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Polarization properties of FEL lamps as applied to radiometric calibration

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Abstract

The polarization of the irradiance from several 1000-W FEL lamps was measured between 450 and 900 nm. These lamps are universally used as irradiance calibration standards in radiometric laboratories. The irradiance was polarized between 2.3–3.2%, with the polarization axis aligned with the coiled filament, nearly perpendicular to the lamp axis. A simple model of the filament is presented that explains the degree of polarization and the plane of polarization, based on the polarized emissivity of tungsten, and gives an approximate value for this polarization. While the irradiance is polarized, this polarization does not significantly effect the polarization of the light when reflected from a Spectralon plaque (Labsphere, Inc.). The polarization of these lamps should be taken into account when using these FEL lamps to characterize optical instruments, particularly grating spectrometers without polarization scrambling devices.

1. Introduction

1000W FEL lamps¹ are commonly used as a light source for radiometric calibration of irradiance detectors.² These lamps are also used in calibration of radiance detectors when light from the lamp is reflected off a diffuse reflector, such as Spectralon, to provide an extended source of radiance.² While it is often assumed that this irradiance is unpolarized, it actually is polarized.³ During calibration, this polarization may interact with the polarization sensitivity of the detector being calibrated, and in addition it may affect the polarization of the radiance obtained by reflecting this irradiance off of a plaque.

This study was aimed at quantifying the polarization properties of this family of lamps in the visible at higher spectral resolution than previously reported and to determine the plane of polarization of the irradiance. To achieve a higher spectral resolution a fiber coupled spectrometer was used, rather than a filtered detector, and to eliminate residual polarization effects in this spectrometer, the analyzing polarizer and the spectrometer were fixed relative to each other and rotated together.

A simple model, using the reported polarized emissivity of tungsten, explains both the degree of polarization and the alignment of the plane of polarization.

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2. Methods

An Ocean Optics fiber coupled spectrometer (USB4000 VIS-NIR) was used as the detector in this study. This spectrometer has a spectral resolution of 1.5–2.3 nm (Full Width at Half Maximum), with measurements at approximately every 0.2 nm from 346 to 1037 nm. The spectrometer is very compact, which allowed the whole spectrometer, fiber, and collector to be mounted on a precision milling rotary table oriented with a horizontal rotation axis.

Figure 1 is a diagram of the measuring device. The spectrometer was mounted on the back of the rotary table, while the optical fiber went through the axis of the rotary table and the collector was mounted on the front of the table, on the axis of the rotary table. In this way the entire system was rotated as one fixed, and rigid piece, thus eliminating issues with the inherent polarization sensitivity of the detection system. The data collection computer, which did not rotate, was connected to the spectrometer via a USB cable.

For measurement of the polarized irradiance, a diffuser (Ocean Optics CC-3) was placed on the collection end of the fiber. The lamp was placed 50 cm away and normal to the surface of the fiber/collector (the specified calibration distance), the exact cosine response characteristics of the diffuser were not important since the lamp flux was normal to the surface of the diffuser. In front of the diffuser a wire grid film polarizer (Edmunds Optics 33-082) was mounted, fixed to the collector. The wire grid film polarizer has both an extended wavelength interval (400 to 1200 nm) and a large useful angular range (up to 45° incident angle), with an extinction coefficient specified to be greater than 1000 over this range.

Each lamp was operated at the standard constant current of 8.00 Amps, provided by an Optronics 83 DS power supply. The lamp voltage was monitored, as was the current via a precision shunt (Fluke Y5020 shunt, HP3478A multimeter). The lamp and power supply were allowed to warm up and stabilize for 15 minutes before the measurement sequence. For each lamp, a quick measurement was performed to determine the angle at which the maximum and minimum signals were obtained with the polarized detector. While the maximum and minimum angles were determined separately, in all cases they were 90° apart. Once these angles had been determined, three measurements of the maximum (I_{max}) and three measurements of the minimum (I_{min}) were obtained. Along with this, two measurements (I_{block}) were done with the light path between the lamp and the detector blocked to allow both the dark noise and amplifier offset in the detector, and background scattered irradiance to be determined. I_{block} was subtracted from I_{max} and I_{min} , forming I'_{max} and I'_{min} , respectively. I_{block} was less than 10% of I_{min} and I_{max} in the range from 500–775 nm, but increased to 30% at 450 and 20% at 900 nm, due to lower lamp signal. Each of these measurements was done with a 10 second exposure time and consisted of 10 individual measurements that were internally averaged in the detector/software system. The polarization factor was defined as:

