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Fast Wavelength Calibration Algorithm for Optical Spectrum Analyzers

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***Abstract*—**In this paper an algorithm for fast wavelength calibration of Optical Spectrum Analyzers (OSAs) using low power reference gas spectra is proposed. In existing OSAs a reference spectrum with low noise for precise detection of the reference extreme values is needed. To generate this spectrum costly hardware with high optical power is necessary. With this new wavelength calibration algorithm it is possible to use a noisy reference spectrum and therefore hardware costs can be cut. With this algorithm the reference spectrum is filtered and the key information is extracted by segmenting and finding the local minima and maxima. Afterwards slope and offset of a linear correction function for best matching the measured and theoretical spectra are found by correlating the measured with the stored minima. With this algorithm a reliable wavelength referencing of an OSA can be implemented on a microcontroller with a calculation time of less than one second.

***Keywords*—**correlation, gas reference, optical spectrum analyzer, wavelength calibration

I. Introduction

Optical Spectrum Analyzers (OSAs) in optical telecommunication systems are used for measuring optical spectra to characterize the wavelengths and powers of the transmission channels. This is done during installation of new transmission systems and after detecting a malfunction of a system during operation.

In modern telecommunication systems channel spacing for DWDM transmission is down to 12.5 GHz [1] which equals a wavelength distance of approximately 100 pm. To measure wavelength deviations it is necessary to use an OSA with an absolute wavelength accuracy of about one tenth of the channel spacing or better. In modern high performance OSAs absolute wavelength accuracy of ±10 pm or less is therefore state of the art.

Looking inside an OSA the wavelength tuning is usually done by rotating the diffraction grating. The maximal angular error of the grating can be calculated with the grating equation for littrow condition [2] (which is a good approximation for many actual OSA setups):

$$m \cdot \lambda = 2 \cdot d \cdot \sin(\alpha) \tag{1}$$

The diffraction order is named m, the wavelength λ, the groove distance d and the incidence angle α.

In littrow condition the wavelength error Δλ resulting from the angular error Δα can be calculated from (1) as

$$\Delta\alpha = \frac{\Delta\lambda}{\sqrt{\left(\frac{2d}{m}\right)^2 - \lambda^2}} \tag{2}$$

Assuming a usual grating period of 1.11 µm (900 lines/mm), first order operation (m=1), 1550 nm wavelength and an allowed wavelength error of 10 pm the angular error of the grating must be less than $6.292 \cdot 10^{-6}$ rad or $3.605 \cdot 10^{-4}$ degrees.

This allowed angular deviation must be fulfilled during the whole recalibration interval of the instrument. For lab instruments this low angular error is difficult to reach due to aging of mechanical parts, for field measurement instrument this wavelength accuracy is very challenging because of additional errors due to temperature variation, moisture, vibration and shock.

To retain the high wavelength precision of the OSA during operation it is essential to recalibrate the wavelength regularly. Different types of wavelength references are used; fiber gratings, Fabry-Perot resonators or references gases are the most common ones. Calibrating an OSA with reference gas is preferable because of the inherent temperature and time stability. Acetylene $^{12}C_2H_2$ is the most used gas in the 1550 nm wavelength region due to its optimal wavelength range, high absorption coefficient, chemical stability and nontoxic behavior.

There are different topologies of optical spectrum analyzers in use. The block diagram of one preferable optical spectrum analyzer topology for continuous wavelength calibration is shown in figure 1 [3]. Two light paths travel independently through the OSA. One light path contains the measured spectrum and the other the reference spectrum. The wavelength reference system consists of a white light source which is preferably realized with a light emitting diode (LED). This emitted light is coupled into a reference gas cell and afterwards into the tunable optical bandpass filter. The bandpass of the monochromator is swept over the reference spectrum; a receiver detects the optical power, amplifies and digitizes the analog value. The digital value consists of the optical power plus noise and distortion from the photodiode,

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the following amplifier and the Analog to Digital Converter.

