HEWLETT® PACKARD

Optical Power Measurement

Solution Note 153-1

The Basis of Fiber Optic Measurement and Calibration

Contents

1. Introduction

Optical power measurement is the most frequent task in fiber optic measurement and calibration. Examples include absolute power measurements, such as laser power, optical amplifier output power, and receiver sensitivity. Equally important are relative power measurements, such as attenuation and gain. This paper discusses typical measurements on connectors, couplers, and optical filters. Various alternatives for optical sources will be compared, such as LEDs, fixed-wavelength lasers, and tunable lasers. The discussion also includes power meter calibration and how the power meter characteristics influence the measurement accuracy.

2. Optical Power Meters

Two main groups of optical power meters can be identified: thermal receivers, in which the temperature rise caused by optical radiation is measured, and photodetectors, in which, in the best case, each incident photon generates one electron-hole pair (see Figure 2-1).

Thermal receivers have the advantage of a wide wavelength range and a flat (i.e. wavelength-independent) response. To improve the accuracy, some of these meters utilize so-called substitution radiometry. In this method, the power meter is first exposed to the optical radiation and then the radiation is switched off and replaced by electrically generated power. This power is controlled so that an equilibrium temperature is maintained. Electrically generated power can be measured very accurately, thereby providing the highest accuracy for optical power. This method also represents self-calibration; most national standards laboratories use thermal radiometry with self-calibration as their reference method. However, the application of thermal power meters is limited to power levels above 10 µW. With the exception of power meter calibration, thermal power meters are rarely used in fiber optics; the reason for this is their low sensitivity, long measurement times and sensitivity to ambient temperature.

In contrast, there is no self-calibration for photodetectors. Although some efforts have gone into the self-calibration of photodetectors, aimed at a quantum efficiency of one [1], this method was abandoned because it is too difficult. The major advantage of photodetectors is that they can measure power levels as low as 1 pW (90 dBm). On the other hand, a relatively strong wavelength dependence is observed, and the spectral band is usually not more than one octave (see section 2.1). Nevertheless, this detector type is nowadays the most important, because of its great sensitivity and ease-of-use.

Photodetector power meters are usually subdivided into two types: small-area power meters, to be used only when power from a fiber is to be measured, and large-area power meters, for open beam and fiber applications. HP's large-area power meters are well-known for their dependable accuracy and this is why many standards laboratories have chosen them for their calibration purposes.

Figure 2-2 shows a cross-section of a commercial large-area optical head based on a photodetector (HP 81520A, HP 81521B, and HP 81524A). The important elements are: anti-reflective coating and the angled position of the detector in order to avoid multiple reflections. Temperature stabilization using a thermoelectric cooler ensures stable measurement results.

Figure 2-1

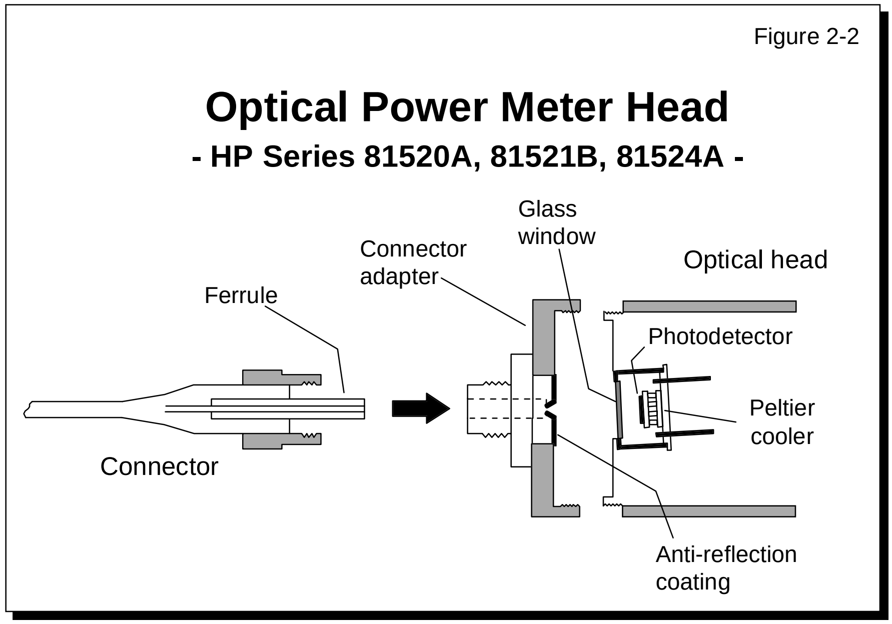
Types of Optical Power Meters

Power meters with thermal detectors:

+ flat wavelength dependence,
+ self-calibration possible,
- - very low sensitivity.

Power meters with photodetectors:

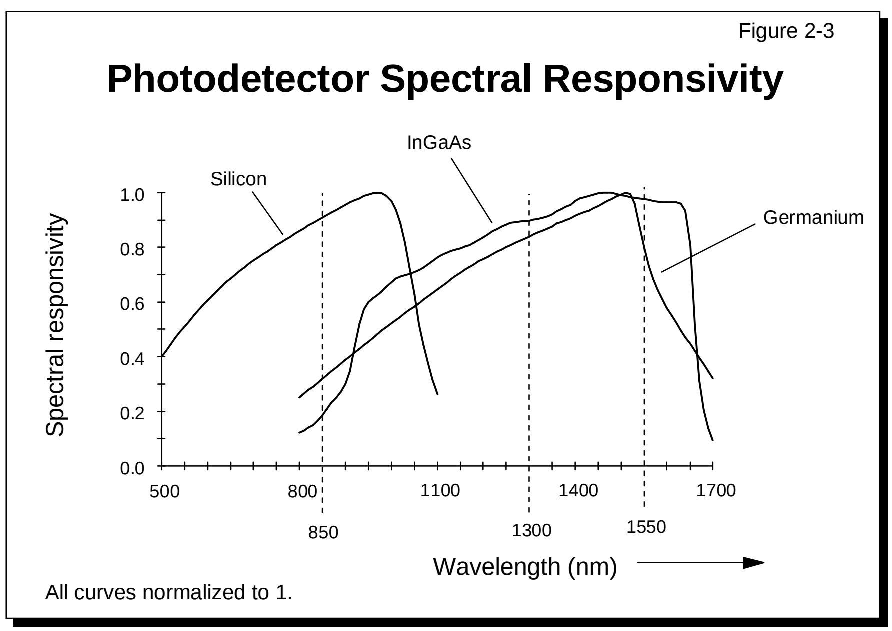
- stronger wavelength dependence,
- no self-calibration,
++ very high sensitivity.



Other performance criteria for optical power meters are discussed in section 2.1.