$$POL = 100 * \frac{(I'_{max} - I'_{min})}{(I'_{max} + I'_{min})} \quad (1)$$

With three measurements of I_{max} and I_{min} , and the 2 I_{block} measurements, 18 different combinations could be formed. The possible combinations of the data were made, and the average and standard deviation of these combinations were determined. This factor is independent of the absolute calibration of the detector system, so an absolute calibration was not performed. After data reduction, the data were smoothed with a 10nm boxcar average.

The FEL lamp is made of a tightly coiled filament that in turn is formed into a right handed helix orientated with its central axis vertical (z-axis, Fig. 2). The tight coils of the filament are then oriented with the axis of the tight coil almost horizontal, but the filament strands approximately vertical. The filament coil helix, when projected on the x-z plane, will make an angle with the horizontal direction (x-axis). This angle was measured at 5 different positions along the front of the helix to get an idea of the variation of this angle along the filament. Eight lamps were measured and Table 1 gives the specification of each lamp and operating conditions of each lamp.

3. Results

Figure 3 shows the polarization factor, POL, versus wavelength, while Table 1 includes the angle of the plane of polarization with the horizontal, with the lamp oriented vertically. The uncertainty, derived from the standard deviation of the permutations of the measurements, is shown as the error bars on the working standard lamp (smaller than the symbol through most of the spectrum). These have approximately the same magnitude for all of the lamps, but are only shown for the working standard. As can be seen, the POL factor is approximately 3.0 for all of the lamps, with the exception of the working standard, which has a lower polarized irradiance. Table 1 tabulates the results for each lamp. The working standard is the lamp that has been used the most, estimated to have been used over 500 hrs, and is used when a relatively stable bright uncalibrated source is required. The 3 lamps, L91793, L91794, and L91795, are used as secondary standards in our lab and have 80–100 hours of use in our lab. Our primary standards, used only to calibrate the secondary standards, have fewer hours. If one arranges the lamps in terms of operating hours (as done in Fig. 2 legend), POL appears to decrease accordingly; the more operating hours the lower the POL factor. However this effect is small, other than for the working standard, which has a much smaller POL factor.

As mentioned, the lamp filament is constructed as a tight coil of tungsten wire, formed into a larger helix. The polarized emissivity of Tungsten as a function of observation angle was measured by Worthing⁴ and reviewed by Sandus.⁵ Worthing found that the emissivity varied with observation angle and the plane of polarization is in the emission plane (plane formed by emission angle and the normal to the surface). Worthing⁴ calculated that the polarization of a straight cylindrical filament was 19%. As the filament of the FEL lamp consists of tight coils, we built a mathematical model of the filament based on the emission expected from a tungsten torus when viewed on the edge. The values of the brightness and polarization of the emissivity were interpolated from the data in Worthing.⁴ With this torus model, the polarization of the light, when the torus is viewed end-on, was found to be 9%, with the plane of polarization being along the central axis of the torus. This is much larger than the value found in our measurements, but the orientation of the polarization axis is correct. A factor that will reduce this model polarization is based on the properties of a coil of tungsten

filament as studied by Coblenz.⁵ He found that the “brightness” (or radiance) of the inner part of the coil was approximately 2.2 times as bright as the outer part of the coil, the part of the coil considered in our model. This increase in brightness was found to be caused by multiple reflections of light from other neighboring coils, combined with the emissivity of the surface. Since the dominate polarization for reflection from a surface is perpendicular to the reflectance plane while it is parallel to the emission plane, it would make sense that the total degree of polarization of the irradiance from the inner part of the coil would decrease. Then the overall effect would be for the inner part of the coil to be responsible for an increase in the total irradiance from the lamp without necessarily increasing the polarized irradiance. Thus this could contribute to the reduction in the POL factor found in the model, 9%, to the measured value of 3%.

