Atom waveguide and 1D optical lattice using a two-color evanescent light field around an optical micro/nano-fiber

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We propose a two-color scheme of atom waveguides and one-dimensional (1D) optical lattices using evanescent wave fields of different transverse modes around an optical micro/nano-fiber. The atom guide potential can be produced when the optical fiber carries a red-detuned light with TE_{01} mode and a blue-detuned light with HE_{11} mode, and the 1D optical lattice potential can be produced when the red-detuned light is transformed to the superposition of the TE_{01} mode and HE_{11} mode. The two trapping potentials can be transformed to each other for accurately controlling mode transformation for the red-detuned light. This might provide a new approach to realize flexible transition between the guiding and trapping states of atoms.

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The last few years have seen an increasing interest in the design of neutral-atom nano traps and guides with optical planar waveguides and fibers. Neutral-atom traps and guides can be used as tools for atom interferometry[1,2], integrated atom optics[3−5], and quantum computation[6,7]. The idea of using evanescent waves (EW) to provide both attractive (red-detuning) and repulsive (blue-detuning) forces is proposed by Ovchinnikov *et al.*[8]. He proposed using two-color (i.e., red and blue detunings) EWs and differing evanescent decay lengths to achieve an atom trap departing from a prism surface. Barnett *et al.*[9] proposed a two-color scheme to trap atoms using an EW above a single-mode, submicron optical channel waveguide. In the proposal, two polarizations are used to enlarger the differing evanescent decay lengths of the two-color lights[10]. Recently, a method for trapping and guiding neutral atoms outside an optical micro/nano-fiber has been proposed[11,12]. Due to the small thickness of the fiber[13], far-off-resonance lights with substantially differing evanescent decay lengths can be used to produce a net trapping potential with a deeper minimum, larger coherence time and trap lifetime. It is interesting that high-order transverse modes carried in a micro/nano-fiber can provide much larger evanescent decay length differences and their EW fields can be used to produce an optical lattice potential resulting from the interference of these different transverse modes[14,15].

In this paper, we proposed a two-color atom guide and one-dimensional (1D) optical lattice scheme based on evanescent light fields of different transverse modes around an optical micro/nano-fiber. The atom guide potential can be produced when the optical fiber carries a red-detuned light with TE_{01} mode and a blue-detuned light with HE_{11} mode. By using the interference of the first-order TE_{01} mode and the fundamental HE_{11} mode, we produced two 1D optical lattices along the optical fiber.

It is well known that atoms in a near-resonant laser field of frequency ω can be exerted on a conservative force and a dissipative force. These forces, which are the results of momentum conservation in the absorption and reemission of photons, make different contributions to trapping atoms. The atom trapping potential is derived from the conservative force due to stimulated exchange of photons, whereas the dissipative force due to spontaneous photon emission is a mechanism for the loss of atoms from a trapping potential. The conservative force is the gradient of a spatially dependent potential $U_{\text{opt}}(x,y,z)$ which can be expressed as the time-averaged induced dipole interaction energy in the electric field. The dipole potential $U_{\text{opt}}(x,y,z)$ for large detuning from resonance, $\Delta=\omega-\omega_0$ (Δ is greater than the excited state hyperfine splitting, but is much less than the atom transition frequency ω_0), is given by

$$U_{\text{opt}}(x,y,z)=\frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta}I(x,y,z), \tag{1}$$

where the spontaneous decay rate of the excited state is $\Gamma=\left(\omega_0^3/3\pi\varepsilon_0\hbar c^3\right)\left|\langle e|\,\mu\,|g\rangle\right|^2$, $\langle e|\,\mu\,|g\rangle$ is the dipole transition matrix element between ground state $|g\rangle$ and excited state $|e\rangle$, $I(x,y,z)$ is the spatially dependent laser intensity, c is the light velocity and ε_0 is the vacuum dielectric constant. An important character for dipole trapping is immediately obvious from Eq. (1), that is the sign of the detuning Δ determining whether the potential is repulsive ($\Delta>0$, blue detuning) or attractive ($\Delta<0$, red detuning). Atoms in blue-detuned light are pushed towards the minimum of the field, whereas in red-detuned light the atoms are attracted towards the maximum of the field. Then we obtain the net dipole potential $U_{\text{opt}}(x,y,z)$ for the two-color light fields,