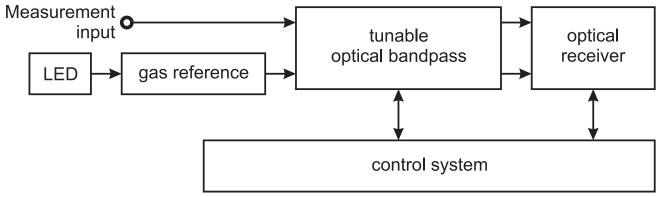

Fig. 1 Block diagram of OSA

From this noisy reference spectrum the absorption wavelengths of the reference gas must be extracted and the calculation of the wavelength correction parameters done. Therefore high optical power at the receiver is desirable for a nearly noise free reference spectrum with precisely detectable gas minima. This solution is very expensive because of the costly high power LED, the low noise photodiode with amplifier and the precise optical coupling between LED, gas cell, tunable optical bandpass and optical receiver.

A solution with cheap hardware for wavelength calibration is favorable to reduce overall device costs and therefore to give a competitive advantage over other vendors. This leads to a low power LED, simple but lossy optical coupling and a receiver with relatively high noise. The measured reference spectrum is noisy and an efficient algorithm is needed which extracts the correct reference wavelengths to calibrate the OSA.

In this paper an efficient algorithm is presented which calculates the reference minima from a noisy spectrum. Additional attention is given to the fact that this algorithm will be implemented on a simple microcontroller without floating point unit. The calibration procedure should not interrupt the regular measurement work of the user. Therefore a maximum execution time of one second is acceptable.

The wavelength errors of the OSA and the resulting calibration demands are shown in Section II. In Section III the characteristics of the used Acetylene spectra are analyzed and the reasons for the used algorithms are developed. In Section IV the wavelength calibration algorithm is presented and in Section V first results are shown. The final Section VI gives an outlook on the future work.

II. Calibration Algorithm Specification

Looking at the setup of the Optical Spectrum Analyzer (figure 2) we see that the light is emitted from an optical fiber. The beam shaping lens collimates the light. A diffraction grating separates the wavelengths by dispersing the light. The deflecting prism reflects the light back to the grating for a second pass and changes the polarization for polarization dependent loss compensation. With the beam shaping lens the light is focused onto an optical fiber which is coupled to a photodiode. The wavelength selection is done by rotating the diffraction grating.

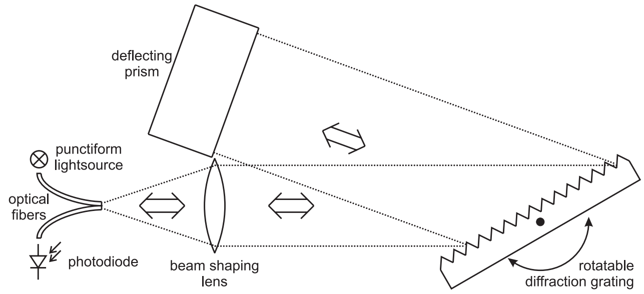

Fig. 2 Optical setup of OSA

The main sources of wavelength errors within this OSA during operation are:

1) Errors of the grating angular sensor due to mechanical tolerances, temperature variation, humidity and aging.
2) Errors of the mechanical setup over temperature due to thermal material expansion, bend and torsion.
3) Change of grating period due to temperature variation.
4) Mechanical deformation of the mechanical setup due to excessive shock and vibration.

To compensate these above described errors it is at least necessary to do a linear correction:

$$\lambda_{corr} = a \cdot \lambda_{meas} + b \tag{3}$$

The corrected wavelength is λ_{corr} which is calculated from the uncorrected wavelength λ_{meas} and the parameters for slope a and offset b which are dependent from the above mentioned error sources and vary during operation.

