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TUNABLE OPTICAL FILTER FOR BIOMOLECULES DETECTION IN BIOLOGICAL FLUIDS

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Abstract — *This paper describes a Fabry-Perot tunable optical filter that can be used in a laboratorial microsystem for biomolecules detection in biological fluids. It consists of two parallel thin silver mirrors with a β-PVDF (poly(vinylidene fluoride)in its β phase) film in the middle as the resonance cavity. The adjustable mirrors spacing is performed through an electric voltage inducing dipolar orientation in the β-PVDF film. Compared with an array of non-tunable optical filters with different cavity lengths, this device has a reduced area, its fabrication process is easier and it covers a wider spectral range, which for the reported application enables the analysis of several biomolecules rather than a fixed number. Moreover, the tunable optical filter enables the measurements using white light illumination, thus avoiding the use of a wavelength dependent light source. This characteristic makes the laboratorial microsystem portable ensuring that the analysis can be performed at any location with instantaneous results, without the use of complex and expensive analysis systems.*

Key Words: *tunable optical filter, biological fluid analysis, PVDF*

I INTRODUCTION

For diagnostic reasons patients are often subject to spectrophotometric analysis of their biological fluids. Usually, the samples need to be sent to a laboratory for spectrophotometric analysis and the results become available after several hours, sometimes days. As a consequence a reliable diagnosis cannot be performed within the consultation time. The need for rapid and on-line measurements with low sample volumes has led to the development of microsystems with the fluidic, detection and readout system integrated in a single module. The advantages associated with shrinking clinical analysis systems include: reduced sample size, reduced costs, high degree of system integration, automation of measurements, short response time, improved analytical performance and laboratory safety [1]. Previously developed laboratorial microsystems in a single module with absorbance detection require a wavelength dependent light or waveguides inserted into the device for illumination [2, 3]. Illumination using only a white light source requires the use of selective optical filters.

This paper describes a tunable optical filter for application in spectrophotometric analysis of biological fluids, especially the colorimetric measurement, by optical absorption, of the concentration of biomolecules in those fluids.

II BACKGROUND

II.1 THE SPECTROPHOTOMETRIC ANALYSIS

In clinical diagnostics, spectrophotometry by optical absorption is often used to determine the concentration and/or amount of a particular biomolecule in biological fluids samples [4]. The measurement is based on colorimetric detection by the optical absorption in a part of the visible spectrum defined by the reaction of the specific biomolecule with a specific reagent. When the biomolecule reacts with the reagent a color is produced. The intensity of that color is directly proportional to the concentration of the biomolecules in the sample. A laboratorial microsystem to measure the concentration of biomolecules in biological fluids samples was previously implemented. It includes an array of 16 non-tunable Fabry-Perot optical filters. The covered spectral range was between 495 and 570 nm [5]. However, in human's biological fluids, there are other biomolecules that have their absorption spectral range outside those values [6]. Rather than an array of optical filters, a tunable optical filter placed on the top of the laboratorial microsystem enables the detection of more biomolecules. Figure 1 shows schematically a cross-section of the complete device. It is composed of a glass die and a silicon die. The glass die contains the fluid channels fabricated using SU-8 techniques and the tunable optical filter. The silicon die includes a photodetector and readout electronics, both fabricated in a CMOS microelectronics process.

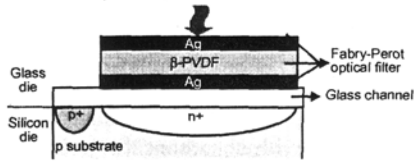

Figure 1. Cross-section of the laboratorial microsystem.

II.2 THE OPTICAL FILTER

The light that travels through the air and reaches any optical filter can show two independent polarizations. The light incident in the reflector surface, forming an angle θ with its normal, can have either the electric field vector or the magnetic field vector parallel to the plane of incidence. In the first case, the polarization is called p and in the second, the polarization is called s. In a general way, the electric field vector forms an angle with the plane of incidence. In this case, it can be decomposed in two components, one of polarization p and other of polarization s.

The normal refractive index n is equal to H/E, where H and E are the amplitudes of the magnetic and electric fields, respectively. In a similar way, a generalized refractive index u can be defined for each of the polarizations, such that:

$$\begin{cases} u_p = H/(E\cos\theta) = n/\cos\theta \\ u_s = H\cos\theta / E = n\cos\theta. \end{cases} \quad (1)$$

Notice that the directions of the electromagnetic fields of the light produced by a scintillator are random and can be decomposed in the two polarizations with equal probability.

In the case of materials absorbing light, the normal refractive index (n in equation (1)) must be replaced by $n - jk$, where k is the extinction coefficient of the material and j is the complex operator $\sqrt{-1}$.