$$\begin{aligned}U_{\text{opt}}(x,y,z)&=U_{\text{opt}}^{(\text{b})}(x,y,z)+U_{\text{opt}}^{(\text{r})}(x,y,z)\\&=\frac{3\pi c^2\Gamma}{2\omega_0^3}\left[\frac{I_{\text{blue}}(x,y,z)}{|\Delta_{\text{blue}}|}-\frac{I_{\text{red}}(x,y,z)}{|\Delta_{\text{red}}|}\right],\end{aligned} \tag{2}$$

where $U_{\text{opt}}^{(\text{b})}$, $U_{\text{opt}}^{(\text{r})}$ are the dipole potentials and I_{blue}, I_{red} are the spatially dependent optical intensities for the blue- and red-detuned lights, respectively.

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Atoms near the surface of a medium undergo an atom-surface potential. The atom-surface potential $U_{\rm surf}$ is mainly contributed form for Van Der Waals force. The Van Der Waals potential of atoms near the surface of a cylindrical dielectric rod is given by[11,12]

$$U_{\rm surf}(r) = \frac{\hbar}{4\pi^3\varepsilon_0}\sum_{n=-\infty}^{\infty}\int_0^{\infty}{\rm d}k[k^2K_n'^2(kr)$$

$$+(k+n/r)K_n^2(kr)]\int_0^{\infty}{\rm d}\xi\alpha(i\xi)G_n(i\xi), \quad (3)$$

where

$$G_n(\omega) = \frac{[\varepsilon(\omega)-\varepsilon_0]J_n(ka)J_n'(ka)}{\varepsilon_0 J_n(ka)K_n'(ka)-\varepsilon(\omega)J_n'(ka)K_n(ka)}, \quad (4)$$

where $\varepsilon(\omega)$ is the dynamical dielectric function, J_n is the modified Bessel function of the first kind, and K_n stands for the modified Bessel function of the second kind.

As shown in Fig. 1, our proposal is to utilize the different evanescent decay lengths of the fundament HE_{11} mode and the first-order TE_{01} mode carried in a dual-mode optical fiber. The optical fiber carries a red-detuned light with the TE_{01} mode and a blue-detuned light with the HE_{11} mode far from resonance. In this paper, we consider trapping ground-state Cs atoms. The ground-state Cs atoms have two strong transitions, 852 nm (D_2 line) and 894 nm (D_1 line). To trap the atoms, we use red- and blue-detuned lights with wavelengths $\lambda_{\rm red} = 1.06$ μm and $\lambda_{\rm blue} = 700$ nm, respectively. The detunings of the lights from the dominant D_2 line of the atoms are $\Delta_1/(2\pi) = -69$ THz and $\Delta_2/(2\pi) = 76$ THz[11,12], respectively. The total trapping potential U of the atoms is the sum of the net optical potential $U_{\rm opt}$ and the atom-surface potential $U_{\rm surf}$,

$$U(x,y,z) = U_{\rm opt} + U_{\rm surf}. \quad (5)$$

In our scheme, a dual-mode optical fiber is employed to carry the red- and blue-detuned light fields. The fiber diameter and refractive index are carefully selected to guarantee that there are exactly two guide modes: the fundamental mode HE_{11} and the first high-order mode TE_{01} for the red-detuned light. The discussion of the cutoff condition for guide modes has been presented in many places[16]. Here we investigated an optical nanofiber fabricated in refractive index $n_1 = 1.46$ and an infinite vacuum clad of refractive index $n_2 = 1$. According to the cutoff condition, we appropriately tailored its diameter, for example $a = 0.82$ μm, which is large enough to carry the lowest two modes (the HE_{11} and TE_{01} modes in our case) for the red-detuned light (1.06 μm), yet small enough to cutoff higher-order modes than the TE_{01} mode.

