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% and 3.2%, with the polarization axis aligned with the coiled filament, nearly perpendicular to the lamp axis. We have presented a simple model of the filament 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 affect the polarization of the light when reflected from a Spectralon plaque (Labsphere, Inc.). The polarization of these lamps should be considered when these FEL lamps are used to characterize optical instruments, particularly grating spectrometers without polarization scrambling devices.

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1. INTRODUCTION

1000 W FEL lamps [1] are commonly used as a light source for radiometric calibration of irradiance detectors [2]. These lamps are also used to calibrate 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 also may affect the polarization of the radiance obtained by reflecting this irradiance off of a plaque.

We performed this study to quantify 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, we used a fiber-coupled spectrometer instead of a filtered detector. To eliminate residual polarization effects in this spectrometer, we fixed the analyzing polarizer and the spectrometer relative to each other and rotated them 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.

2. METHODS

We used an Ocean Optics fiber-coupled spectrometer (USB4000 VIS-NIR) as the detector in this study. This spectrometer has a spectral resolution of 1.5–2.3 nm FWHM, with measurements at approximately every 0.2 nm from 346 to 1037 nm. Because the spectrometer is very compact, we were able to mount the whole spectrometer, fiber, and collector on a precision milling rotary table oriented with a horizontal rotation axis. Figure 1 is a diagram of the measuring device. We mounted the spectrometer 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. This approach allowed the entire system to rotate as one fixed, rigid piece, which eliminated issues with the inherent polarization sensitivity of the detection system. We connected the data collection computer, which did not rotate, to the spectrometer via a USB cable.

For measurement of the polarized irradiance, we placed a diffuser (Ocean Optics CC-3) on the collection end of the fiber. We placed the lamp 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. We mounted a wire grid film polarizer (Edmunds Optics 33-082) in front of the diffuser that was fixed to the collector. The wire grid film polarizer had both an extended wavelength interval (400–1200 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.
We operated each lamp at the standard constant current of 8.00 Amps, provided by an Optronics 83 DS power supply. We monitored the lamp voltage and the current via a precision shunt (Fluke Y5020 shunt, HP3478A multimeter). We allowed the lamp and power supply to warm up and stabilize for 15 min before the measurement sequence. For each lamp, we performed a quick measurement to determine the angle at which the maximum and minimum signals were obtained with the polarized detector. Although we determined the maximum and minimum angles separately, in all cases they were 90° apart. Once we determined these angles, we obtained three measurements of the maximum ($I_{\text{max}}$) and three measurements of the minimum ($I_{\text{min}}$). Along with these measurements, we did two measurements ($I_{\text{block}}$) with the light path between the lamp and the detector blocked to allow us to determine both the dark noise and amplifier offset in the detector and background scattered irradiance. We subtracted $I_{\text{block}}$ from $I_{\text{max}}$ and $I_{\text{min}}$, forming $I'_{\text{max}}$ and $I'_{\text{min}}$, respectively. $I_{\text{block}}$ was less than 10% of $I_{\text{min}}$ and $I_{\text{max}}$ in the range from 500 to 775 nm, but increased to 30% at 450 nm and 20% at 900 nm, due to a lower lamp signal. For each of these measurements, we used a 10 s exposure time and did 10 individual measurements that were internally averaged in the detector/software system. The polarization factor was defined as

$$\text{POL} = 100 \times \frac{(I'_{\text{max}} - I'_{\text{min}})}{(I'_{\text{max}} + I'_{\text{min}})}.$$  

With three measurements of $I_{\text{max}}$ and $I_{\text{min}}$, and the 2$I_{\text{block}}$ measurements, we could form 18 different combinations. We made the possible combinations of the data, and determined the average and standard deviation of these combinations. This factor is independent of the absolute calibration of the detector system, so we did not perform an absolute calibration. After data reduction, we smoothed the data with a 10 nm 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 five different positions along the front of the helix to get an idea of the variation of this angle along the filament. We measured eight lamps and Table I gives the specifications and operating conditions of each one.

### 3. RESULTS

Figure 3 shows the polarization factor, POL, versus the wavelength, while Table I 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 shown, 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 I tabulates the results for each lamp. The working standard was the lamp that was used the most (estimated to have been used over 500 h), and was used when an uncalibrated source that was relatively stable and bright was required. The three lamps—L91793, L91794, and L91795—were used as secondary standards in our lab and had 80–100 h of use. Our primary standards, used only to calibrate the secondary standards, have fewer hours. If we arrange the lamps in terms of operating hours (as done in the Fig. 2 legend), POL appears to decrease accordingly. In other words, more operating hours result in a lower POL factor. This effect is small, however, other than for the working standard, which has a much smaller POL factor.

