Pulsed Solar Simulator System
IR Sens

Temperature Acquisition Device
Operating Manual

Automatic acquisition of module or cell surface temperature

BERGER Lichttechnik

Revision 3.5

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Operating Manual Remarks

Dear Customer,

This manual is designed to teach you how to operate the automatic surface temperature acquisition device type **IR Sens** of your BERGER system.

Please read this manual carefully and follow the instructions, as the system can only operate properly and reliably if the IR Sens is installed correctly.

Make this manual available to all personnel involved in operating the unit and keep it available for future reference.

› The unit must only be operated by trained and qualified personnel and in observance of the technical instructions given by BERGER Lichttechnik.

› The manufacturer accepts no liability for any damage or personnel injury resulting from incorrect use or not following the instructions and warnings given in this manual.

Notes, Notices and Warnings

Throughout the manual the following types of warning notices will be used:
(The signs shown here are examples and do not represent hazardous situations which may arise during the usage of the unit.)

⚠ DANGER

High voltage source
⃠ Touching the connections will result in serious injuries or death
➔ Do not touch the connections if the unit is plugged in

DANGER indicates a hazardous situation which, if not avoided, will result in death or serious injury.

⚠ WARNING

High intensity light source
⃠ Looking at light source during flash could cause retinal burns
➔ Do not look into light source
➔ Avoid looking at specular reflected light

WARNING indicates a hazardous situation which, if not avoided, could result in death or serious injury.

⚠ CAUTION

Hot surface. Temperature > 60°C
⃠ Touching the surface may result in burns
➔ Do not touch the hot surface
➔ Let the surface cool down before touching

CAUTION indicates a hazardous situation which, if not avoided, may result in minor or moderate injury.

NOTICE

Sensitive electrical equipment
⃠ Do not expose the unit to dust or moisture
➔ Use the unit only as directed in the manual

NOTICE indicates a situation which, if not avoided may result in property damage.

NOTE	The metallic sound of the PSS unit when the flash is triggered is normal and does not indicate a problem with the unit.

A NOTE indicates important information that helps you make better use of the BERGER System.

Introduction

The IR Sens is used to measure the surface temperature of your module or cell which is used in the temperature correction of the I-V measurement.

Most of the time the IR Sens is used in conjunction with the PT 100 system. The IR Sens measures the surface temperature of the module or cell while the PT 100 measures the ambient temperature. This setup is chosen to prevent measurements when the temperature gradient between module or cell and the environment is outside the specifications. (A big difference between ambient and object temperature may lead to a temperature gradient on the module / cell and therefore may cause erroneous I-V measurements.)

For a correct I-V measurement the correct measurement of the temperature of the module or cell is essential. So a temperature measurement with a device which reacts quickly to changes and does not have to touch the surface is a good choice.

Figure 1 | Picture of the IR Sens unit

General Safeguards

This unit is manufactured and tested according to the safety regulations for electronic measuring devices. Faultless operation and safety of the unit can only be guaranteed if all usual safety precautions as well as the specific safety regulations in this manual are observed when operating the unit.

Use

⚠ **WARNING**

Incorrect power supply voltage

⃠ Possibility of electrical shock and damage to the system

➔ Make sure that the voltage stated on the unit and the power supply voltage match

Power Sources

The system must be operated only with the type of power sources indicated on the marking label of the respective unit. A wrong connection may cause damage to the unit/system and hazardous voltages may occur on the unit.

Overloading

Do not overload wall outlets, extension cords or convenience receptacles beyond their capacity, since this can result in fire and/or electrical shock.

Object and Liquid entry

Never push objects of any kind into the unit through openings as they may touch dangerous voltage points or short out parts that could result in a fire, electrical shock and/or will damage the unit. Never spill liquid of any kind on the unit.

Attachments

Do not install and use attachments not recommended by the manufacturer, as they may cause hazards.

Cleaning

Unplug the whole system before cleaning any of the accessible parts. Do not use liquid cleaners or aerosol cleaners. Use a cloth lightly dampened with water for cleaning the exteriors of the system. If necessary add a mild household detergent to the water. Use a microfiber cloth to clean the lens of the sensor head.

Damage

If you can assume that the unit can no longer be operated safely it is to be decommissioned and marked appropriately so it will not be used again. The operator's safety can be affected by the unit if the unit i.e.:

› shows visible damages
› does not work as specified anymore
› has been stored under inappropriate conditions for any length of time

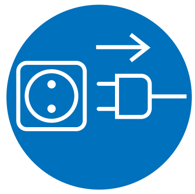
In case of doubt generally send in the unit to the manufacturer for repair or maintenance.

Installation of the IR Sens

⚠ **WARNING**

Electrical connections

⃠ Possibility of electrical shock and damage to the system
➔ Make sure that the system is not plugged into the main grid
➔ Protect the system against accidental activation.



Power-Cord Protection
Route the power cords in such a way that they are not likely to be walked on or pinched by items placed upon or against them. Pay particular attention to the plugs, receptacles, and the points where the cords exit from the respective units.

NOTICE

Fiber optic cable

⃠ Sharp bending may damage the fiber optic cable
➔ Make sure that a bending radius of not less than 15 cm is used
➔ Pay attention to the bending angles at the converter and the plugs

Optical Fiber Cable Protection
Route the fiber optic cables in such a way that they are not likely to be walked on or pinched by items placed upon or against them.

Condensation
Rapid changes in the ambient temperature may cause condensation water to form in the unit. This can result in fire or electrical shock and may damage the unit. Wait an adequate amount of time for the unit to reach thermal equilibrium with the ambiance.

Ventilation
The slots and openings in the unit are provided for necessary ventilation. To ensure reliable operation of the unit, and to protect it from overheating, these slots and openings must never be blocked or covered.

