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Quality Manual
Of
Fibre Optic Power Measurements

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1. Definition

1.1. Scope

This Quality Manual describes the principle and the operation of the equipment used for fibre optic power measurements. The calibrated devices are power meters with a fibre optic connector.

1.2. Object and field of application

Fibre optic power: Optical power [W] that propagates in a fibre. Hereafter referred to as FOP.

Fibre optic power meter: A power meter equipped with a connector with whom the meter can be connected to measure fibre optic power. Hereafter referred to as FOPM.

1.3. Features

Fibre optic power meters are calibrated by comparison to a reference power meter. As reference power meters, two InGaAs photodiodes with fibre optic connectors are used. For high power measurements (> 10 mW), an integrating sphere detector with an InGaAs photodiode and a fibre optic connector is used.

Lasers at 1310 and 1550 nm wavelengths equipped with fibre outputs are available for calibrations. The precise operating wavelengths of the lasers are 1552.5 nm and 1308.4 nm. At 1550 nm wavelength, an erbium doped fibre amplifier (EDFA) is used to produce powers up to 200 mW.

The measurement range at 1310 nm wavelength is 1 nW – 7 mW (-60 dBm – +8 dBm) adjusted with an attenuator. At 1550 nm wavelength the measurement range is 1 nW – 200 mW (-60 dBm – +23 dBm). The achievable measurement uncertainties are 0.9 % (k = 2) at 1 mW power level and 1.3 % at 100 mW power level.

Fibres used are single-mode fibres. Detectors are equipped with FC/PC-connectors.

2. Principle of the realisation

Principle of the realisation is described in [1]. The measurement set-up contains two fibre coupled laser sources, equipped with standard FC-connectors for optical output. The precise operating wavelengths of the lasers are 1552.5 nm and 1308.4 nm. The output power of the lasers can be adjusted by altering the driving current. This also slightly changes the wavelength, but the change is negligible – of the order of 0.1 nm. Relative stability of the output power of the lasers is $6 \cdot 10^{-4}$. Standard single mode cables are used. The power level may be further limited by using an external attenuator. At 1550 nm wavelength, the power can be amplified with an EDFA.

Figure 1 shows the construction of the reference fibre optic power meters FOPM-1 and FOPM-2. The detectors utilise plain InGaAs photodiodes [2]. Photodiodes are fitted into aluminium cases equipped with adapters for fibre optic cable and output connectors for the current signal of the photodiode. On the inside surface of the adapter there is an area of diffusing black paint to reduce back reflections. The distance between the fibre end and the active surface of the photodiode is 2 mm, when the fibre is attached to the connector.

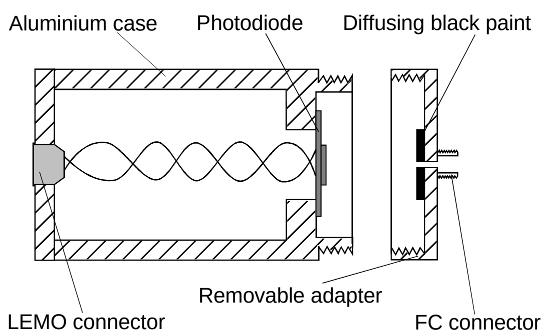


Figure 1. Physical structure of FOPM-1 and FOPM-2.

Figure 2 shows the construction of the integrating sphere detector. The sphere is constructed of Spectralon, the manufacturer is Labsphere Inc. The inner diameter of the sphere is 50.8 mm. The sphere has two input ports (diam. 5 mm) and one output port (diam. 4 mm). One of the output ports can be equipped with a FC/PC fibre adapter, while the other can either be left open or covered with a Spectralon port plug. When the fibre is attached, the fibre end is located at 5 mm distance from the outer wall of the sphere. The thickness of the sphere wall is 8 mm. An InGaAs photodiode of the same type as in FOPM-1 and FOPM-2 is attached on the output port.

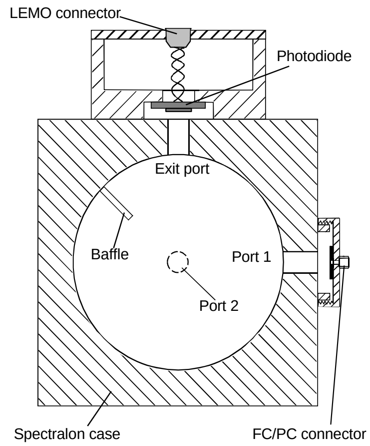


Figure 2. Physical structure of integrating sphere detector.

