GENERATION OF RADIAL POLARIZED LASER BEAM AND ITS APPICATIONS FOR ACCELERATOR

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Abstract

We are developing several methods to generate the radial polarized laser beam. Various polarizations such as radial/azimuth polarizations can be available for many accelerator applications. One of the applications is for a laser wire monitor [1], because fine TEM01 or TEM10 modes are easily obtained from radial polarization with rotating a polarizer. We will also apply radial polarization for Z-polarized photocathode RF gun [2] and broadband EO sampling (3-D femtosecond bunch monitor) [3]. The radial polarization can be generated from linear polarization using a liquid crystal (LC) cell or 8-divided waveplates. Here we demonstrate and evaluate the radial polarized laser beam generation by means of these two methods.

INTRODUCTION

Conversion of Polarization States

Linear polarization of Hermite Gaussian (TEM00) is widely used polarization state. On the other hand, radial/azimuth polarizations, Laguerre Gaussian, and Bessel beam are very unique polarization states. It is possible to generate such a polarization from conventional linear polarization using various optical devices. Figure 1 shows various polarization states and methods how to generate them. Here, we demonstrate the methods to generate radial polarization from linear polarization and discuss its applications for accelerator.

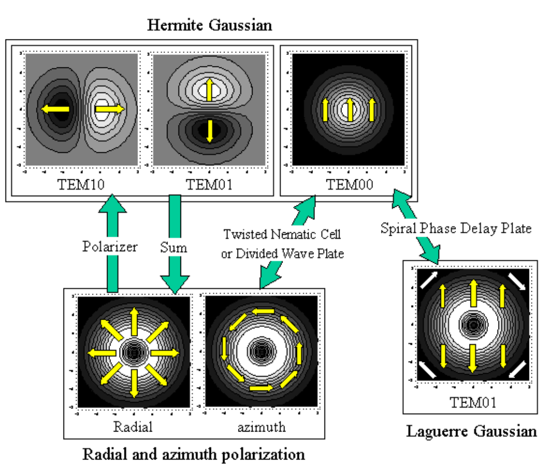

Figure 1: Conversion diagram of polarization states

In linear and circular polarizations, the direction of the electric vector at each point is transversely uniform. In radial polarization, however, the direction of polarization is not uniform but parallel to the radial direction as shown in Figure 1. The radial polarization can be applied for many applications, such as laser cutting, optical trapping, and microscopy. We will discus its applications for accelerator in the following section.

Applications for Accelerator

TEM01 and TEM10 modes can be obtained very easily from radial polarization using a polarizer. For laser wire monitor [1] which is a non-destructive method to measure electron beam spot size, the spatial resolution depends on laser spot size. TEM10 has two-peak distribution, and FWHM of this peak is almost half size of TEM00. It makes TEM10 promising way for higher-resolved laser wire monitor. Usually, it is not very simple to generate TEM10. Therefore, we developed simple and robust methods to generate TEM10 from radial polarization (it is simply generated from conventional TEM00).

The radial polarization can also be applied for Z-polarized photocathode RF gun [2] and 3-D femtosecond bunch monitor (broadband EO sampling) [3]. The streak camera is widely used for bunch length measurements in accelerator field. However, the temporal resolution of the femtosecond streak camera (FESCA200, Hamamatsu) depends on wavelength and is 300 fs (FWHM) at 800 nm, 500 fs at 400 nm and 600 fs at 266 nm [4]. Therefore streak camera cannot apply for the femtosecond bunch measurements in X-FEL.

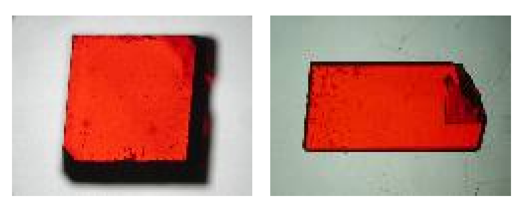

Figure 2: DAST crystal. Size of (001) surface is 1.7 mm × 2.0 mm (left) and 2.3 mm × 1.0 mm (right). Thickness is 1.0 mm (left) and 0.12 mm (right).

