Tungsten Filament Lamps as Absolute Radiometric Reference Sources

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Quartz Tungsten Halogen (QTH) Lamps

- Widely used as transfer standards of spectral irradiance
- FEL & DXW type lamps most common
- Planckian radiators with a few corrections

Spectral Irradiance of QTH Lamp

- Modified Planck's radiation law

$$E(\lambda,T)=B(T)\,\varepsilon_W(\lambda,T)\,\varepsilon_\Delta(\lambda,T)\,\frac{2\pi hc^2}{\lambda^5\left[\exp\left(\frac{hc}{\lambda kT}\right)\right]}$$

- *B*(*T*) is a geometrical factor of the measurement, slightly affected by *T* due to thermal expansion
- ε_W (λ, *T*) is the spectral emissivity of tungsten
- ε_Δ (λ, *T*) is a residual correction due to other minor contributing factors
- M. Ojanen, P. Kärhä, and E. Ikonen, Spectral irradiance model for tungsten halogen lamps in 340–850 nm wavelength range, Appl. Opt. 49, 880–886, 2010.

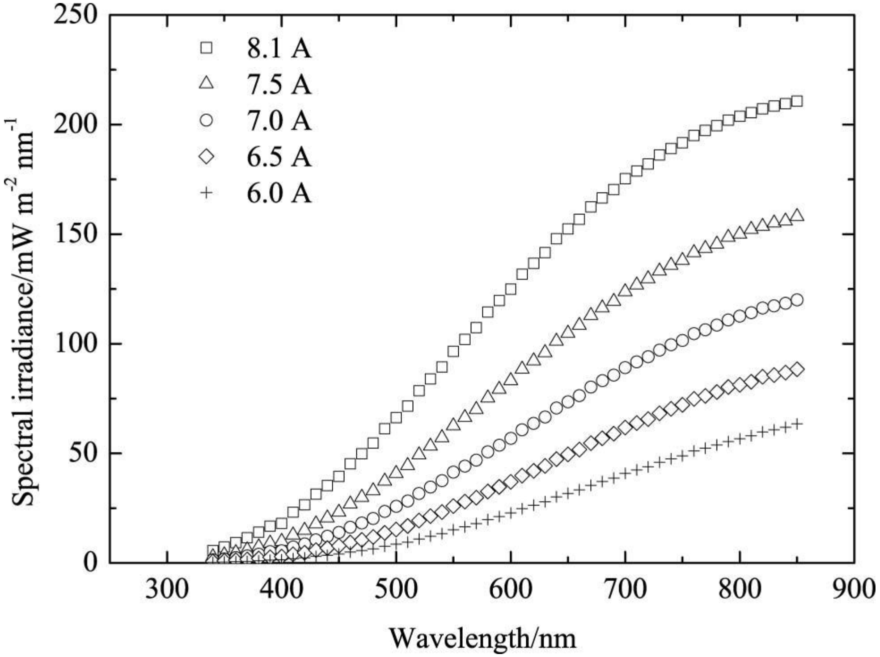


Fig. Spectra of an FEL lamp whose T (2500 – 3050 K) is modified by changing the lamp current.

Emissivity of Tungsten

- Measured extensively in the 50’s by De Vos and Larrabee.
- De Vos data available in analytical form λ = 340 – 2600 nm, T = 1600 – 2800 K. Numerically down to 230 nm!
- Simple to combine with Planck’s law
- Larrabee data considered more accurate (scattering) but λ = 350 – 800 nm and T = 1600 – 2400 K are limited. Non-continuities when extrapolating.

