Magnetooptic biprism for atomic interferometry

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A configuration of laser and magnetic fields which might be used to achieve effective coherent splitting of an atomic beam into two parts is analyzed. This field configuration differs from the standard magnetooptic grating in that it offers a much greater splitting of the atomic beam without deviation from Raman–Nath conditions.

Atomic interferometry has attracted large interest because of the potentially high sensitivity of atomic interferometers to electromagnetic and gravitational perturbations.[1] However, highly sensitive interferometers with a large useful area can be constructed only if the coherent splitting of the atomic beam is large in absolute value. In the existing interferometers of the Ramsey type the transverse splitting of an atomic beam in momentum space is $2\hbar k$.[1]

A significantly greater splitting of a beam of He* atoms, $\simeq 40\hbar k$, has been predicted theoretically[2] and also observed experimentally,[3] with the help of a magnetooptic grating. This magnetooptic grating was produced at a superposition of two counterpropagating monochromatic laser beams with orthogonal linear polarizations in a static magnetic field directed along these beams (Fig. 1). A quantum-mechanical calculation of the magnetooptic strength for an atom with a $J=0 \to J'=1$ transition was carried out in Ref. 2. In this case, two magnetic sublevels of the excited state, with $m'=-1$ and $m'=1$, and the ground state of the atom, which together form a V-shaped level scheme, participate in the interaction with the magnetic and optical fields. A diagonalization of the complete Hamiltonian for the interaction of an atom with the optical and magnetic fields reveals three corresponding dressed states of the atom. In the adiabatic approximation, in which the interaction of the atom with the field is turned on over a time interval much longer than the period of the Rabi oscillations of the population of its level, $2\pi/\omega_R$, and also much longer than the Larmor precession period $2\pi/\omega_L$, atoms initially in the ground state fill only one corresponding dressed state. In this approximation the motion of the atom is governed by the spatial variation of the energy of this dressed state, $U(x)$, which serves as a potential. At $\omega_R=2\omega_L$ (where ω_R is the Rabi frequency corresponding to one of the traveling light waves), the spatial distribution of this potential along the direction of the light, $U(x)$, is a nearly ideal triangle with a period $\lambda/2$ (Fig. 2). This potential represents a phase grating for the atoms incident on it. The momentum distribution of the atoms after their diffraction by this magnetooptic grating is shown in the lower part of Fig. 2. Here we have used a triangular potential profile, which is a very good approximation of the actual shape. The momentum distribution of the diffracted atoms

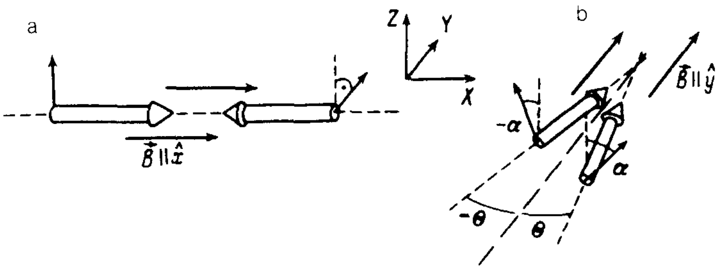

FIG. 1. Configurations of laser and magnetic fields for producing (a) a magnetooptic grating and (b) a magnetooptic biprism. The atomic beam is directed along the z axis.

is found by taking Fourier transforms $\exp[i\int U(x,\,t)dt]$. The duration of the interaction of the atoms with the field is taken to be $t = 10 \cdot 2\pi/\omega_R$. It can be seen from Fig. 2 that this momentum distribution consists of two groups of peaks separated by a distance $\simeq 80\hbar k$. The envelope of these groups (the dashed curve in Fig. 2) is the diffraction function of the scattering of atoms by half the aperture of one element of the phase grating, with a size of $\lambda/4$. The distance from a maximum to the first minimum of the diffraction function for the diffraction of the atoms by an aperture whose size b is equal to half the grating period is given in momentum space by