One of the candidates for femtosecond bunch measurements is EO sampling. The temporal resolution of EO sampling is given by

$$R = \sqrt{t_0 t_c}$$

where the Fourier transform limit of the probe laser is t_0, and the chirped probe pulse duration is t_c. Chirped pulse duration should be longer than timing jitter of electron bunches. Therefore, broadband spectral width (> 400 nm) is required for 20-fs temporal resolution if timing jitter is less than 200fs. The temporal resolution of EO sampling also depends on temporal response of EO crystal. As an EO crystal with femtosecond-order temporal response, we are preparing DAST organic crystal [5,6] which is transparent for 620 nm – 1600 nm wavelength region. Figure 2 shows DAST crystals (Frontier Alliance, Japan). Size of (001) surface where laser beam injects at EO sampling is 1.7 mm × 2.0 mm (left in Fig. 2) and 2.3 mm × 1.0 mm (right in Fig. 2). Thickness is 1.0 mm (left) and 0.12 mm (right). To utilize this broad transmittance, we developed broadband (650 nm – 1100 nm) light source using photonic crystal [3] and optical components such as beam splitters with the separate angle of 106 degrees (it works for 550 nm – 1150 nm) and Fresnel-Rhomb-type waveplates (600 nm – 1100 nm with the allowance of phase difference less than 2.8 degrees). Generation of broadband radial polarization is also required for 3-D bunch monitor [3].

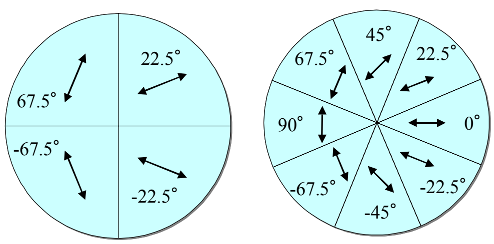

Figure 3: 4-divided waveplate (left) and 8-divided waveplate (right). Arrows represent crystal axes

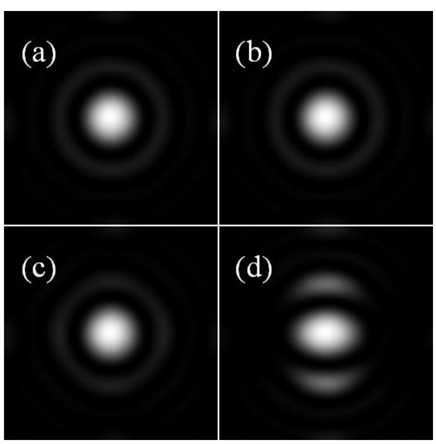

Figure 4: Calculated results for intensity distribution of Z-component $|E|^2$ when laser beam is focused. (a) ideal radial polarization, (b) 8-divided waveplate, (c) 4-divided waveplate, (d) 2-divided waveplate. See the detail in Ref [2].

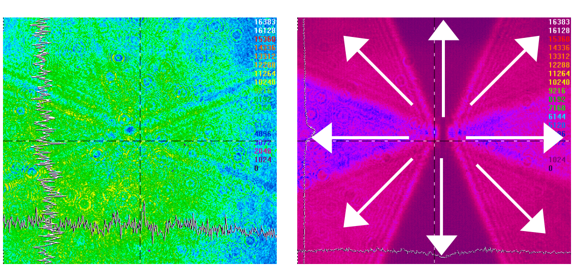

Figure 5: Intensity distribution of radial polarization (left) without a polarizer and (right) with a polarizer. White arrows represent the direction of electric vectors.

DIVIDED WAVEPLATE

Divided Waveplate

One method to generate radial polarizations from linear polarization is to use divided waveplates [2]. It consists of half waveplates with different crystal axes as shown in Figure 3. It is commercially available (ZPol, NanoPhoton). Figure 4 shows the results of calculation for intensity distribution of Z-component $|Ez|^2$ when radial polarized laser beam is tightly focused. In generation of radial polarization with 8-divided waveplate, radial polarization ratio to ideal radial polarization is 95% [2].