2.1 Other performance criteria

Spectral responsivity:
Before selecting an optical head, a choice of detector material has first to be made.

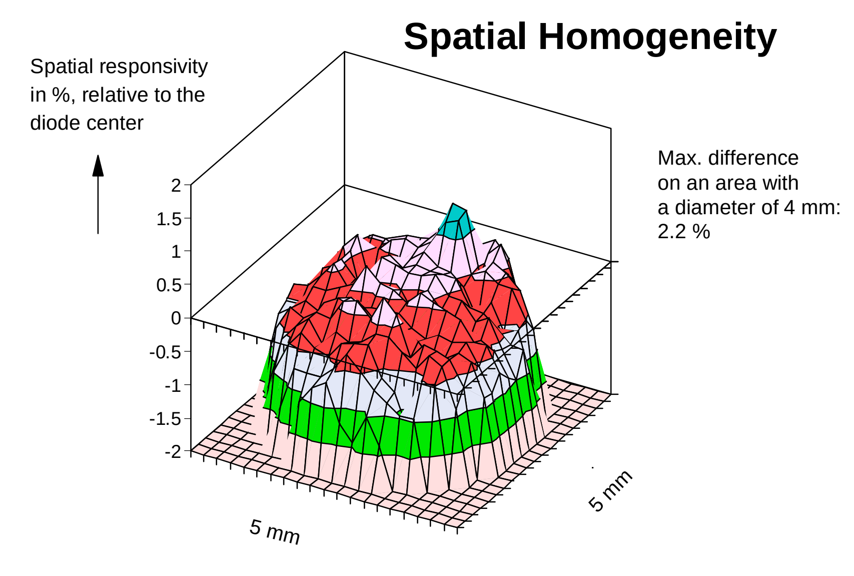


For the long wavelength region, both germanium and InGaAs detectors can be used, as shown in Figure 2-3. However, germanium is the more economical solution, which can be recommended when the sources to be measured are spectrally narrow and the wavelength is well-known. This is particularly important around 1550 nm; in this region, a wavelength error of 1 nm can produce an error of up to 1 %.

In contrast, InGaAs detectors are essentially flat around 1550 nm (less than 0.1 % per 1 nm wavelength error). This makes them well-suited to erbium-doped fiber amplifier (EDFA) applications, as the detector's flat responsivity corresponds well with the usable gain region of EDFAs (1525 to 1570 nm). However, this is a more expensive technology.

Homogeneity:
Figure 2-4 shows the relative responsivity of an InGaAs photodetector of 5 mm diameter at 1550 nm. Wide variations in the homogeneity of commercial detectors, from perfect to marginal (as in Figure 2-4), are usually observed.

Figure 2-4



Power range:
Optical power meters based on photodetectors can measure maximum power levels of a few milliwatts. Beyond this power level, the photodetector goes into saturation. For many years, such power levels were sufficient, because they corresponded well with the output power levels of commercial laser diodes. With the advent of optical amplifiers, this situation has dramatically changed (see section 3.2).

The lower end of the power range is mostly limited by the detector's shot noise, which depends on the active area and the material. When comparing detectors of the same diameter, InGaAs detectors usually have a noise performance which is ten times better than that of germanium detectors.

Power linearity:
Photodetectors are extremely linear over a wide range of power levels. Only at high power levels (above 1 mW) is saturation usually observed. However, the power meter electronics have to convert photocurrents into displayed power levels. Some non-linearities are usually introduced in this process.

Polarization dependence:
Crystalline structures in the semi-conductor material and in the photodetector's coating and mechanical stress are the usual causes of polarization dependence in optical detectors.

Compatibility with different fibers:
A wide range of optical fibers are used in fiber optic communication. There is usually little difficulty in measuring the power from a standard single-mode fiber with a small numerical aperture of 0.1. In contrast, it can be very difficult to measure the output power from a thin-core single-mode fiber with a high numerical aperture of 0.4 (used for optical amplifiers).

Figure 2-5 summarizes the performance criteria for an optical power meter.

Figure 2-5

Performance Criteria for Fiber Optic Power Meters

- individual wavelength correction,
- wide power range,
- good linearity,
- good homogeneity,
- temperature stabilization,
- low reflections (photodetector / mechanics),
- low polarization dependence,
- compatibility with different fiber types.

3. Absolute Power Measurement

Figure 3-1 shows an example in which the power from a pigtailed laser diode is measured. This is a typical production test carried out to ensure the appropriate system margin or compliance with a given laser safety class.

Figure 3-1

Power Measurement of a Pigtailed Laser Diode

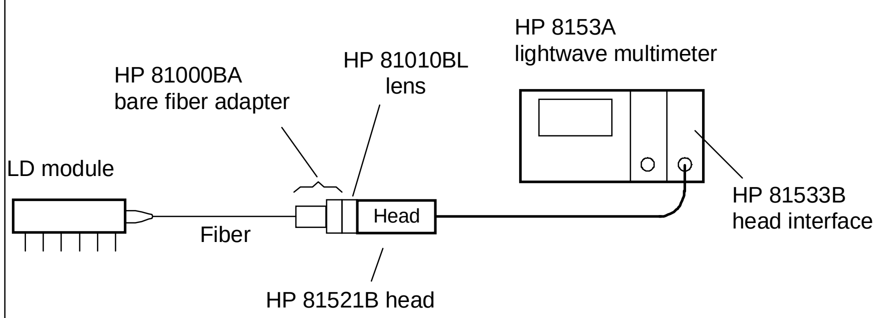


Figure 3-2 lists the important criteria for absolute power measurements.

Figure 3-2

Important Points in Absolute Power Measurement

Wavelength:
- Is the source wavelength known?
- Is the power meter regularly calibrated for this wavelength?
- Is the power meter corrected for this wavelength?

Spectral width:
- Is the detector linear within the source's spectral width (LEDs)?

Beam geometry:
- Is the beam diameter compatible with the detector size?
- Is the beam centered on the diode?
- Is the beam tilted (angled fiber end)?

Power level:
- Is the power level compatible with the meter's power range?

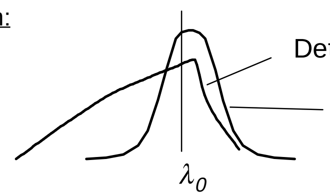
3.1 LED power measurement

LED power is sometimes difficult to measure because of the LED's wide spectral width and the fact that the photodetector is not linear within this spectral range (there is no error if the detector's responsivity is linear in the relevant wavelength range). However, a correction is possible when the detector's spectral responsivity and the LED's spectral power density are known (see Figure 3-3).

