Науковий вісник Ужгородського університету. Серія Фізика. Випуск 8. Частина 2. – 2000

DYNAMICS OF INTERACTION OF ATOM WITH LASER FIELD. PHOTON ECHO AND ITS USE IN THE THEORY OF NEURAL NETWORKS

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The interaction of a multielectron atom with the single-mode and multi-mode laser pulses is studied on the basis of the S-matrix Gell-Mann and Low formalism. We have examined the three-photon transition 6S-6F in the Cs atom. It has been shown that the dynamical shift of atomic line under the multi-mode laser pulse is significantly larger then the corresponding shift under the single-mode pulse. New perspectives of using photon echo as a new physical principle for the realization of neural networks in optical information processing systems are considered. We have studied the operation of an optical neural network, constructed on the basis of the stimulated three-pulse photon echo effect. The latter is used for highly effective realization of the neural network with retarding in optics for processing complicated sequences of images.

1. The interaction of atomic systems with laser field attracts great interest, especially due to the further progress in laser technology [1]. One of the consistent methods for the calculation of the radiation characteristics of an atom in a laser field has been developed in [2, 3]. It is based on the S-matrix formalism and quantum-electrodynamical moments technique. Here we consider the dynamics of interaction of the atomic system with single-mode and multimode laser pulses. The dynamical shift of the atomic line (α-p transition between certain discrete levels with the absorption of k photons is considered) in the laser field can be determined as follows [2,3]:

$$\delta\omega(p\alpha|k) = \int' d\omega \ \mathrm{Im}\, E_\alpha(\omega)\ (\omega - \omega_{p\alpha}/k)\,/\,N,$$
$$\mu_m = \int' d\omega \ \mathrm{Im}\, E_\alpha(\omega)\ (\omega - \omega_{p\alpha}/k)^m\,/\,N, \quad (1)$$

Here $N=\int' d\omega \mathrm{Im} E_\alpha$ is a normalizing factor, $\omega_{p\alpha}$ – the position of the non-shifted line for the atomic transition α-p; $\delta\omega(p\alpha|k)$ is the shift under k-photon absorption and $\omega_{p\alpha}=\omega_{p\alpha} + k\cdot\delta\omega(p\alpha|k)$.

The moments μ_2 and μ_3 determine the atomic line dispersion and asymmetry. In order to calculate $\delta\omega$ and μ_m values it is necessary to expand E_α into the perturbation theory series. The corresponding calculation of the interaction of the atom with a laser pulse of Gaussian form: $f(\omega) = I \exp[\ln 2(\omega^2/\Delta^2)]$ resulted in the following [3]:

$$\delta\omega(p\alpha \mid k) = \{\pi\Delta / (k+1)\mathrm{k}\}\ [\ E(p, \omega_{p\alpha}/k) - E(\alpha, \omega_{p\alpha}/k)], \qquad \mu_2 = \Delta^2/\mathrm{k}$$
$$\mu_3 = \{4\pi\Delta^3 / [k\,(k+1)]\}\ [\ E(p, \omega_{p\alpha}/k) - E(\alpha, \omega_{p\alpha}/k)], \qquad (2)$$

where

$$E(j, \omega_{p\alpha}/k) = 0{,}5 \sum_{p_i} V_{jpi}\, V_{pij} \left[\frac{1}{\omega_{jp_i} + \omega_{p\alpha}/k} + \frac{1}{\omega_{jp_i} - \omega_{p\alpha}/k} \right]$$

As an example, we consider a three-photon transition 6S-6F in the Cs atom. The detailed theoretical and experimental study of the multi-photon processes in Cs atom has been carried out in [4–6]. According to [4], the dynamical shift of the lines is linear versus laser intensity (the laser intensity is increased from 1.4 to 5.7×10^7 W/cm^2) and is determined as follows:

$$\delta\omega(p\alpha \mid k) = bI$$

with b=(5,6+-0,3) $\mathrm{cm^{-1}/GWcm^{-2}}$

(b is expressed in terms of energy of the three-photon transition 6S-6F). The corresponding shift obtained for coherent laser pulse is determined as follows:

$$\delta\omega 0(p\alpha \mid k) = aI$$

with a=2 $\mathrm{cm^{-1}/GWcm^{-2}}$.

Similar theoretical values were obtained on the basis of the calculation within our approach (in the calculation we used our numeric atomic code; cf. [2, 3, 7–9]:

$$\delta\omega(p\alpha \mid k) = bI$$

with b=5.8 $\mathrm{cm^{-1}/GWcm^{-2}}$

$$\delta\omega 0(p\alpha \mid k) = aI$$

with a=2.1 $\mathrm{cm^{-1}/GWcm^{-2}}$.

It should be noted that the atomic line shift due to the interaction of the atom with a multi-mode laser pulse is significantly larger then the corresponding shift under the interaction of the atom with a single-mode pulse. According to the zero-bandwidth model [5, 6], the enhancement factor is equal to 3. One can see that the atomic line shift is enhanced by the photon-correlation effects.

