# Optical Spectrum Analyzers

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# 1. Glossary

## 1.1. Table

| | | | |
|---|---|---|---|
| h | Planck's constant | $6.6260755 \times 10^{-34}$ | $Ws^2$ |
| $\nu$ | Frequency | | Hz |
| $\lambda$ | Wavelength | | m |
| $\Delta\nu$ | Spectral bandwidth in frequencies | | |
| $\Delta\lambda$ | Spectral bandwidth in wavelengths | | |

## 1.2. Conversion and Look-up Tables

# 2. The flat-top of a spectral peak

## 2.1. Explanation

When recording a narrow spectral peak with an Optical Spectrum Analyzer (OSA), it can happen that you observe a flat-top on the peak. It is important to understand that this has nothing to do with saturation of the detector circuit, but is explained by the recording method used in the OSA. Knowing how to interpret the flat-top is crucial and can be used to your advantage.

The flat-top profile is only produced in situations where the resolution setting is lower than the width of the spectral peak. For example, in figure 1, the spectral width of a Helium Neon laser (1523nm line) is much narrower than the chosen 2nm resolution.

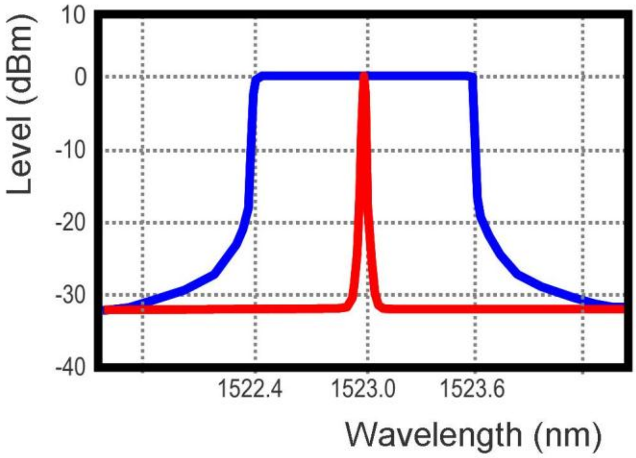



**Figure 1** – The spectrum of the 1523 nm Helium-Neon laser line, recorded with a 20pm resolution (red trace) and with a 2nm resolution (blue trace).

To explain where the flat-top comes from, we need to look at the Czerny-Turner monochromator design (Fig. 2), in which the input wavelengths are separated spatially (different angles) using a diffraction grating. Rotation of the grating will shift the spectrum of wavelengths across an exit slit, blocking all light except for a narrow portion. The power of the light that passes through the slit is recorded as a function of the grating angle (i.e. as a function of the wavelength).

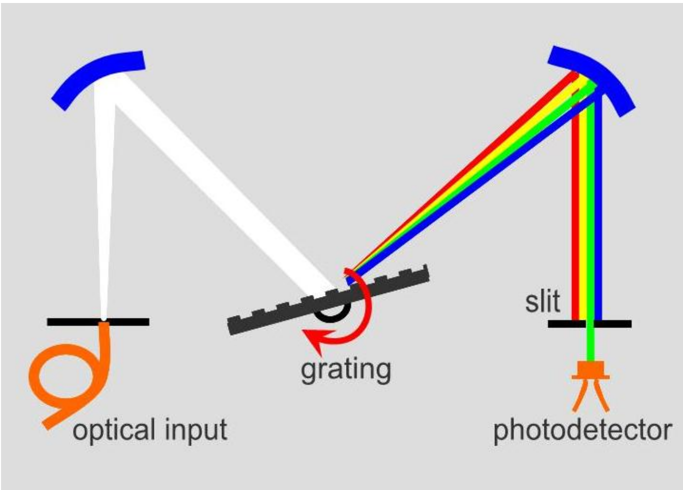
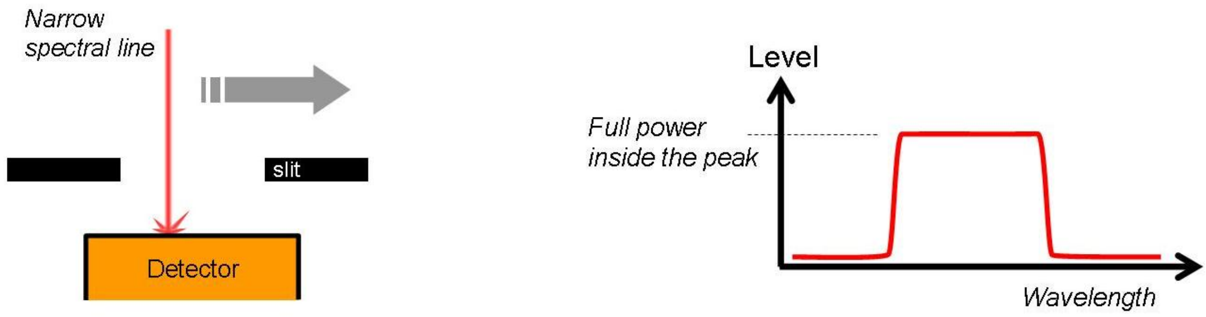



**Figure 2** –The principle of the Czerny-Turner monochromator

The slit acts as a bandpass filter, and the width of the slit is an important factor that determines the spectral resolution of the monochromator (wide slit = low spectral resolution and vice versa).
When a low resolution setting (wide slit) is used to record a narrow spectral peak, 100% of the light beam will fit through the slit for a certain range (Fig. 3.a.). The recorded OSA trace will show a broad peak (Fig. 3.b.) with a flat-top. Because 100% of the light fits through the slit, the level of the flat-top tells the total power inside the spectral peak.




3.a. 3.b.

**Figure 3 -** As a narrow peak is swept across a wide exit slit, the photodetector measures full power of the spectral peak over a range of wavelengths, hence, producing a trace with a flat-top.

## 2.2. Accurate power measurement

A flat-top is essentially a confirmation that the complete spectral peak is captured by the slit, and you are not missing power stored in the flanks of the peak. A single measurement is sufficient to measure power, keeping the measurement error to a minimum.
This is important for (example) in Signal-to-Noise Ratio measurement in optical data communication. Here, modulation of an optical signal will shift part of the power into so called "modulation sidebands". To measure the complete (broadband) signal power, the resolution must be low enough to capture the complete signal spectrum (carrier wave plus modulation sidebands). Then, a flat-top profile is a clear indication that the complete signal is captured, hence, providing an accurate value for calculation of the signal-to-noise ratio.

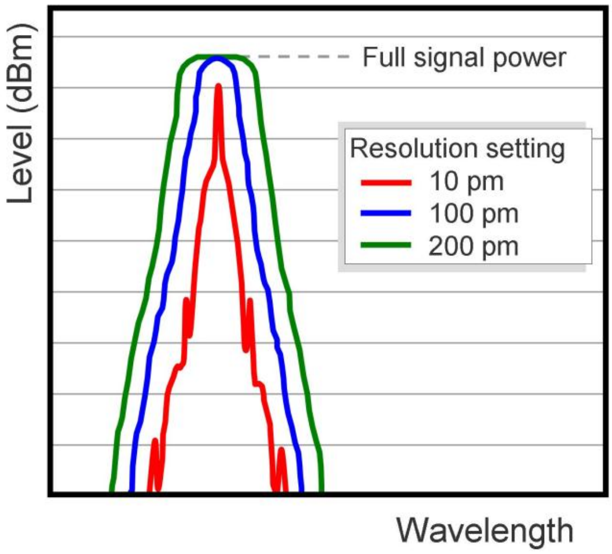



**Figure 5** – 10Gb/s signal (NRZ modulation format). The complete signal power is captured with a resolution setting of lower than 100 pm.

## 2.3. Simple Instrument Check

An OSA is an opto-mechanical instrument, meaning that measurement accuracy depends on the mechanical stability of the instrument. Specially after rough transportation or after large temperature fluctuations, a quick evaluation of a flat-top and the symmetry of the profile can prove the condition of the OSA. For this check, a narrow laser peak needs to be recorded both in highest resolution setting and in lowest resolution setting. When the OSA is in a good condition, the flat-top of the low-resolution trace should be perfectly horizontal. Secondly, the low-resolution trace should be perfectly symmetrical around the (narrow) high resolution trace.

# 3. Optical power and resolution

**Summary**
This article describes the relationship between optical power measurement and resolution in an optical spectrum analyser (OSA), and shows how understanding the operation of the OSA is crucial for correct interpretation of the measurement results.

## 3.1. Introduction

The modern optical spectrum analyser (OSA) is a powerful tool for carrying out a variety of measurements, but many users do not appreciate some of its potential applications. In this article, the relationship between power measurement and resolution will be discussed, with the aim of showing users how understanding the technical principles of the OSA will allow them to get the most out of the instrument.

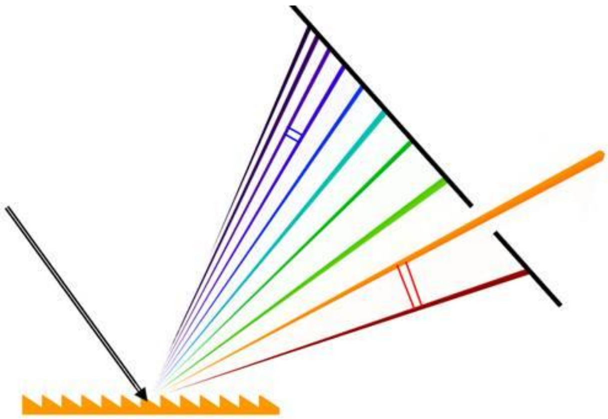


**Figure 1**. - The wavelengths that are diffracted from the grating are not evenly distributed

The particular type of OSA described in this article is based on a Czerny–Turner monochromator. In this type of monochromator, the different wavelengths of input light are spatially separated by a diffraction grating. By rotating the grating, a spectrum of wavelengths is swept across a narrow slit, allowing passage of only a narrow bandwidth of light (Fig.1).

## 3.2. Effective resolution

It is important to understand that the separation between the diffracted wavelengths is not evenly distributed. In fact, at long wavelengths, the separation between the diffracted wavelengths is larger than at short wavelengths.

In the monochromator, almost all of the diffracted wavelengths are blocked. Only a narrow portion of the light passes through the slit and reaches the surface of a photodetector. Here, the slit acts as a bandpass filter. The narrow spectrum that passes through the slit is often referred to as “resolution bandwidth”.

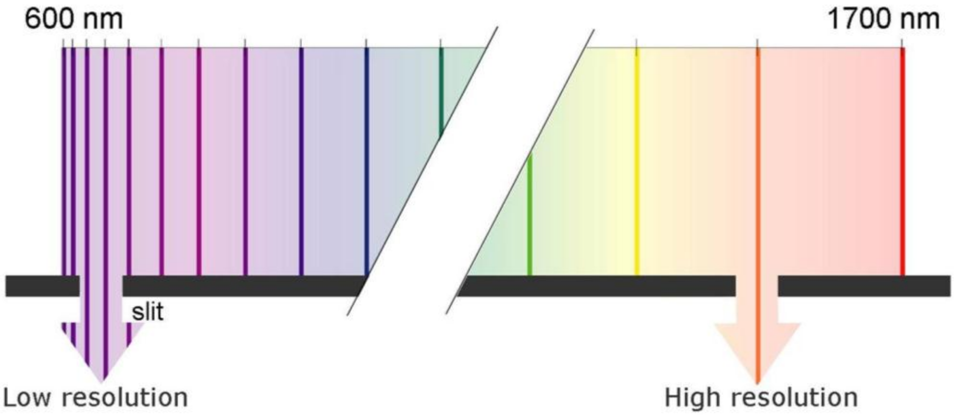



**Figure 2**. - The same slit provides a different resolution for different wavelengths

Owing to the uneven distribution of wavelengths, the bandwidth that is selected by the filter depends on the selected wavelength (Fig.2). Whereas many wavelengths fit through the slit (i.e. low resolution) at short wavelengths, the same slit allows passing of only few wavelengths (i.e. high resolution) at long wavelengths. This means that the bandwidth of this filter (effective resolution) is often quite different from the selected resolution setting on the instrument (Fig. 3). The effective resolution vs. wavelength curve is determined and stored during factory calibration of the OSA.


