

光诱导原子解吸附实验中的光热效应研究

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摘要 利用光诱导原子解吸附效应, 无需加热就可实现碱金属原子浓度的调控, 简易有效, 故常被应用于光纤内碱金属原子的充载和磁光阱内单原子的捕获等。在使用 460 nm 的发光二极管阵列进行原子解吸附时, 发现铷原子池的温度上升, 说明光解吸附效应受到了光热效应的影响, 但目前关于光解吸附实验中的光热效应研究鲜有报道。当解吸附功率密度较小时, 光热效应的影响几乎可忽略。当增大解吸附功率密度时, 光解吸附效应以及光热效应的影响不断增大且对原子浓度增长的贡献趋于接近, 在两种效应的共同作用下, 原子浓度的增长幅度得到进一步提高。研究结论对光子芯片研究具有参考意义。

关键词 量子光学; 光诱导原子解吸附; 光热效应; 光学深度; 原子浓度

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1 引言

光诱导原子解吸附 (light-induced atomic desorption, LIAD) 是可以提高碱金属原子池原子浓度的一种方法^[1]。当非共振光源照射装载碱金属原子的容器时, 吸附在内壁上的碱金属原子发生解吸附, 原子浓度显著增大, 且解吸附的功率及频率均会影响解吸附效果, 这一现象引起了研究者的广泛关注。LIAD 的理论分析^[2-4]和实验研究^[5-8]表明, 影响 LIAD 效果的因素除了解吸附光强度和频率之外, 还有内表面结构^[8-14]、碱金属原子种类^[1,8]及解吸附光性质^[15-16]等。

加热方法同样能提高容器内的原子浓度, 但这与 LIAD 在机制上存在区别。在范德瓦耳斯力和库仑力的共同作用下, 原子会被吸附在容器内壁表面上, 解吸附光的照射破坏了吸附体系的平衡, 导致原子脱落, 从而容器内的原子浓度增大。而温度的升高导致碱金属原子的饱和蒸汽压增大, 故升温同样可实现原子浓度的增大。相较于加热方法, LIAD 在室温下便可以实现, 更加安全高效。

光子器件的集成化是未来的必然趋势, 尤其是装载原子介质的光子芯片是研究的热点之一^[17-18]。

基于原子介质可实现光学非互易^[19-20]、光存储^[21]以及原子钟^[22-27]等器件的集成研究, 但通常需要一定的光学深度, 这在室温条件下难以实现, 目前常用手段便是加热。但是受光子芯片尺寸大小的限制, 在结构上设计加热系统无疑会增加整体结构的复杂性, 提高集成工艺的难度。借助 LIAD 方法, 可以避免引入加热结构, 有效提高光学深度, 有利于光子芯片的集成研究。除此之外, LIAD 在其他光学领域也有重要应用, 如磁光阱内的单原子捕获^[28-31]、光纤内的碱金属原子充载^[16,32-33]及微结构表面光学^[10,34]等。

本文实验研究了 LIAD 效应及光热效应对 LIAD 效果的影响。采用波长为 460 nm 的发光二极管(LED)作为解吸附光源, 发现解吸附光照射时的 LIAD 效应和光热效应引起原子浓度增大。当解吸附光的功率密度较小(低于 25 mW/cm²)时, 光热效应的影响比较小, 基本可以忽略; 但随着解吸附功率密度的增大, LIAD 效应的作用不断增强, 同时产生的光热效应的作用也逐渐显著增强。在本文实验条件下, 当解吸附光的功率密度达到 80 mW/cm² 时, LIAD 效应和光热效应对原子浓度增长的贡献接近。

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2 实验装置与实验结果

2.1 实验装置

图 1 所示为实验光路图。实验中使用的解吸光由波长为 460 nm 的 LED 阵列产生,通过调节 LED 两端施加的电流大小,即可改变光照的输出功率。为了加强解吸效果,实验中采用了一个直径为 15 cm 的亚克力闭合球型圆壳腔将铷原子池罩起来,对解吸光进行会聚。球罩上方开口打光,内壁上涂有纳米高分子反射涂料,用来增强球罩内的光反射,使解吸光更加充分,提高光解吸的效果。