It is necessary to correlate the measured reference spectrum with the saved reference data in two dimensions to get the values of a and b. This task is very computing intensive and it needs a high data reduction algorithm before doing the correlation within a short time.

The maximum error of λ_{corr} must not exceed ±10 pm over the C-band.

III. Characteristics of Gas Reference Spectra

In figure 3 a nearly noise free measured $^{12}C_2H_2$ spectrum can be seen. The exact wavelengths of the minima can be found in [4]. The spectrum is divided into two branches where the lower wavelength minima are named R-branch and the higher wavelength minima P-branch with numbers from inside to outside.

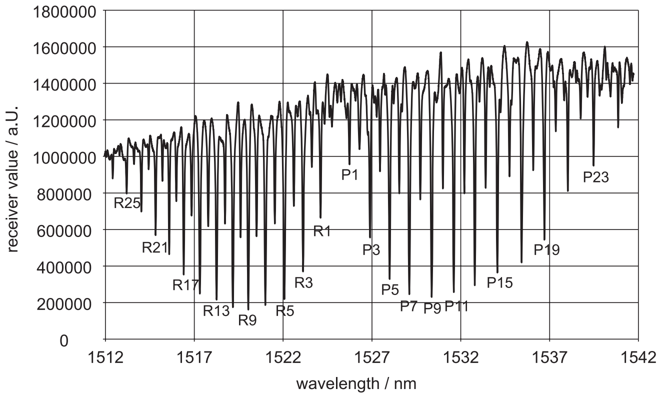

Fig. 3 Gas reference spectrum

The main challenge of the algorithm is the limited computing speed of the microcontroller which is built in the OSA. The spectrum in figure 3 consists of about 9500 measurement points and it is illusory to correlate the whole measured and the reference spectra with respect to offset position and slope. Therefore the amount of data must be reduced and essential information extracted before correlation.

The distance between two adjacent deep minima (with odd numbers) shows the following behavior which is depicted in figure 4. For the minima differences we see a linear function within each branch. If using only the minima difference of one branch it is not possible to determine the correction parameters a and b. Between the R and P branches there is a discontinuity of the minima distances and when the minima R1 and P1 are determined correctly they can be used for finding the correct values of the parameters a and b.

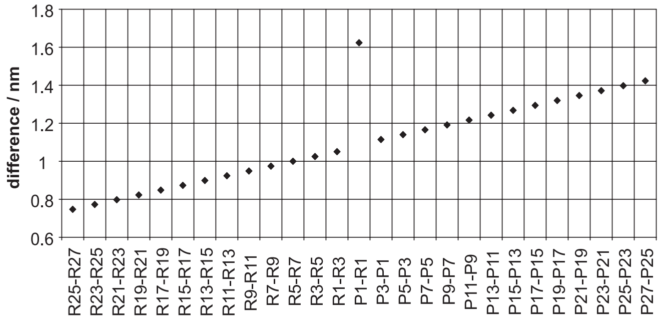

Fig. 4 Wavelength difference between reference gas minima

When having measured a noisy reference spectrum it is nearly impossible to detect reliably R1 and P1 for finding the correct parameters a and b. Therefore it is necessary to use additional information for an efficient and reliable assignment of the theoretical minima with the measured ones.

It is necessary to use the relative depth as additional information for mapping the minima. The R and P minima with low numbers (R1 to R5 and P1 to P7) show a steep depth gradient (figure 3) which gives additional information for correlation. Therefore a reliable mapping of theoretical and measured minima with the information of position and depth is possible.

IV. Algorithm for Wavelength Calibration

The block diagram of the used wavelength calibration algorithm is shown in figure 5. The measured gas reference spectrum is filtered with a Savitzky-Golay filter [5] which width is matched to the bandwidth of the OSA. Afterwards position and relative depth of the minima are extracted and these data are correlated with the saved gas reference data. The best parameters for slope and offset are extracted from the minimal deviation between measured and theoretical spectrum.