As mentioned, the lamp filament was constructed as a tight coil of tungsten wire, formed into a larger helix. Worthing [4] measured the polarized emissivity of tungsten as a function of observation angle and Sandus [5] reviewed it. Worthing found that the emissivity varied with observation angle and the plane of polarization is in the emission plane (the plane formed by the emission angle and the normal to the surface). Worthing [4] calculated that the polarization of a straight cylindrical filament
Table 1. Lamp Operating Conditions and Polarization Results

<table>
<thead>
<tr>
<th>Lamp</th>
<th>Source</th>
<th>Acquisition Date (Month/Year)</th>
<th>Operating Voltage (Volts)</th>
<th>Operating Current (Amp)</th>
<th>Filament Angle with Horizontal</th>
<th>Lamp (h)</th>
<th>Average % Polarization 450–900 nm (std dev)</th>
<th>Plane of Polarization (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F737</td>
<td>Optronics</td>
<td>5/2003</td>
<td>112.9</td>
<td>8.004</td>
<td>9.5° ± 1.2°</td>
<td>7</td>
<td>3.15 (0.21)</td>
<td>15° ± 3°</td>
</tr>
<tr>
<td>F258</td>
<td>Optronics</td>
<td>6/1990</td>
<td>113.9</td>
<td>8.007</td>
<td>10.1° ± 2.4°</td>
<td>10</td>
<td>3.14 (0.20)</td>
<td>15° ± 3°</td>
</tr>
<tr>
<td>F161</td>
<td>Optronics</td>
<td>10/1985</td>
<td>111.5</td>
<td>8.002</td>
<td>9.2° ± 3.5°</td>
<td>34</td>
<td>2.99 (0.20)</td>
<td>10° ± 3°</td>
</tr>
<tr>
<td>F12G</td>
<td>Unknown</td>
<td>9/1985</td>
<td>112.7</td>
<td>8.002</td>
<td>11.0° ± 3.1°</td>
<td>48</td>
<td>2.98 (0.18)</td>
<td>5° ± 3°</td>
</tr>
<tr>
<td>L91795</td>
<td>Hoffman Engineering</td>
<td>9/1993</td>
<td>102.7</td>
<td>7.997</td>
<td>10.2° ± 2.8°</td>
<td>83</td>
<td>2.81 (0.26)</td>
<td>10° ± 3°</td>
</tr>
<tr>
<td>L91793</td>
<td>Hoffman Engineering</td>
<td>9/1994</td>
<td>100.5</td>
<td>8.007</td>
<td>11.5° ± 0.6°</td>
<td>120</td>
<td>2.91 (0.25)</td>
<td>10° ± 3°</td>
</tr>
<tr>
<td>L91794</td>
<td>Hoffman Engineering</td>
<td>9/1994</td>
<td>102.3</td>
<td>8.008</td>
<td>10.0° ± 3.1°</td>
<td>156</td>
<td>2.77 (0.21)</td>
<td>10° ± 3°</td>
</tr>
<tr>
<td>Working Standard</td>
<td>Unknown</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 3. Polarization factor, POL versus wavelength.

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. We interpolated the values of the brightness and polarization of the emissivity from the data in Worthing [4].

With this torus model, we found the polarization of the light, when the torus is viewed end-on, to be 9%, with the plane of polarization 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 Coblentz [6]. 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. He found this increase in brightness 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%.

To calibrate radiance detectors or systems, FEL lamps are often 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 $(I, Q, U, V)^T = (1, 0.03 \cos(10°), 0.03 \sin(10°), 0)^T$ 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 $s$, $sp$, $sp$, and $p$ 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, we could determine the top left quadrant of the Mueller matrix, 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

$$
\begin{bmatrix}
1 & M_{12} \\
M_{21} & M_{22}
\end{bmatrix} =
\begin{bmatrix}
1 & -0.012 \\
0.006 & 0.024
\end{bmatrix}.
$$

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

We measured the polarization of eight FEL incandescent lamps. We found the irradiance from the lamps to be polarized, with the 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. Including the impact of the irradiance from the internal surfaces of the coil, however, 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 is unimportant. However care must be taken when directly illuminating the entrance slit of a grating spectrometer, for example, because they often are very sensitive to polarization [10]. Grating spectrometers, for example, have been shown to have polarization sensitivities that can vary from −50% to +50% in the spectral range from 400 to 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 ±1.5% because of 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 affected by the lamp irradiance polarization at this level. Although it is small, the polarization of the irradiance from the lamp should be considered when doing instrument calibrations and characterizations.

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