Study on beam bunching and rotation characteristics of low power laser in permanent magnetic field

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Abstract. In this paper, a test platform based on the Faraday Effect was designed to investigate the beam bunching and rotation characteristics of low power laser in permanent magnetic field. By changing the structural parameters of the permanent magnetic confined cavity, the effects of permanent magnetic field on the rotation characteristics of linearly polarized light and the beam bunching characteristics of low power laser were studied. In the tests of the rotation characteristics of the linearly polarized light, it was found that the rotation angle of linearly polarized light tended to decrease with the increase of the diameter of the magnetic cavity and the decrease of the number of magnets. The maximum rotation angle of linearly polarized light was 142.6°, and the minimum rotation angle was 13.6°. In the tests of beam bunching characteristics of low power laser, it was found that the laser spot area had a slight reduction and the laser power was slightly enhanced when the magnetic flux density increased from 0.4563T to 0.8243T, which proved that the strong magnetic field had a bunching effect on the low power laser.

1. Introduction

With the development of laser technology, such as laser measurement, laser manufacturing and laser fusion, the demand for high-beam laser in scientific research has been extremely urgent. However, the studies on laser beam bunching properties generally rest on the improvement of laser structure and the composition of auxiliary optical devices. The researches on laser beam bunching methods are of great significance to improve the precision of laser cutting and laser welding and to broaden the application category of laser measurement.

When a beam propagates in a magnetic field, it exhibits different characteristics due to the action of the magnetic field. The commonly mentioned magneto-optical effects mainly include Faraday Effect, Magneto-Optic Kerr Effect, Zeeman Effect and Cotton-Mouton Effect. These effects all originate from the change of the magnetic field on the mechanism inside the substance, and reveal the relation between light and the magnetism of matter.

At present, many researches have been done in the field of magneto-optical effects. Ejlli [1] studied the generation of magneto-optical effects by the cosmic microwave background (CMB) in the presence of cosmic magnetic fields, and investigated four mechanisms which generated polarization of the CMB. An experiment on the origin of the magneto-optic effects of ferrofluids was carried out for a better understanding which included dynamic measurements of their transverse and longitudinal magneto-optic effects [2]. A novel magneto-optical sensor which was based on electron gyration compensation for the Faraday rotation angle in single lead molybdate crystal was proposed so as to provide a promising closed-loop measurement method of current, magnetic field and Verdet constant.
[3]. Telegin et al. [4] presented the results of researches on magneto-optical Kerr effect of natural light in La$_{2/3}$Ba$_{1/3}$MnO$_3$/SrTiO$_3$ films of different thickness that the Kerr effect was the most prominent in visible and near IR range. Escudero et al. [5] discussed the ground state magnetization in graphene, and the results obtained provided insight of the way in which the Zeeman Effect modified the magnetization, which could be useful to control and manipulate the spin degrees of freedom.

Furthermore, some scholars have conducted many studies in the field of laser and magnetic field. The optical emission from laser-induced plasma plumes expanding across an external transverse magnetic field was studied in order to investigate magnetically confined laser-induced breakdown spectroscopy, and the result showed that optical emission lines from Al and Cu targets were obviously enhanced in the intensity of optical emission when a magnetic field was applied, while the optical emission lines from Co targets exhibited a decrease in the optical emission intensity [6]. Sakanaka et al. [7] modulated the betatron tune at a frequency of two-times the fractional betatron frequency using a high-frequency quadrupole magnet while storing single electron bunch in order to investigate the possibility of exciting a transverse quadrupole-mode oscillation of an electron bunch, and observed the transverse quadrupole-mode oscillation clearly. Differences in laser-produced plasmas with and without a magnetic field were observed using interferometric measurements, which was useful to investigate laboratory simulations of magnetic astrophysical jets [8]. He Z H et al. [9] studied the electron diffraction using ultrafast electron bunches from a laser-wake field accelerator at kHz repetition rate, where the phenomenon that the electron bunch distribution could be shaped using a solenoid magnetic lens was observed. Effect of magnetic field on a rotating thermoelastic medium with voids under thermal loading due to laser pulse with energy dissipation was studied in the context of Green–Naghdi (GN) theory of types II and III and obtained the exact expressions for the displacement components, stresses, temperature distribution, and change in the volume fraction field [10]. Nuclear spin optical rotation (NSOR) of linearly polarized light provided a novel probe of nuclear spins through the Faraday Effect which could pave the way to optical detection of nuclear magnetization [11]. The effect of transverse magnetic field on laser induced breakdown spectroscopy of graphite plasma as a function of fluence has been investigated [12]. It was revealed that the emission intensity, electron temperature and number density of graphite plasma had been increased at all fluences and for all environmental conditions due to the presence of the magnetic field. The research showed that more increase in fluence up to a maximum value of 2.9 J·cm$^{-2}$, the saturation or self-sustained regime was achieved. The value of plasma parameter “β” was also evaluated analytically, and it was less than one for all conditions (fluences as well as environments), which confirmed the existence of confinement effect.

