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Shadow-mask evaporation for the fabrication of optical filters with spatially tailored thickness

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ABSTRACT

The fabrication of optical filters whose reflection/transmission response is spatially-graded has been the object of numerous research studies over the past decades given their applications in areas including multi- and hyperspectral imaging, structural colouring and even holographic encryption. In this context, the key enabling feature is the ability to tailor the thickness profile of at least one layer of the optical coating multilayer stack. To-date, this 3-dimensional structuration has been achieved either at the deposition stage or as an additional post-deposition process step. In the former case, the technique relies on the shaping of the material deposition flux thanks to the insertion of a (moving) mask inside the evaporation or sputtering machine. As such, the method is usually limited to the implementation of centimetre-scale variations. A contrario, to reach sub-millimetre-scale features, the preferred approach is based on post-deposition layer structuration, which is performed using grayscale lithography in the form of multi-(mask-)level optical lithography, or using e-beam or laser lithography. All these approaches are nevertheless relatively complex since they involve either multiple steps or need a very precise calibration of the exposition curve.

In this paper, we report that the evaporation through re-usable shadow masks can be used to create optical filters whose spatial variations can be controlled with a $\sim 70\text{-}\mu\text{m}$ -resolution. Using metal-mirror Fabry-Pérot interferometer structures as representative optical filters, we demonstrate the ability to adjust the resonance wavelength, the filter bandwidth and extinction ratio, and the coupling strength and splitting in cascaded resonators.

Keywords: shadow mask, evaporation, graded-thickness thin films, multilayer optical filters

1. INTRODUCTION

The fabrication of optical filters whose reflection/transmission response is spatially-graded has been the object of numerous research studies over the past decades given their applications in areas including multi- and hyperspectral imaging, structural colouring and even holographic encryption. In this context, the key enabling feature is the ability to tailor the thickness profile of at least one layer of the optical coating multilayer stack. To-date, this layer on-purpose

structuration has been performed using either a bottom-up approach where the material deposition flux is spatially tailored using a (moving) shadow mask¹⁻³ or using a top-down approach where the spatially uniform layer is subsequently structured by grayscale lithography (and etching) techniques⁴⁻⁷. Usually, the bottom-up method is used to implement thickness variations at scales greater than the millimetre while the top-down technique provides the highest spatial resolutions (down to sub-micrometric levels) at the expense of a much more complex process, often involving a strict exposure calibration⁸.

In this paper, building upon the work of reference³, we report that the evaporation through re-usable sieve shadow masks that are fixed but separated from the deposition substrate can be used to create optical filters whose spatial variations can be controlled with a $\sim 70\text{-}\mu\text{m}$ -resolution. Using metal-mirror Fabry-Pérot interferometer structures as representative optical filters, we demonstrate the ability to adjust the resonance wavelength, the filter bandwidth and extinction ratio, and the coupling strength and resonance splitting in cascaded resonators.

2. SHADOW MASK FABRICATION AND CHARACTERIZATION

Our method to control the deposition thickness profile, as in reference³, relies on the local restriction of the evaporated material flux by a shadow mask sieve that is set at a fixed position away from the target deposition substrate. In this case, the locally-deposited thickness is essentially proportional to the facing opened surface in the sieve⁹.

We have thus created a shadow mask pattern that includes a matrix of 7×7 rectangular ($300\times 350\mu\text{m}^2$) patches, each of which consisting of a $10\text{-}\mu\text{m}$ -pitch hexagonal array of set-diameter holes. The coded hole diameter varies from patch to patch covering the 2 to 8 μm range with a $0.125\text{-}\mu\text{m}$ step. This range was selected based on the ease of fabrication by direct contact lithography techniques but also to avoid the commonly-observed clogging of nanometric holes¹⁰.

