Pilot Comparison
on the fiber optic power responsivity between TUBITAK UME, IO-CSIC and AS Metrosert
Activity A3.1.4
Final Report

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Abstract

A pilot comparison on the calibration of a fiber optic power meter has been carried out between TUBITAK UME, IO-CSIC and AS Metrosert, within the EURAMET project "Supporting smart specialization and stakeholder linkage in Photometry and Radiometry". The agreed wavelengths and power levels for comparison were 1310 nm and 1550 nm and 0 dBm (1 mW) and -23 dBm (5 μW), respectively. TUBITAK UME piloted the comparison and its power meter was used as the comparison artefact.

1. Introduction

In 2020, European Metrology Programme for Innovation and Research (EMPIR) Project, Smart PhoRa "Supporting smart specialization and stakeholder linkage in Photometry and Radiometry" was started. Work package 3 (WP3) of this project is focused on metrology for fibre optics. In WP3, AS Metrosert (the NMI of Estonia) ,the DI of Spain (IO-CSIC) and NMI of Turkey (TUBITAK UME) work jointly to provide metrology for smart specialization in fibre optics [1]. The aim of this WP3 is to develop the expertise of NMIs/DIs in Estonia and Turkey to enable them to fulfil the needs of their regional industry in the field of fibre optics in the sense of a smart specialisation.

One of the activities of WP3 was to organise a pilot study in spectral responsivity of fibre optics detector between the tree laboratories. A commercial fiber optic power meter device owned by TUBITAK UME was circulated between the laboratories.

2. Participants

The pilot of the comparison is National Metrology Institute of Türkiye (TÜBITAK UME, Türkiye). Participants of the comparison are Instituto de Optica 'Daza de Valdés' (IO-CSIC, Spain) and Central Office of Metrology (AS METROSERT, Estonia).

3. Comparison artefact

The comparison artefact was HP 8153A Lightwave Multimeter having HP 81532A model of power sensor (Fig. 1).

Figure 1. Comparison artefact

The optical sensor inside the HP power meter is an InGaAs-based sensor element. According to technical specification, the sensor size is 5 mm in diameter and covers the range from 800 nm to 1700 nm in a power range from +3 dBm to -110 dBm (the IO-CSIC checked the instrument and the internal sensor, probably has a 1 mm diameter or smaller and has a temperature control probably with two stages TE cooler to achieve a very low noise (-110 dBm)). The sensor is connected by an optical fiber (with lens in the input) and the instrument has FC-adaptor. The optical input of the connector is covered with a special cover to protect it from dust and unnecessary particles. The device has a permanent identifying serial number (2946 G07109) on the back of the instrument. Only parameter of correct wavelength should be changed by using key “Param” on the front panel of the device. Minimum warm-up time of the device is 15 minutes.

The correction in dB for the comparison should be calculated by using the following equation:

$$Correction\ (dB) = P_{ref}(dBm) - P_{test}(dBm) \tag{1}$$

where P_{ref} (dBm) refer to the optical power measured by the reference meter of the participant and P_{test} (dBm) refer to the optical power measured by the comparison artefact.

4. Protocol of the comparison

TUBITAK UME prepared a draft comparison protocol on October 6, 2022 and sent it to the participants for their evaluation. After several suggestions, the final protocol was formed in line with the comments received on December 6, 2022. The TUBITAK UME calibrated the power meter first at the agreed wavelengths and power levels and then sent it to the IO-CSIC. The IO-CSIC calibrated the power meter and performed additional measurement on the linearity of the instrument at 1550 nm in order to be sure of possible differences between the measurements. After that IO-CSIC sent the device to the AS Metrosert. The AS Metrosert calibrated the power meter and sent it to the TUBITAK UME for final measurement at TUBITAK UME. The TUBITAK UME recalibrated the power meter to check the drift during the comparison period. After this process, the participating laboratories prepared a report containing the measurement setup, measurement results and uncertainty budget and sent it to the pilot laboratory.

At the TUBITAK UME the measurement were done over the period 1 December 2022 – 6 December 2022 (first round) and over the period 13 February 2023 – 14 February 2023 (second round). At the IO-CSIC the measurements were done over the period 13 December 2022 - 27 December 2022. At the AS Metrosert the measurements were done over the period 2 January 2022 - 17 January 2023.

5. Comparison measurements and results

5.1. TUBITAK UME Measurements

5.1.1 Laboratory conditions

The TUBITAK UME uses a central automation system for the control of ambient conditions and a calibrated relative humidity and temperature meter manufactured by TUBITAK UME (M/N: ESL1012V2, S/N: 084) was used to measure the related parameters. The temperature and relative humidity in the calibration area have been maintained at (23 ± 2) ºC and (45 ± 10) %rh, respectively.

5.1.2 Traceability

The TUBITAK UME uses an InGaAs detector manufactured by NPL (M/N: InGaAs and S/N: TKIG1) as a reference in optical power measurements, which has a InGaAs photodiode with a 5 mm diameter active area and mounted in a window-less can which is itself mounted in a 35 mm diameter cylindrical detector housing. The generated photocurrent at the output of the detector is converted to voltage by using a calibrated transimpedance amplifier manufactured by VINCULUM (M/N: SP042 and S/N: SP042-01-007) and a calibrated high-precision digital multimeter manufctured by Agilent (M/N: 3458A and S/N: US28029775) is used to measure voltage. The spectral responsivity of the reference detector is traceable to the PTB, whereas the transimpedance amplifier and the digital multimeter are traceable to the TUBITAK UME.

The wavelength measurements of the lasers were carried out using an optical spectrum analyser (OSA) manufactured by Anritsu (M/N: MS9740A and S/N: 6260878459) which has an acetylene calibration cell as an internal calibration standard that recalibrates the equipment as programmed. The TUBITAK UME does not have a calibration service on this subject. Therefore for verification purposes, the wavelength measurement performance of the device was checked at 1064 nm in the Time and Frequency Laboratory of the TUBITAK UME.

5.1.3 Measurement facility and the calibration procedure

The comparison artifact was calibrated using the measurement setup showing in the Figure 2.

