Coherent interaction between light pulses and the ions of a magnetized plasma

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A theory of the coherent radiation from a magnetized plasma is presented, in which the radiation results from short pulses acting on the ion Landau levels in processes such as the decay of free polarization, photon echoes, and delayed optical nutation. It may be possible to eliminate Doppler dephasing of the electric dipoles excited by the coherent radiation pulses and to transform optical information coded in light signals by using ion-cyclotron resonance effects.

1. INTRODUCTION

Rapid progress has been made in experimental and theoretical studies of coherent transient effects of visible radiation. In large measure this is a consequence of the many possibilities for exploiting these effects to determine the quantum-mechanical and relaxational properties of materials and for developing fast memory devices (see, e.g., Refs. 1–6). The resonant interaction between light pulses and the ion component of a magnetized plasma is characterized by the Zeeman splitting of the ion energy levels and the action of the magnetic field on the ion motion. The influence of the Zeeman effect on photon echo in a gas has been considered previously.[7,8] In a time-independent uniform magnetic field H the energy states of an ion with charge Ze and mass m_i split into Landau levels. These are positioned at multiples of the ion cyclotron frequency $\omega_L = ZeH/m_ic$. This splitting has a dramatic effect on the dynamics of coherent transient optical processes.

In the present paper we investigate modulational effects in the response of quantum systems to pulses of coherent light. This response is a consequence of transitions between ion Laudau levels when photons are absorbed or emitted in processes like the decay of free polarization, photon echo, and delayed optical nutation. We demonstrate, among other things, that it is possible to produce a cyclotron ion-photon echo, whose analog in radiospectroscopy is the cyclotron echo from electrons.[9] We show that it is possible to eliminate the Doppler dephasing of an ensemble of electric dipoles excited in a gas by coherent radiation pulses, and to modify the signal-carrying properties of light by means of ion-cyclotron modulation.

2. BASIC EQUATIONS AND RELATIONSHIPS

For an atomic ion, the amount by which the Zeeman splitting exceeds the cyclotron splitting is given approximately by m_i/m_e, where m_e is the electron mass. We therefore restrict ourselves in what follows to describing the cyclotron effects for each separate Zeeman component of an ion line.

In the rotating wave approximation[2] the density matrix element ρ_{mn} corresponding to the Bohr frequency ω_{mn} of the specified Zeeman component of the spectrum has the oscillatory form

$$\rho_{mn}=\rho\exp[-i(\Omega t-\mathbf{kr})],\qquad \Omega=\omega-\omega_{mn}, \tag{1}$$

where $\omega = kc$ is the frequency of the light field. For definiteness we choose the z axis in the direction of the magnetic field H and the x axis in the plane of the vectors $\mathbf{k}$ and $\mathbf{H}$. We transform to cylindrical coordinates in the space of the ion velocities $\mathbf{v}$ and denote by ψ the angle between the x axis and the vector $\mathbf{v}_\perp = \mathbf{v}\times\mathbf{H}/H$. If we take into account the relaxation processes and the excitation of the active levels m and n, the kinetic equations for the density matrix elements can be written in the form

$$\left[\frac{\partial}{\partial t}-\omega_L\frac{\partial}{\partial\varphi}+i(k_\perp v_\perp\cos\varphi-\Omega')+\Gamma\right]\rho=-iG(\rho_{mm}-\rho_{nn}), \tag{2}$$

$$\left(\frac{\partial}{\partial t}-\omega_L\frac{\partial}{\partial\varphi}+\Gamma_j\right)\rho_{jj}=q_i\mp 2\,\mathrm{Re}(iG^*\rho),\qquad j=m,n;$$

$$\Omega'=\Omega-k_zv_z,\qquad G=E(t)d_{mn}/2\hbar. \tag{3}$$

Here $\Gamma = 1/T_2$, where T_2 is the transverse relaxation time, Γ_j are the decay constants for the populations ρ_{jj} of the excited states, $E(t)$ is the amplitude of the traveling wave, d_{mn} is the matrix element of the electric dipole transition, and q_j is a Boltzmann distribution in the level excitation energies. Equations (2) and (3) were derived using methods analogous to those described in Refs. 10–12.

