CALIBRATION OF SPECTROMETERS WITH UNDULATOR RADIATION[#]

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Abstract

A well-calibrated spectrometer is critical for measuring the real spectra of spontaneous radiation of an electron beam in undulators (i.e. undulator radiation), which is important for FEL research. A calibration method of spectrometers based upon the known undulator radiation spectrum has been developed at Duke FEL Laboratory (DFELL). It has been used to provide a precise calibration for spectrometers from infrared (IR) to ultraviolet (UV). This calibration method is expected to be useful for the calibration of spectrometers working in the extreme ultraviolet (EUV) and X-ray region. In this work, we present the details of the calibration method and illustrate the usefulness of the method using a portable spectrometer in the visible region as an example.

INTRODUCTION

A spectrometer is a spectral measurement instrument with an integrated array detector (e.g., linear CCD array detector). By replacing the single photon detector at the exit port in an monochromator with an array detector, all wavelength components, separated by the grating, are focused and directed to different positions of the array detector and thus measured simultaneously. Without rotating the grating, a spectrum can be taken in milliseconds or even a short duration, depending on the performance of the array detector and grating, as well as the intensity of the input photon beam.

Nowadays commercially available spectrometers provide a convenient and fast way to measure radiation spectra, especially in the UV, visible and near-IR spectral region. At Duke FEL Laboratory (DFELL), several spectrometers have been integrated into the photo beam diagnostic system for FEL research, commissioning and operation. For example, using the undulator radiation, in particular, radiation from an optical klystron with two undulators and a dispersion section (a magnet buncher) in-between the undulators, a technique to provide a direct and precise measurement of the electron beam energy spread has been developed [1,2].

However for FEL research, especially when measuring the spectrum of undulator radiation with a relatively broad bandwidth, the spectral response of spectrometer needs to be taken in account. Therefore, a well-calibrated spectrometer is critical for obtaining a detailed and accurate measurement of the undulator spectrum.

[#] This work is supported by US Department of Energy grant DE-FG02-97ER41033.

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The spectral response of a spectrometer is mainly determined by the efficiency of the grating and spectral response of the array detector. For a typical commercial spectrometer in the near-IR, visible, and UV region, the grating efficiency can vary by a factor of 2 to 3 in its working spectral range [3]. In addition, the spectral response of the CCD array can vary by a factor 2 to 5 [4] in the same spectral range. Overall, the response of the spectrometer greatly depends on the wavelength, making it difficult, if not impossible, to provide a precise and detailed measurement of any broad spectrum. Other factors that can contribute to a spectrometer's spectral response include the reflectivity of collimating mirror (which is used to collimate the incoming photo beam toward the grating) and focusing mirror (which is used to focus the dispersed photo beam to the array detector), the transparency of the detector window, et al.

The calibration of the spectral response of a spectrometer can be performed using a conventional, calibrated light source if it is available. However such a source is usually not readily available to users of the spectrometer. Furthermore, in some spectral region, conventional, calibrated light sources are not available. Undulator radiation, with a known spectrum which can be produced in a wide spectral range, from far-IR, to EUV, and to X-ray, can then be a useful light source for spectrometer calibration.

UNDULATOR RADIATION

The intensity of the on-axis spontaneous radiation (fundamental mode) produced by an electron traversing a planar undulator can be expressed as a function of the wavelength as the following [5]:

$$\frac{d^2 I}{d\lambda\, d\Omega}=\frac{e^2 a_u^{\,2} L_u^{\,2}}{4\epsilon_0\gamma^2}\left[J_0(\xi)-J_0(\xi)\right]^2 \cdot\frac{1}{\lambda^4}\left[\frac{\sin\left(\pi N_u(\lambda_c/\lambda-1)\right)}{\pi N_u(\lambda_c/\lambda-1)}\right]^2 , \quad (1)$$

where e is the electron's charge, ϵ_0 is the vacuum permittivity, a_u is the undulator parameter (rms), $L_u=N_u\lambda_u$ is the undulator length, N_u is the number of undulator periods, λ_u is the undulator period length, γ is the electron's relativistic energy factor, $\lambda_c=\lambda_u(1+a_u^{\,2})/2\gamma^2$ is the central wavelength of the undulator radiation spectrum, and $\xi=a_u^{\,2}/2(1+a_u^{\,2})$.

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For an electron beam with a small energy spread, when the beam current and energy are fixed, the peak intensity of the fundamental undulator radiation, I_p, is a function of the undulator parameter a_u only, i.e.

$$I_p = A \times a_u^2 [J_0(\xi) - J_1(\xi)]^2 / (1 + a_u^2)^4 \quad , (2)$$

where $A = 4e^2 \gamma^6 N_u^2 / \epsilon_0 \lambda_u^2$.