2. Note that investigation of multi-photon processes and nonlinear optical phenomena in general may be very useful for some technical applications. In the recent years new perspectives of using the photon echo (multi-photon echo) as a new physical principle for realization of neural networks in optical information processing systems have been opened [10]. Here we study the operation of an optical neural network, constructed with the use of the stimulated three-pulsed photon echo. As it is well known, in the papers of McCulloch and Pitts [11-13] a model of a neural network was proposed, in which neurons are considered as simple threshold elements interacting through a system of inter-neural links. The different models of neural networks are used for the solution of artificial intellect problems, in particular, the Hopfield networks (Hemming, perceptrone and multi-layer perceptrone [11-15]). Different physical, in particular, optical and opto-electronic realizations of these models are intensely studied now. As it is well known , the photon echo is a non-linear-optical effect and represents the phenomena of four-wave interaction in the non-linear medium with time delay between light pulses. The calculation of the medium polarization (a macro-dipole, determined by the sequence of three optical pulses) and substitution into the Maxwell equations gives: E(echo)=$b\,E_1E_2E_3$. Here b is a coefficient, determined by the medium parameters and $E_{(1,2,3)}$ are the amplitudes of (1,2,3) pulses. We consider an internal-product scheme of the optical neural network realization. The optical scheme to memorize the images $\xi^1,\ldots,\xi^p$ is as follows [15]: {↓Input→Accumulative Matrix F1→Correlation Field → Accumulative Matrix F2→ Output→ Threshold Device→↑}. At first one should calculate the internal products between the input vector and the memorized one. The expression for the amplitude of the stimulated photon echo signal is given by

$$u(m) \sim \sum_j {}^{*m}_{jj}\xi^{in}_{ij}\,\xi\,.$$

Here the amplitude of the first pulse is equal to 1. Then the internal products weight the corresponding memory vectors ($\xi^1,\ldots,\xi^p$), accumulated in the matrix F2. This operation leads to the appearance of the stimulated photon echo signals, which are afterwards summated, resulting in a one-dimensional distribution with the amplitude

$$s_i \sim \sum_m u(m)\xi_{ii}^m = \sum_m (\xi_{ii}^m)\sum_j {}^{*m}_{jj}\xi_{ij}^{in}\,\xi \ .$$

The photon echo principle enables a 2-D optical array to be processed. It requires the use of an additional time coordinate. The output signal amplitude in this case is given by

$$a_{kl}^{out} \sim \sum_m u(m)a_{kl}^m = \sum_m a_{kl}^m \sum_{j,i} a_{ij}^m a_{ij}^{in} \ .$$

In order to take into account retarding effects, the retarding values should be include to the network dynamics:

$$\xi_i(n+1) = f[\sum_{j=1}^{N}\sum_{l=0}^{Qk-1} J_{ij}^l \xi_j(n-l)\,] \ ,$$

where the links matrices (corresponding to the retarding values) have the following form:

$$J_{ij}^l = \sum_{k=1}^{s}\sum_{m=1}^{Qk-l} \xi_l^{\kappa,\mu+\lambda-1}\xi_j^{k,m} ...and...\xi_j^{k,mk+1} = \xi_j^{k,l} \ .$$

Here s is the number of chains, Qk – the number of images in the k-th chain. If l=0, one deals with a network with moment response. In order to enable modelling of definition-invariant images and increase the information capacity, one should use the networks of the higher orders. We have developed a new similar scheme. The sums of the non-linear expressions of the following type

$$a_m^{out} = \mathrm{sgn}(\sum_{j1,j2,\dots,jn} W_{mj1,\dots,jn} a_m^{in} a_{j1}^{in} \dots a_{jn}^{in})$$

$$1<j1,j2,,jn<N, \ 1<m<N_o$$

are used instead of the linear (with s) expressions in the image transformations and matrix calculations rules. Here a^{in} is the input image, a^{out} – the output image; j=1,2,…,N_0; W – the strength of the link between the neurons with numbers $m, j1, \dots, jn$:

$$W_{mj1\dots jn} = \sum_{k=1}^{p} a_m^{out} a_{j1}^{in-k} \dots a_{jn}^{in-k} \ .$$

In conclusion we note that it is possible also to recreate the dynamics of the network, which is capable to write hierarchically organized images [15]. In order to write a two-level hierarchy of images one can use the corresponding rule of memorizng and choose the interaction matrix of the type given in [16, 17]. We also propose similar schemes in the neural network theory which can be constructed with the use of another cooperative optical effect, namely, superemission (Dicke emission).

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ДИНАМІКА ВЗАЄМОДІЇ АТОМА З ЛАЗЕРНИМ ПОЛЕМ. ФОТОННА ЛУНА ТА ЇЇ ВИКОРИСТАННЯ В ТЕОРІЇ НЕЙРОМЕРЕЖ

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На основі S-матричного формалізму Гелл-Мана та Лоу досліджується динаміка взаємодії багатоелектронного атома з одномодовим та багатомодовим лазерними імпульсами. Розглянуто трифотонний перехід 6S-6F в атомі Cs. Показано, що динамічне зміщення атомної лінії при дії багатомодового лазерного імпульсу значно більше, ніж відповідне зміщення при дії одномодового імпульсу. Розглянуто нові перспективи використання фотонної (багатофотонної) луни як фізичного принципу для реалізації нейромереж у системах обробки оптичної інформації. Проаналізовано функціонування оптичної нейромережі на основі ефекту трифотонної луни. Останній використано для високоефективної реалізації в оптиці нейромережі з запізненням для обробки ускладненої послідовності образів.