A corresponding set of nickel shadow masks with a $\sim 2\mu\text{m}$ -thick sieve membrane and a $\sim 50\text{-}\mu\text{m}$ -thick supporting structure were made using conventional microelectronic processes and process-flows (involving metal deposition, UV contact lithography and electroplating). Once fabricated, these masks were characterized by Scanning Electron Microscopy and the dimensions of the holes were found to follow the design ones but for a slight ($\sim 0.25\text{ }\mu\text{m}$) undersize.

3. OPTICAL FILTER ARRAY FABRICATION AND CHARACTERIZATION

As a demonstration of this grayscale fabrication technique at the micrometer-scale, we decided to make various arrays of optical filters embedding one layer whose thickness is controlled by the above-described sieve.

The design of the optical filters under study is based on (cascaded) Fabry-Pérot interferometer(s) with aluminum mirrors and silica (SiO_2) spacer(s). The SiO_2 layers were deposited by capacitively-coupled plasma-enhanced chemical vapor deposition while the aluminum layers were evaporated in a Plassys MEB550B system into which the samples and shadow masks were mounted on a custom holder. As a result, only Al layers with varying thickness were deposited

through the shadow masks. This means, in turn, that they could be re-used as the deposited aluminum can be etched away from the nickel masks with a very high selectivity using standard VLSI Al-etchant ($\text{H}_3\text{PO}_4 : \text{HNO}_3 : \text{CH}_3\text{COOH} : \text{H}_2\text{O}$ solution). To obtain filters with a varying-thickness SiO_2 layer, we first deposited Al on the SiO_2 layer through the shadow mask and transferred the patterns into silica by inductively-coupled-plasma-assisted dry (CHF_3) etching with a SiO_2 etch rate of ~ 160 nm/min and Al/ SiO_2 etch selectivity of $\sim 1/4$.

The resulting optical filters were characterized using a micro-reflectivity setup. The latter consists of a tungsten-halogen white light source, a 50/50 multimode fibre (105- μm core, $\text{NA}=0.22$) beamsplitter with one of its ends that is optically relayed to form a ~ 100 - μm -diameter probing beam impinging on the samples at surface-normal incidence, and a UV-visible optical spectrometer (with a sub-1-nm spectral resolution) on the detection side.

As a first proof of the successful deposition of homogenized patches through the shadow mask sieve, we show, in the left part of Figure 1, a stitched optical microscope image of a subsection of the above-described matrix taken on one of the produced samples. The imaged sample is a silicon substrate that has sequentially been covered by 100 nm of aluminum, 1650 nm of SiO_2 and, finally, the stepped-thickness aluminum layer. As can be observed on the right of Figure 1, stylus profilometry of the patches of the matrix seventh column allows to establish that the spatial resolution (taken to be the blurred shadow width) is of ~ 70 - μm , for the current separation between the shadow mask and the sample.

The measured reflectivity curves for a subset of the patches (referred according to their (line, column)=(L,C) distribution and surrounded by a matching color box – see Figure 1. left) are shown in Figure 2. As expected, as the top metal mirror of the Fabry-Pérot interferometer thickens, the resonance dips get spectrally narrower and their depth reduces. We have thus created a matrix of optical filters whose bandwidth and extinction ratio are simultaneously varied.