Figure 3-3

LED Power Measurement

The Problem:



Detector: $r(\lambda) = r_{rel}(\lambda)\ r(\lambda_0)$

LED: $P(\lambda) = p_0\ f(\lambda)$

The Solution:

Correct power (1): $P = p_0 \int f(\lambda)\, d\lambda$

Measurement result (2): $P_m = p_0 \int f(\lambda)\, r_{rel}(\lambda)\, d\lambda$

Correction factor (3): $k = \dfrac{P}{P_m} \quad \dfrac{\int f(\lambda)\, d\lambda}{\int f(\lambda)\, r_{rel}(\lambda)\, d\lambda}$

λ_0 is an arbitrarily chosen wavelength (preferably the LED peak wavelength) for which the power meter is corrected. r_{rel} is the responsivity relative to this wavelength, with $r_{rel}(\lambda_0) = 1$.
The procedure is as follows:

i) set the power meter to the wavelength l0 and measure the LED power,

ii) calculate the ratio of integrals, as in Figure 3-3, to obtain the correction factor,

iii) multiply the measured power with the correction factor to obtain the correct power.

3.2 High power measurement

Many of today's lasers and optical amplifiers produce power levels exceeding the power range of conventional optical power meters with photodetectors. Pump lasers used for EDFAs, for example, produce 100 mW or more. The EDFA's output powers must also be measured. With the exception of preamplifiers, designed to generate a few milliwatts at most, all optical amplifiers generate power levels exceeding the measurement range of conventional power meters. Today's EDFAs can generate power levels up to +27 dBm (500 mW). Since the output power is a key parameter, the question is: how can such large power levels be measured with high accuracy? Figure 3-4 summarizes the challenges.

Figure 3-4

Measuring High Power

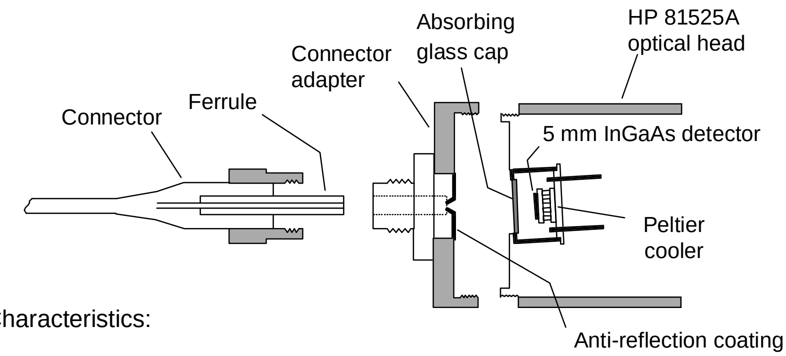
Examples: pump lasers, EDFA output power.

- How to measure optical power up to 500 mW?
  Most optical power meters measure up to a few milliwatts only.
- How to catch wider apertures?
  Dispersion-shifted fiber has numerical aperture (NA) of 0.26.
  EDFA fiber has NA of 0.4 or more.
- How to ensure correct calibration?

Figure 3-5 shows the HP 81525A optical head, which can measure up to 500 mW (+27 dBm) and is fully calibrated over the wavelength range from 900 to 1600 nm. It uses an absorbing glass window to reduce the incident optical power to a suitable level. A slight power level dependence is included in the specification because the absorption depends on the power level. In order to prevent overheating, it is recommended that you create a spot diameter of approximately 3 mm on the detector when the power level exceeds 100 mW. If the fiber is a standard single-mode fiber, the larger spot size can be generated by adding an HP 81000AF filter holder (which acts as a spacer).

Figure 3-5

1. Possibility: The HP 81525A Optical Head



Characteristics:

- power handling up to 500 mW,
- total uncertainty ±5 % at 10 mW, with de-rating of 0.007 dB/dB above 10 dBm,
- calibrated over full wavelength range,
- NA up to 0.2. With HP 81050BL lens, NA up to 0.3.

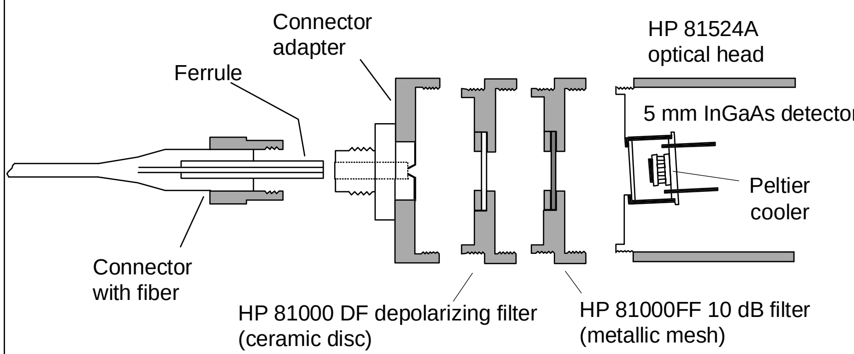
Instead of the spacer, an HP 81010BL single-mode lens can be used as an alternative. For larger numerical apertures up to 0.3, an HP 81050BL multimode lens is required. The insertion loss of the lens can be calibrated using the method outlined below.

The HP 81525A optical head is the preferred solution for measuring high power sources with well-known wavelengths and optical amplifiers in saturation. Due to the wavelength dependence of the absorber material, a wavelength error of 5 nm will produce a worst-case measurement error of 2 %.

An alternative solution for optical power measurement up to 500 mW is the combination of an HP 81000DF depolarizing filter, an HP 81000FF metallic filter with 10 dB attenuation and an HP 81524A (non-attenuated) optical head (see Figure 3-6).

Figure 3-6

Alternative Solution for High Power



Advantages: power up to 500 mW, low PDL, flat response, no thermal drift.
Disadvantages: absolute calibration depends on fiber type and wavelength. Calibration required!

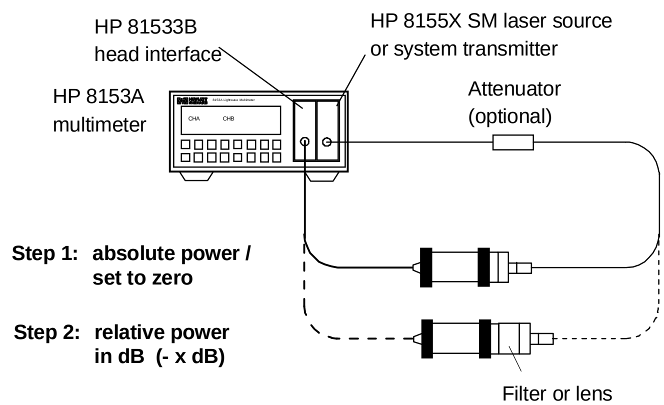
The depolarization of the ceramic disc depends somewhat on the spectral width of the source. For Fabry-Perot lasers with several emission lines, the polarization dependence of this power measurement solution is typically better than 0.003 dB p-p.

