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Development of polarized helium-3 neutron-spin-filter based on spin-exchange optical pumping in Japan

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ABSTRACT

In Japan, a project to develop polarized ^{3}He neutron spin filters (NSFs) has been started. The project aims that the NSFs will be provided for various research experiments using neutron beam from reactors or a spallation neutron source in J-PARC. We adopted for a spin-exchange optical pumping type as the NSFs. A high power laser diode (HPLD) is used as a pumping laser to polarize Rb atoms. The frequency width of HPLD is narrowed by an external cavity using a holographic grating which set on Littorow configuration. The optics of the external cavity was re-designed taking aberrations into consideration by means of ray-trace.

1. Introduction

Polarized neutron beam has been used in various fields, such as material science, fundamental physics, neutron radiography, etc. The polarized neutron beam is usually produced with "supermirrors" [1], Heusler alloy monochromator [2], or a polarized ^{3}He spin filter. The ^{3}He neutron spin filter (NSF) was firstly used for measurement of a time reversal non-invariance [3]. Since the pioneer work, the application to material physics has been done in NIST, ILL, or LANSCE, etc., because the NSF has a greate advantages, such as a large angular acceptance or small scattering angle compared with supermirrors and Heusler alloy monochromator [4].

In Japan, a construction of a multi-purpose accelerator facility, J-PARC has been completed. J-PARC has a spallation neutron source and it can produce high-intense-pulsed neutron beam with 1 MW proton beam. In J-PARC, the NSFs are demanded to conduct material science, neutron radiography, etc. Then, a foundation from "the ministry of education, culture, sports, science and technology, Japan" has been budgeted for a project to improve quality of neutron beam. The development of the NSFs has been started as one of the project [5, 6].

There are two main techniques to produce the polarized ^{3}He gas. In the first technique, the ^{3}He atoms at a pressure of about 1 mbar, are excited into metastable 1s2s $^3S_1$ state by passing a discharge through the gas in a magnetic field. The 2^3S_1-2^3P transition is induced by optical pumping, which polarizes electronic spin of ^{3}He atom. The electric spin is then transferred through the metastability exchange collisions to nuclear spin of the ^{3}He atom. This is called metastability exchange optical pumping (MEOP) type [7]. In the second technique, the ^{3}He nucleus is polarized by spin-transfer from polarized alkali-metal atoms that are polarized by optical pumping method [8]. It is called spin-exchange optical pumping (SEOP) type [9, 10]. We have adopted for the SEOP type as the NSFs. In our SEOP system, Rb atoms are used as alkali-metal atoms because wavelength of a pumping laser is match to a laser diode. Recent improvements of laser technologies bring us a high intensity laser diode with low cost. In our system, a bar type diode-laser is introduced. In the SEOP, a laser frequency should be narrowed because such a laser has large frequency width compared with absorption width of Rb vapor. This makes worse efficiency of the optical puming. To solve this problem, an external cavity method has been used [11–13]. In this paper, the optics study in the external cavity will be described.

2. External cavity

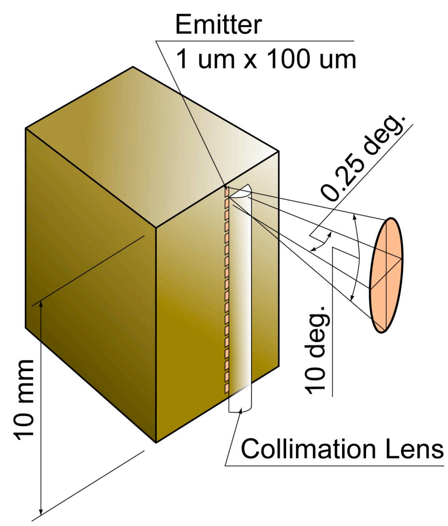

Figure 1: Schematic view of the pumping laser and output beam profile. (30092-VSA-1-100-0796-2-A-R01-F900D, nLight Co.)

A laser diode is a one-bar model of Cascade Vertical Stacked Array series (30092-VSA-1-100-0796-2-A-R01-F900D) fabricated by nLight Photonics Corporation. It is made from AlIn-GaAsP/GaAs. Schematic figure of the laser head is shown in Fig. 1. Laser light is emitted from so called a bar; which is consisted of vertically aligned 64 emitters in a line. Each emitter size is 1 µm × 100 µm (width × height). The laser light from each emitter diverges by 0.25 degrees in horizontal (fast) axis and 10 degrees in vertical (slow) axis with a collimation lens [14].