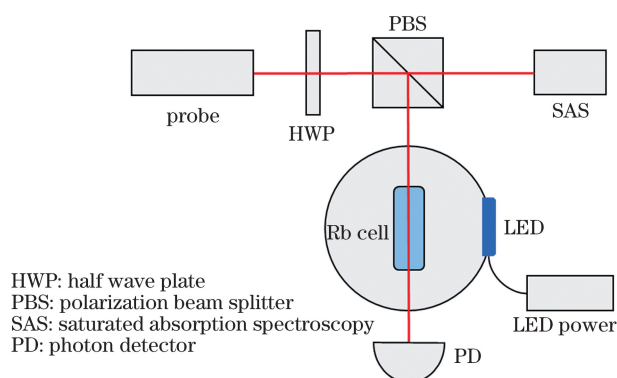


图 1 LIAD 实验光路图

Fig. 1 Experimental optical path diagram for LIAD

当打开解吸光后,碱金属原子池内的 LIAD 分为两个过程,先是解吸光直接照射部分的表层原子脱落,然后周围未被照射位置及深层的原子会向解吸表层扩散,再被解吸释放。其中影响 LIAD 效果的主要因素有解吸光的强度及频率,解吸光强度越大,频率越小,则 LIAD 效果越强^[1]。

实验中使用的探测场由半导体激光器 Toptica DL Pro 产生,波长为 795 nm。探测光通过偏振分束镜后一束进入饱和锁频系统,另一束通过铷原子池后被探测器接收。铷池内充有自然丰度的铷原子蒸气。在未加解吸光时,铷池内为饱和蒸汽状态;当打上解吸光之后,利用探测光经过铷池后的光谱可测得池内光学深度及原子浓度的变化情况。

2.2 实验结果

图 2 所示的是在不同驱动电流下,探测光经过铷池后的归一化透射谱,其中 F 为原子的总角动量。透射窗口的深浅反映了铷池对探测光的吸收强弱,透过率越低,说明铷池的吸收越强,原子池的光学深度及原子浓度越大。从图 2 中可以发现,随着驱动电流的增大,解吸光的功率密度增大,透射窗口的透过率减小。以吸收最强的透射峰为例,透过率

从 15 mW/cm^2 光功率密度时的 84% 下降至 84 mW/cm^2 光功率密度时的 5%,说明原子池的光学深度也在不断增大。

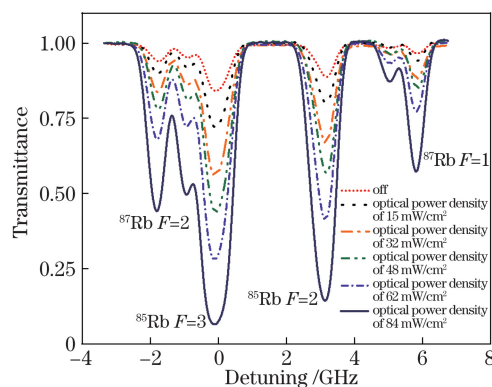


图 2 不同解吸光功率密度下的 LIAD 原子透射谱
Fig. 2 Transmission spectra of LIAD under different desorption light power densities

在实际测量中,当解吸光功率密度增大时,光解吸过程中铷池表面的温度也有一定的上升。事实上,温度对铷池内的原子浓度也有影响,原子浓度随温度的升高而增大。因此,当使用大功率密度解吸光进行照射时,光解吸效果受到光热效应的影响。为了将 LIAD 效应与光热效应区分开,在不加解吸光的情况下,以加热的方式将铷池升温至对应温度,测得的透射光谱如图 3 所示,其中温度和相应 LIAD 过程中的光热作用对应。

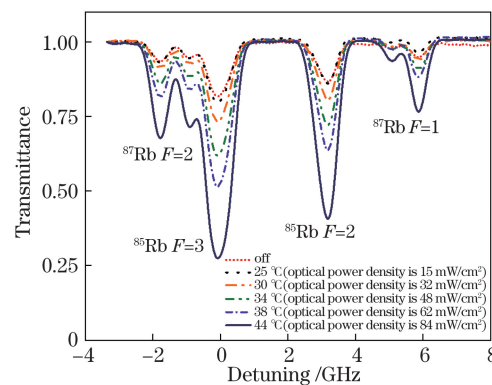


图 3 不同温度下的铷原子透射谱
Fig. 3 Transmission spectra of Rb atoms at different temperatures

