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ABSTRACT
The inhomogeneous potential residual field is the main impediment that prevents atomic samples from reaching sub-nanokelvin temperatures in deep cooling experiments. In this study, we propose a method to reduce the potential inhomogeneity using a pair of perpendicular spatially modulated laser beams. Two 2D distributions have been calculated by decomposing the required 3D compensation field and generated by employing Fourier optical systems. The proposed approach can be used to experimentally investigate Efimov physics in ultracold K-Rb mixtures.

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I. INTRODUCTION
Significant experimental effort has been made toward realizing low temperatures to observe phenomena that occur at extremely low energy scales, such as phase transition to new forms of matter.1,2 Currently, adiabatic decompression or delta-kick cooling is used to realize sub-nanokelvin temperatures in atomic samples.3,4 Inhomogeneous external fields, particularly inhomogeneous magnetic fields, hinder atomic samples from attaining such low temperatures and undergo a long time-evolution.5 In the case of boson, atoms can be coherently transformed into magnetically insensitive hyperfine states to circumvent the adverse effects of inhomogeneous magnetic fields. However, many experiments require the atoms to be in magnetically sensitive hyperfine states. Moreover, fermion has no magnetically insensitive hyperfine state.

In our future research, we plan to experimentally investigate Efimov physics with an ultracold 87Rb and 40K mixture,6 in which both kinds of atoms are in magnetically sensitive hyperfine states and the temperature of the atomic sample is on the order of several hundred picokelvins. Even weak inhomogeneity of the magnetic field can cause the experiment to fail if no measure is adopted to cancel the inhomogeneous potential. Magnetic shielding can reduce the residual magnetic fields drastically but is inapplicable in our future experiment. In this experiment, a magnetic field up to 547 G is needed since we have to use the magnetic Feshbach resonances to tune the scattering length between atoms.2 The coils for generating the magnetic field must be installed inside the magnetic shielding. Evidently, the shielding is not advantageous in improving the homogeneity of the magnetic field, which originates from the coils.

Using external fields to eliminate the potentials from inhomogeneous magnetic fields is an intuitive approach to solving this problem. Attaching coils, such as macroscopic coils or coils formed by etching wires on an atomic chip,7 to compensate inhomogeneous potentials is a common technique. However, this method can be used only for specific inhomogeneous magnetic fields, and...
it often blocks the optical channels of the system. Furthermore, an optical dipole potential generated by a far-detuned laser field can also compensate inhomogeneous potentials. Theoretically, three-dimensional (3D) computational holography\textsuperscript{10} can be utilized to construct the required light field. However, this method is difficult to implement due to the geometrical restrictions of experimental devices.

Therefore, in this study, we demonstrate an alternative method to compensate inhomogeneous potential fields. The basic principle is to construct the required 3D intensity distribution using a pair of orthogonal spatially modulated laser beams. Our calculations indicate that the field uniformity is improved by two orders of magnitude after compensation. Although we only discussed employing the amplitude modulation (AM) and phase modulation (PM) plates in the Fourier optical system, other phase-type diffraction optical elements such as spatial light modulators can be used once the required phase distribution is determined. The time-average method using acoustic optical modulators is another approach to provide such a compensating potential. Although the time-average method provides a smoother compensating potential, it requires accurate and high-speed control of the two-dimensional (2D) diffraction angles and laser power.

II. DECOMPOSING A 3D INTENSITY DISTRIBUTION

Once the required 3D intensity distribution is decomposed into a combination of 2 orthogonal 2D intensity distributions, the 2D intensity distributions can be conveniently realized using a pair of square-crossing spatially modulated laser beams. Here, two important points need to be addressed: the existence of such decomposition and the efficient algorithm to find the optimized decomposition.

Although no certain answer is available to the first point, in actuality, a high-accuracy approximate decomposition is possible due to the symmetry of the magnetic field; in this case, quadratic programming is an efficient tool to realize decomposition. We will discuss the magnetic field generated by current in a pair of macroscopic coils (as shown in Fig. 1), which have been described previously in detail\textsuperscript{9}, as an example.