The detectors are calibrated with the fibre adapters detached. The laser beam is collimated and measured with a pyroelectric radiometer. The known power is then used to calibrate the detectors. After the calibration, the fibre adapters are connected to the detectors.

The geometry of the beam exiting the fibre is far from the geometry of the collimated beam: The beam diverges to a wide solid angle, and covers a larger area on the detector surface. Corrections are determined for these effects. Due to the good quality of the photodiodes used, these corrections for FOPM-1 and FOPM-2 are very small. For the integrating sphere detector the correction is negligible.

3. Equipment

Equipment needed in fibre optic power calibration is presented in Table 1.

Table 1. Calibration equipment

	Description	Quantity	Identification
A. Detectors			
1.	Reference FOP meter	3	FOPM-1, FOPM-2, integrating sphere det.
2.	Pyroelectric radiometer	1	Laser Probe RsP-590, display Rs-5900
3.	Current-to-voltage converter (CVC)	1	Vinculum SP042
4.	Digital voltmeter (DVM)	1	HP 3458A
B. Light sources			
1.	1310 nm laser	1	Thorlabs S3FC1310
2.	1550 nm laser	1	Self-made
3.	EDFA	1	Southampton Photonics
C. Wavelength measurement			
1.	Wave meter	1	
D. Accessories			
1.	Fibre attenuator (0 - 66 dB)	1	JDS Uniphase VA47K
2.	Fibre collimator	1	
3.	*xy*-translator	1	Nanomover
4.	Rotational stage	1	Aerotech ADRS-200
5.	Controller of rotational stage	1	BAI10-320
6.	Linear translator or magnetic posts		
7.	IR viewing card	1	
E. Control and data acquisition			
1.	Computer	1	
2.	Software		Self-made Labview software

3.1. Maintenance

Calibration schedule for devices needing calibration is presented in Table 2. The characterisation of the measurement system is performed according to schedule presented in Table 3.

Table 2. Calibration schedule of the fibre optic power measurement devices

Device to be calibrated	Calibration interval [years]
Current-to-voltage converter	See [3]
Digital voltmeter	See [3]
Temperature and humidity meter	See [3]
Pyroelectric radiometer	1
Reference FOPM	1
Wave meter	1

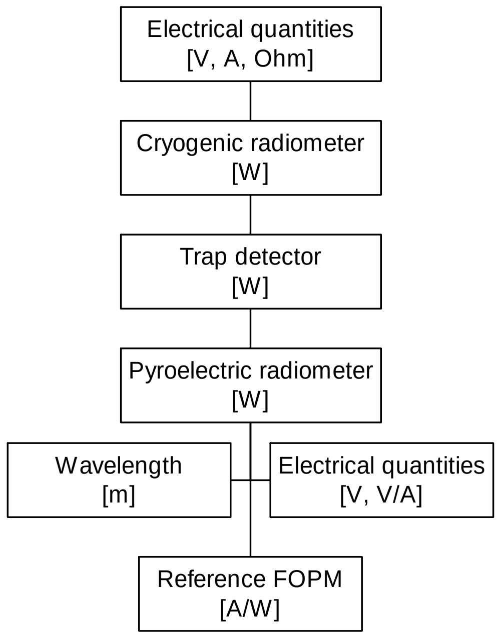
Table 3. Schedule for the system characterisation measurements

Characterisation component	Characterisation interval [years]
Wavelengths of the lasers	2
Angular uniformities of FOPMs	2
Spatial uniformities of FOPMs	2

4. Measurement traceability

The measurement traceability is presented in Figure 3

Figure 3. Traceability chain of fibre optic power



4.1. Measurement range and uncertainty budget

The theoretical measurement range for calibrations is approximately 1 nW – 1 W at 1550 nm and 1 nW – 6 mW at 1310 nm. The measurement ranges are limited by the maximum powers of the lasers/EDFA at the upper end and by noise at the lower end. At the moment we do not have any information of the linearity of the integrating sphere detector at powers higher than 200 mW, so the upper limit of our measurement range at 1550 nm is set to 200 mW. The linearities of FOPM-1 and FOPM-2 have been studied at 1 – 7 mW level, where nonlinearity was expected to cause problems [4]. The nonlinearity at the range of 1 mW – 7 mW was measured to be less than 10^{-3} for both detectors at both wavelengths. The nonlinearity of the integrating sphere detector has not been accurately measured, but inter-comparisons with other laboratories imply that it is better than 1 % throughout the 1 mW – 200 mW range.