**Figure 3**. - Application example: at 1550 nm, the OSA has a stored value for the effective resolution of 17 pm, i.e. higher resolution than the selected 20pm

## 3.3. Absolute power display

Assume an OSA that records the output of a lamp with a perfectly flat spectral power distribution, so that within each 1 nm bandwidth the lamp offers the same amount of radiant power. One might expect that the OSA (with its power/wavelength display) will produce the same perfectly flat spectrum. However, this is not the case (Fig. 4).


**Figure 4**. - Absolute power display: the recorded spectrum of a perfectly flat spectrum is dropping towards longer wavelengths

In fact, the increasing effective resolution towards longer wavelengths causes the recorded trace to drop. At short wavelengths, the slit allows passing of more wavelengths (i.e. more power reaches the photodetector). On the other hand, at long wavelengths the same slit offers higher resolution and less power reaches the photodetector. The spectrum is shown in an absolute power display, which plots power ($P_{dBm}$) against wavelength.

Dividing the recorded power at each point by the local effective resolution again produces the flat spectrum. Now the spectrum is shown in the power density display, which plots power per nanometre ($P_{dBm/nm}$) as a function of wavelength (Fig. 5). The OSA does this automatically when the user selects dBm/nm instead of dBm for the power level scale. For the calculation, the OSA uses values for the effective resolution that are determined during factory calibration.


**Figure 5**. - Recorded OSA trace (a) is converted to the power density spectrum (b) by dividing the measured power by the local effective resolution

Because of the opto-mechanical nature of the OSA, the stored values for the effective resolution will deviate slightly from the true value. This will cause a small error in the calculation of the power density display. These errors are kept to a minimum by regular calibration of the instrument, but the absolute power display will always offer slightly better level accuracy.

## 3.4. Power density display

In contrast to the absolute power display, the power density display can immediately be read and understood. This is the display used for publication of results. There is no need to know the effective resolution at each point in the spectrum for interpretation of the power level. This means that power levels at different wavelengths can be compared in a single view, and the power inside a peak is easily calculated by integrating the trace over the desired bandwidth.

If the recorded spectrum is extremely narrowband (i.e. less than the effective resolution bandwidth), the absolute power is independent of the effective resolution. Here, the recorded peak level equals the total power inside the spectral peak.

# 4. Monochromator bandpass filtering

**Summary**
The monochromator of an optical spectrum analyser (OSA) acts as a tuneable bandpass filter, where the width of the bandpass determines the spectral resolution of the OSA. The width of the bandpass filter is user-determined by the OSA resolution setting – achieved by selecting the appropriate monochromator exit slit. For OSAs with a so-called “free space” input, the bandpass filter can also be affected by the input fibre type. Here, a narrow core input fibre provides the highest resolution performance, and a large core input fibre can be used to produce a much stronger input signal with tolerance to misalignment.

## 4.1. The tunable bandpass filter

The main property that describes the quality of an optical spectrum analyser (OSA) is its ability to produce the exact spectrum of the light offered at the input. This is more commonly described as the ability to separate two closely spaced spectral lines. For an OSA, this quality is mainly determined by the internal monochromator block.

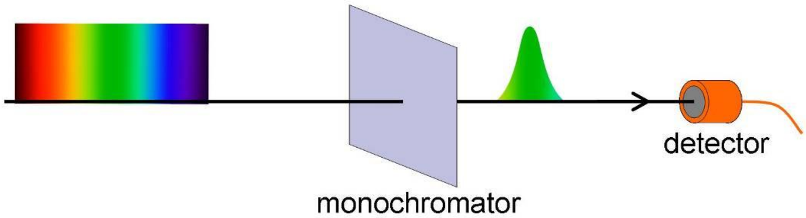



**Figure 1. -** The monochromator in an OSA acts as a tuneable bandpass filter

As implied by its name, a monochromator isolates a single wavelength out of the complete spectrum that is offered and allows it to exit. A monochromator, therefore, can be considered to be a narrow optical bandpass filter (Fig.1). For the demanding applications in which OSAs are typically used, the shape and size of the bandpass filter is very important, since it determines the limitations in the spectral resolution of the instrument.

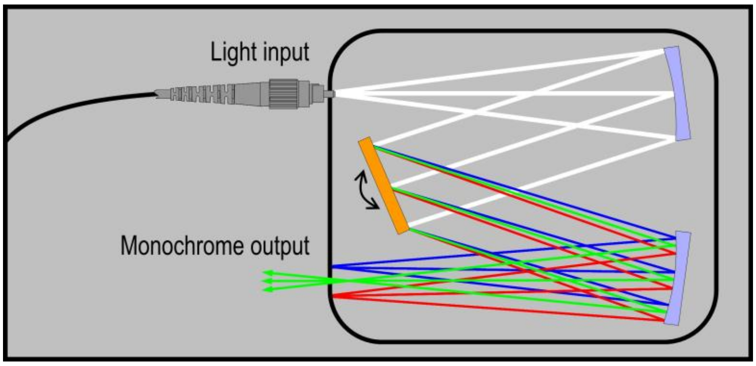



**Figure 2. -** A basic version of the Czerny-Turner monochromator

Typically, OSAs are based on the Czerny-Turner monochromator (Fig.2), in which input wavelengths are spatially separated by a diffraction grating. The majority of the diffracted wavelengths are blocked, and only a narrow portion is allowed to pass through a slit (spatial filter) and exit the monochromator. In reality, an OSA monochromator is much more sophisticated than the simplified diagram in Fig.2, with a folded beam path that passes a single grating multiple times before leaving the device.

## 4.2. The instrumental bandpass

Assume that a perfect single wavelength (i.e. pure monochrome) light is injected into the monochromator. The light that is emitted by the fibre is imaged onto the exit slit. This produces a light spot that is shifted across the slit when performing a wavelength sweep (Fig.3). In this situation, the recorded spectrum is identical to the input spectrum only when a perfect Czerny-Turner monochromator is used (Fig.4a). This perfect monochromator has the following properties:

1. Input light is infinitely small, i.e. a point source.
2. All optics are infinitely large, i.e. collecting all light with no edges and no unwanted diffraction (stray light).
3. Optics are perfectly shaped and positioned; i.e. aberrations and misalignments do not exist.
4. Blocked light is completely absorbed, i.e. no internal reflections (stray light).
5. The exit slit is infinitely narrow.

It is clear that these are requirements that cannot be met in practice.

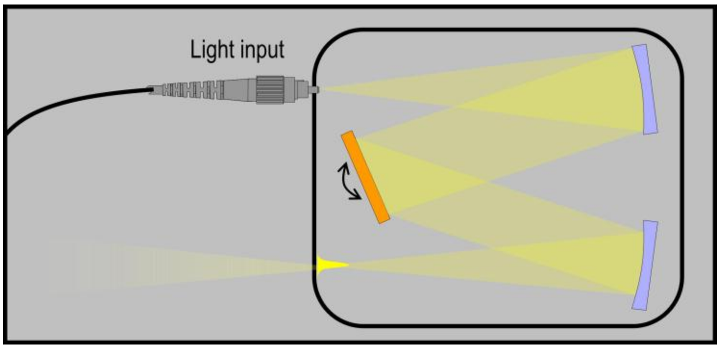



**Figure 3. -** A perfect single wavelength is injected into the monochromator. The end face of the fibre is imaged on the exit slit. Rotating the grating shifts the light spot across the exit slit

Typically, an optical fibre is used to couple light into an OSA. The size of the input light is therefore not a point source, but is given by the mode field diameter (MFD) of the input fibre. For convenience, the size of the input light is assumed to be equal to the core diameter of the input fibre, i.e. a value closely related to the mode field diameter.

The input light is imaged onto the exit slit, producing a light spot that is further broadened due to small misalignment of optics, aberrations and stray light (internal reflections and diffraction).

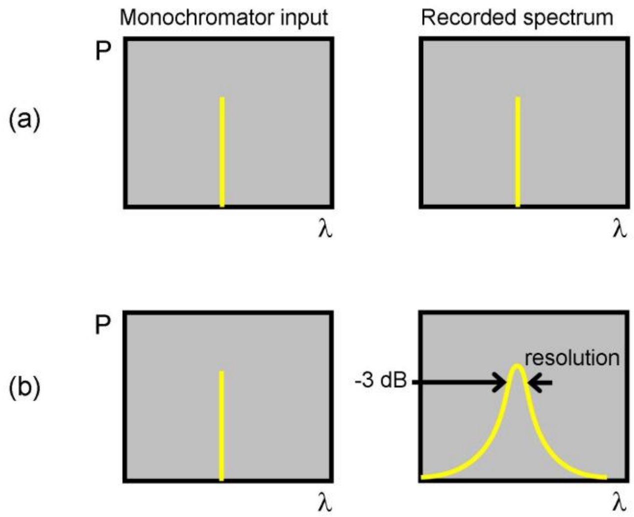



**Figure 4 -**(a) A perfect monochromator displays the exact input spectrum with infinite detail. (b) Offering the same single wavelength input, an actual monochromator shows a broadened profile – i.e. the instrumental bandpass.

Due to the size of the light spot, the OSA trace will show a peak that is much broader than the infinitely narrow input spectrum (Fig.4b). The recorded peak is known as the “instrumental bandpass”, and the FWHM (full-width/half-maximum) of the bandpass is defined as the spectral resolution of the instrument.

## 4.3. Spectral blurring

The limitations of the optical setup cause a “blurring” of the recorded spectrum, potentially obscuring detailed information; for example, two closely spaced spectral lines may appear as a single line (Fig.5a).

