Development of Cost-Effective Polychromator System with Two Angled Filters for Thomson Scattering Measurement System

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We constructed the cost-effective polychromator system for multi-channel Thomson scattering measurement systems, in which scattered light is reflected between two angled interference filters. The number of interference filters was reduced to less than half of the number of wavelength channels, by using the reflections between two filters whose transmitted wavelength decreases with its angle of incidence. The developed polychromator successfully separated five different wavelength bands (1055.5, 1044.9, 1050.0, 1035.0, and 1024.3 nm), reducing its cost by saving the number of interference filters.

Keywords: polychromator, Thomson scattering, avalanche photodiode, interference filter, angle of incidence

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Nd:YAG Thomson scattering diagnostics, using an interference filter polychromator, is one of the most reliable methods to measure electron temperature and density [1]. To measure the profile, a lot of measurement points (spatial channels) and polychromators are needed, for example, 144 spatial channels for Thomson scattering diagnostics on the Large Helical Device [2]. In the polychromator, interference filters are usually used to transmit a specific wavelength band and reflect others. The number of interference filters are corresponding to the number of measurement points multiplied by the number of wavelength channels [3–5].

However, the cost of the polychromator is significant due to expensive interference filters. For example, two-dimensional Thomson scattering diagnostics which has $6 \times 6 = 36$ measurement points needs 180 interference filters, because each measurement point needs to separate five different wavelength bands.

At least three wavelength channels should be used for its Gaussian-fitting to measure the electron temperature. The reasonable number of wavelength channels is about five to measure electron temperature ranging within one order. Our target electron temperature and density are from 10 to 100 eV and from 10^{19} to 10^{20}/m^3, respectively.

To reduce the cost of the polychromator, we reduced the number of interference filters in each polychromator. Historically, our idea is related with the spectral analyzer for the ruby Thomson scattering system, which used a single interference filter to separate four wavelength bands [6]. This polychromator uses the dependence of the transmitted wavelength varying with the angle of incidence. However, the polychromator with few interference filters for the Nd:YAG Thomson scattering system which has more than four channels is not studied yet.

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First, we measured the dependence of the transmitted wavelength of two interference filters (1050 nm, 1059 nm) on the angle of incidence. We used a monochromator, which has 0.3 nm resolution, to make specific wavelength of light. Also, we used an avalanche photodiode (APD) to detect the light passing through the interference filter. To investigate its dependance on the angle of incidence, we varied the wavelength of monochromator from 1000 nm to 1070 nm.

Figure 1 shows the wavelength of transmitted light as a function of the angle of incidence of two interference filters. It indicates that the transmitted wavelength decreases with the angle of incidence. Also, the transmitted wavelength is fitted to the curve:

$$\lambda_\theta = \lambda_0 \sqrt{1 - \left(\frac{\sin\theta}{n_{\text{filter}}}\right)^2}, \tag{1}$$

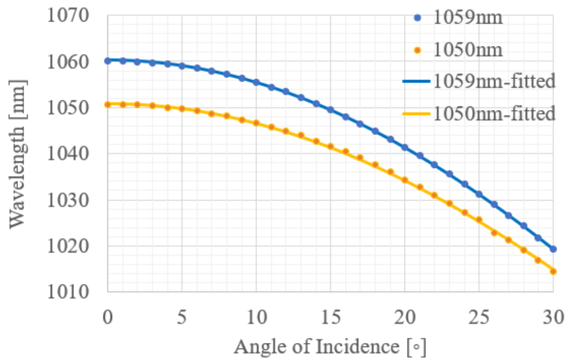

Fig. 1 Dependence of the transmitted wavelength on the angle of incidence of two interference filters (1059 nm, 1050 nm).

