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Dec 28, 2019

Dear Editor,

We are submitting a manuscript titled "*In-situ* measurement of vacuum window birefringence using $^{25}Mg^{+}$ fluorescence." for consideration of publication in Journal of Visualized Experiments. The paper presents a simple method to measure the degrees of circular polarization of laser light inside a vacuum chamber and the birefringence of vacuum window by means of fluorescence emitted by Doppler cooled ions in ion trap. The reported simple method can be extended to be used in other quantum optics experiments. The authors of the paper are W. H. Yuan, H. L. Liu, W. Z. Wei, Z. Y. Ma, P. Hao, Z. Deng, K. Deng, J. Zhang, and Z. H. Lu. The corresponding author is H. L. Liu and Z. H. Lu. H. L. Liu's email address is liuhongli@hust.edu.cn, Z. H. Lu's contact phone is +86 15927477455, and email address is zehuanglu@mail.hust.edu.cn. The manuscript is an original contribution, and was not under consideration for publication in other journals.

Sincerely yours,
H. L. Liu
Z. H. Lu

TITLE:

In Situ Measurement of Vacuum Window Birefringence using $^{25}Mg^+$ Fluorescence

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KEYWORDS:
Polarization, birefringence, fluorescence, waveplate, vacuum window, ion trap

SUMMARY:
Presented here is a method to measure the birefringence of vacuum windows by maximizing the fluorescence counts emitted by Doppler cooled $^{25}Mg^+$ ions in an ion trap. The birefringence of vacuum windows will change the polarization states of the laser, which can be compensated by changing the azimuthal angles of external wave plates.

ABSTRACT:
Accurate control of the polarization states of laser light is important in precision measurement experiments. In experiments involving the use of a vacuum environment, the stress-induced birefringence effect of the vacuum windows will affect the polarization states of laser light inside the vacuum system, and it is very difficult to measure and optimize the polarization states of the laser light in situ. The purpose of this protocol is to demonstrate how to optimize the polarization states of the laser light based on the fluorescence of ions in the vacuum system, and how to calculate the birefringence of vacuum windows based on azimuthal angles of external wave plates with Mueller matrix. The fluorescence of $^{25}Mg^+$ ions induced by laser light that is resonant with the transition of $|3^2\mathrm{P}_{3/2}, \mathrm{F}=4, \mathrm{m}_F=4\rangle \rightarrow |3^2\mathrm{S}_{1/2}, \mathrm{F}=3, \mathrm{m}_F=3\rangle$ is sensitive to the polarization state of the laser light, and maximum fluorescence will be observed with pure circularly polarized light. A combination of half-wave plate (HWP) and quarter-wave

plate (QWP) can achieve arbitrary phase retardation and is used for compensating the birefringence of the vacuum window. In this experiment, the polarization state of the laser light is optimized based on the fluorescence of $^{25}Mg^{+}$ ion with a pair of HWP and QWP outside the vacuum chamber. By adjusting the azimuthal angles of the HWP and QWP to obtain maximum ion fluorescence, one can obtain a pure circularly polarized light inside the vacuum chamber. With the information on the azimuthal angles of the external HWP and QWP, the birefringence of the vacuum window can be determined.

INTRODUCTION:

In many research fields such as cold atom experiments[1], measurement of the electric dipole moment[2], test of parity-nonconservation[3], measurement of vacuum birefringence[4], optical clocks[5], quantum optics experiments[6], and liquid crystal study[7], it is important to precisely measure and accurately control the polarization states of laser light.

In experiments involving the use of a vacuum environment, the stress-induced birefringence effect of vacuum windows will affect the polarization states of laser light. It is not feasible to put a polarization analyzer inside the vacuum chamber to directly measure the polarization states of the laser light. One solution is to use atoms or ions directly as an in situ polarization analyzer to analyze the birefringence of vacuum windows. The vector light shifts of Cs atoms[8] are sensitive to the degrees of linear polarization of the incidence laser light[9]. But this method is time consuming and can only be applied to the linearly polarized laser light detection.

Presented is a new, quick, precise, in situ method to determine the polarization states of laser light inside the vacuum chamber based on maximizing single $^{25}Mg^{+}$ fluorescence in an ion trap. The method is based on the relationship of the ion fluorescence to the polarization states of the laser light, which is affected by the birefringence of the vacuum window. The proposed method is used for detecting the birefringence of vacuum windows and degrees of circular polarization of laser light inside a vacuum chamber[10].

The method is applicable to any atoms or ions whose fluorescence rate is sensitive to the polarization states of laser light. In addition, while the demonstration is used to prepare a pure circularly polarized light, with the knowledge of the birefringence of the vacuum window, arbitrary polarization states of laser light can be prepared inside the vacuum chamber. Therefore, the method is quite useful for a wide range of experiments.

PROTOCOL:

1. Set up the reference directions for polarizers A and B

1.1. Put polarizer A and polarizer B into the laser beam (280 nm fourth harmonic laser) path.

1.2. Ensure that the laser beam is perpendicular to the surfaces of the polarizers by carefully adjusting the polarizer holders to keep the back-reflection light coincident with the incident light.

NOTE: All the following alignment procedures for the optics components must follow the same rule. The placement of polarizer A and B in the laser path is not important. The spacing between them should be large enough for the future convenient adjustment.

1.3. Put a power meter behind polarizer A and rotate the polarizer to maximize the output power. Define the azimuthal angle (see **Results** and **Discussion**) of the optical axis of polarizer A as 0˚. Define the clockwise direction as the positive direction and the counterclockwise direction as the negative direction when observing along the direction of light propagation.

1.3.1. Use a stepper motor rotation stage to hold polarizer A and put the power meter behind polarizer A to record the rotation angles and the output laser powers. Fit the angle vs power curve with a sinusoidal function; the maximum output power position of polarizer A is 0˚ azimuthal angle position.

1.4. Put the power meter behind polarizer B and rotate polarizer B to maximize the output power. The azimuthal angle of the optical axis of polarizer B is then also 0˚.

1.4.1. Use another stepper motor rotation stage to hold polarizer B and put the power meter behind polarizer B to record the rotation angles and the output laser powers. Fit the angle vs power curve with a sinusoidal function; the maximum output power position of polarizer B is 0˚ azimuthal angle position (see **Figure 1**).

2. Set up the reference directions for the azimuthal angles of the waveplates

2.1. Put an HWP into the beam path between polarizer A and polarizer B and rotate the HWP to maximize the output power. The azimuthal angle of the optical axis of the HWP is then 0˚.

2.1.1. Use a stepper motor rotation stage to hold the HWP and put the power meter behind polarizer B to record the rotation angles and the output laser powers. Fit the angle vs power curve with a sinusoidal function; the maximum output power position of the HWP is 0˚ azimuthal angle.

2.2. Put a QWP into the beam path between the HWP and polarizer B, rotate the QWP to maximize the output power. The azimuthal angle of the optical axis of the QWP is then 0˚.

2.2.1. Use a stepper motor rotation stage to hold the QWP and put the power meter behind polarizer B to record the rotation angles and the output laser powers. Fit the angle vs power curve with a sinusoidal function; the maximum output power position of the QWP is 0˚ azimuthal angle position.

2.3. Remove polarizer B and the power meter from the beam path. Use two mirrors to direct laser beam into the vacuum chamber that houses an ion trap to interact with $^{25}Mg^{+}$ ions.

NOTE: The laser propagation direction should be along the magnetic field direction inside the vacuum chamber. A magnetic field is used to define the quantization axis of the ions.

