STRAY-LIGHT COMPENSATION IN THIN-FILM FABRY-PEROT OPTICAL FILTERS: APPLICATION TO AN ON-CHIP SPECTROMETER

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ABSTRACT

This paper describes a method for significantly improving the performance of integrated Fabry-Perot- based optical spectral analysers, in terms of spectral selectivity and/or requirements on the input light beam conditioning. The method is based on compensation of the stray-light components induced by the non-idealities of both the incident light beam and a Fabry-Perot (F-P) resonator.

The compensation structure consists of the same layer stack as used in the active F-P filter. The difference is that the optical length of the cavity is decreased below $\lambda/10$ (<40 nm if applied for measurements in the visible spectral range). This avoids any resonance inside the cavity for the spectral range of interest. However, the parasitic signal that is caused by stray-light transmittance is similar to that of the active channel and can be used for compensation.

The method was applied to an array-type on-chip spectrometer operating at the visible spectral range. The spectral selectivity is improved by a factor 10 compared to the device without compensation. Moreover, applicability of the device is enlarged, as the requirements on the measured light beam (e.g. presence of stray-light, light beam divergence, background light levels, etc.) are less demanding.

INTRODUCTION

In previous work [1], it was demonstrated that a thin-film Fabry-Perot (F-P) resonance filter can be used as an effective wavelength-selecting element for application in spectral analysers. Moreover, it was shown that an array composed of fixed cavities of different width [2] has several operational advantages compared to devices that involve mechanical scanning [3].

Based on this principle, a 16-channel, IC fabrication compatible, on-chip spectrometer operating in the visible spectral range was realised. Each of the 16 channels is composed of an F-P thin film optical filter (tuned to a certain wavelength) integrated on top of a pn-junction photodiode (see Fig. 1). As can be seen in Fig. 2 (typical measured spectral response), such a device suffers from relatively high background signal levels caused by imperfections in the F-P filter structure and in the input light beam (stray light). This paper introduces a new compensation technique applicable for devices based on thin-film Fabry-Perot optical filters.

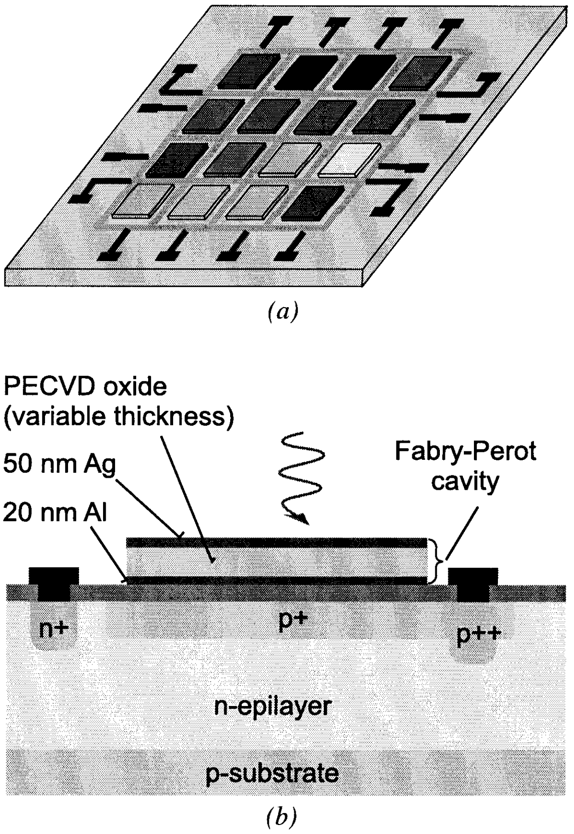

Fig. 1: Schematic view of a 16-channel array-type on-chip spectrometer for the visible spectral range: concept (a); cross-section of one of the channels based on a Fabry-Perot optical resonance filter (b).

