第 45 卷 第 7 期/2025 年 4 月/光学学报 研究论文

光学学报

超冷原子光晶格阱深的高精度标定

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摘要 光晶格是超冷原子量子调控实验的重要工具，为凝聚态物理、强关联电子系统以及新奇拓扑物态的量子模拟提供了理想的研究平台。高精度标定光晶格阱深是实现高保真量子态操控和提升量子系统性能的关键。基于多脉冲Kapitza-Dirac衍射原理，通过施加一系列预设的光晶格脉冲，提高了衍射信号的强度和分辨率，实现了光晶格阱深的高精度标定。对比分析了多脉冲及单脉冲Kapitza-Dirac衍射、Raman-Nath衍射和参量振荡加热法标定光晶格阱深的实用性和局限性，为围绕光晶格开展的量子精密测量和量子模拟实验提供了技术参考。

关键词 原子与分子物理；光晶格；超冷原子；阱深标定；精密测量

中图分类号 O43 **文献标志码** A **DOI**：10.3788/AOS241833

1 引 言

超冷原子光晶格是开展量子计算、量子模拟和量子精密测量的重要物理系统[1-4]。它为冷原子提供了一个具有多种构型的高度可控晶格势场[5-9]，可实现多自由度量子态的精确操控，是模拟固体材料的理想量子体系[10]，因此光晶格中的超冷原子物理研究成为连接微观世界和宏观凝聚态的一座桥梁，可用来模拟强关联量子多体系统[11-12]、规范场[13-14]和新奇拓扑量子物态[15-16]等。在这些实验中，光晶格阱深是调控相互作用强度、能级结构的关键参数，直接影响原子在光晶格中的动力学特性，包括量子态操控[17-19]、布洛赫振荡[20-21]、隧穿效应[22-23]和量子相变[24-25]等，因此高精度标定光晶格阱深对实现超冷原子系统的精确量子操控至关重要[26-28]。

本文提出一种基于多脉冲Kapitza-Dirac(KD)衍射原理的高精度阱深标定方法，通过测量光晶格中原子一阶动量态的衍射效率，实现了光晶格阱深的精确标定。为了验证该方法的有效性，对比了单脉冲KD衍射、Raman-Nath(RN)衍射及参量振荡加热法。本文全面系统地测量了光晶格阱深并基于实验结果分析了这4种方法的实用性和局限性，研究结果为光晶格的高精度测量提供了技术支持，并为未来量子模拟和量子计算领域的光晶格应用奠定了坚实基础。

2 实验过程

首先，利用交叉光学偶极阱实现^{87}Rb原子的玻色-爱因斯坦凝聚(BEC)，根据不同实验条件将原子装载到一维光晶格中，如图1所示。然后，利用时间飞行展开成像技术在动量空间观测原子的衍射分布，通过精确分析其动力学行为得到光晶格阱深[29]。光晶格激光波长为798 nm，激光的频率、幅度和开启时间均由声光调制器精确调控。分别利用RN衍射、单脉冲KD衍射、

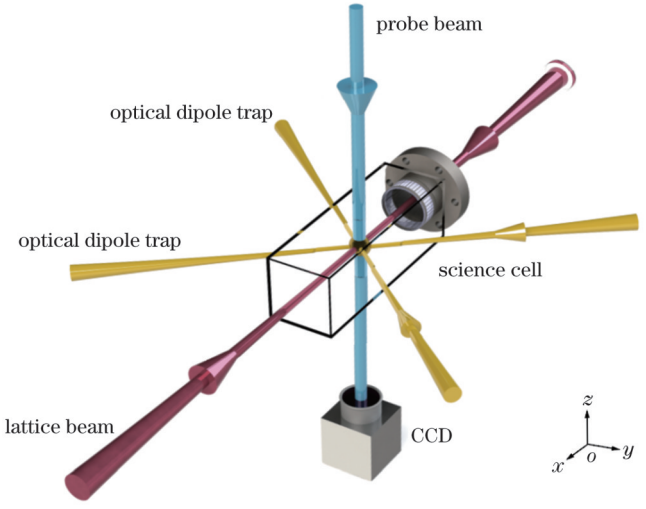


图1 一维光晶格装置图。光晶格沿着x方向，探测光沿着z轴方向(重力方向)，交叉光学偶极阱在x-y平面

Fig. 1 Diagram of one-dimensional optical lattice device. The optical lattice is along the x direction, the probe light is along the z axis (the direction of gravity), and the crossed optical dipole trap is in the x-y plane

