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An integrating sphere radiometer as a solution for high power calibrations in fibre optics

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Abstract.

This paper describes the design, characterization and calibration of a high power transfer standard for optical power measurements in optical fibres based on an integrating sphere radiometer. This radiometer, based on two detectors (Si and InGaAs) can measure powers between 100 nW and 10 W within the wavelength range of 400 to 1700 nm. The radiometer has been calibrated along the total spectral range of use against an electrically calibrated pyroelectric radiometer and different fibre laser diodes and ion lasers. The total uncertainty obtained is lower than ±1.5% for these wavelengths and power ranges (excluding the water absorption region).

1. Introduction

The proliferation of high power fibre lasers used for pumping Raman amplifiers whose output powers are several watts requires an improvement in the calibration capabilities for absolute power measurements in optical fibres at levels from 100 mW to 10 W.

Integrating sphere radiometers (ISR) have been demonstrated as a realizable system to develop fibre-optic power scales [1, 2, 3], and NIR spectral responsivity scales using monochromator-based cryogenic radiometers [4] or laser-based cryogenic radiometer facilities [5]. In [6], three national standards laboratories have realized a high fiber optics power scale all of then based on ISR radiometers with an uncertainty of 1.3 % for 1 to 200 mW power level.

In order to fully benefit from the high accuracy of the cryogenic radiometer, it is important that the transfer radiometers have the best possible radiometric properties. These include good long-term stability, a high degree of spatial uniformity, a small variation of responsivity with angle of incidence, a small temperature variation of the responsivity and a high degree of linearity.

In a previous paper [7], we have demonstrated the possibility of carrying out a sphere radiometer of high accuracy for optical fibres useful for powers until 0.8 W in the range of wavelengths from 1250 to 1650 nm. In this paper a further development of this type of radiometer is presented. The new radiometer has been designed for working in the 400-1700 nm wavelength range. In order to cover all this spectral range we ensemble a Si and an InGaAs detectors in an integrating sphere. The characterization of the new radiometer was performed in two steps: firstly, we made a complete characterization of all of the single elements (sphere material, Si and InGaAs detectors) before they were coupling into the sphere radiometer. Secondly, we calibrated the ensemble sphere radiometer at 1 mW (0 dBm), and using the linearity figure of the detectors and the properties measured of the sphere, we extended the results and estimated the uncertainties in the optical power range from 100 nW to 10 W (-40 to +40 dBm).

2. Design of the Integrating Sphere Radiometer

The structure of the sphere radiometer designed is depicted in figure 1.

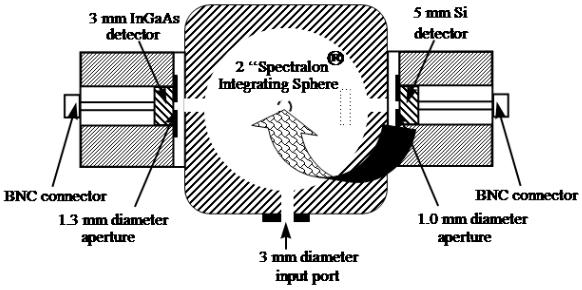

Figure 1: Structure of the integrating sphere radiometer.

The radiometer is composed of a Spectralon® integrating sphere manufactured by Labsphere, Inc., and two detectors. The sphere has an internal diameter of 50.8 mm with a thickness of the walls of 12.7 mm. In this radiometer a Spectralon type SRM-99L (laser-graded Spectralon) was used, since it exhibits highly lambertiam behaviour. The SRM-99L is a formulation of a resin that gives enhanced performance when it is used in laser applications and presents high reflectance close to 0.99 from 400 nm to 1700 nm. The manufacturer claims that Spectralon is an extremely hydrophobic material that may only absorb non-polar solvents like greases and oils. Thus, no sealing windows and no other device was used to control the inner atmosphere of the radiometer. Such a design avoids probable damage of the windows for high power levels.