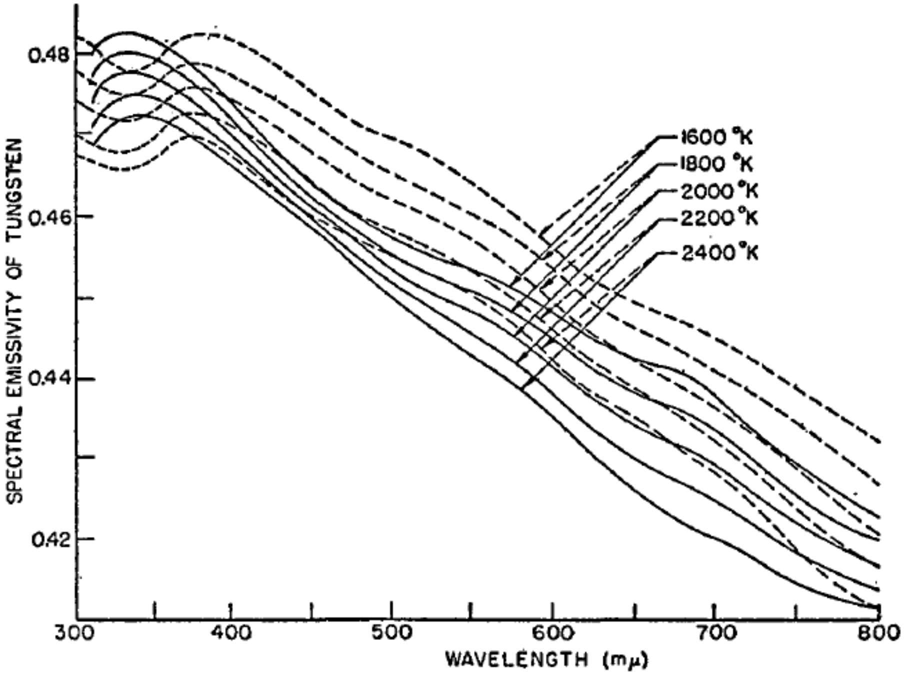


Fig. Spectral emissivities of sheet tungsten according to De Vos (Dashed lines, 1954) and Larrabee (solid lines, 1959).

Residual correction

- Planck’s law modified with tungsten emissivity was fitted to a temperature-varied 1-kW FEL-lamp.
- With the presented residual correction, a common solution was found.
- Lamp model with two free parameters, *B* (geometry) and *T* (temperature).
- Tests with Aalto and NPL data on DXW and FEL type lamps indicate <1% interpolation/extrapolation uncertainty for λ = 340 – 850 nm.

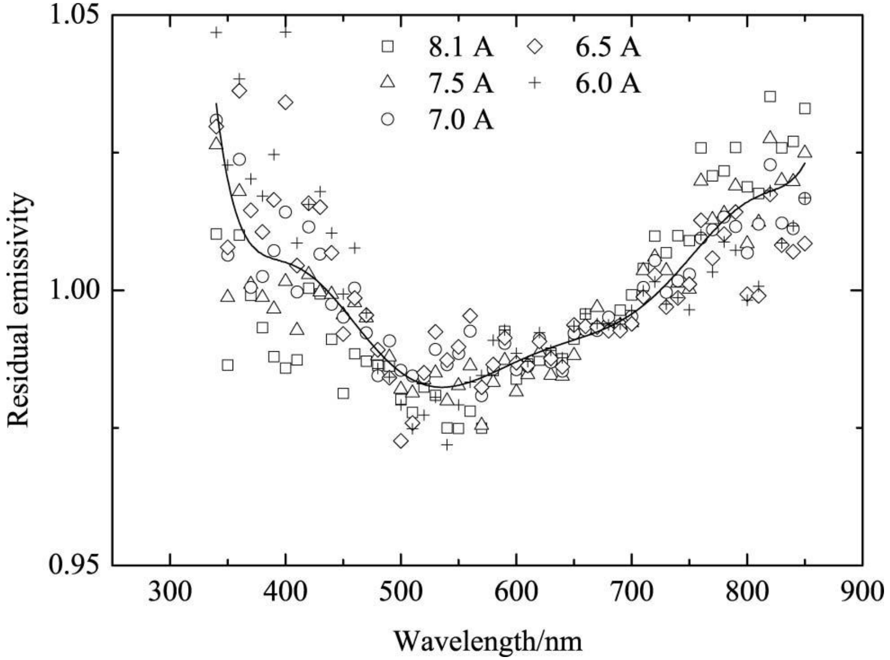


Fig. Residual correction needed for Planck’s law with FEL and DXW type lamps after correcting for tungsten emissivity of de Vos. [Ojanen et al, Appl. Opt. 2010]