收稿日期：2024-12-05；**修回日期**：2025-01-15；**录用日期**：2025-02-10；**网络首发日期**：2025-02-12

基金项目：科技创新2030重大专项(2021ZD0302003)、国家重点研发计划(2022YFA1404101，2021YFA1401700)、国家自然科学基金(12034011，U23A6004，12322409，12474252，12474266，12374245)

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多脉冲KD衍射、参量振荡加热法测量了光晶格阱深。

2.1　RN衍射

RN效应[30]是指原子在短时间内与光晶格发生相互作用的衍射现象。因为光晶格与原子的相互作用时间t很短($t\omega \ll 1$,$\omega = 2\sqrt{V_0 E_r}/\hbar$,其中$V_0$为光晶格阱深,单光子反冲能量$E_r = (\hbar k)^2/(2m)$,$k$为光晶格激光波数,$m$为原子质量),原子的动量变化可以忽略不计,可近似为光晶格势场直接作用在原子波函数的相位上(即相位调制)[31],原子在各阶动量态上的布居数遵循$P_n(V_0, t) = \left|\mathrm{J}_n\left(V_0 t/2\right)\right|^2$[32],其中$\mathrm{J}_n$为第一类贝塞尔函数,$n$为衍射阶次。$\mathrm{J}_n(2.4048) = 0$(即$V_0 t_0/2 = 2.4048$,其中$V_0 t_0$为常数,定义为固定脉冲面积)表示阱深为$V_0$的光晶格在最短脉冲时间$t_0$内,将零动量态的原子全部转移到高阶动量态。因此,通过调控光晶格脉冲时间,测量零阶动量态的原子数就可获得最短脉冲时间,从而得到光晶格阱深$V_0 = 4.8096/t_0$。

为了确定RN衍射的适用范围,将待测阱深的光晶格脉冲作用到BEC原子团,测量零动量态的原子衍射,得到最短脉冲时间$t_0 = 4\ \mu\mathrm{s}$,衍射效率$N_0/N = 0.61\%$,见图2(a)。由此得到阱深$V_0 = 49.8E_r$(此时光晶格的光电探测器电压$V_d = 600\ \mathrm{mV}$,光晶格阱深与光电探测电压呈线性关系),脉冲面积为$2400\ \mu\mathrm{s}\cdot\mathrm{mV}$。

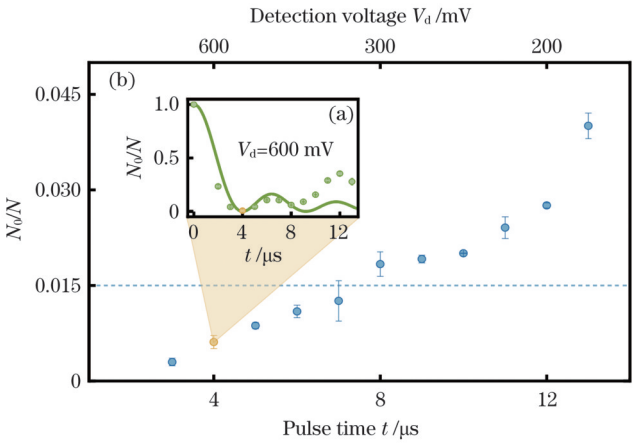


图2　$n = 0$级动量态原子数概率分布随时间的演化。(a)阱深$V_0 = 49.8E_r$,光电探测器电压$V_d = 600\ \mathrm{mV}$的原子数概率分布;(b)原子数概率分布随不同脉冲时间和探测电压的演化过程,固定脉冲面积为$2400\ \mu\mathrm{s}\cdot\mathrm{mV}$,虚线为零动量态原子的高效率转移上限值