In this paper, based on the theory of magneto-optical effect, combined with the research experience, a test platform was built to investigate the beam bunching and rotation characteristics of low power laser in a permanent magnetic field; the permanent magnetic confined cavity was modeled and simulated, and the variation of the magnetic flux density inside the cavity was analyzed when the structural parameters of the cavity were changed; a measurement and control system of magneto-optical interaction was developed, and the effects of the strong magnetic field on the Faraday rotation angle of the linearly polarized light and the spot area and power of the low power laser beam were studied by testing the magneto-optical interaction characteristics in the magnetic field with different structural parameters. The light source selected in this paper was a low power helium-neon laser with the output wavelength of 632.8nm and the power of 2mW, which had the characteristics of high brightness, pure color and good directivity. The magnetic field inside the magnetic cavity was generated by the NdFeB permanent magnet with the grade of N35. The magnetic flux density of the permanent magnetic cavity could be adjusted from 0.2277 to 0.8243T, which belonged to the strong magnetic field in the division standard of magnetic field.
2. Experimental principle

2.1. The rotation characteristics

According to the Faraday magneto-optical effect, when a beam of linearly polarized light propagates in the medium, if a strong magnetic field is applied parallel to the propagation direction of the light, the polarization plane will rotate at an angle, which is called the Faraday rotation angle. Using the magnetic flux density $B$ and the length of magneto-optical medium $L$, an equation defining the rotation angle $\theta$ can be written as:

$$\theta = VBL$$  \hspace{1cm} (1)

where $V$ is the Verdet constant with the unit of rad/T•cm, which is related to the nature of the medium and the frequency of the light passing through the medium.

![Figure 1. Measurement of the rotation angle of linearly polarized light.](image1)

In this test, the light extinction method was used to measure the Faraday rotation angle, and the measurement system was shown in Figure 1. When the magnetic field was not applied, the polarizer was adjusted to reach the light extinction position, where the number of laser power meter reached the minimum, and the rotation angle of the analyser was recorded as $\theta_1$. After applying the magnetic field, the polarization plane of the linearly polarized light rotated due to the Faraday Effect, and part of the light passed through the analyser increasing the number of laser power meter. At this time, the analyser was adjusted to minimize the number of laser power meter again, and the rotation angle of the analyser was recorded as $\theta_2$. The difference between the two rotation angles was the rotation angle of linearly polarized light which was recorded as $\theta$.

2.2. The beam bunching characteristics

The spot area, laser power and other parameters should be measured in the experiment of beam bunching characteristics. The spot area was measured by the contrast method, as shown in Figure 2. The laser beam was projected onto the film imaging screen after being acted by the magnetic field; after obtaining spot projection from CCD industrial camera, the corresponding number of pixels was processed and obtained by software system; the laser spot area was obtained according to the calibration curve between the spot area and the number of pixels. The laser power was measured directly by a laser power meter.

![Figure 2. Measurement of spot area.](image2)
3. Simulation analysis

3.1. Simulation calculation of the magnetic field

Using the ANSYS finite element analysis software, the permanent magnet constraint model was established shown in Figure 3. According to the structural parameters and typical values set out in Table 1, each case was simulated separately to analyse the magnetic flux density distribution of the magneto-optical medium region inside the permanent magnetic confined cavity.

Table 1. Structural parameters of the permanent magnetic confined cavity.

| The number of magnetic pole groups (m) | 1 | 2 | 3 |
|--------------------------------------|---|---|---|
| The magnetic cavity diameter (d/mm)   | 10| 11| 12| 13| 14| 15| 16| 17| 18| 19| 20 |

Figure 3. Permanent magnet constraint model.