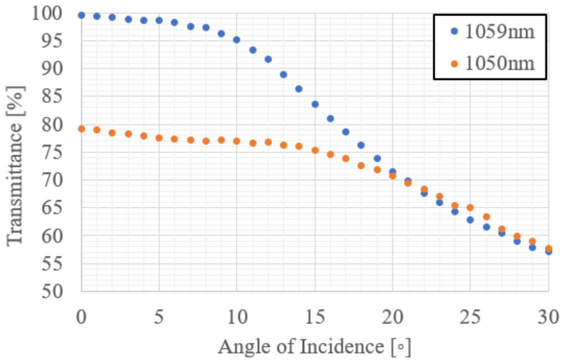

Fig. 2 Transmittance dependence on the angle of incidence of two interference filters (1059 nm, 1050 nm).

where θ, λ_θ, λ_0 and n_{filter} are the angle of incidence, the transmitted wavelength at θ, λ_θ for normal incidence (θ = 0°), and the effective refractive index of each interference filter, respectively.

For 1059 nm and 1050 nm interference filters, λ_0 = 1060.2 nm, n_{filter} = 1.820, and λ_0 = 1050.9nm, n_{filter} = 1.926 are obtained respectively.

Figure 2 shows the transmittance of two interference filters as functions of their angles of incidence. Figure 2 indicates that the transmittance decreases with the angle of incidence.

If the two interference filters are angled (not parallel), the angle of incidence to interference filters gradually increases while light reflects between them. This is the key for reducing the number of interference filters.

The schematic of the polychromator system with two angled interference filters (1059 nm, 1050 nm) and its experimental setup are shown in Figs. 3 (a) and (b), respectively. The scattered light enters this polychromator through an optical fiber whose diameter and numerical aperture (NA) are 2 mm and 0.25, respectively. Achromatic lenses are used to minimize aberrations of the polychromator system. Focal lengths of the achromatic lenses are 40 mm and 100 mm.

The number of filters is determined by the size of the filter and the diameter of the scattered light that passes through it. Considering that the current filter diameter is 35 mm and the size of scattered light is from 6.35 mm to 9.0 mm, five lenses cannot be arranged in a row on a single filter.

The scattered light passing through the achromatic lenses forms an image around Field lens 1 in Fig. 3 (a) whose beam spot size calculated by CODE V is 4.985 mm; it enters the interference filter (1059 nm) and reflects between the interference filters. The angles of interference filters for 1059 nm and 1050 nm are set at 7° and 3.5°, respectively, to the red line connecting the optical fiber and Mirror 1. The scattered lights for channels (Chs) 1, 2, 3, 4 and 5 are indicated by red, blue, green, yellow, and purple lines in Fig. 3. Also, we use the field lenses to control the