The uncertainty budgets of FOPM-1 and FOPM-2 are presented in Table 4. The obtainable uncertainties are 0.93 % and 0.94 % (k = 2) at the wavelengths of 1310 nm and 1550 nm, respectively. The results hold for both detectors. The uncertainty budget of the integrating sphere detector is presented in Table 5. The obtainable uncertainty is 0.84 % (k = 2) at ~1 mW level and 1.3 % (k = 2) at ~100 mW level.

Table 4. Uncertainty budget for FOPM-1 and FOPM-2.

	Standard Uncertainty	
Source of uncertainty	1310 nm	1550 nm
Pyroelectric radiometer	0.27%	0.27%
Spatial uniformity	0.10%	0.10%
Angular uniformity	0.05%	0.05%
Reproducibility	0.35%	0.35%
Linearity	0.05%	0.05%
Inter-reflections	0.06%	0.11%
Combined standard uncertainty	0.46%	0.47%
Expanded uncertainty (*k* = 2)	0.93%	0.94%

Table 5. Uncertainty budget for integrating sphere detector. Numbers in parentheses are considered when using EDFA at ~100 mW power level.

Source of uncertainty	Standard Uncertainty
Pyroelectric radiometer	0.27%
Spatial and angular non-uniformities	0.10%
Effect of removing fibre adapter during absolute calibration	0.05%
Reproducibility	0.30%
Linearity	0.05%
Linearity at >10 mW power range	(0.50%)
Ground noise of EDFA	(0.14%)
Combined standard uncertainty	0.42% (0.65%)
Expanded uncertainty (*k* = 2)	0.84% (1.3%)

5. Calibration methods and procedures

5.1. Absolute calibration of the reference FOPMs

The reference FOPM’s are calibrated with the pyroelectric radiometer:

1. Lasers and EDFA should be allowed to stabilise for 30 minutes before starting calibrations.
2. Remove fibre adapters from the FOPM’s.
3. Attach fibre collimator to the laser.
4. Align the laser beam to the middle of the photodiode or the input port of the integrating sphere (using the IR viewing card). FOPM should be attached in such a way (linear translator, magnetic rod) that it can be easily replaced with the pyroelectric radiometer.
5. Align pyroelectric radiometer in the corresponding way.
6. Measure the optical power first with the FOPM, second with the pyroelectric radiometer, and third with the FOPM again. With each measurement, measure the dark current by blocking the beam and subtract it from the measurements.
7. Calculate responsivity as the ratio of the average of the measured photocurrents to the measured power.
8. Repeat measurements in order to find out the repeatability.
9. Compare the results with earlier calibrations (listed in this document) and record the new values into new version of this manual.

Table 5 shows the results of absolute responsivity measurements carried out in 2003. Detectors were calibrated – adapters removed – with collimated laser beams against a pyroelectric radiometer. Calibrations were done for 1310 nm and 1550 nm wavelengths separately. The powers used in the measurements were ~1 mW.

Table 5. Results of absolute responsivity measurements with collimated beams.

Detector	Responsivity [A/W]	
	1310 nm	1550 nm
FOPM-1	0.8422	0.9287
FOPM-2	0.9080	1.0186
Integrating sphere	$6.858 \cdot 10^{-3}$	$6.768 \cdot 10^{-3}$

5.2. Determination of corrections

5.2.1. Measurement of beam properties

The spread of the beam emerging from the end of the fibre was measured in 2001. The power exiting the fibre was measured with FOPM-1 at several distances in order to determine the angular distribution of the exit power (Figure 4). These data, together with the data of the angular responsivity measurements, were used to calculate a correction due to the error caused by the angular power distribution. The power distribution was measured at the 1550 nm wavelength. The data should be valid at the 1310 nm wavelength as well. The correction was calculated to be $1.2 \cdot 10^{-4}$ at maximum.

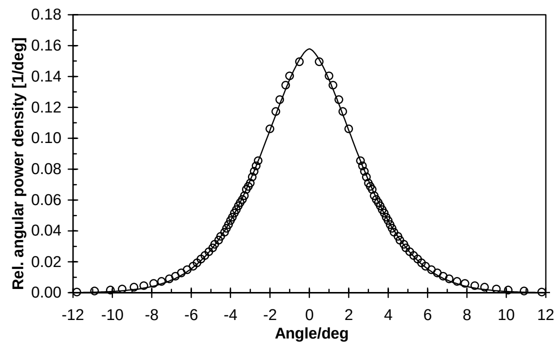


Figure 4. Distribution of the optical power exiting the fibre as a function of exit angle.