The schematic layout of the external cavity is shown in Fig. 2 and the principle is same as described one in [13]. The emitted laser beam is focused on a holographic grating and the image is magnified 4 times to decrease wavelength width due to a divergence of the laser beam and a smile of the laser bar [13]. A groove density of the holographic grating is 2400/mm and the grating set on a Littorow configuration and reflects fist-order-diffracted light back to each emitter. Light from an emitter should be returned to the same emitter. This means that the optics should be telecentric; in the telecentric system, all principal rays of the emitters are parallel to the optical axis. If the emitters are close to an optical axis, it is satisfactorily paraxial approximated. However, usually, laser beam from emitters located at far position from the optical axis does not meet such a condition due to an aberration, as the result the laser beam does not focus on the emitters. A way to decrease this is to extend focal length but it make the optics path larger (more than 1 m). The other method is an aberration correction. It will avoid the optics length to be extended and can keep short in length. Here, the latter method is adopted.

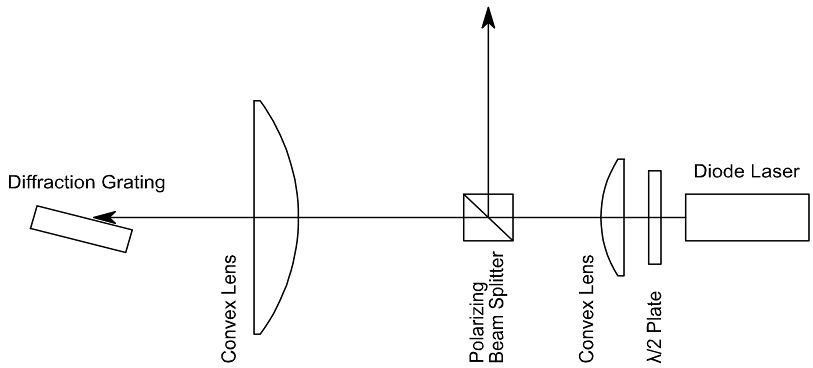

Figure 2: The schematic layout of the external cavity (plan view).

3. Ray-Trace

3.1. Ray-Trace Software

To calculate optics evolving the aberration, ray-trace simulation is performed. For this purpose a ray-tracing code, OSLO Premium 6.4 (Lambda Research Co) is used.

3.2. Optics Layout

The pumping laser has a collimation lens and it collimates the laser beam to 1 μm in horizontal for each emitter while it does not collimate in vertical. In the ray-trace simulation, the optics system is configured with no collimation lens and the initial beam divergence is set to be same divergences as the divergence after the collimation lens.

In this paper, ray-trace simulations have been performed for two types of optics shown as follows and in Fig. 3.

- Optics-A: Configuration consisted of two plano-convex lenses.
- Optics-B: Configuration consisted of three plano-convex lenses.

Optics parameters for above optics are tabulated in Table I.

The laser light is reflected back to the laser at the grating by 180 degrees. The optics is not different with optics which is aligned in symmetry with respect to a plane on grating surface. So calculation was performed with the symmetric optics. The light from laser emitter goes lens L1 and L2 and reflected at the grating and goes through lens L2 and L1 to the laser emitter.

Table I: Optics parameters. Units are in mm.

	$f_1/f_{1\text{-a,b}}$	f_2	d_1	d_2	d_3
Optics-A	50	200	50	240	120
Optics-B	100	200	50	240	130

3.3. Initial Beam Condition

To evaluate optics, three ray-fans were used. Each ray-fan consist of three rays which are consisted of a chief ray and two rays whose angle between the chief ray are ± 5.0 degrees which correspond to divergence of the laser beam from each emitter in slow axis. The start position of the three ray-fans are, respectively, 0 mm, 3.5 mm, and 5.0 mm in height. The maximum height corresponds to half height of the diode array bar. All chief ray of the three ray-fans are emitted parallel to the optics axis (telecentric mode).

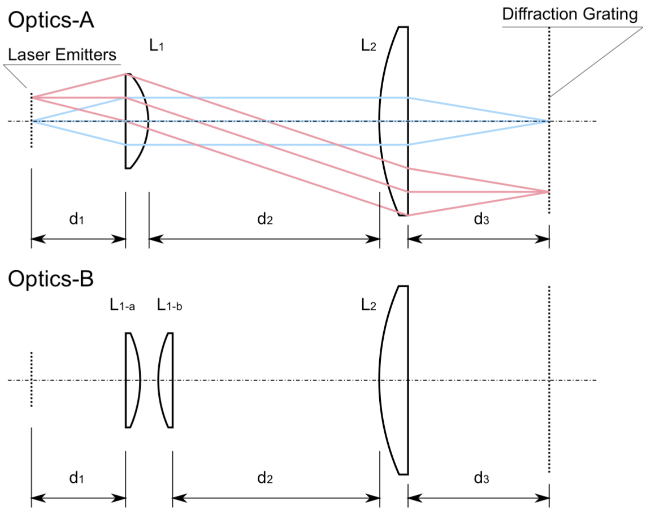

Figure 3: Two type optics systems for the external cavity (side view)

The laser beam from each emitter is not circular symmetry. Since the divergence in the fast axis is very small and emitters are lined on the y-axis, the beam of that axis meet paraxial approximation. In this calculation, only slow axis beam is con- sidered.