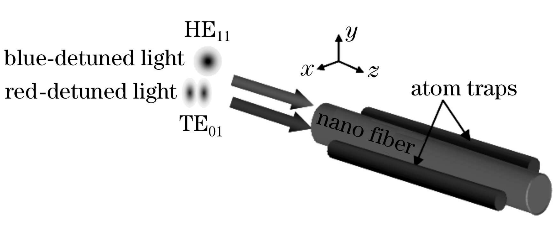

Fig. 1. Two-color scheme for atom guides.

It is noticeable that the evanescent fields for the transverse modes provide a large difference of evanescent decay lengths. By using the full-vector finite element numerical simulation[10], we obtain the normalized intensity distributions in x-y plane (as shown in Fig. 2), and the propagation constants $\beta_0 = 7.6104 \times 10^6$ m^{-1} and $\beta_1 = 6.0765 \times 10^6$ m^{-1}, respectively for the HE_{11} and TE_{01} modes. The maximal value of the intensity distribution of the HE_{11} mode is at the center of the waveguide, but the maximal values of the TE_{01} mode are near the edges of the waveguide. This leads to substantially different evanescent waves of the two modes. In order to quantify the difference, we calculated the evanescent decay lengths for the TE_{00}, TM_{00} and TE_{01} modes as a function of light wavelength λ, as shown in Fig. 3. Apparently, a larger decay-length difference can be obtained

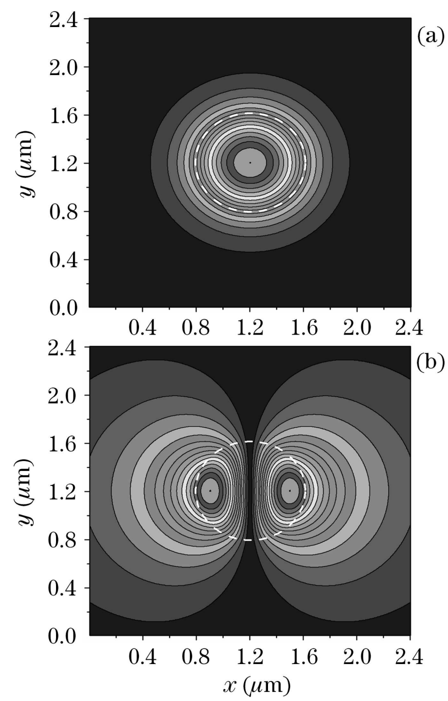

Fig. 2. Normalized intensity distributions in x-y plane for (a) the HE_{11} mode and (b) the TE_{01} mode for the light $\lambda_{\rm red} = 1.06$ μm, where the dashed lines denote the geometry of the fiber ($a = 0.82$ μm) as shown in Fig. 1.

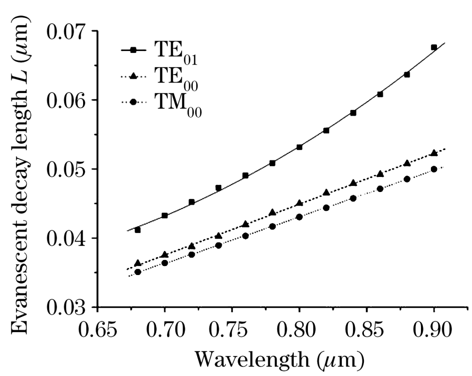

Fig. 3. Evanescent decay lengths for the TE_{00}, TM_{00} and TE_{01} modes as a function of light wavelength, where L are the characteristic lengths for the exponential decay electric fields $E \propto {\rm e}^{-y/L}$.

than that for the case of different polarizations carried in a single-mode optical waveguide[10]. In general, a larger difference in decay lengths will provide a stronger trap for a given laser power as well as a smaller spontaneous decay rate at a given trap depth and detuning.

