λ/8-period optical potentials

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A Raman configuration consisting of two pairs of counterpropagating traveling wave fields is shown to lead to optical potentials having λ/8 periodicity. Such optical potentials may be used to construct optical lattices having λ/8 periodicity. Using numerical diagonalization, we obtain the optical potentials for ^{85}Rb atoms.

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Recently, we proposed a method for producing atom gratings having λ/4 periodicity, where λ is the wavelength of the radiation field driving the optical transitions [1]. The method is based on Raman transitions that are simultaneously driven by two pairs of counterpropagating waves. Usually, atom interactions with counterpropagating resonant fields lead to atom gratings having overall periodicity λ/2. A number of techniques have been developed to reduce this periodicity, such as harmonic suppression [2–7], fractional Talbot effect [8,9], atom lens filtering [10,11] and large-angle beam splitters [12–18], but the basic starting point is the λ/2 periodicity atom gratings. The scheme considered in Ref. [1] allows one to reduce this fundamental periodicity to λ/4; the methods referred to above can then be used to reduced this periodicity even further. In this brief report, we show that the basic Raman geometry leads to optical potentials having λ/8 periodicity.

The atom-field geometry of the Raman scheme is depicted in Fig. 1. One needs *two* pairs of counterpropagating fields. Each pair of fields, labeled by the subscript $j=1,2$, itself consists of a pair of counterpropagating fields labeled by the subscript $\alpha=1$ or 2. The value $\alpha=1$ corresponds to a field that drives transitions $|G,m_g\rangle \leftrightarrow |H,m_h\rangle$ and the value $\alpha=2$ corresponds to a field that drives transitions $|G',m_g'\rangle \leftrightarrow |H,m_h\rangle$, where H,m_h are angular momenta and Zeeman quantum numbers of the excited state hyperfine manifold and G,m_g and G',m_g' are angular momenta and Zeeman quantum numbers of two ground-state hyperfine manifolds, separated by frequency $\omega_{G'G}$. Field $\mathbf{E}_{\alpha j}=\mathbf{E}_{11}$ corresponds to a field in the first Raman pair that drives $G\leftrightarrow H$ transitions, field $\mathbf{E}_{21}$ corresponds to a field in the first Raman pair that drives $G'\leftrightarrow H$ transitions, field $\mathbf{E}_{12}$ corresponds to a field in the second Raman pair that drives $G\leftrightarrow H$ transitions, and field $\mathbf{E}_{22}$ corresponds to a field in the second Raman pair that drives $G'\leftrightarrow H$ transitions. Each pair of Raman fields produces two-quantum transitions $|G,m_g\rangle \leftrightarrow |G',m_g'\rangle$ and the Raman detuning δ is the same for each pair of fields. However, a critical assumption of the model is that the different pairs of Raman fields cannot interfere on single-photon transitions, e.g., the excited state population in the H manifold has no interference term associated with fields $\mathbf{E}_{11}$ and $\mathbf{E}_{12}$ and no interference term associated with fields $\mathbf{E}_{21}$ and $\mathbf{E}_{22}$. This can be accomplished in a number of ways—fields $\mathbf{E}_{11}$ and $\mathbf{E}_{12}$ can have different frequencies, different polarizations, or random frequency noise. Even though interference on single-photon transitions is suppressed, the pairs of Raman fields can interfere and act as a *standing-wave Raman field* in driving transitions between states G and G'. If the fields propagate along the z axis and if second Raman pair counterpropagates relative to the first, one is led to a transition amplitude evolving as $\cos(2kz)$ and an atomic density having λ/4 periodicity.

Gratings involving Raman transition have been analyzed [19–22] for the case of standing-waves acting on the each optical transition. Owing to the spatially modulated ac-Stark shifts of the atomic levels, one can achieve in this case only λ/2 overall periodicity. Our geometry is different. Since the fields do not interfere on single-photon transitions, the λ/2 periodicity is suppressed.

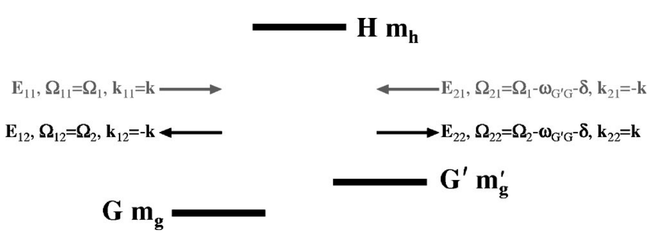

FIG. 1. Basic Raman configuration.

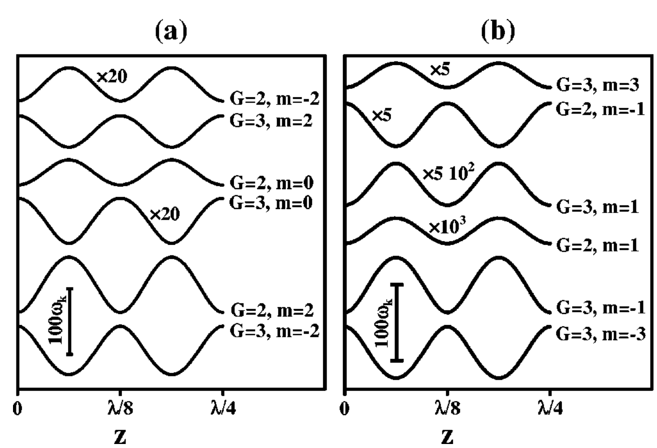

FIG. 2. Two groups of λ/8-period potentials produced on the transition between $G=2$ and $G=3$ hyperfine sublevels of ^{85}Rb atoms, corresponding to the subsystems with even (a) and odd (b) magnetic quantum numbers. The magnetic quantum numbers correspond to the potentials in the limit that the optical fields approach zero.