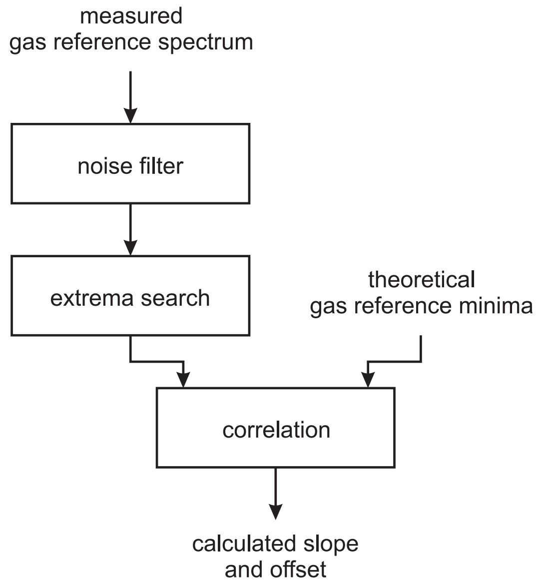

Fig. 5 Block diagram of wavelength calibration algorithm

Figure 6 shows a measured reference spectrum. This noisy signal was measured with the target OSA for the algorithm implementation.

The low LED power leads to a reference spectrum which is within the noise of the receiver circuit. In the following sections this spectrum is taken as an example to show the operation of the correlation algorithm.

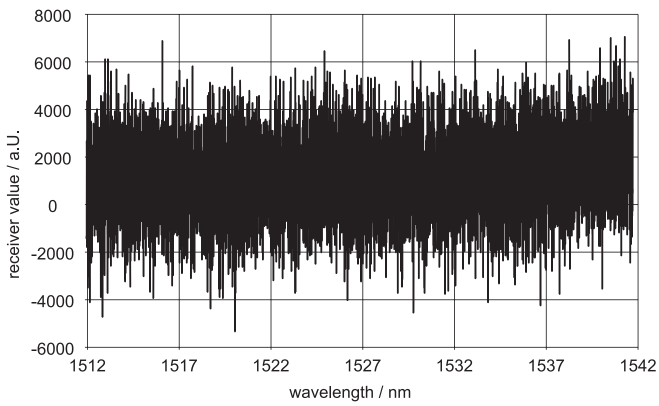

Fig. 6 Exemplary measured reference spectrum

During the next subsection the parts of the calibration algorithm processing the exemplary spectrum are explained in detail.

A. *Filtering the optical spectrum*

The spectrum in figure 6 was filtered using a Savitzky-Golay filter [5]. The filter shape is parabolic and the filter width is matched with the width of the reference minima (in this implementation 61 filter points). So the shape of the minima is unchanged while the noise is suppressed.

The filtered values Rf are calculated out of the measured values R and the filter coefficients F of a filter with width 2n+1.

$$Rf_k = \frac{\sum_{i=-n}^{n} R_{k+i} \cdot F_i}{\sum_{i=-n}^{n} F_i} \tag{4}$$

All numbers are integers for efficient calculation on a small microcontroller. The sum of filter values is

$$\sum_{i=-n}^{n} F_i = 2^m \tag{5}$$

with an integer m for replacing the division by a shift operation.

This filtering needs $O(n \cdot k)$ operations where n is the filter with and k is the number of points in the measured spectrum.

The spectrum shown in figure 6 was filtered and the result is now shown in figure 7. In contrast to figure 6 gas minima can now be seen.

