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IR Microspectrometers based on Linear-Variable Optical Filters

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Abstract

This paper presents the design, fabrication and characterization of Infra-Red (IR) Linear Variable Optical Filter (LVOF)-based micro-spectrometers. Two LVOF microspectrometer designs have been realized: one for operating in the 1400 nm to 2500 nm wavelength range and another between 3000 nm and 5000 nm. The IR LVOFs have been fabricated in an IC-Compatible process using resist reflow. The LVOF provides the possibility to have a small size, robust and high-resolution micro-spectrometer in the IR on a detector chip. Such IR microspectrometers can be fabricated at low-cost in high volume production and have huge potential in applications such as liquid identification (e.g. water in alcohol, water in oil) and gas sensing.

Keyword: microspectrometer; IR; Linear-Variable Optical Filter

1. Introduction

Low-cost single-chip spectrometers have huge potential in systems for biomolecule identification and chemical analysis by optical absorption, fluorescence and emission line characterization. Such microspectrometers offer significant advantages over existing instruments, including size reduction, small sample size, low cost, fast data-acquisition and high reliability. Many interesting gases (e.g. CO, CO_2, N_2O, C_xH_y) have absorption spectra in the 1000 nm – 5000 nm spectral range. Moreover, many liquids (e.g. methanol, ethanol, water, oil) can be identified using their IR spectral absorption signature [1].

A Linear Variable Optical Filter (LVOF) is based on a tapered cavity on top of a linear array of photodetectors and enables the transfer of the optical spectrum into a lateral light intensity profile over the array of photodetectors. The same concept of the system can be designed and realized for wavelengths

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from UV to IR (300 nm – 5000 nm). The difference is in the choice of the dielectric materials and the layer thickness. In earlier works LVOF microspectrometers for UV and Visible spectral ranges were presented [2]-[3].

2. Design of the LVOF microspectrometer

The multilayered filter designs used for the LVOF in the two spectral ranges are shown in Table 1 and Table 2. SiO2 and sputtered Si have been used as high-n and low-n materials. Figure 3a shows the spectral transmission for LVOF based on table 1, which is designed to operate in 1500 nm to 2500 nm wavelength range. Figure 3b shows the spectral transmission based on Table 2, which is designed for operation between 3000 nm and 5500 nm.

Table 1. Thickness of the layers for the IR LVOF in the 1500 – 2000 nm wavelength range.

Layer #	Material	Thickness (nm)
1	SiO_2	330 nm
2	Si	125 nm
3	SiO_2	330 nm
4	Si	125 nm
5	SiO_2	**1000 – 1800 nm**
6	Si	125 nm
7	SiO_2	330 nm
8	Si	125 nm

Table 2. Thickness of the layers for the IR LVOF in the 3000 – 5500 nm wavelength range.

Layer #	Material	Thickness (nm)
1	SiO_2	720 nm
2	Si	270 nm
3	SiO_2	720 nm
4	Si	270 nm
5	SiO_2	**2300 – 4000 nm**
6	Si	270 nm
7	SiO_2	720 nm
8	Si	270 nm

The thickness of the tapered cavity layer, at the center of the Fabry-Perot filter structure, changes linearly from 1000 nm to 1800 nm in the first design and from 2300 to 4000 nm in the second and covers the intended spectrum.

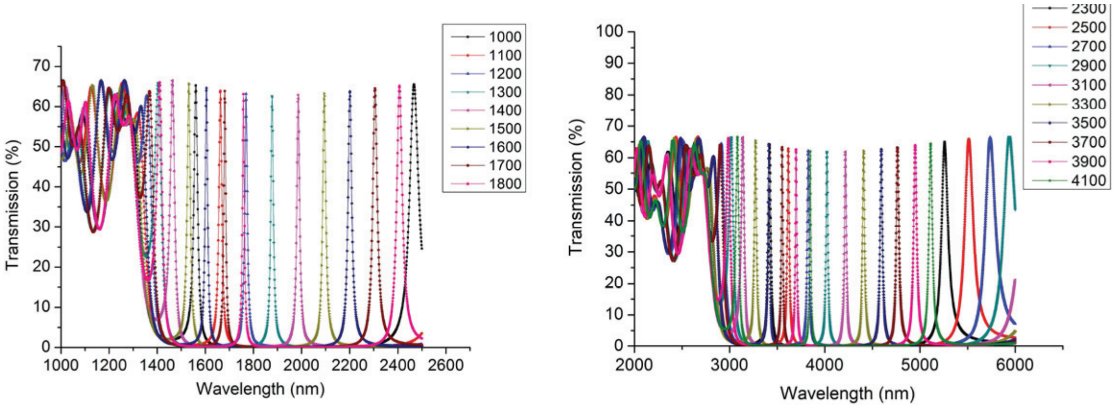

Fig. 1. (a) Transmission spectrum of IR LVOF in table 1 for different values of the cavity thickness, values in nm. (b) Transmission spectrum of IR LVOF in table 2 for different values of the cavity thickness, values in nm.