Installation location
The unit is designed to be used in closed rooms. Any kind of electromagnetic field or disturbance in the power supply can influence the measurement or render it useless. The sensing head is designed to operate at ambient temperatures from 0 °C up to 85 °C.

Air purity
Smoke, vapors, dust and other impurities (see ISO 8571.1) can lead to coatings on the lens that can cause incorrect measurement values. To prevent this, the air purge jacket (not included; accessories) is recommended.

Sensing Head and Cable
The connection cable between sensing head and electronics housing is preinstalled.
The length of the cable cannot be changed. The curvature radius of the cable should not be less than 25 mm.

Maintenance and Service

You have to set a regular cleaning cycle for the IR Sens sensor head to prevent dust from accumulating.
Use a microfiber cloth, like it is used for cleaning spectacles, or a soft, damp and lint free cloth.
Do not use pressured air or aerosol cleaners.

NOTE	Check the calibration of the system after cleaning the sensor head with a daughter module or cell. If the measured values of the daughter module or cell are out of your specified limits you have to check the temperature measurement of the system.

For questions regarding problems with the operation of the unit contact the manufacturer at:

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Annual Calibration

According to ISO 9000 and your Quality Management it is necessary to perform periodical checks on all measurement equipment.

For the IR Sens unit you have to check the function of the unit and the correctness of the temperature measurement.

This check can be done either by sending the IR Sens unit back to BERGER Lichttechnik for a calibration service which is traceable to the DKD or it can be done by your own Quality Management department.

To check the function of the unit you have to open the software, switch the operating mode to manager and open the item IR Temperature Calibration. The window that opens should look like the one shown in figure 14 on page 15 of this manual. You should see a temperature displayed for an object and the head. If this is not the case you should check the communication between the PC and the IR Sens unit (see also the **Installation Procedure** in this manual).

To check the correctness of the temperature measurement on site there are two different ways how your Quality Management department can perform this check:

› Comparing the surface temperature of a cell / module / measurement target measured with the IR Sens unit to the temperature measured with a second certified contact sensor unit
› Using a certified cell / module and compare the measured V_{OC} to the V_{OC} stated in the certificate.

The temperatures used during this test should cover the whole range of temperatures which may occur during the production process throughout the year.

NOTE	If one or more measured temperature(s) during this check of the IR Sens unit differ(s) more than ± 2 K from a given temperature the unit has to be sent back to BERGER Lichttechnik for repair.

Using a certified second sensor to check the IR Sens unit does not negate the necessity of verifying the setup with a certified cell / module. It does also not negate the necessity to set the emissivity and offset values correctly in the software.

BERGER Lichttechnik favours using a certified cell / module as it was found that it increases the correctness in relation to the certified cell / module.

Assembly

If you are installing the IR Sens in a new system you can skip the following part named »Shutdown procedure« of the installation manual and go directly to the parts named »Installation procedure for a PSL 8/ PSL AU/ PSL SCD system« (according to the system you have). If you have to exchange the IR Sens in a system that is already in use, follow the instructions in the chapter named »Shutdown procedure«.

Shutdown procedure

This procedure describes the steps to shutdown the BERGER system for installation of the IR Sens. This is **not** a complete shutdown of the production system. **Only** the BERGER system is affected by this procedure. If there are other systems like conveyors, etc. they have to be shutdown according to their respective instruction manuals if it is necessary to install the IR Sens.

⚠ WARNING

High intensity light source

⊘ Looking at light source during flash from a short distance may cause retinal burns

➔ Do not look into light source

➔ Avoid looking at specular reflected light

To install the IR Sens you should switch the generator and measuring load off to prevent an accidental flash.

In the first step you have to switch off the generator by pressing the red button labeled "**Emergency Stop**" on its front. Then switch off the measuring load by pressing the green illuminated button on its front panel. These two steps will prevent an accidental flash.

After this step remove the mains plugs from the generator and the PSL unit to prevent the system from being turned on accidentally.

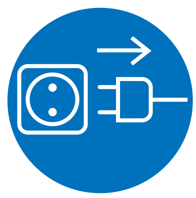
⚠ WARNING

Electrical connections

⊘ Possibility of electrical shock and damage to the system

➔ Make sure that the system is not plugged into the main grid

➔ Protect the system against accidental activation.



Installation procedure for a PSL 8 system

The sketch below shows the sequence of the fiber optic connections.

PC COM-Port ❯ **PT 100** ❯ **IR Sens** ❯ **PSL 8** ❯ **PSS 8**

The pictures in figures 2 to 5 show the correct connection of the fiber optic cables for a PSL 8 system. You have to connect the output of one unit to the input of the next. This can be achieved by always connecting the fiber optic jack which is marked red with the socket marked "out" on the respective unit.