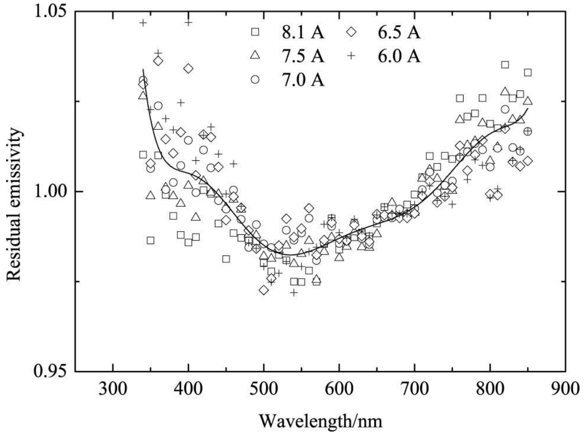
Simple Spectral Irradiance Scales

$$E(\lambda,T) = B(T)\varepsilon_W(\lambda,T)\varepsilon_\Delta(\lambda)\frac{2hc^2}{\lambda^5\left[\exp\left(\frac{hc}{\lambda kT}\right)-1\right]}$$

- Two unknowns *B* and *T* may be obtained
  - – With two filter radiometer
  - – Illuminance and color temperature
  - – Illuminance and electrical measurements
  - – Other combination
- Not strictly traceable and accuracy limited (~3%) but may give valuable info for end users

QTH Lamp as Absolute Reference Source

- Temperature of the filament can be obtained from published values of resistivity and hot/cold resistance measurements of filament
- In theory, the geometrical factor can be calculated. However, one intensity measurement is more accurate.
- Corrections for
  - Filament shape (light recycling factor)
  - Quartz glass transmittance
  - Filling gas absorption
  - Tungsten material???



Light recycling

- Filament is not sheet metal as in emissivity measurements.
- Coiled structure enhances the emissivity by

$$\varepsilon_{\mathrm{LRC}} = \frac{\varepsilon_{\mathrm{W}}}{1-\xi\left(1-\varepsilon_{\mathrm{W}}\right)}$$

- For FEL's we estimate $\xi = 0.5 \pm 0.1$
- Appears as a temperature change of 17 – 20 K.

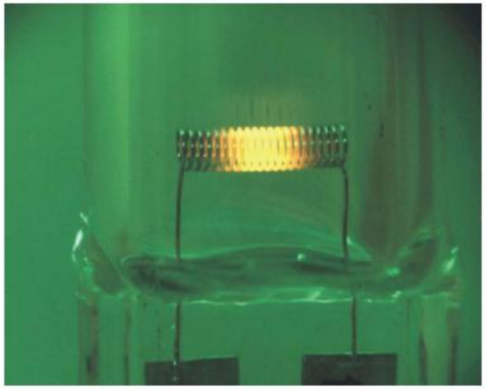
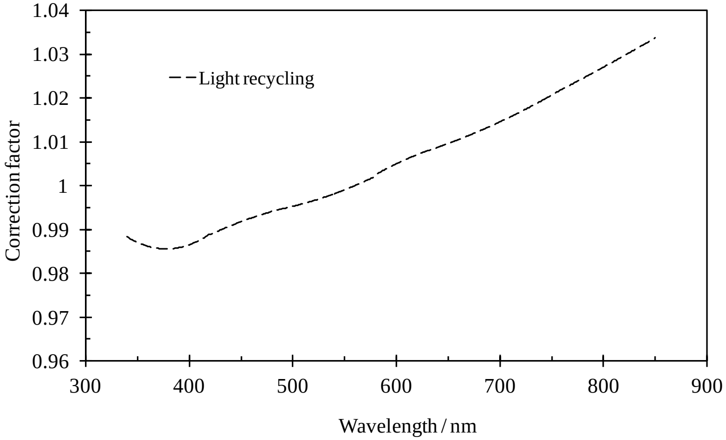


