Spectral Density Measurements

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State of the art supercontinuum white light lasers are now able to produce several Watts of average power in a spectral range covering more than 2000nm. For such systems, stating the total average power in the entire supercontinuum spectrum is a poor specification of system performance, as significant power can be concentrated in discrete spectral bands. Specification of spectral density reveals such pitfalls and shows the true optical performance of the source. Precise characterization of the spectral density is thus very important for evaluation of a given light source. This note will show how spectral density from high power supercontinuum lasers can be correctly quantified.

Introduction

Users of supercontinuum sources tend only to require light covering a certain spectral area of the total spectrum e.g. visible, near-IR or telecom wavelengths, for their applications. This is why specifying only total power of the supercontinuum light source is inadequate - it does not inform the users of how much light is contained in *their* spectral region of interest. *Spectral Power Density* i.e. the amount of optical power contained in a finite bandwidth of wavelength is a much better indicator, as the users can quickly see how much optical power is available for their particular experiment. A light source which has a high total power is not useful to a user requiring visible light, if most of the light is contained in the IR. Similarly, a light source with lower total power can still be very useful if most of this power is concentrated in the right spectral band. The EXW series of the SuperK Extreme, for example, tend to have lower total powers, but achieve the highest visible powers on the market due to the extremely efficient conversion of pump light. In brief, Spectral Power Density, not total power, is the most important parameter when choosing the correct supercontinuum laser.

Spectra from supercontinuum lasers can be conveniently recorded via an integrating sphere connected to a spectrometer. Average power can be measured with power meters based on thermal or semiconductor heads. Most detectors are calibrated in order to compensate for wavelength dependency of the response, but very few detectors can span the entire range of state-of-the-art white light lasers. Similarly, spectrometers are also designed to work in a specific spectral range and cannot measure the entire spectrum exhibited by the supercontinuum laser. With these measurement limitations, obtaining an accurate spectral power density curve can be difficult.

NKT Photonics has established a standard measurement protocol based on two spectrometers, two thermal power meters and various filters. Filters are required to avoid crosstalk in the spectrometers and ensure correct power measurements, but inclusion of filters is non-trivial as the wavelength dependent loss distorts the real spectral profile. In general, all optical components must be carefully analyzed so correct compensation can take place.

To illustrate the importance of the measurement method, consider a typical, but *erroneous* approach to measure the spectral density is the following

1) Record the spectrum via a spectrometer
2) Measure the total power of supercontinuum laser with a detector
3) Normalize the spectrum with the measured total power

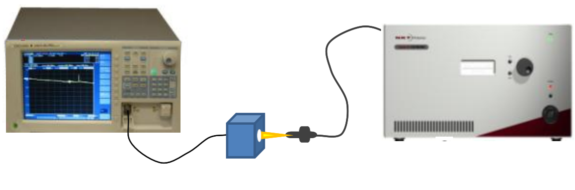


Figure 1 shows the comparison of the spectral density from a typical EXR-15 source when correct normalization and this erroneous 'simple' normalization schemes are used. There is a clear difference which emphasizes that one must not only specify spectral density, but also how the spectral density is measured.

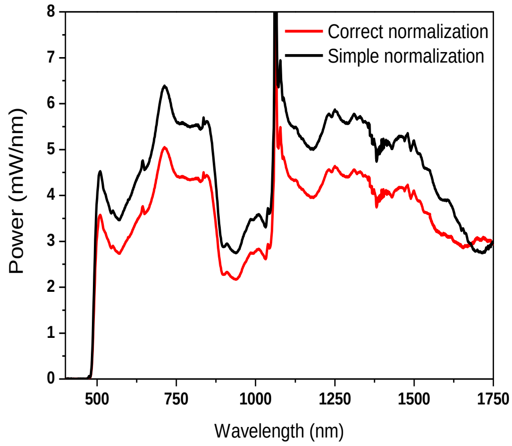


Figure 1 : Calculated spectral density from EXR-15 with different normalization schemes

The main cause of the error illustrated in figure 1 is readily identified by noting the significant spectral density toward the red edge of the spectrum. The normalization is clearly wrong as there is a power contribution outside the detection window of the spectrometer. More subtle, the spectrometer itself has limited resolution and unreliable calibration across the spectrum, which gives rise to 'tilted' spectra. Power meters also show significant wavelength dependence so the total error can be substantial.

The solution is to divide the spectrum into smaller portions where detectors are more accurate and then stitch the data to form the full spectrum. The following pages will show the details in the procedure used at NKT Photonics.