3.4. Calculation results

3.4.1. Traced Ray

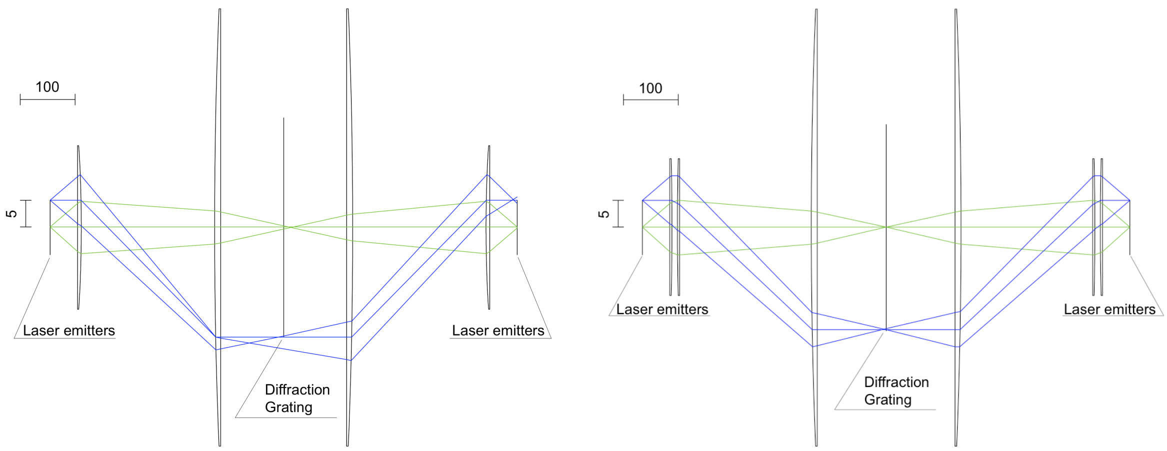

Figure 4: Traced rays on the external cavity for the optics-A (left figure) and the optics-B (right figure). Light beams are emitted from left side and fed on a right end. These figures are magnified 10 times on a vertical axis compared with a horizontal axis. The scale unit is mm.

Firstly, calculated traced rays are shown in Fig. 4. The optics was optimized so that the light beam emitted at height of 2.5 mm is focused on the laser emitter at the end of the optics and the chief ray emitted at height of 5 mm should be parallel to the optics axis on the grating. Aspect ratio is changed to make it clear. It can be seen that in the optics-A, focus points of ray-fans are defferent depending on the emitter position.

On the other hand, in optics B and C, the focus point is almost same for all ray-fans.

3.4.2. Spot diagram

Next, performances of the optics are compared with spot diagram of reflected laser beam on the emitter surface. In Fig. 5, the spot diagrams are shown and left figures and right figures are those of optics-A and optics-B. The numbers on left side for each diagram indicate fractions of initial hight of the laser emitter. It can be seen that the spot size of the optics-B is smaller than the optics-A. The spot size should be smaller than emitter size in y direction, 0.1 mm. The optics-A does not satisfy this condition, so it is expected that the efficiency for a frequency narrowing is worse. On the other hand, in the optics-B, the spot size is smaller than emitter size or comparable.

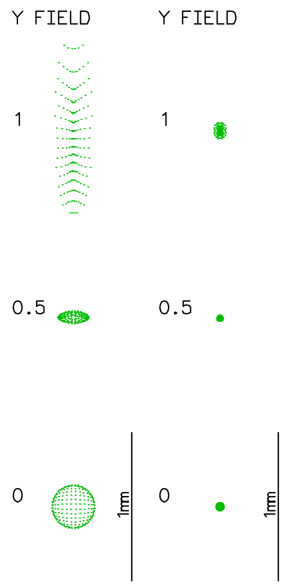

Figure 5: Spot diagrams of the returned-laser beam on the emitter.

4. Summary

The optics calculation for the external frequency-narrowing cavity has been perfomed by means of a ray-trace. It was found that the aberrations were very large compared with the laser emitter size on a far distance from the optical axis. The aberrations were corrected by installing the doublet lens system instead of the singlet one. It is expected that the efficiency of the frequency narrowing will be significantly improved.

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