the input plane, the sub-pulses are completely separate, and thus the ratio defined by (I) is zero. Case (II) is an indicator of the ripples and oscillations which might add to the output data pulse as it propagates in the medium. Again the ratio defined by (II) is zero at the input plane.

V. 2-PULSE SIMULATION RESULTS

In a typical two pulse experiment, a data pulse which has some time structure, and then a brief pulse are applied to the medium. The medium then emits the time reversed version of the data pulse.

The data pulse in our simulation consisted of four Gaussian sub-pulses, each having an amplitude of 0.5 Ghz (Rabi frequency) and 0.03 ns width, corresponding to an area of 0.0177π for each sub-pulse (Fig. 1).

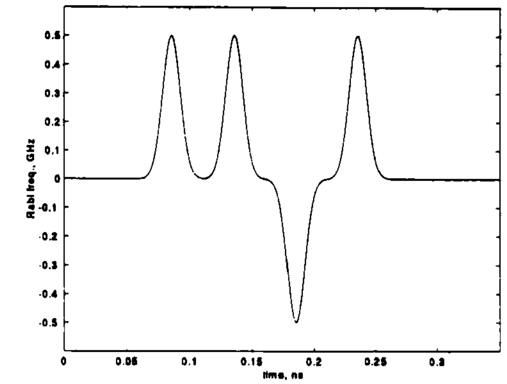

FIGURE 1. The input data pule

The third sub-pulse has been given a negative amplitude to make the data pulse asymmetric so it would be easier to recognize the output and possible distortions.

In the case of an absorber, the most efficient brief pulse is found to be a pulse with an area greater than π/2, and to prevent distortion, less than π. We have thus chosen a brief Gaussian pulse with a width of 3 ns and an amplitude of 30 Ghz (Rabi frequency) corresponding to an area of 0.6380π. The amplitude distortion for this sequence of pulses is about 17%. With these parameters, the echo achieves it's maximum amplitude for a Beer's length of approximately 1.5. The amplitude efficiency is 0.38, and the power efficiency is 0.14.

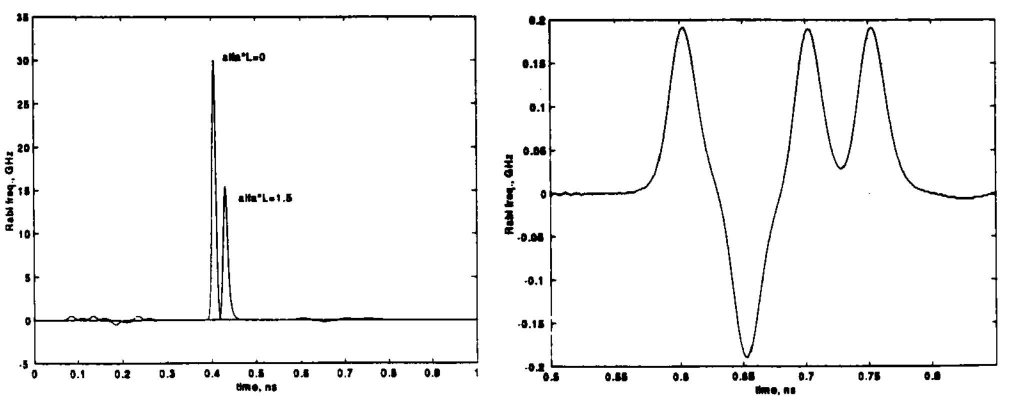

FIGURE 2. Two pulse echo in an absorber: a)Input and output pulses (left), b) Details of the output pulse (right).

Fig. 2.a shows the general form of the input and output pulses, and Fig. 2.b just shows the output.

The result for the same data and brief pulses in an inverted medium is a much larger output. The same pulse area for the brief pulse was used to make a direct comparison with the previous case. We have performed the calculation for a sample Beer length of 3. The results are shown in Fig. 3.