3. Doppler cooling of single $^{25}Mg^{+}$ ions

3.1. Turn on the 532 nm ablation laser, which is a Q-switched Nd:YAG laser. Its repetition rate is 1 kHz, with pulse energy of 150 µJ. The ablation laser irradiates a magnesium wire target surface inside the vacuum chamber, and then magnesium (Mg) atoms are ejected from the target surface.

NOTE: The power supply for the ion trap should be turned on.

3.2. At the same time, turn on the 285 nm ionization laser to ionized Mg atoms. The ionization laser is a fourth harmonic laser with an output power of 1 mW. The ionization laser will illuminate the center of the ion trap.

3.3. Make sure only one ion is trapped in the ion trap by looking at the image of an electron multiplied charged coupled device (EMCCD). An example image showing trapped ions is shown in **Figure 2**. Each bright spot is one ion. If there is more than one ion in the trap, turn off the power supply of the ion trap to release the ions. Then repeat steps 3.1-3.2 until only one (i.e., single) ion is trapped.

NOTE: The homemade imaging system of the EMCCD consists of four lenses, and its magnification is 10x. The ion spacing is about 2-10 µm and the pixel spacing of the EMCCD is 16 µm. The EMCCD can, therefore, be used to identify the existence of one single ion.

3.4. Set the magnetic field to be 6.5 Gauss by adjusting the current of Helmholtz coils. The magnetic field is measured by comparing the different frequencies between the two ground state transitions, $|\mathrm{F}=2,\mathrm{m_F}=2\rangle \rightarrow |\mathrm{F}=3,\mathrm{m_F}=3\rangle$ and $|\mathrm{F}=2,\mathrm{m_F}=0\rangle \rightarrow |\mathrm{F}=3,\mathrm{m_F}=0\rangle$. For details of the method please refer[11].

4. Lock the 280 nm Doppler cooling laser frequency to a wavelength meter [12]

4.1. Scan the frequency of the 280 nm laser and count the fluorescence photon numbers collected by a photon multiplier tube (PMT) by a frequency counter. At the same time, record the frequency of the laser using a wavelength meter. Find the resonant frequency ν_0 where the fluorescence rate reaches a maximum.

NOTE: The fluorescence counts will increase when the laser frequency is moving close to the ion resonant frequency and will reach a maximum at the resonant frequency ν_0.

4.2. Lock the laser frequency to the wavelength meter using a digital servo control program that is running on an accompanying computer. Click on the **Lock** button on the program graphic interface when the wavelength meter shows a reading of ν_0.

5. Set the intensity of the laser to equal the saturation intensity[12]

5.1. Change the power of the laser by adjusting the driving power of an acousto-optic-modulator (AOM), which is used in the beam path to change the frequency and power of the laser. Record the power and the fluorescence counts.

5.2. Fit the curve of the power and the fluorescence counts with Equations 1-(1), and obtain the saturation power P_s.

5.3. Set the laser power to P_s by adjusting the driving power of the AOM.

6. Measure the birefringence of the vacuum window.

6.1. Alternately, adjust the azimuthal angles of the HWP and the QWP to maximize the fluorescence counts. Record the azimuthal angles of the HWP and the QWP at maximum counts, which are α and β.

6.1.1. Use the stepper motor rotation stages to rotate the HWP and the QWP and record the rotation angles and the corresponding fluorescence counts.

6.2. Use Equation (4) and Equation (5) to calculate the birefringence of the vacuum window θ and δ.

REPRESENTATIVE RESULTS:

Figure 3 shows the beam path of the experiment. Polarizer B in **Figure 3a** is removed after angle initialization (**Figure 3b**). The laser passed through a polarizer, an HWP, a QWP, and the vacuum window, sequentially. The Stokes vector of laser is $S_L = [S_{L0}, S_{L1}, S_{L2}, S_{L3}]^T$, where S_{L0} is the normalized laser power. The Stokes vector should be $[1,1,0,0]^T$ after passing the polarizer, which means the laser was linearly polarized. The Mueller matrices for the polarizer, HWP, QWP, and vacuum window were M_{GL}, $M_{\lambda/2}$, $M_{\lambda/4}$ and M_W, respectively. Finally the ion was excited by the laser and the fluorescence was collected by a PMT. The Stokes vector of the laser inside the vacuum chamber was

$$S = M_W R(-\beta) M_{\lambda/4} R(\beta) R(-\alpha) M_{\lambda/2} R(\alpha) M_{GL} S_L, \quad (1)$$

where R is the rotational matrix, α and β are the azimuthal angles of the HWP and the QWP, respectively. The Mueller matrix of each optical components and the rotational matrix are given below:

$$\mathrm{M_{GL}} = \frac{1}{2}\begin{pmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix},$$

$$\mathrm{M_{\lambda/2}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix},$$

$$\mathrm{M_{\frac{\lambda}{4}}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}, \tag{2}$$

$$\mathrm{R}(\gamma) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\gamma & \sin 2\gamma & 0 \\ 0 & -\sin 2\gamma & \cos 2\gamma & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

$$\mathrm{M}_w = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1-(1-\cos\delta)(\sin 2\theta)^2 & (1-\cos\delta)\sin 2\theta\cos 2\theta & -\sin\delta\sin 2\theta \\ 0 & (1-\cos\delta)\sin 2\theta\cos 2\theta & 1-(1-\cos\delta)(\cos 2\theta)^2 & \sin\delta\cos 2\theta \\ 0 & \sin\delta\sin 2\theta & -\sin\delta\cos 2\theta & \cos\delta \end{pmatrix}$$

From Equation (1), the Stokes vector of the laser inside the vacuum chamber is:

$$\mathrm{S} = [\mathrm{S}_0 \quad \mathrm{S}_1 \quad \mathrm{S}_2 \quad \mathrm{S}_3]^T. \tag{3}$$

Here

$$\begin{aligned} \mathrm{S}_0(\alpha,\beta,\delta,\theta) &= 1, \\ \mathrm{S}_1(\alpha,\beta,\delta,\theta) &= \sin(4\alpha-2\beta)\sin\delta\sin 2\theta \\ &\quad + \cos(4\alpha-2\beta)\{\cos 2\beta\,[\cos^2(\delta/2)+\cos 4\theta\sin^2(\delta/2)] \\ &\quad + \sin 2\beta\sin^2(\delta/2)\sin 4\theta\}, \\ \mathrm{S}_2(\alpha,\beta,\delta,\theta) &= -\cos 2\theta\sin(4\alpha-2\beta)\sin\delta \\ &\quad + \cos(4\alpha-2\beta)\left[\cos^2\left(\frac{\delta}{2}\right)\sin 2\beta - \sin^2(\delta/2)\sin(2\beta-4\theta)\right], \\ \mathrm{S}_3(\alpha,\beta,\delta,\theta) &= -\cos\delta\sin(4\alpha-2\beta) - \cos(4\alpha-2\beta)\sin\delta\sin(2\beta-2\theta). \end{aligned}$$

Specifically, when the laser is circularly polarized, that is $\mathrm{S}_3(\alpha,\beta,\delta,\theta) = 1$, there must be

$$\delta = \pi/2 + (4\alpha - 2\beta), \quad \theta = \beta + \pi/4. \tag{4}$$

or

$$\delta = -\pi/2 - (4\alpha - 2\beta), \quad \theta = \beta - \pi/4. \tag{5}$$

The two results correspond to whether we define the fast axis angle as 0˚ or the slow axis angle as 0˚. They were equivalent when the fast axis was exchanged with the slow axis. Equation (4) and Equation (5) are the relationships between the azimuthal angles of the waveplates and the birefringence of the vacuum window when the laser in the vacuum chamber is circularly polarized.

