

APPLICATION NOTE

Automated Gain Flattening

Scope and Overview

A flat optical power spectrum is essential for optical telecommunication signals. This stems from a need to balance the channel powers across large distances. E.g. in long-haul fibre networks that require many optical amplifiers in order to maintain power across large transmission distances. Commonly used amplifiers such as Erbium Doped Fibre Amplifiers (EDFA) and Raman amplifiers provide optical amplification that varies with wavelength. One solution is to flatten out the powers across the transmission window by attenuating higher power channels comparatively to the lower power channels. This is more generally referred to as gain flattening.

There are many gain flattening (or equalisation) systems available, many of which are time-invariant and passive devices e.g. fibre Bragg gratings or thin film based. They remain fixed after production and cannot be altered in response to spectral fluctuations and drifts that might occur over the network lifetime. Such changes can occur due to drifts in temperature, changes in channel loading, system reconfiguration, or the replacement of optical components. Passive gain flattening systems must be replaced under these circumstances.

This application note describes how a WaveShaper¹ combined with an optical spectrum analyser (OSA) or optical channel monitor (OCM) can be used to create a robust automated gain flattening system that adapts on-the-fly to changes in the optical power spectrum. The system is not only applicable to EDFA, but any other optical amplifier or broadband source e.g. Raman amplifiers or supercontinuum lasers. This system algorithm can successively improve the level of flatness down to as little as ± 0.1 dB² deviation from the mean. The system is versatile and applicable for use both in the field and as part of an optical test bed.

¹ Excludes the WaveShaper 100 Family.

² This figure depends on the accuracy of the OSA or OCM that is used in the AGF system. ± 0.1 dB was achieved using the Yokogawa AQ6370 Optical Spectrum Analyser.

1. Experimental Setup

This application note uses a WaveShaper 120S Gain Equalizer designed specifically for gain flattening in mind.

Four key pieces of hardware are needed for the automated gain flattening system: the computer, the WaveShaper, the fibre tap, and the OSA. A schematic of the experimental setup is shown in Figure 1.

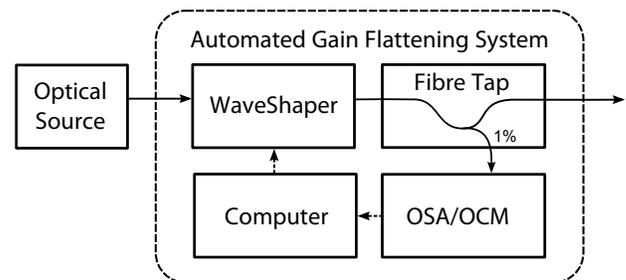


Figure 1: Experimental Setup Schematic for an AGF system.

The optical source to be flattened is connected to the WaveShaper common port. The WaveShaper output is then connected to a fibre tap, sending a small amount of optical signal to an OSA/OCM. This fibre tap can be part of an optical amplifier further down the transmission line. The OSA/OCM can be any device capable of providing the computer with an accurate reading of optical power as a function of wavelength. This application note uses the Yokogawa AQ6370 optical spectrum analyser as part of the gain flattening system, however it could be substituted with a suitable optical channel monitor (OCM) or another OSA.

The data from the OSA is sent to the computer and is used to perform the gain flattening algorithm.



Figure 2: Illustrates the algorithm feedback loop used in the AGF system.

The automated gain flattening (AGF) system uses a feedback loop shown in Figure 2 to maintain a flat spectral profile

even after spectral changes occur. Conceptually, this feedback loop allows the WaveShaper profile to be systematically modified based on the OSA measurement.

The key idea behind the AGF algorithm is to attenuate the power level at each frequency down to common power level. In other words, additional attenuation is introduced into spectral regions of increased power. The deviation in measured power from the common level is added to the WaveShaper attenuation profile at each iteration of the algorithm. This algorithm can be expressed mathematically by Eq. 1:

$$\begin{aligned} B_n &\equiv A_n - \text{Meas}(A_n), \\ A_{n+1} &= B_n - \min(B_n). \end{aligned} \quad 1$$

Where A_n is the WaveShaper attenuation profile i.e. the 2nd column of the *.wsp file. $\text{Meas}(A_n)$ denotes the OSA measurement of the attenuation after applying profile A_n . It is the *negative* of the measured power spectrum. The initial WaveShaper profile A_0 can be set to zero attenuation for all frequencies. A schematic of this process showing the first two iterations is illustrated in Figure 3.