Three ports were opened in the sphere with 90° orientation between one another. The input port is 3 mm diameter aperture and a FC-PC fibre connector. The other two ports are placed in the two detectors, a 5 mm diameter Si detector (EG&G JUDSON model UV-250B) and a 3 mm diameter InGaAs detector (EPITAXX model ETX-3000). Several adapters were designed in order to ensure, by changing the distance fibre/sphere, that the maximum irradiance on the sphere wall does not overcome 1.7 W/cm^2

3. Individual elements characterization

We characterized all the single elements of the ISR individually. The linearity, the relative spectral response, the relative temperature variation of the responsivity of Si and InGaAs detectors and the relative wavelength reflectance of the Spectralon are measured before to be ensemble in the final radiometer. This section shows the most relevant results obtained related to theses properties.

3.1 Linearity of the detectors

The linearity of the detectors is the essential characteristic of the radiometer, since it should be only calibrated in absolute values at 1 mW power level, and should be used in a wide power range. Si and InGaAs detectors are highly lineal when are illuminated within their active area [8 and 9]. In order to assure the overfilled illumination in the detector surface, two apertures of 1.0 and 1.3 mm of diameter were placed just in front of the Si and InGaAs detectors respectively (these apertures were calculated and probed in order to assure the non-saturation of the detector response at 10 W input powers).

The Si linearity was measured using a 514 nm stabilized Argon laser, a neutral filter of absorbance 1, and varying continuously the power of the laser over the total response signal on the detector-aperture set. In the case of the InGaAs detector-aperture set, the linearity was measured using an addition method implemented in single mode optical fibre at 1550 nm [8]. Figures 2 and 3 show the non-linearity and its uncertainty associated (k=2) for both Si and InGaAs detectors, before to be coupled to the sphere radiometer. In the upper axis of these figures we represent the equivalent power level in the ISR calculated with their final responsivities at 632.8 and 1550 nm respectively. The maximum non-linearity found in the range between 100 nW and 10 W was +0.21x100, with an uncertainty of 0.50x100 (k=2) in the ISR-Si detector, and +0.41x100, with an uncertainty of 0.36x100 (k=2) for the ISR-InGaAs detector.

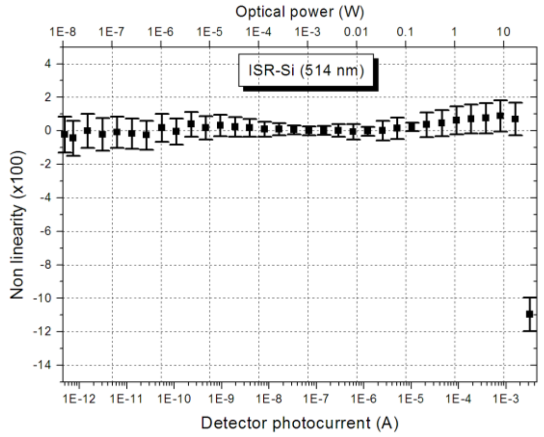

Figure 2: ISR-Si linearity response.

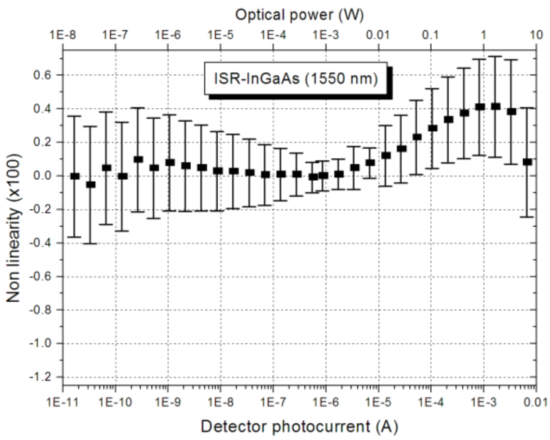

Figure 3: ISR-InGaAs linearity response.

3.2 Spectral relative behaviour of the components

The spectral behaviour of the different components was studied in the wavelength range from 400 to 1700 nm. The relative spectral responsivity of the Si and InGaAs detectors was measured in our halogen lamp-monochromator facility. The results normalized to 632.8 and 1300 nm are depicted in figure 4. In the case of the Spectralon the relative reflectance was measured in a Perkin Elmer Lambda 900 spectrophotometer. The result normalized at maximal reflectivity is represented in the right axis of figure 4.

