Spectral measurement with a linear variable filter using a LMS algorithm

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Abstract

This paper presents spectral measurements using a linear variable optical filter. A LVOF has been developed for operation in the 530 nm - 720 nm spectral band and has been fabricated in an IC-compatible process. The LVOF has been mounted on a CMOS camera. A Least Mean Square algorithm has been implemented to calculate the spectrum of light from the recorded image on the CMOS camera. A spectral resolution of 0.5 nm has been achieved using the algorithm. The spectral resolution is limited by the monochromator accuracy used for calibration.

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Linear Variable Filter, micro-spectrometer, on-chip, Least Mean Square

1. Introduction

The growing number of applications of compact spectroscopic devices has prompted research in the area of spectrometer design and the development of miniature dispersion elements, detectors and optics. A very attractive approach to design a compact spectrometer is to use MEMS technologies for the fabrication of spectrometer components, which makes it possible to achieve a small overall system size, low production cost per item and provides the possibility to integrate several components on the same wafer, thus reducing assembling and alignment work [1]. Various spectrometers fabricated with MEMS technologies were reported in the literature, including Fourier Transform Spectrometers and Fabry-Perot tunable spectral filters as well as diffraction grating based spectrometers implemented according to classical principles or in a planar waveguide. However, the small size of a miniaturized spectrometer implies that the size of the entrance aperture is also small. This results in reduced optical throughput and, consequently, in a decreased sensitivity. Fabry-Perot spectrometers have inherently higher throughput – resolving power product than grating and prism based devices. This implies that a Fabry-Perot microspectrometer potentially is more sensitive than other types of devices. Moreover, an IC-compatible fabrication of Fabry-Perot filters allows higher level of device integration. A 16-channel Fabry-Perot filters array integrated with photodetectors has been demonstrated in [2]. However, the increase in the number of spectral channels...
complicates the fabrication process since more lithography steps are required to make many Fabry-Perot cavities of different thicknesses. An alternative approach for the fabrication of an IC-compatible tapered Fabry-Perot has been introduced by authors in earlier works [3]. A Linear Variable Optical Filter (LVOF) is fabricated with an IC-compatible process on top of a substrate which contains a CMOS array of photodetectors. Adding external optical components including entrance aperture and collimating lens (see Fig. 1), such a filter provides a spectral distribution which can be read by the photodetector array. The LVOF is a Fabry-Perot etalon with the spacing between etalon mirrors varying linearly along one direction. It can be implemented as a tapered structure consisting of a variable thickness spacer between two multilayer dielectric mirrors (see Fig. 2). The mirrors are fabricated by the IC-compatible deposition of SiO₂ and TiO₂ layers. The spacer is fabricated using a photoresist reflow process [4]. In this process, a lithographically patterned resist layer on top of a SiO₂ layer reflows at a glass transition temperature resulting in a variable thickness photoresist layer. The photoresist pattern is transferred into SiO₂ using plasma etching.

![Fig. 1. (a) The concept of LVOF-based micro-spectrometer (b) operation of a LVOF illuminated by collimated light](image)

For any monochromatic wavelength there is a stripe of pixels that would be illuminated on the CMOS camera. The width of the stripe can be calculated as: \( \Delta x = \frac{\text{HPBW}}{\theta} \), in which HPBW is the bandwidth of the LVOF at any position and \( \theta \) denotes the slope of the LVOF. When the LVOF is illuminated with light containing several spectral lines, the recorded image is the superposition of stripes illuminated for each wavelength. Therefore, the recorded image on the camera does not directly show the spectrum of light. The spectrum of the light has to be calculated from the raw data recorded by the camera. Different algorithms and approaches can be suggested [5]. In this paper a Least Mean Square algorithm has been used to extract the real spectrum of light out of the raw data recorded on the pixels of the camera.

2. Calibration of the LVOF spectrometer

Let us assume the spectral bandwidth of interest is divided into N spectral channels and there exists N spectrally different (independent) detectors. The element \( C_{ij} \) in matrix C is defined as the intensity of channel i of the detector to component j in the spectrum (i, j = 1..N). The matrix C can be directly formed with the data from a calibration measurement process. The maximum value of N is the number of the pixels on the camera, but can be limited by the spectral capability of the calibrating instrument (a monochromator). Hence, the measured intensity on the detector channels can be described as:

\[
\begin{bmatrix}
    d_1 \\
    d_2 \\
    \vdots \\
    d_N
\end{bmatrix}
= \begin{bmatrix}
    c_{11} & c_{12} & \cdots & c_{1N} \\
    c_{21} & c_{22} & \cdots & c_{2N} \\
    \vdots & \vdots & \ddots & \vdots \\
    c_{N1} & c_{N2} & \cdots & c_{NN}
\end{bmatrix}
\begin{bmatrix}
    I_1 \\
    I_2 \\
    \vdots \\
    I_N
\end{bmatrix}
\]

or \( D_{IN} = C_{IN} \times I_N \).