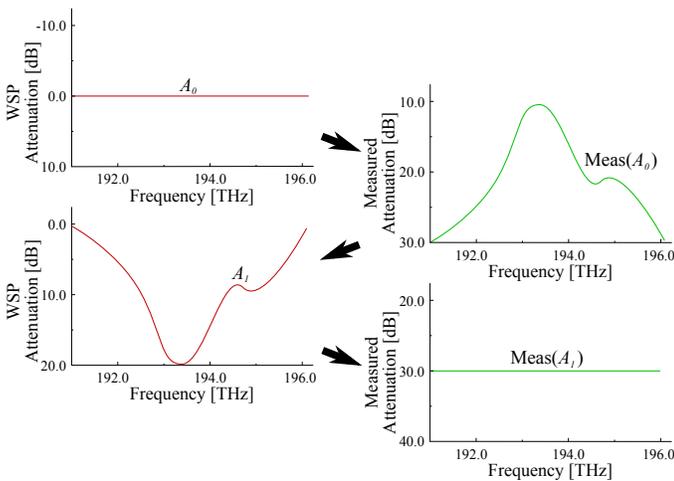


Figure 3: Schematic showing the automated gain flattening algorithm. The left figures show the WSP attenuation profiles uploaded to the WaveShaper, while the right figures show the corresponding experimental measurements.

In practice, the following steps are taken for the n th iteration:

1. A wsp profile with an attenuation profile of A_n is uploaded to the WaveShaper.

2. The resulting power spectrum is measured using the OSA.
3. The power spectrum data is transferred to the computer, converted to attenuation and then filtered.
4. This data is subtracted off A_n to give B_n .
5. To remove the possibility of negative attenuation, the profile for the next iteration is equal to B_n minus a constant given by the minimum value of B_n .

The WaveShaper is capable of producing filters containing spectral features as small as 10 GHz. Features smaller than 10 GHz are beyond the resolving capabilities of the WaveShaper and are filtered out by the internal optics. As a result, spectral features smaller than 10 GHz in the measured OSA data can lead to instabilities and diverging profiles. This is prevented by using an appropriate filtering algorithm.

2. Measuring and Filtering

There are two main regimes that an AGF system may run under: the first encompasses the flattening of a broadband light source with a continuous power spectrum e.g. an ASE light source. The second involves flattening a light source consisting of a series of optical comb lines of varying peak power. The implementation of the flattening algorithm varies slightly for each regime. Specifically the measurement i.e. in Eq. 1, $\text{Meas}(A_n)$ is interpreted differently for each regime.

2.1 Flattening a Continuous Power Spectrum

Many optical light sources e.g. ASE broadband sources have a non-flat power spectrum, and flattening this light source is often essential for many applications. For flattening this type of source, the entire spectrum is measured with the OSA and then filtered with a smoothing filter. In this regime, Meas from Eq. 1 includes the filtering process. An illustration of this smoothing filter is shown in Figure 4.