The depolarizer creates a scattered beam which is much wider than the diameter of the detector. This means that the filter solution requires fiber / connector-dependent calibration. Figure 3-7 shows that this is a simple two step procedure, which can be performed by the user for the specific fiber and wavelength used.

An optical attenuator may have to be inserted between the source and the detector to ensure stable output power.

Figure 3-7

Calibrating Filtered / Lensed Optical Heads



To prepare the filtered / lensed head for measurement,
enter CAL = -x dB into HP 8153A!

If the additional calibration step is acceptable, this solution can then be recommended for all EDFA measurements, particularly when signal and amplified spontaneous emission covering a wide spectral range are to be measured.

4. Relative Power Measurement

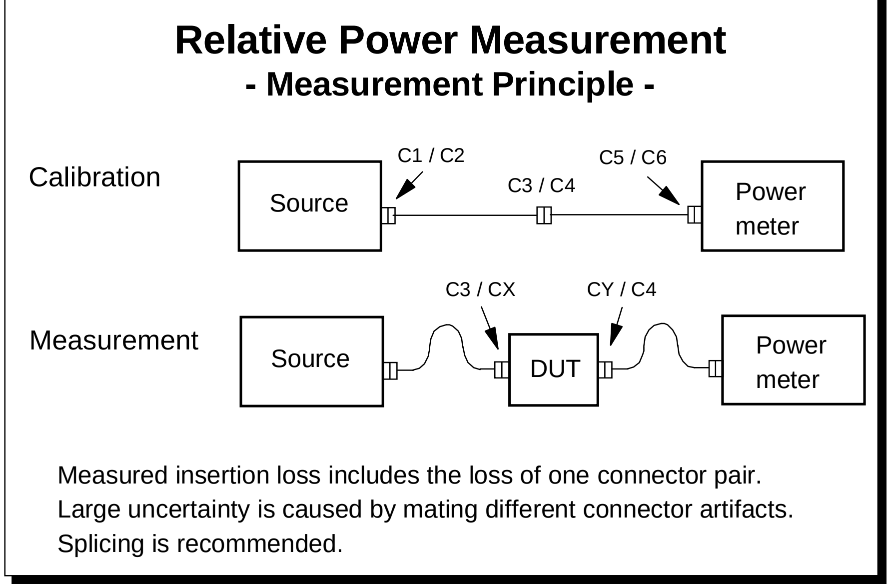
Relative power measurement includes insertion loss and gain (e.g. EDFA gain). These measurements always include two steps: in the first step, the reference power is measured, and in the second step, the test device (DUT) is inserted and the power is measured again. The two results are divided by each other, and the attenuation is displayed in dB.

The way in which the optical connectors influence this measurement is often misunderstood. In the setup of Figure 4-1, for example, the calibration is carried out by mating connectors C3 and C4. Then, the test device is inserted. Incidentally, two more changes have occurred:

i) connector pair C3 / C4 is replaced by connector pair C3 / CX.

ii) another connector pair, CY / C4 is added to the setup.

Figure 4-1



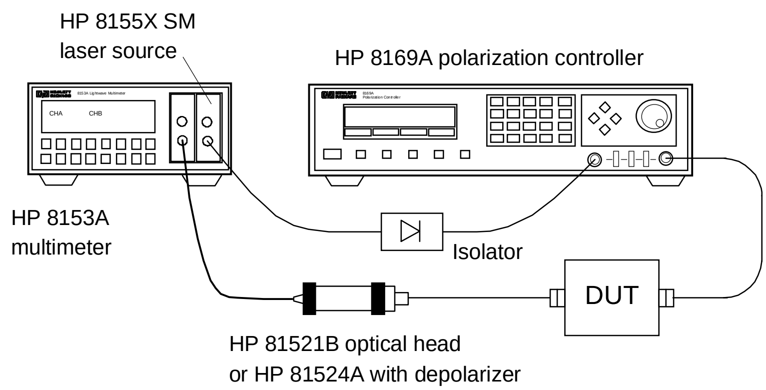
Consequently, the measured insertion loss includes the loss of one connector pair, and there is a large uncertainty because the same connector pair C3 / C4 is not used again. These problems are frequently solved by splicing.

Other sources of uncertainty are the polarization dependent loss (PDL) of the test device and the power meter's polarization-dependent responsivity. Laser sources produce almost 100 % polarized radiation. When the wave arrives at the input of the test device (DUT), the polarization state is completely unpredictable. If we assume that the power meter is perfect and that the DUT has a polarization dependence of 0.2 dB p-p, the measured insertion loss (on the basis of a single measurement value) will then have an additional uncertainty of ±0.2 dB.

There are two possible solutions for removing this uncertainty from the test result: either using a broadband, unpolarized source, such as an LED, or polarization randomizing. Figure 4-2 shows that the HP 8169A polarization controller is well-suited for polarization randomizing.

Figure 4-2

Polarization Randomizing



HP 8169A covers Poincaré sphere in 0.5 seconds.
This removes all effects from the PDL of the test device (DUT).

The best performance is achieved when the polarization controller is set to fast mode (0.5 seconds) and the power meter is set to 0.5 seconds averaging. Notice that an isolator may have to be inserted after the source in order to prevent the changing polarization state of the reflected waves from influencing the output power of the laser.

Another possible way of removing the effects of polarization dependence is by using the average of the displayed minimum and maximum values. This technique is used in the HP E5574A optical loss analyzer (mainly a PDL tester).

The situation becomes more complicated when both the DUT and the power meter exhibit polarization dependence. In this case, polarization scrambling or averaging minimum / maximum values do not perfectly cure the problem, which is a good reason to search for a power meter with known and low polarization dependence.

Altogether, the criteria for these measurements are completely different from those in absolute power measurement, as shown in Figure 4-3.

Figure 4-3

Important Points in Relative Power Measurement

Source stability:
Is the source power constant in both steps (reflection sensitivity)?
Power monitoring may be necessary.

Linearity:
Is the power meter's linearity known for the power range used?

Polarization sensitivity:
Is the DUT's polarization dependence sufficiently small?
Is the power meter's polarization dependence sufficiently small?

Connectors / splices:
Is the reproducibility known?
Is the connector type the same in both steps?
(e.g. first step with a straight, second step with an angled connector)

Irrelevant:
Wavelength setting, absolute calibration.

4.1 Testing wavelength-dependent insertion loss

Years ago, insertion loss was usually tested at a single wavelength using a Fabry-Perot laser. Today, swept-wavelength measurements are becoming increasingly important, for the reasons outlined in Figure 4-4.