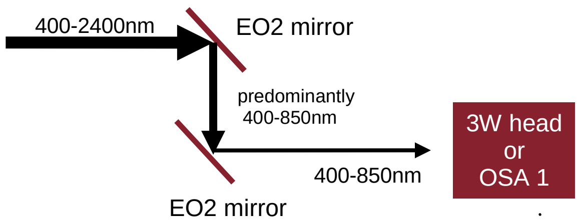
Equipment

2 Optical Spectrum Analysers:
OSA1[1]
OSA2[2]
Integrating sphere[3]
200 micron low-OH delivery fiber[4]
2 power meters - 3W and 30 W thermal heads[5]
2 EO2 mirrors[6]
1250 nm long pass filter[7]

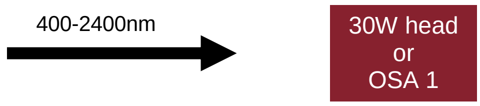
Procedure

The process is divided into the following stages:

1) Record spectrum (S1) after 2 EO2 mirrors with OSA1 (2nm resolution, 350-1750nm)
2) Measure optical power (P1) after 2 EO2 mirrors with a 3W head (setting : λ < 800nm)
3) Integrate and normalize S1 to P1

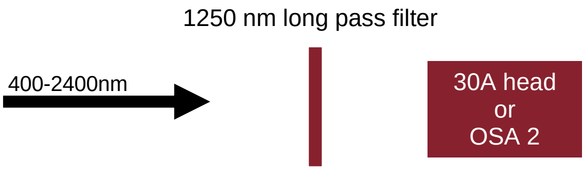


4) Record spectrum (S2) with OSA1 (2nm resolution, 350-1750nm)
5) Measure total power (P2) with 30W head (setting: 0.8< λ <6 microns)
6) Stitch S2 to normalized S1 at 600nm



7) Record spectrum (S3) after FEL1250 filter with OSA2 (2nm resolution, 1200-2400nm)

8) Measure optical power (P3) after FEL1250 filter with 30W head (setting: 0.8< λ <6 microns)
9) Correct S3 and normalize to P3



10) Stitch corrected S3 to normalized S2.
11) Integrate total spectrum and verify that the calculated power matches P2

Example of normalization process

Figure 2 shows typical spectra (S1,S2,S3) from an EXR-15 light source as an example. The visible part of the spectrum is characterized with OSA1 after reflection off two EO2 mirrors. If correctly calibrated OSA1 compensates internally for grating resolution variation and variations in detector response and contains filters which dampen the effect of higher order diffraction. Therefore the unit gives reliable readings in the 400-1600nm range. The delivery fiber and the Integrating Sphere (IS) have virtually zero wavelength dependent loss in this span as well so it is possible to obtain correct spectral shape within a few percent without any sort of compensation.

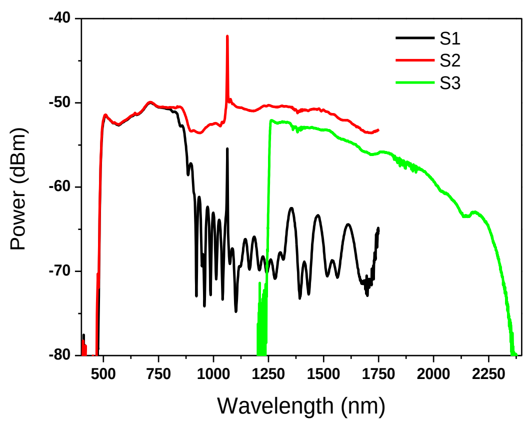


Figure 2: Typical spectra S1,S2,S3. In this case the power levels are respectively 1505 mW, 6260 mW, 2740 mW.

The loss on the EO2 mirrors is practically zero (R_{AVG} > 99 %) in the 400-800nm range[8] while the high loss above 1000 nm ensures that very little power is outside the detection window of OSA1 – as can be seen on figure 2 (black). The missing power is confirmed to be less than 5% - which means that the normalization is accurate within that value as well. The normalization is done by integrating the spectrum, divide it with the obtained area and then multiply with the measured power – in this case 1505 mW.

S2 is then integrated and normalized to overlap perfectly with the normalized S1 in the visible range (400-700nm). Figure 3 shows the two normalized spectra of which the corrected S2 (red curve) is now assumed correct until roughly 1600 nm.

