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# Porous optical filter with spatially graded response

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## ABSTRACT

Glancing angle deposition was used to grow a spatially-graded thin film optical Rugate filter. The graded thickness of the rugate filter resulted in spatially varying spectral characteristics. The defect-induced transmittance peak location varied approximately 150nm across a 25mm length of film. This type of thin film will be useful as a position sensor. Because of its highly porous nature, micro-fluidic and microchromatographic devices are also possible.

**Keywords:** rugate, porous, graded, optical, sensor

## 1 INTRODUCTION

Glancing angle deposition (GLAD) has become a common technique for producing thin films with various structural features [1]. Through physical vapour deposition at an oblique angle, self-shadowing is utilized to create nanocolumns of different architectures. In the current work, we have further modified GLAD in order to create porous structures that have spatially graded profiles, suitable for application in fluidic and sensor devices.

Various methods can be employed to create thin films with spatially graded profiles. A sliding mask can be used during sputtering [2,3], epitaxial [4], or chemical [5] deposition. Alternatively, the thin film thickness dependence on the distance, and angle of incidence, between the substrate and evaporant source can be exploited [6]. Our method takes advantage of the fact that with GLAD the substrate is kept at an oblique angle to the deposition source. As such, any object placed near the substrate will shadow it during the deposition. By employing substrate motion, the shadow's area and duty cycle can be controlled, thus controlling the thickness gradient on the substrate.

To illustrate the usefulness of this macroscopic shadowing property, an optical rugate interference filter was grown using the GLAD shadowing method. Optical rugate filters have been demonstrated in the past, using the conventional GLAD deposition method [7,8], but all have had a uniform thickness and constant spectral profile across the substrate. Graded-thickness optical rugate filters have been created by [2] and [3], among others, but all have required a complex multiple step process to lay down the multiple layers required to generate the rugate filter. The advantage of using the GLAD process is that a spatially-graded rugate filter can be created in a single step.

During the single-step GLAD process, macroscopic shadowing was used to produce a film with a variation in thickness across its length. Conventional GLAD substrate motion was used, but at the centre of the substrate holder a large shadowing cylinder was placed. Figure 1 shows the substrate holder and shadow block used for this deposition.

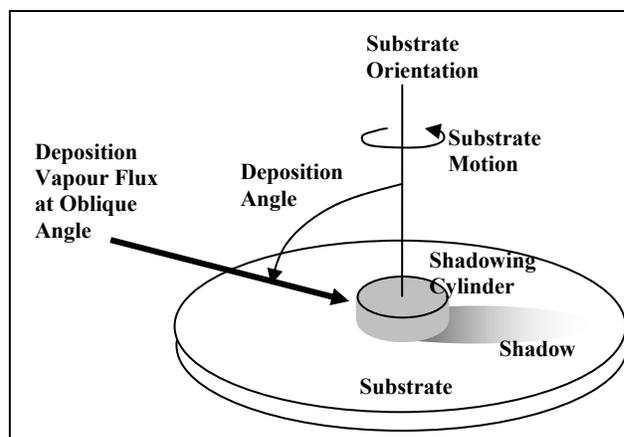


Figure 1: Substrate holder and shadowing block used to create spatially graded thin film

## 2 BACKGROUND

A thin film rugate filter has a periodically varying refractive index profile. The resultant interference effects lead to a transmission stop band whose bandwidth depends on the pitch of the refractive index variation. The stop band center wavelength ( $\lambda_{SB}$ ) depends on the average refractive index of the film ( $n_{avg}$ ) and the pitch ( $p$ ) [9].

$$\lambda = 2n_{avg}p \quad (1)$$

When a defect, such as a phase shift or section of constant index, is introduced in the rugate structure a narrow transmittance peak emerges within the stopband [7].

To create the spatially-graded rugate filter, the orientation of the substrate, relative to the source, was sinusoidally varied throughout the deposition. The oblique deposition angles employed, in tandem with self-shadowing, resulted in the growth of nanocolumns with periodically changing diameters. The shadowing cylinder caused the column heights to vary across the radial distance of the substrate, as illustrated in Figure 2.