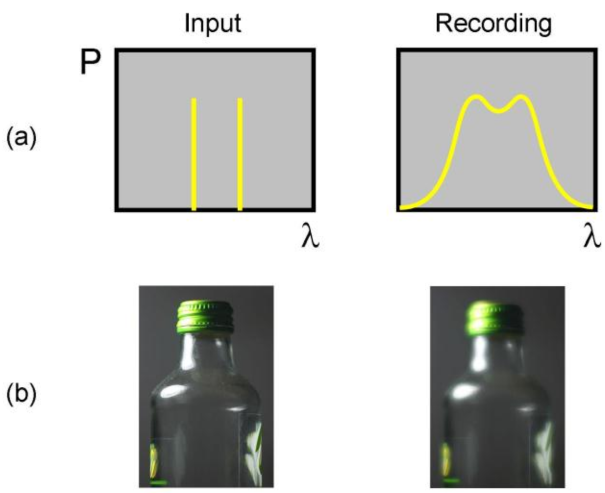



**Figure 5. -** **(a)** Spectral information is lost due to spectral blurring. **(b) The** effect that can be compared to the blurring effect of an out-of-focus camera

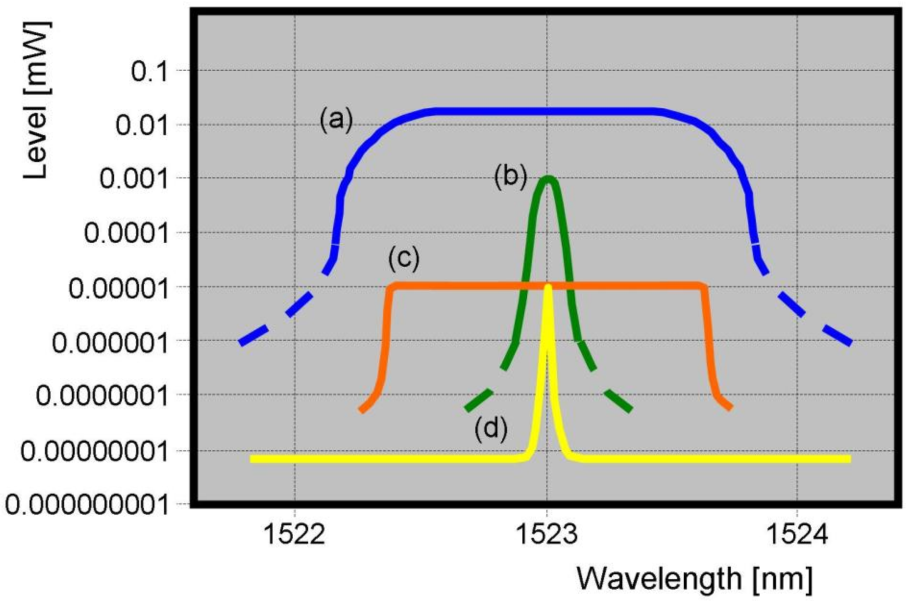
Any input spectrum can be considered to be a sum of many perfect single wavelengths, each travelling through the monochromator and producing its own line profile. The recorded spectrum is therefore the result of the convolution of the input spectrum and the instrumental bandpass filter. The result is a blurred version of the input spectrum that can be compared to photography using an out-of-focus camera (Fig.5b).

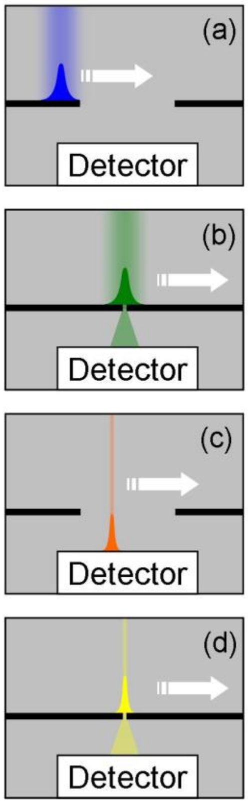
## 4.4. Controlling the filter shape

The resolution setting on an OSA refers to a specific width of the exit slit. For the majority of the commercially available OSAs, the selection of the exit slit is the only influence a user has on the shape of the bandpass filter.

In these OSAs, an internal fibre is used to guide the light from the input fibre to the monochromator block, so that the size of the input light is pre-determined and fixed. Only OSAs with a so called “free space input” offer an extra influence on the shape of the bandpass filter. Here, the light that exits the input fibre immediately enters the monochromator – i.e. the size of the input light is user-selectable.

The advantages and disadvantages of the different bandpass filters are illustrated by a simple experiment in which the spectrum is recorded of the extremely narrow 1523nm line of a Helium-Neon laser. The laser light is collected without making use of focusing optics (fibre launcher) for maximising the amount of light coupled into the fibre. By using different fibre sizes and different resolution settings, the different filter shapes are clearly visible (Fig. 6).




| Trace | Fibre core diam. | Resolution setting | Effective resolution |
|---|---|---|---|
| (a) | 800 µm | 2.00 nm | 1.26 nm |
| (b) | 800 µm | 0.020 nm | 0.085 nm |
| (c) | 9 µm | 2.00 nm | 1.26 nm |
| (d) | 9 µm | 0.020 nm | 0.017 nm |

**Figure 6. -** Experimentally determined bandpass filter of the model AQ6370 at 1523nm using different input fibres and resolution settings

## 4.5. Narrow-core input fibre

The highest resolution performance is obtained by using the most narrow core input fibre available, in combination with the highest resolution setting of the instrument (Fig.6d). At 1523nm the measured resolution is 17pm. Notice that the effective resolution is higher than the resolution setting.

When using a narrow core input fibre, the bandpass filter curve is guaranteed by the “Close-in Dynamic Range” specification, also referred to as Optical Rejection Ratio. Here, the bandpass filter suppression (i.e. rejection) is specified at specific intervals from the selected wavelength.

When a flat top is observed on a spectral peak, it can be concluded that all the power inside the peak is captured by the internal photodetector; i.e. the complete light spot fits through the monochromator exit slit.

## 4.6. Large-core input fibre

With a large surface area (i.e. effective area) of the input fibre, collection of light from a source is very efficient. Typically, this produces a much stronger signal than can be offered by a narrow core input fibre. In Fig.6, the signal in trace (a) is much stronger than that in trace (c).

Note that the freedom to choose the monochromator input fibre is only provided by an OSA with a free space optical input such as the Yokogawa AQ6370C.

The loss of resolution caused by using a large core fibre may be acceptable. From Fig.6b and 6d, it follows that going from a 9 µm to an 800 µm core fibre results in the effective resolution dropping from 17 to 85 pm.

Another thing to consider is that a large-core fibre is tolerant to misalignment. Using a narrow core fibre, the amount of injected light often needs to be maximised using focusing optics and a sophisticated alignment stage. A large core fibre, however, can often be used without such an alignment critical fibre launcher.

# 5. Measurement on pulsed light

It is not uncommon for an Optical Spectrum Analyzer (OSA) to be used in combination with a pulsed laser (e.g. in laser development).
Here, the OSA produces the spectrum of the pulsed input signal, by sampling the optical power during a continuous wavelength sweep. For the sweep, it is assumed that the optical input signal is constant and present at all times, i.e. an assumption that is not valid when analyzing a pulsed input signal.
The absence of light in-between pulses can have a disturbing effect on the measurement, e.g. producing a comb-like on/off structure on the spectrum (Fig.1). This is effect is easily resolved by selecting instrument settings that are appropriate for the pulse repetition frequency of the input signal.

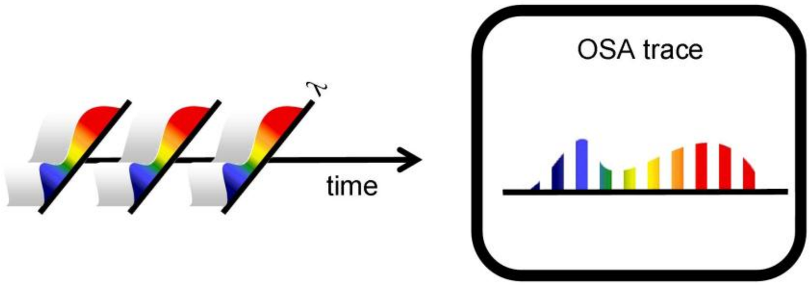



**Figure 1** – Due to the scanning wavelength nature of the OSA, a distinct on/off distortion of the spectrum can be observed when recording a pulsed input signal.

## 5.1. Testing of Pulsed Lasers

A very common OSA application is the analysis of laser output, often in the development phase of a new laser product, or in production of lasers (quality control).
Lasers are designed and optimized for specific applications, many of which require a very high-power laser beam. To produce a high-power laser beam, typically, laser power is stored for some time, after which it is released in a short pulse. By repeating this process, the laser produces high-power pulses with a certain pulse repetition frequency.
From the point of view of an Optical Spectrum Analyzer, we can separate three groups of pulsed lasers, i.e. lasers with low, high and ultra-high pulse repetition frequencies.

### 5.1.1. Ultra-high Pulse Repetition Frequencies (MHz)

For extremely high pulse repetition frequencies (MHz domain), the photo-detection circuit inside the OSA will be too slow to react to the extremely fast changes of the input signal. Independent of instrument settings, the OSA will produce a spectrum as if the light source was continuous wave, i.e. not pulsed.

### 5.1.2. High Pulse Repetition Frequencies (kHz)

When testing of lasers with pulse repetition frequencies in the kHz range, it is possible that the effect of the laser pulses is noticeable on an OSA trace.
The solution is to make sure that the OSA spends sufficient time on each measurement (sample) during the wavelength sweep, ideally capturing many light pulses per sample. This is done by selecting a sufficiently high sensitivity setting on the instrument.

Each sensitivity setting of an OSA corresponds to a specific amplifier circuit, used for amplification of the photo-detector signal (Fig. 2). And each amplifier circuit offers a specific signal gain and response time.
A high sensitivity setting corresponds to a high-gain circuit with relatively slow response (and vice versa). Due to the slow response, the OSA needs to spend more time for each sample measurement, hence, capturing more laser pulses.

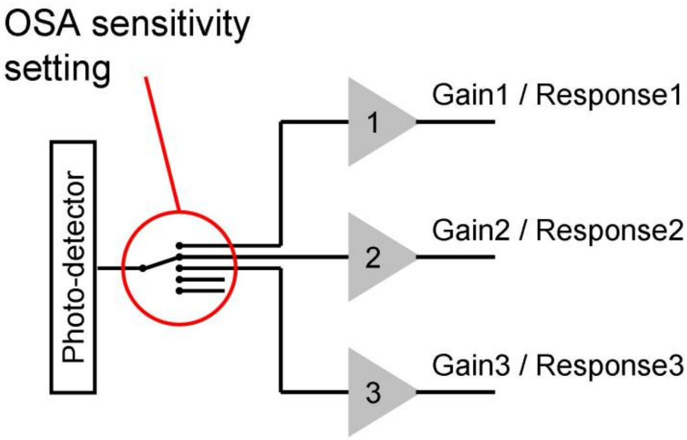
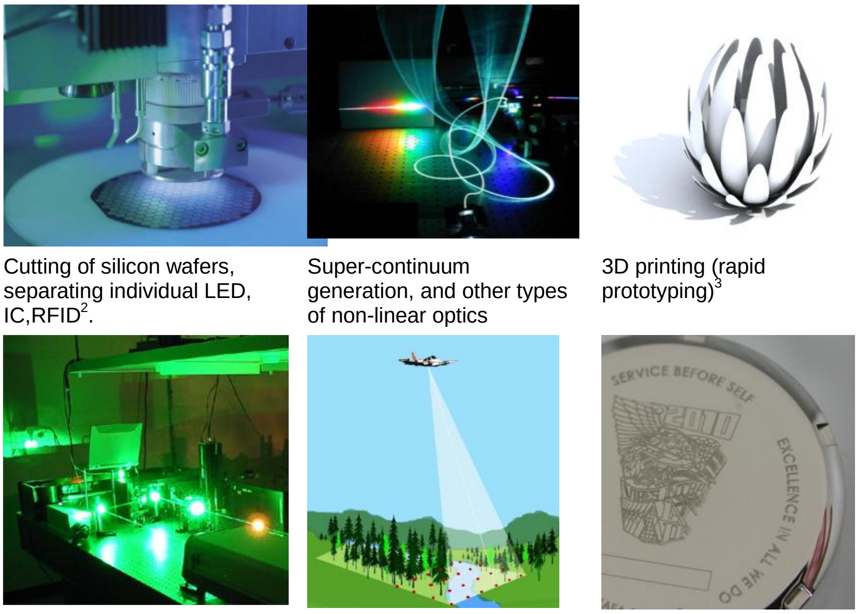



**Figure 2** – Each sensitivity setting on the OSA corresponds to a specific signal amplifier circuit, each offering a specific gain and time-response.