对图 2、3 进行比较,可以发现,图 3 中的透射窗口深度明显比图 2 的小。此时若用图 2 中光解吸后的透射谱减去图 3 中光热效应下的透射谱,得到的便是无光热影响的 LIAD,即纯 LIAD(pure-LIAD)。

在根据透射谱计算原子池的光学深度时,需对吸收峰进行拟合。对应 $^{85}\text{Rb } F=3$ 吸收峰,实际包含两条跃迁路径: $^{85}\text{Rb } F=3 \rightarrow F'=2$ 及 ^{85}Rb 的

$F=3 \rightarrow F'=3$ 。受到多普勒增宽和碰撞增宽的影响,两条跃迁路径的吸收峰被包络在一个吸收峰内,需用 Voigt 线型对两条跃迁路径进行拟合。通过拟合之后可以得到透射窗口的最低透过率 T_{\min} 。根据光学深度 (O_D) 的定义,有 $O_D = -\ln \frac{T_{\min}}{T_{\max}}$ (T_{\max} 为最低透过率),对于透射光谱,归一化后 T_{\max} 为 1,故有 $O_D = -\ln T_{\min}$ 。再由 $O_D = nL\sigma_0$ (L 为介质长度, σ_0 为介质的有效吸收截面, n 为原子浓度),便可计算对应的原子浓度。

按此计算方法可以分别得到图 2、3 中 LIAD 效应以及光热效应引起的原子浓度增长,两者相减得到的便是纯 LIAD。当未加解吸光时(室温条件下),铷原子池内的原子浓度 n_0 约为 $1.14 \times 10^{16} \text{ m}^{-3}$ 。通过测量不同驱动电流下的解吸光功率密度,得到不同光功率密度下纯 LIAD 及光热效应导致的原子浓度增长情况,如图 4 所示,其中实线对应纯 LIAD,虚线对应光热效应。可以发现,随着光功率密度的增大,两种效应对原子浓度增长的贡献都在增大,且当解吸光功率密度较大时,光热效应的影响更加显著。

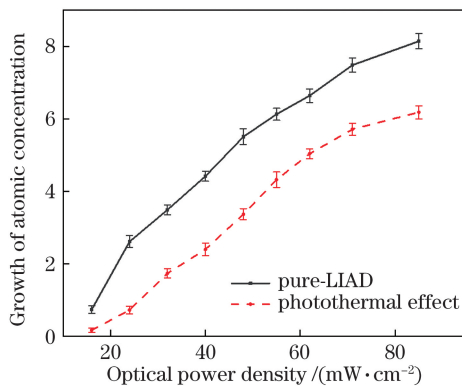


图 4 不同光功率密度下纯 LIAD 及光热效应引起的原子浓度增长情况

Fig. 4 Growth of atomic concentration induced by pure-LIAD and photothermal effect with different optical power densities

为了更好地研究光热效应在光解吸过程中的作用,分析了不同光功率密度下纯 LIAD 和光热效应引起的原子浓度增长值的比值 $\Delta n'_{\text{pure-LIAD}} / \Delta n_{\text{photothermal}}$,如图 5 所示。可以发现,当解吸光的功率密度较低时,LIAD 效应以及光热效应的贡献差异较大,如当解吸光功率密度为 15 mW/cm^2 时,纯 LIAD 的贡献接近光热效应的 6 倍,在这种情况下,光热效应导致的原子浓度增长基本可以忽略;而当解吸光的功率密度较大如 80 mW/cm^2 时, $\Delta n'_{\text{pure-LIAD}} / \Delta n_{\text{photothermal}}$ 接近 6:4,这说明此时光热效应的贡献和纯 LIAD 的贡献基本相当。