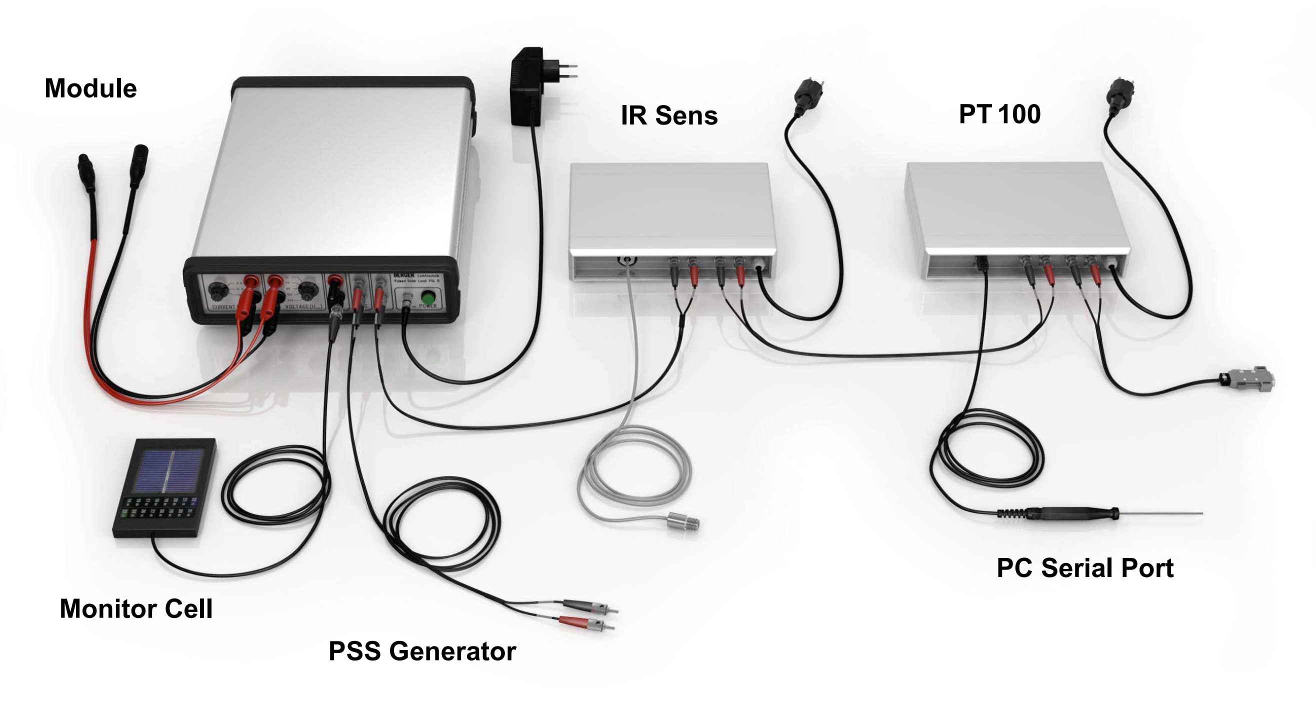


Figure 2 | Overview of the connections for a Berger measuring system

Figure 3 | Fiber optic cable connections at the PT 100 unit

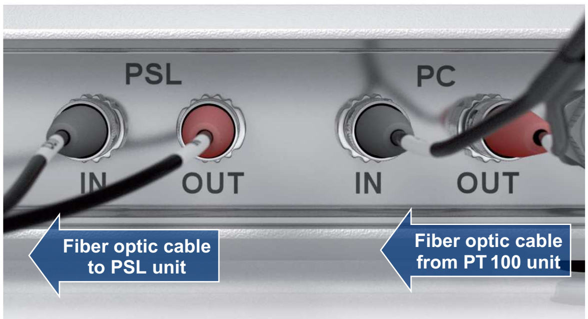


Figure 4 | Fiber optic cable connections at the IR Sens unit

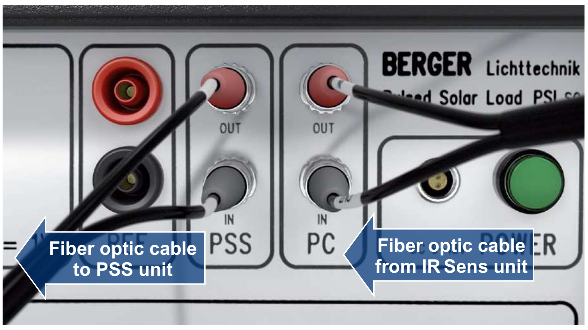
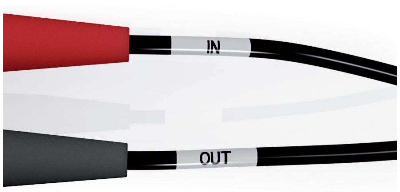


Figure 5 | Fiber optic cable connections at PSL unit

Mind the labels on the fiber optic cable (see figure). You have to connect always the red “IN” connector with the corresponding “OUT” on the unit and the black “OUT” connector with the corresponding “IN” on the unit!



Fiber optic cable labels

After connecting the fiber optic cables, place the IR Sensor in such a way that it does only see the surface of the module or cell it should measure. Keep in mind that a solar cell is a good IR mirror. The length of the cable from the sensor head to the IR Sens box cannot be changed. So you have to position the box accordingly.

Then plug the power plug into the power grid. Reconnect the PSL unit and the generator to the main grid.

NOTE	Position the sensor in such a way that it measures only the surface temperature of the module or cell. Make sure that the sensor head is not hit by the airflow from the air conditioning or any other exhaust airflow. Do not place the sensor head near ahot surface like a motor. Check that no hot component can be mirrored into the field of view of the IR Sens system.

After connecting all parts of the Berger system switch on all units and start the software on the PC.

Installation procedure for a PSL AU system

The sketch below shows the sequence of the fiber optic connections.

Edge-Port ❯ PT 100 ❯ IR Sens ❯ PSL AU ❯ PSS 8

The pictures in figures 6 and 7 show the correct connection of the fiber optic cables for a PSL AU unit. In an AU unit the PT 100 is preinstalled and two long fiber optic cables are provided to connect the IR Sens unit with the PT 100 and then back to the PSL AU unit. You have to connect these fiber optic cables from the PT 100 to the IR Sens and from there to the AU unit. To do this you have to connect the output of one unit to the input of the next. This can be achieved by always connecting the fiber optic jack which is marked red with the socket marked "out" on the respective unit.

After connecting the fiber optic cables, place the IR Sensor in such a way that it does only see the surface of the module or cell it should measure. Keep in mind that a solar cell is a good IR mirror. The length of the cable from the sensor head to the IR Sens box cannot be changed. So you have to position the box accordingly.