The structure of an LVOF-based microspectrometer is shown in Figure 2, which is used as the starting point for the design of the required collimating optics. Light passes an aperture and collimating optics before being projected onto the LVOF, which is placed or deposited on the top of the detector. Equations 1 and 2 can be used to design the focal length of the collimating lens and the aperture size.

$$f = \frac{D}{2\mathrm{NA}} \tag{1}$$

$$d = \frac{D\varphi}{\mathrm{NA}} \tag{2}$$

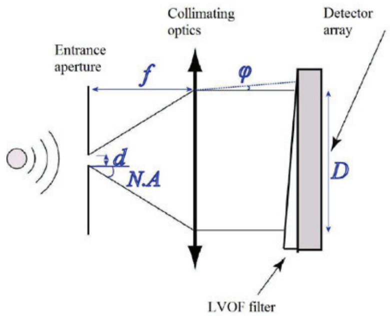

Fig. 1. Schematic of a LVOF-microspectrometer.

In which D is size of the LVOF, f is the focal length of the lens and NA is entrance numerical aperture, d is the diameter of the aperture and φ is maximum acceptable angle of incidence on the LVOF. Since these equations depend on φ, transmission through the multilayered Fabry–Perot filter (which can be at any position along the length of the LVOF) is simulated at different angles. Figure 3 shows the result. Based on this graph and desired spectral accuracy a value for φ is chosen.

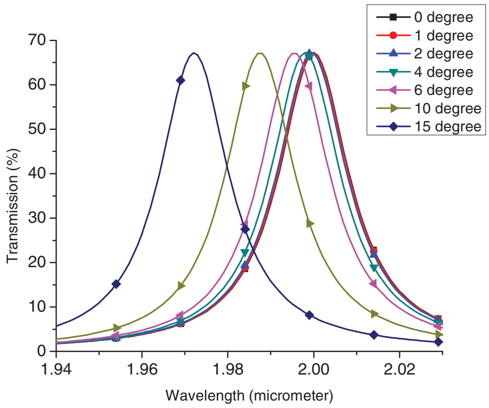

Fig. 3. Simulated transmission through the LVOF structure at different angles.

3. Fabrication and completed LVOF

LVOF fabrication is based on reflow of a specially patterned layer of resist. The process starts by deposition of the lower dielectric mirror stack and the oxide layer that results in the cavity layer (layers 1-5 in Table 1 and Table 2). Photoresist is spin coated as the next step and lithography is applied to define the strip-like structure in the resist layer to be reflowed. A series of trenches of constant width and with variable spatial frequency or trenches of variable width and constant pitch are etched over the length of the strip of resist to vary the effective amount of resist per unit area. The subsequent reflow transfers this gradient volume of resist into a smooth tapered resist layer. The topography of the tapered resist layer is transformed into the thick oxide cavity layer by an appropriate plasma etching process. The process is completed by deposition of the top dielectric mirror stack (layers 6-8). This LVOF is fabricated on a Silicon substrate. However, fabrication directly on a detector chip as a compatible post-process is well possible.

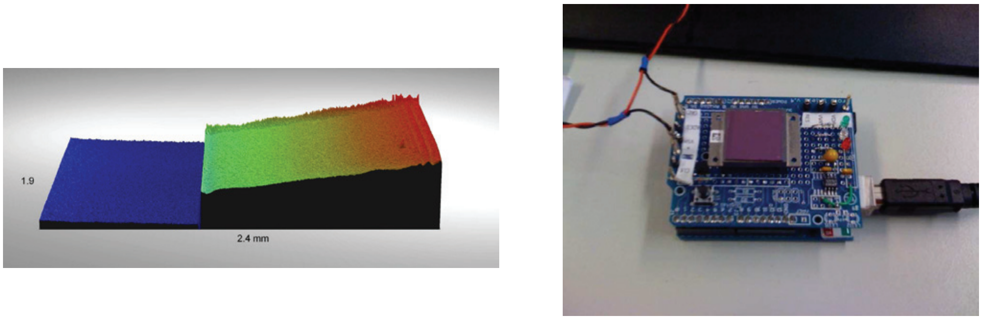

Fig. 4. (a) 3D profile of the fabricated IR LVOF measured by an optical profile meter. (b) IR LVOF mounted on a detector array.

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