The magnetic field generated by each coil is calculated using complete elliptic integrals, following which all are accumulated.\textsuperscript{11} The magnetic strength is 546.9972 G at the geometric center at a current of 20.3 A. The maximum variation $|\Delta B|$ of the magnetic strength is 274.9 mG in a cubic space of $\pm 0.5$ mm. Because the geometric center is the saddle point of the magnetic field, atoms can escape a weak trap if a compensation field is not present.

Next, we use quadratic programming to decompose the 3D distribution into a combination of two orthogonal 2D distributions. The 3D distribution $t(x_n, y_n, z_n)$ is the original magnetic field subtracting a uniform base of 546 G. We slice the $t(x_n, y_n, z_n)$ into a series of discrete $t_n(x_n, y_n)$ along different $z_n$. Quadratic programming is employed to seek the optimal solution to decompose $t_n(x_n, y_n)$ into $g_n(x_n) + h_n(y_n)$, which must satisfy the following conditions:

\textbf{FIG. 1.} (a) Wire arrangement of the coils. (b) Configuration of the pair of coils with 900 turns. (c) Magnetic field created by the coils along the z axis. (d) Magnetic field created by the coils along the x axis.

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FIG. 2. (a) Pseudo-color image of the 2D intensity distribution \(g(x_n, z_n)\) after quadratic programming in the \((x, 0, z)\) plane. (b) Pseudo-color image of the 2D intensity distribution \(h(y_n, z_n)\) after quadratic programming in the \((0, y, z)\) plane. (c) Deviation of the magnetic strength between those created by coils and reconstructed with two 2D intensity distributions along the \((0, 0, z)\) plane. (d) Deviation of magnetic strength along the \((x, 0, 0)\) plane.

\[
\begin{align*}
    \min & \sum (g_n(x_n) + h_n(y_n) - t(x_n, y_n))^2, \\
    \text{s.t.} & \begin{cases}
        g_n(x_n) > 0, \\
        h_n(y_n) > 0.
    \end{cases}
\end{align*}
\]

(1)

We use a Matlab program to calculate the two decomposed 2D distributions along the y and x axes based on the built-in function \textit{fmincon}, which can find the minimum of the constrained nonlinear multivariable. Two 2D distributions, \(g(x_n, z_n)\) and \(h(y_n, z_n)\), are obtained, as showed in Figs. 2(a) and 2(b), respectively. The maximum deviation between \(t(x_n, y_n, z_n)\) and \(g(x_n, z_n) + h(y_n, z_n)\) is less than \(2.4091 \times 10^{-3}\) mG, indicating that the relative error is less than \(10^{-5}\). In addition, we plot the deviation between \(t(x_n, y_n, z_n)\) and \(g(x_n, z_n) + h(y_n, z_n)\) along \((0, 0, z)\) and \((x, 0, 0)\), as showed in Figs. 2(c) and 2(d), respectively. Our calculation indicates that decomposition can be realized with negligible errors using quadratic programming.

**III. ESTABLISHING THE REQUIRED 2D LIGHT FIELDS**

Section II discusses about successfully decomposing a 3D distribution into two 2D plane distributions using quadratic programming. In this section, we discuss generating the required 2D optical potential using a Fourier optical system.

First, the intensity distribution of the light field on the rear focal plane of the Fourier optical system must match the decomposed 2D plane intensity distribution. Moreover, a smooth phase distribution on the rear focal plane is crucial because a long diffraction depth of focus is required. In principle, a Fourier optical system with a phase-only spatial modulator can generate the required intensity distribution on the rear focal plane with a highly effective utilization rate of light. Iterative algorithms such as Gerchberg-Saxton or Yang-Gu are needed to optimize the required phase distribution.\(^{13,16}\) However, these algorithms produce random patterns of the iterated phase distribution, leading to random phase relations on the rear focal plane.\(^{17}\) Because the result has highly visible holographic noise and short depth of focus, the phase-only spatial modulation method does not suit our purpose. Thus, the simple solution is to modulate both the amplitude and phase distributions of the light field to generate the required 2D intensity distribution.