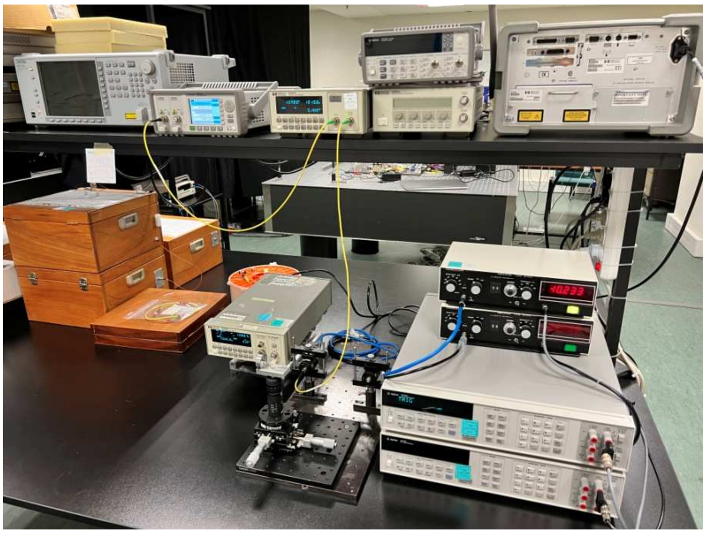


Figure 2. Photograph showing the calibration setup of TUBITAK UME

DFB laser sources manufactured by Agilent (M/N: 8163B and S/N: DE42100688) with two laser modules at 1310 nm and 1550 nm (M/N: 81663A) were used as sources in the calibration. After the measurements were completed with the first laser (1310 nm), the other laser (1550 nm) was used. Output of the laser source used was connected to an optical attenuator manufactured by Agilent (M/N: 8156A and S/N: 3328 G 02645) using the first FC/PC patchcord and output from optical attenuator connected to the reference detector using the second FC/PC patchcord. All tips of patchcords have been carefully cleaned before connection. After stabilization period of all electronic devices, the power level of 1 mW (0 dBm) was aligned by using the reference system by using the obtained voltage, gain of the transimpedance amplifier and the spectral responsivity of the reference detector in unit of mW and then mathematically converted to the unit of dBm. During voltage measurement, both the number of reading and the number of power line cycles of the digital multimeter were set to 50. The measurements repeated 10 times. After this process, the fiber optic patchcord was disconnected from the reference detector and connected to the calibrated device and 10 measurements were made. The same measurements were repeated for the second agreed power level, 0,005 mW (-23 dBm).

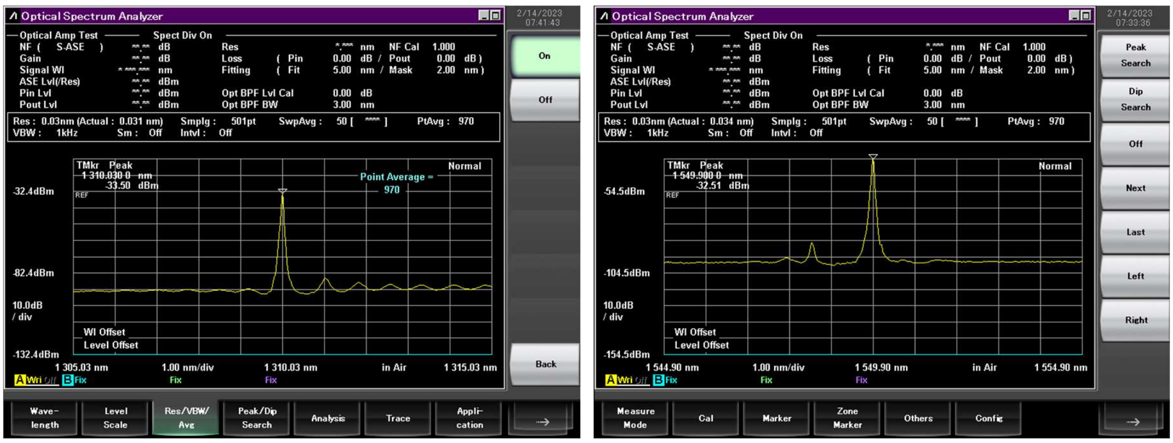
The same operations were performed for the wavelength of 1550 nm.

Table 1 gives the summary of results and uncertainties.

Table 1. Calibration results and uncertainties of TUBITAK UME

Wavelength (nm)	Optical power Reference (dBm)	Optical power DUT (dBm)	Correction (dB)	Uncertainty *k* = 2
1310.0 nm	0,002	-0,033	0,035	0,098
1310.0 nm	-23,01	-23,02	0,012	0,098
1549.9 nm	0,018	0,066	-0,048	0,097
1549.9 nm	-23,00	-22,96	-0,045	0,097

Figures 3 shows the results of the lasers measured by OSA.



Figures 3. Measurement results of the laser sources with a wavelength of 1310 nm (left side) and 1550 nm (right side).

5.1.4 Uncertainty budget

The calibration uncertainty at agreed wavelengths and power levels are given in Table 1 and detailed uncertainty budgets at 1310 nm and 1550 nm wavelengths are shown from Table 2 to Table 5.

Table 2. Uncertainty budget at 1310 nm wavelength and 0 dBm power level

#	Quantity, X_i	Estimate, x_i	standard uncertainty, $u(x_i)$	sensitivity coefficient, c_i	uncertainty contribution, $u_i(y)$
Reference power measurement					
1	Measured voltage	10,25782 V	0,00229 V	$9{,}76\cdot10^{-5}$ W/V	$5{,}01\cdot10^{-14}$ W^2
2	Calibration factor of DMM	0,001162 V	0,000020 V	$-9{,}76\cdot10^{-5}$ W/V	$3{,}81\cdot10^{-18}$ W^2
3	Transimpedance gain	10001 V/A	0,5 V/A	$-1{,}00\cdot10^{-14}$ (A*W^2)/V	$2{,}50\cdot10^{-15}$ W^2
4	Spectral responsivity of detector	1,025 A/W	0,010 A/W	$-9{,}76\cdot10^{-4}$ W^2/A	$1{,}00\cdot10^{-10}$ W^2
5	Annual drift of the detector responsivity	0	0,001 A/W	$9{,}76\cdot10^{-4}$ W^2/A	$9{,}53\cdot10^{-13}$ W^2
6	Laser stability	0	0,003	$1{,}00\cdot10^{-3}$ W	$7{,}85\cdot10^{-12}$ W^2
7	Connection repeatability	0	0,004	$1{,}00\cdot10^{-3}$ W	$1{,}85\cdot10^{-11}$ W^2
	Measured reference power	**1,00 mW**		k = 1	0,011 mW
				k = 2	0,023 mW
1	Measured reference power	0,002 dBm	0,049 dBm	1 dBm	$2{,}38\cdot10^{-3}$ dB^2
2	Measured power (artefact)	-0,033 dBm	0,003 dBm	-1 dBm	$8{,}55\cdot10^{-6}$ dB^2
Calculated correction (Eq.1)		**0,035 dB**		k = 1	0,049 dB
				k = 2	0,098 dB