Fig. 2　Evolution of probability distribution of the number of atoms in the $n = 0$ diffraction order with time. (a) Probability distribution of the number of atoms with trap depth $V_0 = 49.8E_r$ and detection voltage $V_d = 600\ \mathrm{mV}$; (b) evolution of probability distribution of the number of atoms with pulse time and detection voltage when the fixed pulse area is $2400\ \mu\mathrm{s}\cdot\mathrm{mV}$, and the dashed line represents the upper limit of high-efficiency transfer of atoms in the zero-momentum state

基于该脉冲面积可计算得到任意光晶格脉冲时间和光强的组合。将原子团穿过不同脉冲时间、光强的光晶格,测量衍射后的零动量态原子数。由图2(b)可知,只有当光晶格脉冲时间$t_0 \leqslant 7\ \mu\mathrm{s}$时,零阶动量态的原子才能高效率转移到高阶动量态(本文中高效率范围为$\leqslant 1.5\%$),因此RN衍射只在光与原子作用时间很短时才会出现。如图2(a)所示,当光晶格作用时间较长时,原子的动量变化无法忽略,RN衍射的近似条件失效,无法利用第一类贝塞尔函数J_n进行拟合。

2.2　单脉冲KD衍射

当光晶格与原子相互作用时间较长时,原子会经过KD效应[33]在动量空间产生± 1、± 2等更高级次的衍射分布,各衍射级次的原子数与晶格作用时间、阱深有关[34],因此基于KD衍射原理的数值计算可以更为精确地标定光晶格阱深。与RN衍射相比,KD衍射方法不受时间和阱深的限制。

原子初始制备在零动量态$|\Psi(t=0)\rangle$,在光晶格脉冲势场$V_0\cos^2(kx)$作用后,该体系的量子态随时间t演化为$\left|\Psi(t)\right\rangle = \exp\left[Ht/(\mathrm{i}\hbar)\right]\left|\Psi(t=0)\right\rangle$,其中$H$为哈密顿量。随后将量子态随时间演化的实验数据与数值求解得到的理论数据进行拟合,就可以得到光晶格的阱深。图3(a)、(b)的实验数据为低阱深光晶格情况,阱深分别为$10.2E_r$、$19.7E_r$,原子衍射主要分布在0、± 1级,因此0级原子数呈周期性振荡。图3(c)、(d)的实验数据为高阱深光晶格情况,阱深分别为$40.1E_r$、$50.3E_r$,原子被衍射到± 1、± 2等更高级次,因此各衍射级次的原子数呈非周期性振荡。

2.3　多脉冲KD衍射

多脉冲KD衍射法是对RN衍射和单脉冲KD衍射法的改进,通过施加一系列预设的光晶格脉冲[35],不同级次衍射动量态的原子将会产生干涉效应,原子会全部转移至± 1级衍射动量态[36],由此增强原子的衍射信号,提高衍射分辨率,进而提升光晶格阱深的测量精度。

多脉冲KD衍射法中光晶格脉冲序列的时间和幅度是确定的(与2.2节量子态随时间演化的理论方法相同),分别为(t_1, t_2, t_3)和$(V_0, V_1 = 0, V_0)$,见表1的理论值,只有当实际光晶格阱深与理论预设阱深V_0相同时,原子才能以最大概率被转移至± 1级衍射动量态。因此,通过± 1级衍射动量态的原子数或最大转移效率就可以高精度地标定光晶格阱深。

将表1中光晶格脉冲序列的理论值($t_1 = 52.617\ \mu\mathrm{s}$,$t_2 = 29.777\ \mu\mathrm{s}$,$t_3 = 28.840\ \mu\mathrm{s}$)应用到实验中,测量一级衍射动量态原子的布居数比例随光晶格光强探测器电压的变化,最大衍射效率为$N_1/N = 99.78\%$,见图4,此时电压为$114.9\ \mathrm{mV}$,阱深$V_0 = 9.04E_r$。