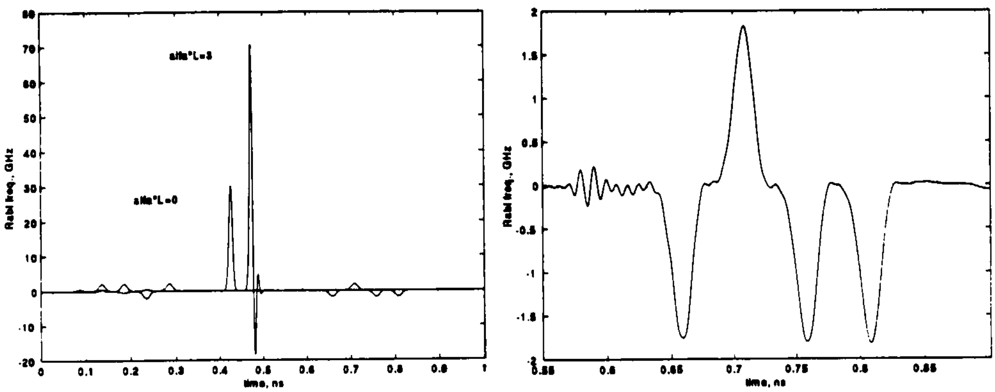

FIGURE 3. Two pulse echo in an inverted medium: a)Input and output pulses (left), b) Details of the output pulse (right).

The amplitude efficiency increases to 3.7, and the power efficiency to 13.7. The amplitude distortion is about 11%. The choice of a Beer length of 3 is for computational rather than theoretical reasons. Increasing the Beer length further causes more distortions, some of which with numerical reasons, and in general demands more computer power and

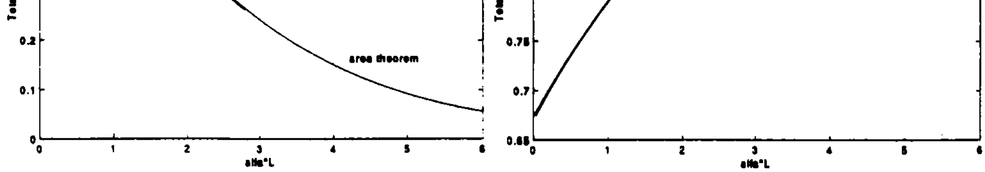

FIGURE 4. Comparison between the predictions of the area theorem and our numerical calculations. a) Absorbing medium (left) b) Inverted medium (right).

better integration routines. Therefore, the question of an "optimum" Beer length for an initially inverted medium remains open.

These results were also verified by the fact that in both cases the total pulse area closely coincides with the predictions of the area theorem (Fig. 4).

VI. 3-PULSE SIMULATION RESULTS

In a typical three pulse experiment, a brief (write) pulse and a data pulse are applied to the medium. This causes the information to be stored in the atomic populations. Then a brief third (read) pulse is applied, after which the medium emits a replica of the initial data pulse. In our simulations a homogenous dephasing is applied to the system after the second pulse to make sure all the coherences are lost and only the information in the populations remain.

The optimum read and write pulses in a three pulse experiment for an absorber are found to be slightly larger than $\pi/2$ pulses. In our simulations, the data pulse is the same as before. We have used brief 0.553π Gaussian pulses for read and write pulses, resulting in a distortion of about 10% in the output. Further increasing the brief pulse areas will increase the distortion. The maximum echo occurs at a Beer's length of about 2.45. The amplitude efficiency is 0.62, and the power efficiency is 0.38 (Fig. 5).