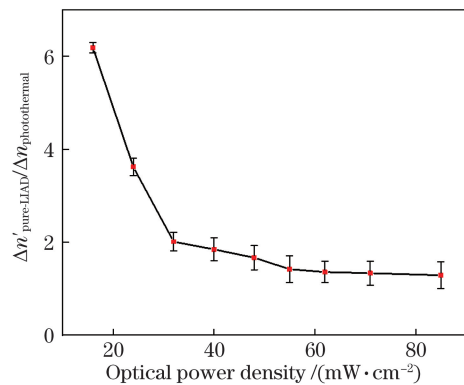


图 5 不同光功率密度下的 $\Delta n'_{\text{pure-LIAD}} / \Delta n_{\text{photothermal}}$

Fig. 5 $\Delta n'_{\text{pure-LIAD}} / \Delta n_{\text{photothermal}}$ under different power densities

除光热效应之外,LED 阵列发热产生的热传导对铷池是否造成影响也需要进一步验证。本文采用水冷机对 LED 阵列进行降温,使 LED 阵列的温度控制在 $22 \text{ }^\circ\text{C}$,并加入玻璃板隔绝热对流,以减小 LED 发热产生的热传导对铷池热辐射的影响。利用水冷机对 LED 阵列进行降温,发现铷池温度比水冷散热前低 $1 \sim 2 \text{ }^\circ\text{C}$,如图 6 所示。在水冷散热的基础上再隔绝热对流,发现与仅水冷散热时的温度几乎无差异。这意味着 LED 阵列发热产生的热辐射对铷池的影响不大,而对流造成的影响更是可以忽略,也就说明光解吸过程中的温度变化主要是由光热引起的。

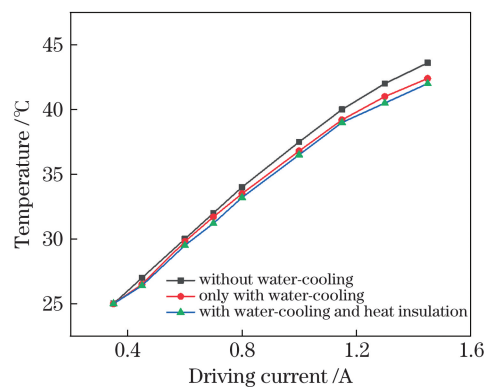


图 6 LED 阵列发热及热对流对铷池升温的影响

Fig. 6 Influences of LED array heating and thermal convection on temperature increase of Rb cell

3 分析与讨论

LIAD 效应与光热效应虽然都能使容器内的碱金属原子浓度增大,但两者的作用机制存在本质区别。本文发现,在 LIAD 过程中铷池温度有上升现象,说明光解吸效果受到热效应的影响。考虑到除光热效应之外,LED 阵列发热产生的热传导也可能造成铷池的升温现象,故采用水冷及隔热等形式对 LED 阵列进行降温并减少热对流,发现导致升温的主要因素是光热效应,而非热传导。为了研究光热效应

的影响,实验中采用纯加热的方式,在没有解吸光的情况下得到对应温度下的原子浓度,并与纯 LIAD 的影响进行对比,发现在解吸光功率密度较小时,光解吸效应与光热效应的影响相去甚远,光热效应的影响很小,几可忽略;但随着解吸光功率密度的增大,光解吸效应与光热效应对原子浓度增长的贡献趋于接近,光热效应对原子浓度增长的贡献约占 40%。

4 结 论

目前用于提高碱金属原子浓度的常用手段主要有升温 and LIAD。对于热原子蒸气池,为了在不加热的方式下实现理想的光学深度,通常需要较大功率密度的解吸光,此种情况下光热效应的影响较为明显。实验研究了不同光功率密度下光解吸过程中纯 LIAD 及光热效应的影响,发现随着解吸光功率密度的增大,两者的影响都在增大,且对原子浓度增长的贡献趋于接近。在大光功率密度下进行光解吸实验时,光解吸效应与光热效应的共同作用使得原子浓度的增长得到进一步提高。

装载原子介质的集成光子芯片是研究热点,但集成芯片体积较小,传统的加热方式会导致系统结构复杂,而 LIAD 具有应用前景。实验发现,在使用大功率密度光解吸时,纯 LIAD 和光热效应的共同作用使得原子浓度的增长得到进一步提高。另一方面,若是增大解吸光波长,则 LIAD 的影响会减小,而光热效应的影响会增大。因此,通过改变解吸光波长能够调控光解吸过程中光解吸效应与光热效应的贡献大小。此外,由于不同功率密度的解吸光引起的升温情况不同,可以通过调节解吸光功率密度大小来实现对原子池温度的调控。研究结果对光子芯片的集成研究有重要参考价值。