We will solve this system of equations using perturbation theory, expressing the time dependence by means of the Green's functions $f(\phi,t|\phi',t')$ and $f_j(\phi,t|\phi',t')$:

$$f=\frac{\theta(\tau)}{2\pi}\exp[-(\Gamma-i\Omega')\tau+i\xi\sin\varphi]\sum_{l,l'=-\infty}J_l(\xi)\cdot\exp[-i(l-l')(\varphi+\omega_L\tau)-il'\varphi'], \tag{4}$$

$$f_j=\theta(\tau)\exp(-\Gamma_j\tau)\frac{1}{2\pi}\sum_{l=-\infty}^{\infty}\exp[il(\varphi-\varphi'+\omega_L\tau)],$$

$$\tau=t-t';\qquad \theta(\tau)=\begin{cases}1, & \tau\geqslant 0;\\ 0, & \tau<0.\end{cases} \tag{5}$$

The Green's function for Eq. (2) is written as an expansion in Bessel functions with argument $\xi = k_\perp v_\perp/\omega_L$. If typical light pulse intensities are not too large ($G_2\ll\Gamma\Gamma_j$), the recurrence relations

$$\rho^{(s+1)}(\varphi,t)=-i\int_0^{2\pi}d\varphi'\int_{-\infty}^{\infty}dt'\,G(t')N^{(s)}(\varphi',t')f(\varphi t|\varphi't');$$

$$N=\rho_{mm}-\rho_{nn}, \tag{6}$$

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$$\rho_{jj}^{(s+1)}(\varphi, t) = \mp 2\,\mathrm{Re}\left[i\int_0^{2\pi} d\varphi' \int_{-\infty}^{\infty} dt' G^{\bullet}(t')\rho^{(s)}(\varphi', t') f_i(\varphi t | \varphi' t') \right]. \quad (7)$$

can serve as the basis for constructing a perturbation expansion in $G(t)$. The velocity distribution function in level j in the absence of the electromagnetic field is given by

$$\rho_{jj}^{(0)} = N_j F(\mathbf{v}), \quad F(\mathbf{v}) = (\pi^{1/2}\bar{v})^{-3}\exp(-v^2/\bar{v}^2), \quad (8)$$

where N_j denotes the number of ion excitation events per unit volume in level j in a time Γ_j^{-1} and $\bar{v}$ is the mean ion thermal speed. In the sections of the paper that follow, we consider external sources exciting the quantum system of electric dipoles, in the form of pulses of electromagnetic radiation whose length is short compared with the irreversible relaxation times T_2 and Γ_j^{-1}, which allows us to neglect the effect of relaxation on these light signals.

3. DECAY OF FREE POLARIZATION OF THE PLASMA IONS IN A MAGNETIC FIELD

When an external light field is switched on instantaneously, a freely induced drop occurs in the intensity of the coherent optical pulse propagating in the medium. Under these conditions, the optical free induction for the ions of a magnetized plasma is given by the linear term in the expansion of the matrix element ρ_{mn} in powers of the external pulse amplitude.

The time transformation of the optical free induction is simplest if the pulse is ultrashort and its envelope has the form of a delta-function,

$$G(t) = \theta_1\delta(t), \quad (9)$$

where $\theta_1 = G_1\tau_1$ is the area under the pulse, whose duration is τ_1. In the present case we find

$$\rho^{(1)}(\varphi, t) = -iN^{(0)}(\mathbf{v})\theta_1 \exp[-(\Gamma - i\Omega')t + i\xi\sin\varphi] \cdot \sum_{l=-\infty}^{\infty} J_l(\xi)\exp[-il(\omega_L t + \varphi)]. \quad (10)$$

The electric dipoles oscillate at harmonics of the gyrofrequency ω_L, in consequence of the ion motion in spiral trajectories in the magnetic field and the ion-cyclotron splitting into components corresponding to transitions between the Landau levels m and n.

The light signal emitted because of the external pulse acting on the medium is given by the free polarization of the ions, $d_{mn}\langle\rho^{(1)}(\mathbf{v})\rangle_{\mathbf{v}}$, found by averaging Eq. (10) over direction in velocity space. For $\mathbf{v}\|\mathbf{H}$ or in the absence of cyclotron gyration ($Ze = 0$), we obtain the familiar result

$$\langle\rho^{(1)}(t)\rangle_{\mathbf{v}} = -iN_0\theta_1 \exp[-\Gamma t - (k\bar{v}t)^2/4], \quad \Omega = 0,$$
$$N_0 = N_m - N_n, \quad (11)$$

which exhibits the role of Doppler dephasing in free polarization decay. For $k\bar{v} \gg \Gamma$, inhomogeneous relaxation of the medium due to the Doppler effect gives rise to a rapid nonexponential drop in the free polarization signal, concealing information about the homogeneous linewidth Γ.