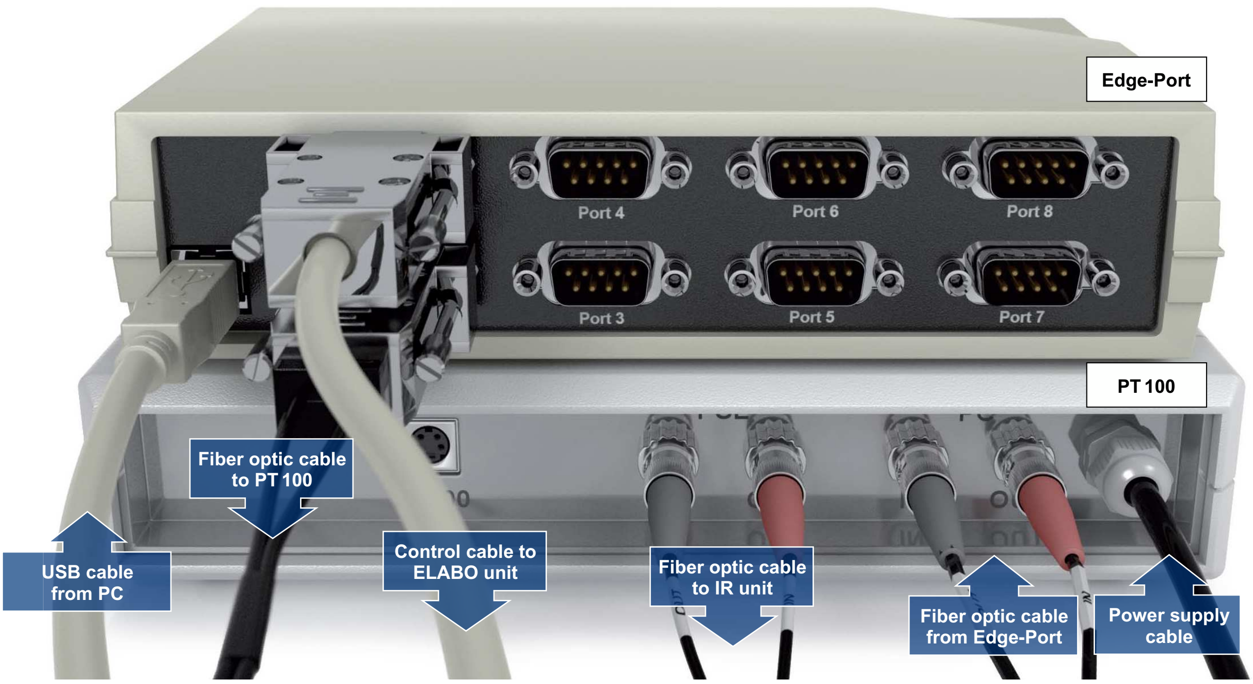


Figure 6 | Connection schematic of the PT 100 sensor

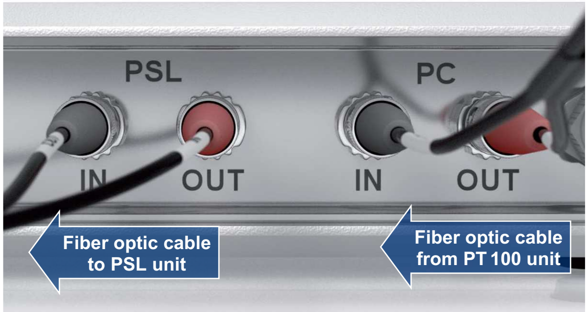
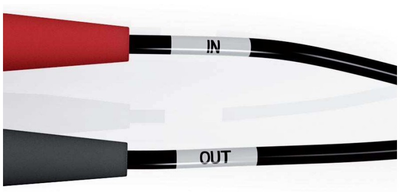


Figure 7 | Fiber optic cable connections at the IR Sens unit

Mind the labels on the fiber optic cable (see figure). You have to connect always the red “IN” connector with the corresponding “OUT” on the unit and the black “OUT” connector with the corresponding “IN” on the unit!



Fiber optic cable labels

After connecting all parts of the Berger system switch on all units and start the software on the PC.

NOTE	Position the sensor in such a way that it measures only the surface temperature of the module or cell. Make sure that the sensor head is not hit by the airflow from the air conditioning or any other exhaust airflow. Do not place the sensor head near a hot surface like a motor. Check that no hot component can be mirrored into the field of view of the IR Sens system.

Installation procedure for a PSL SCD system

Depending on the speed of the system or the presence of a PSL DF box there are two different versions of connecting the fiber optic cables.

PSL SCD system with a data transfer rate of 19200 baud

The sketch below shows the sequence of the fiber optic connections.

PC COM-Port › **PT 100** › **IR Sens** › **PSL SCD** › **PSS 10**

The pictures in figure 8 to 10 show the correct connection of the fiber optic cables for a PSL SCD unit. You have to connect the output of one unit to the input of the next. This can be achieved by always connecting the fiber optic jack which is marked red with the socket marked “out” on the respective unit.

Figure 8 | Fiber optic cable connections at the PT 100 unit

Figure 9 | Fiber optic cable connections at the IR Sens unit

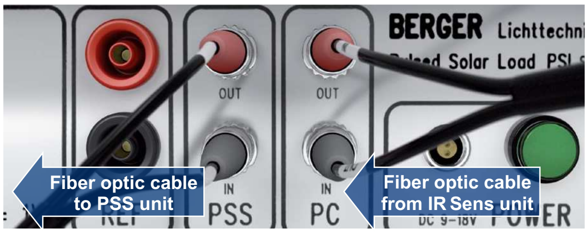
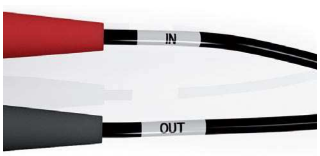


Figure 10 | Fiber optic cable connections at PSL unit

Mind the labels on the fiber optic cable (see figure). You have to connect always the red “IN” connector with the corresponding “OUT” on the unit and the black “OUT” connector with the corresponding “IN” on the unit!