We use Eqs. (2), (3), and (5) to calculate the total potential U_{tot} of the ground-state Cs atoms. In Fig. 4, we present an example of a two-dimensional (2D) trapping potential in x-y plane and y-z plane outside the optical waveguide. Assuming an input of 4 mW of the red-detuned light (TE_{01}, 1.06 μm) and 50 mW of the blue-detuned light (HE_{11}, 700 nm), we find a potential minimum $x_{\min} \approx 0.174$ μm departed from the waveguide surface with trapping depths of $U_{\mathrm{D}} \approx 363.1$ μK. In the trapping potential, atoms are confined in x and y dimensions and freely propagate in z direction. We estimated some critical trapping parameters for the case of Fig. 4. The rates of scattering due to the trapping fields at the potential minimum are $\Gamma_{\mathrm{sc}}^{(\mathrm{r})} \approx 4.9$ s^{-1} and $\Gamma_{\mathrm{sc}}^{(\mathrm{b})} \approx 1.3$ s^{-1} for the red- and blue-detuned light fields, respectively. The light scattering rate $\Gamma_{\mathrm{sc}} \approx 6.2$ s^{-1} and the coherence time $\tau_{\mathrm{coh}} \approx 161.5$ ms can be obtained. Due to the recoil heating $E_{\mathrm{r}}^{(\mathrm{r})} = 0.064$ μK, $E_{\mathrm{r}}^{(\mathrm{b})} = 0.147$ μK for the red- and blue-detuned lights respectively, we characterize the trap lifetime $\tau_{\mathrm{trap}} \approx 361.88$ s for the trap depth $U_{\mathrm{D}} \approx 363.1$ μK.

Next, we discuss the scheme to produce 1D lattices utilizing evanescent fields of the red-detuned light with a superposition of the HE_{11} and TE_{01} modes. From the mode field analysis, we know that the fundamental mode HE_{11} is even mode and the first-order mode TE_{01} is odd mode. We can express arbitrary optical fields carried in the dual-mode optical field as a superposition of the HE_{11} and TE_{01} modes,

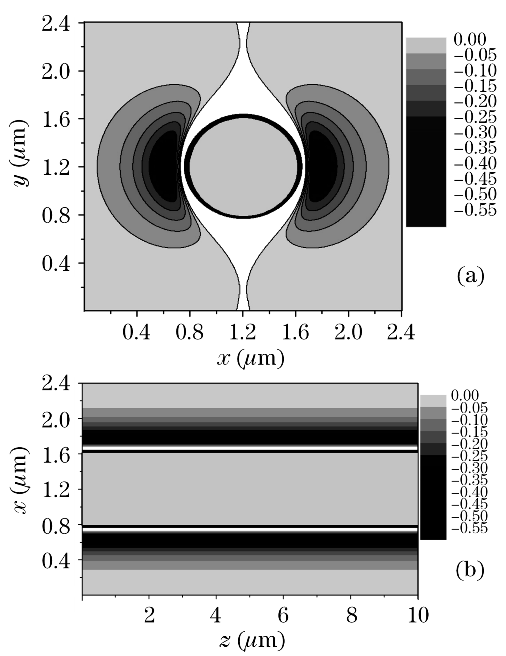

Fig. 4. Two-color trapping potentials of atom guides in (a) x-y plane and (b) x-z plane. The waveguide structure are shown in Fig. 1. A maximum trapping depth of 363.1 μK is achieved using 4-mW red light (TE_{01}, 1.06 μm) and 50-mW blue light (HE_{11}, 700 nm).

$$\phi(r,\varphi,z) = C_0 E_0(r,\varphi)\,\mathrm{e}^{i(\beta_0 z+\theta_0)} + C_1 E_1(r,\varphi)\,\mathrm{e}^{i(\beta_1 z+\theta_1)}, \tag{6}$$

where $E_0(r,\varphi)$ and $E_1(r,\varphi)$ are the electric-field components, θ_0 and θ_1 are the phases for HE_{11} and TE_{01} modes, respectively. Then, the optical intensity distribution of the mode superposition can be obtained,