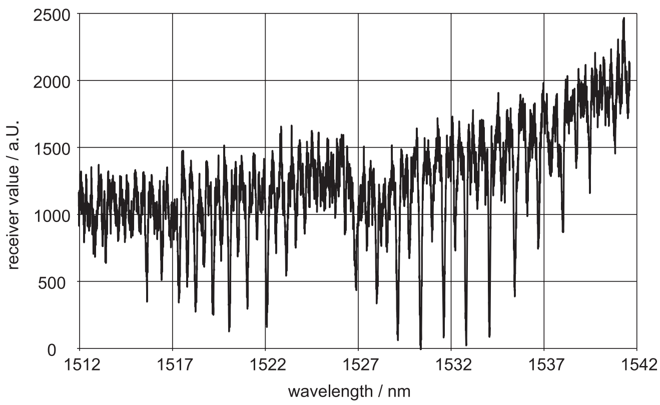

Fig. 7 Exemplary filtered reference spectrum

B. *Minimum and Maximum search*

To reduce the amount of data for the correlation it is necessary to extract the local minima with position and relative depth.

A simple local minima and maxima search algorithm tests the local minimum and maximum condition within an area of ±n points around each point i of the measured and filtered reference spectrum Rf:

$$\begin{aligned} Rf_{min,i} &= \min(Rf_{i-n} \dots Rf_{i+n}) \\ Rf_{max,i} &= \max(Rf_{i-n} \dots Rf_{i+n}) \end{aligned} \tag{6}$$

The found local minima are $Rf_{min,i}$ and the adjacent local maxima are $Rf_{max,i}$.

This algorithm needs $O(n \cdot k)$ operations with k depicting the number of reference spectrum points and n the distance of the local extreme value search.

To save computing time a modified algorithm is used to calculate the extreme values. In the first step the spectrum is pre-segmented and an absolute minimum and maximum is extracted from each segment. During the second step each local extreme is calculated from five neighbored segments. Due to the segmentation the second calculation step needs negligible time compared to the first step. Compared to the simple minimum search algorithm the number of operations is reduced to $O(k)$.

In figure 8 the reference spectrum with the calculated maxima (red circles) and minima (green crosses) is shown.

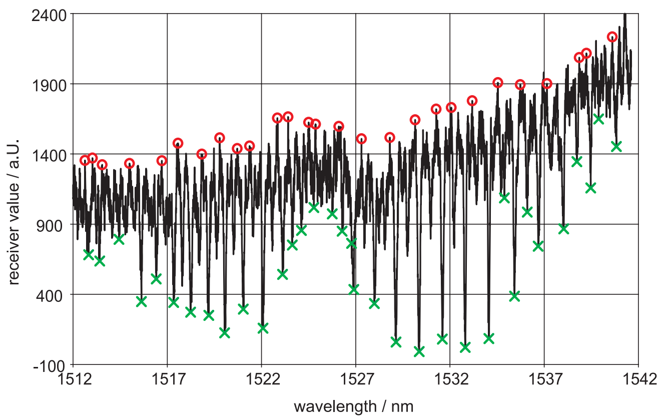

Fig. 8 Minima and maxima of measured reference spectrum

The power of the reference spectrum varies with LED power, coupling coefficient, aging, device tolerances. Therefore it is necessary to normalize the minima before comparing with the saved reference values:

$$nRf_{min,i} = \frac{\frac{Rf_{min,i}}{Rf_{max,i}}}{\min\left(\frac{Rf_{min,1}}{Rf_{max,1}} \dots \frac{Rf_{min,j}}{Rf_{max,j}}\right)} \tag{7}$$

The normalized minima are $nRf_{min,i}$ and j is the maximum number of minima.

With these normalized minima the following time efficient correlation is possible.

C. Correlation

During the correlation the best parameters for slope a and offset b (see also equation 3) must be found to match the measured reference spectrum optimally with the stored reference data. The algorithm for the spectral correlation works as follows:

5) Set the parameters for slope a and offset b.
6) Calculate for all measured minima $nRf_{min,i}$ the corrected wavelength (equation 3) using parameters a and b.
7) Find for each stored reference minimum the measured minimum with minimal distance of wavelength and depth.
8) Sum up all found minimal distances for all reference minima to find the deviation between stored reference minima and measured reference minima.