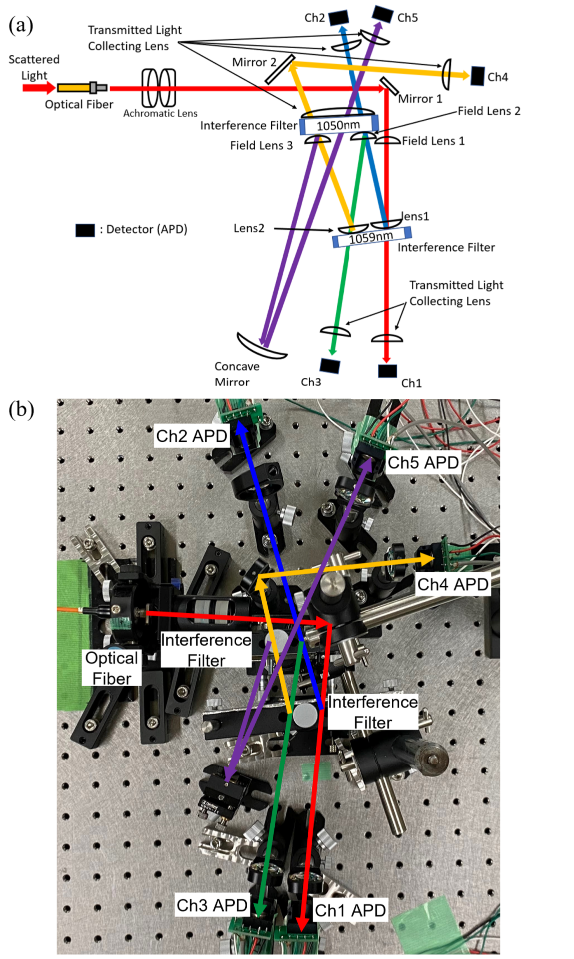

Fig. 3 (a) The schematic of the polychromator system with two angled filters (1059 nm, 1050 nm). (b) The experimental setup of the polychromator system with two angled filters (1059 nm, 1050 nm).

spread of scattered light. The light which enters the detector (APD) is focused by the transmitted light collecting lens.

The scattered light is reflected between the interference filters while the angle of incidence increases along with reflection-by-reflection at two filters. It reduces the number of required interference filters to less than half of the conventional polychromator, realizing a cost-effective polychromator. Because each filter costs about $1800, we can reduce huge costs. We designed this polychromator using CODE V (an optical path simulation program) for verification.

Figure 4 shows the APD signals of five channels whose central wavelengths are 1055.5, 1044.9, 1050.0, 1035.0 and 1024.3 nm, when the wavelength of the input light is varied from 1005 nm to 1065 nm by use of a monochromator with 0.3 nm resolution. We successfully separated the input light into five wavelength bands. The size of the images of all channels are smaller than 3 mm, because the photosensitive size of the APD is 3 mm in di-

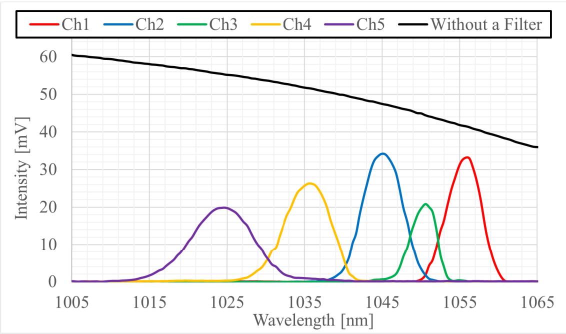

Fig. 4 The intensity of the polychromator system with two angled filters (1059 nm, 1050 nm).

ameter.

Figure 4 shows that the intensity decreases as the channel number is increased. This is because the light loss before the APDs increases with the number of reflections of interference filters and mirrors, and transmissions of lenses. Another reason is the decrease in transmittance when the angle of incidence increases. Since the sensitivity of the APD depends on wavelength, we normalize each APD signal by the corresponding one without filter at central wavelength. The normalized intensities of all five channels are 79, 73, 44, 48, and 35%, in order of all channels. The intensity of Ch3 is lower than that of Ch1 and Ch2, because the wavelength band of Ch3 overlaps with that of Ch1 and Ch2. According to the transmitted wavelength curve, some change in the refractive index of interference filters due to deterioration is a possible reason for the difference between the designed and measured values.

In summary, we developed the cost-effective polychromator system with two angled filters for the multichannel Thomson scattering measurement system. We reduced the number of interference filters to less than half of the number of wavelength channels, using the reflection between two interference filters whose transmitted wavelength decreases with their angle of incidence.

We successfully separated the scattered light into five wavelength bands. The values of their normalized intensity and central wavelengths are 79% (1055.5 nm), 73% (1044.9 nm), 44% (1050.0 nm), 48% (1035.0 nm), and 35% (1024.3 nm). Thus, we successfully demonstrate our idea of the cost-effective polychromator using the transmitted wavelength dependence of angle of incidence. It may be possible to improve the intensity of Ch3, by using the interference filters which have smaller refractive indices. According to the transmitted light fitting curve, the transmitted wavelength depends on the refractive index of the interference filter. A smaller refractive index of each interference filter will increase the difference between the central wavelengths of Ch1 and Ch2, which may increase the intensity of Ch3.

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