We use ZPol to generate radial polarization. ZPol is 8-divided waveplate and can be applied for 395 ± 15 nm (or 790 ± 30 nm). Figure 5 shows the results of laser beam profile measurements using CCD camera which is set at 50-mm downstream from ZPol. It is clearly seen in right figure of Figure 5 that intensity after a polarizer changes at each segment. It indicates that laser beam is radially polarized.

Combination of 4-Divided Waveplates

As discussed the last section, radial polarization is able to be generated using divided waveplate. This method has advantage to generate radial polarization at VUV region. If number of segments become increasing, it is getting difficult to fabricate it and costs more. Therefore, it is available with the combination of two 4-divided waveplates to be able to generate same polarization state as 8-divided waveplate.

Figure 6 shows the combination of 4-divided plates to generate radial polarization. This combination can generate radial polarization from right-handed circular polarization with TEM00. Because there is phase difference between each segment without phase shift plate, the phase shift plate compensates this phase difference.

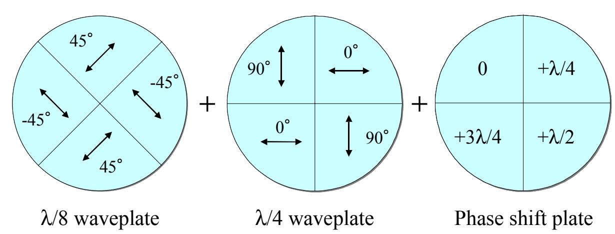

Figure 6: Combination of 4-divided waveplates to generate radial polarization. Arrows show crystal axes.

LC CELL

Liquid Crystal Cell

LC (Liquid Crystal) cell is the other method to generate radial polarizations. It is twisted nematic LC cell and has an inner structure as shown in Figure 7. Injected linear polarization rotates according to twist angles of each molecule. The distribution of twist angle is circularly symmetric so that radial polarization can be generated as shown in right image of Figure 7. This TN (twisted nematic) effect works for broadband spectral range. It makes possible to realize 3-D femtosecond bunch monitor as discussed in the reference [3]. It is impossible for divided waveplate to generate such broadband (over 400 nm) radial polarization.

We use Radial Polarization Converter (ARCoptix, Switzerland) [7]. This transmittance is 70%, laser power threshold is 200 W/cm^2 (CW) and 100 mJ/cm^2 (10-ns pulse), and broad spectral range is 400 nm – 1700 nm. Figure 8 explains the function of LC cell for radial polarization generation. These images are taken for LCD (Liquid Crystal Display) and LC cell with rotating a polarizer. Because light from LCD is linear polarization, intensity changes according to the angle of polarizer axes. And for light passed through LC cell, we can see dark area rotates radially with rotating a polarizer. It means that linear polarization converts to radial polarization with LC cell.

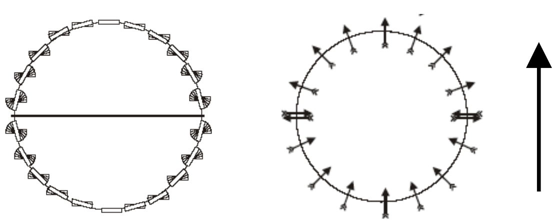

Figure 7: Inner structure of LC cell (left) and distribution of electric vectors of generated radial polarized beam (right). Large arrow represents the direction of injected linear polarization points [7].