Many types of lasers exist with a pulse repetition frequency in the kHz range, of which the Q-switched DPSS[1] laser is the most common type, offering a pulse repetition frequency in the 1 – 250 kHz range.In Figure 3. just a few examples are given for applications of this class of lasers.




Cutting of silicon wafers, separating individual LED, IC,RFID[2].

Super-continuum generation, and other types of non-linear optics

3D printing (rapid prototyping)[3]

Laser pumping

Distance measurement (LIDAR)

Laser marking[4] of text, logo's, serial numbers, etc.

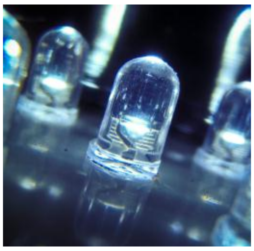
**Figure 3** – Different applications of kHz pulsed lasers

[1] DPSS laser stands for diode pumped solid state laser, using a crystal (e.g. Nd:YAG) for the laser gain medium.
[2] Image courtesy of Synova SA, Switzerland (www.synova.ch)
[3] Using a technique called selective laser sintering (SLS) or stereo-lithography
[4] Image courtesy of Laser Impressions Inc, USA (www.laserimpressions.com)

### 5.1.3. Low Pulse Repetition Frequencies (Hz)

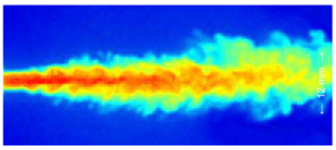
For low pulse repetition frequencies, even the highest sensitivity setting may not be able to remove the distortion of the recorded spectrum. The repetition frequency is simply too low and a different method should be used to eliminate the distortion from the spectrum.
Lasers that fall in the low-repetition frequency category are pumped by flash lamps or gas discharge (i.e. pulsed pumped), e.g. Nd:YAG lasers, excimer lasers, Nitrogen laser. Other light sources can also be considered to fall into this category, i.e. pulsed driven LEDs, gas discharge lamps, or the chopped output of a continuous source. Figure 4 shows a few examples of applications of light sources with low pulse repetition frequencies.

Pulsed high-power lasers are used in environmental monitoring

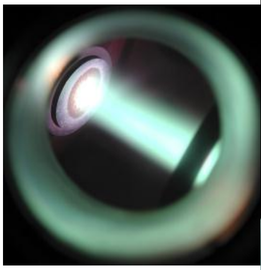


LEDs in pulsed operation to achieve a higher brightness

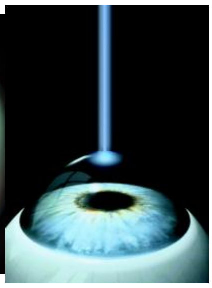
Xenon flash lamps are used for hair and pigment removal



Combustion study, using Laser Induced Fluorescence (LIF) for mapping concentration, velocity, etc.



Laser chemistry using cavity ringdown spectroscopy[5]



For laser assisted eye surgery (LASIK), typically a pulsed excimer laser is used

**Figure 4** – Example applications of sub-kHz pulsed light sources.

<u>Measurement with trigger input</u>

If the pulsed laser provides a trigger signal, it is advised to make use of it by feeding it to the OSA trigger input. After selecting trigger-mode on the OSA, each sample measurement will be derived from a single pulse. A faster pulse repetition frequency will produce a faster sweep speed of the OSA.

Because each sample is derived from a single light pulse, it is important to avoid a high-sensitivity setting. The slow response of the detector circuit cannot react quickly enough to the sudden light pulse (Fig. 5.b.). The fast response-time of a low-sensitivity setting will produce a much stronger integrated detector signal (Fig. 5.c.), i.e. better signal-to-noise ratio of the OSA trace.

[5] Ref. M.D. Wheeler et al. J. Chem. Soc. Faraday Trans. 94, 337 (1998)

**Figure 5.a.**
Assuming a laser producing square shaped pulses.

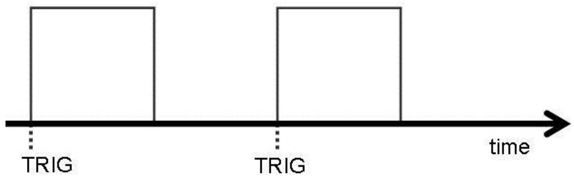



**Figure 5.b.**
The time-integrated detector signal is weak due to the slow time-response of the OSA in a high-sensitivity setting.

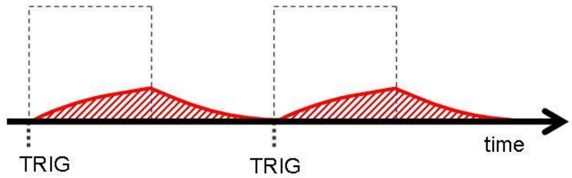
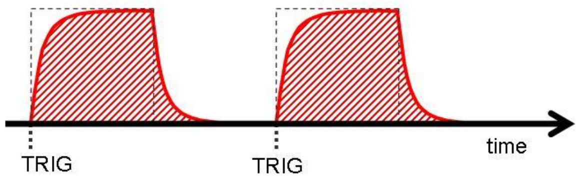



**Figure 5.c.**
The fast response of a low-sensitivity setting produces a substantial signal, i.e. a better signal-to-noise ratio.




<u>Measurement without trigger input</u>
If the light source does not provide a trigger output signal, the "Peak Hold" function of the OSA will offer a solution.
Using the Peak Hold function, the OSA records the signal at each sample point for a period of time (Fig. 6). The maximum signal value that is detected during the time interval is taken as the measurement value for each sample, i.e. not the average value during the interval.

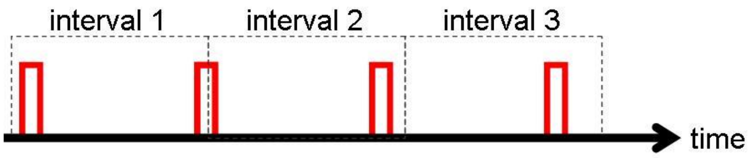
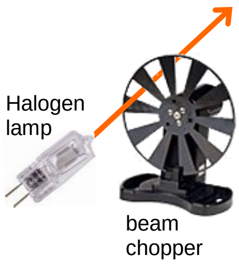


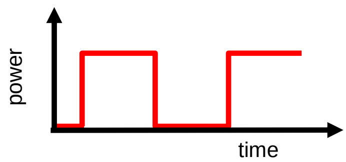

**Figure 6** – For each sample, the detector signal is recorded over a certain time interval. The maximum signal value obtained over each time interval is taken as the correct measurement value for each sample.

The time interval is user selectable (0 – 9999 msec), so that it can handle pulse frequencies of 0.1 Hz and higher. The time interval should be set to a larger value than the time between two pulses (i.e. 1 / rep. frequency), so that at least one pulse is captured during each time interval.
For an optimal setting, the pulse repetition frequency should be known, so that a time interval can be chosen close to the period between pulses, i.e. optimizing the OSA for measurement speed.

## 5.2. Measurement Example

The above is illustrated with a simple experiment, in which the flat spectrum of a 270Hz chopped (50% duty-cycle) Halogen source is recorded using an AQ6370C optical spectrum analyzer.



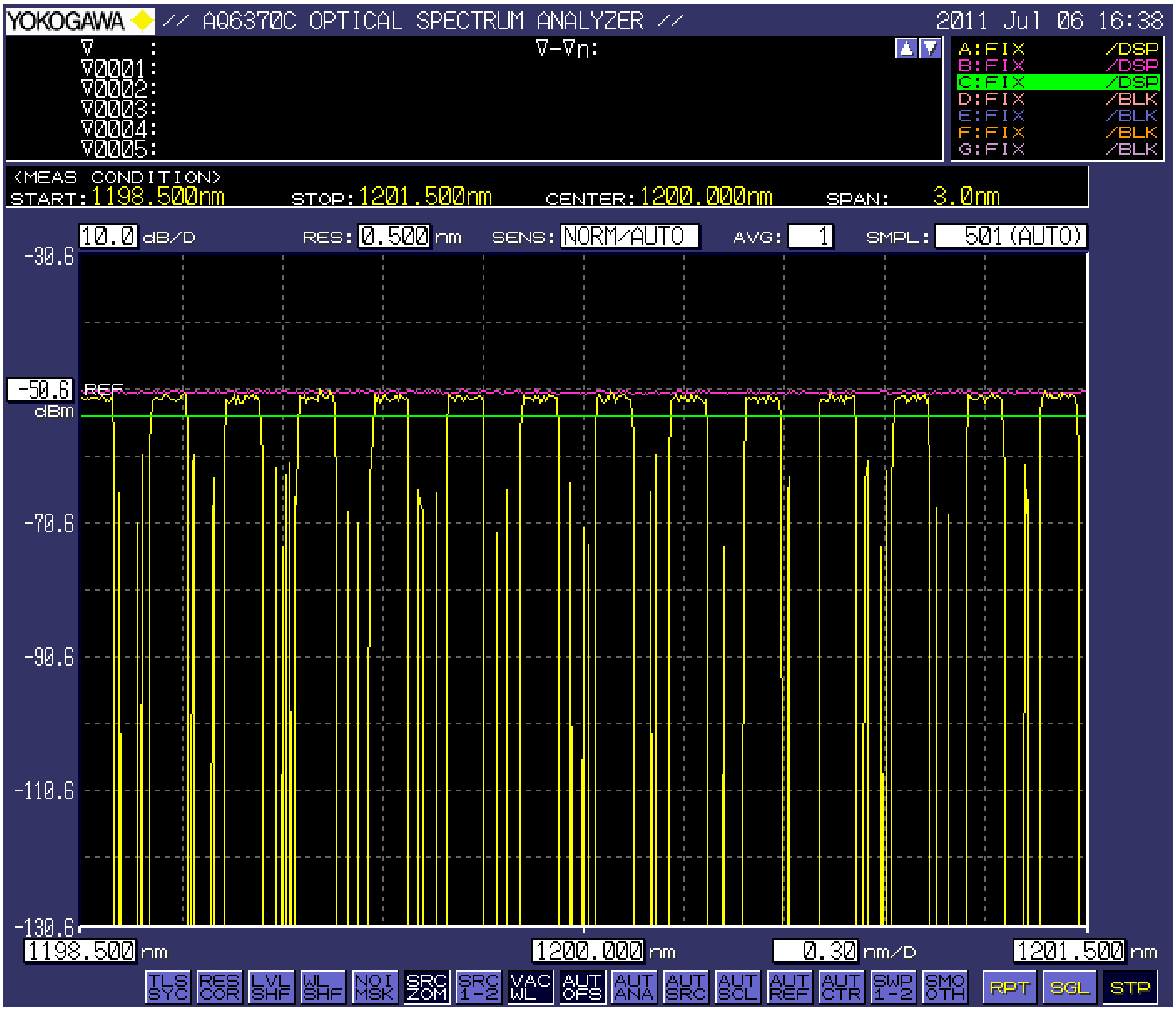




**Figure 6 –** The recorded spectrum of a 270 Hz Halogen lamp using (yellow trace) a low sensitivity setting, (green trace) a high sensitivity setting, (purple trace) a low-sensitivity setting combined with the peak hold function.