Table 3. Uncertainty budget at 1310 nm wavelength and -23 dBm power level

#	Quantity, X_i	Estimate, x_i	standard uncertainty, $u(x_i)$	sensitivity coefficient, c_i	uncertainty contribution, $u_i(y)$
Reference power measurement					
1	Measured voltage	0,512404 V	$6{,}20\cdot10^{-5}$ V	$9{,}76\cdot10^{-6}$ W/V	$3{,}66\cdot10^{-19}$ W^2
2	Calibration factor of DMM	0,0001690 V	$1{,}00\cdot10^{-6}$ V	$-9{,}76\cdot10^{-6}$ W/V	$9{,}52\cdot10^{-23}$ W^2
3	Transimpedance gain	99974 V/A	5,0 V/A	$-5{,}00\cdot10^{-11}$ (A*W^2)/V	$6{,}25\cdot10^{-20}$ W^2
4	Spectral responsivity of detector	1,025 A/W	0,010 A/W	$-4{,}88\cdot10^{-6}$ W^2/A	$2{,}50\cdot10^{-15}$ W^2
5	Annual drift of the detector responsivity	0	0,001 A/W	$4{,}88\cdot10^{-6}$ W^2/A	$2{,}38\cdot10^{-17}$ W^2
6	Laser stability	0	0,003	$5{,}00\cdot10^{-6}$ W	$2{,}56\cdot10^{-16}$ W^2
7	Connection repeatability	0	0,004	$5{,}00\cdot10^{-6}$ W	$4{,}00\cdot10^{-16}$ W^2
	Measured reference power	**0,005 mW**		k = 1	0,000056 mW
				k = 2	0,00011 mW
1	Measured reference power	-23,011 dBm	0,049 dBm	1 dBm	$2{,}37\cdot10^{-3}$ dB^2
2	Measured power (artefact)	-23,023 dBm	0,003 dBm	-1 dBm	$7{,}61\cdot10^{-6}$ dB^2
Calculated correction (Eq.1)		**0,012 dB**		k = 1	0,049 dB
				k = 2	0,098 dB

Table 4. Uncertainty budget at 1550 nm wavelength and 0 dBm power level

#	Quantity, X_i	Estimate, x_i	standard uncertainty, $u(x_i)$	sensitivity coefficient, c_i	uncertainty contribution, $u_i(y)$
	Reference power measurement				
1	Measured voltage	11,3387 V	0,00104 V	$8{,}86\cdot10^{-5}$ W/V	$8{,}40\cdot10^{-15}$ W^2
2	Calibration factor of DMM	0,001162 V	0,000020 V	$-8{,}86\cdot10^{-5}$ W/V	$3{,}14\cdot10^{-18}$ W^2
3	Transimpedance gain	10001 V/A	0,5 V/A	$-1{,}00\cdot10^{-7}$ (A*W^2)/V	$2{,}52\cdot10^{-15}$ W^2
4	Spectral responsivity of detector	1,129 A/W	0,011 A/W	$-8{,}89\cdot10^{-4}$ W^2/A	$1{,}01\cdot10^{-10}$ W^2
5	Annual drift of the detector responsivity	0 A/W	0,001 A/W	$8{,}89\cdot10^{-4}$ W^2/A	$7{,}91\cdot10^{-13}$ W^2
6	Laser stability	0	0,003	$1{,}00\cdot10^{-3}$ W	$9{,}07\cdot10^{-12}$ W^2
7	Connection repeatability	0	0,004	$1{,}00\cdot10^{-3}$ W	$1{,}16\cdot10^{-11}$ W^2
	Measured reference power	**1,00 mW**		*k* = 1	0,011 mW
				k = 2	0,023 mW
1	Measured reference power	0,018 dBm	0,049 dBm	1 dBm	$2{,}37\cdot10^{-3}$ dB^2
2	Measured power (artefact)	0,066 dBm	0,003 dBm	-1 dBm	$8{,}55\cdot10^{-6}$ dB^2
	Calculated correction (Eq.1)	**-0,048 dB**		*k* = 1	0,049 dB
				k = 2	0,097 dB

Table 5. Uncertainty budget at 1550 nm wavelength and -23 dBm power level

#	Quantity, X_i	Estimate, x_i	standard uncertainty, $u(x_i)$	sensitivity coefficient, c_i	uncertainty contribution, $u_i(y)$
	Reference power measurement				
1	Measured voltage	0,565728 V	$3{,}31\cdot10^{-5}$ V	$8{,}86\cdot10^{-6}$ W/V	$8{,}58\cdot10^{-20}$ W^2
2	Calibration factor of DMM	0,0001690 V	$1{,}00\cdot10^{-6}$ V	$-8{,}86\cdot10^{-6}$ W/V	$7{,}85\cdot10^{-23}$ W^2
3	Transimpedance gain	99974 V/A	5,0 V/A	$-5{,}01\cdot10^{-11}$ (A*W^2)/V	$6{,}28\cdot10^{-20}$ W^2
4	Spectral responsivity of detector	1,129 A/W	0,011 A/W	$-4{,}44\cdot10^{-6}$ W^2/A	$2{,}51\cdot10^{-15}$ W^2
5	Annual drift of the detector responsivity	0 A/W	0,001 A/W	$4{,}44\cdot10^{-6}$ W^2/A	$1{,}97\cdot10^{-17}$ W^2
6	Laser stability	0	0,003	$5{,}01\cdot10^{-6}$ W	$2{,}26\cdot10^{-16}$ W^2
7	Connection repeatability	0	0,004	$5{,}01\cdot10^{-6}$ W	$4{,}02\cdot10^{-16}$ W^2
	Measured reference power	**0,005 mW**		*k* = 1	0,000056 mW
				k = 2	0,00011 mW
1	Measured reference power	-23,001 dBm	0,048 dBm	1 dBm	$2{,}35\cdot10^{-3}$ dB^2
2	Measured power (artefact)	-22,956 dBm	0,003 dBm	-1 dBm	$7{,}61\cdot10^{-6}$ dB^2
	Calculated correction (Eq.1)	**-0,045 dB**		*k* = 1	0,049 dB
				k = 2	0,097 dB

5.2. IO-CSIC Measurements

5.2.1. Laboratory conditions

A calibrated thermo-hygrometer (DELTA OHM (M/N: HD2101-1R and S/N: 13038962) with a temperature & relative humidity sensor (Sicram (M/N: RH-Pt100 and S/N: 13042304) was used for temperature measurements. The temperature and relative humidity in the calibration area has been maintained at (23 ± 2) ºC and (25 ± 5) %rh, respectively

5.2.2. Traceability

An electrically calibrated pyroelectric radiometer (ECPR) was used as a reference radiometer in the measurements. The ECPR is manufactured by LASER PROBE (M/N: Rs-5900/RsP-590 and S/N: 045-121-003) and use a chopper in the normal operation (M/N: CtX-515 and S/N: 041-133-002/041-002-001). The ECPR is traceable to the standard cryogenic radiometer of the IO-CSIC and the Si trap detectors at the wavelength of 633 nm. The responsivity value of the radiometer at this wavelength and the corrections for IR wavelengths due to the change in absorbance of the black coating of the radiometer are taken into account in its IR responsivity used in this report. The recognized uncertainty in CMC for optical fiber power meters of IO-CSIC is ± 1 % (± 0,043 dB) [2, 3].

Wavelength measurements of the lasers used were carried out by using an interferometric wavelength meter manufactured by EXFO (M/N: WA-1650 and S/N: 352391). The recognized uncertainty in CMC is 3 pm.

5.2.3. Measurement facility and the calibration procedure

The calibration of the calibration artefact was done directly by comparison with the ECPR in the setup shown in the Figure 4.