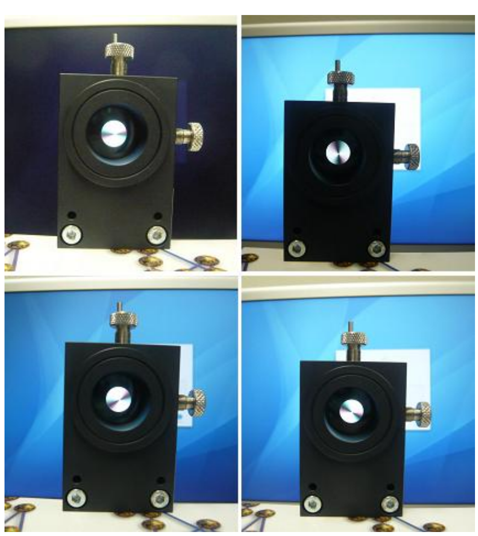

Figure 8: Generation of radial polarization with LC cell. These pictures are taken with rotating a polarizer before camera.

Wavefront Measurements

It is very crucial for many applications whether laser beam can propagate for long distance. Therefore, we measure the wavefront of generated radial polarization with Hartmann Wavefront Analyzer (SPIRICON). It can measure the wavefront of a broadband laser beam. The experimental setup is shown in Figure 9 and results shown in Figure 10. In Figure 10 (c) and (d), a polarizer is inserted after LC cell. We demonstrate TEM10 mode can be obtained from radial polarization using a polarizer.

In these measurements with Hartmann Wavefront Analyzer, we cannot see any distortion of wavefront. LC cell, however, should make "phase step". As shown in Figure 7, the electric vectors in the upper half are directed radially outward and in the lower half inward. It means there is a pi-phase step compared to ideal radial polarization mode which the all electric vectors are directed outward (or inward). This phase step will have a bad influence on laser propagation. Actually, ARCoptix also provides so-called phase shifter to compensate this phase step. However it cannot work for broadband spectral range over 400 nm as we required. To make solutions for this issue, we can use one more LC cell to compensate the phase step over wide spectral range. And we are going to measure wavefront precisely using interferometer.

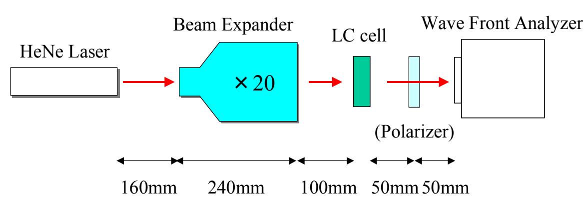

Figure 9: Setup for wavefront measurements.

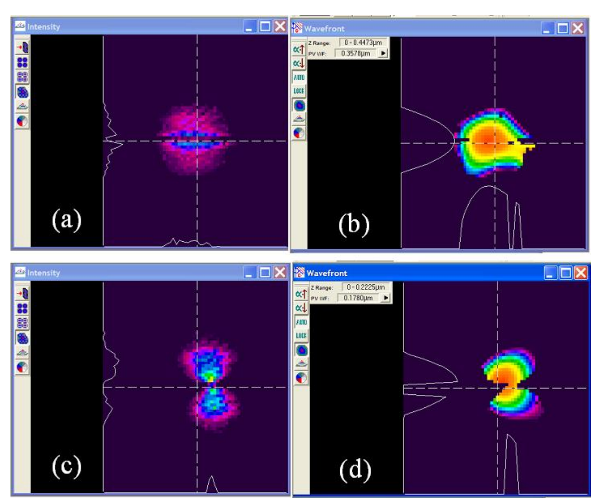

Figure 10: Intensity distribution (a), wavefront (b) of radial polarizations, intensity distribution (c) and wavefront (d) of radial polarizations with a polarizer.

SUMMARY

We demonstrated the generation of radial polarized beam with two different methods. For the method using divided waveplate, we show generation of radial polarization and feasibility which combination of 4-divided waveplates can generate same polarization state as 8-divided waveplate. For the method using LC cell, we demonstrate that radial polarization is generated from linear polarization. We can obtain both of TEM10 and TEM01 from radial polarization with rotating a polarizer. It is very simple and robust method to generate TEM10 and TEM01.

We need generation of broadband radial polarization and its evaluation with wavefront measurements. As future works, we are preparing to measure the optical properties of DAST crystals and broadband optical components (such as beam splitter and waveplates) required for 3-D femtosecond bunch monitor.

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