To determine the polarization states of the light inside the vacuum chamber, one should know the relationship between the polarization states of the light and the fluorescence counts. Because $^{25}Mg^{+}$ ion has 48 Zeeman levels, as shown in **Figure 4**, analytical solutions cannot be derived from the rate equations. But these can be simulated by numerical program, and the numerical results are shown in **Figure 5**. In the figure, the relationships between the polarization states and the fluorescence counts under different light intensities are shown. From the relationships, we know the polarization state of the light inside the vacuum chamber is $S_3 > 0.999$ when the fluorescence counts are maximized. At this position, the fluctuation of the fluorescence count is <2%.

In the protocol section 5, the intensity of the laser is set to the saturation intensity. When the frequency of the laser is fixed, the fluorescence count $F(P)$ depends on the intensity of the laser. The relation is [14]

$$F(P) = \frac{\eta\Gamma/2}{1 + \left(1 + \frac{4\Delta_D^2}{\Gamma^2}\right) \cdot \frac{I}{I_S}}, \qquad (6)$$

where Δ_D is the laser detuning from the resonant frequency, $\Gamma = 41.7$ MHz is the natural linewidth of the magnesium ion's upper energy level. I and I_S are the laser intensity and the saturation intensity, respectively. The intensity and power have relationship of $\frac{I}{I_S} = \frac{P}{P_S}$, so the light intensity is I_S if the power is P_S. **Figure 6** shows the relationship of the laser power and the fluorescence counts under different detuning frequencies. We can fit the curves with Equation (6) to obtain the saturated power P_S.

By fixing the azimuthal angle of one waveplate and rotating the other, and recording the angles and the fluorescence counts, we got **Figure 7**. The red line is the theoretical result and the black dots with error bars are the experimental results. They agree with each other very well, demonstrating the reliability of the method.

FIGURE AND TABLE LEGENDS:

Figure 1: Relationship between the azimuthal angle of polarizer B and the laser power. Rotate the azimuthal angle of polarizer B and record the laser power. The fitted cure is a sinusoidal function. The azimuthal angle of polarizer B is 0˚ when the power is maximum. There are two

maximum points corresponding to two polarization axis positions with angle difference of 180˚.

Figure 2: Picture of trapped ions taken by the EMCCD. The first row shows the example of two trapped ions, and the second row shows an example of one trapped ion. Each bright spot corresponds to one ion.

Figure 3: Schematics for the experimental set up. (a) The experimental setup for defining the azimuthal angles of different optical components. Polarizer A (GL-A) was used to initialize angles of each components, and polarizer B (GL-B) was used to analyze this initialization. $\lambda/2$ is HWP, $\lambda/4$ is QWP. (b) The experimental setup for determining the birefringence of the vacuum window. A 280 nm laser passes through a polarizer A (GL-A), an HWP, a QWP and vacuum window, and then illuminates $^{25}Mg^{+}$ ions.

Figure 4: The relevant energy levels of $^{25}Mg^{+}$ ion. F is the total angular momentum quantum number, and m_F is the magnetic quantum number. Different m_F values correspond to different Zeeman levels that have different energy values under a magnetic field. There are 48 Zeeman levels in the figure (each is shown with a short horizontal lines) that are used for simulating the population distribution.

Figure 5: Simulation results showing the relationship of the laser polarization state S_3 and the fluorescence counts with different laser intensities. The magnetic field was fixed at 6.5 G, which is consistent with our experimental parameter. This figure was modified from Yuan et al.[10].

Figure 6: Fluorescence count per 0.1 s vs laser power for different laser frequency detuning Δ_D. This figure was modified from Yuan et al.[13].

Figure 7: The relationship of the fluorescence counts with the azimuthal angles of the wave plates. (**a**) Varying the azimuthal angles of the HWP with the angle of the QWP set at 149˚. (**b**) Varying the azimuthal angles of the QWP with the angle of the HWP set at 2.6˚. The black dots are the experimental results, the error bars were determined by the standard deviations of the fluorescence count fluctuations. The red lines are the theoretical calculation results based on simulation results. This figure was modified from Yuan et al. [10].

DISCUSSION:

This manuscript describes a method to perform in situ measurement of the birefringence of the vacuum window and the polarization states of the laser light inside the vacuum chamber. By adjusting the azimuthal angles of the HWP and the QWP (α and β), the effect of the birefringence of the vacuum window (δ and θ) can be compensated so that the laser inside the vacuum chamber is a pure circularly polarized light. At this point, there exists a definite relationship between the birefringence of the vacuum window and the azimuthal angles of the HWP and the QWP, from which we can infer the birefringence of the vacuum window. Measurement errors of the azimuthal angles affect the accuracy of the birefringence measurement. Therefore, in the initialization of the waveplate azimuthal angle step, the stepper motor rotation stage should be sufficiently accurate (~0.001˚). As an alternative, other common phase retarder, such as crystal wave plates, liquid-crystal-based wave plates or electro-optic modulators, could be used for compensating the birefringence of the vacuum window. Some other systematic uncertainties will also affect the measurement accuracy, such as the frequency and the power stability of laser, dark count of PMT, shot noise, and so on. These are discussed in Yuan et al. [10].

To perform the method accurately, one needs to prepare lasers to ionize Mg atoms and irradiate the $^{25}Mg^{+}$, a pair of HWP and QWP for adjusting the polarization states of the laser, two Glan-Taylor polarizers to guarantee and test polarization states, ion trap for ion storage, mirrors, Mg target material, PMT for counting the photon, EMCCD for imaging the ion in the trap, stepper motor rotation stages to adjust the azimuthal angles of polarizers and waveplates.

In vacuum-based experiments, such as optical clocks[5], cold atoms[1], atom interferometers[15], quantum optics experiments[6], this method can be used to in situ measure the birefringence of the vacuum window. The birefringence is caused by the stress on the vacuum window; hence it will be different when the temperature changes. As the method is much simpler and faster, it can be applied to compensate the thermal effect in real-time by feedback to the waveplates.

The success of this method hinge on the extremely high sensitivity of the fluorescence rate to the laser polarization states. There might have atom or ion systems whose fluorescence rates are not sensitive to the laser polarization states. Therefore, in other atom or ion systems, for the method to work, simulation of the relationship of the laser polarization states and the fluorescence counts needs to be performed to determine whether this method is suitable. Simulation is based on rate equations. More steps and smaller step size will make the result more accurate, with the downside of longer measurement time. The steps should be small enough, in our experience it is about $1/(10\Gamma)$. The population of each level will reach stable state after sufficient time. The proper time is associated with the energy level structures of specific ion or atom. As for $^{25}Mg^{+}$ ion, the simulation contains 48 energy levels, so 10^6 times steps are suitable. For other atoms or ions, the population should be first simulated to determine the suitable step number.

ACKNOWLEDGMENTS:

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DISCLOSURES

The authors have nothing to disclose.