Taking the simulation result as an example when the number of magnetic pole groups was 3 and the magnetic cavity diameter is 20mm, the distribution of magnetic flux density in the magneto-optical medium region was shown in Figure 4. The region with greater magnetic flux density was the middle red region where $B_{\text{max}}$ was about 0.298T, and both sides of the blue-green part of the magnetic field were relatively weak. The magnetic induction line entered from one end of the medium region and propagated along the center line of the magnetic cavity and emitted from the other end, forming a constrained magnetic field which was evenly distributed in the middle of the medium region and parallel to the central axis of the magnetic cavity.

3.2. Simulation analysis of the magnetic field

When the permanent magnet constraint model was meshed by ANSYS software, there might be no nodes located at the center of the magnetic cavity, so it was hard to obtain the magnetic flux density at the center of the magnetic cavity. According to the simulation results of medium region under different structural parameters, it was found that with the increase of the diameter of the magnetic cavity, the maximum magnetic flux density $B_{\text{max}}$ of the medium region was gradually closer to the middle of the region from the position near the permanent magnet, gradually forming a uniform magnetic field with an approximate value of $B_{\text{max}}$ in the middle of the medium region. Therefore, the maximum magnetic flux density $B_{\text{max}}$ of the medium region was selected as the study object.

According to the simulation data, the $B$-$d$ relational curve was plotted in Figure 5. It showed that the magnetic flux density $B$ decreased with the increase of the cavity diameter $D$ in the case of different number of magnetic pole groups. The magnetic flux density decreased rapidly when the diameter of the magnetic was small and the magnetic flux density decreased slowly when the diameter of the magnetic cavity was large. When the diameter of the magnetic cavity was constant, the magnetic flux density $B$ increased with the increase of the number of magnetic pole groups, and the increase reduced gradually. According to the simulation results, in the process that the diameter of the
cavity increased from 10mm to 20mm, the magnetic flux density of the magnetic cavity was reduced from 0.7263T to 0.2256T when the number of magnetic pole groups was 1; the magnetic flux density of the magnetic cavity was reduced from 0.7997T to 0.2805T when the number of magnetic pole groups was 2; the magnetic flux density of the magnetic cavity was reduced from 0.8226T to 0.2977T when the number of magnetic pole groups was 3.

![Figure 5. Simulation curve between magnetic cavity diameter and magnetic flux density.](image1)

![Figure 6. Simulation curve between the number of magnetic pole groups and magnetic flux density.](image2)

According to the simulation results, taking the simulation data that the magnetic cavity diameter were \( \phi 10 \text{mm}, \phi 15 \text{mm} \) and \( \phi 20 \text{mm} \), the relationship between the number of magnetic pole groups and the magnetic flux density was studied, and the \( B-m \) relational curve was plotted as shown in Figure 6. It could be seen that the magnetic flux density of the magnetic cavity increased with the increase of the number of magnetic pole groups for different magnetic cavity diameters.

4. **Experiment**

4.1. **Test platform construction**

The test platform was composed of a laser emission module, a permanent magnet constraint module and a parameter measurement module, which was shown in Figure 7. The laser emission module was used to generate the laser beam and adjust the position of the laser; the permanent magnet constraint module was used to form a magnetic confined cavity which had approximately uniform and strong magnetic field inside and could be adjusted; the parameter measurement module integrated high-precision sensors to detect the variation of beam bunching and rotation characteristics of laser.

![Figure 7. Magneto-optical interaction test platform in permanent magnetic field.](image3)
The permanent magnet constraint module was composed of multiple permanent magnet loading disks connected in series, as shown in Figure 8. The permanent magnets were mounted on the loading disks in the form of an array of 60° spaced circumferentially around the centerline of the magnetic cavity. The adjustment of the magnetic cavity diameter was realized by changing the screwing depth of the position adjustment screw to change the distance between the permanent magnet and the centerline of the cavity. The permanent magnet was NdFeB permanent magnet (Nd$_2$Fe$_{14}$B), whose grade was N35, remanence intensity was 1.17T, and coercive force was 868KA/m.