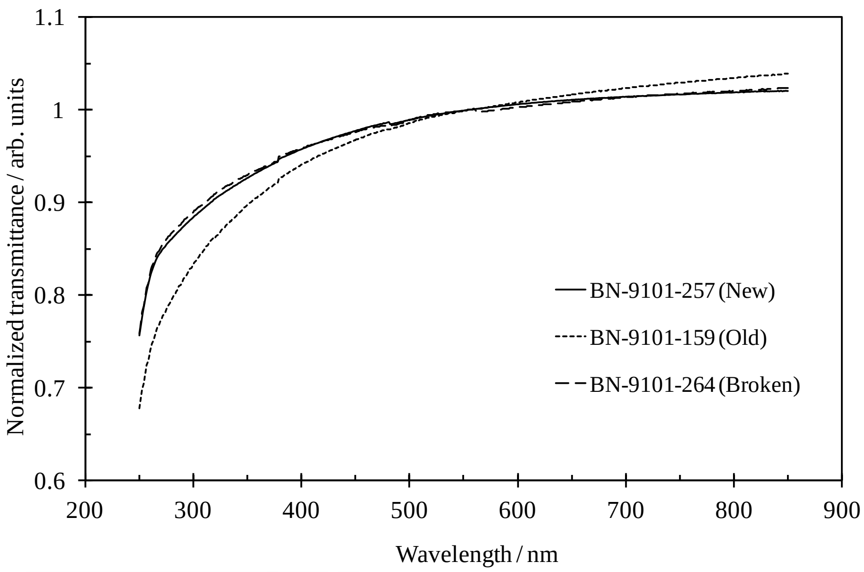
FIG. 1. (Color online) Photograph of the 20 W halogen lamp at a very low current for better visualization. The temperature is highly inhomogeneous in this regime.

L. Fu *et al*, *J. Appl. Phys.* 100, 103528 (2006).



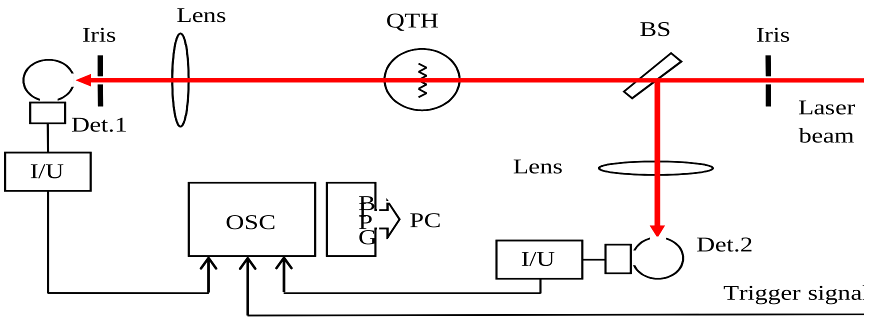
Bulb Transmittance

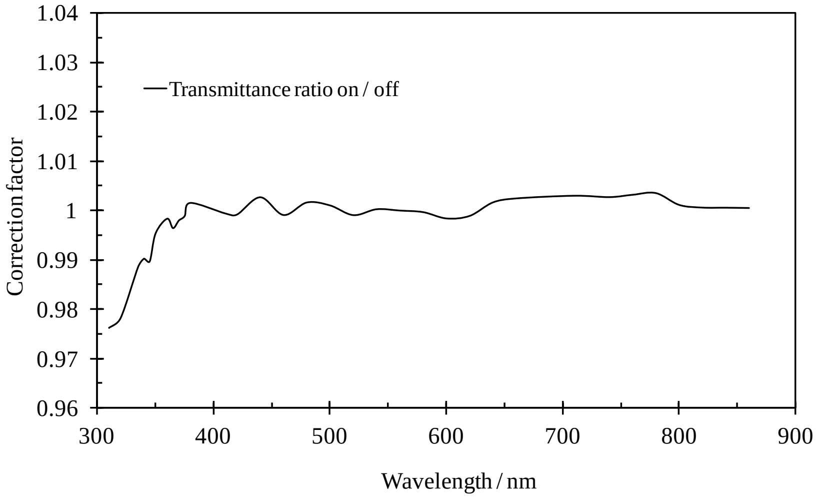
- Light from the filament passes through one glas surface and ~1 cm of filling gas.
- We measured three FEL lamps (new, old, broken) for bulb transmittance.
- Absorption of filling gas not seen
- Glass absorbs heavily. Changes when the lamp ages.
- Introduces a temperature change of 5 – 15 K.