The recorded on/off pattern (yellow trace) is easily removed by changing instrument settings. A higher sensitivity setting produces the green trace (average optical power), while the peak-hold function produced the purple trace.

# 6. Optical amplifier analysis

Despite the fact that optical fibers have an extremely low attenuation, often signals need to be amplified along the way. Specially, in long distance communication typically multiple amplifier stages are required.
To produce the best signal-to-noise ratio at the end of the line, each of the amplifiers should contribute a minimal amount of noise. Therefore, it is crucial that amplifiers are tested for their properties during the product development phase, in manufacturing quality control, and before deployment in the field.

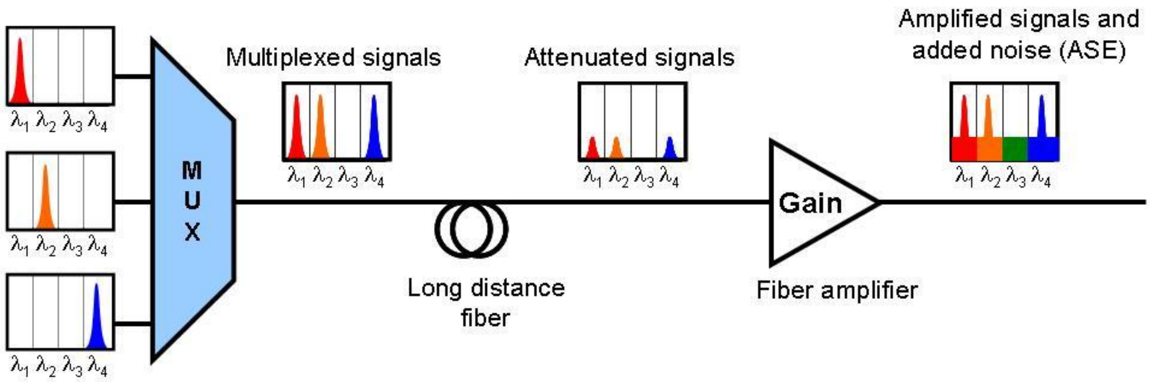



**Figure 1** – The multiplexed optical signals are weak after long distance travelling. The optical amplifier increases the signal strength but also contributes a significant amount of noise, decreasing the signal-to-noise ratio.

To analyze the noise and gain properties of fiber amplifiers, an optical spectrum analyzer (OSA) can be used. For convenience, a modern OSA like the Yokogawa AQ6370C has an automated function for amplifier analysis, in which calculations are made in the background, and a table with relevant values is displayed and can be exported.
To achieve a thorough understanding amplifier analysis, this application note describes the method step by step, down to the individual calculations in which the relevant values are obtained. Understanding the method allows users to correctly compare and explain differences in obtained values. The described method can be found in more detail in the related IEC standards given in table 1.

| IEC Ref. | Optical Amplifier Test Methods |
|---|---|
| 61290-1-1 | Power and gain parameters - Optical spectrum analyzer method |
| 61290-2-1 | Test methods for optical power parameters - Optical spectrum analyzer |
| 61290-3-1 | Test methods for noise figure parameters - Optical spectrum analyzer test method |
| 61290-5-1 | Reflectance parameters – Optical spectrum analyzer method |

**Table 1** – IEC standards for optical amplifier test methods, using an optical spectrum analyzer.

## 6.1. Fiber Amplifiers

In this application note the so called Erbium Doped Fiber Amplifier (EDFA) is taken as an example. Know however that other types of amplifiers exist, but that the same analysis method is valid, i.e. reasoning used in this application note remains the same.

The EDFA is a commonly applied amplifier due to its convenient optical properties and manufacturing properties. Signal gain is provided by a silica fiber with an Erbium ($Er^{+3}$) ion doped core. The Erbium atoms are excited with 980nm or 1480nm pump radiation (Fig. 2), producing energy storage inside the fiber core. In turn, photons from the communication signal stimulate the Erbium dopants to release their excess energy by emitting a photon[6] of the same energy (i.e. wavelength) and direction. The creation of these extra signal photons produces the amplification of the data signal

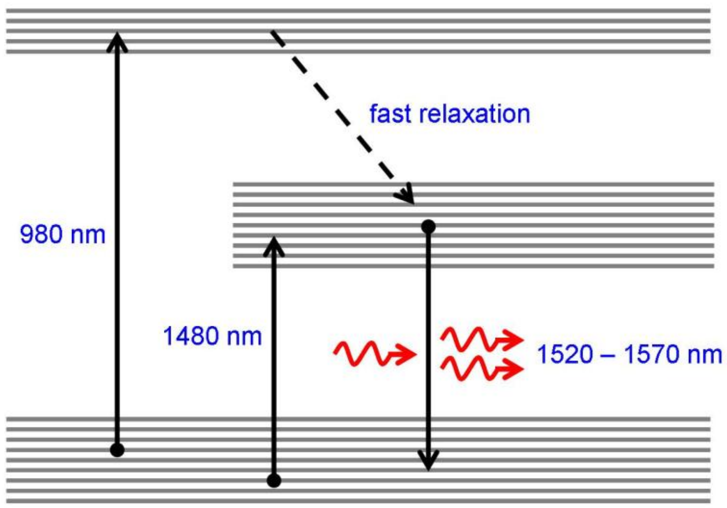



**Figure 2** – Energy level diagram of an Erbium doped fiber amplifier

### 6.1.1. Noise Production

Besides the desired signal amplification, amplifiers also generate a significant amount of noise. The reason is that the excited Erbium atoms can release their excess energy spontaneously by producing photons of random wavelengths and random propagation direction.
Many spontaneous photons will be lost in the fiber cladding. Some however travel along with the optical signal[7], undergoing the same process of amplification. Because this Amplified Spontaneous Emission (ASE) obscures the data signal it is noise, and it is therefore an important parameter to control.

### 6.1.2. Amplifier Performance Indicators

To be able to judge the performance of an amplifier, specific parameters are calculated form measurement values. The most straightforward parameter is the amplifier gain, which follows from the ratio between input and output signal levels.
Also, it is important to evaluate the degradation of the signal-to-noise ratio caused by the amplifier. This is expressed by a value called the Noise Figure (NF). And often it is also appreciated to know the absolute amount of noise that is contributed by the amplifier, i.e. the ASE level.
Because gain and noise properties of the amplifier vary with wavelength, these parameters need to be analyzed at all relevant wavelengths, i.e. all communication channels for which the amplifier is designed, and not just at one wavelength.

[6] This mechanism of (pumping, population inversion, stimulated emission) is in fact the same mechanism as takes place inside the gain medium of a laser. The acronym LASER stands for Light Amplification by Stimulated Emission of Radiation.

[7] Note that a similar amount of noise photons will travel in the opposite direction of the signal, hence, back towards the signal source.

## 6.2. Measurement

### 6.2.1. Experimental Setup

A typical measurement setup for amplifier testing is shown in figure 3(a). It consists of a set of multiplexed DFB lasers[8], an attenuator for tuning the DFB laser power level, an optical spectrum analyzer and of course the optical fiber amplifier. The set of DFB lasers and the attenuator are typically provided by a so called Multi Application Test System (MATS[9]), which is a modular instrument that allows configuration for each specific experiment.

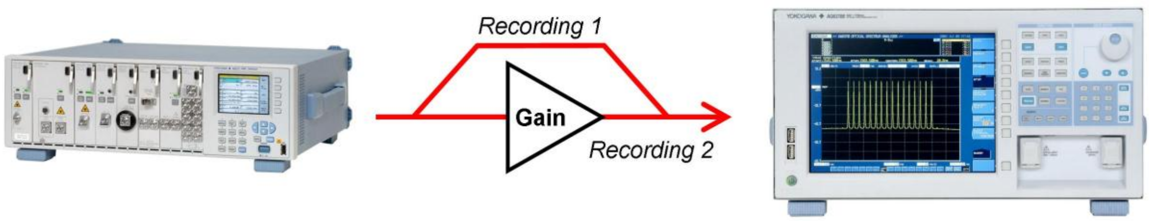



**Figure 3 –** The typical experimental setup for optical amplifier testing.

The OSA takes two high-resolution recordings of the wavelength range that is covered by the DFB lasers. One trace is taken before amplification and one after amplification. The obtained result will be close to the results shown in figure 4.
Immediately, it will be noticed that the recorded peaks after amplification will be higher than before amplification. The same holds for the noise levels.

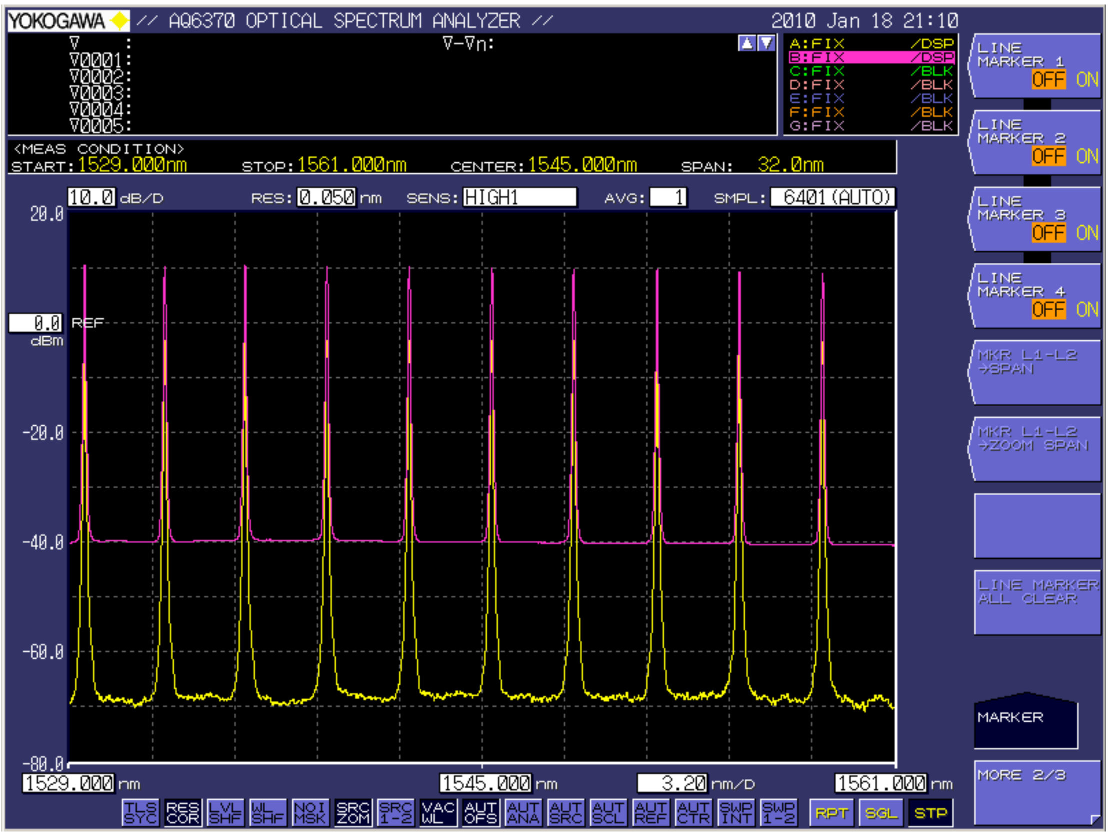



**Figure 4 –** Typical obtained measurement result showing two traces; one before amplification (yellow) and one after amplification (purple).