Figure 3 shows our proposed scheme. Two laser beams are coupled and transmitted through two polarization-maintaining optical fibers (PMFs). The output surface of the PMF is located at the front focal plane of the collimating lens \(L_1\). The focal length and diameter of \(L_1\) are 11.07 mm and 11.0 mm, respectively; thus, the output Gaussian beam has a waist size of 2.1 mm and a flat phase distribution on the rear focal plane of \(L_1\). An AM and a PM plate are overlapped and located at the rear focal plane of \(L_1\), which is the same location as the front focal plane of the Fourier transform lens \(L_2\). \(L_2\) has a diameter of 25.4 mm and a focal length of 100 mm. The center of the target area is located on the rear focal plane of \(L_2\). A charge-coupled device (CCD) camera with an imaging lens \(L_3\) is used to monitor the light intensity distribution in the target area. To avoid interference between two laser beams during overlapping, two methods can be adopted. One is to create two beams using two independent lasers with a slight difference in wavelength. Alternatively, one laser beam can be divided into two, and the frequency of one can be shifted to the other 100–200 MHz using acousto-optic modulators (AOMs). In this study, we chose the former. In addition, two feedback loops are used to ensure stable and accurate output.
FIG. 3. Schematic of the apparatus. L1—collimating lens, L2—Fourier transform lens, L3—imaging lens of the CCD, AM—amplitude modulation plate, and PM—phase modulation plate. The rear focal plane of L1 coincides with the front focal plane of L2, where the AM and PM are located. The center of the target area is located on the rear focal plane of L2.

laser power. Approximately 5% of the laser beam is reflected by a beam sampler and detected by a photodiode (PD). The error signal is obtained by differencing the photodiode signal and the computer-controlled reference. Then, the error signal is integrated using a proportional-integrator (PI), and the correction signal is applied to the laser current controller or used for the amplitude modulation control of AOMs. Therefore, a relative power noise that is reduced to the order of $10^{-8}$ Hz$^{-1/2}$ in the range 1–100 kHz is achieved.

The external potential field $U$ generated by the inhomogeneous magnetic field is given by

$$U = m_F \cdot \mu_B \cdot g_F \cdot B.$$  \hspace{1cm} (2)

Here, $m_F$ is the magnetic quantum number, $\mu_B$ denotes the Bohr magneton, $g_F$ represents the Lande factor, and $B$ denotes the magnetic strength.

The optical dipole potential $U_{dp}(r)$ is characterized by the intensity $I(r)$,

$$U_{dp}(r) = \frac{\pi^2 \Gamma}{2\omega_0^2} \left( 2 + \frac{p \cdot g_F \cdot m_F}{\Delta_2,F} + \frac{1 - p \cdot g_F \cdot m_F}{\Delta_1,F} \right) I(r).$$  \hspace{1cm} (3)

Here, $p$ is the polarization parameter of trapping light. In this study, we use the linear polarization laser with $p = 0$. $\Delta_{1,F}$ and $\Delta_{2,F}$ are the detunings of trapping light for the lines $D_1$ and $D_2$, respectively.

The wavelength of the laser is 754.3 nm. We will discuss the selection of wavelength in Sec. IV. $\Gamma$ denotes the decay rate between two energy levels, and $\omega_0$ denotes the atomic resonance transition angular frequency.

Once the 2D magnetic strength is obtained using quadratic programming, the required 2D optical field distributions $I_1(x, z)$ and $I_2(y, z)$ are calculated using Eqs. (2) and (3). Because the two light paths are the same, we describe only one here. As an example, we calculate the distribution $I_1(x, z)$ for $^{87}$Rb in the $|F = 1, m_F = 1 \rangle$ state in the inhomogeneous magnetic field at $\Gamma = 2\pi \times 6.0666$ MHz and $\omega_0 = 2\pi \times 384.230484$ THz. The distributions on the front and rear focal planes of L2 are Fourier transforms of each other. Furthermore, we select the central region of 0.4 mm $\times$ 0.4 mm of $I_1(x, 0, z)$, subtract its minimum value for low light intensity and scattering rates, as shown in Fig. 4(a), and embed it in a 4 mm $\times$ 4 mm square. In addition, we assume an identical phase $\pi$ on the plane to ensure a long diffraction depth of focus and then perform the 2D Fourier transform. The intensity distribution of the light