Often, for calibration of radiance detectors or systems, the FEL lamps are used as sources of irradiance, which are reflected from a diffuse surface, most often Spectralon (Labsphere, Inc.), to form a uniform source of radiance.² The question then is how would the polarization of the FEL lamp influence this reflected radiance? Stokes vector and Mueller matrix calculus can help determine this influence.⁷

With the common definition of the Stokes vector,⁷ the Stokes vector of the lamp irradiance (normalized to the total irradiance and assuming the plane of polarization is 10° with respect to the horizon as seen in our measurements), will be $(I, Q, U, V)^T = (1, 0.03 \cos(10^\circ), 0.03 \sin(10^\circ), 0)^T$ or $(1, 0.029, 0.005, 0)^T$. Here the reference plane for the Stokes vector is the horizontal, x - y , plane. Several measurements have been reported for the polarized reflectance from Spectralon,^{8,9} specifically the cases of ss , pp , sp , and ps reflectance. In each of these cases the first letter corresponds to the polarization of the incident light, while the second corresponds to the polarization of the reflected light with s being perpendicular to the plane of reflectance, while p is parallel to the reflectance plane. Using these measurements, the top left quadrant of the Mueller matrix can be determined, which describes the effect of the Q element in the incident light field on I and Q in the reflected light field. Using the results of Bhandari et al.,⁹ the upper quadrant of the normalized Mueller matrix is:

$$\begin{bmatrix} 1 & M12 \\ M21 & M22 \end{bmatrix} = \begin{bmatrix} 1 & -0.012 \\ 0.006 & 0.024 \end{bmatrix} \quad (2)$$

They state that their standard deviation was approximately 1%, indicating that the uncertainty of these elements is on the order of 0.01. The effect of the incident light having a small Q (being linearly polarized in or perpendicular to the reflectance plane) would be a small change in the overall intensity and in the final Q value. Since M12 and M22 are less than 3% and Q is on the order of 3%, this effect would be less than 10^{-3} .

4. Conclusions

The polarization of eight FEL incandescent lamps were measured. The irradiance from the lamps was found to be polarized, with a degree of polarization between 2.3% and 3.2%, with a plane of polarization parallel to the tightly coiled filament axis. It appeared that the

strength of the polarization was inversely related to the operating hours on the lamp. A simple model treating the coiled filament as a torus, and using measured values for the polarized emissivity of the tungsten filament overestimates this polarization, however including the impact of the irradiance from the internal surfaces of the coil improves the agreement between the model and the data.

Since many instruments that measure irradiance include a diffuser as the first element in the optical train, and are thus inherently polarization insensitive, this level of polarization will not be important. However care must be taken when directly illuminating the entrance slit of a grating spectrometer, for example, as these often have a large polarization sensitivity.¹⁰ For example, grating spectrometers have been shown to have polarization sensitivities that can vary from -50% to $+50\%$ in the spectral range from 400–700 nm.¹¹ If care is not taken to add a polarization scrambling device, the absolute calibration of the spectrometer will be in error by $\pm 1.5\%$ due to the 3% polarization of the FEL lamp. The polarization of radiance resulting when the lamp irradiance is used to illuminate a reflectance plaque is not strongly effected by the lamp irradiance polarization, at this level. While small, the polarization of the irradiance from the lamp should be taken into account when doing instrument calibrations and characterizations.