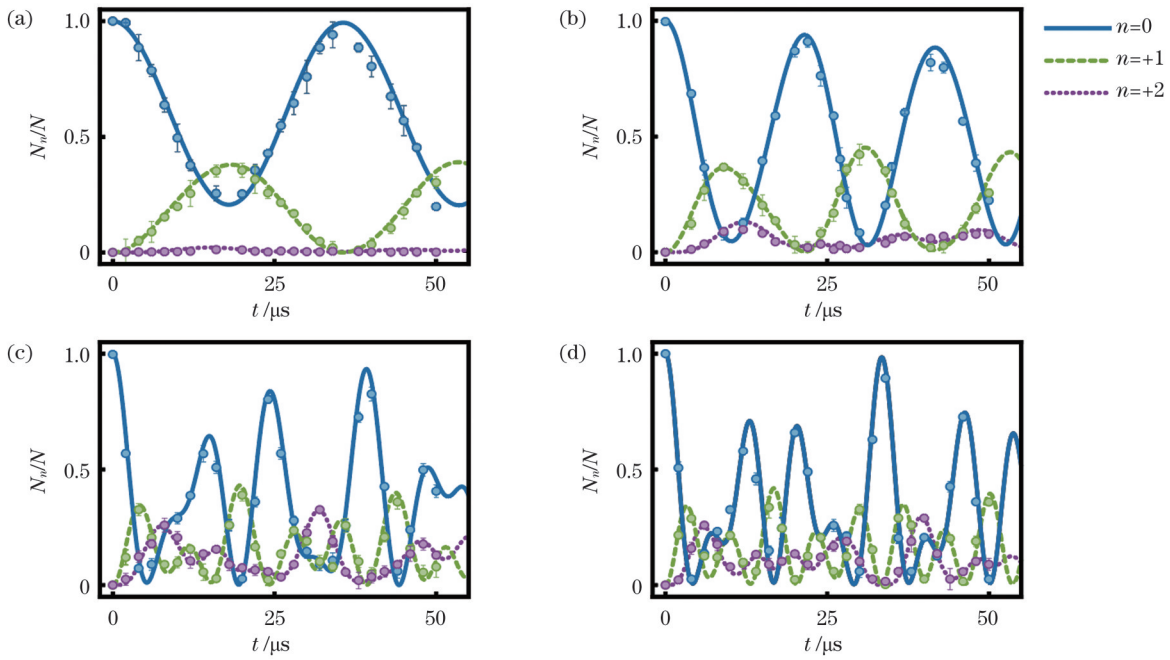


图 3　$n=0$、+1、+2 级原子数随时间的演化，其中散点为实验数据，导视线为理论数据。(a)阱深为 $10.2E_r$；(b)阱深为 $19.7E_r$；(c)阱深为 $40.1E_r$；(d)阱深为 $50.3E_r$

Fig. 3　Evolution of the number of atoms at the $n=0,+1,+2$ diffraction orders with time, where the scatter points represent the experimental data and the guiding lines represent the theoretical calculation. (a) Trap depth is $10.2E_r$; (b) trap depth is $19.7E_r$; (c) trap depth is $40.1E_r$; (d) trap depth is $50.3E_r$

表 1　光晶格脉冲序列的时间、阱深和 $n=\pm1$ 级衍射动量态的原子数比例

Table 1　Time of optical lattice pulse sequence, trap depth, and proportion of the number of atoms in $n=\pm1$ diffraction orders

V_0/E_r	t_1/μs	t_2/μs	t_3/μs	$\frac{N_1}{N}$/%
9.04	52.617	29.777	28.840	99.99964
11.08	26.002	11.504	54.261	99.98054
19.48	24.561	40.180	55.917	99.97501
24.88	25.206	27.916	32.819	99.75577