In a general case of a filter constituted by multiple layers, its behavior can be derived from [7]:

$$\begin{bmatrix} E_q^+ \\ E_q^- \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1/u_q \\ 1 & -1/u_q \end{bmatrix} M_i \ldots M_1 \begin{bmatrix} 1 \\ u_o \end{bmatrix} E_o^+, \quad (2)$$

where E_q^+, E_q^- and E_o^+ represent the electric field vectors of the incident, reflected and transmitted waves, respectively. u_q and u_o are the generalized refractive indexes of the incident and the exit media, respectively, and:

$$M_i = \begin{bmatrix} \cos g_i & j\sin g_i / u_i \\ ju_i \sin g_i & \cos g_i \end{bmatrix}, \quad (3)$$

is an array that contains all the details of the filter's film i and relates the values of E and H of one side of the film with the ones of the other side. The generalized refractive index of the thin film i is then represented by u_i, and g_i is the phase thickness of the thin-film, given by:

$$g_i = \frac{2\pi u_i d \cos\theta_i}{\lambda} \quad (4)$$

where d is the film thickness and θ_i is the angle of incidence of the light given by the Snell's law:

$$u_q \sin\theta_q = u_i \sin\theta_i = u_o \sin\theta_o \quad (5)$$

A Fabry-Perot optical filter is constituted by three films (see Figure 2): the one at the top and the one at the bottom have high refractive indexes (they are the mirrors) and the one in the middle has a low refractive index (it is the resonance cavity). In this case, equation (2) comes:

$$\begin{bmatrix} E_q^+ \\ E_q^- \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1/u_q \\ 1 & -1/u_q \end{bmatrix} M_3 . M_2 . M_1 \begin{bmatrix} 1 \\ u_o \end{bmatrix} E_o^+, \quad (6)$$

where $M_3 = M_1$. The resonant condition is achieved when the phase change in the second film is null, i. e. $\cos g_2 = 1$. This condition is achieved making $g_2 = k\pi u_2$, $k = 0, 1, 2, \ldots$

By applying a DC field to the dielectric polymer, the dipolar orientation will change, and so the dielectric properties of the films, having influence in the phase thickness of the filter.

Therefore, in a Fabry-Perot optical filter the thickness of the resonance cavity determines the tuned wavelength. Two types of highly reflective coatings are used in mirrors: dielectric and metallic. Dielectric mirrors, when properly designed and fabricated, offers high performance characteristics (high reflectivity with low absorption losses). However, despite the high absorption losses of the metallic mirrors, they are attractive due to the simplicity of their fabrication (only one layer is deposited). Also, the wavelength selection is performed by changing only the thickness of the middle layer.

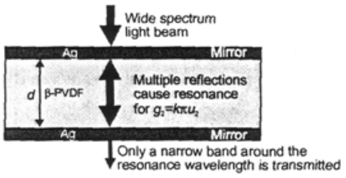

Figure 2. Fabry-Perot optical filter.

II.3 THE PIEZOELECTRIC POLYMER

As the best all-round piezoelectric polymer is still poly(vinylidene fluoride) -PVDF, in its β-phase, this material was used as the active part of the Fabry-Perot filter.

As the material is piezoelectric, two effects can be used in order to be implemented in the filter: the application of an ac-voltage that will change the dimensions of the film or the application of a dc-voltage that will mainly act on the dipolar orientation and consequently in the polymer dielectric response. Whereas in the first case, the thickness variation will affect the wavelength response, in the second case, the transmittance will be affected.

In this investigation we will report mainly on the second approach. One of the main advantages of the present approach in comparison to the more traditional ones is that the variations in thickness and/or dielectric properties are due to variations at a molecular level, so, the changes are rather homogeneous within the samples. This reflects itself, for example, in the ability to maintain parallel mirrors, other wise a problem in conventional Fabry-Perot systems.

III FABRICATION

III.1 MICROFLUIDIC SYSTEM

Figure 3 shows a photograph of the microchannels fabricated using a layer of photoresist SU-8 deposited on the glass substrate. This epoxy-based material offers good properties, such as high mechanical strength, good adhesion on many different substrate materials and biocompatibility. The SU-8-based fabrication is a low-cost process, UV lithography semiconductor compatible and does not require expensive masks (it is a regular transparency foil like the one used in printed circuit boards). It can be processes with a spincoating and UV maskaligner. Moreover, SU-8-based processing enables the fabrication of deep microchannels with very low sidewall roughness and is suitable for optical absorption measurement [8]. The holes on the top glass wafer are drilled by using a CNC (Computer Numerically Controlled) machine. The top glass wafer and the microchannels wafer are superimposed, aligned and pressed against each other with a hardbake temperature of 150-200 °C for the bonding of both wafers.