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[8] DFB lasers are very commonly used in fiber-optic communication, where DFB stands for Distributed Feedback, which referrers to a specific class of diode lasers with an extremely narrow spectrum output.
[9] See the Yokogawa AQ2200-Series

### 6.2.2. Determining Signal and Noise levels

All the required information for calculating the relevant parameters (NF, ASE, Gain) is extracted from the signal and noise levels recorded in the two OSA traces.

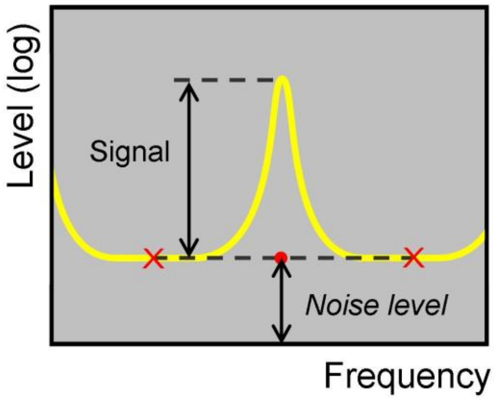



**Figure 5** – The noise level at the center-wavelength of the laser peak cannot be measured. It is, therefore, generally adopted to interpolate between noise levels left and right of the spectral peak.

The peak levels follow straightforward from the measurement. The local noise level is however obscured by the peak and cannot be measured. Hereto, it is generally adopted to interpolate between the noise levels left and right of the peak (Fig. 5). The signal power follows from subtracting the noise level from the peak level.

It is important to understand that the true DFB laser peaks are much narrower than is displayed in the recorded trace. An OSA is not able to record the extremely steep flanks of the (line) profile of the laser peak due to the blurring-effect[10] of the monochromator. The result is that the area immediately next to each laser wavelength is affected by the laser peak, and cannot be used for noise measurement.
For good measurement accuracy, it is important to place the interpolation noise points in a wavelength area that is not affected by neighboring peaks (Fig. 6).

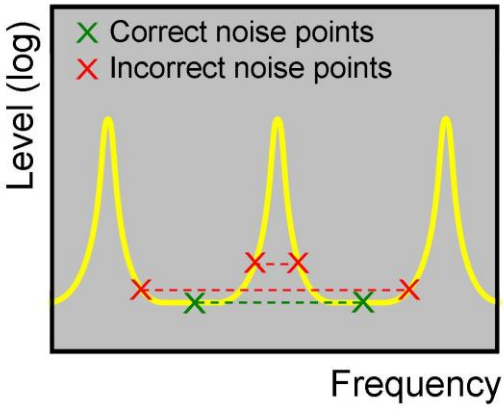



**Figure 6** – The true noise level can be obscured due to the relative broad flanks of the recorded laser peaks. For an accurate measurement, the noise (interpolation) points should not be too close the peak wavelengths or its neighbors.

[10] In an OSA recording, each sample measurement is affected by the optical power of neighboring wavelengths, an effect that results in blurring off the complete spectrum. This effect is explained in more detail in the Yokogawa "The filter shape of a monochromator".

For the same reason it is important to use instrument settings that produce the best Close-in Dynamic Range (also known as Optical Rejection Ratio) properties – e.g. high resolution setting. This will produce the narrowest laser peaks in the recording, allowing the noise interpolation points to be placed close to the laser peak and, thereby, keeping the measurement error to a minimum.

## 6.3. Amplifier Analysis

The noise and signal values that are required for the calculations are defined in figure 6.

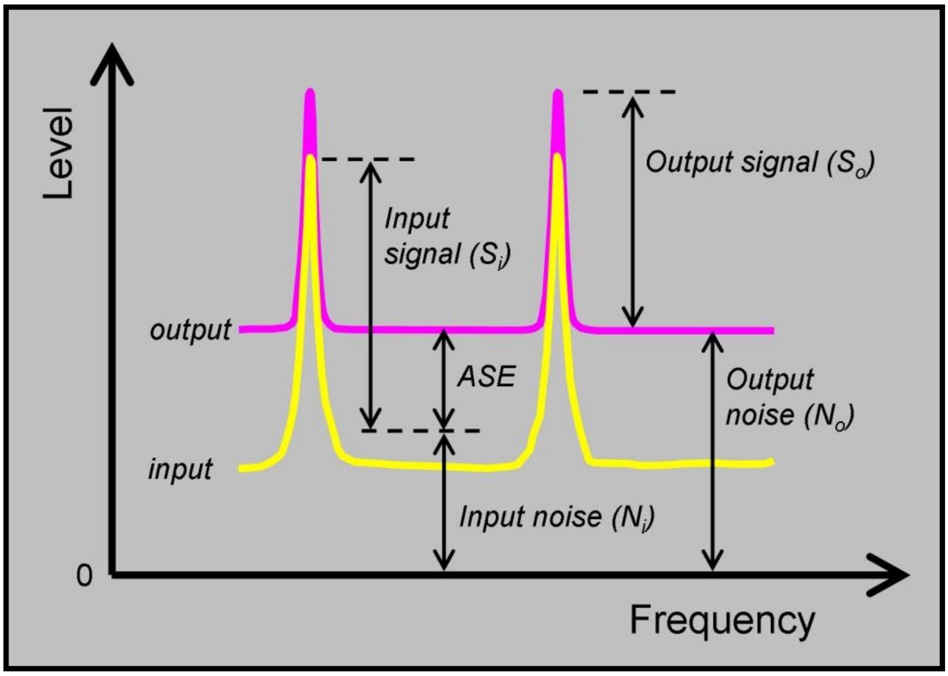



**Figure 7** – All required signal and noise values follow from the two OSA recordings, except for the amplifier input noise.

All required signal and noise values follow from the measurement traces, except for the amplifier input noise ($N_i$).

### 6.3.1. Input Noise Level ($N_i$)

It is generally adopted that the amplifier input noise ($N_i$) purely consists of shot noise and is therefore calculated by $N_i = h \cdot \upsilon \cdot \Delta\upsilon$ (Fig. 2), with Planck's constant[11] (h), frequency ($\upsilon$) and resolution bandwidth ($\Delta\upsilon$) expressed in Hertz.
To give a feel for the value; at a wavelength of 1550nm, with a 17 picometer resolution bandwidth, the assumed input noise is -66 dBm (i.e. 0.27 nanoWatt).

[11] Planck's constant (h) is equal to 6.6260755•10-34 Ws$^2$

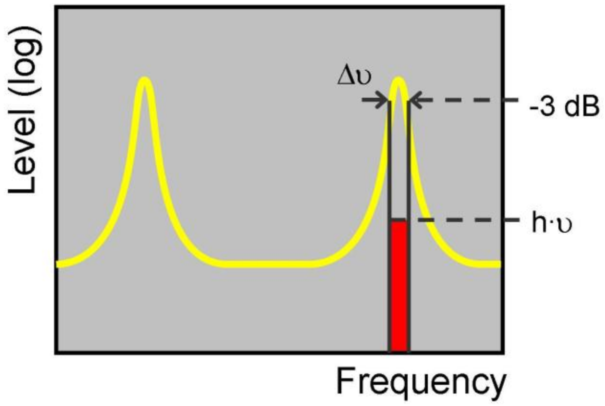


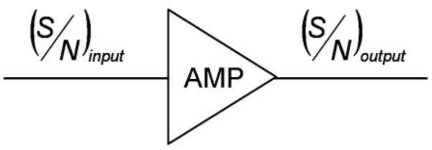

**Figure 8** – Input noise ($N_i$) is assumed to be on the shot noise level ($h \cdot \upsilon$). The local resolution bandwidth ($\Delta\upsilon$) follows from the spectral width of the laser peaks at -3dB from the peak level.

### 6.3.2. Resolution Bandwidth ($\Delta\upsilon$)

It is important that the resolution bandwidth, as used in the calculations is in fact the true (effective) resolution of the OSA at the particular laser wavelength, and not the value of the resolution setting. The effective resolution[12] varies with wavelength and is therefore different for each of the laser wavelengths.
Conveniently, the DFB laser output is much narrower than the local effective resolution bandwidth. This means that an accurate value of the effective resolution can be obtained from the measurement itself. Hereto, the width of the recorded laser peaks at -3dB points is determined (Fig. 8).

### 6.3.3. Noise Figure (NF)

In its most clean and simple form, the equation for calculating the noise figure equation is expressed by dividing signal-to-noise ratios:




$$NF = \frac{\left(S/N\right)_{input}}{\left(S/N\right)_{output}}$$

**Equation 1**

It is clear that for the perfect amplifier NF = 1, i.e. it does not add noise to the communication channel. With the Noise Figure expressed in decibel, and with $Signal_{out}$ = Gain x $Signal_{in}$, the noise figure equation is written as:

*Working with frequencies…*

$$NF = 10 \cdot {}_{10}Log\left(\frac{N_o}{Gain \cdot \Delta\upsilon \cdot h \cdot \upsilon}\right)$$

**Equation 2.a.**

*Working with wavelengths…*

$$NF \approx 10 \cdot {}_{10}Log\left(\frac{N_o \cdot \lambda^3}{Gain \cdot \Delta\lambda \cdot h \cdot c^2}\right)$$

**Equation 2.b.**

[12] The difference between resolution setting and effective resolution is explained in more detail in the Yokogawa article "Optical power measurement and resolution".

With $N_o$ = Noise power at the output of the amplifier [Watt]
Gain = Amplification factor [-]
$\lambda$ = Center wavelength of the amplified signal [m]
$\Delta\lambda$ = Effective resolution bandwidth (wavelength) used for the measurement [m]

### 6.3.4. Amplifier Gain

The Gain value follows straightforward from the signal power before and after amplification. The input noise level $N_i$ (the shot noise term) does not contribute significantly to the equation and is therefore neglected.

$$Gain_{dB} = 10 \cdot {}_{10}LOG\left(\frac{S_o - N_o}{S_i}\right)$$

**Equation 3.**

### 6.3.5. Amplified Spontaneous Emission

From figure 7 it follows that the equation for calculating the ASE value is expressed by:

*Working with frequencies…*

$$ASE = N_o - h \cdot \upsilon \cdot \Delta\upsilon$$

**Equation 4.a.**

*Working with wavelengths…*

$$ASE \approx N_o - \frac{\Delta\lambda \cdot h \cdot c^2}{\lambda^3}$$

**Equation 4.b.**

Because only noise levels play a role in this equation, the shot noise term plays a more dominant role and cannot be neglected.