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Figure 1

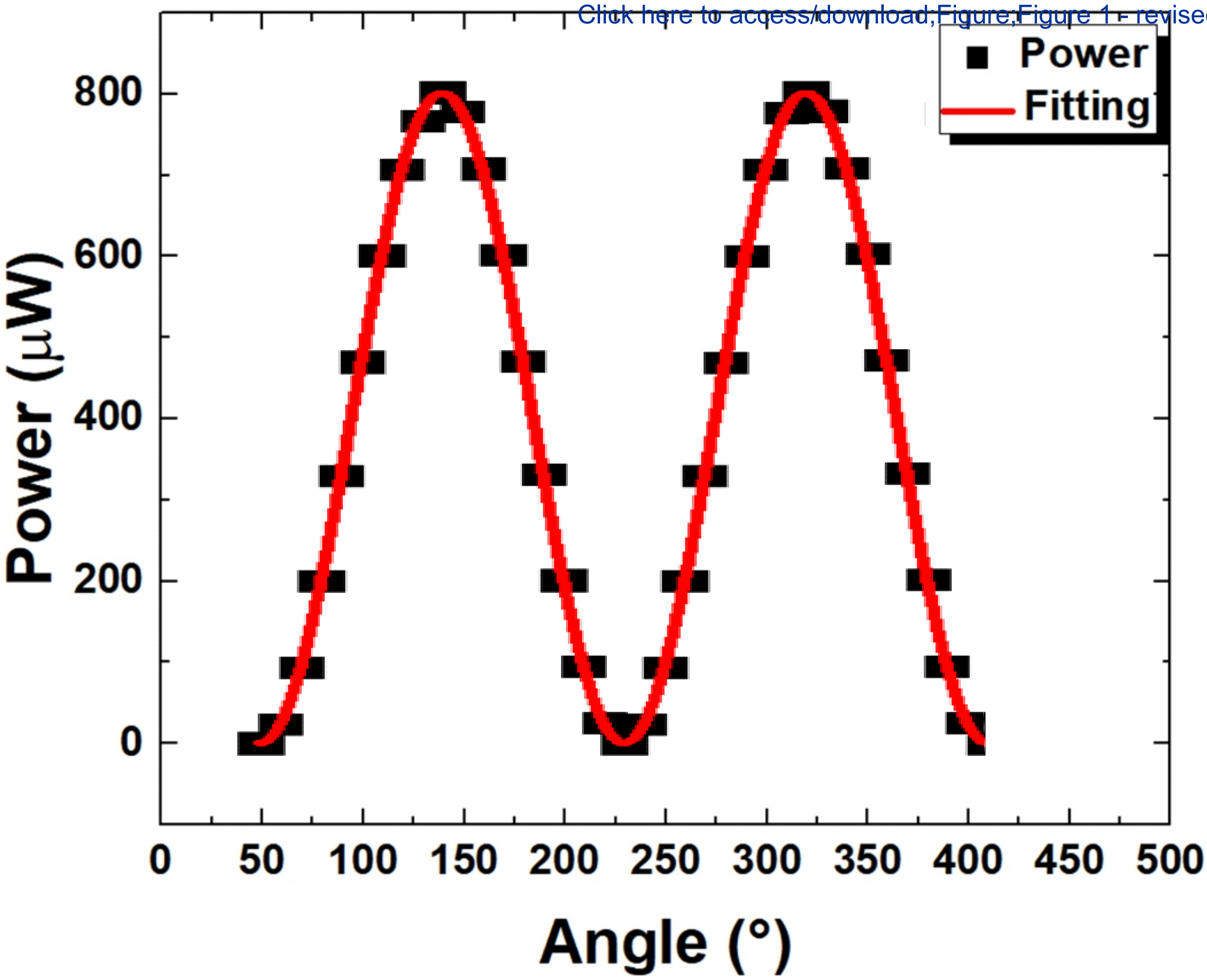
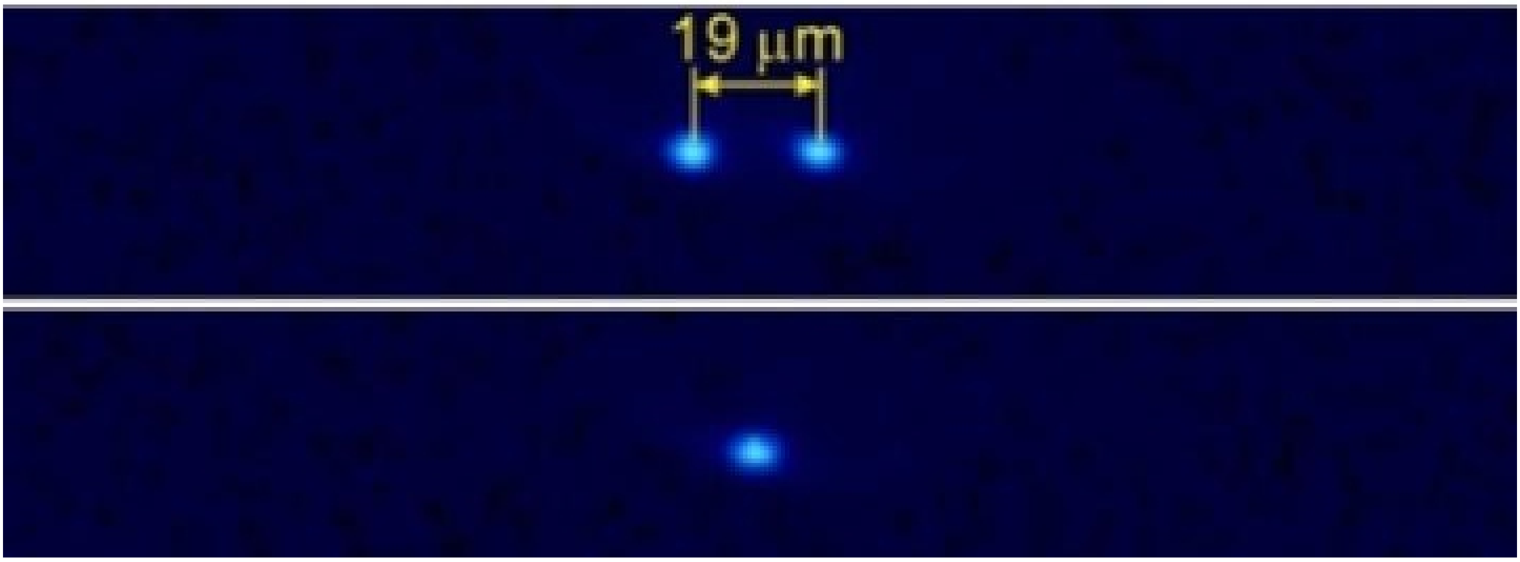
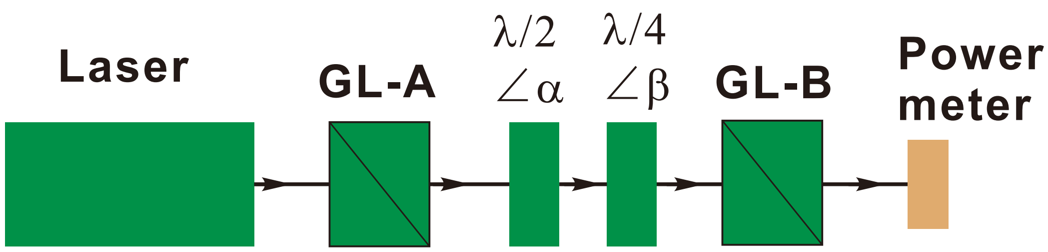

Power
Fitting
800
600
400
200
0
Power (μW)
0
50
100
150
200
250
300
350
400
450
500
Angle (°)

