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## Polarization characteristics of a 1000-W FELtype filament lamp

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Radiant light sources are known to emit partially polarized light.<sup>1,2</sup> When a source of this type is used as a spectral-irradiance transfer standard in conjunction with a polarization sensitive detector, the accuracy of the calibration will be influenced by the degree and orientation of the polarized component of light emitted from the lamp. Little published information exists, however, on the polarization properties of actual spectral-irradiance lamp standards. This Letter summarizes the polychromatic and quasi-monochromatic polarization characteristics produced from four samples of a 1000-W FEL-type tungsten-halogen lamp. This lamp is currently recommended by the National Bureau of Standards (NBS) as a spectral-irradiance calibration standard.<sup>3</sup>

A diagram of the instrument used to determine the degree of polarization of these lamps is illustrated in Fig. 1. The lamp, dichroic polarizer, filter, and detector are centered on an optical axis. When the polarizer is rotated, the partially polarized light emitted from the lamp will be transmitted or attenuated depending on the relative angle between the polarizer axis and the polarization axis of the light emitted by the lamp.

Polychromatic and quasi-monochromatic polarization properties were determined by inserting broad or narrow bandpass transmission filters, respectively, in front of the detector. To minimize errors from background light, the field of view of the detector was limited to the height of the lamp filament.

The degree of polarization, expressed as a percentage, is given by the standard relation<sup>4</sup>

$$P = \frac{E_{\text{MAX}} - E_{\text{MIN}}}{E_{\text{MAX}} + E_{\text{MIN}}} \times 100\%, \tag{1}$$

where  $E_{\text{MAX}}$  and  $E_{\text{MIN}}$  are, respectively, the maximum and minimum irradiance values obtained when the polarizer is rotated.

The four lamps tested are 1000-W FEL-type, clear bulb, quartz-halogen lamps with coiled coil (CC-8) filaments (Fig. 2). Three lamps were obtained from a secondary calibrating facility and the fourth from NBS as a certified spectral-irradiance standard.

All measurements were performed with the detector and lamp 50 cm apart and with the lamps energized with 8.00 A of current. These operating conditions are recommended by NBS<sup>5</sup> when performing spectral-irradiance calibrations with these lamps. The detector was an EG&G UV444B silicon photodiode.

Polychromatic polarization properties were determined with a 200-nm bandpass transmission filter having 50% absolute transmittance at 545 nm and decreasing to 4% transmittance at 450 and 650 nm. Quasi-monochromatic polarization characteristics were assessed with a series of interference filters having FWHM bandwidths of ~10 nm.

To check the polarization sensitivity of the detector, the set







Fig. 2. FEL-type 1000-W lamp illustrating the helical structure of the coiled coil filament.



Fig. 3. System used for determining the detector's sensitivity to polarization orientation. The lamp and integrating-sphere combination provide a source of depolarized light which is then polarized and rotated on the surface of the detector.

up of Fig. 3 was used. The lamp-integrating sphere–polarizer arrangement provides a source of linearly polarized light, the axis of which can be rotated on the surface of the detector. A full rotation of the polarizer produced variations in the degree of polarization of  $0.33 \pm 0.04\%$ .

The degrees of polarization obtained from each lamp in both broad- and narrow-wavelength intervals are given in Table I. The degree of polarization is  $\sim 2.5-3.5\%$  for both broad- and narrow-wavelength regions and is nearly constant at different wavelengths. The polarization of the NBS certified lamp was 0.7-1.0% less than that from the other lamps.

It was also observed that the polarization axis of each lamp is oriented  $\sim 90^{\circ}$  to the filament helix axis. (In Fig. 1, the filament helix axis is parallel to the y axis, and the observed polarization axis is parallel to the x axis.)

Table I. Degree of Polarization from Four Samples of a 1000-W FEL-Type Tungsten-Halogen Lamp