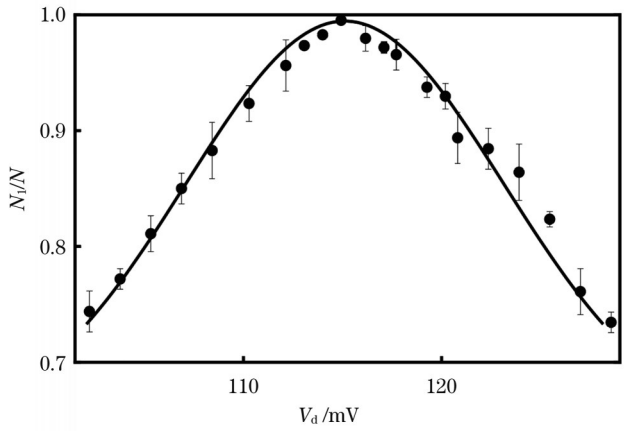


图 4　多脉冲 KD 衍射中 $n=\pm1$ 级衍射动量态的原子数比例

Fig. 4　Proportion of the number of atoms in $n=\pm1$ diffraction orders in multiple-pulse KD diffraction

2.4　参量振荡加热

超冷原子光晶格系统的参量振荡[37]是通过周期性调制光晶格的强度来调控系统的参量振荡加热效应，当周期性调制的驱动频率等于光晶格的本征频率(即能带跃迁频率)时，超冷原子将会被共振加热，从而导致原子数减少[38]。

在实验中，首先将超冷原子绝热制备到光晶格的 s 能带，然后对光晶格的光强进行幅度调制，光强为 $I_0\left[1+0.1\sin(\omega t)\right]$，其中 I_0 为绝热装载后的光强，ω 为周期性调制的驱动频率。因此，周期性调制的参量振荡可以将原子从 s 能带激发跃迁到 d、f 等高阶偶数能带，其分别对应不同的周期性调制频率(即能带跃迁频率)，图 5(a)所示为阱深与能带跃迁的调制频率关系。因此，通过扫描调制频率观测原子数的损耗就可以测量能带跃迁频率，从而标定光晶格的阱深。图 5(b)中出现两个共振频率，分别为 41.4 kHz 和 79.4 kHz，其中第②个共振频率对应 s→d 能带跃迁，见图 5(a)的实线箭头，由此得出光晶格的阱深为 $40.8E_r$。图 5(b)中第①个、第③个共振频率分别为 s→d 能带的双光子跃迁频率和 s→g 能带的跃迁频率[39]。

2.5　实验结果分析

图 6 所示为以上 4 种方法标定光晶格阱深的结果以及线性拟合结果。其中单脉冲 KD 衍射方法和多脉冲 KD 衍射方法得到的光晶格阱深与探测器电压在全范围内保持着高线性度，其阱深和电压转换关系分别