Figure 2

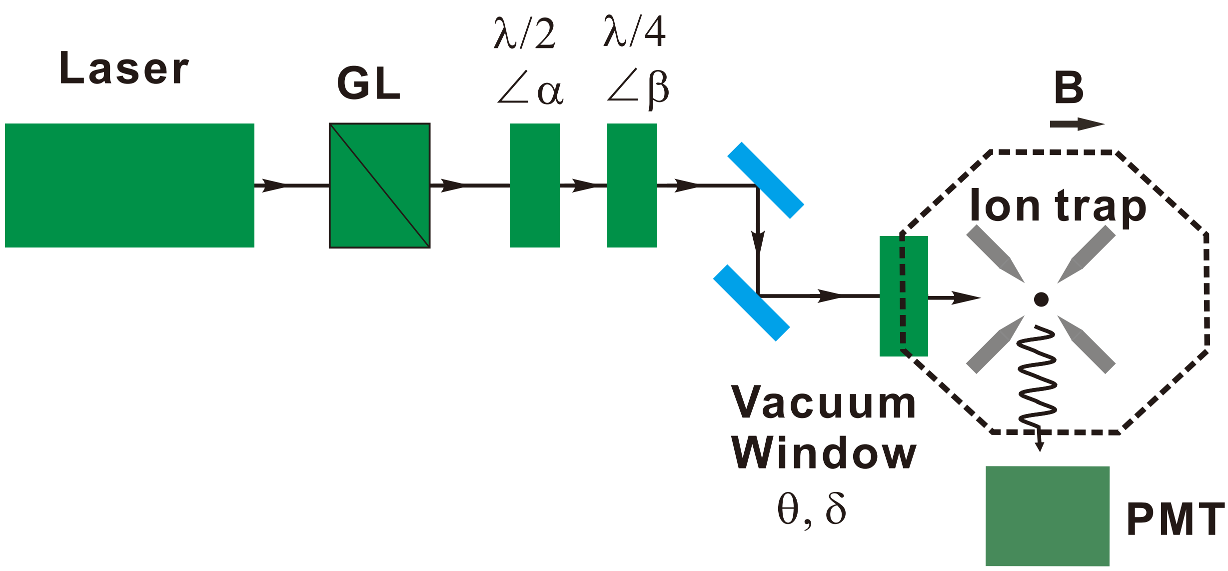
Click here to access/download;Figure;Figure 2.pdf





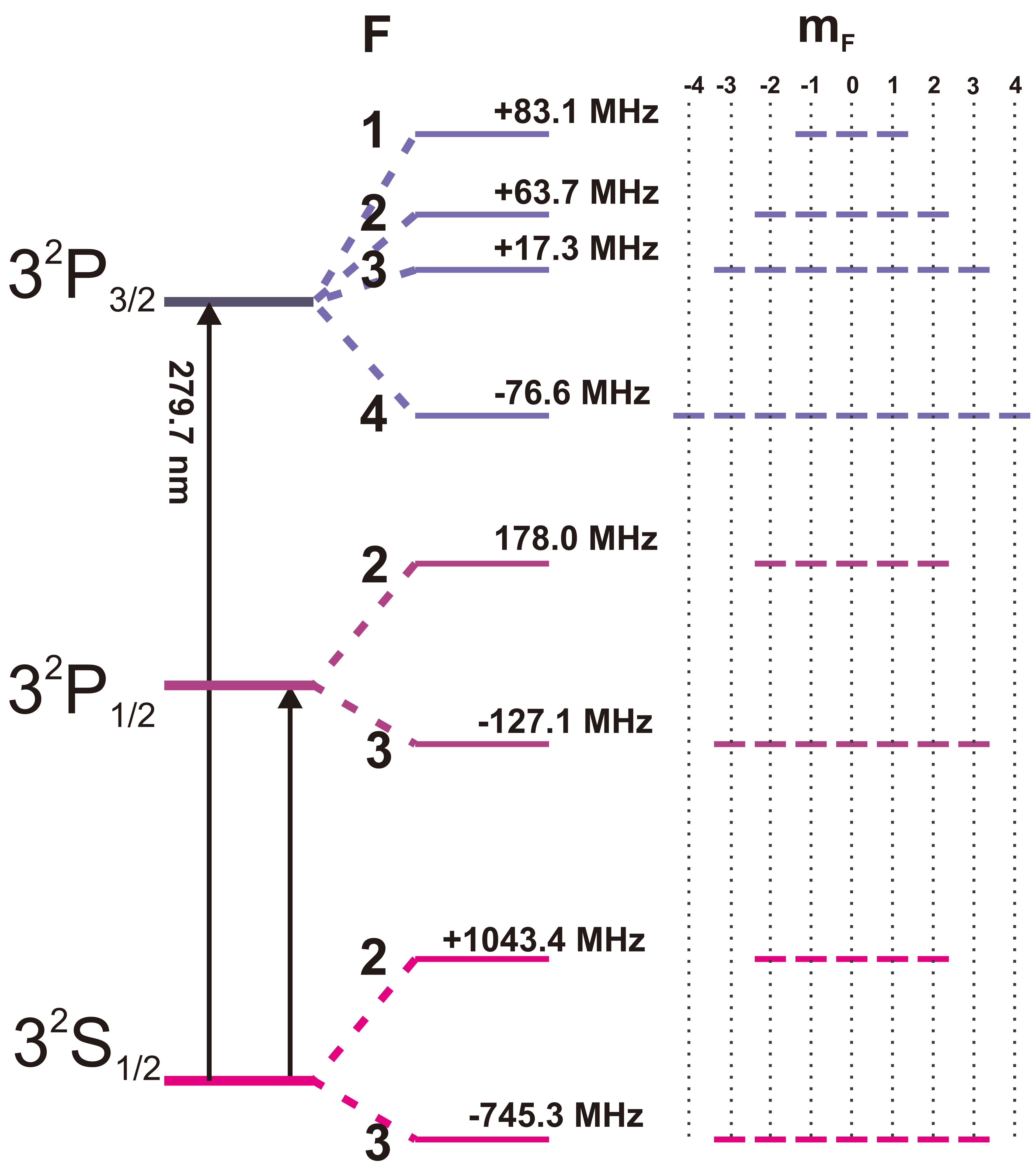
Laser
GL-A
λ/2
∠α
λ/4
∠β
GL-B
Power
meter

(a)



Laser
GL
λ/2
∠α
λ/4
∠β
B
Ion trap
Vacuum
Window
θ, δ
PMT

(b)