TABLE I. Average values of the potentials shown in Fig. 2 in units of recoil frequency $\omega_k = \hbar k^2/2M$ ($M = {}^{85}$Rb mass).

$G=3,\ m=-2$	$G=2,\ m=2$	$G=3,\ m=0$	$G=2,\ m=0$	$G=3,\ m=2$	$G=2,\ m=-2$
−744	−282	−22	4360	4804	12781
$G=3,\ m=-3$	$G=3,\ m=-1$	$G=2,\ m=1$	$G=3,\ m=1$	$G=2,\ m=-1$	$G=3,\ m=3$
−721	344	−4	−3	8983	12077

In our previous article [1], we showed that the periodicity of the atom gratings could be reduced to $\lambda/8$ if one pair of Raman fields is lin⊥lin (perpendicular) polarized and the other is lin‖lin (parallel) polarized, e.g.,

$$\mathbf{E}_{11} \| \mathbf{E}_{12} \| \mathbf{E}_{22} \perp \mathbf{E}_{21}. \tag{0.1}$$

This result is the Raman analogue of the conventional lin⊥lin polarized field geometry for electronic transitions, which, in the far-detuned case, leads to the $\lambda/4$-period atom gratings [23] and optical lattices [24]. The calculations of Ref. [1] were aimed mainly at situations involving atom scattering in the Raman-Nath approximation; however, it was pointed out in that article that the formalism could also be applied to *cw* optical fields.

To illustrate this possibility, we proceed to calculate the optical potentials for ^{85}Rb when the field polarizations are given by Eq. (0.1). The resulting optical potentials have $\lambda/8$ periodicity and may enable one to construct optical lattices having this periodicity. By diagonalizing numerically the Hamiltonian derived in Ref. [1], we obtain the optical potentials associated with the $G=2,3$ ground-state hyperfine manifolds of ^{85}Rb. The results of the calculations are shown in Fig. 2 and Table I. The optical potentials have been displaced to fit on a single graph—mean values for each of the potentials are listed in the Table.

If the quantization axis is chosen along the wave vectors, the selection rule for two-quantum transitions is $\Delta m_g = 0, \pm 2$, implying that subsystems having even and odd Zeeman quantum numbers are decoupled from one another, and can be diagonalized independently. We assume that all fields drive only D_2 transitions in ^{85}Rb, such that the electronic angular momenta for ground and excited states are $J_G = 1/2$ and $J_H = 3/2$. We choose field detunings Δ_{1j} for $|G=2\rangle \leftrightarrow |H=1\rangle$ transitions as $\Delta_{11} = 2\pi \times 40$ MHz and $\Delta_{12} = 2\pi \times 61$ MHz (both detunings between the $H=2$ and $H=3$ excited state hyperfine levels), Poynting vectors $S_{\alpha j} = 0.2$ W/cm^2, and a Raman detuning $\delta = 2\pi \times 1.0$ MHz. The eigenstate for each potential is a z-dependent mixture of magnetic sublevels belonging to the different hyperfine manifolds. Each eigenstate maps into a single magnetic substate only when one turns off the fields. Even in this case identification of the potentials is a problem, since magnetic sublevels for different manifolds are degenerate. To overcome this problem we insert a small $\sim 2\pi \times 10$ kHz equidistant splitting of the sublevels. Following the smooth dependence of the potentials' positions and amplitudes as the fields' Poynting vector is reduced to $S_{\alpha j} = 20\ \mu$W/cm^2, we can assign in Fig. 2 the asymptotic identification of each potential curve with a specific magnetic state sublevel.

It is not always possible to produce $\lambda/8$ period optical potentials using the field polarizations given in Eq. (0.1). In certain limiting cases, the potentials are flat for these polarizations. For example, if one detunes far from each hyperfine transition, fields $\mathbf{E}_{11}$ and $\mathbf{E}_{21}$ do not drive Raman transitions [see Eq. (11) of Ref. [1]] and no interference between the different pairs of Raman fields is possible. Also for transitions such as $G,G',H = 1,2,1$ or $G,G',H = 1,2,2$ the fact that the transition matrix elements vanish between states having the same angular momentum and $m=0$ suppresses interference between the different pairs of Raman fields. This implies that the optical potentials for ^{87}Rb are flat with the field polarizations given in Eq. (0.1).

The possibility to produce optical potentials having a depth of a 100 recoil energy shifts with available laser sources suggests that $\lambda/8$-period optical lattices could be constructed using the Raman technique. It remains to calculate diffusion losses and nonadiabatic coupling to determine the equilibrium spatial distribution of atoms in these potentials.

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