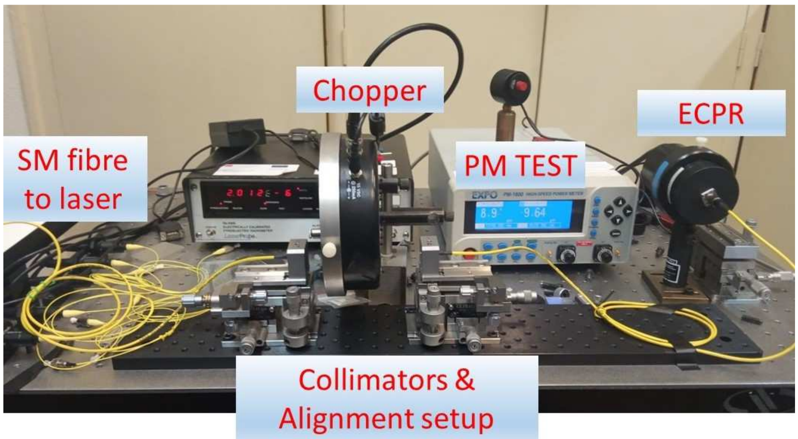


Figure 4. The calibration setup of the IO-CSIC

The whole assembly is made on single mode 10/125 μm optical fiber (SMF-28), the collimators allow the light to be taken out of the fiber to make it possible to use the ECPR chopper. The connectors used on the ECPR and the PM test are FC-PC. By modifying the collimation, optical power levels at each wavelength were selected to the required values of 0 dBm and -23 dBm, respectively.

The lasers used for the calibration are two tunable lasers manufactured by EXFO Tunincs XS (M/N: 3642 HE-1300 and S/N 1010262) for 1310 nm, and EXFO (M/N: T100S-HP-CLU+EWT and S/N: EO19440032) for 1550 nm. The spectra of the lasers used for the calibration are shown in the Figure 5.

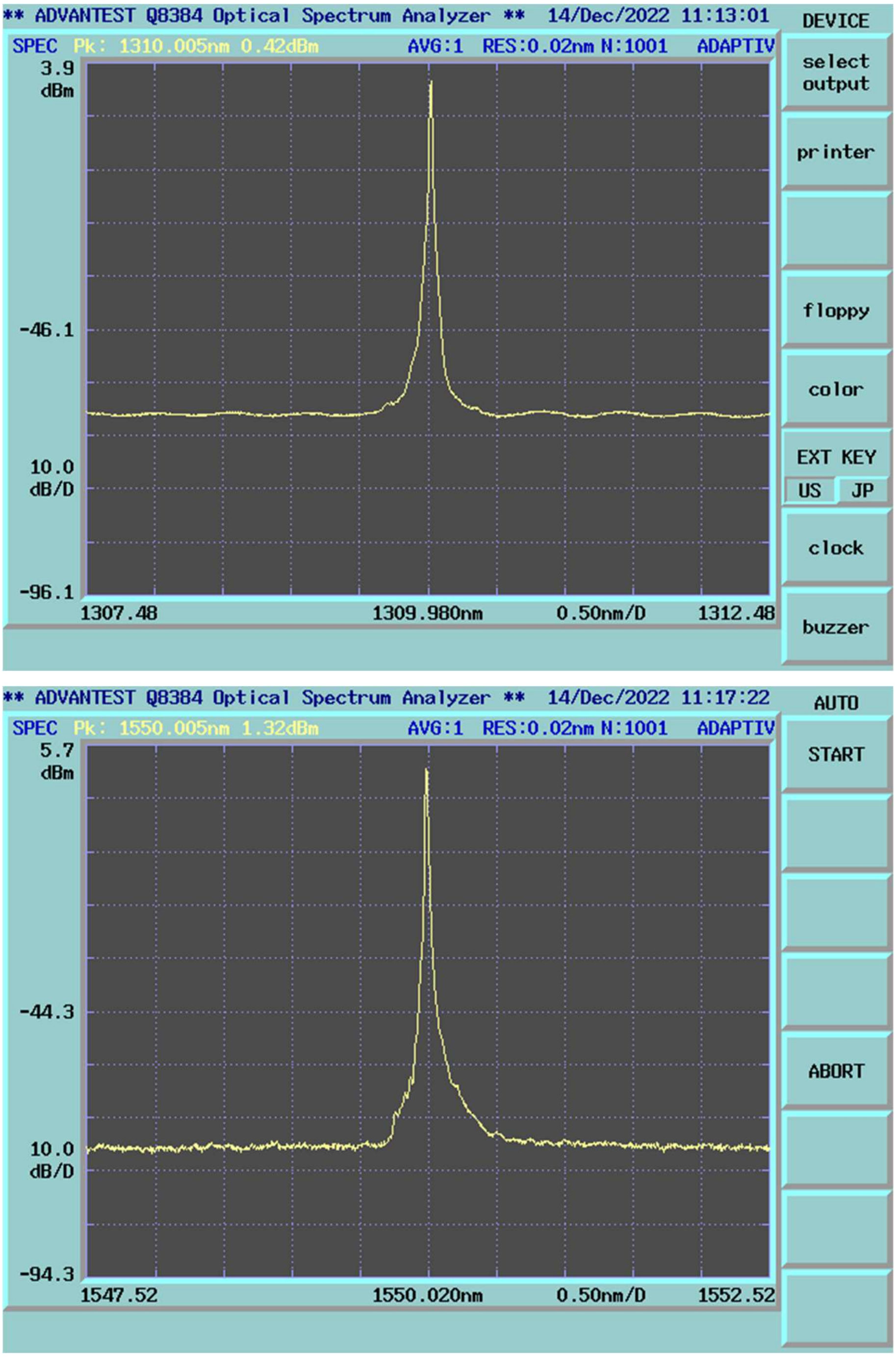


Figure 5. The spectra of the lasers used for the calibration.

The measurements were performed after careful cleaning of the fiber optic connectors and selection of the desired power levels at each wavelength. Before starting the measurements, the wavelength was selected in the calibration artefact (PM Test) and the equipment was zeroing as well as the ECPR. The measurements were taken after

10 connections and disconnections of the fiber optic connector alternately between the ECPR and the calibrated artefact. Between measurements, the movement of the chopper was stopped and waited to ensure that it did not interrupt the optical path. The calibration results are given in Table 6.

Table 6. Summary of calibration results of the IO-CSIC

Wavelength λ /nm	Uncertainty k = 2 λ /nm	Optical Power P_{ref}/dBm	Optical Power P_{ref}/mW	Correction dB	Uncertainty k = 2 dB	FC	Uncertainty k = 2
1310,0000	0,0030	0,06	1,014	-0,029	0,043	0,9934	0,0099
1310,0000	0,0030	-23,00	0,005	-0,041	0,043	0,9907	0,0099
1550,0060	0,0030	0,05	1,012	-0,006	0,043	0,999	0,010
1550,0060	0,0030	-22,95	0,005	0,007	0,043	1,002	0,010

FC is calculated using the following equation:

$$FC = \frac{P_{\text{ref}}(mW)}{P_{\text{TEST}}(mW)} \tag{2}$$

Additional measurement on the linearity of the power meter between +3 dBm and -24 dBm levels has been performed by the stimulus additive method at 1550 nm wavelength [4,5]. The results are shown in the Table 7 and Figure 6.