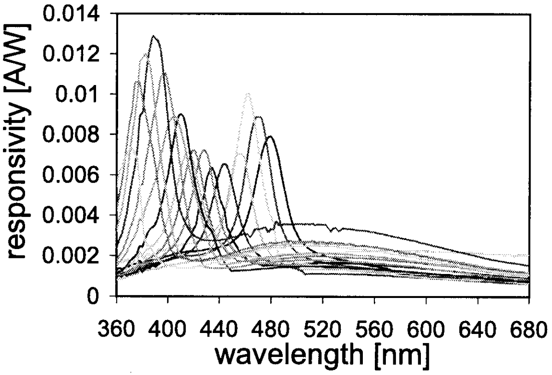

Fig. 2: Typical measured spectral response of 16-channel on-chip F-P based spectrometer for the visible spectral range.

STRAY-LIGHT COMPENSATION TECHNIQUE FOR F-P OPTICAL FILTERS

Ideal Fabry-Perot resonator

If an ideal plane-wave of normal incidence interacts with an ideal F-P resonance cavity (optical length $\lambda_{res}/2$), as shown in Fig. 3, only a narrow spectral band around the resonance wavelength (λ_{res}), is transmitted.

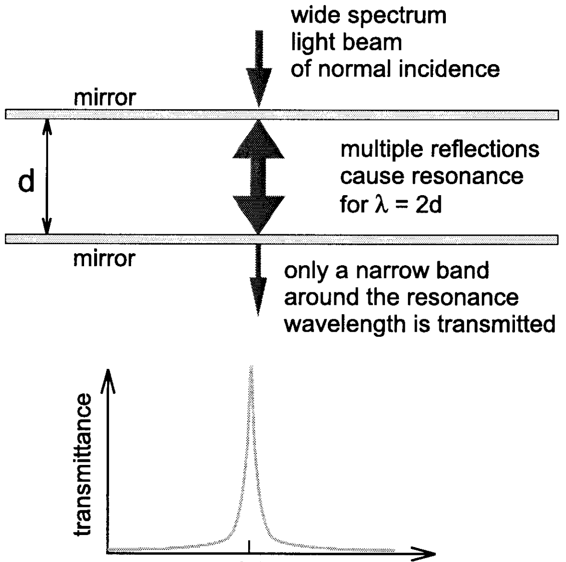

Fig. 3: Interaction of an ideal light beam with an ideal Fabry-Perot optical filter.

Non-ideal Fabry-Perot resonator

In a real F-P structure, composed by a stack of deposited thin-film layers, the interfaces between different layers are not ideal. As an example, Fig. 4 shows AFM roughness measurement of a 40 nm silver layer evaporated on a 300 nm thick silicon nitride membrane. Typical root mean square (RMS) surface roughness values between 8 to 15 nm were measured [4]. Such a roughness yields total integrated scattering (TIS) in the visible spectral range that exceeds 1 % of the impinging light [5]. This scattered light results in the increased transmittance outside the narrow resonance band to which the F-P filter is tuned (Fig. 5).

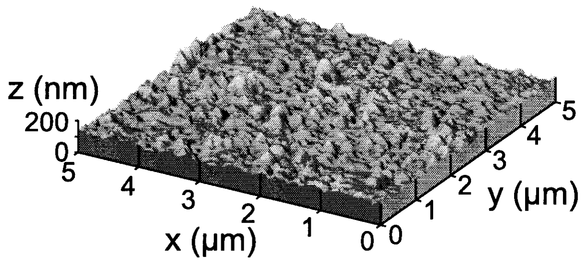

Fig. 4: AFM surface scan of a 40 nm silver layer evaporated on a 300 nm silicon nitride membrane.