Transmittance as Function of Temperature

- Theoretically the filling gas absorption could change as a function of temperature.
- A halogen lamp was measured for transmittance in on and off states using PLACOS.
- Lamp burn increases absorprtion in UV, no effect in visible.





Electrical measurements

- Temperature can be obtained from cold resistance and hot dynamic resistance measurements as
- $T = R(T) / [0.0063\ \mathrm{K{-}1}R(295\ \mathrm{K})] + 393\ \mathrm{K}$.
- $R(T)$ measured as lamp voltage / driving current
- 4-wire measurement for $R(293\ \mathrm{K})$
- The uncertainty is 4% / 19 K

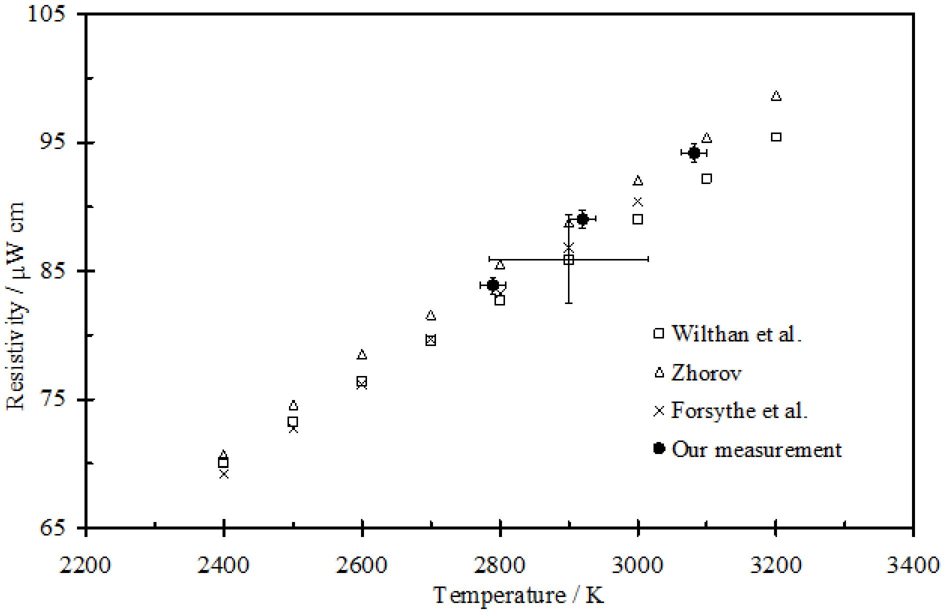


Fig. Our resistivity values calculated from measured spectra are in good agreement with other groups.

Summary

- Simple modest-uncertainty spectral irradiance scales may be obtained by modeling incandescent lamps
- In addition to tungsten emissivity
  - Light recycling and bulb transmittance change the temperature of the lamp by 23 – 36 K (in the *T* range 2770 – 3080 K)
  - Filling gas does not absorb
  - Increased temperature increases absorption in UV, but no effect in visible
- Residual correction of ±2.5 % still needed. Tungsten properties probably differ from those tabulated.
- Lamp temperature may be obtained from electrical measurements with reasonable uncertainty

Further Reading

- L. O. Björn, Simple Methods for the Calibration of Light Measuring Equipment, Physiol. Plant. 25, 300-307, 1971.
- M. Ojanen, P. Kärhä, and E. Ikonen, Spectral irradiance model for tungsten halogen lamps in 340–850 nm wavelength range, Appl. Opt. 49, 880–886, 2010.
- J.C. de Vos, A new determination of the emissivity of tungsten ribbon, Physica 20, 690–714, 1954.
- R. M. Pon and J. P. Hessler, Spectral emissivity of tungsten: analytic expressions for the 340 nm to 2.6 μm spectral region, Appl. Opt. 23, 975–976, 1984.
- L Fu, R Leutz and H Ries, Physical modeling of filament light sources, J. Appl. Phys. 100, 103528 (8 pages), 2006.