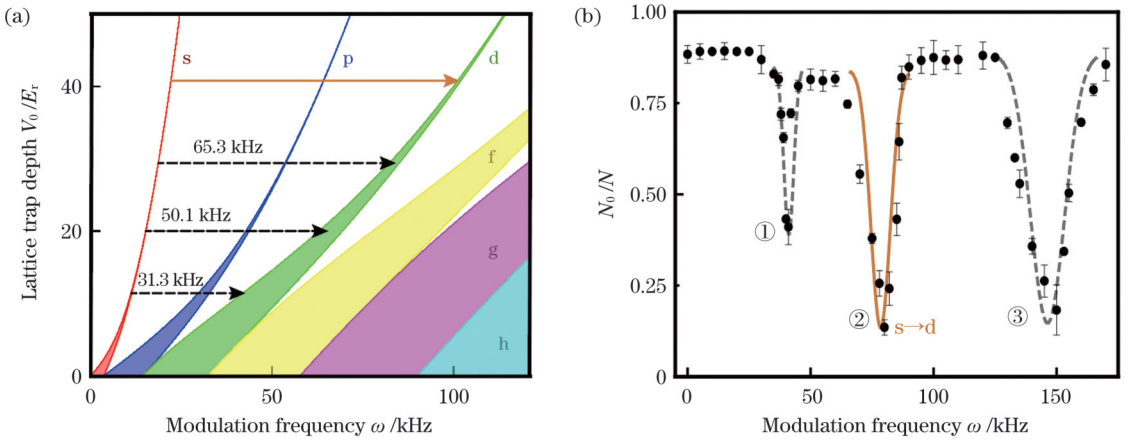


图 5　晶格阱深与调制频率的关系及参量振荡加热实验测量结果。(a)一维光晶格的 s→h 能带宽度，其中实线箭头为参量振荡加热得到的 s→d 能带跃迁频率；(b)$n=0$ 级原子数损耗与参量振荡加热调制频率的关系

Fig. 5　Relationship between depth of lattice trap and modulation frequency, and experimental measurement results of parametric oscillation heating. (a) s→h energy band widths of one-dimensional optical lattice, where the solid arrow indicates s→d energy band transition frequency obtained by parametric oscillation heating; (b) variation in atomic number loss of $n=0$ diffraction order with modulation frequency of parametric oscillation heating

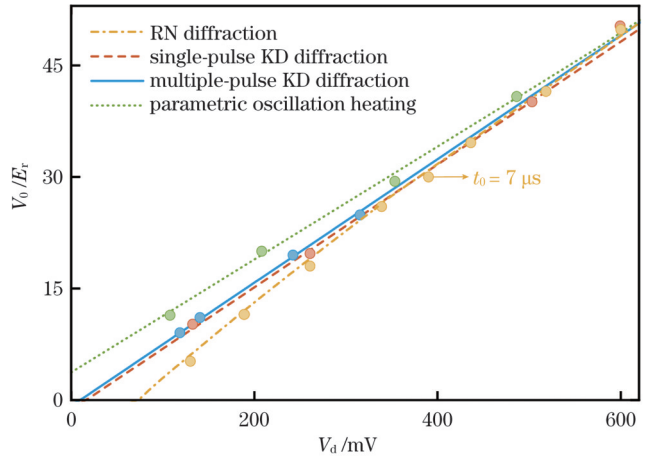


图 6　RN 衍射、单脉冲和多脉冲 KD 衍射、参量振荡加热法的阱深标定结果以及线性拟合结果

Fig. 6　Trap depth calibration results and linear fitting results of RN diffraction, single-pulse KD diffraction, multiple-pulse KD diffraction, and parametric oscillation heating methods

为 $V_0=(0.085\pm0.004)V_d-(1.721\pm1.737)$ 和 $V_0=(0.081\pm0.001)V_d-(0.159\pm0.175)$，转换关系中的斜率不确定度主要由光晶格阱深的校准误差引起，截距的不确定度主要来源于探测器的偏置电压，因此该转换关系可标定光晶格阱深和不确定度大小。虽然这两种方法适用于较大的阱深和时间范围，但是单脉冲 KD 衍射法通过实验数据的拟合来确定光晶格阱深，拟合过程会引入误差，并且为了提高拟合精度，需要采集大量实验数据，这不仅增加了测量的复杂性，还放大了实验过程中的系统误差。多脉冲 KD 衍射法中，通过多个光晶格脉冲，将原子全部转移至一级衍射动量态，衍射效率达到 $N_1/N=99.78\%$，提高了阱深测量精度，同时测量过程中不需要拟合，避免了拟合参数误差。

当激光作用时间 $t_0\leqslant7$ μs 时，RN 衍射法测得的光晶格阱深与前两种方法一致，阱深与探测器电压的转换关系为 $V_0=(0.097\pm0.003)V_d-(7.297\pm1.166)$，其斜率和截距的不确定度比多脉冲 KD 衍射法大一个数量级左右。但是随着光晶格与原子作用时间加长（图 6 中箭头处标记点），衍射过程无法忽略原子动量变化，因此该方法获得的光晶格阱深会出现偏差（当 $t_0>7$ μs 时，与多脉冲 KD 衍射方法相比，$\Delta V_0=0.026V_d-8.209$），见图 6 的点划线。