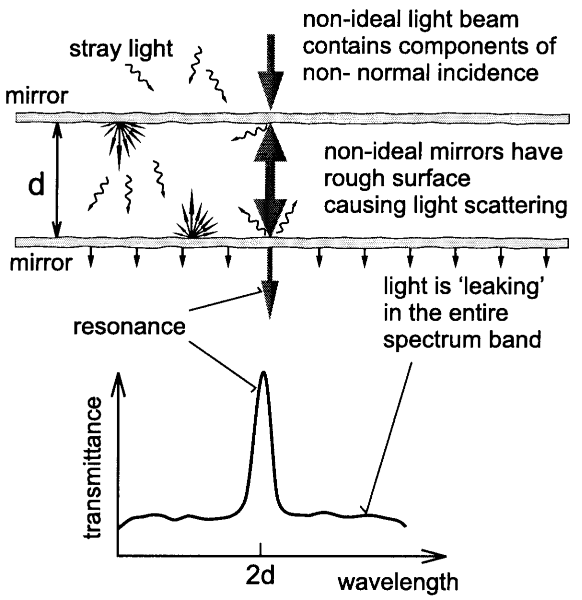

Fig. 5: Interaction of a non-ideal light beam with a non-ideal Fabry-Perot optical filter.

Chemical mechanical polishing (CMP) can be used to decrease the surface roughness to below 1 nm [6] so that TIS will significantly be reduced. However, CMP is not always easily applicable. Furthermore, any imperfection of the incident light wave (components with non-normal incidence, stray-light) also contributes to an increased parasitic background signal, which therefore cannot be entirely avoided.

Compensation structure

A solution to this problem is to use a compensation structure, as shown in Fig. 6. It consists of the same layer stack as used in any of the active channels. The difference is that the optical length of the cavity is decreased below λ/10 (<40 nm if applied for measurements in the visible spectral range). This excludes any resonance inside the cavity. However, the parasitic signal caused by stray-light transmittance is similar to that of the active channel and can be used for compensation. Photodiodes are integrated underneath both the active and the compensating device and, after subtraction of the photocurrents, a compensated signal results. It should be mentioned that the conventionally used dark current compensation (an opaque layer deposited on top of a photodetector) compensates only for the non-idealities (dark current) of the detector itself. The presented method, in contrary, compensates for the non-idealities of the detector, F-P filter and incident light beam at the same time.

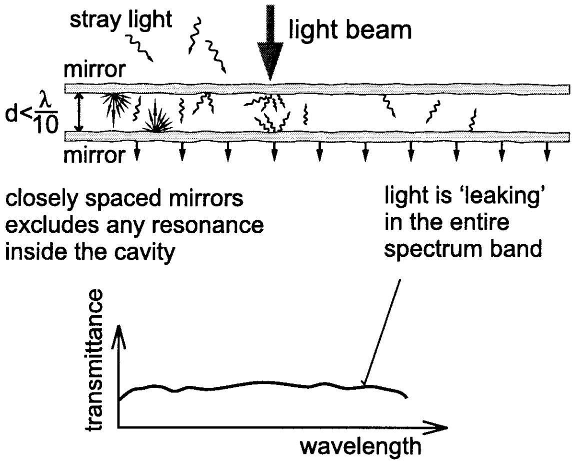

Fig. 6: Cross-section of the compensation structure and its principle, as introduced in this paper.

EXPERIMENTAL: APPLICATION TO AN ON-CHIP SPECTROMETER

An on-chip spectrometer with 8 active channels and 8 used for compensation has been realised to demonstrate effectiveness of the compensation method presented. Fig. 7 shows photographs of a realised device with photodiodes in a 2x8 configuration and the compensation channel placed next to the associated active one. If the impinging light beam has a uniform spatial distribution, only one compensation channel for all active channels is sufficient.

Fig. 8 shows the typical measured spectral response of both an active and a compensation channel. Unlike in Fig. 2, this measurement was performed without any optics for light beam conditioning. After photocurrent subtraction, the average background signal level is decreased by a factor of 10 and, as a consequence, the spectral selectivity of the device is increased. When the overall contribution of the background component to the output signal (integral of the photocurrent over the entire measured spectral band) is considered, the significance of the method presented for application in on-chip spectrometers is even more obvious.