FIG. 4. (a) Required intensity distribution of light in the central region, with the minimum value for low light intensity and scattering rate subtracted. (b) Required intensity distribution on the front focal plane of L2. (c) Required phase distribution on the front focal plane of L2.
field on the front focal plane is obtained by squaring the required amplitude distribution, as shown in Fig. 4(b). Based on the required amplitude distribution and the input Gaussian beam, we obtain the transmissivity distribution of the AM plate, as shown in Fig. 5(a). The required amplitude distribution is generated when a Gaussian laser beam of power 1.8878 W passes through the AM plate. The required phase distribution on the front focal plane of L2 is shown in Fig. 4(c). The phase distribution of the PM plate must be the same as that in Fig. 4(c) because it is flat on the input wavefront. Both of the pixel sizes of AM and PM are 2 μm × 2 μm.

We calculate the light field on the rear focal plane of L2 using a 2D Fourier transform lens by considering the actual errors; in this case, the aperture effect of the lens of diameter 20 mm is considered. For a realistic calculation, we add 1% random noise to the transmissivity distribution of the AM plate and 0–0.01 π random phase to the PM plate. Finally, we obtain the actual intensity and phase distributions on the rear focal plane of L2. The deviation between the real intensity distribution and that required is shown in Fig. 5(b); the results indicate that the relative deviation is on the order of 10⁻³. In addition, to determine the long diffraction depth of focus in the target area, we calculate the light intensity at a distance ±0.1 mm from the rear focal plane of L2. The calculation result demonstrates that the deviation of optical intensity is on the order of 10⁻³ similar to that mentioned above. Considering all the above-mentioned factors, it can be stated that the inhomogeneous potential can be reduced by two orders of magnitude.

IV. APPLICATION IN THE INVESTIGATION OF EFIMOV PHYSICS

The Efimov effect, which serves as a popular example of universality in few-body physics, has been observed in experiments with ultracold Bose, Bose-Fermi, and heteronuclear Bose-Fermi gases. However, Efimov-related resonance has not been observed in ⁸⁷Rb-⁸⁷Rb-⁴⁰K mixtures so far. Recent studies indicate that the ground state Efimov resonance of ⁸⁷Rb-⁸⁷Rb-⁴⁰K mixtures is absent due to the positive back-ground scattering length \( a_{RbRb} \). The first Efimov resonance is expected to occur around Rb-K scattering length \( a^{(1)} \) ≤ −30000a₀. Unfortunately, the typical temperature of atomic samples in current experiments is on the order of several hundred nanokelvins, which limits the useful observation window of a scattering length \( |a| \) to less than several thousand Bohr radii \( a₀ \). K-Rb mixtures of temperatures on the order of sub-nanokelvin can be prepared by deep cooling under microgravity. If the temperature of the atomic sample reduces to 600 pK, the useful range of \( |a| \) can be extended to more than 60000a₀. Then, it is hopeful to observe the Efimov effect of Rb-K mixtures and to compare with theory.

In experiments involving Efimov physics with ⁸⁷Rb-⁸⁷Rb-⁴⁰K mixtures, the ⁸⁷Rb atoms are prepared in the \( |F = 1, m_F = 1\rangle \) state \( (g_F = -1/2) \) and ⁴⁰K atoms are prepared in the \( |F = 9/2, m_F = -9/2\rangle \) state \( (g_F = 2/9) \). Neither of these states are magnetically insensitive. Even a weak inhomogeneity of the magnetic field can induce the atoms to escape the shallow trap; thus, compensating the external potentials is necessary. For a ⁸⁷Rb atomic cloud in an optical dipole trap, when the trap frequency \( \omega = 2\pi \times 0.6 \text{ Hz} \) and temperature \( T = 600 \text{ pK} \), the scale of the atomic cloud in the trap is \( \sigma \approx 64 \mu \text{ m} \). Therefore, the 0.4 mm × 0.4 mm × 0.4 mm optical compensating region is sufficient. The inhomogeneous magnetic field discussed above is generated by a poorly designed coil assembly. Principally, optimally designed and well-assembled coils can generate a sufficiently uniform magnetic field in the target region. Although manufacturing and assembly errors prevent it from reaching the uniformity requirement, a maximum variation \( |\Delta B| \) of less than 2 mG in the cubic space of ±0.5 mm can be easily realized because of which the required laser intensity can be reduced by approximately two orders of magnitude. The potential variation after optical compensation is approximately 100 pK in the target region, which is much less than the temperature of atoms and the trap potential.