参量振荡加热法通过测量能带跃迁频率获得光晶格的阱深，该方法能有效地避免系统中的随机误差。由于共振频率与阱深的变化关系明确，该方法适用于不同深度的光晶格，并且在较宽的参数范围内有效。但是在低阱深下，光晶格能带较宽，共振加热导致原子数损失的频率范围增大，会影响共振频率的确定，阱深与探测器电压的转换关系为 $V_0=(0.076\pm0.003)V_d+(3.543\pm0.806)$，其斜率和截距的不确定度比多脉冲 KD 衍射法大。如图 6 的点线所示，在高阱深时参量振荡加热法与多脉冲和单脉冲 KD 衍射法的实验数据重合，但是在低阱深时会出现偏差 $\Delta V_0=-0.007V_d+4.542$（与多脉冲 KD 衍射方法相比）。

3　结　　论

在超冷原子光晶格的实验中，光晶格阱深是原子运动、相互作用强度和能级结构的关键影响参数。本文基于实验结果分析了 4 种阱深测量方法的实用性和局限性。

1）RN 衍射

RN 衍射适用于光晶格与原子的相互作用时间较

短的情况，其核心是基于动量态的相位调制。在这种条件下，原子动量变化可忽略不计，衍射分布通过贝塞尔函数描述。该方法的主要优点是操作简单，但它的适用范围有限，仅在短脉冲情况下适用。当光晶格作用时间变长时，动量变化将不可忽略，导致衍射模式的近似条件失效。

2）单脉冲KD衍射

KD衍射是通过理论模拟原子在光晶格势场中的时间演化过程，从而标定光晶格阱深。该方法的优势在于时间和阱深的适用范围较广，能够准确描述多级衍射现象，尤其在高阱深下依然有效。然而，与其他方法相比，单脉冲KD衍射法需要统计多级衍射现象，因此需要更长的实验时间、更大的数据量和复杂的数值计算才能实现准确的数值拟合，实验过程较为繁琐。

3）多脉冲KD衍射

相比于单脉冲，多脉冲KD衍射法基于干涉效应，通过施加一系列预设的光晶格脉冲，将原子全部转移至一级衍射动量态，与RN衍射和单脉冲KD衍射法相比，多脉冲KD衍射法提高了衍射信号的强度和分辨率，提升了阱深测量精度，并且该方法的时间和阱深适用范围广。

4）参量振荡加热

参量振荡加热法通过精确调控光晶格幅度调制的频率，引发超冷原子系统在晶格本征频率（即能带跃迁频率）处发生共振加热，由此通过观测原子数的损耗来精确测量光晶格阱深。该方法的优势在于对晶格能带结构的直接探测，根据能带跃迁频率与阱深的关系进行标定，具有高精度和抗随机误差的特性，适用于较宽的光晶格阱深范围。但是该方法在低阱深时，共振加热会导致原子数损失的频率范围增大，会影响共振频率的确定。另外，该方法还需要精确的频率扫描和观测复杂的加热效应，实验耗时较长。

本文利用多脉冲KD散射原理和干涉效应，通过施加一系列预设的光晶格脉冲，将原子全部转移至一级衍射动量态，提高了衍射信号的强度和分辨率，对比RN衍射和单脉冲KD衍射，所提方法提升了阱深测量精度，有望为光晶格量子精密测量和量子调控等提供技术参考。

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High-Precision Calibration of Optical Lattice Trap Depth for Ultracold Atoms

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Abstract

Objective Optically trapped ultracold atoms in optical lattices are important physical systems for conducting quantum computing, quantum simulation, and quantum precision measurement. The study of ultracold atoms in optical lattices serves as a bridge connecting the microscopic world and macroscopic condensed matter. It can be used to simulate strongly correlated quantum many-body systems, gauge fields, and novel topological quantum states. In these experiments, the depth of the optical lattice is a key parameter for regulating interaction strength and energy level structure. It directly affects the dynamical properties of atoms in the optical lattice, including Bloch oscillations, tunneling effects, and quantum phase transitions. Therefore, high-precision calibration of the optical lattice trap depth is crucial for achieving precise quantum control of ultracold atom systems.