This algorithm is repeated for several slopes a and offsets b to find the minimal deviation between the stored reference minima and the measured reference minima. The corresponding parameters a and b for this minimal deviation are the wavelength calibration parameters for calculating equation (3).

Figure 9 shows the resulting error between the stored and measured reference minima for different parameters a and b. The colors in the graphic depict the distance between the stored minima and the measured minima corrected by the parameters a and b. The blue area in the middle of the figure shows the area with the minimal wavelength and depth difference between stored and measured minima. This is the global optimum and the corresponding parameters a and b are used for wavelength calibration.

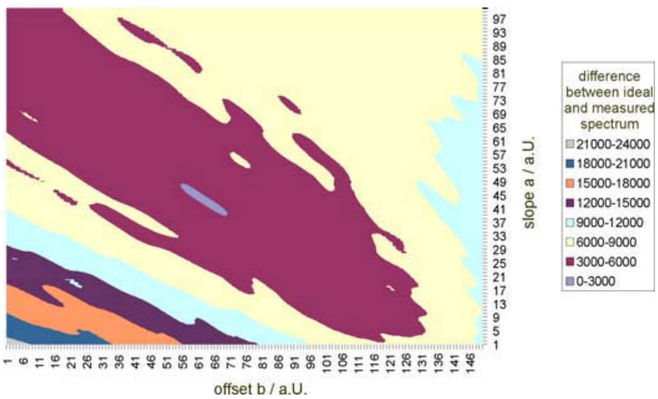

Fig. 9 Topology of correlation distance

It is not possible to find the optimum parameters a and b with a straightforward minimum search algorithm because depending on the measured reference spectrum several local minima are in the topology of figure 9 which can lead to wrong calibration parameters. Therefore it is necessary to scan the whole parameter ranges of a and b to find the absolute minimum.

In a first iteration of this correlations algorithm the stored and measured reference spectrum deviations for the whole area of a and b are calculated to find the global minimum. After finding the approximate values for a and b these are refined with additional iterations.

Looking at the needed number of computing operations we see that the basic correlation algorithms needs $O(j \cdot o \cdot na \cdot nb)$ operations where j is the number of measured minima, o the number of stored reference minima, na the number of different slope values a and nb the number of different offset values b.

It is not necessary to search all measured minima for each stored minimum to find the minimal difference. Therefore the computing operations can be reduced to $O((j + o) \cdot na \cdot nb)$ by pre-selecting suitable pairs of measured and stored minima.

V. Results

After the above described theoretical calculations the algorithm was implemented using a C++ compiler on a PC. For testing the correct work several gas line spectra were measured using the target OSA. These measured reference spectra were analyzed using the algorithm and the calculated parameters a and b were compared with the values measured with different methods. The shown spectra in figure 3 and figure 6 are two examples with different LED power. The algorithm shows correct operation even with lower LED power than the spectrum shown in figure 6.

Time measurements of the wavelength reference calculation were made using an Intel Celeron Processor with 1.5 GHz clock speed. The whole algorithm with filtering, minima search and correlation needed 52 ms calculation time for a 9500 point measured reference spectrum. When using a microcontroller with a tenfold lower performance the calculation time is much below the targeted one second and therefore acceptable for practical work with an OSA.

VI. Conclusion and Future Work

During this work a computing time efficient algorithm working completely with integer arithmetic was developed. This algorithm extracts from the complete spectrum the significant minima with wavelength and depth. The following correlation extracts the correct slope and offset parameters within some milliseconds. Therefore the first goals of this work were achieved by implementing a time efficient algorithm which is capable to extract the correct wavelength parameters out of a noisy measured reference spectrum.

In the next step it is planned to test the algorithm stability and wavelength deviation with different noise levels by using a Monte-Carlo simulation on a PC.

The next further step will be the implementation into a real OSA to verify the wavelength calibration under practical conditions and compare the algorithm to existing ones.

Acknowledgment

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