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References

1. Walker JH, Saunders RD, Jackson JK, McSparron DA. NBS Measurement Services: Spectral Irradiance Calibrations. 1987 NBS SP 250-20.
2. Zibordi, G., Voss, KJ. In situ Optical Radiometry in the Visible and Near Infrared. In: Zibordi, G., Donlon, CJ., Parr, AC., editors. Optical Radiometry for Ocean Climate Measurements. Academic; 2014.
3. Kostuk RK. Polarization characteristics of a 1000-W FEL-type filament lamp. Appl Opt. 1981; 20(13):2181–2182. [PubMed: 20332912]
4. Worthing AG. Deviation from Lambert's Law and polarization of light emitted by incandescent Tungsten, Tantalum, and Molybdenum and changes in the optical constants of Tungsten with temperature. J Opt Soc Am and Rev Sci Instruments. 1926; 13(6):635–649.
5. Sandus O. A review of emission polarization. Appl Opt. 1965; 4(12):1634–1642.
6. Coblentz WW. Emissivity of straight and helical filaments of tungsten. Bul Bureau of Standards. 1918; 14:115–131.
7. Goldstein, D. Polarized Light. CRC Press; 2003.
8. Haner DA, McGuckin BT, Bruegge CJ. Polarization characteristics of spectralon illuminated by coherent light. Appl Opt. 1999; 38(30):6350–6356. [PubMed: 18324164]
9. Bhandari A, Hamre B, Frette O, Zhao L, Stamnes JJ, Kildemo M. Bidirectional reflectance distribution function of spectralon white reflectance standard illuminated by incoherent unpolarized and plane-polarized light. Appl Opt. 2011; 50(16):2431–2442. [PubMed: 21629324]
10. Palmer, C. Diffraction Grating Handbook. Newport Corp; 2005.
11. Poulsen O. Polarization calibration of a grating spectrometer. Appl Opt. 1972; 11(8):1876–1878. [PubMed: 20119251]

Fig. 1. Illustration of measurement setup. Spectrometer, fiber, irradiance collector, and polarizer all rotate together, eliminating problems due to residual polarization sensitivity of the spectrometer or transmission changes due to bending the fiber.

Fig. 2.

Picture of FEL lamp, and enlarged image of the filament element. The filament consists of a tight coil (wires in coil are almost vertical) formed into a larger right handed helix. Shown in the figure are the vertical (z-axis) and horizontal (x-axis). The projection of the filament helix onto the x-z plane will make an angle with the horizontal that was measured at several positions along the lamp filament

Fig. 3.
Polarization factor, POL versus wavelength.

Table 1

Lamp operating conditions and polarization results

Lamp	Source	Acquisition date (Month/year)	Operating Voltage (Volts)	Operating current (Amp)	Filament angle with horizontal	Lamp hours	Average % polarization, 450-900 nm (std dev)	plane of polarization (degrees)
F737	Optronics	5/2003	112.9	8.004	$9.5^{\circ} \pm 1.2^{\circ}$	7	3.15 (0.21)	$15^{\circ} \pm 3^{\circ}$
F258	Optronics	6/1990	113.9	8.007	$10.1^{\circ} \pm 2.4^{\circ}$	10	3.14 (0.20)	$15^{\circ} \pm 3^{\circ}$
F161	Optronics	10/1985	111.5	8.002	$9.2^{\circ} \pm 3.5^{\circ}$	34	2.99 (0.20)	$10^{\circ} \pm 3^{\circ}$
F12G	Unknown	9/1985	112.7	8.002	$11.0^{\circ} \pm 3.1^{\circ}$	48	2.98 (0.18)	$5^{\circ} \pm 3^{\circ}$
L91795	Hoffman Eng.	9/1993	102.7	7.997	$10.2^{\circ} \pm 2.8^{\circ}$	83	2.81 (0.26)	$10^{\circ} \pm 3^{\circ}$
L91793	Hoffman Eng.	9/1994	100.5	8.007	$11.5^{\circ} \pm 0.6^{\circ}$	120	2.91 (0.25)	$10^{\circ} \pm 3^{\circ}$
L91794	Hoffman Eng.	9/1994	102.3	8.008	$10.0^{\circ} \pm 3.1^{\circ}$	156	2.77 (0.21)	$10^{\circ} \pm 3^{\circ}$
Working Standard	Unknown	Unknown	104.5	8.004	$12.0^{\circ} \pm 3.9^{\circ}$	>500	2.28 (0.23)	$10^{\circ} \pm 3^{\circ}$