F
m_F
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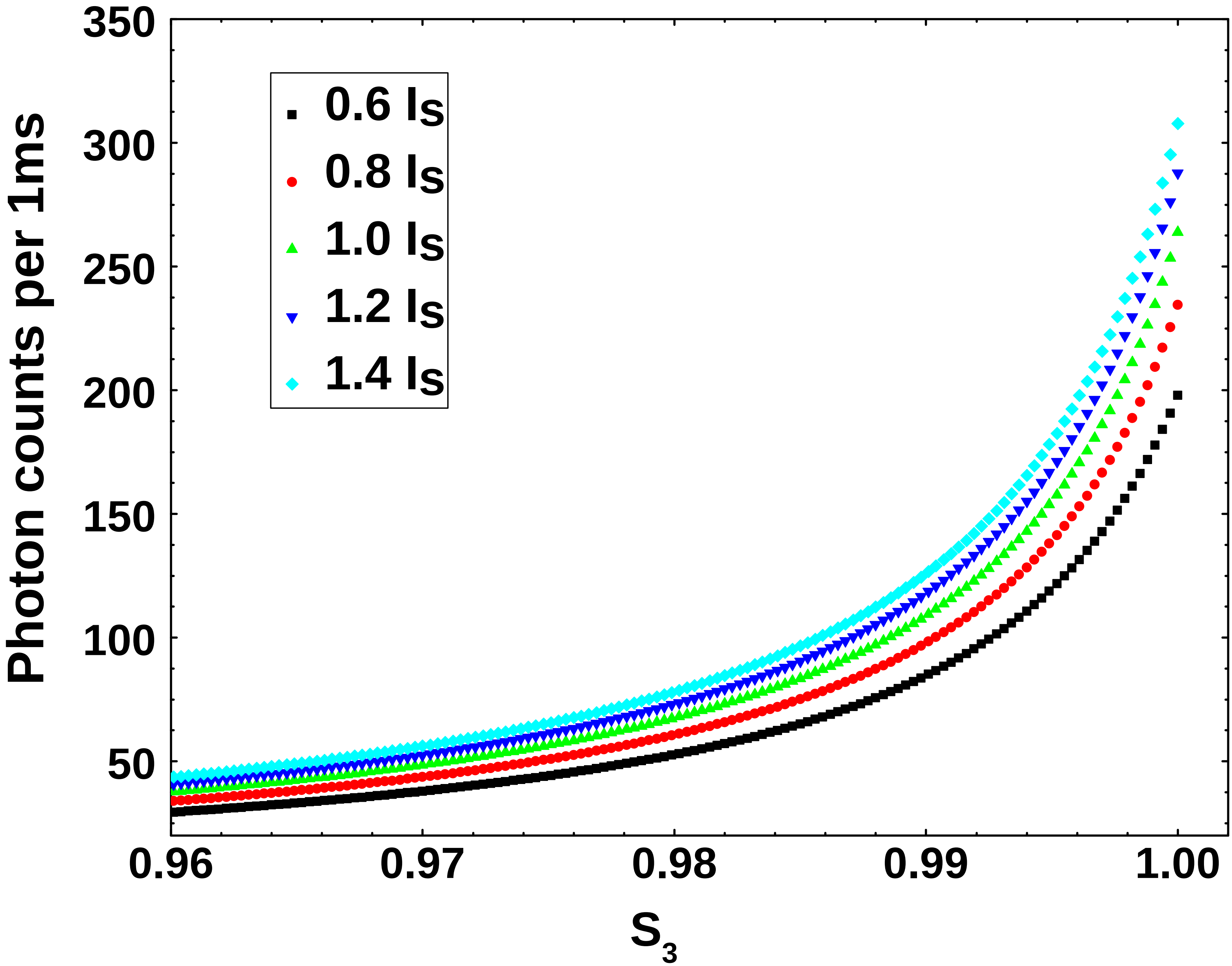
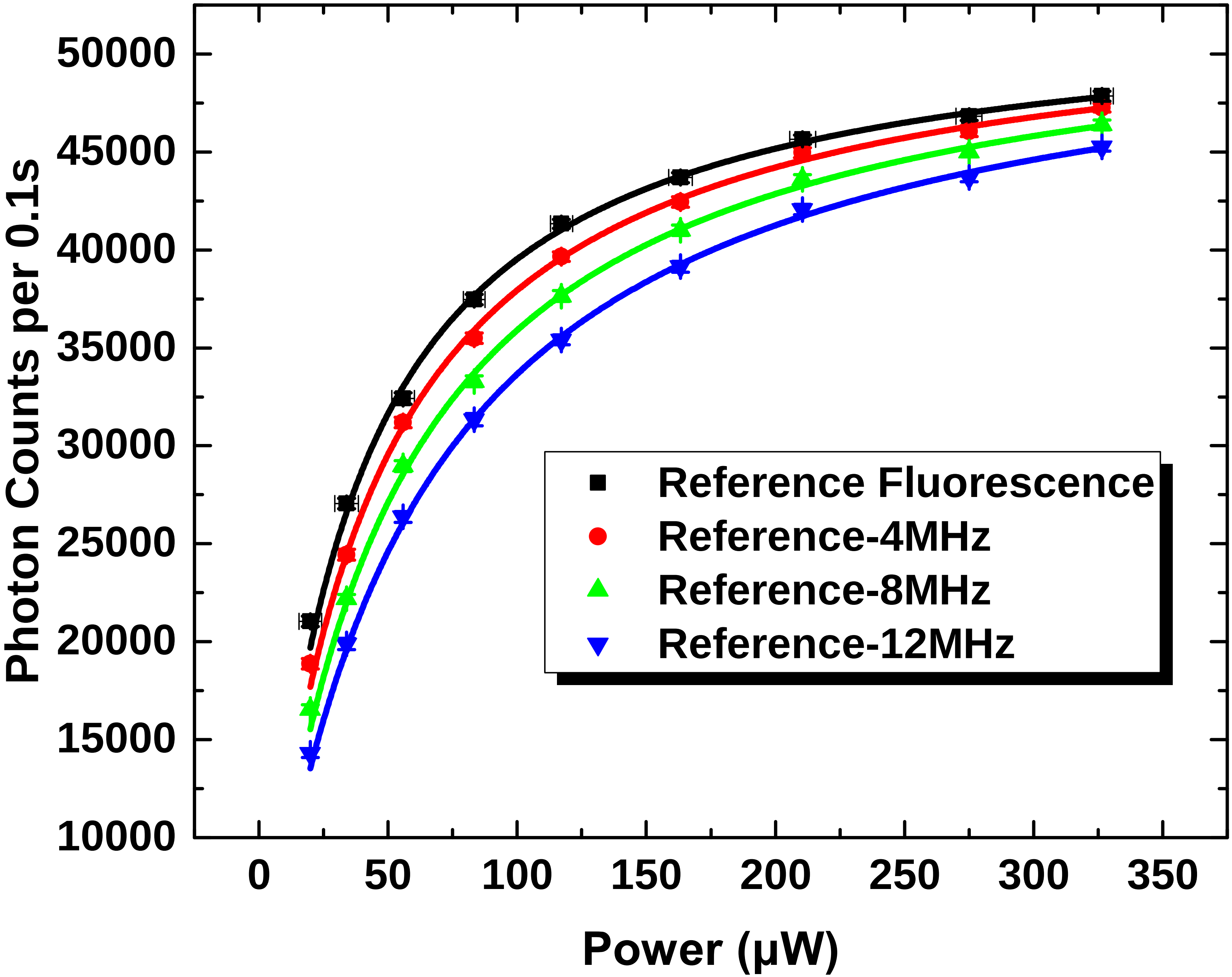
$3^2P_{3/2}$
279.7 nm
1
+83.1 MHz
2
+63.7 MHz
3
+17.3 MHz
4
-76.6 MHz
$3^2P_{1/2}$
2
178.0 MHz
3
-127.1 MHz
$3^2S_{1/2}$
2
+1043.4 MHz
3
-745.3 MHz

Figure 5



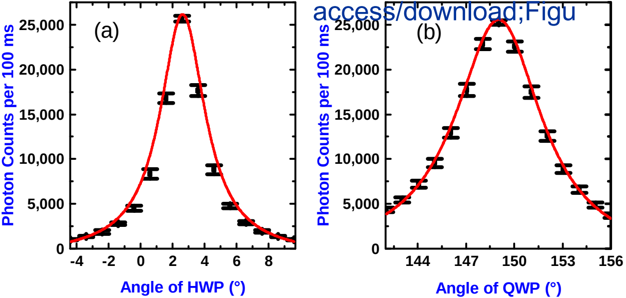
Photon counts per 1ms
350
300
250
200
150
100
50
0.96
0.97
0.98
0.99
1.00
S3
0.6 Is
0.8 Is
1.0 Is
1.2 Is
1.4 Is

Figure 6



Photon Counts per 0.1s
50000
45000
40000
35000
30000
25000
20000
15000
10000
0
50
100
150
200
250
300
350
Power (μW)
Reference Fluorescence
Reference-4MHz
Reference-8MHz
Reference-12MHz

Figure 7


(a)
Photon Counts per 100 ms
25,000
20,000
15,000
10,000
5,000
0
-4
-2
0
2
4
6
8
Angle of HWP (°)
(b)
Photon Counts per 100 ms
25,000
20,000
15,000
10,000
5,000
0
144
147
150
153
156
Angle of QWP (°)