Table 7. Linearity measurement results

Optical Power (dBm)	**Optical Power (W)**	**NL (dB)**	**Uncertainty (dB) (*k* = 2)**	**NL**	**Uncertainty (*k* = 2)**
3,04	$2{,}016\cdot10^{-3}$	0,0482	0,0020	1,0112	0,0005
-0,01	$9{,}975\cdot10^{-4}$	0,0000	0,0020	1,0000	0,0005
-3,02	$4{,}988\cdot10^{-4}$	0,0003	0,0020	1,0001	0,0005
-6,02	$2{,}498\cdot10^{-4}$	0,0006	0,0028	1,0001	0,0007
-9,04	$1{,}248\cdot10^{-4}$	0,0019	0,0035	1,0004	0,0008
-12,04	$6{,}255\cdot10^{-5}$	0,0022	0,0040	1,0005	0,0009
-15,05	$3{,}125\cdot10^{-5}$	0,0035	0,0045	1,0008	0,0010
-18,05	$1{,}566\cdot10^{-5}$	0,0033	0,0049	1,0008	0,0011
-21,06	$7{,}836\cdot10^{-5}$	0,0041	0,0053	1,0010	0,0012
-24,06	$3{,}931\cdot10^{-5}$	0,0054	0,0057	1,0013	0,0013

Between +3 dBm and 0 dBm it shows a non-linearity jump of 1%, probably due to a change in the analogue-to-digital converter, although the PM test shows a good linearity between the values of 0 dBm and -23 dBm with a cumulative non-linearity of less than 1.0013 ± 0.0013 on the calibration factor and (0.0054 ± 0.0057) dB on the correction. In any cases this non-linearity correction factor are smaller than the uncertainty of the absolute correction factor.

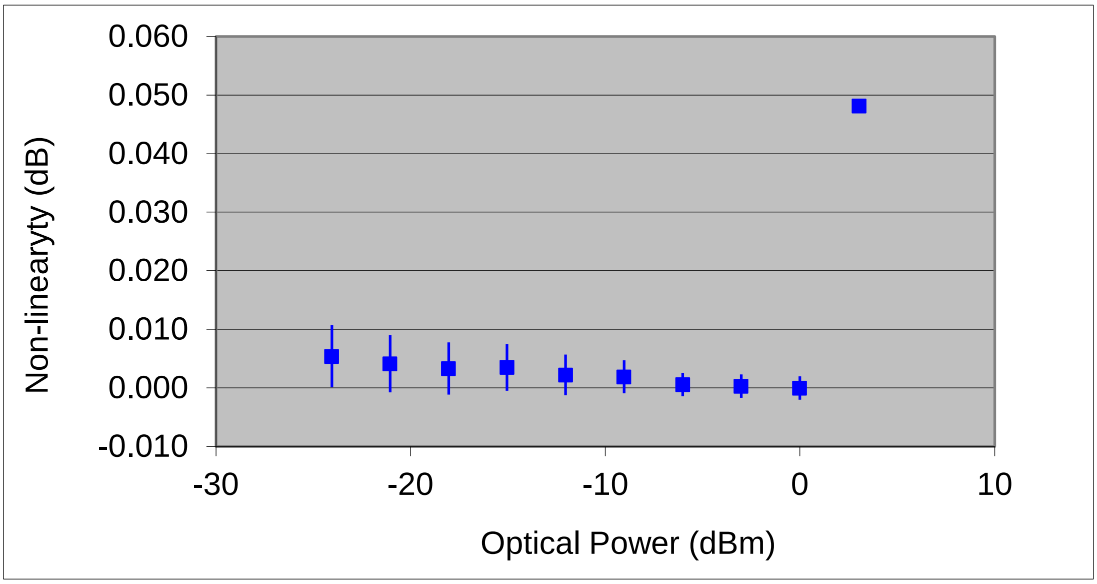


Figure 6. Linearity of the comparison artifact at 1550 nm wavelength.

5.2.4. Uncertainty budget

The calibration uncertainty at agreed wavelengths and power levels are given in Table 6 and detailed uncertainty budgets at 1310 nm and 1550 nm wavelengths are shown from Table 8 to Table 11.

Table 8. Uncertainty budget at 1310 nm wavelength and 0 dBm power level

DETAILED UNCERTAINTIES

Magnitude X	Symbol	Value x	Standard uncertainty u(x)	Type of assessment	Degrees of freedom n	Sensitivity coefficient c	Contribution to uncertainty u(y)
Standard reading	$P_S(\lambda)$	1,0151E-03	6,11E-07	A	9	979	5,979E-04
Standard resolution	$\delta P_S(\lambda)$	0,0000	2,89E-07	B	100	979	2,825E-04
Responsivity	$K_S(\lambda)$	0,9988	3,78E-03	B	100	1	3,764E-03
Drift of standard	$\delta K_S(\lambda)$	0,0000	1,15E-03	B	100	1	1,147E-03
Test reading	$P_X(\lambda)$	1,0231E-03	6,16E-07	A	9	971	5,979E-04
Test resolution	$\delta P_X(\lambda)$	0,0000	2,89E-07	B	100	971	2,803E-04
Calibration Factor	$K_X(\lambda)$	0,9934		n_{ef}	5,000E+05		3,990E-03
				k=	2,0000		
Calibration Factor (k=2)	$K_X(\lambda)$	0,9934	0,0080				
Calibration Factor (CMC)	$K_X(\lambda)$	0,9934	0,0099				

Table 9. Uncertainty budget at 1310 nm wavelength and -23 dBm power level

DETAILED UNCERTAINTIES

Magnitude X	Symbol	Value x	Standard uncertainty u(x)	Type of assessment	Degrees of freedom n	Sensitivity coefficient c	Contribution to uncertainty u(y)
Standard reading	$P_S(\lambda)$	5,0260E-06	9,80E-09	A	9	197113	1,931E-03
Standard resolution	$\delta P_S(\lambda)$	0,0000	2,89E-09	B	100	197113	5,690E-04
Responsivity	$K_S(\lambda)$	0,9988	3,78E-03	B	100	1	3,754E-03
Drift of standard	$\delta K_S(\lambda)$	0,0000	1,15E-03	B	100	1	1,144E-03
Test reading	$P_X(\lambda)$	5,0795E-06	9,90E-09	A	9	195036	1,931E-03
Test resolution	$\delta P_X(\lambda)$	0,0000	2,89E-09	B	100	195036	5,630E-04
Calibration Factor	$K_X(\lambda)$	0,9907		n_{ef}	5,000E+05		4,410E-03
				k=	2,0000		
Calibration Factor (k=2)	$K_X(\lambda)$	0,9907	0,0088				
Calibration Factor (CMC)	$K_X(\lambda)$	0,9907	0,0099				