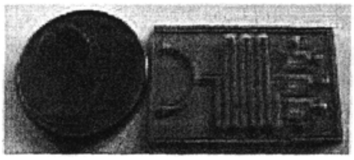

Figure 3. The SU-8-based structure microchannels.

III.2 TUNABLE OPTICAL FILTER

The optical filter is fabricated on top of the glass die. The glass substrate was cleaned in acetone ultrasonic bath, and blown dried with nitrogen. The first fabrication step is the deposition of the thin silver contact layer (30 nm thick) on the glass, by thermal evaporation process. Then, a 6 µm thick β-PVDF film is deposited on the silver contact. A second layer of silver is then deposited over the β-PVDF film, creating the second contact. The rate of 4 Å/sec was maintained during the deposition of silver, using a thermal heated molybdenum boat in a vacuum pressure of $2\text{x}10^{-6}$ torr. The substrate temperature was 300K during the evaporation. The thickness of the grown silver contacts was monitored with a crystal-oscillating thickness monitor, calibrated with the density of bulk silver ($10.5\ \text{g.cm}^{-3}$). Thinner PVDF films can be achieved either by spin coating or Langmuir Blodgett technique.

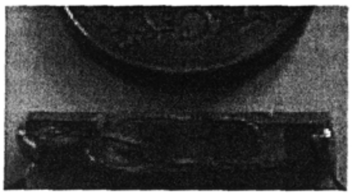

Figure 4. The 1st prototype tunable optical filter.

IV TEST RESULTS

The experimental arrangement used in the measurements comprises a 250 W quartz tungsten halogen lamp with a monochromator ORIEL Cornerstone 130^{TM} that is used as light source. A Keithley 487 picoammeter (full-scale range from 10 fA to 2 mA and a resolution of 5-1/2 digit) is used for measuring the photodiodes current. These photodiodes were calibrated with a commercial photodiode as reference (Hamamatsu S1336-5BQ). To test the concept of the 1st prototype tunable Fabry-Perot filter, a voltage between 0 V and 15 V was applied to the electrodes on the silver mirrors. Figure 5 shows the measured transmittance for the 30 nm-Ag / 6005 nm-β-PVDF / 30 nm – Ag layer stack. As it can be seen there are changes in the optical behavior of the filter with the increase of the applied voltage. The transmittance decreases continuously until a critical voltage of ~ 8 V, corresponding to a field of ~ 1 MV/m. For higher field the transmittance remain almost unaltered. The applied voltage and the corresponding dipolar orientation allow controlling the transmittance of the system.

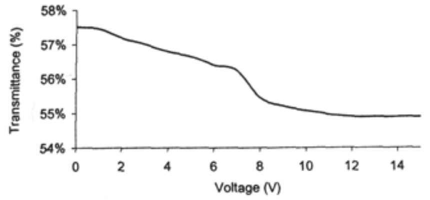

Figure 5. Measured transmittance versus applied voltage.

In a similar way, computer simulations (Figure 6) show that the variation of thickness that can be induced due to the piezoelectric effect will also affect, and in a larger way, the transmittance of the system. Future work on the filter fabrication is being done to reduce the cavity thickness for about 350 nm. Simulation results show a higher cavity displacement (Figure 7)

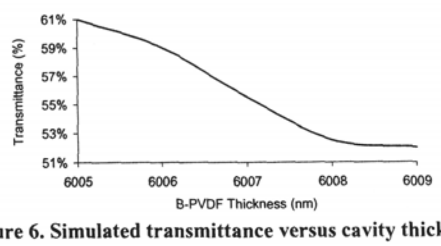

Figure 6. Simulated transmittance versus cavity thickness

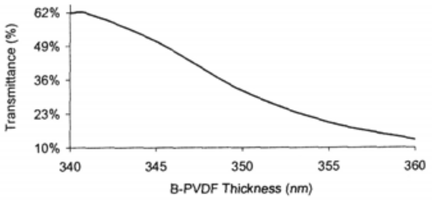

Figure 7. Simulated transmittance versus cavity thickness

V CONCLUSIONS

The concept, fabrication and performance of a tunable Fabry-Perot optical filter with a piezoelectric polymer as the resonance cavity were reported. Due to this cavity material, which features thickness variations at a molecular level, the ability to maintain parallel mirrors, during the tunning of the filter, is achieved. The filter can be an integrated part of portable (bio)chemical micro total analysis systems once it enables the spectrophotometric measurements using only white light source.

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