In which \( d_i \) denotes the measured intensity in channel i and \( I_i \) denotes the input spectrum intensity in channel i that has to be calculated. In other words, Matrix \( D_{IN} \) is the raw data recorded on the camera pixels, matrix \( I_{IN} \) is the spectrum of light that has to be calculated and matrix \( C_{IN} \) is the calibration matrix which is determined during the calibration process. Figure 2 shows schematically how the calibration is done. The light from a broadband source (Xenon lamp) is filtered by a monochromator and the selected wavelength is varied in the spectral range of interest for all the N spectral channels. For each spectral channel from the above equations, calibration is equivalent to
deliberately having: \( t = \{0, 0, \ldots, 0\} \) when channel \( m \) is selected from the monochromator. In this case the recorded intensities on the pixels gives the values of column \( m \) of the \( C \) matrix.

![Fig. 2. Principle of calibration process of LVOF spectrometer.](image)

For a properly designed and fabricated LVOF, Matrix \( C \) has no singularity and it is possible to take the inverse transform of the matrix. Therefore matrix \( I \) can be calculated as:

\[
\begin{bmatrix}
I_1 \\
I_2 \\
\vdots \\
I_N
\end{bmatrix} =
\begin{bmatrix}
c_{11} & c_{12} & \cdots & c_{1N} \\
c_{21} & c_{22} & \cdots & c_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
c_{N1} & c_{N2} & \cdots & c_{NN}
\end{bmatrix}^{-1}
\begin{bmatrix}
d_1 \\
d_2 \\
\vdots \\
d_N
\end{bmatrix}
\]

or \( I_{IN} = C_{N}^{-1} \cdot D_{IN} \)

However, since the measured matrix \( D \) is added with noise the above solution does not give the best answer. The sources of the disturbance (or noise) in the measured data include primarily insufficient collimation and out of band signal. If the disturbance in the system is not negligible to the signal (low SNR) the result of the above approach would be negative values in some spectral channels which are not physically acceptable. An iterative procedure needs to be implemented to calculate matrix \( I \) minimizing matrix \( E \):

\[
E =
\begin{bmatrix}
d_1 \\
d_2 \\
\vdots \\
d_N
\end{bmatrix} -
\begin{bmatrix}
c_{11} & c_{12} & \cdots & c_{1N} \\
c_{21} & c_{22} & \cdots & c_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
c_{N1} & c_{N2} & \cdots & c_{NN}
\end{bmatrix}
\begin{bmatrix}
\hat{I}_1 \\
\hat{I}_2 \\
\vdots \\
\hat{I}_N
\end{bmatrix}
\]

In which matrix \( \hat{I} \) is the estimate of \( I \). The LVOF used operates in 530 nm – 720 nm spectral range. It is fabricated on a glass substrate and mounted on a CMOS camera. Figure 3a shows inverted images recorded on the camera at several wavelengths in the calibration process. Fig 3b shows the intensity profile of the pixels at different wavelengths. It can be seen that the peak of the illuminated region on the CCD is shifted as the wavelength is changed. It can be noted from Fig. 3b that for each monochromatic wavelength light HPLW (Half Power Line Width) is 7-9 pixels. An automatic calibration program has been implemented to sweep the wavelength in minimum possible steps of 0.5 nm and record the intensity of the pixels to form the \( C \) matrix.

![Fig. 3. (a) Inverted recorded image on the camera and (b) intensity profile on camera pixels at different wavelength in calibration process](image)
3. Spectral measurements

The spectral range of the LVOF makes it suitable to measure the spectrum of a Neon lamp, which has most of its peaks in that region. Fig. 4a shows and image recorded on the CMOS camera and Fig. 4b the intensity profile of the pixels when the LVOF illuminated with a Neon lamp through the collimating optics. An Infrared blocking filter has been used to remove the Infrared part of the Neon lamp spectrum. Fig. 4b is the raw data, as described before, from which the spectrum of the Neon lamp has to be calibrated. The iterative LMS is based on the following equations:

![Image of a spectrum](image)

Fig. 4. (a) recorded image on the camera when illuminated with Neon lamp (b) intensity of the pixels when illuminated with Neon lamp

A Least Mean Square algorithm is applied to minimize matrix E. The final value of E should be comparable with the noise and disturbance in the system. Fig. 5 shows the final result of the LMS algorithm which gives the values of matrix \( \mathbf{J} \), the best estimate of the spectrum of light. The calculated spectrum has very good agreement with previous measurements using a high-resolution grating-based microspectrometer [6] and proves the possibility to achieve high-resolution micro-spectroscopy with LVOFs when signal processing is applied. Using a calibration source and additional mathematical modeling, it could be possible to avoid a long calibration process to find the matrix and is the subject of future research.

![Image of a spectrum](image)

Fig. 5. Calculated spectrum of Neon lamp using the LMS algorithm

References