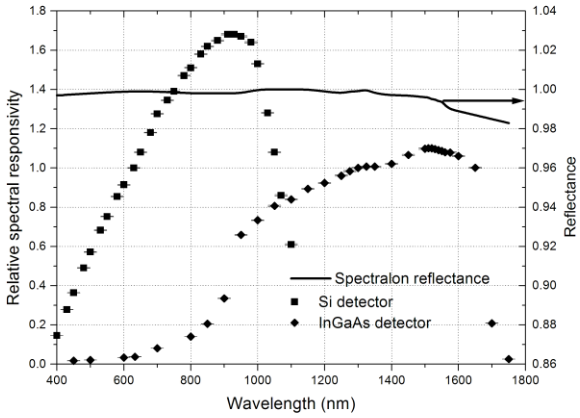

Figure 4: Spectral relative responsivity of Si and InGaAs detectors. The right axis represents the spectral relative reflectivity measured for the Spectralon

3.3 Variation of responsivity with Temperature

The temperature coefficient of the responsivity and the relative spectral responsivity of the detectors were measured in a halogen lamp-monochromator facility for two temperature values (20º, 30ºC). The variation of the responsivity for the Si detector was less than $2x10^{-3}$ $^{o}C^{-1}$ in 400-950 nm wavelength range. In the case of the InGaAs detector, the temperature responsivity coefficient in the spectral range between 1000 and 1650 nm was lower than $2x10^{-4}$ $^{o}C^{-1}$ while in the range between 800 and 1000 nm the temperature coefficient was approximately $2x10^{-3}$ ^{o}C.

4. Integrating sphere radiometer characterization

Once the detectors and the Spectralon sphere were individually characterized and adapted as sphere radiometer, to complete the characterization of the ISR, we studied the spatial uniformity, and the connector/numerical aperture influence. Finally the ISR was calibrated at several laser wavelengths against an electrically calibrated pyroelectric radiometer. This section shows the results of these tests.

4.1 Spatial uniformity and angular response

A perfect integrating sphere produces a spatially uniform, lambertian angular and unpolarized optical field in the output port. Under these conditions, the uncertainties caused by reflectivity, interference effects in the anti-reflection coatings and the irregular far-field patterns (speckle patterns) generated by multimode fibres are avoided.

The spatial non-uniformity of the responsivity of the sphere radiometer was measured using our uniformity mapping facility [8]. The sphere radiometer was attached into a computer-controlled translation stage, while two collimated laser beam (632.8 nm and 1550 nm) were scanning with steps of 0.2 mm a square of 2 mm side over the input port of the radiometer. The diameter of the collimated laser beam used in this test was 1.2 mm at $1/e^2$, approximately. The photocurrent of the radiometer was measured for each point of the two detectors and normalized for the central value. Figure 5 shows the result for the ISR-Si output at 632.8 nm and figure 6 shows the non-uniformity map of the ISR-InGaAs at 1550 nm.

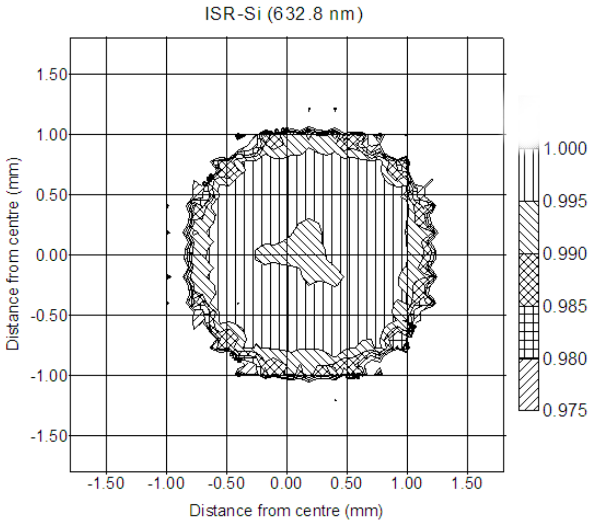

Figure 5: Spatial uniformity of the ISR-SI at 632.8 nm.