Table 10. Uncertainty budget at 1550 nm wavelength and 0 dBm power level

DETAILED UNCERTAINTIES

Magnitude X	Symbol	Value x	Standard uncertainty u(x)	Type of assessment	Degrees of freedom n	Sensitivity coefficient c	Contribution to uncertainty u(y)
Standard reading	$P_S(\lambda)$	1,0122E-03	1,53E-06	A	9	987	1,507E-03
Standard resolution	$\delta P_S(\lambda)$	0,0000	2,89E-07	B	100	987	2,848E-04
Responsivity	$K_S(\lambda)$	0,9988	3,78E-03	B	100	1	3,784E-03
Drift of standard	$\delta K_S(\lambda)$	0,0000	1,15E-03	B	100	1	1,153E-03
Test reading	$P_X(\lambda)$	1,0148E-03	1,53E-06	A	9	984	1,507E-03
Test resolution	$\delta P_X(\lambda)$	0,0000	2,89E-07	B	100	984	2,841E-04
Calibration Factor	$K_X(\lambda)$	0,9987		n_{ef}	5,000E+05		4,243E-03
				k=	2,0000		
Calibration Factor (k=2)	$K_X(\lambda)$	0,9987	0,0085				
Calibration Factor (CMC)	$K_X(\lambda)$	0,999	0,010				

Table 11. Uncertainty budget at 1550 nm wavelength and -23 dBm power level

DETAILED UNCERTAINTIES

Magnitude X	Symbol	Value x	Standard uncertainty u(x)	Type of assessment	Degrees of freedom n	Sensitivity coefficient c	Contribution to uncertainty u(y)
Standard reading	$P_S(\lambda)$	5,0710E-06	9,80E-09	A	9	197536	1,935E-03
Standard resolution	$\delta P_S(\lambda)$	0,0000	2,89E-09	B	100	197536	5,702E-04
Responsivity	$K_S(\lambda)$	0,9988	3,78E-03	B	100	1	3,796E-03
Drift of standard	$\delta K_S(\lambda)$	0,0000	1,15E-03	B	100	1	1,157E-03
Test reading	$P_X(\lambda)$	5,0687E-06	9,79E-09	A	9	197627	1,935E-03
Test resolution	$\delta P_X(\lambda)$	0,0000	2,89E-09	B	100	197627	5,705E-04
Calibration Factor	$K_X(\lambda)$	1,0017		n_{ef}	5,000E+05		4,452E-03
				k=	2,0000		
Calibration Factor (k=2)	$K_X(\lambda)$	1,0017	0,0089				
Calibration Factor (CMC)	$K_X(\lambda)$	1,002	0,010				

5.3. AS Metrosert Measurements

5.3.1. Laboratory conditions

A thermo-hygrometer from Rotronic S/N A190303825 calibrated by AS Metrosert was used to record laboratory conditions. The temperature and relative humidity in the calibration area has been maintained as (20.0 - 20.6) ºC and (24 -28) %rh, respectively.

5.3.2. Traceability

In the measurements the photodetector 2XIGA [6] was used as a reference detector whose spectral responsivity is traceable to Aalto University. The photocurrent of the detector was measured by using the digital multimeter type 1281 from Wavetek S/N 45019 which is traceable to national standard of electrical quantities of AS Metrosert. The wavelengths of the lasers (type LPS-1310-FC, S/N 220620-21 and type LPS-1550-FC, S/N 22030-18 both from Thorlabs) were not measured, the datasheets provided by the manufacturer was used instead.

5.3.3. Measurement facility and the calibration procedure

The measurement set-up used in the measurement at AS Metrosert is depicted in Figure 7.

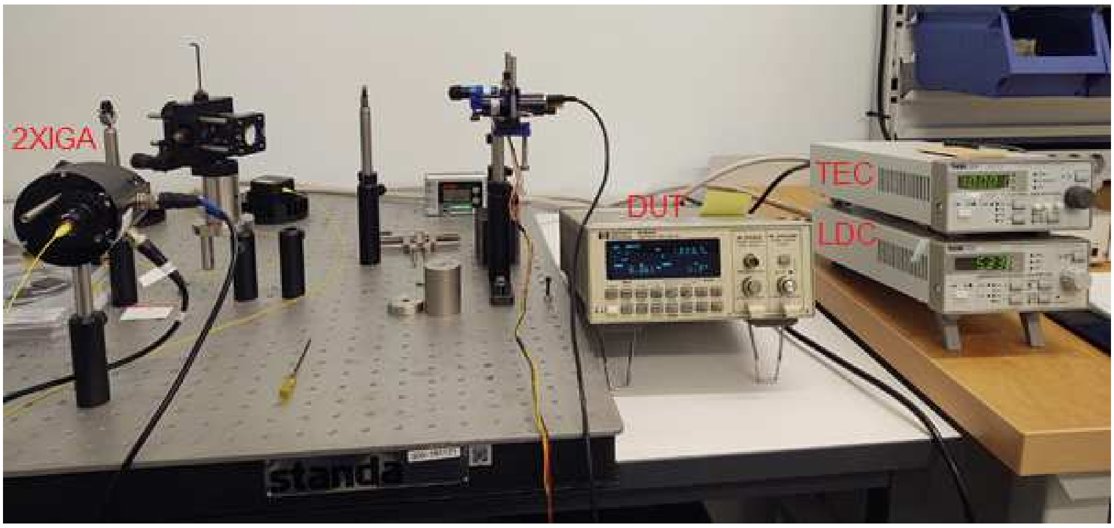


Figure 7. The measurement set-up used for the pilot study on the fiber optic power meter calibration at AS Metrosert.

In the measurements the photodetector 2XIGA was used as a reference detector. The photodetector includes two InGaAs-photodiodes type G8370-10 (windowless) from Hamamatsu. The configuration of photodiodes in the detector is insensitive to the polarization state of incoming beam [6].

As the light sources two diode lasers from Thorlabs were used

a) CWL λ=1309.2 nm, bandwidth $\Delta\lambda$ not specified, number of longitudinal modes 6 (manufacturer specifications) (Figure 8)

b) CWL λ =1545.5 nm, bandwidth $\Delta\lambda$ not specified, number of modes 8 (manufacturer specifications) (Figure 9)