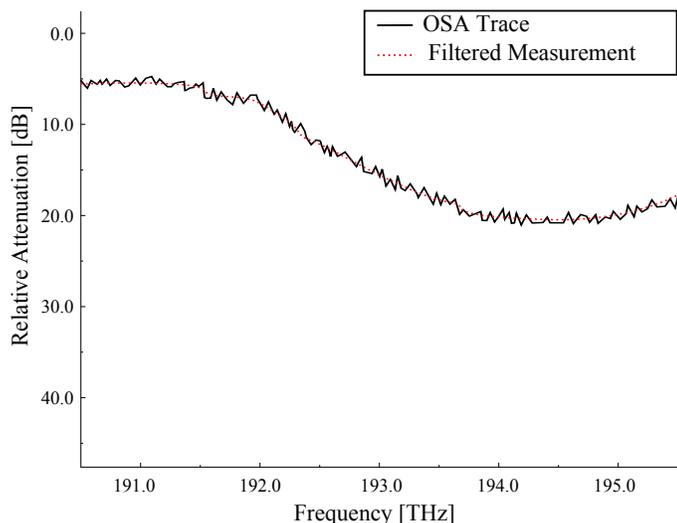


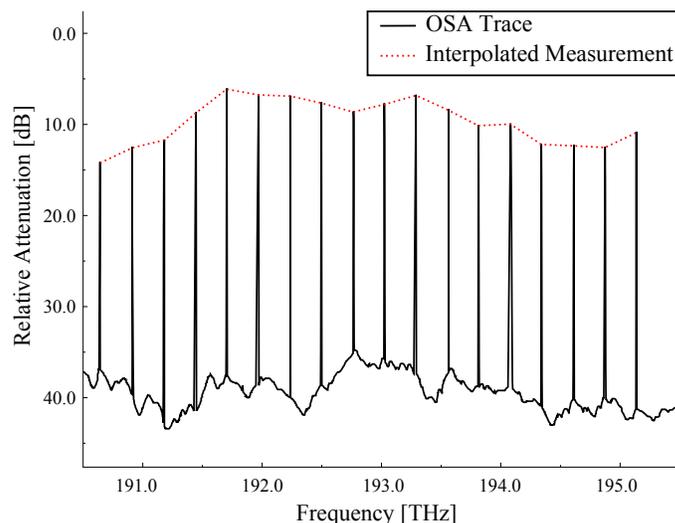
Figure 4: Illustrating measuring and filtering the power spectrum of a continuous light source. The black line represents the data taken from an OSA trace, while the red line represents $Meas(A_n)$, the smoothed data used to calculate the next iteration.

The OSA trace must be filtered in order to remove sharp features which would otherwise cause instabilities in the iterative system. It is sufficient to suppress features smaller than around 20 GHz. This application note uses a zero-phase Butterworth filter, however other filters such as a Savitzky-Golay, or Gaussian filter are suitable.³

2.2 Flattening an Existing Channel Plan

When the optical signal already contains a set of modulated optical channels, the measured power spectrum will consist of a series of comb lines, each corresponding to an optical channel. If the same approach taken when using a continuous light source is applied here, the algorithm would aim to flatten the comb lines themselves, rather than the comb line peak power. For this reason, the approach taken in Section 2.1 is not suitable under this regime.

To perform spectral flattening on a set of optical comb lines, the OSA measurement, denoted by $Meas$, is calculated by measuring the peak power level at each comb line peak and linearly interpolating for power levels between peaks. This process is illustrated in Figure 5. Unlike in the previous regime, no filtering is required.



3. Algorithm Implementation

This section provides information about how to implement the AFG system using the WaveShaper's dedicated API.

3.1 Formatting Data

As the format of the trace data supplied by the OSA may vary, the data must be interpolated to the same resolution used by the WSP profile string, e.g. a 1 GHz grid. Furthermore, before being used in Eq. 1, care should be taken to make sure that the trace data is converted to attenuation, i.e. the negative of power in dB.

3.2 Limiting the Attenuation Range

It can be useful to place a limit on the total amount of flattening that can occur. For example, if a light source varies in intensity by more than 20 dB, it might be useful to prevent the algorithm from attenuation larger than 20 dB. To do this, simply coerce each evaluation of A_{n+1} to values between 0 and 20 dB.

3.3 API Implementation

The WaveShaper API allows the WaveShaper to be remotely controlled with many programming languages including C, C++, LabVIEW, MATLAB, Python, etc. Each language makes calls to a common set of API commands. The basic program flow is illustrated in Figure 5.

³ The smoothing filter must be a zero-phase filter to prevent the data from misaligning.

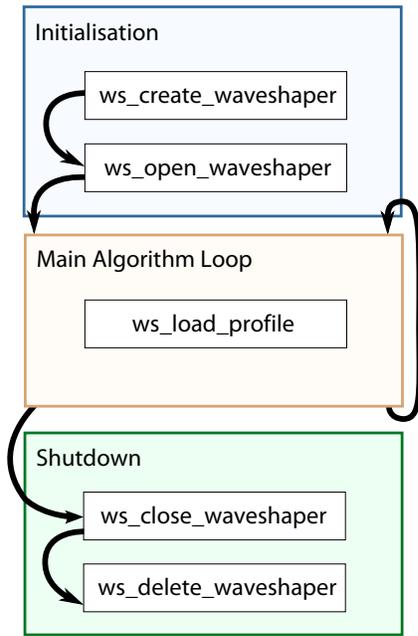


Figure 5: Flow-diagram of the relevant API functions used in the AGF system.

3.4 Program Initialisation

The following functions are called when the AGF application first starts:

ws_create_waveshaper

The WaveShaper object is created using the `ws_create_waveshaper` API function. This function loads all the necessary calibration files required to properly drive the WaveShaper.

ws_open_waveshaper

Communication is established using the `ws_open_waveshaper` function. This function requires the WaveShaper to be connected to your computer.

3.5 Main Algorithm Loop

The following function is called as part of the main iterative gain flattening loop:

ws_load_profile

WSP profile strings are generated by the algorithm and applied to the WaveShaper using the `ws_load_profile` function. This function is called once every iteration loop.