Methods We propose a high-precision methodology for calibrating the trap depth of optical lattices based on the principle of multiple-pulse Kapitza-Dirac (KD) diffraction. Accurate calibration of the optical lattice depth is achieved by measuring the high diffraction efficiency of the first-order momentum state of atoms within the optical lattice. To validate the effectiveness of this method, a comprehensive comparison is made with single-pulse KD diffraction, Raman-Nath (RN) diffraction, and parametric oscillation heating. In the experimental process, Bose-Einstein condensation (BEC) of ^{87}Rb atoms is initially realized using a crossed optical dipole trap. The atoms are then loaded into a one-dimensional optical lattice under various experimental conditions. Finally, the diffraction distribution of the atoms is observed in momentum space using time-of-flight expansion imaging. By carefully analyzing their dynamic behaviors, the depth of the optical lattice is precisely determined.

Results and Discussions The multiple-pulse KD diffraction method proposed in this paper utilizes the interference effect produced by a multiple-pulse optical lattice sequence to enhance the diffraction resolution of atoms, thereby improving the accuracy of calibrating the depth of the optical lattice. A comprehensive and systematic measurement of the experimental process is performed for lattice depth calibration, and the practicality and limitations of the four methods—multiple-pulse

KD diffraction, single-pulse KD diffraction, RN diffraction, and parametric oscillation heating—are analyzed. The optical lattice depths obtained using the single-pulse and multiple-pulse KD diffraction methods maintain a high degree of linearity with the detection voltage over the entire range, and these two methods are applicable to a wide range of depths and time intervals. However, the single-pulse KD diffraction method determines the depth of the optical lattice through the fitting of experimental data, which requires collecting a large amount of data. This fitting process introduces potential errors and increases the complexity of the measurement. In the multiple-pulse KD diffraction method, the transmission fidelity of diffraction orders is highly sensitive to the lattice depth, and no data fitting is required during the measurement process, which ensures highly accurate calibration of the optical lattice depth. When the laser interaction time is long, the optical lattice depth measured by the RN diffraction method is consistent with the first two methods. However, as the interaction time between the optical lattice and the atoms increases, the diffraction process must account for changes in atomic momentum, and thus the optical lattice depth obtained by this method may have deviations from the true value. The parametric oscillation heating method can be used for optical lattices of different depths and is effective within a wide parameter range. However, at low depths, the wide energy band of the optical lattice increases the frequency range of atomic loss due to resonant heating, which affects the determination of the resonant frequency and further increases measurement error.

Conclusions Through the analysis of the experimental results, we assess the practicality and limitations of the four trap depth measurement methods. RN diffraction is suitable for cases with short interaction time between the optical lattice and the atoms, and its core mechanism is phase modulation based on the momentum state. When the optical lattice interaction time becomes longer, the momentum change becomes significant, which leads to the breakdown of the diffraction mode approximation. The KD diffraction method has the advantage of a broad range of applicability in both time and depth. It can accurately describe multi-stage diffraction phenomena and remains effective even at high depths. Compared to the single-pulse method, the multiple-pulse KD diffraction method is based on the interference effect. By applying a series of pre-set optical lattice pulses, all atoms are transferred to the first-order diffraction momentum state. Compared to RN diffraction and the single-pulse KD diffraction method, this approach improves the intensity and resolution of the diffraction signal, thereby enhancing the accuracy of depth measurements. Furthermore, it has a broad range of applicability in both time and depth. The advantage of the parametric oscillation heating method is its direct detection of the lattice band structure and calibration through the relationship between band transition frequency and depth. However, at low depths, the frequency range of atomic loss caused by resonance heating increases, which can affect the determination of the resonance frequency. The multiple-pulse KD diffraction method enhances lattice depth measurement accuracy. Therefore, this method is expected to provide a technical reference for optical lattice quantum precision measurements and quantum regulation.

Key words atomic and molecular physics; optical lattice; ultracold atom; trap depth calibration; precision measurement