$$\begin{aligned} I(x,y,z) &= \frac{1}{2}\varepsilon_0 c\phi(r,\varphi,z)\,\phi^*(r,\varphi,z) \\ &= \frac{1}{2}\varepsilon_0 c[|C_0|^2|E_0(r,\varphi)|^2 + |C_1|^2|E_1(r,\varphi)|^2 \\ &\quad + C_0C_1^*E_0(r,\varphi)\,E_1^*(r,\varphi)\,\mathrm{e}^{i(\Delta\beta z+\Delta\theta)} \\ &\quad + C_0^*C_1E_0^*(r,\varphi)\,E_1(r,\varphi)\,\mathrm{e}^{-i(\Delta\beta z+\Delta\theta)}], \end{aligned} \tag{7}$$

with the propagation constant difference $\Delta\beta = \beta_0 - \beta_1$ and the relative phase $\Delta\theta = \theta_0 - \theta_1$. The last two terms in Eq. (7) result from the coherent superposition of the two modes, which contain a periodic function of z (the propagation direction). This leads the intensity distribution to periodically vary (a fringe pattern) along the propagation direction.

In order to produce 1D lattice potentials, we utilize the red-detuned light excited in the superposition of the HE_{11} and TE_{01} modes and the blue-detuned light excited in the HE_{11} mode. The intensity distribution of red-detuned light introduces two attractive potentials periodically varying along the propagation direction z that form two 1D lattices. We numerically simulate the propagation of the red-detuned light in superposition of the HE_{11} and TE_{01} modes by using the finite differential beam propagation method[17−19]. The intensity distribution varies periodically along the propagation direction z with a period of $2\pi/\Delta\beta = 4.096$ μm. Assuming the input powers and wavelengths of the red- and blue-detuned lights to be the same as the atom guides, we present an example of the 1D lattice in Fig. 5. A series of periodical potential minimums along z can be found at $x_{\min} \approx 0.144$ μm departed from the waveguide surface with trapping depths of $U_{\mathrm{D}} \approx 378.9$ μK and the variation period is the same as the variation period 4.096 μm of the intensity distribution. Further, we obtain the trapping potential distributions in x-y plane at three different positions along z with the results shown in Fig. 6. Apparently, the trapping potentials provide three-dimensional (3D) atom confinements.

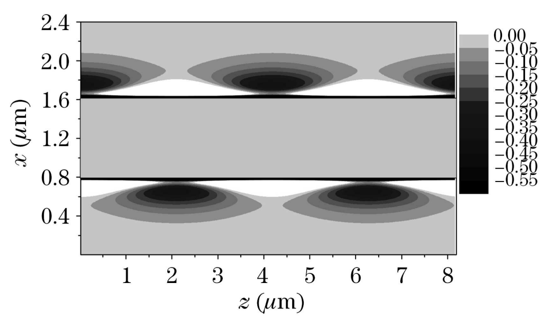

Fig. 5. A trapping potential of the 1D optical lattice periodically varying along the z direction.

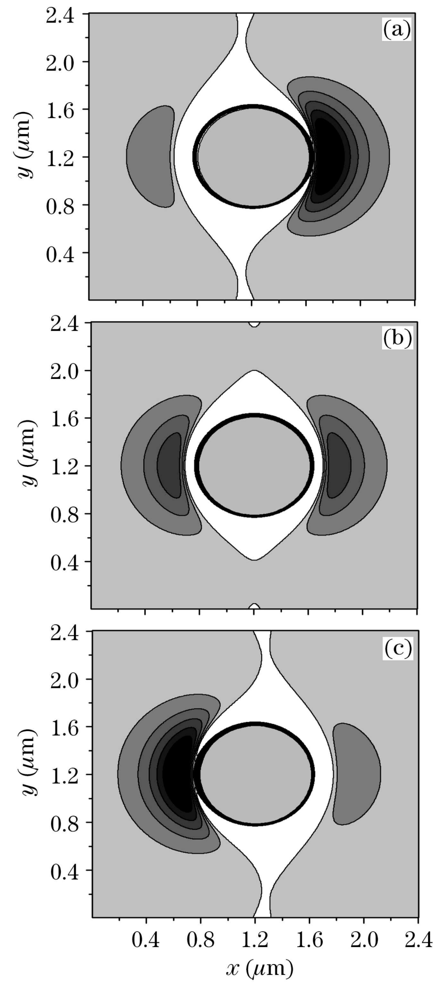

Fig. 6. Trapping potential distributions in x-y plane at (a) $z = 0$ μm, (b) $z = 1.024$ μm, (c) $z = 2.048$ μm.