Figure 4-4

Testing Wavelength Dependent Insertion Loss / Gain

- Single wavelength measurements leave room for surprises from unknown wavelength dependence.
- Swept-wavelength measurements show:

  DUT's wavelength dependence,
  DUT's usable wavelength range,
  Optical interference problems in the DUT.

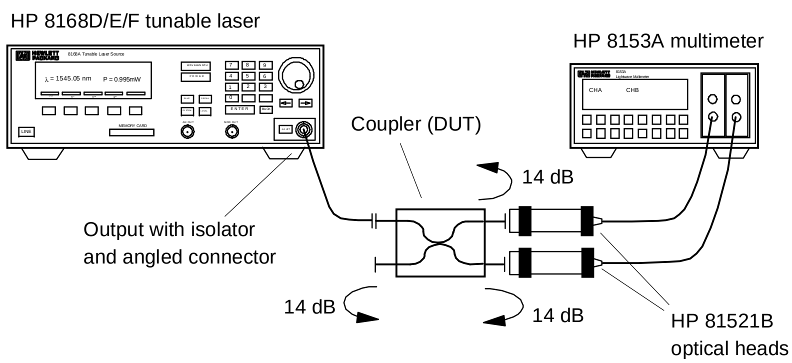
- Swept-wavelength measurement is a must for EDFA and WDM systems (filter measurements).

An important requirement for swept-wavelength measurements stems from the fact that tunable lasers usually have very narrow linewidths. If the setup has serious reflections, optical interference will occur, and the measurements will be noisy. This is why coherence control was added to HP's tunable lasers, which increases the linewidth from 100 kHz to more than 50 MHz (see Figure 4-5).

Figure 4-5

Testing Insertion Loss vs. Wavelength

Example: testing coupling ratio of optical coupler



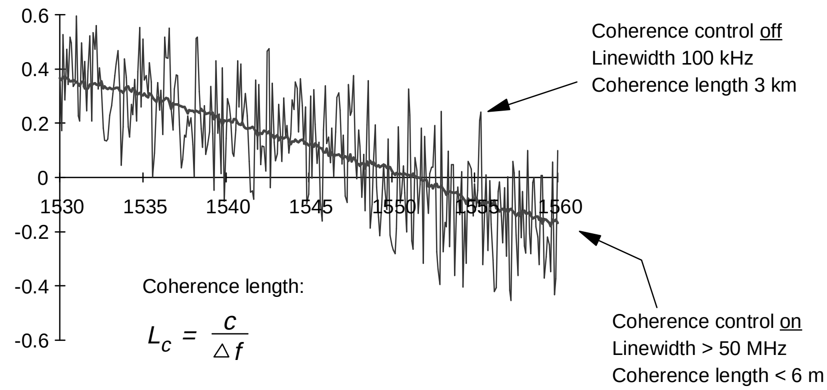
Optical interference is caused by reflections from TLS output, connectors and optical heads.
Uncertainty depends on source linewidth; narrow width means large uncertainty.

To show how well optical interference can be suppressed by coherence control, an optical coupler was measured for its wavelength-dependent coupling ratio. The setup contained three reflections of 14.6 dB (3.5 %) which were separated by two meters.

Coherence control operates most effectively when the coherence length (see formula in Figure 4-6) is less than twice the shortest spacing between the reflection points.

Figure 4-6

Coupling Ratio Test Result



Ripples are resonances in optical cavity between connectors (cavity length 2 m).
For best performance, the coherence length should be < 2 x cavity length.

Figure 4-7 summarizes the source's critical performance parameters for swept-wavelength measurements.

Figure 4-7

Critical Source Parameters for Swept-Wavelength Measurements

- **Tuning range:**
  wide range is desirable.
- **Wavelength resolution / linearity:**
  necessary for narrow WDM filters.
- **Source spontaneous emission (SSE):**
  low SSE needed for EDFA and filter measurements.
- **Source linewidth:**
  narrow linewidth may cause interference problems.
- **Absolute wavelength accuracy:**
  typical accuracy of ±0.1 nm is sufficient for most cases.
- **Power stability / repeatability:**
  re-setting the wavelength should not change the power level.

5. Optical Sources Used In Power Measurement

In component measurement, there is usually a choice between three types of sources: LEDs, Fabry-Perot lasers and tunable lasers, each of which has its own advantages and disadvantages (see Figure 5-1).

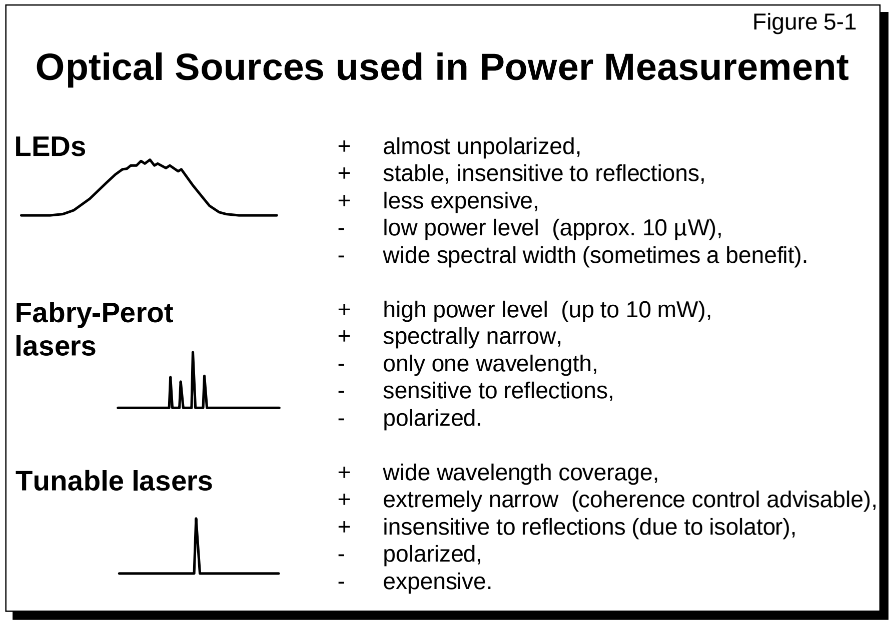


Figure 5-1

Optical Sources used in Power Measurement

LEDs generate almost unpolarized radiation with stable power levels and spectral widths of 50 nm or more. Quite often, the characteristics of fiber optic components change dramatically within a 50 nm range, which means that narrower sources are usually required.

The spectral width of Fabry-Perot lasers is approximately 1-2 nm and is therefore better suited to lightwave component testing. However, they produce polarized radiation, which usually causes some variation in the measurement result due to the polarization dependence of the test component and the power meter. This problem can be solved, however, by polarization randomizing (as previously discussed). Another potential problem is the laser's sensitivity to back-reflection; a change in the reflected power level causes a change in the output power. Often, an optical attenuator of 10 dB is necessary to isolate the source from the measurement setup. Another possibility is monitoring and correcting the power changes.