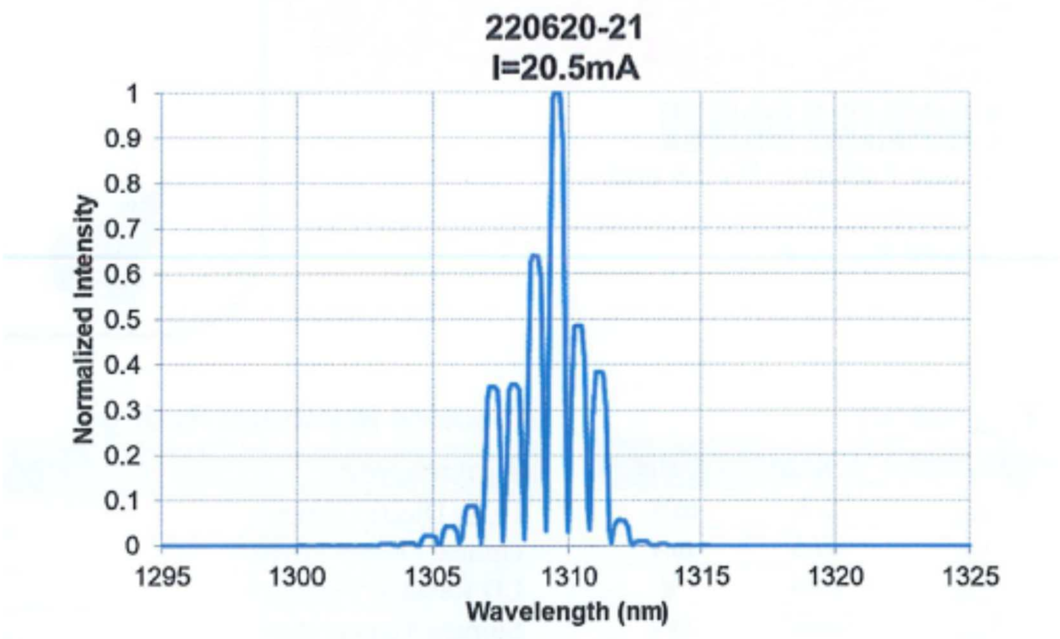


Figure 8. The spectra of the laser Thorlabs 220620-21 (1310 nm) at 20,5 mA.

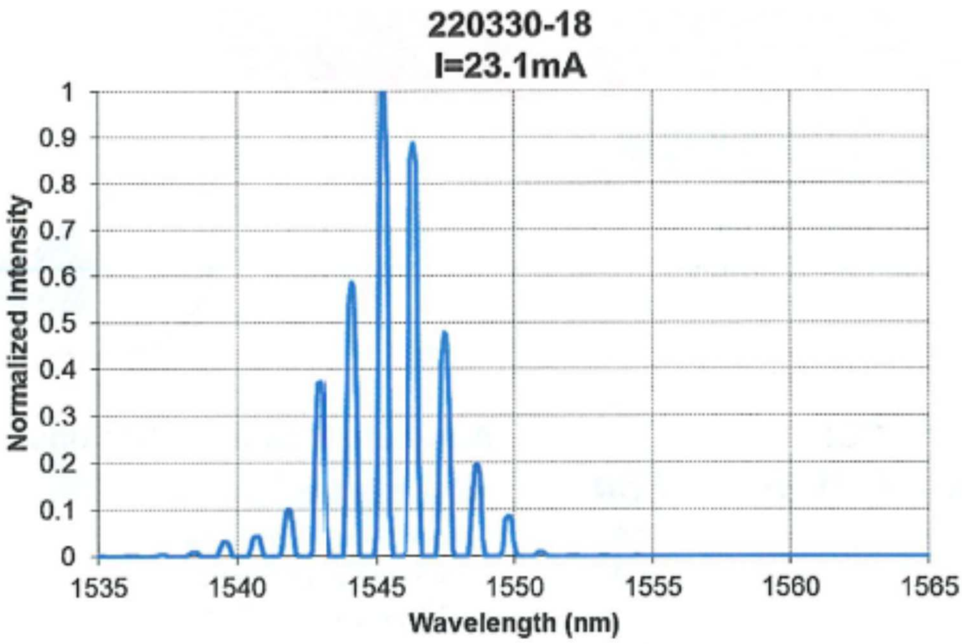


Figure 9. The spectra of the laser Thorlabs 220330-18 (1550 nm) at 23,1 mA.

The lasers’ current and temperature assembled in LD/TEC mount for Thorlabs Fiber-Pigtailed Laser Diodes model LDM9LP were set by using current driver LDC202C (S/N M00834933) and temperature controller TEC200C (S/N M00657257), both from Thorlabs. In the measurements with photodetector 2XIGA, the collimators model F240FC-C and model F240FC-1550 were used with the lasers at the wavelengths 1309.2 nm and 1545.5 nm, respectively.

The photocurrent from the detector 2XIGA was recorded by using digital multimeter Wavetek 1281.

The device under test (the comparison artefact) was powered on and let to warm up for 1 hour before start of measurements. Only parameter of correct wavelength was changed by using key “Param” on the front panel of DUT.

The measurements were performed in cycles. The sequence in the measurement cycle was:

a) Optical power measurement with reference detector with collimator attached to the fiber laser output;
b) Optical power measurement with DUT without collimator attached to the fiber laser output;
c) Optical power measurement with reference detector with collimator attached to the fiber laser output.

In total, 10 measurement cycles were conducted at each laser wavelength and each optical power level.

Table 12 gives the summary of results and uncertainties.

Table 12. Calibration results and uncertainties of AS Metrosert

Wavelength (nm)	Optical power (dBm)	Calibration Factor (correction / dB) (a)	Type A Standard Uncertainty (*k*=1) (b)	Type B Standard Uncertainty (*k*=1) (c)	Total Expanded Uncertainty *k*=2 (d)
1309,2	-23	-0,01	0,13	0,05	0,28
	-20	0,06	0,10	0,05	0,22
	-10	0,06	0,11	0,05	0,24
	0	0,15	0,09	0,05	0,20
1545,5	-23	-0,07	0,12	0,08	0,29
	-20	-0,01	0,13	0,05	0,27
	-10	0,08	0,09	0,05	0,22
	0	0,07	0,08	0,05	0,20

5.3.4. Uncertainty budget

The calibration uncertainty at agreed wavelengths and power levels are given in Table 12 and the detailed uncertainty budgets at 1310 nm and 1550 nm wavelengths are shown in Tables 13- 16.

Table 13. Uncertainty budget at 1310 nm wavelength and 0 dBm power level

Reference	Value	Standard deviation	Unit	PDF	Standard uncertainty contribution, dB
Calibration of responsivity	0,9646	0,0193	mA/mW	Normal	-0,087
Aging	0	0,0096	mA/mW	Uniform	-0,013
Spatial uniformity	0	0,0193	mA/mW	Uniform	-0,025
Effect of collimator	0	0,0019	mA/mW	Uniform	-0,005
Fibre connection	0	0,008	dB	Uniform	0,005
DMM calibration	0	1	µA	Normal	-0,005
DMM reading	919,69	1,46E+00	µA	Normal	-0,007
DMM resolution	0	0,01	µA	Uniform	-0,00001
LD stability	0	0,010	-	Uniform	-0,013
LD wavelength	0	0,2	nm	Uniform	0,0007
Calibrated power meter					
Reading	-0,36	0,004	dBm	Normal	0,004
Resolution		0,001	dBm	Uniform	0,0003
Fibre connection		0,120	dBm	Uniform	0,035
Combined standard uncertainty					
Type A					0,087
Type B					0,047
Total (*k*=1)					0,099
Expanded uncertainty (*k*=2)					0,20