In this paper, we discussed two-color atom guides and optical lattice schemes using evanescent light fields of high-order transverse modes carried in a micro/nano fiber. Due to substantially differing evanescent decay length, we can produce a net trapping potential with deeper minimum, larger coherence time and trap lifetime than other single-mode schemes. By using a dual-mode waveguide Mach-Zehnder interferometer (MZI), we can accurately control mode transformation between HE_{11} and TE_{01} modes[14]. The mode transformation provides a new approach to realize flexible transition between the atom guides and 1D optical lattices, which would be desired in applications such as atom interferometer and quantum information.

It is interesting to mention that large decay-length differences provided by different transverse modes may greatly increase the robustness of the two-color trap to light scattered by defects, junctions, etc. in the fibers.

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References

1. C. S. Adams, M. Sigel, and J. Mlynek, Phys. Rep. **240,** 143 (1994).
2. M. A. Olshanii, Laser Phys. **4,** 995 (1994).
3. D. Cassettari, B. Hessmo, R. Folman, T. Maier, and J. Schmiedmayer, Phys. Rev. Lett. **85,** 5483 (2000).
4. D. Müller, E. A. Cornell, M. Prevedelli, P. D. D. Schwindt, A. Zozulya, and D. Z. Anderson, Opt. Lett. **25,** 1382 (2000).
5. W. Hänsel, J. Reichel, P. Hommelhoff, and T. W. Hänsch, Phys. Rev. Lett. **86,** 608 (2001).
6. T. Calarco, H.-J. Briegel, D. Jaksch, J. I. Caral, and P. Zoller, J. Mod. Opt. **47,** 2137 (2000).
7. D. Frese, B. Veberholz, S. Kuhr, W. Alt, D. Schrader, V. Gomer, and D. Meschede, Phys. Rev. Lett. **85,** 3777 (2000).
8. Y. B. Ovchinnikov, S. V. Shul'flga, and V. I. Balykin, J. Phys. B **24,** 3173 (1991).
9. A. H. Barnett, S. P. Smith, M. Olshanii, K. S. Johnson, A. W. Adams, and M. Prentiss, Phys. Rev. A **61,** 023608 (2000).
10. J. P. Burke, J. S.-T. Chu, G. W. Bryant, C. J. Williams, and P. S. Julienne, Phys. Rev. A **65,** 043411 (2002).
11. F. L. Kien, V. I. Balykin, and K. Hakuta, Phys. Rev. A **70,** 063403 (2004).
12. F. L. Kien, V. I. Balykin, and K. Hakuta, Phys. Rev. A **73,** 053823 (2006).
13. L. M. Tong, R. R. Gattass, J. B. Ashcom, S. He, J. Y. Lou, M. Y. Shen, I. Maxwell, and E. Mazur, Nature **426,** 816 (2003).
14. K. Christandl, G. P. Lafyatis, S.-C. Lee, and J.-F. Lee, Phys. Rev. A **70,** 032302 (2004).
15. J. Fu, X. Yin, and L. Tong, arXiv quant-ph 0704.3460 (2007).
16. D. Marcuse, *Theory of Dielectric Optical Wave Guides* (Academic Press, New York, 1991).
17. D. Yevick and B. Hermansson, IEEE J. Quantum Electron. **26,** 109 (1990).
18. W. P. Huang, C. L. Xu, S.-T. Chu, and S. K. Chaudhuri, J. Lightwave Technol. **10,** 295 (1992).
19. A. Locatelli, F.-M. Pigozzo, D. Modotto, A.-D. Capobianco, and C. D. Angelis, IEEE J. Sel. Top. Quantum Electron. **8,** 440 (2002).