Tunable laser diodes offer wide wavelength coverage up to 100 nm. They are usually insensitive to reflections, provided that an optical isolator is included. The spectral width is typically 100 kHz, which is equivalent to 10^{-6} nm or a coherence length of 3 km. This extremely narrow linewidth requires coherence control, as discussed above.

6. Optical Power Meter Calibration

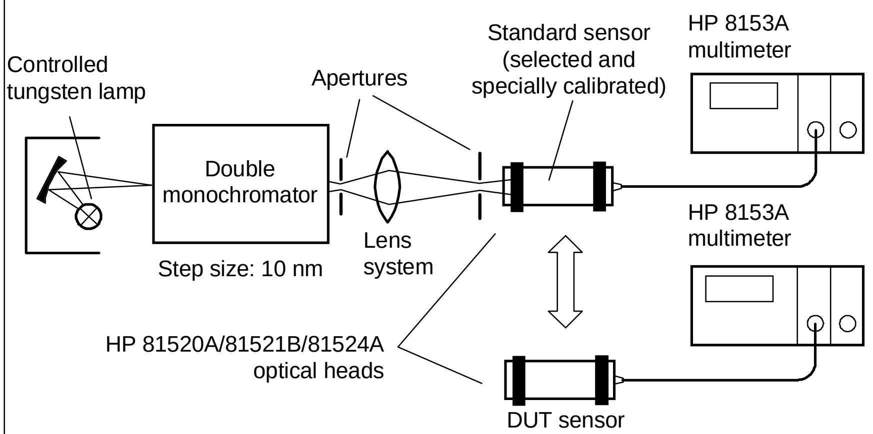
6.1 Absolute calibration

The most important question in conjunction with absolute power measurement is calibration. Generally, all power meters are calibrated through comparison; a test meter and a power measurement standard are exposed to a suitable radiation source, either sequentially or in parallel. Frequently, the source is a halogen white light source, which is spectrally filtered with a monochromator. A power level of around 10 µW and a spectral width of 5 nm are desirable. Figure 6-1 shows the calibration setup used at Hewlett-Packard's Böblingen Instruments Division.

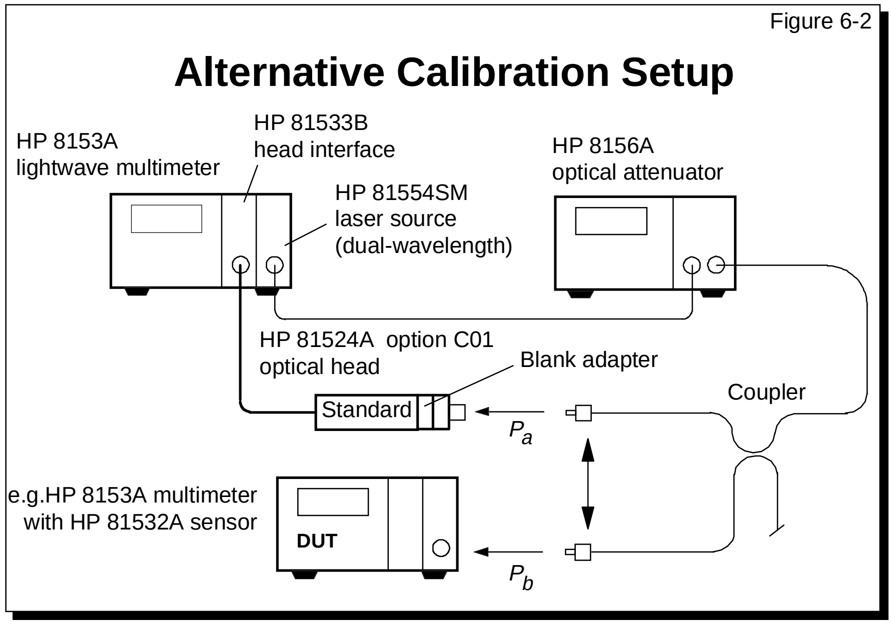
Two types of standard sensors are used: an electrically calibrated pyroelectric radiometer (ECPR), which is regularly calibrated by the German national standards laboratory (PTB), and selected, specially calibrated optical power sensors, as shown in Figure 6-1.

Figure 6-1

HP's Calibration Setup

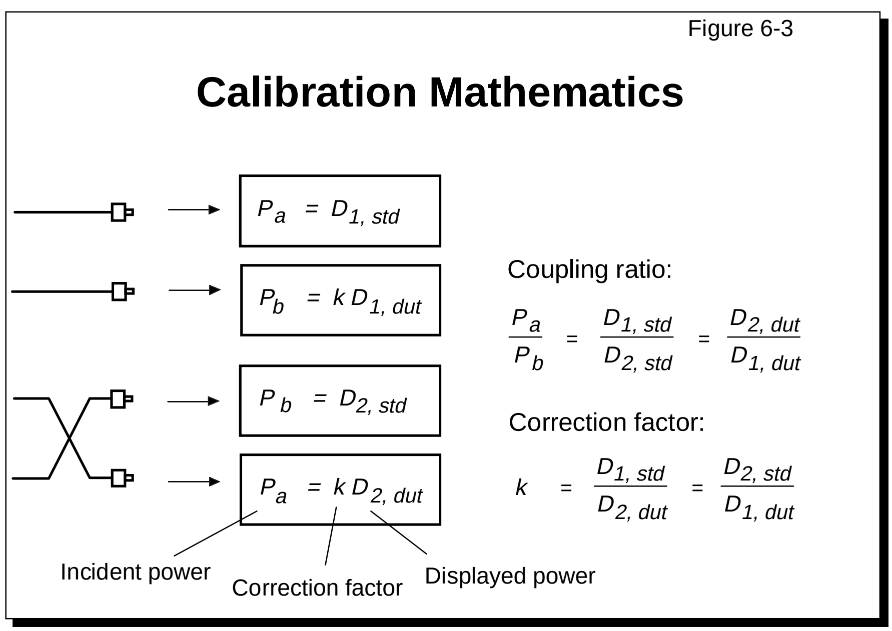


Most calibration laboratories cannot afford the equipment shown in Figure 6-1 as it is too expensive to purchase and maintain. A more feasible setup, therefore, is shown in Figure 6-2. The dual-wavelength source HP 81554SM features precisely-known wavelengths in the range of 1300 and 1550 nm (Fabry-Perot lasers with a spectral width of 3-5 nm). The attenuator is used to isolate the source and to set the appropriate power level. The coupler is used both to split the power and to provide power monitoring. A selected HP optical head is used as the standard and is specially calibrated in HP's standards laboratory (special calibration and re-calibration is available as option C01). The blank adapter serves as a means to enlarge the spot size on the detector to approximately 2.4 mm (at the 5 % points).