For ions in a magnetic field, it follows from (10) that for $\Omega = 0$ the free polarization decay takes the form

$$\langle\rho^{(1)}(t)\rangle_{\mathbf{v}} = -iN_0\theta_1 \exp\left[-\Gamma t - \frac{(k_z\bar{v}t)^2}{4} - \frac{k_\perp^2\bar{v}^2}{\omega_L^2}\sin^2\frac{\omega_L t}{2}\right]. \quad (12)$$

Because of the ion cyclotron gyration, the Doppler dephasing enters only through the projection v_z of the ion velocity on the magnetic field and drops out entirely if $k_z = 0$ and the emitted pulse propagates normal to the magnetic field $\mathbf{H}$. The cyclotron oscillations of the signal are similar to the oscillations resulting from phase modulation or parametric resonance.[13] The free polarization signal drops exponentially when it is measured at intervals

$$t_l = 2\pi l/\omega_L, \quad l = 1, 2, \ldots, \quad (13)$$

for which

$$\langle\rho^{(1)}(t)\rangle_{\mathbf{v}} \propto \exp(-\Gamma t_l). \quad (14)$$

Since modulating the free polarization decay at the known ion-cyclotron frequency does not interfere with measurement of the homogeneous relaxation constants, the prospects for using it as a coherent transient spectroscopic technique improve notably. According to (13), it is only necessary to synchronize the observation times with the cyclotron gyration period.

4. CYCLOTRON ION-PHOTON ECHO

We consider the process by which stimulated three-pulse echoes form as a result of optical transitions between ion Landau levels associated with a four-wave interaction of the form

$$\mathbf{k} = \mathbf{k}_3 + \mathbf{k}_2 - \mathbf{k}_1, \quad (15)$$

where k_1, k_2, k_3 are the wave vectors corresponding to the triggering, encoding, and readout external pulses, and $\mathbf{k}$ is the wave vector of the photon echo pulse. The inhomogeneous relaxation time $T_2^* = (k\bar{v})^{-1}$ is assumed to be substantially shorter than the other characteristic times, including the pulse length and the interval between pulses. According to (6) and (7), the echo signal is determined by third-order (in the amplitude of the external pulses) perturbation theory.

Following the second pulse, a nonlinear correction to the active level populations is induced:

$$\rho_{jj}^{(2)} = \mp 2N^{(0)}(\mathbf{v})\,\mathrm{Re}\Big\{\int_{-\infty}^{t} dt_2 \int_{-\infty}^{t_2} dt_1\, G_1(t_1)G_2^{*}(t_2) \cdot \sum_{l=-\infty}^{\infty} J_l\left[2\xi\sin\frac{\omega_L(t_2-t_1)}{2}\right]\exp[-(\Gamma - i\Omega')(t_2-t_1) - \Gamma_j(t-t_2) + i\omega_L(t - {}^1\!/_2(t_1+t_2))]\Big\}. \quad (16)$$

The oscillations of the populations at the frequency ω_L result from splitting of the levels into an infinite number of equivalent components, spaced ω_L apart.

The coherent response of a quantum system to the third (readout) pulse when the system is spatially synchronized according to (15) is found by averaging the density matrix element $\rho^{(3)}(t)$ over ion velocities. When we substitute expression (16) in the recurrence relation (6) we find (assuming $\Omega = 0$)

$$\langle\rho^{(3)}(t)\rangle_v = iN_0 \sum_{j=m,n} \int_{-\infty}^{t} dt_3 \int_{-\infty}^{t_3} dt_2 \int_{-\infty}^{t_2} dt_1\, G_1^*(t_1) G_2(t_2) G_3(t_3)$$

$$\cdot \exp\Big\{ -\Gamma(t-t_3+t_2-t_1) - \Gamma_j(t_3-t_2) - {}^1/_4 (k_z^2\bar{v}^2)(t-t_3-t_2+t_1)^2 - \frac{k_\perp^2\bar{v}^2}{\omega_L^2}\Big[\sin^2\frac{\omega_L(t-t_3)}{2} + \sin^2\frac{\omega_L(t_2-t_1)}{2} - 2\sin\frac{\omega_L(t-t_3)}{2}\sin\frac{\omega_L(t_2-t_1)}{2}\cos\frac{\omega_L(t-3t_3+t_2+t_1)}{2}\Big]\Big\}. \quad (17)$$

For $k_z\bar{v} \gg \Gamma$ the Doppler dephasing associated with ion motion parallel to the magnetic field has a major effect on the dynamic properties of the echo. In this limit the exponential factor in Eq. (17) that depends on the k_z component of the wave vector can be approximated by $\delta(t-t_3-t_2+t_1)\pi^{1/2}/k_z\bar{v}$.