Name of Material/ Equipment	Company	Catalog Number
280 nm Doppler cooling laser	Toptica	SYST DL-FHG Pro 280
285 nm ionization laser	Toptica	SYST DL-FHG Pro 285
Ablation laser	Changchun New Industries	EL-532-1.5W
AOM	Gooch & Housego	AOMO 3200-1220
EMCCD camera	Andor	iXon3 897
Glan-Taylor polarizer	Union Optic	Custom
Half waveplate	Union Optic	Custom
Photon multiplier tube	Hamamatsu	H8259-09
Power meter	Thorlabs	PM100D
Quarter waveplate	Union Optic	Custom
Mirror	Union Optic	Custom
Stepper motor roation stage	Thorlabs	K10CR1/M
Vacuum chamber	Kimball Physics	MCF800-SphSq-G2E4C4
Vacuum window	Union Optic	Custom

Comments/Description

Doppler cooling laser
ionization laser
Q-switched Nd:YAG laser
wavelengh down to 257 nm
imaging of $^{25}Mg^{+}$ in ion trap
distinction ratio 1e-6
made of quartz
fluorescent counting
laser power monitor
made of quartz
dielectric coated for 280 nm
rotating wave plates
made of Titanium
made of fused silica

Dear Editor,

Thanks for your letter and the careful reviews provided by the three reviewers. We have made substantial revisions to our manuscript. A marked pdf copy showing all the changes is attached together with the revised manuscript. We hope the manuscript can be accepted for publication now, and can serve its tutorial purpose for interested parties.

Sincerely yours,

Zehuang Lu

The followings are our responses to the editor's and reviewers' comments. Our responses are marked with red color.

Editorial comments:

Changes to be made by the Author(s):

1. Please take this opportunity to thoroughly proofread the manuscript to ensure that there are no spelling or grammar issues. The JoVE editor will not copy-edit your manuscript and any errors in the submitted revision may be present in the published version.

We have made necessary revisions to the manuscript.

2. Please define all abbreviations during the first-time use.

We have defined all abbreviations during the first-time use.

3. Please define all abbreviations during the first-time use.

See above.

4. Please ensure that the long Abstract is within 150-300-word limit and clearly states the goal of the protocol.

We have made necessary revisions to the long Abstract.

5. Please revise the Introduction to include all of the following with citations:

a) A clear statement of the overall goal of this method

b) The rationale behind the development and/or use of this technique

c) The advantages over alternative techniques with applicable references to previous studies

d) A description of the context of the technique in the wider body of literature

e) Information to help readers to determine whether the method is appropriate for their application

We have made necessary revisions to the Introduction.

6. JoVE cannot publish manuscripts containing commercial language. Please remove all commercial language from your manuscript and use generic terms instead. All commercial products should be sufficiently referenced in the Table of Materials and Reagents.

For example: Glan-Taylor polarizer, etc.

We have made the necessary changes in the manuscript, and changed Glan laser to Glan-Taylor polarizer in Materials Table.

7. Please reword lines 29-31, 49-51, 149-152, as it matches with previously published literature.

We have made the necessary revisions.

8. Please ensure that all text in the protocol section is written in the imperative tense as if telling someone how to do the technique (e.g., "Do this," "Ensure that," etc.). The actions should be described in the imperative tense in complete sentences wherever possible. Avoid usage of phrases such as "could be," "should be," and "would be" throughout the Protocol. Any text that cannot be written in the imperative tense may be added as a "Note."

We have made revisions to the protocol section.

9. Please ensure that individual steps of the protocol should only contain 2-3 actions per step.

Done.

10. Please add more details to your protocol steps. Please ensure you answer the "how" question, i.e., how is the step performed? Please include all the button clicks, knob turns, command lines, etc.

We have added enough details to the protocol steps.

11. How was the laser beam path generated? Where specifically A and B polarizer are present with respect to each other and the laser beam path. For section 1 please provide a schematic to show the position of the polarizers, beam path and HWP etc. Need more clarity on how to find the azimuthal angles in your experimental setup.

The laser beam is generated by a 280 nm commercial fourth harmonic laser (Toptica DL-FHG pro). We have added the required schematic (Fig. 1(a)). The placement of polarizer A and B in the laser path is not important. The spacing between them should be large enough for future convenient adjustment.

12. Please include the source of ablation and ionization laser in the experiment being performed. How do you view with EMCCD?

We have added the description of the ablation laser and ionizaiton laser. The ablation laser irradiates the Mg target surface, and then the Mg atoms are ejected from the target surface. Mg atoms are then ionized by the ionization laser. The homemade imaging system of EMCCD consists of four lenses, and its magnification is 10 times. The ion spacing is about 2-10 μm, and the pixel spacing of EMCCD is 16 μm, so EMCCD can distinguish single ion.

13. Please describe all the actions associated with the step and how it is performed.

We have added those contents to the paper.

14. There is a 10-page limit for the Protocol, but there is a 2.75-page limit for filmable

content. Please highlight 2.75 pages or less of the Protocol (including headings and spacing) that identifies the essential steps of the protocol for the video, i.e., the steps that should be visualized to tell the most cohesive story of the Protocol.

Has highlighted those steps.

15. Please ensure that the Representative Results are in the context of the technique you have described, e.g., how do these results show the technique, suggestions about how to analyze the outcome, etc. The paragraph text should refer to all of the figures. Data from both successful and sub-optimal experiments can be included.

The Representative Results are in the context of the technique we have described.

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We have asked for permissions from PRA and RSI.

17. Each Figure Legend should include a title and a short description of the data presented in the Figure and relevant symbols.

Done.

18. As we are a methods journal, please revise the Discussion to explicitly cover the following in detail in 3-6 paragraphs with citations:

a) Critical steps within the protocol

b) Any modifications and troubleshooting of the technique

c) Any limitations of the technique

d) The significance with respect to existing methods

e) Any future applications of the technique

Has been revised.

19. Please sort the materials table in alphabetical order.

We have sorted the materials table.

20. Please ensure that the references appear as the following: [Lastname, F.I., LastName, F.I., LastName, F.I. Article Title. Source. Volume (Issue), FirstPage – LastPage, (YEAR).] For more than 6 authors, list only the first author then et al.

We have revised the references.

Reviewers' comments:

Reviewer #1:

Manuscript Summary:

The method introduced is widely used in laser trapping community and it would be useful to introduce it for a larger appeal (see e.g., Applied Physics Letters 82, 4657 (2003); doi:

10.1063/1.1588366).

Major Concerns:

The protocol step 1.7 speaks about the mirrors which are not shown in setup in fig 1. Mirrors can be metallic or dielectric and phase change of circularly polarised light can take place at the reflection. Consequently, ellipticity of polarisation will change. This is very important step to explain and describe in the protocol how to tackle the issue. The discussion part could have a section where compensation of the polarisation changes is counterbalanced. The birefringence in the window is assumed to be simple uniaxial. depending on the window mounting, more complex birefringence patterns can be introduced. What protocol changes are required then?

The mirrors have been added in Fig. 1. The mirrors are dielectric coated. The reflection difference of s and p light is less than 1%. This negligible effect can be incorporated into the birefringence of the vacuum window since in most experiments we are more concerned about the polarization states of the laser light inside the vacuum chamber. As discussed in the manuscript, the polarization changes are actually compensated by the combination of the half-wave plate and the quarter-wave plate first to obtain the maximum fluorescence counts. The vacuum window birefringence is inferred as an after-fact.

The case dealing with much more complex birefringence patterns is beyond the scope of this manuscript.