5.2.2. Measurement of spatial uniformity correction

The spatial non-uniformities of FOPM-1 and FOPM-2 were measured in 2001 by using a computer controlled translation stage. The detector was attached to the translation stage, and a collimated laser beam was swept over the active surface of the photodiode with steps of 0.5 mm. Photocurrent of the photodiode was measured at each point. Both detectors were measured at the wavelengths of 1310 and 1550 nm. The diameters of the beams were approximately 2 mm ($1/e^2$). Figure 5 shows an example of the measurement results. When the optical power exiting the fibre hits the active surface of the photodiode, 99% of the power will remain within a circle of a diameter of 1 mm. Within this area the relative standard deviations of the responsivities are $9.0 \cdot 10^{-4}$ for FOPM-1 and $1.3 \cdot 10^{-3}$ for FOPM-2. Wavelength had very little effect on the values.

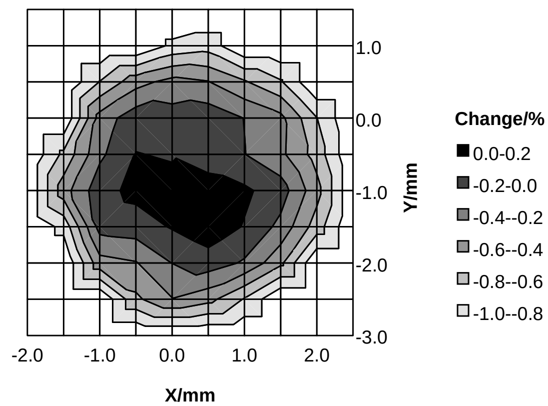


Figure 5. Spatial non-uniformity of FOPM-1 at 1310 nm wavelength.

5.2.3. Measurement of angular uniformity correction

The angular non-uniformities of the detectors were measured in 2003 with a similar method as the spatial uniformities. A computer-controlled turntable was used to rotate the detector so that the angle between the collimated laser beam and the normal of the active surface of the photodiode was swept from –10 to +10 degrees, with steps of 1 degree. Measurements were repeated at both wavelengths for each detector. For the integrating sphere the measurement was repeated with vertical and horizontal axes of rotation. Figures 5 and 6 show the results of these measurements.

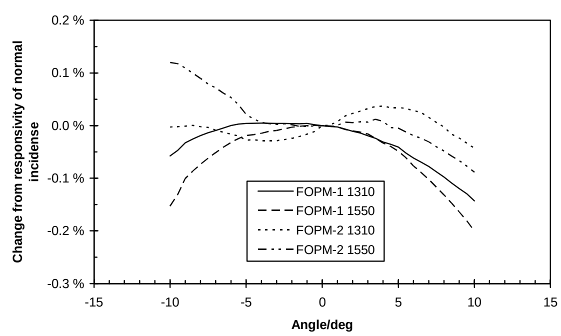


Figure 5. Measured angular responsivities of FOPM-1 and FOPM-2, given as relative change from the responsivity measured at zero angle. Notice the effect of the different anti-reflection coatings.

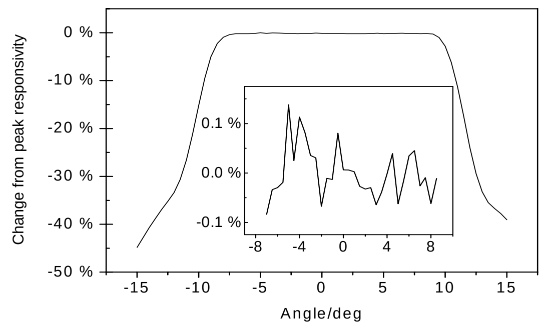


Figure 6. Example of angular uniformity measurements of sphere detector. The wavelength was 1550 nm, rotation axis was vertical. The diameter of the collimated laser beam was 1.2 mm. The axis of rotation was located at the place of the fibre end when the fibre adapter is attached.

5.2.4. Inter-reflections

In a structure such as FOPM-1 and FOPM-2, it is possible, that once the optical radiation hits the active surface of the photodiode, it may reflect back to the inner surface of the adapter, and again on the diode surface, thus causing an unwanted increase in the response of the detector. Although the adapter type used in this study had an area of diffusing black paint on the inner surface around the fibre optic connector (see Figure 1), we decided to measure the reflectance of each of the two plain photodiodes. These measurements were done in 2001. The results for FOPM-1 are 4.2 % and 8.8 % for the wavelengths of 1310 nm and 1550 nm, respectively. For FOPM-2 we measured 1.5 % for 1310 nm and 5.8 % for 1550 nm. It can be seen that the reflectances of the active surfaces of the photodiodes are small enough to prevent, together with the black paint, any significant inter reflections.