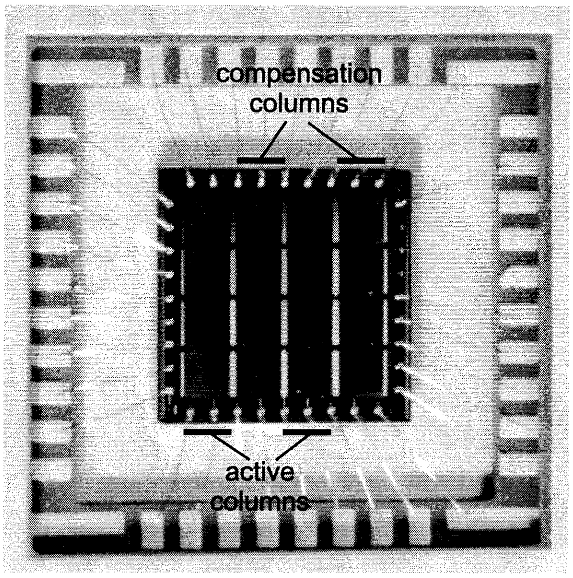

Fig. 7: A photograph of an 8-channel on-chip spectrometer with 8 active and 8 compensating channels.

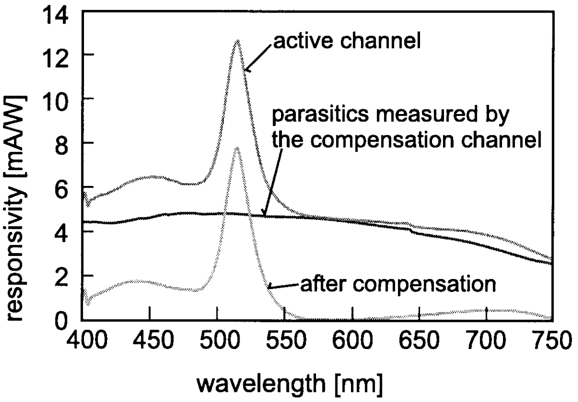

Fig. 8: Measured spectral response of both the active and compensating channel; when subtracted, the parasitic signal decreases by about a factor 10.

SEM photograph of one of the active channels in cross-section is shown in Fig. 9. Above the silicon substrate with integrated pn-junction photodetector, 4 different layers can be observed: a 250 nm thermal SiO_2 field oxide, 20 nm Al bottom mirror, 250 nm PECVD-oxide resonance cavity and 50 nm Ag upper mirror.

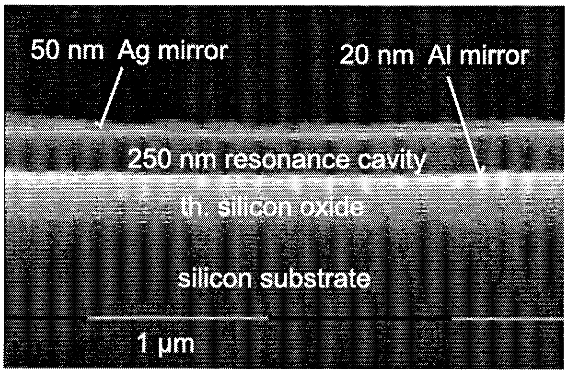

Fig. 9: SEM photograph of one of the active channels in cross-section.

CONCLUSIONS

A compensation method, applicable to devices based on thin-film Fabry-Perot optical resonators, has been demonstrated. The method was applied to an array-type on-chip spectrometer operating at the visible spectral range. The spectral selectivity is improved by a factor 10 compared to the device without compensation. Moreover, applicability of the device is enlarged, as the requirements on the measured light beam (e.g. presence of stray-light, light beam divergence, background light levels, etc.) are less demanding.

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