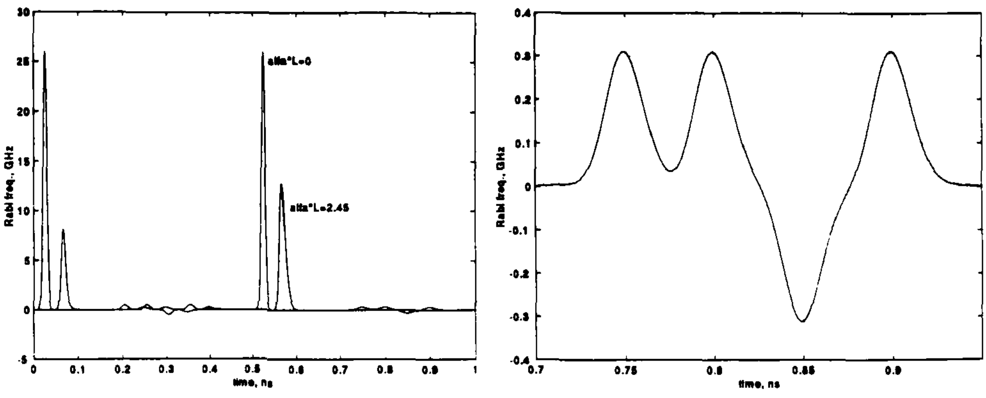

FIGURE 5. Three pulse echo in an absorber: a)Input and output pulses(left), b) Details of the output pulse (right).

In an inverted medium, the optimum read and write pulses are smaller. We have chosen a brief 0.17π Gaussian pulse as the write and a brief 0.25π Gaussian pulse as the read pulse. The data pulse is the same as before. The output is calculated for a Beer length of 4. As with the two pulse case, the choice of a Beer length of 4 is due to computational reasons, and more work is required to determine how far it can be increased. The input and output pulses are shown in Fig. 6. The amplitude and power efficiencies in this case are 2.8 and 7.8 respectively. These results as well as the results of two pulse simulations are summarized in table 1.

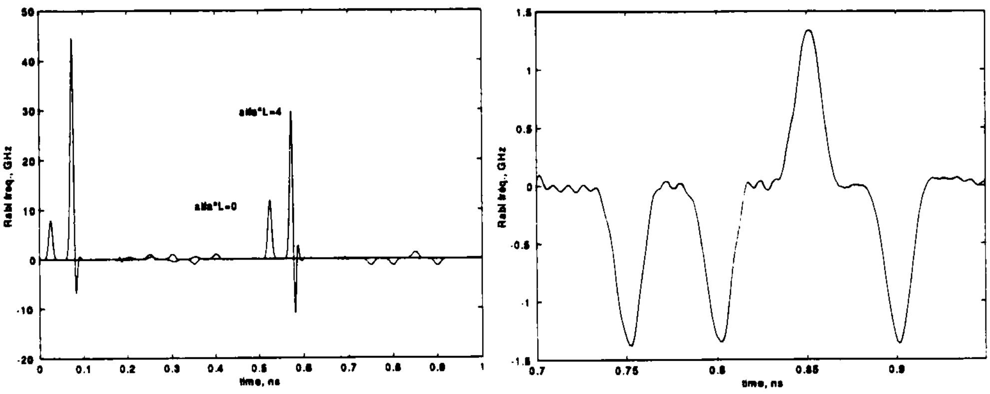

FIGURE 6. Three pulse echo in an inverted medium: a)Input and output pulses (left), b) Details of the output pulse (right).

TABLE 1. Summary of the results for two and three pulse echoes in inverted and non-inverted media.

	2-Pulse Echo		3 Pulse Echo	
	Non-inverted	Inverted	Non-inverted	Inverted
Pulse1	Data	Data	Brief (0.553π)	Brief (0.553π)
Pulse 2	Brief (0.6380π)	Brief (0.6380π)	Data	Data
Pulse 3	-	-	Brief (0.553π)	Brief (0.553π)
Beer's length	1.5	3	2.45	4
Amplitude Efficiency	0.38	3.7	0.62	2.8
Power efficiency	0.14	13.7	0.38	7.8
Amplitude Distortion	17%	11%	10%	6%

VII. SUMMARY AND CONCLUSION

We have presented and compared the simulation results for photon echoes in absorbing and initially inverted media. We have found that using an optically thick inverted medium may substantially improve the efficiency of the photon echoes. This improvement is more evident in the case of two pulse echoes compared with the three pulse case. Moreover, we have found that the pulses tend to broaden in an absorbing medium and narrow in an inverted medium. This means that structured data pulses (such as digital signals) may propagate much further in an amplifier without losing their structure compared with an absorber.

It should be mentioned that the simulation results discussed so far are based on a simple theory which treats atoms as ideal two level systems, assumes plane wave illumination, and neglects the possibility of self-modulation of laser pulses. Therefore, further experimental work is necessary to determine the validity of these results in practical cases.

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