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Photothermal Effect in Light-Induced Atomic Desorption

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Abstract

Objective Recently, the study of integrated photonic devices is an important field of investigation, especially the photonic chip loaded with an atomic medium is one of the research hotspots. Based on the atomic medium, the

integration of optical non-reciprocity, optical storage, and atomic clocks can be achieved. This requires an efficient interaction between light and atoms, which means that a certain optical depth is necessary and it is difficult to achieve at room temperature. The optical depth of an atomic medium can be increased by heating, but it is limited to the size of the photonic chip, which is not suitable in this scheme. Therefore, the use of light-induced atomic desorption (LIAD) is necessary, which does not require a heating system and it is beneficial to the integration of photonic chips.

LIAD is an impressive phenomenon observed in a sodium-vapor glass cell, whose inner surface is coated with a thin siloxane film. It has been observed in experiments that an incoherent light illuminates a cell filled with alkali atoms and these atoms adsorbed on the inner surface fall off. Thus, LIAD can effectively increase the atomic concentration in the vapor cell, which is completely different from the thermal effect, and many parameters influence the effect of light-induced atomic desorption, such as the intensity and frequency of desorption light, the atom species, the geometry of the cell, and the inner surface morphology. In this paper, it is found that the atomic concentration increases due to the LIAD effect and photothermal effect. The influences of two mechanisms are experimentally studied, which is of great significance to the research of photonic chips.

Methods A 150 mm diameter sphere with a highly reflective coating on the inner surface is used to enhance the LIAD effect, and a 460 nm light-emitting diode (LED) array mounted on the sphere is used as the illumination source. The power of the desorption light is changed by adjusting the driving current of the LED. When LIAD is carried out in a rubidium vapor cell, it is found that the temperature of the cell rises, which means that the atomic concentration increases due to the LIAD effect and the photothermal effect. By measuring the photothermal temperatures under different desorption light powers, the increase of atomic concentration caused by the photothermal effect is distinguished, and thus the relative influences of pure LIAD and photothermal effect are obtained. In order to verify whether the heat conduction caused by the LED array affects the cell or not, a water cooler is used to cool the LED array in the experiment. Besides, a glass plate is used to isolate the heat convection, which can reduce the effect of heat radiation on the cell.

Results and Discussions With the increase of desorption light power, the effects of LIAD and photothermal effect are both increased (Fig. 4). When the intensity of desorption light is 15 mW/cm^2 , the contribution of pure LIAD is close to 6 times that of the photothermal effect. In this case, the increase in atomic concentration caused by photothermal effect is basically negligible, and when the intensity reaches 80 mW/cm^2 , the ratio of atomic concentration increase caused by pure LIAD to that caused by photothermal effect is close to 6:4, which means that the effects of these two mechanisms are comparable (Fig. 5).

By cooling the LED array with a water cooler and isolating the heat convection, the temperature of the rubidium cell is $1\text{--}2 \text{ }^\circ\text{C}$ higher than that without water cooling (Fig. 6), which means that the heat radiation caused by the LED array has little effect on the cell. Besides, the effect of heat convection is even negligible, which means that the increase of temperature in LIAD is mainly caused by the photothermal effect.

Conclusions LIAD is a useful method to increase alkali atomic concentration without heating. In this paper, it is found that when using desorption light with high power density, the combined action of pure LIAD and photothermal effect further enhances the increase in atomic concentration. Besides, when increasing the wavelength of desorption light, the LIAD effect is reduced, while the photothermal effect is undoubtedly increased. Therefore, by changing the wavelength of desorption light, the contribution of these two mechanisms can be adjusted. In addition, since the desorption light with different power densities corresponds to different temperatures, the temperature of the atom cell can be controlled by adjusting the power density of the desorption light. These results have important reference value for the research of integrated photonic chips.

Key words quantum optics; light-induced atomic desorption; photothermal effect; optical depth; atomic concentration

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