4.2. Characteristic parameter measurement
The parameter measurement module was shown in Figure 9. The center of film imaging screen, the center of the lens of CCD industrial camera and the center of laser power meter photosensitive surface were at the same height. The baseplate was fixed on the horizontal linear guide rail to realize the switch of the sensor. The horizontal linear guide rail was fixed on the independent lifting platform to realize the adjustment of the sensor height.
After adjusting the test device, the distance between two adjacent groups of magnets was kept at 14mm during the test, and the diameter of the magnetic cavity could be adjusted from 10mm to 20mm. The Hall probe of the Tesla meter was placed in the center of the magnetic cavity and the magnetic flux density at the center of the cavity was measured when the diameter of the cavity was different. The $B$-$d$ relational curve was plotted as shown in Figure 10 based on the measured data. It could be seen that the magnetic flux density decreased with the increase of the cavity diameter when the number of magnetic pole groups was different. The magnetic flux density decreased rapidly when the diameter of the magnetic was small and the magnetic flux density decreased slowly when the diameter of the magnetic cavity was large. When the diameter of the magnetic cavity was constant, the magnetic flux density increased with the increase of the number of magnetic pole groups, and the increase reduced gradually.

According to the measurement results, taking the data that the magnetic cavity diameter were $\phi 10\text{mm}$, $\phi 15\text{mm}$ and $\phi 20\text{mm}$, the relationship between the number of magnetic pole groups and the magnetic flux density was studied, and the $B$-$m$ relational curve was plotted as shown in Figure 11. It could be seen that the magnetic flux density of the magnetic cavity increased with the increase of the number of magnetic pole groups for different magnetic cavity diameters. Therefore, the test was mainly carried out in the magnetic cavity where the number of magnetic poles groups was 3, and the magnetic flux density increased obviously and reached maximum.

The phenomena above also proved the correctness of the modeling and simulation results.

4.3. Experiments of the rotation characteristics

4.3.1. Effect of magnetic cavity diameter on rotation characteristics. The number of magnetic poles groups of the permanent magnet constraint module was adjusted to 3, and magneto-optical glass with the size of $\phi 6\text{mm} \times 10\text{mm}$, $\phi 8\text{mm} \times 10\text{mm}$ and $\phi 10\text{mm} \times 37\text{mm}$ were used as filling medium. The rotation angles of linearly polarized light of different magnetic cavity diameters in three media were measured respectively, and the curves of $\theta$-$d$ were plotted as shown in Figure 12. It could be seen that the rotation angle decreased as the diameter of the cavity increased. When the diameter of the magnetic cavity was small, the rotation angle decreased rapidly with the increase of the diameter of the magnetic cavity. When the diameter of the magnetic cavity was large, the rotation angle decreased slowly. Meanwhile, the rotation angles of the magneto-optical glass with the size of $\phi 10\text{mm} \times 37\text{mm}$ were much larger than those of other two mediums, and the reason was that the rotation angle $\theta$ is proportional to the length of the magneto-optical medium when the magnetic flux density and the Verdet constant of the medium were constant. However, the rotation angles of the glass with the size...
of ϕ6mm × 10mm and ϕ8mm × 10mm showed little differences. It was presumed that the diameter of the magneto-optical glass had no effect on the magnitude of the rotation angle.

4.3.2. Effect of geometrical parameters of magneto-optical glass on rotation characteristics. The number of magnetic poles groups of the permanent magnet constraint module was adjusted to 3, and magneto-optical glass with the size of ϕ6mm × 10mm, ϕ6mm × 25mm, ϕ6mm×30mm and ϕ6mm × 37mm were used as filling medium. The effect of the length of magneto-optical glass on the rotation angle was studied under the condition of the same diameter of magneto-optical glass and magnetic flux density, and the relational curve of θ-l was plotted, as shown in Figure 13. It could be seen that the rotation angle increased linearly with the increase of the length of the magneto-optical glass when the diameter of magnetic cavity and diameter of the magneto-optical glass were constant. When the diameter of magnetic cavity was small, the rotation angle increased rapidly, and when the diameter of magnetic cavity was large, the increase was relatively slow.

The effect of magneto-optical glass diameter on the rotation angle was studied when the length of magneto-optical glass and diameter of magnetic cavity were the same. The magneto-optical glass with the size of ϕ6mm × 10mm, ϕ8mm × 10mm and ϕ15mm × 10mm were selected to test respectively when the diameters of magnetic cavity were ϕ16mm, ϕ18mm and ϕ20mm. It was found that for magneto-optical glass of the same length, changing the diameter of the magneto-optical glass when the diameter of the magnetic cavity was constant did not cause a regular change in the rotation angle but made it fluctuate within a certain range.