Table 14. Uncertainty budget at 1310 nm wavelength and -23 dBm power level

Reference	Value	Standard deviation	Unit	PDF	Standard uncertainty contribution, dB
Calibration of responsivity	0,9646	0,0193	mA/mW	Normal	-0,087
Aging	0	0,0096	mA/mW	Uniform	-0,013
Spatial uniformity	0	0,0193	mA/mW	Uniform	-0,025
Effect of collimator	0	0,0019	mA/mW	Uniform	-0,005
Fibre connection	0	0,008	dB	Uniform	0,005
DMM calibration	0	0,1	µA	Normal	-0,096
DMM reading	4,52	1,57E-02	µA	Normal	-0,015
DMM resolution	0	0,01	µA	Uniform	-0,00277
LD stability	0	0,010	-	Uniform	-0,013
LD wavelength	0	0,2	nm	Uniform	0,0007
Calibrated power meter					
Reading	-23,42	0,012	dBm	Normal	0,012
Resolution		0,001	dBm	Uniform	0,0003
Fibre connection		0,120	dB	Uniform	0,035
Combined standard uncertainty					
Type A					0,131
Type B					0,047
Total (*k*=1)					0,140
Expanded uncertainty (*k*=2)					0,28

Table 15. Uncertainty budget at 1550 nm wavelength and 0 dBm power level

Reference	Value	Standard deviation	Unit	PDF	Standard uncertainty contribution, dB
Calibration of responsivity	1,146	0,0184	mA/mW	Normal	-0,069
Aging	0	0,0115	mA/mW	Uniform	-0,013
Spatial uniformity	0	0,0229	mA/mW	Uniform	-0,025
Effect of collimator	0	0,0023	mA/mW	Uniform	-0,005
Fibre connection	0	0,002	dB	Uniform	0,001
DMM calibration	0	1	μA	Normal	-0,004
DMM reading	1162,1	9,4E+00	μA	Normal	-0,035
DMM resolution	0	0,01	μA	Uniform	-0,00001
LD stability	0	0,020	-	Uniform	-0,025
LD wavelength	0	0,2	nm	Uniform	0,0006
Power meter					
Reading	-0,018	0,024	dBm	Normal	0,024
Resolution		0,001	dBm	Uniform	0,0003
Fibre connection		0,120	dBm	Uniform	0,035
Combined standard uncertainty					
Type A					0,082
Type B					0,051
Total (*k*=1)					0,097
Expanded uncertainty (*k*=2)					0,20

Table 16. Uncertainty budget at 1550 nm wavelength and -23 dBm power level

Reference	Value	Standard deviation	Unit	PDF	Standard uncertainty contribution, dB
Calibration of responsivity	1,146	0,0229	mA/mW	Normal	-0,087
Aging	0	0,0115	mA/mW	Uniform	-0,013
Spatial uniformity	0	0,0229	mA/mW	Uniform	-0,025
Effect of collimator	0	0,0023	mA/mW	Uniform	-0,005
Fibre connection	0	0,002	dB	Uniform	0,001
DMM calibration	0	0,1	μA	Normal	-0,077
DMM reading	5,61	2,2E-02	μA	Normal	-0,017
DMM resolution	0	0,01	μA	Uniform	-0,00223
LD stability	0	0,02	-	Uniform	-0,025
LD wavelength	0	0,2	nm	Uniform	0,0006
Calibrated power meter					
Reading	-23,15	0,021	dBm	Normal	0,021
Resolution	0	0,001	dBm	Uniform	0,0003
Fibre connection	0	0,120	dBm	Uniform	0,069
Combined standard uncertainty					
Type A					0,119
Type B					0,079
Total (*k*=1)					0,143
Expanded uncertainty (*k*=2)					0,29

6. Results and conclusion

A pilot comparison on the calibration of fiber optic power meter between three metrology institutes (TUBITAK UME, IO-CSIC and AS Metrosert) is performed within the described European project study. In the comparison, TUBITAK UME was the pilot laboratory, IO-CSIC and AS Metrosert were participating laboratories. The comparison results of three participants at agreed wavelengths and power levels are shown in Table 17 and Figure 10 [7]. Ratios of IO-CSIC to TUBITAK UME and IO-CSIC to AS Metrosert were used in the calculations. As can be seen from the figure, there are good agreement between the results at both wavelengths.

Table 17. Correction factor and uncertainty obtained by each laboratory

LAB.	λ (nm)	Power level (dBm)	Correction (dB)	Uncertainty (dB (k = 2))
TUBITAK UME	1310.0	0	0,035	0,098
	1310.0	-23	0,012	0,098
	1549.9	0	-0,048	0,097
	1549.9	-23	-0,045	0,097
IO-CSIC	1310.0	0	-0,029	0,043
	1310.0	-23	-0,041	0,043
	1550.0	0	-0,006	0,043
	1550.0	-23	0,007	0,043
AS Metrosert	1309.2	0	0,15	0,20
	1309.2	-23	-0,01	0,28
	1545.5	0	0,07	0,20
	1545.5	-23	-0,07	0,29

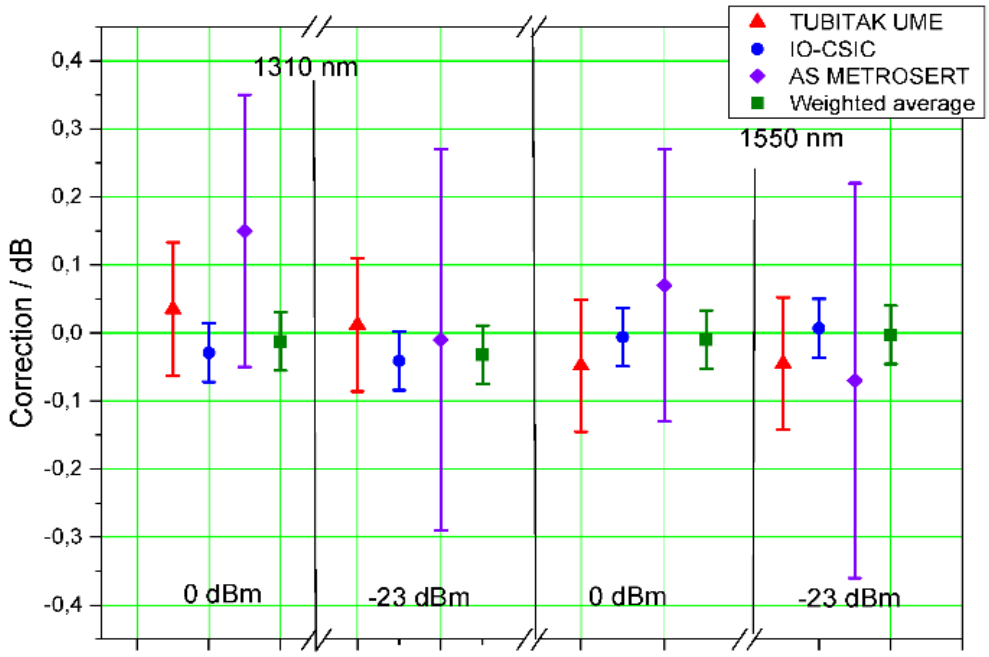


Figure 10. Comparison results showing the correction (dB) versus optical power measurements at 0 dBm and - 23 dBm of three participants at 1310 nm and 1550 nm wavelengths

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