If dual-wavelength calibration is unsatisfactory, e.g. because absolute power measurements at other wavelengths are required, then a tunable laser source can also be used (although don't forget to enable the coherence control).

Switching the two coupler arms between the standard and the test meter (DUT) enables you to determine both the split ratio and the correction factor (see Figure 6-3). Two results can be calculated for each of these quantities. It is recommended that the average be used for the correction factor and the difference be used to estimate the uncertainty.



$P_a = D_{1,std}$

$P_b = k\,D_{1,dut}$

$P_b = D_{2,std}$

$P_a = k\,D_{2,dut}$

Coupling ratio:

$$\frac{P_a}{P_b} = \frac{D_{1,std}}{D_{2,std}} = \frac{D_{2,dut}}{D_{1,dut}}$$

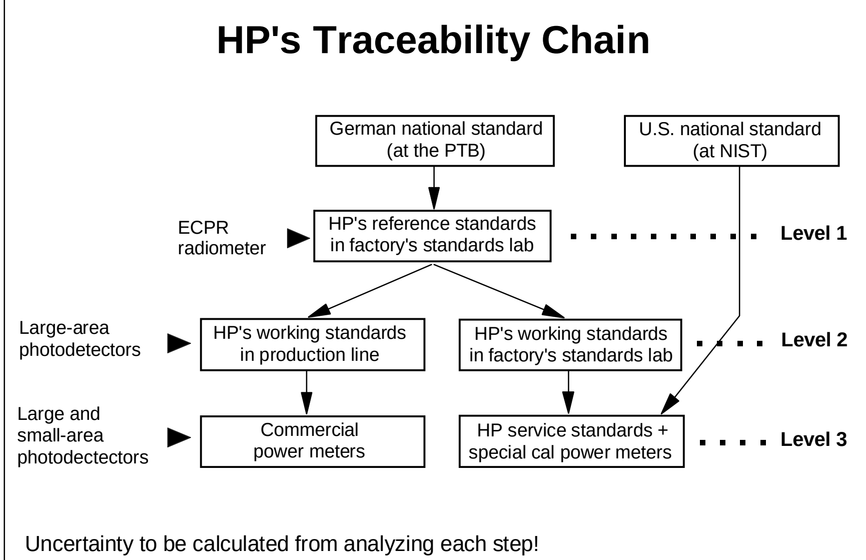
Correction factor:

$$k = \frac{D_{1,std}}{D_{2,dut}} = \frac{D_{2,std}}{D_{1,dut}}$$

The correction factor can be used either to correct the test meter or for the calibration certificate without correcting the test meter.

An unbroken chain of comparisons with the national laboratory is considered to be proof of traceability. Each of these comparisons needs to be repeated in regular intervals (see Figure 6-4). Hewlett-Packard's power meter calibrations are traceable both to the PTB and the NIST.

Figure 6-4



In the calculation of the measurement uncertainty for the test meter (the end of the chain), it is important to know the calibration conditions for each of the steps, e.g. the measurement instrumentation, the power levels, the wavelengths and the beam diameters. Only then can one calculate the uncertainties for each step, and finally, for the test meter. The subject "Calibration of optical power meters" is thoroughly discussed in [2]. The calibration accuracies achieved today are around ±1 to ±2 %. Further advice on optical power meter calibration, including a sample uncertainty calculation, can be found in [3].

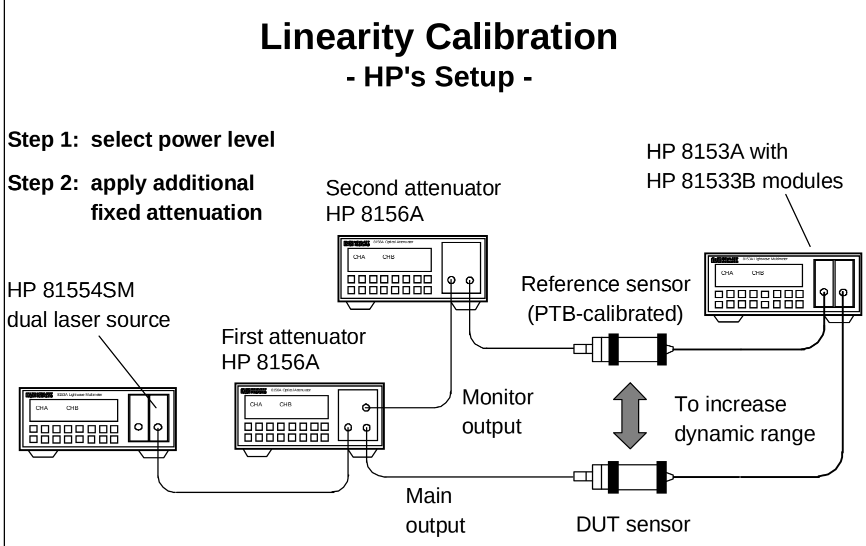
6.2 Linearity calibration

In order to extend the calibration of absolute power to the whole power range, a linearity calibration has to be performed. In this measurement, the optical power has to cover a wide range of about six or more orders of magnitude. The linearity is expected to be almost wavelength-independent, and it is therefore sufficient to select only one or two wavelength "windows" in the detector's spectral responsivity region.

Photodetectors provide excellent linearity from the noise level to approximately 1 mW, and because of this, the linearity of a power meter is usually limited by the data acquisition electronics (amplifiers, ADC, etc.). In a well-designed power meter, the electronic non-linearity is also very small. Therefore, the uncertainty which can be specified is frequently not limited by the linearity of the instrument, but by the performance of the linearity calibration setup. Two calibration methods are discussed below.