Fiber optic cable labels

After connecting the fiber optic cables, place the IR Sensor in such a way that it does only see the surface of the module or cell it should measure. Keep in mind that a solar cell is a good IR mirror. The length of the cable from the sensor head to the IR Sens box cannot be changed. So you have to position the box accordingly.

Then plug the power plug into the power grid.

NOTE	Position the sensor in such a way that it measures only the surface temperature of the module or cell. Make sure that the sensor head is not hit by the airflow from the air conditioning or any other exhaust airflow. Do not place the sensor head near ahot surface like a motor. Check that no hot component can be mirrored into the field of view of the IR Sens system.

After connecting all parts of the Berger system switch on all units and start the software on the PC.

PSL SCD system with a data transfer rate of 38400 baud or with a PSL DF box

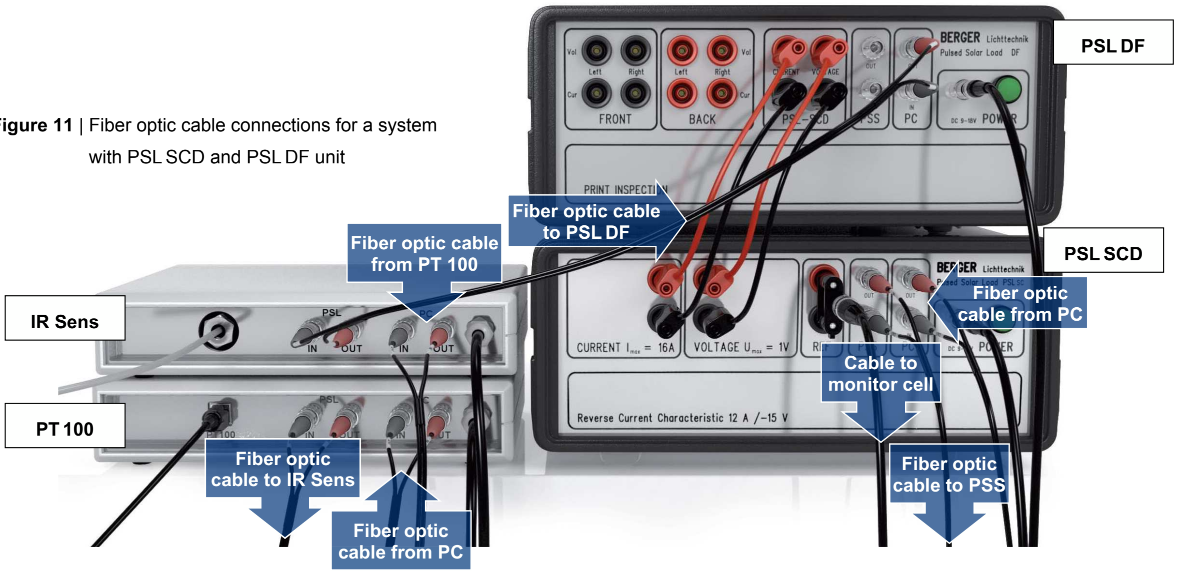
The sketch below shows the sequence of the fiber optic connections.

PC COM-Port 1 › **PSL SCD** › **PSS 10**

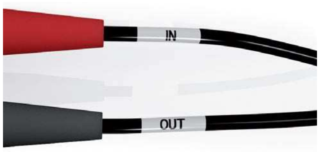
PC COM-Port 2 › **PT 100** › **IR Sens** › **PSL DF**

The picture in figure 11 shows the correct connections of the fiber optic cables for a PSL SCD (38400 baud) and a PSL DF unit. You have to connect the output of one unit to the input of the next. This can be achieved by always connecting the fiber optic jack which is marked red with the socket marked “out” on the respective unit.

Figure 11 | Fiber optic cable connections for a system with PSL SCD and PSL DF unit



Mind the labels on the fiber optic cable (see figure). You have to connect always the red “IN” connector with the corresponding “OUT” on the unit and the black “OUT” connector with the corresponding “IN” on the unit!



Fiber optic cable labels

After connecting the fiber optic cables, place the IR Sensor in such a way that it does only see the surface of the module or cell it should measure. Keep in mind that a solar cell is a good IR mirror. The length of the cable from the sensor head to the IR Sens box cannot be changed. So you have to position the box accordingly.

Then plug the power plug into the power grid.

NOTE	Position the sensor in such a way that it measures only the surface temperature of the module or cell. Make sure that the sensor head is not hit by the airflow from the air conditioning or any other exhaust airflow. Do not place the sensor head near ahot surface like a motor. Check that no hot component can be mirrored into the field of view of the IR Sens system.

After connecting all parts of the Berger system switch on all units and start the software on the PC.