5.3. Accounting for corrections

Based on the correction measurements in 2001 and 2003, one may conclude that the corrections do not need to be applied to obtain the ~0.9 % uncertainties. The absolute responsivities according to chapter 5.1 may be used as such as the responsivities of the FOPM's. However, the characteristics must be checked according to intervals described in chapter 3.1 in order to detect possible changes.

5.4. Customer calibrations

Customer calibrations at ~1 mW level are carried out with FOPM-1 and FOPM-2. The procedure given in chapter 5.1 are used in suitable parts. Measurements are done with both detectors. The results should not deviate more than the uncertainties imply. Measurements can be done upto 200 mW by using EDFA. Integrating sphere source should be used as reference detector.

General operation and condition of customer meter is to be checked before calibration. No attempts should be made to clean customer meters without consulting the customer. Fibre ends should be cleaned before calibrations.

6. Safety and handling precautions

- Persons operating with wavelength calibrations must be trained to follow laser safety precautions.
- Always avoid direct exposure of laser beam.
- With lasers classified to class 2 or higher, protective eyewear must be used when the lasers are turned on.
- Do not touch the end of the optical fibers. Before use, always clean the fibers with soft tissue. Isopropyl-alcohol can be used to ease the cleaning.
- If, by accident, any of the optical components get dirty or damaged, notify all colleagues who might be using the equipment.

7. Laboratory accommodation and environment

Fibre optic power calibrations are performed in the Spectral Responsivity Laboratory (I128). The laboratory is located in the first floor of the I-wing of the Department of Electrical and Communications Engineering. No special conditions are needed for the calibrations.

8. Records

All the measurement data from calibrations and characterisation measurements are stored in Jouni Envall's computer in room I427 in a folder labelled "E:\FOP". The computer programs needed in the measurements are stored in the measurement computer in room I128. The folder is labelled "C:\jouni". The paper copies of the calibration certificates are stored in the metal cabinet in room I440 (the meeting room of the Metrology Research Institute).

9. Certificates

Calibration certificates are handled according to [5]. Include in the calibration certificate:

- Ambient temperature and relative humidity.
- Wavelengths and power levels of the lasers used.
- Responsivities of the calibrated FOPMs [A/W] or correction factors required, with uncertainties.

- Type of fibres and connectors used.

10. International comparisons

In 2003, we made a trilateral comparison [6] of the fibre optic power scales with Swedish National Testing and Research Institute (SP) and Danish Fundamental Metrology (DFM). The comparison was done at 1550 nm wavelength, at power levels 1 – 200 mW. Figure 7 shows the results of the high power part of the comparison. In this comparison, we (TKK) deviated 0.19 % from the average of the three laboratories. The deviations of all the three laboratories were within measurement uncertainties.

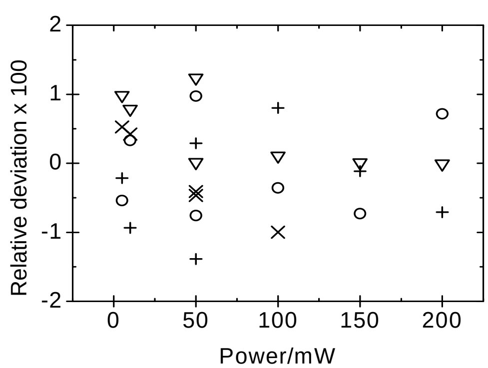


Figure 7. Results of the high power comparison given as the relative difference from the average power measured by TKK, SP and DFM. Signs: + is SP, O is TKK integrating sphere, X is DFM (JS11) and ∇ is DFM (LPM40).

11. References

[1] J. Envall, P. Kärhä, and E. Ikonen, “Measurements of fibre optic power using photodiodes with and without an integrating sphere,” *Metrologia* **41**, 353-358 (2004).

[2] Germanium Power Devices Inc. Type GAP5007 with the protective windows removed.

[3] MRI calibration schedule: http://metrology.hut.fi/quality/Calsched.pdf

[4] J. Envall, *Kuituoptisen tehomittarin karakterisointi*, mittaustekniikan erikoistyö, 16 p. (2001).

[5] Instructions for writing calibration certificates.

[6] J. Envall, A. Andersson, J. C. Petersen and P.Kärhä, “Realization of the scale of high fiber optic power at three national standards laboratories”, *Appl. Opt.* **44**, 5013-5017 (2005).