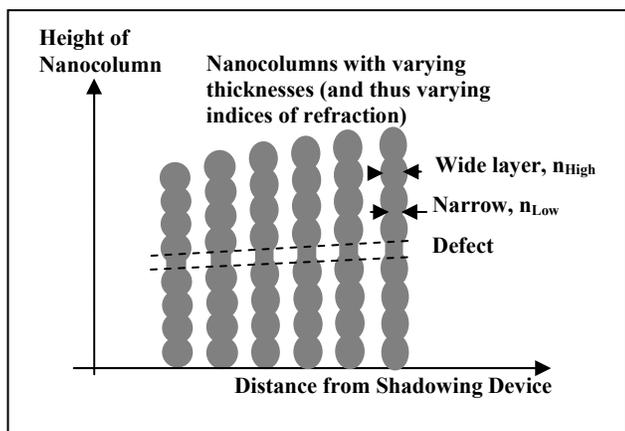


Figure 2: Spatially-graded rugate filter with defect

### 3 RESULTS

Spatially-graded titanium dioxide (Cerac, Inc., 99.9% pure) Rugate filters were fabricated on glass and silicon substrates using custom-built GLAD-equipped Kurt J. Lesker electron-beam physical vapour deposition systems. Scanning Electron Microscope (SEM) images of these Rugate films were taken using a Hitachi field emission S4800. Figure 3 shows the SEM images of a spatially-graded 12-turn Rugate filter grown using the macroscopic shadowing GLAD method. The periodicity of the nanocolumns is apparent in this figure. Also of note is the tilt of the columns towards the shadowing cylinder. This tilt is due to the fact that deposition flux can only impinge on the columns from a restricted range of deposition angles.

The thickness profiles of 12-turn Rugate films versus radial distance were taken from the SEM images. The thickness profiles are plotted, for two different shadowing cylinder heights, in Figure 4. The thickness of the thin film grown on top of the shadowing block is also plotted (as a dashed line). As the radial distance is increased the thickness grows until it reaches some maximum value. Because of the dependence of film thickness on substrate-source geometry the shadowed film does not quite reach the same final thickness as the top-of-cylinder film.

With a larger shadowing cylinder the shadow cast is longer and the thickness slope is more gradual. The height of the shadowing cylinder can therefore be used to tailor the thickness profile of the deposited thin film.

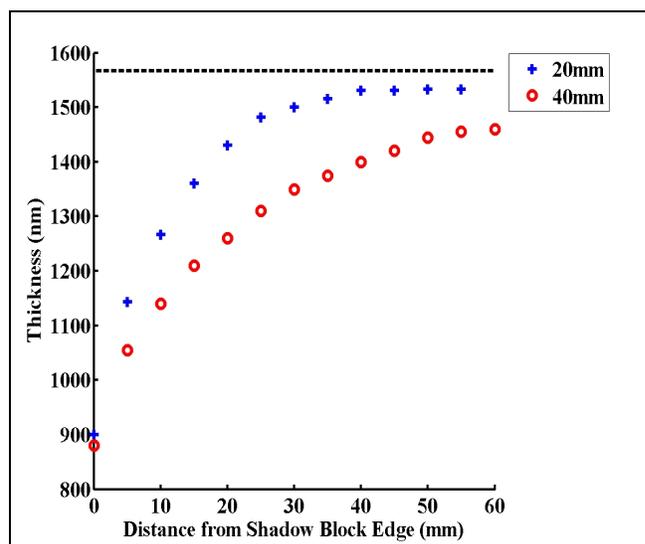


Figure 4: Increasing thickness of a spatially graded 12-turn Rugate thin film versus radial distance for a) a 20mm cylinder height, b) a 40mm cylinder height.