Software setup

In the measurement software you are able to set a zero displacement (offset) and a scale correction (emissivity) to adjust the IR Sens unit to your cell / module surface. To adjust the offset and the emissivity you have to change from operator mode to manager mode by clicking “**Settings**” then “**Operating mode…**”. (See figure 12)

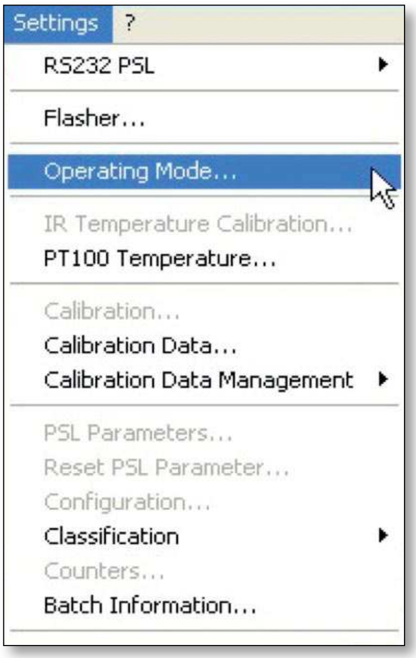


Figure 12

After entering the manager mode password go to the “**IR Temperature Calibration…**” item in the settings menu. (See figure 13)

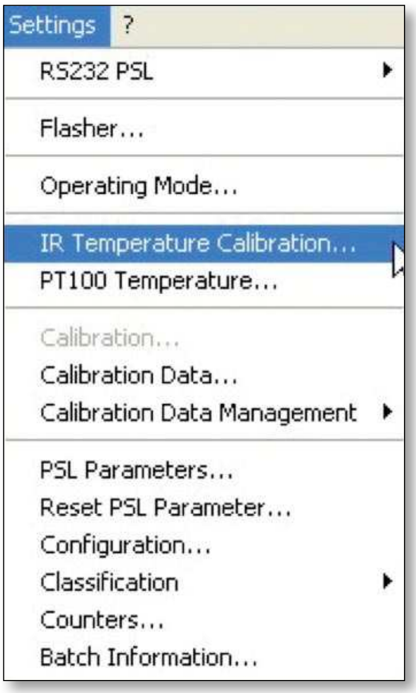


Figure 13

The following setup window for the IR Sens settings will pop up:

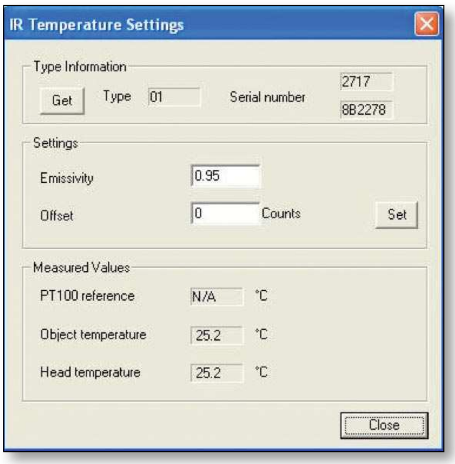


Figure 14

Emissivity
Emissivity is a dimensionless value for the ability of materials to absorb and emit infrared energy.
The value ranges from 0 to 1 (i.e. mirror: 0,1; blackbody: 1). Accurate measurements can only be achieved if the emissivity is set correctly (see the following description). A wrongly set emissivity will show up as a non-linear temperature (V_{OC}) behaviour.

Determination of Emissivity and Offset
The emissivity is comparable to the scaling for this measurement. So the emissivity should only be changed if you see a non – linear behaviour in the measured V_{OC} of a cell / module at different temperatures. A wrong emissivity value may result in incorrect measurements.

If you see a constant difference of the measured V_{OC} to the certified V_{OC} at different temperatures you have to change the offset. The offset describes a shift in the measurement scale.

NOTE	A wrong emissivity factor may result in incorrect measurements. Check any changes thoroughly.

There are two ways to determine the correct emissivity. Check that the offset is set to 0 and then choose one of the following ways:

1. If the cell / module temperature can be measured with a touching contact sensor change the emissivity value on the non-touching sensor until both temperatures match. Take care to measure the temperature with the non-touching sensor on a spot adjacent to the touching contact sensor. Now the actual setting equals the emissivity of the cell / module.

2. Apply matt varnish or plastics glue to the cell’s / module’s surface (front- or back side depending on which side the IR Sensor is looking) on an area big enough to cover the measurement spot. Wait for the paint or glue to adopt the cell’s / module’s temperature. Now measure the temperature with an emissivity set at 0.95 (default setting). Then, immediately measure the cell’s / module’s temperature on an adjacent, uncovered spot. Change the emissivity value until both spots display the same temperature. Now the actual setting equals the emissivity of the cell’s / module’s material.

After entering a new value you have to press the “Set” button in the software to have it take effect otherwise it will not be used.

Record the determined emissivity value and then determine the offset.

To determine the value of the offset place a reference cell/module in the machine and measure it in automatic mode. Make sure that the reference cell/module is passing the IR-Sensor. The IR-Sensor has to be activated for the temperature acquisition in automatic mode. Make sure that the temperature correction factors given in the calibration certificate are set in the software.

Compare the measured V_{OC} with the known one of the reference cell / module and set the offset-value of the IR-Sensor (see figure 15) according to the following formula:

$$\frac{V_{OC\,known} - V_{OC\,measured}}{V_{OC\,known}} = (25\,C° - T_{measured}) \cdot T_K$$

$$\frac{V_{OC\,known} - V_{OC\,measured}}{V_{OC\,known}} = \frac{\text{offset [counts]}}{33\text{counts}} \cdot T_K$$

with $T_{measured}$ = **Temperature of the cell / module in °C**; T_K = **Temperature coefficient of the voltage (-0.0032 1/K)**

This results in the simplified formula:

$$\frac{V_{OC\,known} - V_{OC\,measured}}{V_{OC\,known}} \cdot 10.000 \text{ counts} = \text{offset (counts)}$$

After entering the new values you have to press the “**Set**” button. Then you can close the window by pressing “**Close**”. (See figure 15; **the values in figure 15 are just examples and in no way recommended changes!)**