4.4. Experiments of beam bunching characteristics

4.4.1. Detection and analysis of spot area. The number of magnetic poles groups of the permanent magnet constraint module was adjusted to 3, and magneto-optical glass with the size of ϕ6mm × 10mm, ϕ8mm × 10mm and ϕ10mm × 37mm were used as filling medium. The laser spot areas in three medium were measured respectively when diameter of magnetic cavity was different. An image of the laser spot is shown in Figure 14. After being processed by the software system, the corresponding gray scale and the binarized gray scale of the laser spot were obtained in Figure 15 and 16. According to the measured data, the relational curves of S-d were plotted in Figure 17.
It could be seen from Figure 17 that for magneto-optical medium of different size, the laser spot area had a slight fluctuation and decrease when the diameter of magnetic cavity was reduced from φ14mm to φ10mm. In the permanent magnetic confined cavity, the magnetic flux density increased as the diameter of the cavity decreased from 14mm to 10mm; since the relative permeability of the magneto-optical medium was much larger than that of the air, the magneto-optical medium was easily magnetized; when the magnetic flux density was large, the propagation direction of the low power laser was affected by the magneto-optical medium, and the propagation direction of the epitaxial portion of the laser beam was shifted toward the center of the beam, which caused the laser spot area to decrease.

4.4.2. Detection and analysis of laser power.

• No filling medium

The number of magnetic poles groups of the permanent magnet constraint module was adjusted to 3, and the initial value of laser power \( P_0 \) was measured first when there was no filling medium and no magnetic field, and the result was 0.775mW. After the magnetic field was applied, the effect of the diameter of the magnetic cavity on the laser power was studied. According to the test results, it was found that the diameter of magnetic cavity did not cause a regular change of laser power but made it fluctuate in a certain range, and there was barely no difference compared with the initial value of laser power. Based on the analysis above, changing the structural parameters of the cavity did not cause the regular change of the laser power when there was no filling medium.

• With filling medium

Magneto-optical glass with the size of φ6mm × 10mm, φ8mm × 10mm and φ10mm × 37mm were used as filling medium, and the effect of diameter of magnetic cavity on laser power was studied when there was filling medium and magnetic field. According to the measured data, the relational curve of
$P-d$ was plotted as shown in Figure 18. It could be seen that for magneto-optical glass of different size, the laser power increased with the decrease of the cavity diameter when the diameter of magnetic cavity was less than 14 mm. When the magnetic flux density was large, the propagation direction of the low power laser was affected by the magneto-optical medium, and the propagation direction of the epitaxial portion of the laser beam was shifted toward the center of the beam, which caused the laser power to increase slightly. When the diameter of magnetic cavity was greater than 14 mm, changing it did not cause the laser power to change regularly but fluctuate in a certain range.

Compared with the initial value of laser power, it was found that when the magneto-optical glass medium was filled, the laser power decreased and the reduction was about 0.231 mW, which accounted for 29.8% of the initial value of laser power. When the laser passed through the magneto-optical glass, the light intensity would be attenuated to a certain extent, which caused that the measured power value was smaller than the initial value of laser power.

5. Conclusion

- In the experiments of the rotation characteristics of the linearly polarized light, the effects of the diameter of magnetic cavity and the geometrical parameters of the magneto-optical medium on the rotation angle of the linearly polarized light were studied. The maximum rotation angle of the linearly polarized light was 142.6° and the minimum rotation angle was 13.6°. With the increase of the diameter of magnetic cavity and the decrease of the number of magnets, the rotation angle of the linearly polarized light decreased gradually; when the diameter of the magnetic cavity was the same, the rotation angle increased as the number of magnets increased, which was more obvious when the diameter of magnetic cavity was smaller; when the length of magneto-optical medium was increased, the rotation angle of linearly polarized light increased at the same time. However, the rotation angle of linearly polarized light did not exhibit a regular change when the diameter of magneto-optical medium was changed.

- In the experiments of beam bunching characteristics of low power laser, the effects of the diameter of magnetic cavity and the number of magnetic poles groups on the beam bunching characteristic of low power laser were studied. In the experiment, it was found that the laser spot area was slightly reduced and the laser power was slightly enhanced when the magnetic induction intensity increased from 0.4563T to 0.8243T, which proved that the strong magnetic field had a bunching effect on the low power laser.

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