Reviewer #2:

Manuscript Summary:

In their manuscript "In-situ measurement of vacuum window birefringence ...", Wenhao Yuan and coworkers propose a method to determine in situ the birefringence of a vacuum window. Even so the method might not have an industrial application, the authors clearly motivate the application potential for basic science. The method has been introduced by the authors earlier, the papers are properly cited as references [9] and [11]. Also, figures are directly taken from these references.

The steps listed in the procedure are clearly explained and seem to be appropriate to demonstrate the application potential of the method. However, the measurement of two different windows or window materials with vastly different values of birefringence instead of a single window would probably help the reader to appreciate and to understand the method even better.

Thank you for your comments. Different windows and window materials will be tested in the future.

Major Concerns:

none

Minor Concerns:

1. Line 131, Step 4.3: The AOM for adjusting laser power is not included in the table of needed equipment.

We have included the AOM in the table.

2. Line 142, Step 5.2: What values for the birefringence do the authors expect?

The birefringence can be quite different for different installations, and is affected by materials of window, and can even be affected by the ambient temperature.

3. Line 188: The authors state that "at which situation the photon counts fluctuation of light is less than 2% when the photo counts are maximized". How can one see that?

The photons are counted by a PMT and a digital counting unit. The numbers are processed by computer, and the fluctuation (its standard deviation) is less than 2%.

4. Line 197: How large is the saturation intensity?

The saturation intensity of Mg+ is $I_S = \hbar\omega^3\Gamma/(12\pi c^2) \approx 2470\ \mathrm{W/m^2}$.

5. A number of typos in the Table of materials: Qudra vs quarter, multifier vs multiplier, winodow vs window, ioninzation vs ionization, monintor vs monitor

We have made corrections to the table.

Reviewer #3:

1. Original Submission

1.1 Recommendation

Major Revision

2. Comments to Author:

Manuscript Number: JoVE61175

Title: (Instructions) In-situ measurement of vacuum window birefringence using 25Mg+ fluorescence

Overview and general recommendation:

Precise measurement and control of the polarization of the laser light is important to many research fields. Especially when windows mediate between the laser light and the sample, stress-induced polarization can affect the polarization of the laser light and hence the experiment. Therefore, an in-situ method to measure the birefringence of the window could be of help. Such a method is proposed and described in the paper and is based on polarization sensitive fluorescence measured in single Mg+ in an ion trap.

The method is using a quarter- and a half-wave plate to arbitrarily change the polarization of the light while before having determined the position of the 0 axis of the plates. This way the discrepancy between the initial 0 axis angles and the adjustment of the angles needed for maximum ion fluorescence, gives the birefringence of the incident window.

2.1 Major Comments

1. There are many typos, commas missing as well as grammar or syntax mistakes in the text. I tried to list some of them, but it needs more careful reading.

We have made corrections to the manuscript.

2. References are completely missing from the mathematical formulation of the problem in pages 4 and 5. For example, where is formula (6) taken from?

Formula (6) is taken from:

[12] Loudon, R., The Quantum Theory of Light, 3rd ed. (Oxford University Press, New York, 2000).

3. What is in the end the accuracy of this method? How well can we estimate birefringence? The transmission ratio of G-T should also be taken into account while estimating the sensitivity of the method. In the Discussion line 236 you claim 0.001 rad is accurate enough. How does was this number calculated?

The error budget of the fluorescence counts was analyzed in ref. [9]. The main concern is S_3 (degree of circular polarization of the laser light). The variance of S_3 we suspect is caused by fluctuation of the ambient temperature and pressure.

As the error of the fluorescence counts is less than 2%, using equation (9) in ref. [9], we can get the error of S_3 is about 1.1%. Using equation (3) in this paper we get the error of δ and θ is about 0.05° and 0.39°. This is the accuracy of the birefringence using the method.

The distinction ratio of our Glan-Taylor polarizer is 10^{-6}, its effect can be neglected relative to other polarization components.

As mentioned above, the birefringence error is 0.05° and 0.39°. The precision of the stepper motor rotation stage is about 0.03°, so it is the main accuracy limit for δ. In the future, a rotation stage with higher precision (~0.001°) will be helpful to reduce error.

2.2 Minor Comments

1. Abstract on the first page is repeating itself, please rephrase to look like the one in line 33.

We have rephrased.

2. Half-wave plate and quarter-wave plate instead of half wave plate and quarter wave plate

We have made the changes in the manuscript.

3. Line 34:…by laser light which resonated or resonating with…

We have corrected the sentence.

4. Line 48: …,the stress-induced birefringence effect of the vacuum window

We have made the necessary revision.

5. Line 52: to analyze the birefringence

We have made the necessary revision.

6. Line 52: …shifts of Cs atoms are sensitive

We have made the necessary revision.

7. Consider making the steps of the protocol either bold or use a bigger font size so they can stand out

We have made the necessary revision.

8. I find having titles and subtitles at the end of the page not optimal to the reader. For example, Step 2 at the end of page 2 or "representative results" at the end of page 3.

We have made the necessary revision.

9. It is not clear to me why we need the Glan-Taylor B polarizer in this method. It would be useful to elaborate more on the use of these optical elements.

The Glan-Taylor polarizer B is used as a polarization analyzer to determine the azimuthal angles of the HWP and the QWP. In step 1.3, when the power detected by the power meter is maximized, the azimuthal angle of Glan-Taylor polarizer B is parallel to that of A, whose azimuthal angle is defined as 0°. Same as step 2.1 and 2.2.

10. Line 148: first passes through a…

We have made the necessary revision.

11. Line 187-189: The numbers mentioned (0.999 and 2%) are not clear to me how they are extracted from the figure. On the same note, what is "ls" in figure 3?

The fluctuation of the fluorescence counts recorded by PMT is 2%, this result is analyzed in ref. [11]. That is to say the maximum photon counts is 260(5) per 1 ms. From the simulation results shown in Fig. 3, we can calculate the uncertainty of S_3 is about 0.001. So at the point of maximum photon counts S_3>0.999. Is in figure 3 is the saturation intensity.

12. Line 204: How good is the agreement?

As can be seen from Fig. 5, the experimental results with error bars agree very well with theoretical results.

13. Consider putting the legends under the corresponding figures, it could be more pleasant to the eye.

We have made the changes.

14. Line 241: The birefringence is caused by the stress on the vacuum window; hence it will be different…

We have made the necessary revision.

15. Line 248: reference on 10/Γ?

There is no reference here. In a two level system, minimum period of population evolution is 1/Γ. In order to shorten the simulation time but not reduce the accuracy, we believe 1/(10 Γ) is proper.

16. Line 248: The sentence "The population…energy structures" is badly phrased

We have changed "The population of each level will be stable after enough times transitions, the times are associated with the energy structures." to "The population of each level will reach stable state after sufficient time. The proper time is associated with the energy level structures of specific ion or atom."

17. Line 249: As for…suitable. How are these numbers estimated?

The simulation equations and parameters are introduced in our previous paper (see Rev. Sci. Instrum. **90**, 113001 (2019); doi: 10.1063/1.5121568). Based on the equation, we simulated the population evolution over time. With the increase of time steps, the population changes tend to zero very quickly. Hence, we do not need too many steps, which waste too much time. In our case, 10^6 steps are enough to show the actual situation.

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   Title: In-situ measurement of vacuum window birefringence using 25Mg+ fluorescence•

   Authors: Wenhao Yuan, Hongli Liu, Zhiyu Ma, Peng Hao, Zhuo Deng, Ke Deng, Jie Zhang and Zehuang Lu.

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Best Wishes

Hongli Liu