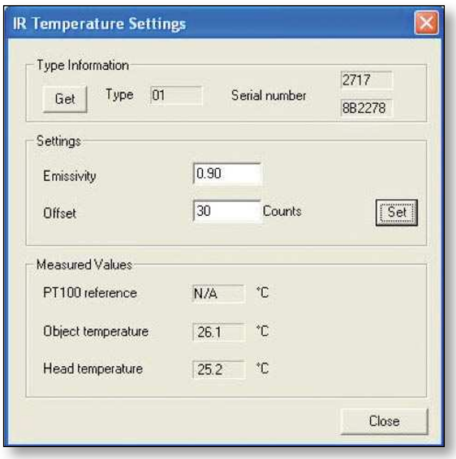


Figure 15

To verify if the used values are correct you should measure one cell / module at different temperatures. The measured values should not differ significantly. The temperatures used in this test should cover the whole range of temperatures which may occur during the production process throughout the year.

Technical Data

Basic Device

Power supply requirements:	100 – 240 V, 50 – 60 Hz, approx. 20 W
Protection Class:	Protection Class II
Communication:	Beam waveguide system 660 nm, PFO
Code:	

RS 232 9600 Baud 1 Stoppbit no parity [1]	RS 232 19200 Baud 1 Stoppbit no parity [1]

Dimensions:	Housing ABS 40 x 205 x 145 mm (H x W x L)
Relative Humidity:	0 to 80 % r. F. (non-condensing)
Working Temperature:	0 to 45 °C
Nominal Temperature:	25 °C

Measurement Range

Temperature Range:	- 40 – 600 °C
Spectral Response:	8 – 14 µm
Optical Resolution:	10 : 1 (90 % energy, distance 400mm)
System Accuracy:	± 1 % or ± 1 °C [2] (at ambient temperature 23 °C ± 5 °C)
Repeatability:	± 0,05 % or ± 0,5 °C (whichever is greater)
Temperature Resolution:	± 0,1 K (temperature range 100°C – 400°C)
Temperature Coefficient:	± 0,15 % / K or ± 0,15 K / K (whichever is greater)
System Response Time:	150 ms (95 %)
Emissivity:	0,100 … 1,100 (adjustable)
Transmission:	0,100 … 1,000 (adjustable)

General Specifications Sensing Head

Material:	Stainless steel
Dimensions:	28 x 14 mm (L x diameter)
Environmental Rating:	IP 65 (NEMA 4)
Ambient temperature:	0 – 65 °C
Relative Humidity:	10 – 95 % (non-condensing)
Vibration (Head):	IEC 68-2-6: 3 G’s, 11 – 200 Hz, each axis
Shock (Head):	IEC 68-2-27: 50 G’s, 11 ms, each axis

[1] The Baudrate of your unit is given on its label.

[2] with calibration

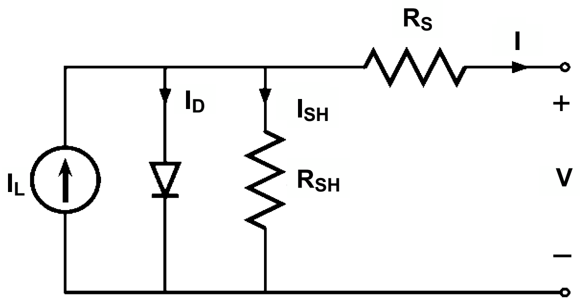
The purpose of measuring the temperature

Like all other semiconductor devices, solar cells are sensitive to temperature. The temperature of a semiconductor influences the valence – conduction band gap and therefore the energy that is necessary to transport electrons from the valence to the conduction band.

Increasing the temperature of a solar cell results in a smaller band gap and photons with a lower energy are able to move electrons from the valence to the conduction band (This is because the electrons in the solar cell already have a higher energy level). This results in a greater amount of available electrons and therefore a higher current. The difference in the band gap between the valence and the conduction band mirrors the open circuit voltage of the solar cell and so the V_{OC} decreases with increasing temperature.

These two opposite effects do not compensate each other. The open circuit voltage V_{OC} of a silicon solar cell decreases with about **0,37** $\%/°C$ whereas the short circuit current I_{SC} increases only with about **0,06** $\%/°C$. This adds up to a decrease in the maximum power output of a silicon solar cell of about **0,4 to 0,5** $\%/°C$.
As can be seen quite clearly it is mandatory to know the temperature of the solar cell or solar module get an accurate measurement of their respective power output.

Equivalent circuit of a solar cell



I_L = photogenerated current [A]
I_D = diode current (dark current) [A]
I_{SH} = shunt current [A]
R_{SH} = shunt resistance [Ω]
R_S = serial resistance [Ω]
I = current output [A]
V = voltage between the output terminals [V]

Figure 16

Figure 16 shows the equivalent circuit of a solar cell. The photo generated current constitutes the current that is generated by the incidenting photons. To simulate the behavior of an ideal solar cell one has to deduct the diode current / dark current I_D from the photogenerated current I_L. The behavior of a real solar cell can be simulated by adding two resistances to the circuit diagram. R_{SH} symbolizes crystal defects, non-ideal doping dispersal and other material defects, which result in leakage currents, which shunt out the p – n junction. R_S symbolizes all effects, which result in a higher total resistance of the element. These are mainly the resistance of the semiconductor material and the resistance at the terminal points and the cables. According to the circuit schematic, the generated current can be calculated using the following formula:

$$I = I_L - (I_D + I_{SH})$$ Formula 1

The current flow through these components is defined by the impressed voltage:

$$V_i = V + I \cdot R_S$$ Formula 2

with V_i = **voltage at element i**; **V = voltage between the output terminals**; **I = current output** and R_S = **serial resistance**