## 6.4. Calculation Example

### 6.4.1. Manual approach

In this example, the required calculations are done manually for one of the laser peaks using the following measurement data:

| | | |
|---|---|---|
| Input signal level | : | $0.478 \times 10^{-3}$ W |
| Output signal level | : | $10.328 \times 10^{-3}$ W |
| Output Noise level | : | $10^{-7}$ W |
| Center frequency | : | $194.396 \times 10^{12}$ Hz |
| Resolution bandwidth | : | $6.38 \times 10^{9}$ Hz |

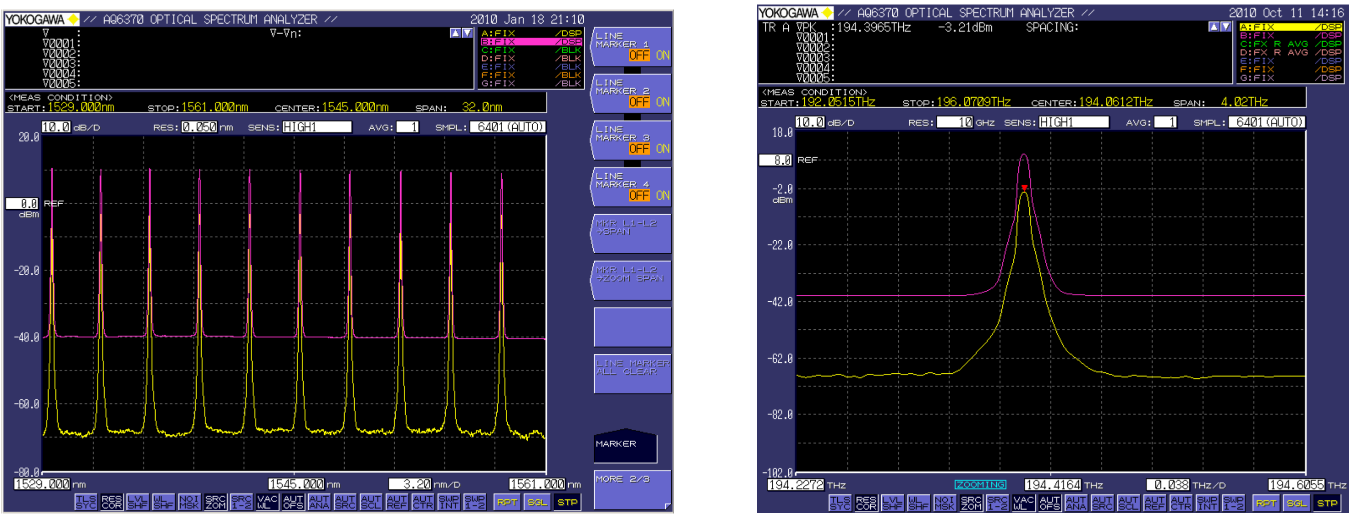



**Figure 9 –** Manual determination of noise and signal values is done on peak number 5 of an actual measurement

Filling the given equations provides the following:

$$ASE = N_o - RBW \cdot h \cdot \upsilon$$

$$= 10^{-7} - 0.00638 \times 10^{12} \cdot 6.6260755 \times 10^{-34} \cdot 194.396 \times 10^{12}$$

$$= 99.178 \times 10^{-9} \text{ Watt}$$

$$ASE = \text{-40.04 dBm}$$

$$Gain = \frac{Peak_{out} - ASE}{\text{Peak}_{\text{in}}} = \frac{10.328 \times 10^{-3} - 99.178 \times 10^{-9}}{0.478 \times 10^{-3}} = 21.60$$

$$Gain_{dB} = 10 \cdot Log(21.60) = 13.35 \text{ dB}$$

$$NF = 10 \cdot {}_{10}Log\left(\frac{N_o}{Gain \cdot RBW \cdot h \cdot \upsilon}\right)$$

$$= 10 \cdot {}_{10}Log\left(\frac{10^{-7}}{21.60 \cdot 0.00638 \times 10^{12} \cdot 6.6260755 \times 10^{-34} \cdot 194.396 \times 10^{12}}\right)$$

$$= 10 \cdot {}_{10}Log(5.63)$$

$$NF_{dB} = 7.50 \text{ dB}$$

### 6.4.2. The OSA Amplifier Analysis Function

The Yokogawa AQ6370x OSA has an automated function for amplifier analysis under the name “EDFA-NF”. Despite the name, is in fact suitable for all types of optical amplifiers. The routine automatically detects the DFB laser peaks, extracts the required measurement values, performs the calculations and displays the result in a table (Fig. 9).

Using the EDFA-NF function, the automatically determined values obtained from laser peak #5 agree with the values, manually determined earlier (Fig. 9)


**Figure 10** – The automated routine for optical amplifier analysis provides a table with the relevant parameters. Notice that the results of peak number 5 is in agreement with the manually obtained values.

# 7. Reducing the effect of stray light

## 7.1. Stray light

Straylight is all the light with wavelengths different than the selected wavelength that reaches the photodetector surface and, therefore, has a disturbing influence on the measurement. Straylight can originate from reflections inside the monochromator (Fig. 6.a), from imperfections of the imaging optics (Fig. 6.b) or from a natural phenomenon like higher order grating diffraction* (Fig. 6.c).

The OSA monochromator is designed to minimize the influence of straylight by using a folded beam path, diffuse black coated parts, shields and compartments. For demanding applications, straylight can still be a limiting factor – e.g. analyzing the noise-floor in the vicinity of a strong light peak.

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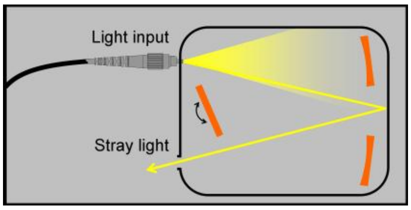
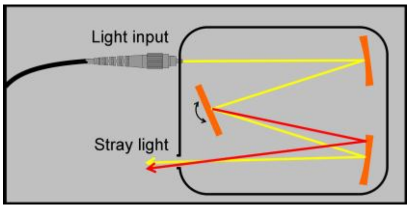
* The grating diffracts each wavelength at multiple angles (diffraction orders). The OSA records just one of these orders. A second order diffraction can cause a "ghost peak" at twice the wavelength of the true input wavelength.

(a) Off-wavelength light that reaches the photodetector due to reflections in the monochromator.




(b) Off-wavelength light that reaches the photodetector due to imperfections in the monochromator (imaging) optics.




(c) Off-wavelength light that reaches the photodetector due to natural phenomena, e.g. higher order grating diffraction.

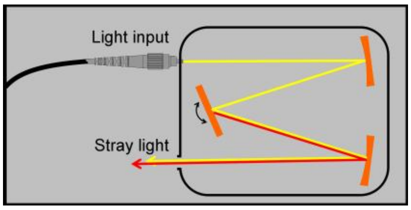



**Figure 6** –Unselected wavelengths may still reach the photodetector, having a disturbing influence on the measurement.

### Elimination the effect of straylight

In the OSA design, a number of precautions are taken for (passive) elimination of straylight, i.e. components inside the monochromator are diffusely black coated, beam shields are positioned to stop straylight from propagating, and optics is used with a minimal amount of imperfections.

The modern Yokogawa OSA reaches the same level of straylight reduction passively as older generation instruments did actively, i.e. using a straylight suppression method involving a chopper.

For extra reduction of the straylight effect, the Yokogawa OSA can be used in so called "switch mode" or "high dynamic mode".
When "switch mode" is selected, the OSA automatically records two separate traces; one containing signal + straylight, and one containing straylight only. Subtraction of the two is provided as the measurement result.

# 8. Trade-offs in OSA performance (part 1)

When working with Optical Spectrum Analyzers (OSA), it is quickly found that optimizing the instrument in one direction goes at the expense of the performance in another. For each application, this trade-off needs to be made.
Also in the purchase process of an OSA, trade-offs are important to consider. Instrument specifications guarantee performance in a specific area, but typically do not mention the trade-off that needs to be made to get this performance level. Not a complete picture is sketched, making it hard to compare apples to apples.

In this article, step by step the most commonly encountered trade-offs are discussed (Fig. 1).

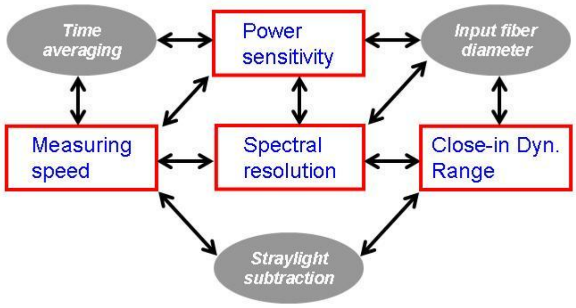



**Figure 1** – Inter-dependent parameters

To explain the background of each trade-off, it is important to have a basic understanding of the Czerny-Turner monochromator that is applied in Optical Spectrum Analyzers.

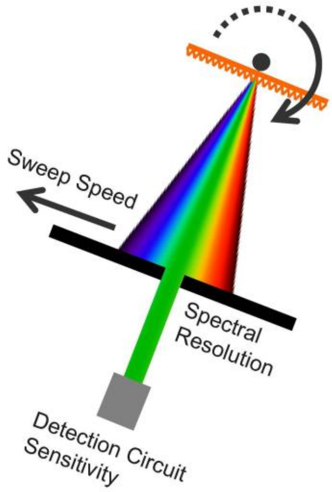



**Figure 1** –The performance triangle describes the three inter-dependent parameters; spectral resolution, detector sensitivity and sweep speed of the instrument.

In this type of monochromator, input wavelengths are spatially separated by a diffraction grating (Fig. 1). Only a narrow portion of the diffracted wavelengths passes through an exit slit and reaches the surface of a photodetector. Note that the exit slit acts as a band-pass filter. By rotating the grating, the diffracted spectrum is shifted across the exit slit allowing the photodetector to record a complete spectrum.

## 8.1. Resolution vs. Sensitivity

In a low-resolution setting, the monochromator uses a wide exit slit for measurement. Generally, this means that more light (more power) is passing through the slit, producing a strong detector signal. Specially when measuring with low light levels, a low-resolution setting may produce a better sensitivity and, hence, more accurate measurement. The trade-off is of course made on spectral resolution.
The narrow slit that is used for high-resolution measurement, typically* produces a weaker detector signal, i.e. a signal more close to the noise floor of the detector circuit. The gain in spectral resolution goes at the expense of sensitivity.

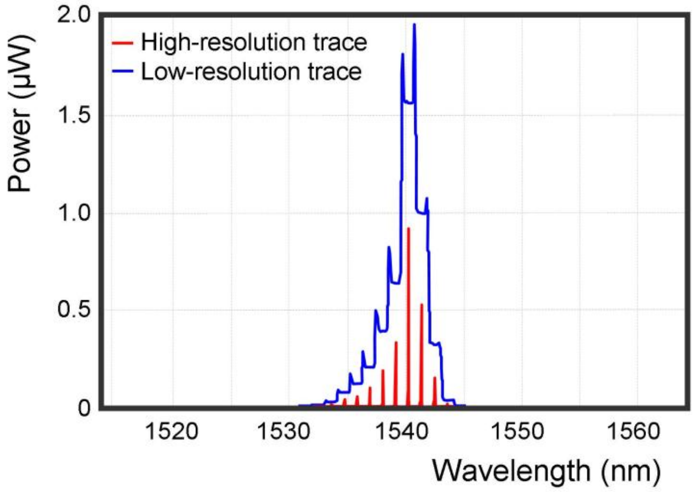



**Figure 3 -** The spectrum of a Fabry-Perot Diode Laser** recorded with an AQ6370 Optical Spectrum Analyzer. The low-resolution trace produces a a stronger detector signal (higher instrument sensitivity) at the expense of spectral detail.

To illustrate the principle, a low and high-resolution recording is made of the comb-like mode structure of a Fabry-Perot laser (Fig. 3). It is clearly visible that the low-resolution setting produces a stronger detector signal at the expense of spectral detail.

---

* There are exceptions, i.e. for an extremely narrow input spectrum (laser line), the complete input power is captured by both the narrow slit and the wide slit. Here, there is no difference in strength between the detector signals (i.e. signal-to-noise ratio).