The peak intensity of the measured undulator radiation spectrum, scaled with I_p, therefore gives the spectral response of the spectral measurement system at the central wavelength λ_c. By tuning a_u, and thus varying λ_c in the wavelength range of interest, we can then obtain the spectral response curve of the spectral measurement system.

SPECTRAL RESPONSE CALIBRATION

As an example of the calibration method, the calibration of a spectrometer used for FEL research is presented here. The calibration was performed with a planner undulator system, the OK-4 undulators [6,7] at the Duke FEL facility. Each OK-4 undulator has 33 periods with a period length of 10 cm. The undulator radiation was extracted using a 45° broadband reflecting mirror located immediately before the downstream FEL cavity mirror. The measurements were performed using a 450 MeV electron beam with a relatively low beam current (about 2 mA) to minimize the impact of spectral broadening due to the electron beam energy spread.

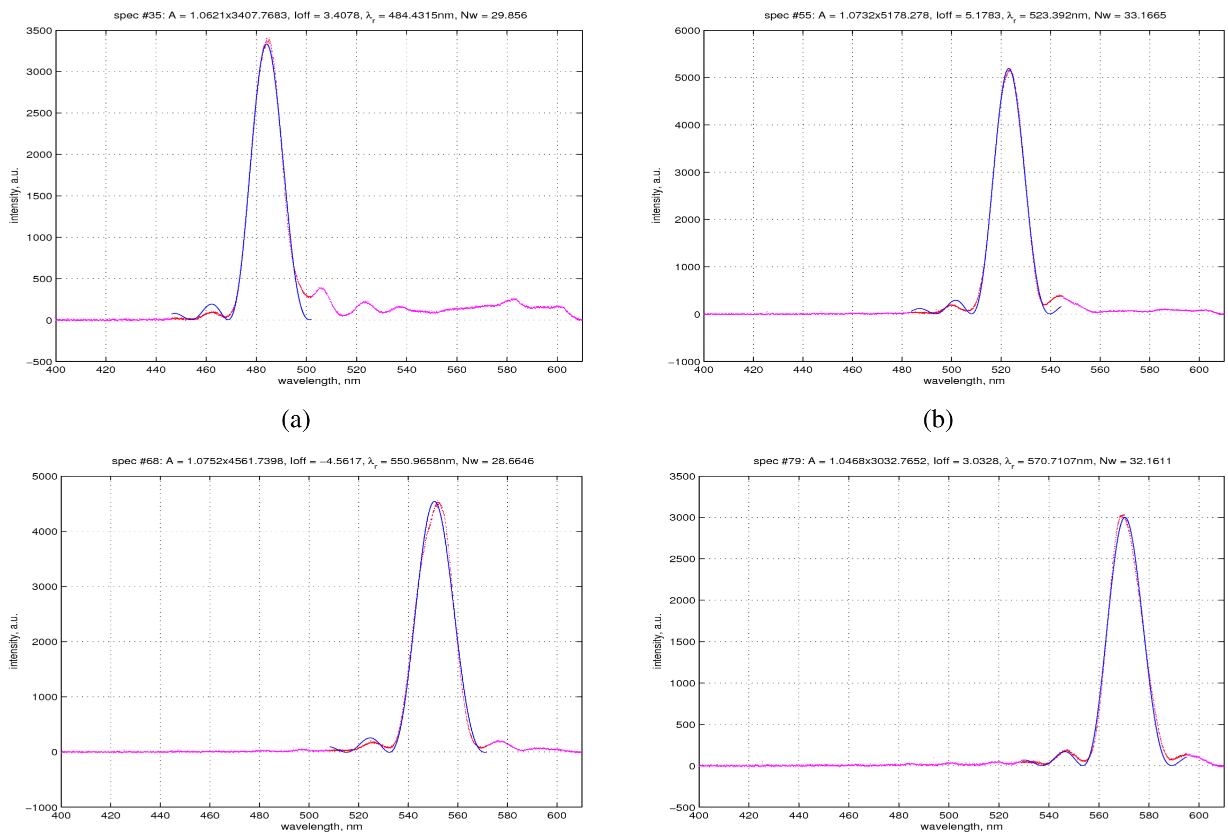

Figure 1: Undulator radiation spectra with varying a_u. The measured spectra (magenta dots and red dots) and fit curves (blue lines) are shown in the figures.

In order to cover the wavelength range of interest (from 420 to 580 nm), a_u was varied between 2.30 and 2.85. For each a_u, the individual undulator radiation spectrum was taken simultaneously with other relevant parameters, including the electron beam current, electron beam energy, integration time of the spectrometer, et al. Shown in Figure 1 are some undulator radiation spectra with four different values of a_u.