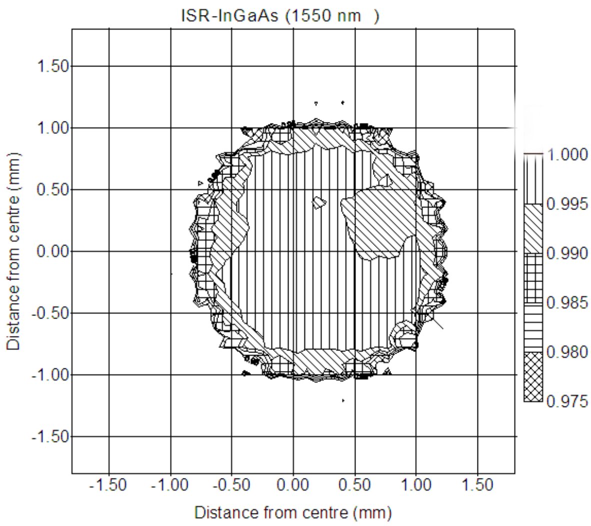

Figure 6: Spatial uniformity of the ISR-InGaAs at 1550 nm.

According to the spatial uniformity result, the change in the spatial uniformity of ISR is within $0.33x10^{-3}$ for the ISR-Si and $0.29x10^{-3}$ for the ISR-InGaAs. We did not observe any significant wavelength effect over the spatial uniformity between 632.8 and 850 nm for the ISR-Si, and between 850, 1300 and 1550 nm for the ISR-InGaAs.

The angular response of the integrated sphere was measured without the fibre adaptor. In these conditions the radiometer was placed in a setup similar to the system used in the uniformity test, including a rotatory table. Once the rotation axis was located at the position of input port, the measure of the angle influence was done at 850nm for the Si detector and at 1300 and 1550 nm for the InGaAs detector separated in vertical and horizontal directions. Figures 7 and 8 show the measurement results.

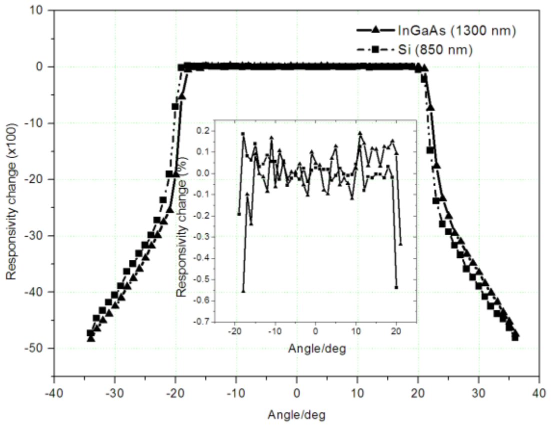

Figure 7: Angular response of the ISR-InGaAs at 1300 nm and ISR-Si at 850 nm for the vertical scan.

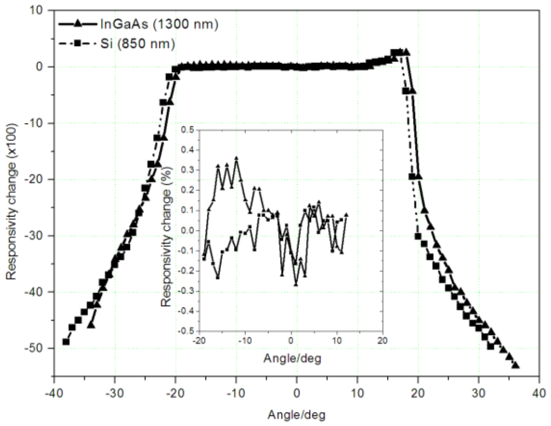

Figure 8: Angular response of the ISR-InGaAs at 1300 nm and ISR-Si at 850 nm for the horizontal scan.

From theses results we can estimate the solid angle over which the sphere accepts light from the fibre end. The value estimated, ±15° was the same for the vertical and horizontal directions. The relative standard deviation of the angular responsivity depicted in figures 7 and 8 was calculated to be 0.05% over the region -15° to +15°.

4.2 *Absolute spectral responsivity calibration*

The absolute spectral responsivity of the ISR was performed by direct comparison with an Electrically Calibrated Pyroelectric Radiometer (ECPR) model RsP 590 with RS5900 display, manufactured by Laser Probe Corp., USA [10]. This ECPR radiometer is traceable to our cryogenic absolute radiometer [5]. Four tuneable laser diodes covering the spectral range between 1250 and 1650 nm were used in a calibration setup similar to the system used in reference [5]. We used a multimode laser diode for the calibration at 850 nm. For the visible range we employed the emission lines of an Ar and a He-Ne laser.