** Yokogawa Model AQ4270-01 Fabry-Perot Laser Diode.

## 8.2. Sensitivity vs. Sweep Speed

The main factor that determines the sensitivity of an OSA is the amplification circuit immediately after the photodetector. Each of the sensitivity settings of the OSA is associated to a specific amplifier circuit, each having its specific gain and response time.

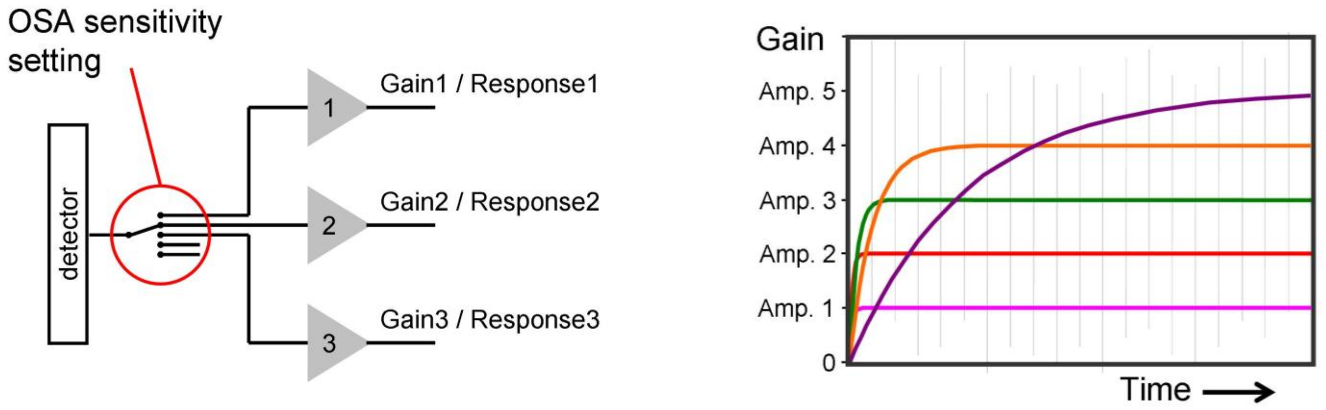



**Figure 4** –Each sensitivity setting is associated to a specific amplifier circuit, each with its own gain and bandwidth (response time)

In a low-sensitivity setting (low gain) the detection circuit is fast, allowing the OSA move quickly from sample point to sample point, thereby, producing a fast sweep time (Fig. 4).
In a high-sensitivity setting (high gain), the detection circuit has a significantly slower response. The OSA needs to sweep at a lower speed, allowing the detection circuit to reach its final value for each sample point.

The long signal integration of a slow-response circuit provides noise cancellation (averaging) and, thereby, contributes to an improved signal-to-noise ratio.
The appropriate sensitivity setting depends on the amount of light input and the required measurement speed.

## 8.3. Sweep Speed vs. Resolution

For good coverage of a certain wavelength range, a high-resolution recording requires more sampling points than a low-resolution recording. More sampling points means more time is needed to complete a measurement sweep, hence, a slower measurement speed.

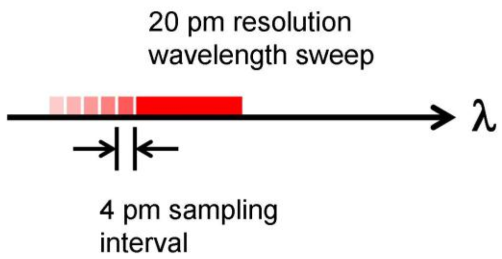


**Figure 5** –The optical spectrum is sampled with a certain resolution. For a Yokogawa OSA the sampling interval that is (default) 20% of the chosen resolution setting, but can be changed manually.

By default, the sampling interval of a Yokogawa OSA is selected automatically and is set to 20% of the selected resolution – i.e. for a measurement with a 20 picometer resolution, the sampling interval will be 4 picometer.
To optimize for measurement speed (for example), the user can deviate from this by manually selecting the sampling interval.
For a Yokogawa OSA, the user is free to choose values as long as the following limits are not exceeded

The user is free to choose the values he wants. The OSA, however, will not exceed the following limits:

| | ***Minimum*** | ***Maximum*** |
|---|---|---|
| ***# Sampling points*** | *101* | *50.001* |
| ***Sampling interval*** | *1 picometer* | *span/100* |

# 9. Trade-offs in OSA performance (part 2)

In this article, step by step the most commonly encountered trade-offs are discussed (Fig. 1).

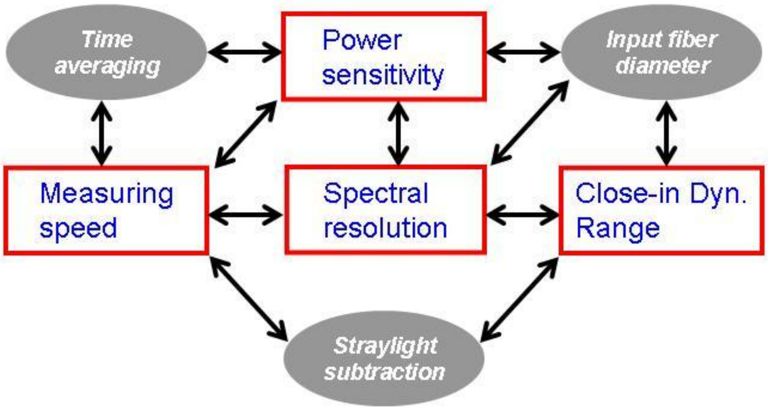



**Figure 1** –Inter-dependent parameters

## 9.1. Time-averaging

Noise cancellation due to time-averaging of measurement values reduces the peak-peak values of the noise fluctuations.

Temporal noise is contributed by the optical input signal (e.g. fluctuating light source) and by the internal photodetector circuit (i.e. shot noise). With time-averaging, noise is cancelled out, effectively reducing the peak-peak values of the noise fluctuations. Because the average value is closer to the true value, averaging has a positive effect on the measurement accuracy.

Averaging of the detector noise reduces the noise-floor and therefore improves the sensitivity of the OSA, i.e. a weak optical signal may be clearly visible where, otherwise, it would be lost in the noise floor.

A Yokogawa OSA offers two types of time-averaging of measurement results.

**Sample averaging:** At each wavelength (sample point) the OSA determines the average value over a selected* number of measurements before progressing to the next sample point.

**Trace averaging:** Also referred to as "rolling average". After a trace is recorded it is added to the collection** of previously recorded traces, after which the average trace is calculated. After each wavelength sweep, the average trace is displayed so that the averaging progress is visualized.

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* Averaging is offered over up to 999 values.

** Rolling average is offered over up to 100 traces.

Averaging means that multiple measurements are taken to determine a value. More measurements means slower measurement. Two times averaging doubles the sweep time, three times averaging triples the sweep time, and so on.

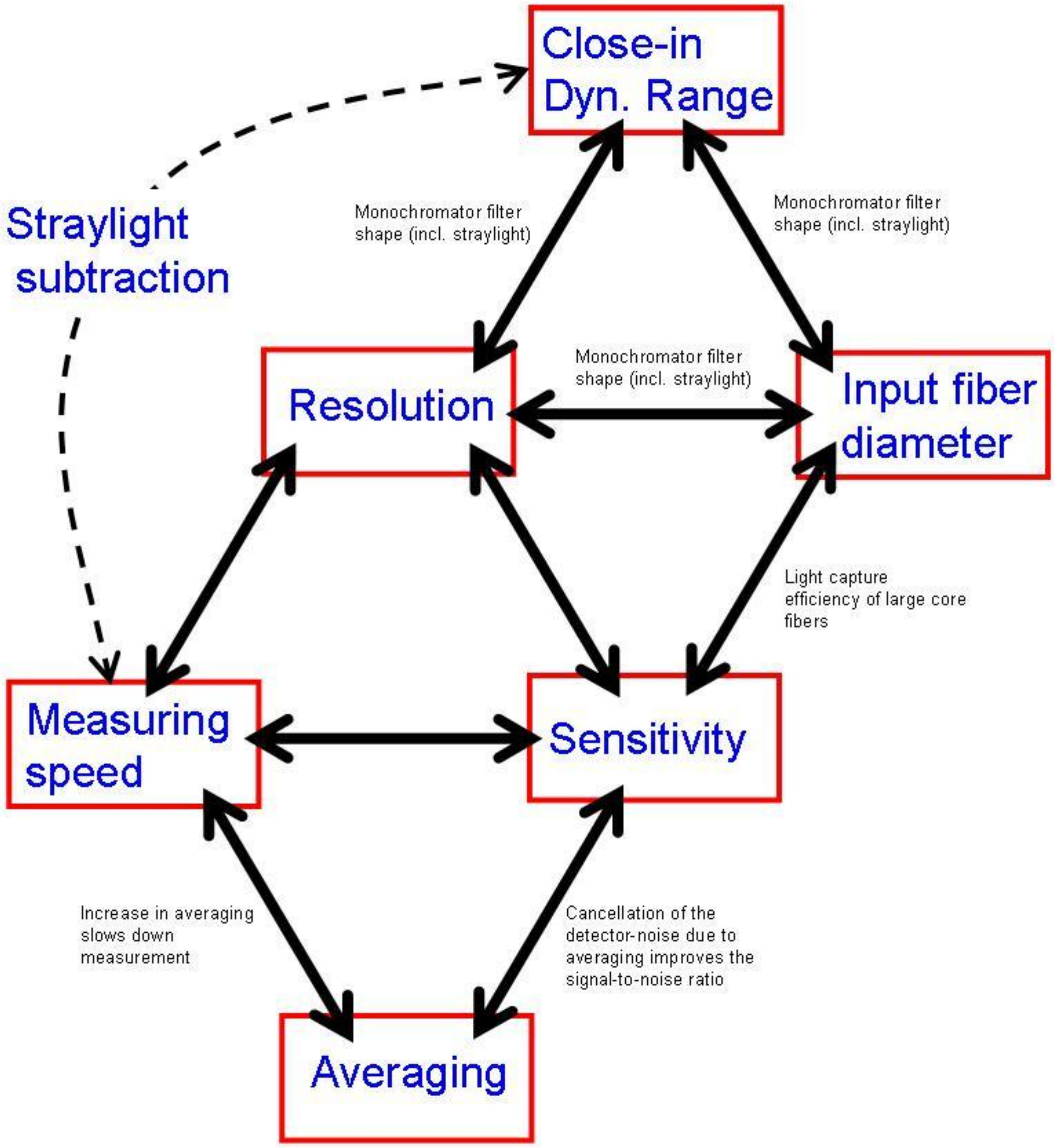
Trade-off

Time-averaging produces high accuracy and better sensitivity at the expense of measurement speed

## 9.2. Straylight Subtraction

**Measurement Speed vs. Close-in Dynamic Range and Level Accuracy**

- What is straylight, and why is it disturbing? (loss in ORR and level accuracy)
- Solution offered: straylight subtraction feature
- How do we measure straylight?



Close-in Dyn. Range
Straylight subtraction
Monochromator filter shape (incl. straylight)
Monochromator filter shape (incl. straylight)
Monochromator filter shape (incl. straylight)
Resolution
Input fiber diameter
Light capture efficiency of large core fibers
Measuring speed
Sensitivity
Increase in averaging slows down measurement
Cancellation of the detector-noise due to averaging improves the signal-to-noise ratio
Averaging

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