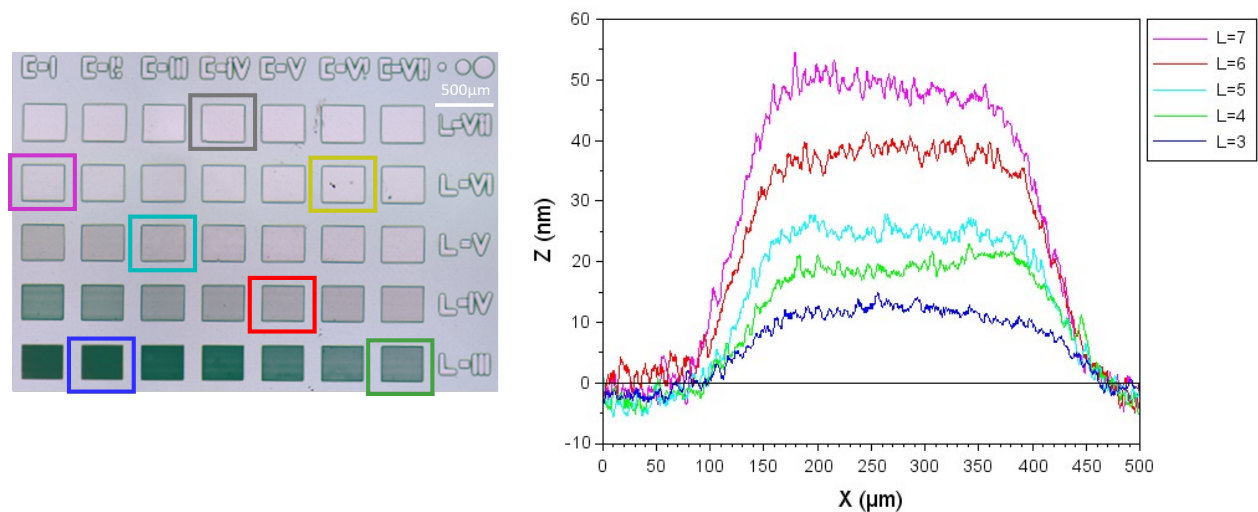


Figure 1. (left) Stitched optical microscope image and (right) experimental thickness characteristics of a Fabry-Pérot interferometer with a variable thickness top Al mirror.

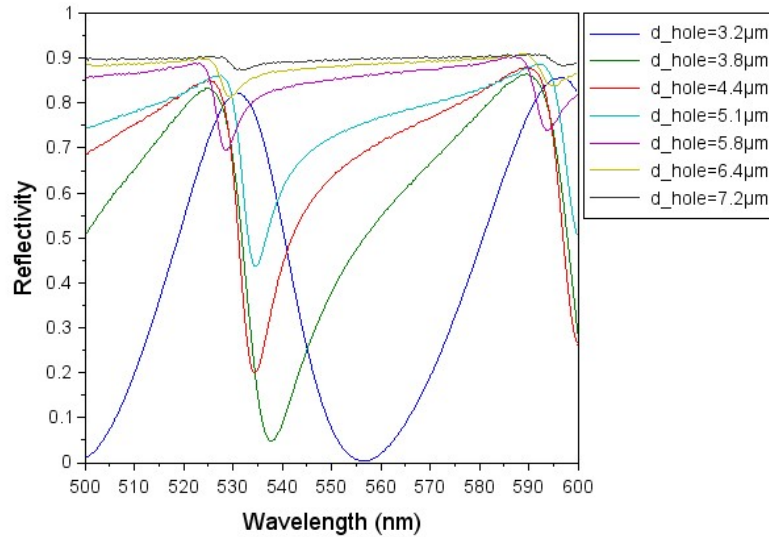


Figure 2. Experimental characteristics of a Fabry-Pérot interferometer with a variable thickness top Al mirror. The blue curve corresponds to the patch referred by $(L,C)=(3,2)$ that has been surrounded by the matching-color box in Figure 1. left.

Similarly, the stepped thickness aluminum layer can be used to control the coupling ratio in cascaded Fabry-Pérot interferometers. We thus fabricated samples whose multilayer structure is given as follows : air/Al (16nm) /SiO₂ (~1536 nm) /Al /SiO₂ (~1545 nm) /Al (100nm)/ Si substrate. As it can be observed in Figure 3 and as expected, the thinner the metallic intermediate mirror thickness (i.e. the smaller the sieve hole diameter), the larger the resonance splitting (culminating here (blue curve) with a ~30-nm splitting which occurs between the dips at ~523 and 553 nm).