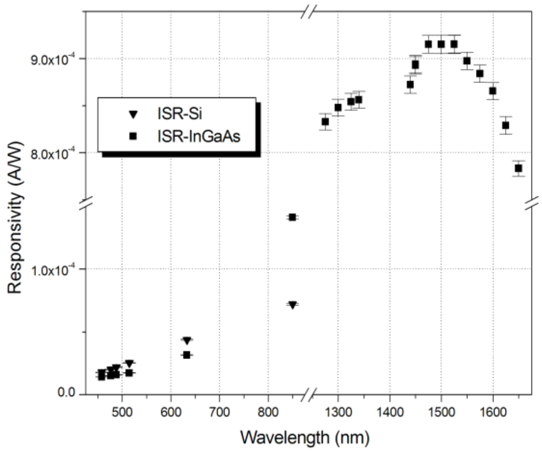

Figure 9: Absolute responsivity of the radiometer.

Figure 9 and table 1 show the responsivities associated to ISR-Si and ISR-InGaAs electrical outputs for laser wavelengths under study.

As can be seen, some results corresponding to the wavelengths lying from 1350 and 1440 nm are missing. This is so because the ISR shows a high sensitivity to the absorption lines of water [7].

Table 1: Absolute responsivity of the radiometer

λ (nm)	ISR-Si		*ISR-InGaAs*	
	R(λ) (A/W)	uR(λ) (A/W)	R(λ) (A/W)	*uR(λ) (A/W)*
457.9	1.79E-05	1.73E-07	1.42E-05	*1.35E-07*
476.5	2.01E-05	1.92E-07	1.52E-05	*1.45E-07*
488.0	2.18E-05	2.08E-07	1.59E-05	*1.52E-07*
514.5	2.54E-05	2.48E-07	1.74E-05	*1.68E-07*
632.8	4.38E-05	4.17E-07	3.16E-05	*3.00E-07*
850.0	7.21E-05	7.75E-07	1.41E-04	*1.37E-06*
1250.0			8.11E-04	*8.44E-06*
1275.0			8.33E-04	*8.68E-06*
1300.0			8.48E-04	*8.81E-06*
1325.0			8.54E-04	*8.88E-06*
1340.0			8.56E-04	*8.90E-06*
1450.0			8.93E-04	*9.27E-06*
1475.0			9.15E-04	*9.51E-06*
1500.0			9.15E-04	*9.61E-06*
1525.0			9.15E-04	*9.50E-06*
1550.0			8.98E-04	*9.31E-06*
1575.0			8.84E-04	*9.19E-06*
1600.0			8.66E-04	*8.99E-06*
1625.0			8.29E-04	*9.53E-06*
1650.0			*7.83E-04*	*8.16E-06*

In order to extend the calibration values to all the wavelengths (400 to 1700 nm), we calculated an expected spectral relative responsivity of the ISR from the relative spectral responsivity of the individual detectors and the spectral relative reflectivity of the Spectralon. Figure 10 shows the comparison between the responsivity of the radiometer calculated and the relative responsivity calculated at the laser wavelengths. The agreement between the expected and the measured relative spectral responsivity is ±1.5% for all the wavelength range, but large differences close to 3% and 5% are found at 850 nm for the ISR-Si and ISR-InGaAs detectors respectively. This different is difficult to be explained, but the multiwavelength emission of the 850 nm laser (that includes some red power) could be a possible explanation. Taking into account the behaviour of the radiometer in the water absorptions lines in the 1400 nm region, we can conclude that this radiometer is not useful in the other water absorption bands centred in 940 nm and in 1120 nm.

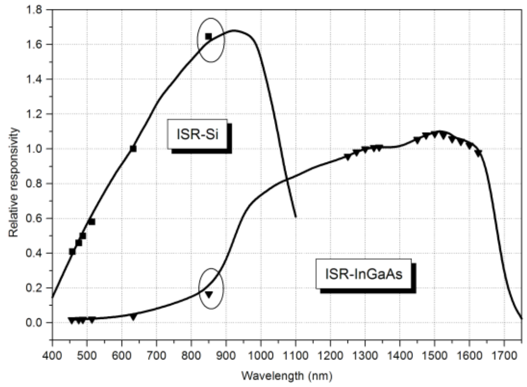

Figure 10: Spectral relative responsivity of the radiometer.