The energy level shifts caused by the magnetic field are usually different for different types of atoms and molecules. The magnetic field of ⁴⁰K is twice that of ⁸⁷Rb, indicating that the energy level shift of the ⁴⁰K atom caused by the magnetic field is twice that of the ⁸⁷Rb atom. Thus, the optical dipole potential of the ⁴⁰K atom caused by the laser must also be twice that of the ⁸⁷Rb atom.

We calculate the optical dipole potentials and plot them against the wavelength, as shown in Fig. 6. The laser power is set to 1 mW with a waist of 0.5 mm. Furthermore, the laser is linearly polarized, with its polarization being parallel to the z axis. We find the magic wavelength as 754.3 nm at the intersection of the two curves.

Finally, we discuss the heating effect caused by photon scattering. The scattering rate is expressed as follows:
The atomic cloud in the ultrahigh vacuum chamber can be used to prepare atoms of sub-nanokelvin temperatures with magnetically sensitive states.

\[ R_\alpha (\mathbf{r}) = \frac{\pi c^2 I^2}{2\hbar \omega_0^2} \left( \frac{2 + p \cdot g_F \cdot m_F}{\Delta_{JF}^2} + \frac{1 - p \cdot g_F \cdot m_F}{\Delta_{F}^2} \right) I(\mathbf{r}). \]  (4)

Using the data in Sec. III, which are based on the poorly designed coil assembly, an intensity \( I(\mathbf{r}) \) of the compensating light field at the geometric center is obtained as 0.8382 W/mm\(^2\). In addition, the scattering rate of \(^{87}\text{Rb}\) is 0.0403 s\(^{-1}\) at the geometric center. As mentioned above, for an optimally designed and well-assembled coil, the scattering rate is reduced to 4 \( \times \) 10\(^{-4}\) s\(^{-1}\) and the possibility of photon scattering during an experimental period of tens of milliseconds is less than 1 \( \times \) 10\(^{-6}\), which is negligible. Moreover, the power required for a single beam is less than 19 mW, which can be easily provided.

V. OUTLOOK AND CONCLUSION

In this study, we proposed a scheme to compensate the inhomogeneous potential using spatially modulated laser fields. The key principle is to decompose the required 3D intensity distribution into two 2D intensity distributions with quadratic programming, which can be realized using a Fourier optical system. We demonstrated that the inhomogeneous potential of a magnetic field generated by a pair of coils decreases by two orders of magnitude. In addition, other types of inhomogeneous potentials, such as the potential of gravity or inertial force field due to vibration, can be effectively reduced using this technique if they can be decomposed into two 2D distributions.

The discussion thus far is based on the known inhomogeneous potentials; however, in actuality, the potential must be measured. The atomic cloud in the ultrahigh vacuum chamber can be used to probe the nonuniform magnetic field by measuring the microwave resonance or density distribution. If the inhomogeneous potential can be decomposed as discussed above, the absorption images along the perpendicular directions contain all the information on the potential. Furthermore, the compensating laser field is applied based on the absorption images. Then, the absorption images are compared with the last group images, and this information is used to calculate the new compensation laser field. This feedback process is iterated until the distribution of the atomic cloud becomes similar to that without the inhomogeneous potential. The algorithm and the details of the experiment will be discussed in future.

In conclusion, we have developed an optical method to compensate inhomogeneous potentials, especially the inhomogeneous potentials of nonuniform magnetic fields. This technique reduces the inhomogeneity of the residual potential by two orders of magnitude and overcomes the major impediments in experiments for preparing atoms of sub-nanokelvin temperatures with magnetically sensitive states.

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FIG. 6. Optical dipole potentials of \(^{87}\text{Rb}\) and \(^{40}\text{K}\). The red line indicates the optical dipole potential of \(^{87}\text{Rb}\) and the blue dashed line indicates that of \(^{40}\text{K}\) divided by 2.
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