As the first iteration of spectral response calculation, we calculate I_p and then scale the peak intensity of the measured undulator radiation spectrum with the computed peak intensity I_p, integration time of spectrometer, and electron beam current. This is done for a number of measured undulator spectra for their central wavelengths λ_c. The spectral response curve of the spectrometer (first iteration result) is then obtained (red dash curve in Figure 2a).

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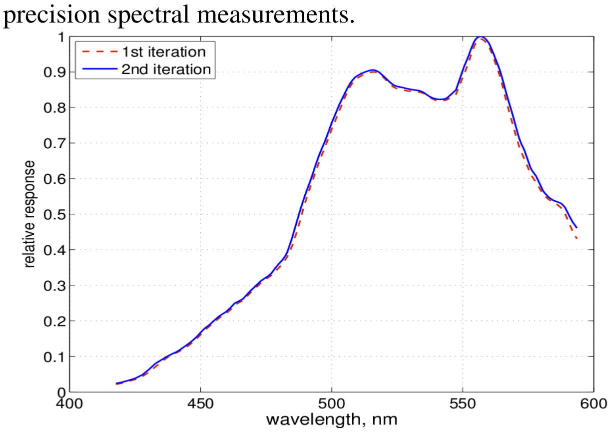
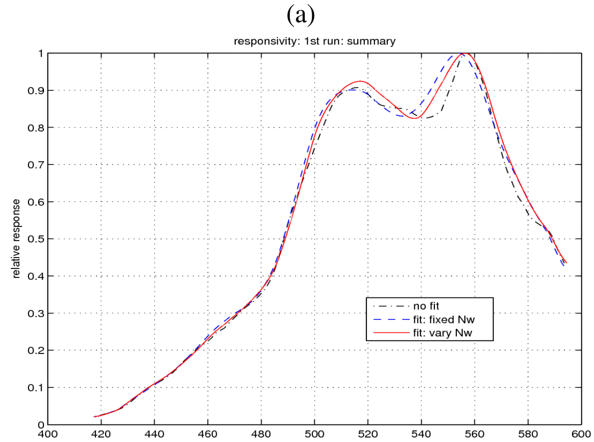
A second iteration is carried out by correcting the measured undulator radiation spectra with the spectral response curve (from the first iteration), followed by a repeat of the calibration process described above. With the second iteration, a more accurate result is then obtained (blue solid curve in Figure 2a). Typically, the difference between subsequent iterations is small, and the second iteration yields a reasonably converged spectral response curve.

Figure 2a indicates that the spectral response increases by about 4 times in the wavelength region between 450 and 500 nm. It is inappropriate to assume a uniform response when measuring any spectrum with a broad spectral feature. Therefore, the spectral response calibration for the spectrometer is critical for high precision spectral measurements.



(a)



(b)

Figure 2: Spectral response curves. (a) Spectral response was obtained by taking the peak intensity of undulator radiation spectra scaled by I_p, integration time of spectrometer and electron beam current; (b) The fitting method is used to calculate the peak intensity and peak location of undulator radiation spectra.

As can be observed from the undulator radiation spectra (Figure 2), measurement noise makes it difficult to measure the peak intensity and peak location of spectra with good precision. Although smoothing method has been employed to reduce the effect of the noise, the peak intensity and according central wavelength cannot determined well enough, especially for undulator radiation spectra with noisy data points around the peaks.

A least square fitting method of the undulator radiation spectrum is therefore used to provide a more accurate determination of the peak intensity and central wavelength of the spectra. Some of the fitted curves are shown in Figure 1 (blue solid curves).

Plotted in Figure 2b are the spectral response curves calculated with different methods. Obvious differences between the curves can be observed from 500 to 590 nm, nevertheless the response curves have a similar trend and the maximum deviation is within 10%. Also can be observed is that the spectral response curves agree well between 420 and 500 nm. More effort is being made to improve this calibration method and related fitting techniques.

This spectral response curve in fact includes the spectral response of optical components in the beamline (including mirrors, window, etc.) between the undulator and spectrometer. A new calibration may be necessary if the spectrometer is used for another beamline or for a different optical setup. By excluding the spectral response of optical components in the beamline, the spectral response curve of the spectrometer along can then be obtained.

SUMMARY

A calibration method of spectrometers based upon the known undulator radiation spectrum is described. It can be used to precisely calibrate spectrometers from IR to VUV spectral region. This method can also provide a means for calibrating spectrometers in spectral regions where conventional, calibrated light sources are unavailable, in particular, in the EUV and X-ray region.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of the DFELL staff.

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