The current flowing through the diode is described by the Shockley - Diode - Equation:

$$I_D = I_0 \cdot \left(e^{\left[\frac{e_0 \cdot V_i}{n \cdot k_B \cdot T}\right]} - 1 \right)$$ Formula 3

with I_D = **diode current**; I_0 = **reverse saturation current**; **n = diode ideality factor** (1 for an ideal diode); **T = absolute temperature** [K]; k_B = **Boltzman constant** [1,380 6504(24) * 10^{-23} JK^{-1}]; e_0 = **elementary charge** [1,602 176 487(40) * 10^{-19} C];

The current flowing through the shunt resistance is defined by Ohm's law:

$$I_{SH} = \frac{V_i}{R_{SH}}$$ Formula 4

with R_{SH} = **shunt resistance**

Substituting the formulas 2 to 4 in the first formula results in the characteristic equation of a solar cell:

$$I = I_L - I_0 \cdot \left(e^{\left[\frac{e_0 \cdot (V + I \cdot R_S)}{n \cdot k_B \cdot T}\right]} - 1 \right) - \frac{(V + I \cdot R_S)}{R_{SH}}$$ Formula 5

This equation shows how the parameters I_0, n, R_{SH} and R_S define the voltage and the current of a solar cell.

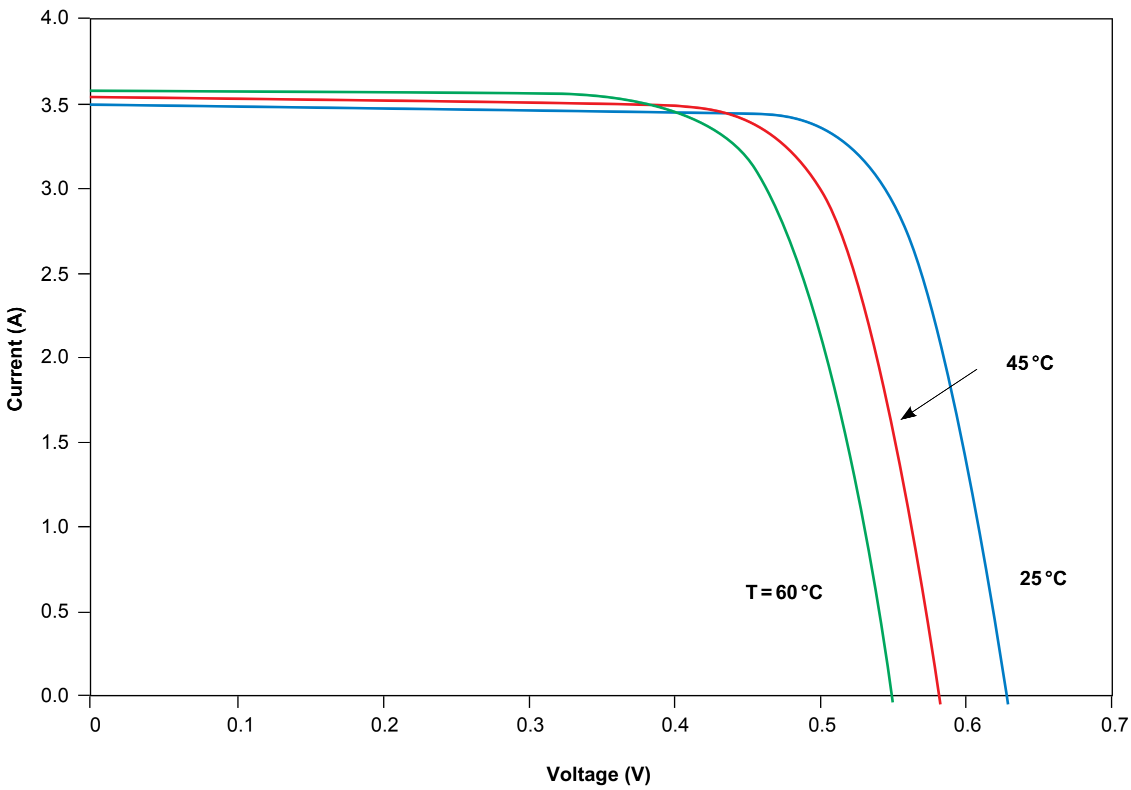
Influence of the temperature on the current-voltage characteristic

Temperature affects the characteristic equation (Formula 5) in two ways: directly, via **T** in the exponential term, and indirectly via its effect on $\mathbf{I_0}$. (Strictly speaking, temperature affects all of the terms, but these two are far more significantly than the others.) Increasing the temperature **T** reduces the magnitude of the exponent in the characteristic equation. The value of $\mathbf{I_0}$ increases proportional to $\mathbf{e^T}$. This results in a linear reduction of $\mathbf{V_{OC}}$ with increasing temperature. The magnitude of the reduction is inversely proportional to $\mathbf{V_{OC}}$, that is, a solar cell with high values for $\mathbf{V_{OC}}$ will have a smaller reduction of the voltage with increasing temperature. The photocurrent increases slightly if the temperature is increased. This is because of the higher number of thermal generated charge carriers in the cell. The resulting effect of an increase in the temperature on the efficiency of the cell can be calculated with the characteristic formula. However, as the change in the voltage is much bigger than the change in the current, the voltage mostly determines the overall effect.

Most of the crystalline silicone solar cells lose efficiency with about **0,4 to 0,5** $^{\%}/_{°C}$.

Most of the amorphous solar cells will lose efficiency with about **0,15 to 0,25** $^{\%}/_{°C}$.

Figure 6 shows an example of an **I-V curve** of a crystalline silicone solar cell at different temperatures.



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entsprechend / in accordance with / selon ISO/IEC 17050-1/-2:2004

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