Suppose that the first and third pulses have the form of delta-functions and are separated by a delay time T. Using the relations

$$G_3 = \theta_3\delta(t-T), \qquad \theta_3 = G_3\tau_3, \quad (18)$$

together with (9), after carrying out the time integrals we obtain from (17) the expression

$$\langle\rho^{(3)}(t)\rangle_v = \frac{i\pi^{1/2}N_0\theta_1\theta_3}{k_z\bar{v}} G_2(t-T) \sum_{j=m,n} \exp\Big[-2\Gamma(t-T) - \Gamma_j(T-t_k) - 4\frac{k_\perp^2\bar{v}^2}{\omega_L^2}\sin^2\frac{\omega_L(t-T)}{2}\sin^2\frac{\omega_L(T-t_k)}{2}\Big] \quad (19)$$

Here t_k represents the arrival time of the encoding pulse, the shape of which for $t - T \ll T_2$ is copied by the echo pulse that appears at time $t = T + t_k$. The maxima in the echo signal, modulated at harmonics of the frequency ω_L, are given by the cyclotron resonance conditions

$$T - t_k = 2\pi l_1/\omega_L, \qquad t - T = 2\pi l_2/\omega_L, \quad (20)$$

where l_1 and l_2 are integers. The ion cyclotron gyration contributes to the time synchronization conditions (20) by partly eliminating the Doppler dephasing, thereby increasing the echo signal by a factor k/k_z in comparison with the $\mathbf{H}\|\mathbf{k}$ case.

If the magnetic field is perpendicular to the wave vector $\mathbf{k}$, Doppler dephasing is completely eliminated. The signal of the cyclotron ion-photon echo associated with a delta-function encoding pulse with profile area $\theta_2 = G_2\tau_2$ can then be represented as

$$\langle\rho^{(3)}(t)\rangle_v = iN_0\theta_1\theta_2\theta_3 \sum_{j=m,n} \exp\Big\{ -\Gamma(t-T+t_k) - \Gamma_j(t-t_k) - \frac{k^2\bar{v}^2}{\omega_L^2}\Big[\sin^2\frac{\omega_L(t-T)}{2} + \sin^2\frac{\omega_L t_k}{2} - 2\sin\frac{\omega_L(t-T)}{2}\sin\frac{\omega_L t_k}{2}\cos\frac{\omega_L(t+t_k-3T)}{2}\Big]\Big\}. \quad (21)$$

Because the relaxation is nonuniform, the maximum value of the echo signal grows by a factor τ_2/T_2^*, where τ_2 is the length of the second pulse. The resulting modulation of the emitted signal is typical of that found in echo-spectroscopy of multilevel systems.[3,14] It appears when $\omega > \Gamma$ holds, but in the present example where the cyclotron resonance conditions (20) are satisfied exactly, the magnitude of the echo signal is given as an exponential function due to the homogeneous relaxation of the excited electric dipole transition moment and the decay of the active levels.

This behavior and the effect of the light echo on transitions between ion Landau levels is also typical of the original two-photon echo, corresponding to the spatial synchronization condition $\mathbf{k} = 2\mathbf{k}_2 - \mathbf{k}_1$. A closed expression for the two-pulse echo can easily be gotten from the general equation (17) by setting $G_2(t) = G_3(t)$. Note also the possibility of increasing the efficiency of phase conjugation[15] which results from eliminating the dephasing of electric dipoles by the use of both the two-pulse and three-pulse forms of the cyclotron ion-photon echo.

5. DELAY OF OPTICAL NUTATION ON ION LANDAU LEVELS

The method of delayed optical nutation can be successfully employed to measure level relaxation rates by means of three-pulse photon echoes. The two-pulse form of a coherent process like delayed optical nutation is implemented by first exciting the quantum system with a short initializing pulse, which then decays to an equilibrium state over some time T, and after that turning on a resonant light field and recording the first absorption response signal.[2]