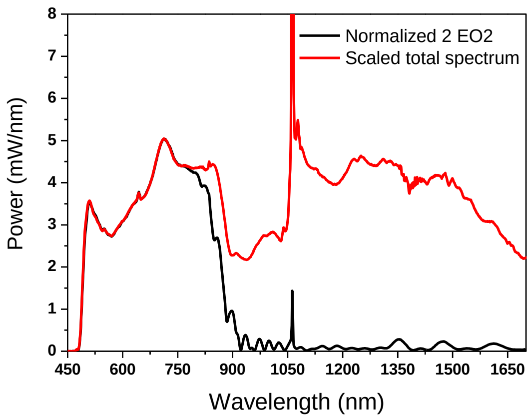


Figure 3: Correct spectral density from 400~1500 nm is obtained by stitching normalized S1 and S2 at 600 nm.

Above this point the OSA1 reading is less reliable so the overlapping S3 is used from 1500 nm and upwards. The infrared spectrum, S3, is recorded with OSA2 after transmission through a 1250 nm long pass filter. The filter is required because OSA2 suffers from significant higher order diffraction and stray light within the apparatus - without external filters, light at 1 micron will be detected at 2 microns etc., resulting in large aliasing errors. Further corrections are needed because of a level error from the internal detectors[9] and finally there are significant corrections from the loss in the integrating sphere[10] and the delivery fiber[11].

Figure 4 shows the summed compensation factor for fiber absorption, integrating sphere response, filter transmission and OSA2 detector correction.

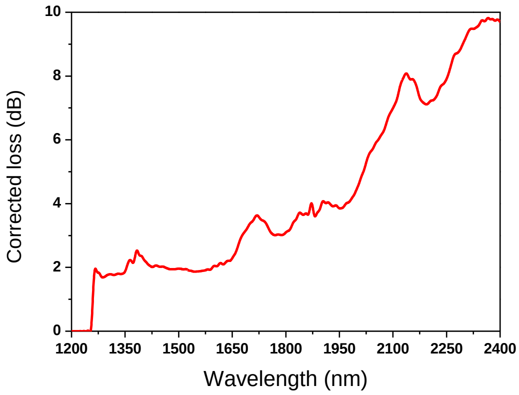


Figure 4: Accumulated error (extra loss) from OSA2 detectors, delivery fiber, integrating sphere and filter transmission.

S3 is corrected according to the curve in figure 4, normalized to P3 (2740 mW) and finally stitched to the corrected S2. The resulting curve is shown in figure 5 - this spectrum is considered the 'true' spectral profile of the light source. As a final checkpoint the power in the corrected spectrum is integrated and compared to the total power P2. In this particular case, the integrated power is 6090mW which is within 3% of the measured power.

Verification of calibration

An alternative method of characterizing spectral shape and density relies on discrete narrowband filters. Such filters with square profiles of a few nm spectral widths are commercially available and can be used to verify our calibration method. Firstly, the full transmission of the filter is measured (400-2400nm) to ensure that there is no power leak outside the desired spectral range. Compensating for the insertion loss of the filter, the transmitted power then directly gives the average spectral density within the filter transmission window. The results from 10 such measurements are included as black crosses in figure 5 - confirming that the global calibration process is sound.

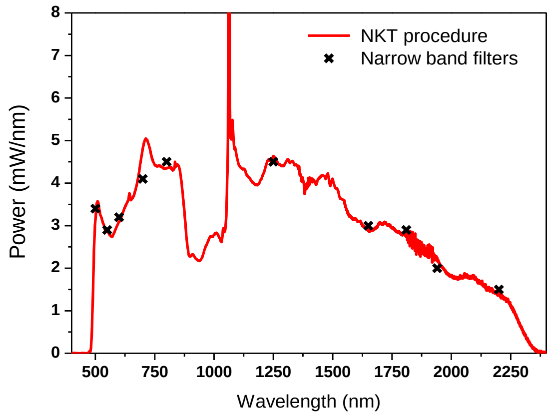


Figure 5: Comparison of normalization methods. Red curve based on stitching of three normalized spectra. Crosses indicate spectral density measured through narrowband filters.

Simplified version

The procedures described above are fairly time consuming and require expensive apparatus. The average users of white light lasers are usually satisfied with less rigorous characterization and when the main priority is visible or near IR light, the process can be reduced to simply measuring and normalizing the spectrum after two EO2 mirrors. EO2 mirrors are readily available and NKT Photonics recommends steps 1-3 as a quick first order approach – it will yield correct spectral shape and density in the 400-1500nm range with a very simple measurement.

Conclusion

This Application Note highlights the importance of Spectral Power Density over total power as a specification. Furthermore, it has been shown that simple measurement of the spectral power density leads to an incorrect specification. When choosing a supercontinuum laser source, it is vital that the *method* used to provide power specifications is clarified to ensure the true optical performance is obtained.

References:

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