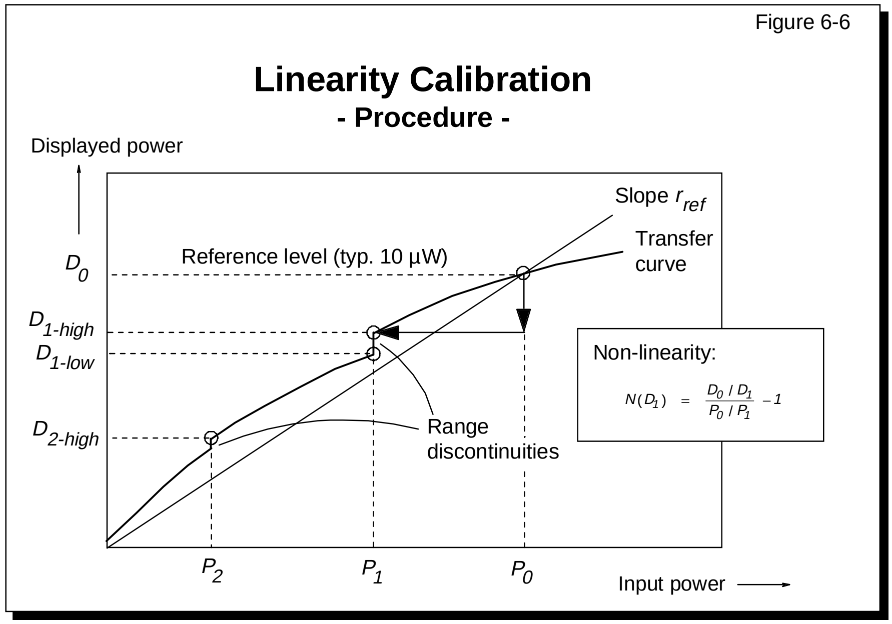
The easiest way to perform a linearity calibration is to measure an arbitrary attenuation with both the test meter (DUT) and a reference meter (e.g. a meter calibrated by a national laboratory) and to compare the two attenuation results. The setup used in Hewlett-Packard's standards laboratory is illustrated in Figure 6-5.

Figure 6-5



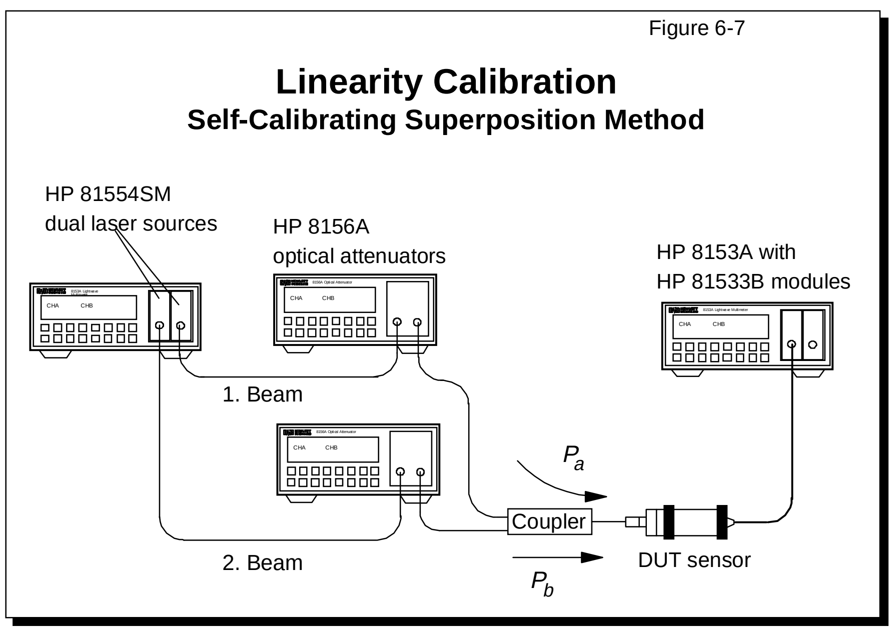
The first attenuator is used to split the power, to select the desired starting level P_0 and to generate additional fixed attenuations (e.g. 10 dB). The power levels with and without this fixed attenuation step are measured with the DUT and the reference meter in parallel. Then, the first attenuator is set in such a way that P_1 is the new starting level and the same fixed attenuation step is applied again, leading to a new power level P_2. The power ratios P_0/P_1 and P_1/P_2 can be precisely determined with the reference meter. The DUT's power readings can be used to determine the non-linearity.

The second attenuator is used to increase the measurement range; for very high power levels, it reduces the power level to the usable range for the reference sensor, whereas for very low power levels, the two sensors are switched and the second attenuator produces the low power levels.



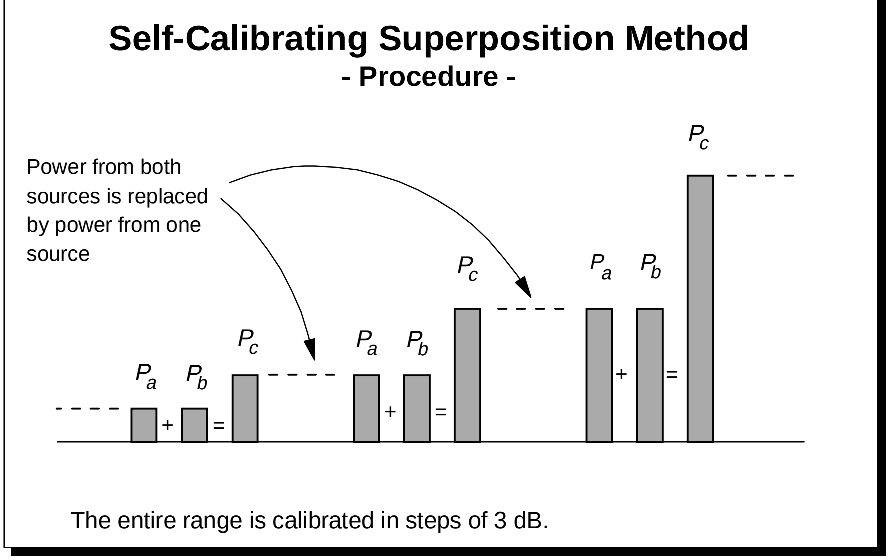
Range discontinuities are caused by switching from one range to another, and this effect is considered to be a part of the non-linearity. It can simply be obtained by measuring each power level on both sides of the range transition (see Figure 6-6).

Because of its self-calibrating feature, the setup illustrated in Figure 6-7 does not need a reference meter. The so-called superposition method is based on the linear superposition of two incoherent beams. This principle was first mentioned in [4].



In the first step, the two attenuators are set so that each beam separately generates the same reading at the DUT; the shutter of the other attenuator remains closed. Then, the two beams are combined by opening both shutters at the same time. The reading at this moment should be the sum of the two preceding, individual readings. Any deviation from this is an indication of a non-linearity. By setting the attenuators appropriately, the whole power range can be covered by making the combined power of the preceding step the single-beam power of the next step (see Figure 6-8).

Figure 6-8



State-of-the-art accuracies achieved in linearity calibration are ±0.5 % for a power range of several decades.

Summary

This is a paper on optical power meters. The range of topics includes all aspects of this instrument: construction, applications, such as absolute and relative power measurement and calibration. In most cases, the potential accuracy limitations are also discussed, with the aim of improving the accuracy of optical power measurement.

Special thanks to my colleague, Andreas Gerster, for his contribution on linearity calibration.

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[4] C.L. Sanders: A photocell linearity tester, Applied Optics, May 62, Vol. 1, No. 3, 207-211.

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