An expression for the delayed optical nutation signal may be obtained from Eq. (17) by setting $G_2 = G_3 = G = \text{const}$. If the first pulse is taken to be a delta-function as in Eq. (9), summing over the infinite set of cyclotron harmonics and integrating over time gives rise for $k_z\bar{v} \gg \Gamma$ to the following result:

$$\langle\rho^{(3)}(t)\rangle_v \cong \frac{i\pi^{1/2}N_0\theta_1 G^2}{k_z\bar{v}} \sum_{j=m,n} \int_T^t dt' \exp\Big[-2\Gamma(t-t') - \Gamma_j(2t'-t) - 4\frac{k_\perp^2\bar{v}^2}{\omega_L^2}\sin^2\frac{\omega_L(t-t')}{2}\sin\frac{\omega_L(t-2t')}{2}\Big]. \quad (22)$$

It is clear that the dynamics of the optical transitions is determined by ion-cyclotron modulation in the present case also. For $t - T \ll T$, the ensemble of electric dipoles which get out of phase in the interval between pulses get back into phase again only in the case of exact ion-cyclotron resonance, where the delay time is an integral multiple of the ion gyration period:

$$T = 2\pi l/\omega_L, \qquad l = 1, 2, \ldots \quad (23)$$

When this condition holds, maxima appear in the modulated curve of the drop in the delayed optical nutation signal as a function of the delay time T, given by

$$\langle\rho^{(3)}(t)\rangle_v \cong \frac{i\pi^{1/2}\theta_1 G^2}{k_z v} \sum_{j=m,n} (t-T)e^{-\Gamma_j T}, \quad (24)$$

i.e., the delayed optical nutation signal, which is k/k_z times stronger due to ion cyclotron gyration, depends exponentially on the level decay constants Γ_j.

When we observe the delayed optical nutation signal in the direction perpendicular to the magnetic field and the cyclotron period is synchronized with the delay time T, we find

$$\langle\rho^{(3)}(t)\rangle_v \cong 2iN_0\theta_1 G^2 (t-T)^2 e^{-\Gamma T}. \quad (25)$$

Here, because the effect of the irreversible relaxation on the coherent response of the quantum system has been totally eliminated, the possibility of finding the uniform relaxation time of the medium from the nutation signal is manifest. It follows from (22) that in studies of the timedependent reversal of optical nutation,[5] these ion-cyclotron modulation effects may arise and become useful.

6. WAYS OF OBSERVING AND USING ION-CYCLOTRON RESONANCE EFFECTS

In this work we have established the basic laws describing coherent radiation produced by a magnetized plasma in response to short optical pulses acting on the ion Landau levels. We now make some estimates which give an idea of the range of applicability of this theory of ion-cyclotron effects in coherent transient spectroscopy. After an external light pulse has propagated a distance L through an optically thin medium, the intensity I of the reemitted field, measured by heterodyning the detected signal, has the form[2]

$$I(t)=2\hbar\omega L|\mathrm{Re}\langle iG^{*}\rho\rangle_{v}|. \qquad (26)$$

From (11) it follows that in the case of decay of free polarization, the ratio of the peak values of the heterodyne beat signal I_p to the external intensity $\tilde{I}=c|E|^2/4\pi$ is given by

$$I_p/\tilde{I}=3\pi|N_0|LA_{mn}\tau_1/2k^2, \qquad (27)$$

where A_{mn} is the Einstein coefficient for a resonant optical transition. For stimulated cyclotron ion-photon echo resulting from coherent excitation of ions by a series of three pulses of approximately equal intensity $\tilde{I}$, the ratio of the maximum echo signal I_e to $\tilde{I}$ for $\mathbf{H}\perp\mathbf{k}$ can be written according to (21) and (26) in the form

$$\frac{I_e}{\tilde{I}}=\frac{9\pi^2|N_0|L}{8c\hbar k^5}A_{mn}{}^2\tau_1\tau_2\tau_3\tilde{I}\sum_{j=m,n}e^{-\Gamma_j T}, \qquad t_k\ll\Gamma^{-1}. \qquad (28)$$

In the absence of a magnetic field the maximum value of the echo signal is smaller by a factor of $\tau_2 k\bar{v}/2\pi^{1/2}$ than that given by (28).

We analyze the conditions under which ion-cyclotron modulation of the reemitted signals will be observed for the case of a quasineutral lithium plasma subjected to nanosecond pulses at wavelength 5485 Å, resonant with the $2s^3S_1$–$2p^3P_0$ transition of 7LiII ions. Radiative decay in this transition is described by a transition with relatively large width $\gamma=A_{mn}/2\approx10^7$ s^{-1} (see, e.g., Ref. 16). In the electric dipole approximation we have $\Gamma_m=A_{mn}$ and $\Gamma_n=0$. At an ion temperature $T_i\sim10^3$ K the doppler width is $k\bar{v}\sim10^{10}$ s^{-1}. To be specific, we suppose that a plasma with an electron density $n_e\sim10^{12}$ cm^{-3} and a neutral lithium atomic density $n_a\sim10^{11}$ cm^{-3} fills a cylindrical chamber of length $L\sim10$ cm and radius $a\sim1$ mm, along the axis of which a light pulse of the same radius propagates. We suppose also that the populations of levels m and n satisfy $N_n\sim n_e$ and $N_n/N_m\sim10^4$.