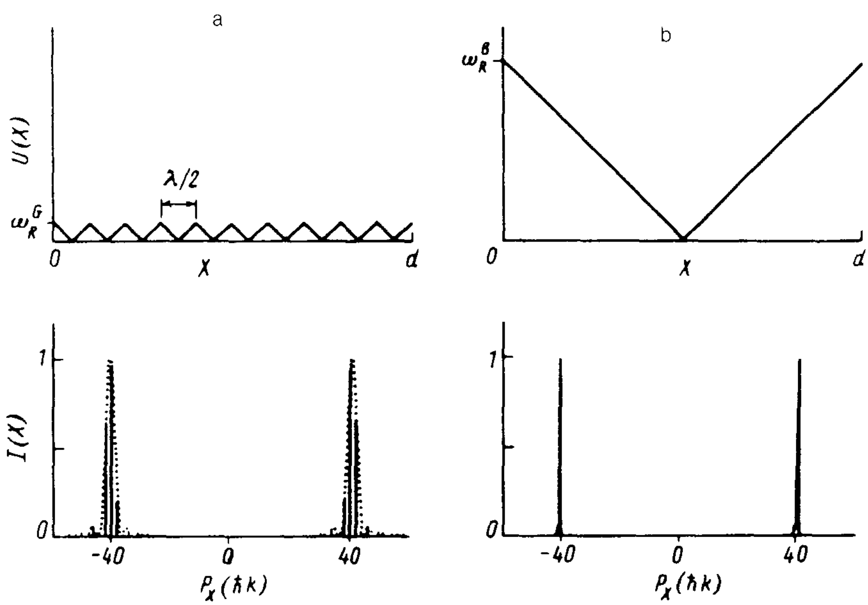

FIG. 2. Top: Spatial distribution of the magnetooptic potential for (a) a magnetooptic grating and (b) a magnetooptic biprism. Bottom: Corresponding momentum distributions of atoms diffracted by these potentials.

$$\Delta p_x = (2\pi/bk)\hbar k. \quad (1)$$

Since we have $b=\lambda/4$ in the case of a magnetooptic grating, the uncertainty in the transverse momentum of the atoms, (1), is $\Delta p_x \simeq 4\hbar k$. The interference of the atoms at the grating with a period of $\lambda/2$ gives rise to peaks within the diffraction envelope which are separated by a distance of $2\hbar k$ and which have a width given by (1), where b is determined by the transverse dimension of the atomic beam.

The parameters characterizing the splitting of the atomic beam can be improved by increasing the period of the magnetooptic grating and by using only one of its periods. Figure 1b shows the corresponding configuration of optical and magnetic fields which might be proposed. In this case, laser beams with a linear polarization making angles of $\mp\alpha$ with the z axis, intersect at a small angle 2θ, and the static magnetic field is directed along the y axis, their symmetry axis. For this geometry of the laser beams, the reradiation of a photon from one wave into the other imparts a momentum $\Delta p_x = \pm 2\hbar k \sin\theta$ to the atom along the x axis. For an atom with a $J=0 \to J'=1$ transition, we can calculate the magnetooptic strength by using the model of dressed states. Here it is convenient to write the linear polarizations $\hat{\mathbf{e}}_{-\alpha}$ and $\hat{\mathbf{e}}_{\alpha}$ of the two counterpropagating light waves as follows:

$$\hat{\mathbf{e}}_{-\alpha} = \left(\frac{1-\epsilon^2}{2}\right)^{1/2} \{\hat{\mathbf{e}}_{+}\exp(i\beta) + \hat{\mathbf{e}}_{-}\exp(-i\beta)\} + \hat{\mathbf{e}}_{y}\epsilon, \quad (2a)$$

$$\hat{\mathbf{e}}_{\alpha} = \left(\frac{1-\epsilon^2}{2}\right)^{1/2} \{\hat{\mathbf{e}}_{+}\exp(-i\beta) + \hat{\mathbf{e}}_{-}\exp(i\beta)\} + \hat{\mathbf{e}}_{y}\epsilon. \quad (2b)$$

Here $\beta = \arctan(\tan\alpha \cdot \cos\theta)$, $\epsilon = \sin\alpha \cdot \sin\theta$, and $\hat{\mathbf{e}}_{\pm} = 1/\sqrt{2}(\hat{\mathbf{e}} \pm i\hat{\mathbf{e}}_x)$ are the circular polarization components whose axis is directed along the magnetic field. The distribution of the optical field along the x axis is a superposition of σ^+-, σ^- —and π-polarized standing waves with a period $\lambda/(2\sin\theta)$. For the case $\beta=\pi/4$, in which we have $\alpha = \arctan(1/\cos\theta)$, σ^+ and σ^- are standing waves which are shifted along the x axis in such a manner that the nodes of one coincide with antinodes of the other. These standing waves form a magnetooptic grating whose "ruling" has a symmetric profile. At $\omega_R = 2\omega_L$ this profile is approximately triangular. The presence of the π component, in addition to the σ^+ and σ^- components, leads to a local perturbation of the dressed state, which is adiabatically populated by atoms initially in the ground state. If the angle θ is small, however, the intensity of the π-polarized field will be lower by a factor $\simeq\theta^2$ than the intensities of the σ^+ and σ^- components, and the corresponding perturbation will be negligible.