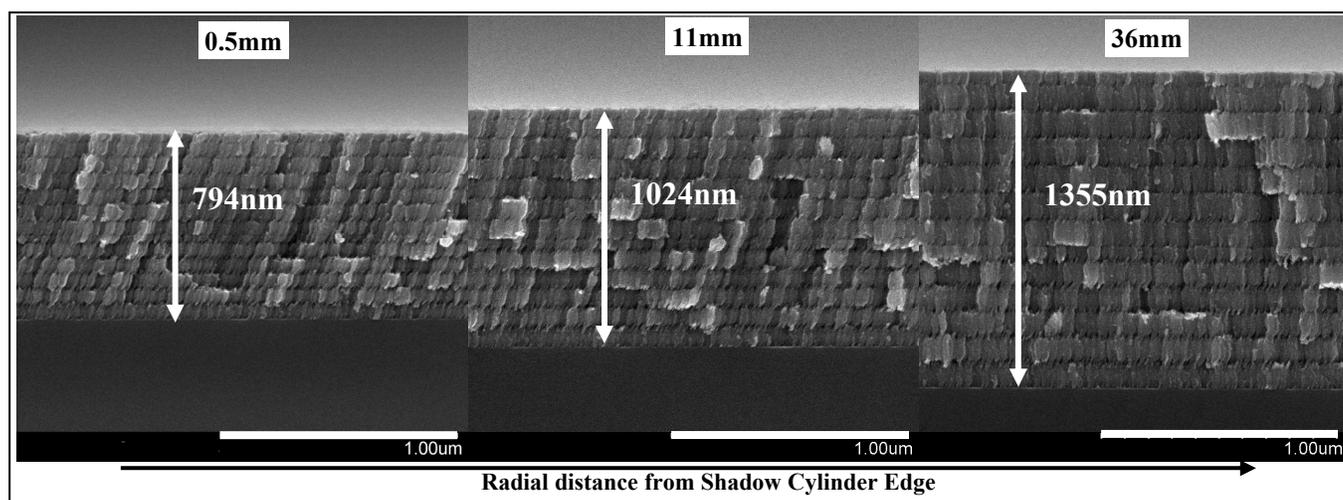
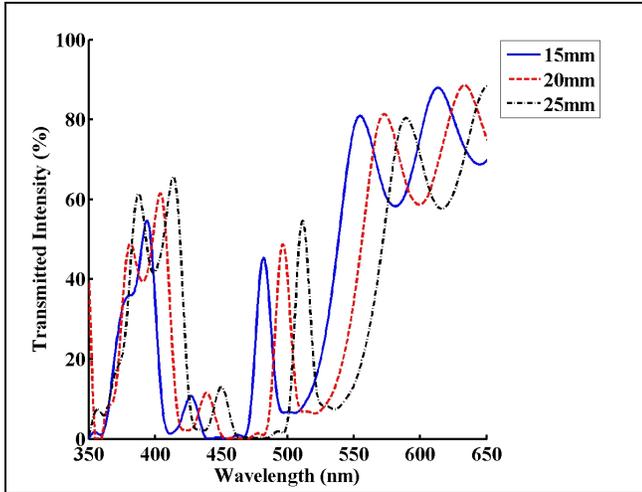


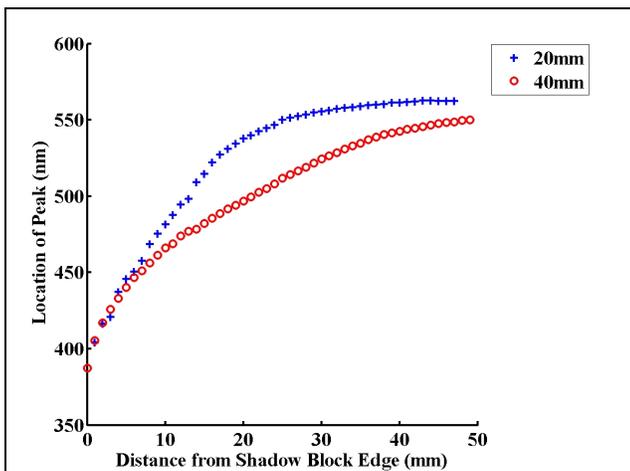
Figure 3: SEM images of spatially graded rugate thin film show increase in thickness with radial position

The optical spectra for the different Rugate filters were obtained using an Ocean Optics HR4000 spectrometer. Figure 5 shows the transmittance profile obtained for the graded Rugate filter grown using the macroscopic shadowing GLAD method. This film is 12-turn Rugate filter, grown with a 40mm shadowing block.