The total contribution to the homogeneous width Γ from inelastic collisions with electrons and Stark broadening is estimated using the relation[17,18] $\nu_e\sim10^{-5}n_e$ cm^3 s^{-1}. The effective rate of resonant charge exchange for lithium ions colliding with neutral lithium atoms is given (cf. Ref. 19) by $\nu_a\sim10^{-9}n_a$ cm^3 s^{-1}. Coulomb ion-ion broadening[20,21] is the maln source of ion diffusion in velocity space, since the electron temperature in a gas-discharge plasma is often much higher than that of the ions. When optical free induction decay is observed in a plasma with these parameters, the contribution of Coulomb scattering to the homogeneous linewidth is characterized by the ion-ion collision frequency $\nu_i\sim10^{-5}n_e$ cm^{-3} s^{-1}. Consequently, the effect of collisional relaxation on the evolution of free polarization can be neglected: $\nu_{e,a,i}\ll\gamma\approx\Gamma$.

If dipoles are coherently excited by an external light pulse of length $\tau_i\approx1$ ns and intensity $\tilde{I}\sim1$ MW cm^{-2}, then $I_p/\tilde{I}\sim10^{-2}$ holds. For $H\gtrsim10$ kG the homogeneous linewidth is small compared with the ion-cyclotron frequency: $\omega_L>\Gamma$. Hence the signal of the optical free induction undergoes several cyclotron oscillations before the amplitude of its envelope $I_p\exp(-2\pi l\Gamma/\omega_L)$ equilibrates with the level of spontaneous emission from the plasma:

$$I_s\approx\hbar ck^3A_{mn}N_m a^3. \qquad (29)$$

For modulation of the free polarization signal to occur, the typical magnitude of the variation in the perpendicular magnetic field must satisfy the condition

$$\Delta H\ll\Gamma m_i c/e, \qquad (30)$$

We estimate the size of the cyclotron ion-photon polarization signal for exciting light pulses with the properties $I\approx10$ kW cm^{-2}, $\tau_1=\tau_3=0.1$ ns, $t_k=\tau_2=1$ ns, and $T\sim1$ μs. The rate at which the echo signal decays in this case due to Coulomb scattering is given by

$$I_e\propto\exp(-\nu_i\bar{v}^2k^2t_k{}^2T/2). \qquad (31)$$

In obtaining this relation we can make use of the method of Ref. 21, which presented a theory of Coulomb broadening of ion spectra. In coherent optical processes like echoes and delayed nutation, ion-ion scattering is accompanied by a substantial change in the rate of dipole dephasing. Expression (31) resembles the relaxation behavior of the signal observed in experiments on spin echo based on nuclear magnetic resonance in inviscid liquids.[22] For pulses with the parameters given above we therefore obtain from (28) and (29) $I_e/\tilde{I}\sim10^{-2}$ and $I_e/I_s\sim10^3$. In perpendicular fields $H\gtrsim10$ kG the echo signal can be modulated and its maximum value can grow.

For coherent transient gas spectroscopy the paramount task is to eliminate Doppler dephasing of electric dipoles and to increase the intensity of the observed signals. A way of doing this using ion-cyclotron modulation substantially extends the practical resources of conventional laser spectroscopy techniques for time-dependent processes and makes relaxometric information about quantum transitions, radiative decay, and collisions in plasmas accessible. In order for the cyclotron resonance to appear in multipulse excitation, the interval between synchronized pulses must be a multiple of the ion gyration period. In studies of fine and hyperfine structure of ion terms and the Stark effect, the ion-cyclotron modulation method is most efficient when the line splitting in question is a multiple of the cyclotron frequency. We also wish to call attention to the prospect of carrying out in-line transformation of light signals through ion-cyclotron modulation in pulse-coded communication and optical storage systems. The Fourier-transformation properties of resonant systems with Landau levels make possible correlation analysis of excitation pulses with simultaneous scale transformations. The ion-cyclotron modulation of the coherent responses of spontaneous emission can be utilized in plasma diagnostics, especially in measuring internal magnetic fields in plasmas.

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