Let us examine the advantages conferred by a magnetooptic grating with a larger period. In the first place, an n-fold increase in the period leads to an n-fold decrease in the width of the transverse momentum distribution of the split parts of the atomic beam [see (1)]. If only a single period of this grating is used (i.e., if we work with a magnetooptic biprism), we eliminate the interference structure inside the diffraction envelope of the momentum distribution of the two parts of the atomic beam. Second, an increase in the size of a magnetooptic biprism to a factor of n greater than the period of the magnetooptic grating makes it possible to increase, again by a factor of n, the maximum splitting of the atomic beam, which is determined by the limit of Raman–Nath conditions.

Figure 2 compares the momentum distribution of atoms split by the magnetooptic grating and by a magnetooptic biprism with a dimension 5λ ($\theta=0.1$) along the x axis. In each case we used an ideal triangular shape for the magnetooptic potential. For a magnetooptic grating a splitting of the atomic beam by an amount $p_x=\pm 40\hbar k$ is realized if the atoms interact with the field for a time $\tau=10\cdot 2\pi/\omega_R$. Achieving the same splitting by means of the magnetooptic prism requires a time $\tau=10\cdot 2\pi/\omega_R \sin\theta$. At a fixed interaction time τ, attaining the same splitting in the case of a magnetooptic biprism requires a Rabi frequency greater by a factor of $1/\sin\theta$ than in the case of a magnetooptic grating. The reason is that in the case of the biprism an individual event of a reradiation of a photon between the light waves making up the biprism imparts a momentum of $2\hbar k \sin\theta$ to the atom, while the corresponding momentum in the case of a magnetooptic grating is $2\hbar k$.

An ideal candidate for magnetooptic splitting is the atom ^{40}Ca, which has the transition $J=0 \rightarrow J'=1$ ($^1S_0 \rightarrow {}^3P_1$) with a wavelength $\lambda=657.46$ nm. The long lifetime ($\tau=0.4$ ms) of the $^3P_1$ state makes this an ideal transition for achieving a coherent interaction of the Ca atom with electromagnetic radiation. In addition, the Ca atom has an intense $^1S_0 \rightarrow {}^1P_1$ transition ($\lambda=423$ nm), which makes it possible to carry out effective laser cooling of the atomic beam.[4] What splitting could we achieve for a beam with a velocity $v=40$ m/s? We assume that the diameter of the laser beams forming the magnetooptic biprism is 20 μm. In this case the duration of the interaction of the atoms with the field is $\tau=0.1$ μs. This duration is about three orders of magnitude shorter than the lifetime of the $^3P_1$ excited state, so the interaction of the atoms with the laser field would be highly coherent. A power level of 200 mW for each of the laser beams forming the magnetooptic biprism would lead to a Rabi frequency $\omega_R=1.4\times 10^9$ s^{-1}. For an angle $\theta=0.1$ the momentum splitting of the atomic beam by the magnetooptic biprism,

$$p_x=\pm 4(\omega_R/2\pi)\tau\sin\theta\cdot\hbar k, \tag{3}$$

is $p_x\simeq \pm 44.4\hbar k$, and the width of each of the split parts is $\Delta p_x=0.4\hbar k$. The corresponding splitting angle is 3.3×10^{-2} rad! It would be essentially impossible to achieve such an angular splitting of atoms by means of an ordinary magnetooptic grating without deviating from Raman–Nath conditions.

Figure 3 shows a possible layout of an atomic interferometer using a magnetooptic biprism. This interferometer uses atomic mirrors based on surface light waves. A second magnetooptic biprism is used to reduce the angle between the directions of the components of the atomic beam, in order to give the interference pattern a macroscopic period. This interferometer has the advantages that there is no loss of atoms, the transverse area of the interferometer is large, and there is a macroscopic spatial separation of the arms of this interferometer. An interferometer of this sort, with a distance of 20 cm between the magnetooptic biprisms, would have arms separated by 3.3 mm. The total area of this interferometer would be 3.3 cm^2, so its sensitivity to the Sagnac effect[5] would be sufficient to detect the rotation of the earth!

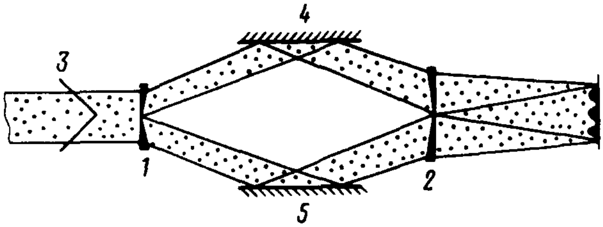

FIG. 3. Schematic diagram of an atomic interferometer using magnetooptic biprisms (1 and 2); 3—atomic beam; 4, 5—atomic mirrors.

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