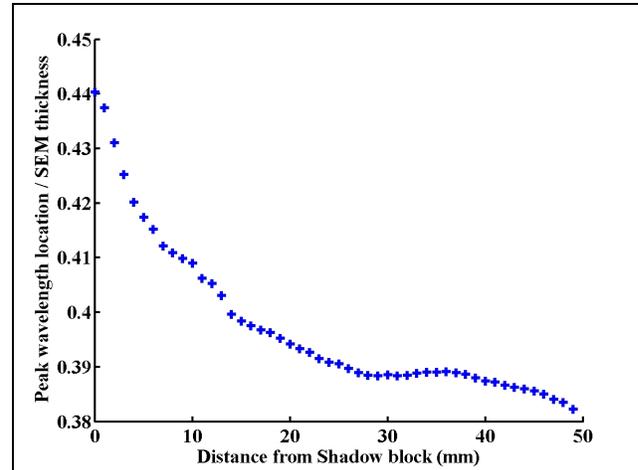
**Figure 5: Increase in stop-band and peak wavelength location with radial position (Peak at ~480nm 15mm from shadow block, ~500nm at 20mm, and ~510nm at 25mm) of a thin film 12-turn Rugate filter**

Figure 6 shows the defect-induced transmittance peak location dependence on the radial position from the shadowing cylinder edge. This figure reveals a smooth and monotonic relationship between peak wavelength location and position. The peak location depends on radial distance from the shadow cylinder edge, as well as on the height of the shadowing cylinder. Comparison of Figure 6 to Figure 4 reveals that the peak location dependence on radial distance follows a similar trend as the thickness variation.



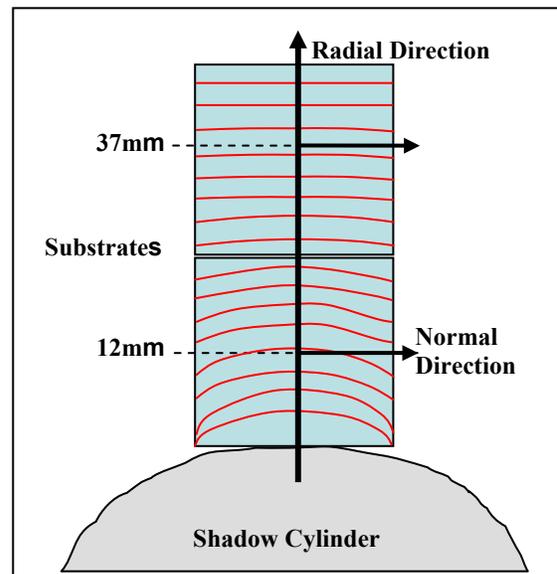
**Figure 6: 12-turn Rugate film peak wavelength location as a function of radial distance from (20mm and 40mm high) shadow cylinder edge**

The relationship between the location of the peak wavelength and the thickness of the film is of interest. Figure 7 shows a plot of this relationship for a 12-turn film. The relationship is not a constant, indicating that the pitch or refractive index is not constant as a function of radial position. This behaviour is left for further investigation.



**Figure 7: The non-constant ratio of peak wavelength location to thickness (for a 12turn film with 40mm shadowing cylinder) indicates that either the pitch or refractive index varies as a function of radial position**

Of interest is whether there is a spectral dependence of the filter in only the radial direction. This concept is illustrated in Figure 8 and shown to not be the case in Figure 9. There is a spectral dependence in the normal direction as well, for radial distances close to the shadowing cylinder. As the radial position is increased the wavelength dependence becomes more constant across the normal direction.



**Figure 8: Measuring spectral dependence graded Rugate filter normal to radial direction**