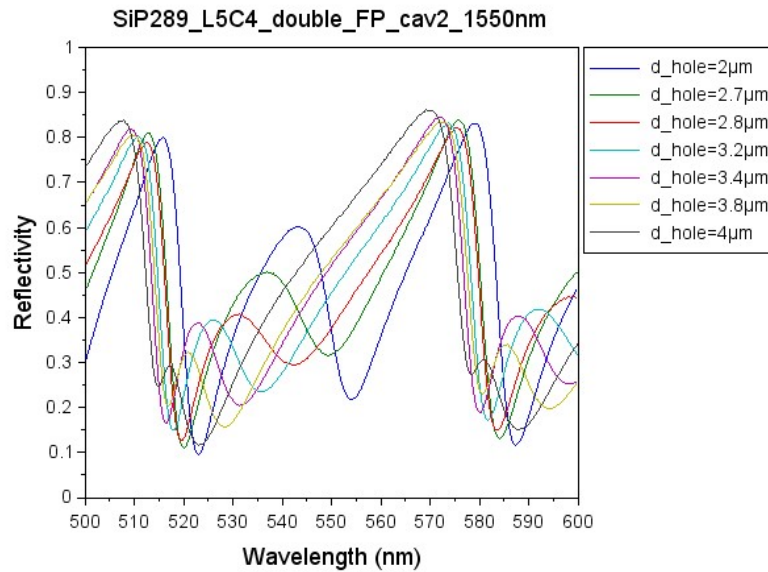


Figure 3. Experimental characteristics of a cascaded Fabry-Pérot interferometer with a variable thickness intermediate mirror.

Finally, as a second stage in this study, and as already mentioned above, we have made use of the ability to create aluminum patches of variable thickness to transfer this thickness variation into an underlying (here SiO₂) material by using the corrugated aluminum layer as a hard mask in a subsequent dry etching step. As an example of application, we have created optical filters with variable resonance wavelength(s). The chosen multilayer structure is air/Al (18nm) /SiO₂ /Al (100nm) on a silicon substrate. As shown in Figure 4, the measured resonance dip (step)-tunes with the spacer thickness (sieve hole diameter) over the whole ~84-nm free spectral range of the interferometer.

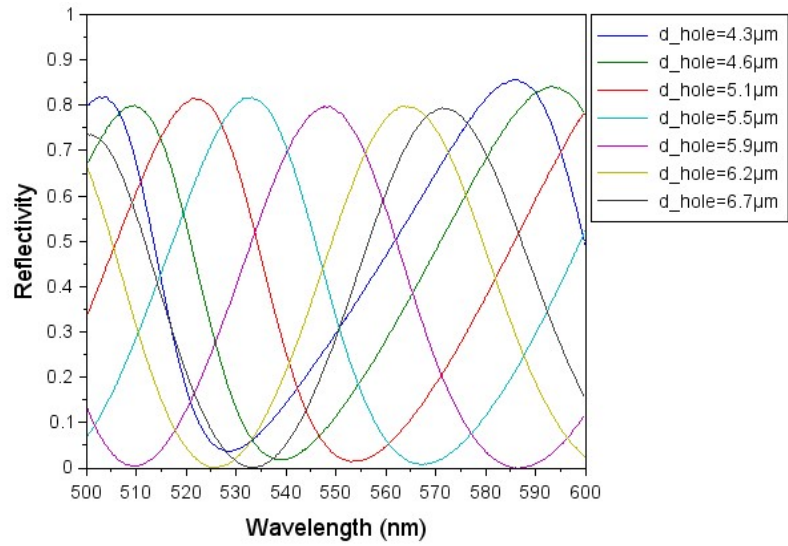


Figure 4. Experimental characteristics of a Fabry-Pérot interferometer with a variable thickness spacer layer.

4. CONCLUSIONS

We have reported that sieve shadow masks made of nickel can be used as re-usable flux control elements for the evaporation of aluminum layers. As a direct application of this graded thickness deposition method, we have fabricated matrices of optical filters where the thickness of at least one layer can be controlled with a lateral resolution of ~ 70 μm . Practical use in metal-mirror Fabry-Pérot interferometers has permitted to demonstrate optical filters presenting tunable the resonance wavelength, adjustable filter bandwidth and extinction ratio, and controllable coupling in cascaded resonators.

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