4.3 Connector and numerical aperture influence.

To use the integrating sphere radiometer with an optical fibre we provide it with a FC-PC connector at the input port.. Using the optical fiber connector the responsivity of the sphere radiometer obtained in absolute calibration must be corrected by a geometrical factor related to the fact that the input port of the sphere is now closed by the fiber connector, so all the light is trapped in the sphere, unlike the air case. This correcting value was studied for similar sphere radiometers and evaluated as 0.1x100 [7].

In order to evaluated the influence of the connector and the numerical aperture of different fibres over the radiometer, the variation of the responsivity of the sphere radiometer was measured by direct comparison with other sphere radiometer for the wavelength of 850, 1300, 1480, 1550, 1620 nm using five fibre adapters. These adapters, with of 5.0, 12.0, 17.0, 27.0 and 46.0 mm length, were designed in order to define, for a standard single mode fibre, different numerical apertures: 0.11, 0.12, 0.13, 0.14 and 0.17 respectively. These NA values ensure that the maximum irradiance on the sphere walls does not overcome 1.7 W/cm^2. Figure 11 represents this scheme. Each adapter was used in this test three times, rotating it along their axis, in order to evaluate as the same time the effect of the manufacturing errors. These results (15 measures with each wavelength) are summarized in table 2.

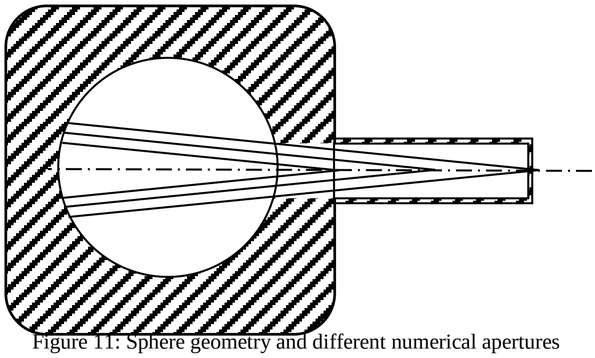

Figure 11: Sphere geometry and different numerical apertures tested.

Table 2: Connectors and numerical aperture influence

WAVELENGTH (NM)	R(λ)	σ	CHANGE (X100)
850	1.412E-04	3.43E-07	0.24
1300	8.480E-04	2.20E-06	0.26
1475	9.152E-04	2.38E-06	0.26
1550	8.975E-04	2.33E-06	0.26
1625	8.290E-04	2.38E-06	0.29
Medium value			***0.26***

5. Uncertainty budget for the sphere radiometer calibration.

The different error sources contributions to the final calibration uncertainty of the radiometer are summarized in Table 3. The total uncertainty was calculated as the square root of the square sum of all uncertainties. The results obtained show a total expanded uncertainty lower than ±1.5x100 (k=2) in the useful wavelength range and for power levels from 100 nW to 10W.

Table 3: Uncertainties in the calibration of the integrating sphere radiometer with the ECPR

Source of error	**ISR-SI (x100)**	**ISR-INGAAS (x100)**
ECPR calibration constant	0.200	0.200
ECPR power measurement	0.100	0.100
ECPR resolution	0.020	0.020
ECPR wavelength response	0.165	0.165
ECPR spatial uniformity	0.100	0.100
ISR current measurement	0.200	0.200
ISR resolution	0.030	0.030
Picoammeter calibration	0.025	0.025
Picoammeter drift	0.020	0.020
ISR spatial uniformity	0.033	0.029
ISR angular response	0.050	0.050
ISR temperature coefficient	0.240	0.080
Connector effect (ISR)	0.260	0.260
ISR linearity (10 nW to 10 W)	0.495	0.360
Uncertainty (k=2)	**1.416**	**1.156**

6. Conclusions.

The design, construction, characterization and calibration of a sphere radiometer useful for laser and optical fibre power meter calibrations have been described. The radiometer uses two detectors: Si and InGaAs and covers the wavelength range between 400 and 1700 nm. Their calibration was done by direct comparison with an electrically calibrated pyroelectric radiometer. Using the linearity factors of the detectors, we extend the radiometer calibration up to 10 W, with an estimated uncertainty lower than ±1.5x100 (k=2) in this spectral range.

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