3.6 Shutdown

When the AGF system is finished operation, there are some functions that must be called on shutdown:

ws_close_waveshaper

The `ws_close_waveshaper` function is used to close communication with the WaveShaper.

ws_delete_waveshaper

The `ws_delete_waveshaper` function is called to finally delete the WaveShaper object created during initialisation.

4. Results

A gain automated system was implemented to flatten the power spectrum of a broadband ASE light source using a C+L Band WaveShaper 120S, with experimental results shown in Figure 6.

In this experiment, the gain flattening algorithm was operated in a frequency range of 187.5 to 196.275 THz. The maximum attenuation limit was set to 10 dB. The regions between 186 THz to 188 THz and 195 THz to 196 THz are not flattened because doing so requires attenuating the whole profile beyond the 10 dB limit. The results show that only 3 – 4 iterations were needed before the profile converged to within 0.1 dB.

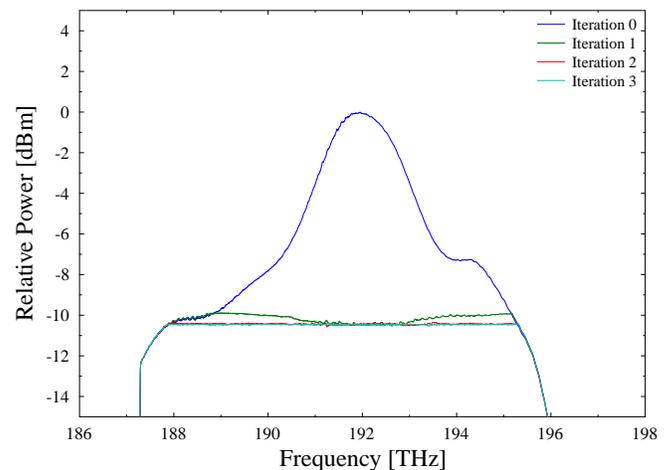


Figure 6: Experimental results showing the automated gain flattening of a broadband ASE light source using a C+L band WaveShaper 120S. It shows the first 4 iterations.

5. Further Applications

The gain flattening algorithm produces a WSP profile that is specifically tailored to flatten the power spectrum of a particular optical light source. It is possible to apply additional WSP filters to 'carve' out new filter shapes while simultaneously counteracting the non-flat power spectrum of the light source.

5.1 Carving Comb Lines

Optical test beds often require optical sources that emulate the power spectrum of real-life optical communication systems. The WaveShaper can be used to accurately reproduce the power spectrum of a modulated data signal by carving out comb lines. The shape of the comb line filter could correspond to a particular modulation format of a WDM system. Furthermore, the automated gain flattening system allows the power of each channel to be equalised.

5.1.1 Methodology

The automated gain flattening system is first used to flatten a broadband light source. The final attenuation profile generated by the algorithm acts as a base flattening profile that will then have the attenuation of another WSP profile added onto it. In this case, a series of comb lines designed to emulate a DPSK channel plan with 50 channels equally spaced at 50 GHz spacing are filtered out.

5.1.2 Results

A filter profile featuring 21 Gaussian channels with a channel spacing of 200 GHz. Each channel had a 3-dB bandwidth of 40 GHz. This attenuation profile of this filter was added to the attenuation profile of a flattened light source and then measured with a Yokogawa AQ6370 OSA. The experimental results are shown in Figure 7.

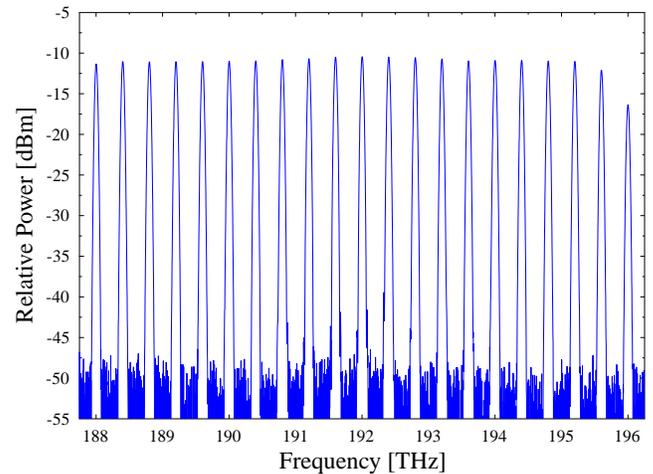


Figure 7: Experimental measurement of Gaussian channels spaced every 200 GHz. Each channel has a 3-dB bandwidth of 40GHz.

The peak power of each channel was found to be equalised to within 0.6 dB.