The near-field effect in a quantum computer

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(Submitted 13 April 1999)

Pis’ma Zh. Éksp. Teor. Fiz. 69, No. 10, 750–754 (25 May 1999)

It is shown that in principle it is possible to write optical information on individual quasiresonant atoms in a concentrated system by changing the angle of incidence of an external light wave. © 1999 American Institute of Physics. [S0021-3640(99)01510-8]

PACS numbers: 03.67.Lx

The near-field effect was predicted theoretically in Ref. 1, and its properties have been investigated in detail in certain boundary-value problems of classical, nonlinear, and quantum optics. The crux of the method is that the self-consistent interaction of polarizing fields of closely arranged atoms substantially changes the field of these atoms at any point of observation located in the near or wave zone with respect to these atoms. This effect is the basis of the idea, advanced in Refs. 5 and 6, of using optical radiation to investigate the structure of small objects with linear dimensions \( a \ll \lambda \), where \( \lambda \) is the wavelength of the light wave. In Refs. 5 and 6 the interaction of a light wave whose wave vector was directed along an axis connecting two dipole atoms was studied. The microscopic field at the location of the atoms and the field in the wave zone, which, as shown in Refs. 5 and 6, depends strongly on the interatomic distance, the polarizability of the atoms, the frequency of the external field, and so on, was calculated. In the present letter it is suggested that the near-field effect be used to write information on individual atoms in a concentrated system of two-level atoms by varying the angle of incidence of the external light wave. To demonstrate this method we examine a system of two close quasiresonant atoms (small object) in the field of an intense light wave that can change substantially the inversion of the atomic states. We shall fix the location of each atom by means of a corresponding phase factor of the resulting microscopic field.

Three basic problems can be distinguished in a quantum computer. 1. Identifying in a system of atoms an individual qubit atom which carries definite information for a sufficiently long period of time. In the method of Ref. 9, which is based on the use of a system of cold atoms in optical traps, the qubit atoms are located at distances \( a \ll \lambda \) and despite this, as will be shown below, they can be distinguished according to the magnitude of the field at the location of each qubit atom. As specific qubit atoms we can consider Cr\(^{3+}\) ions in ruby with energy relaxation time \( T_1 = (4 \omega_0 d^2 / 3 \hbar c^3)^{-1} \), where \( d = 4.8 \times 10^{-21} \) cgs esu is the transition dipole moment and \( \omega_0 \) is the transition frequency, corresponding to the \( R_1 \) line in ruby. 2. Encoding information and performing basic logical operations. In the method proposed, this can be done by using different angles of incidence of an external light wave, which can be changed using acoustooptic or elec-
trooptic modulators. 3. A method for reading information after the calculations have been performed. In our analysis probe radiation can be used for this purpose. It was shown in Ref. 5 that the near-field effect also occurs when a weak light wave acts on a system of dipole atoms, which were treated as Lorentzian oscillators.

We shall determine the microscopic field $E(r,t)$ of a light wave at an observation point $r$ at time $t$ by the equation\(^{3,11}\)

$$
E(r,t) = E_0(r,t) + \sum_{j=1}^{2} \text{curl} \text{curl} \frac{p_j(t-R/c)}{R_j},
$$

where $E_0(r,t)$ is the intensity of the electric field of the external light wave propagating with the speed of light $c$ and $p_j$ is the induced dipole moment of the $j$th atom. The distance $R_j = |r - r_j|$, where $r_j$ is the radius vector of the $j$th atom relative to the origin of the coordinate system, which is placed, for example, at the center of the first atom. The differentiation in Eq. (1) is performed with respect to the coordinates of the observation point.

Let us consider the interaction of atoms with the field of an external light wave $E_0(r,t)$

$$
E_0(r,t) = eE_0 \exp(-i[k_0 \cdot r - \omega t]) + \text{c.c.}
$$

where $e$ is a unit polarization vector of the electric field, $E_0$ is the real amplitude of the wave, and $\omega$ and $k_0$ are the frequency and wave vector ($k_0 = \omega/c$) of the external wave. Then we represent the dipole moment of the $j$th atom as

$$
p_j = (1/2)d_j(u_j + iv_j)\exp(i\omega t) + \text{c.c.}
$$

where $d_j$ is the transition dipole moment between two chosen quantum states of the $j$th atom, and the quantities $u_j$ and $v_j$ satisfy the equations\(^{3,10}\)

$$
\dot{u}_j = - (\omega_{0j} - \omega)u_j + \frac{2}{\hbar}(d_j \cdot E_{0j})w_j - \frac{u_j}{T_2},
$$

$$
\dot{v}_j = (\omega_{0j} - \omega)v_j + \frac{2}{\hbar}(d_j \cdot E'_{0j})w_j - \frac{v_j}{T_2},
$$

$$
\dot{w}_j = \frac{2}{\hbar}(d_j \cdot E''_{0j})u_j - \frac{2}{\hbar}(d_j \cdot E'_{0j})v_j - \frac{w_j - w_0}{T_1},
$$

where $\omega_{0j}$ is the resonance transition frequency in the spectrum of the $j$th atom, and $w_j$ is the inversion of the quantum states of the $j$th atom which are coupled by the resident transition, $w_0$ is the initial inversion, and $T_1$ and $T_2$ are relaxation times.\(^{10}\) The quantities $E'_{0j}$ and $E''_{0j}$ are the real and imaginary parts of the amplitude of the electric field at the $j$th atom:

$$
E(r,t) = (E'_{0j} + iE''_{0j}) \exp(i\omega t) + \text{c.c.}
$$

This determines the system of equations that will be used to solve the self-consistent problem of the interaction of two dipole atoms with an external field.

We shall assume that the time elapsed from the moment the external field is switched on $t \gg T_1$, $T_2$, i.e., all processes occurring in the system can be assumed to be