λ(nm)	PERCENT POLARIZATION (P)			
	Lamp 1ª	Lamp 2	Lamp 3	Lamp 4b
450-650	3.15 <u>+</u> 0.03	3.22 <u>+</u> 0.03	3.06 <u>+</u> 0.00	2.31 + 0.02
450	3.20 <u>+</u> 0.05	3.39 <u>+</u> 0.15	3.47 ± 0.18	2.56 <u>+</u> 0.10
480	3.15 + 0.03	3.47 ± 0.06	3.41 ± 0.02	2.56 ± 0.04
515	3.09 <u>+</u> 0.05	3.23 <u>+</u> 0.07	3.14 <u>+</u> 0.04	2.39 ± 0.03
546.1	3.18 ± 0.08	3.07 <u>+</u> 0.05	3.10 ± 0.04	2.39 ± 0.02
589.6	3.08 ± 0.04	3.31 ± 0.03	3.20 <u>+</u> 0.02	2.38 ± 0.02
620	3.17 <u>+</u> 0.01	3.52 ± 0.01	3.50 ± 0.01	2.51 ± 0.09
644	3.16 ± 0.13	3.43 ± 0.04	3.16 <u>+</u> 0.01	2.44 + 0.07

a Data for Lamps #1 through 4 are the mean and standard error based on three measurements.

b Lamp #4 is the NBS supplied spectral irradiance standard.

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## Infrared electric quadrupole transitions of atmospheric oxygen

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It had long been considered unlikely that electric quadrupole transitions would be observed in atmospheric absorption spectra. In 1938 Herzberg<sup>1</sup> suggested the possibility of detecting molecular hydrogen and nitrogen in planetary and cool stellar atmospheres by means of the vibration-rotation spectra in the ground electronic state produced by the quadrupole moment. Herzberg<sup>2</sup> reported the observation of electric quadrupole vibrational spectra of H2 in 1949. Electric quadrupole transitions of oxygen in emission in the terrestrial atmosphere were observed between excited electronic states  $(b^1 \Sigma_g^+ \leftarrow a^1 \Delta_g)$  by Noxon<sup>3</sup> in 1961. The recent use of highresolution high-throughput spectrometers, such as the Michelson interferometer, has now allowed the detection of electric quadrupole transitions in absorption through long atmospheric paths. Brault<sup>4</sup> has observed such transitions in the A-band of atmospheric oxygen at 7600 Å, and Niple et al.<sup>5</sup> observed transitions within the electronic ground state around 1600 cm<sup>-1</sup>. Quadrupole transitions of both N<sub>2</sub> and O<sub>2</sub> were identified<sup>6</sup> in the solar spectra of Ref. 5. We describe here the calculation of the IR electric quadrupole transitions of 16O2.

The oxygen molecule is in a  ${}^{3}\Sigma_{g}^{-}$  electronic ground state. This state approximately satisfies the conditions for Hund's case (b) with the angular momentum vector of end-over-end



Fig. 1. S-branch quadrupole transitions between 1601 and 1606 cm<sup>-1</sup> [very weak <sup>S</sup>Q(7,8) line not shown].

rotational motion,  $\mathbf{N} = \mathbf{J} - \mathbf{S}$ , being approximately a good quantum number. For a given level, the total angular momentum  $\mathbf{J}$  takes on the values J = N, N + 1, N - 1 giving rise to the  $\rho$ -type triplets. The selection rules for the electric quadrupole transitions are  $\Delta N = 0, \pm 2, \Delta J = 0, \pm 1, \pm 2$ . In addition, only odd values of N exist for the principal isotope of oxygen, owing to the fact that <sup>16</sup>O has zero spin and obeys Bose-Einstein statistics. These selection rules produce 21 lines for a given N'' > 1. (For the discussion that follows we use double primes for lower state values and single primes for upper state values.) Figure 1 is an example of S-branch lines originating from the N'' = 7 level of the ground vibrational state to the v' = 1 vibrational state. (The very weak <sup>S</sup>Q transition is not shown.)

Absorption line parameters have been calculated for the AFGL atmospheric absorption line parameters compilation<sup>7</sup> and will appear in the next version. Table I gives the frequencies, intensities, lower state energies, and rotational quantum assignments for the electric quadrupole transitions of the vibration fundamental within the  $X^{3}\Sigma_{g}^{-}$  electronic state. The standard atmospheric cutoff has been applied to these lines. The frequencies were calculated using the diagonalization of the Hamiltonian in the Hund's case (b) representation<sup>8</sup> with the corresponding constants from Refs. 9–12 shown in Table II. The intensities have been calculated from the expression

$$S = C\nu^3 S_J^N \exp(-c_2 E''/T) \left[1 - \exp(-c_2 \nu/T)\right],$$

where  $c_2$  is the second radiation constant, T = 296 K is the standard temperature of the AFGL compilation, E'' is the lower state energy, and  $\nu$  is the frequency of the transition.  $S_J^N$  are the transition probabilities based on angular momentum theory<sup>13</sup> and are given by