Bandpass filter arrays patterned by photolithography for multi-spectral remote sensing

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ABSTRACT

Optical remote sensing of the earth from air and space typically utilizes several channels from visible (VIS), near infrared (NIR) up to the short wave infrared (SWIR) spectral region. Thin-film optical filters are applied to select these channels. Filter wheels and arrays of discrete stripe filters are standard configurations. To achieve compact and light weight camera designs multi-channel filter plates or assemblies can be mounted close to the electronic detectors.

Optics Balzers has implemented a micro-structuring process based on a sequence of multiple coatings and photolithography on the same substrate. High-performance band pass filters are applied by plasma assisted evaporation (plasma IAD) with advance plasma source (APS) technology and optical broad-band monitoring (BBM). This technology has already proven for various multi spectral imager (MSI) configurations on fused silica, sapphire and other substrates for remote sensing application.

The optical filter design and performance is limited by the maximum coating thickness micro-structurable by photolithographic lift-off processes and by thermal and radiation load on the photoresist mask during the process

Recent progress in image resolution and sensor selectivity requires improvements of optical filter performance. Blocking in the UV and NIR and in between the spectral cannels, in-band transmission and filter edge steepness are subject of current development. Technological limits of the IAD coating accuracy can be overcome by more precise coating technologies like plasma assisted reactive magnetron sputtering (PARMS) and combination with optical broadband monitoring (BBM).

We present an overview about concepts and technologies for band-pass filter arrays for multi-spectral imaging at Optics Balzers. Recent performance improvements of filter arrays made by micro-structuring will be presented.

Keywords: Remote sensing, Optical filters, Photolithography, Ion-Assisted Deposition, Multi-spectral strip filter assembly

1 INTRODUCTION

Optical multi-spectral remote sensing of the earth from air and space uses visible and infrared spaceborne sensors to measure the amount of radiation reflected or emitted back from the Earth and its overlying atmosphere.

Multi spectral imaging systems rely on imaging techniques that either disperse the optical signal across multiple imaging sensors or to different regions of a sensor area or use a filter wheel to spectrally discriminate images focused on a single imaging sensor. These systems include beam splitters, lenses, mirrors and band pass filters placed in the optical path to focus images onto separate sensors or sensor areas responding to different spectral bands.

Various remote sensors acquire data using scanning systems. A sensor with a narrow field of view sweeps over the ground and builds up a two-dimensional image. Scanning systems collecting data over a variety of different wavelength ranges are multispectral scanners (MSS). Common scanning methods to acquire multispectral images are across-track (ACT) and along-track (ALT) scanning.

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ACT scanners scan the surface in a series of lines oriented perpendicular to the motion direction (across swath) using rotating mirrors. Moving forward the scanner builds up a 2D image of the Earth´s surface. A bank of internal detectors each sensitive to a specific range of wavelengths, detects and measures the energy for each spectral band.

ALT scanners use instead of a scanning mirror a linear array of detectors located at the focal plane of the image formed by lens systems which move along in the flight track direction (also referred to as pushbroom scanners). A separate linear array is required to measure each spectral band or channel.

Along-track scanners with linear arrays have some advantages. The detector arrays combined with the pushbroom motion allow each detector to measure for a longer period of time. This improves the radiometric resolution, allows smaller IFOVs and narrower bandwidths. Finer spatial and spectral resolution can be achieved. Detectors become smaller, lighter, require less power, and are more reliable because they have no moving parts[1,2].

Compact pushbroom imaging systems typically use multispectral filter assemblies mounted directly above the sensor. The multispectral filter plates consist of stripe shaped linear sliced filters, each corresponding to one spectral band. Those stripe filter bars can be bonded together side-to-side or mounted in a supporting frame. Another possibility is the manufacturing of filter arrays on a joint substrate by a sequence of micro-structuring and coating on the same substrate.

The multispectral filters are dielectric multilayer interference filters with optimized transmission and bandwidth selectivity. Average in-band transmissions of greater than 90 percent and out-of-band transmissions typically much less than 1 percent are required.

Modern CCD and CMOS fabrication techniques like multi segmented linear sensors combined with advanced dichroic filter arrays result in cost-effective sensor designs. By bonding filter plates onto the cover glass directly in the imaging path, a single device can image numerous visible and IR bandwidths[5].

2 CONCEPTS

Figure 1 shows two basic approaches for multispectral filter arrays manufactured at Optics Balzers.
Frame mounted filter plates consist of single filter stripes. These stripes are made by coating of blank glass bars, machined by precision optics manufacturing or by stripe separation out of coated plates or wafers[3,4].
These stripes are then mounted to plates with supporting frames, aperture plates and channel separating foils.

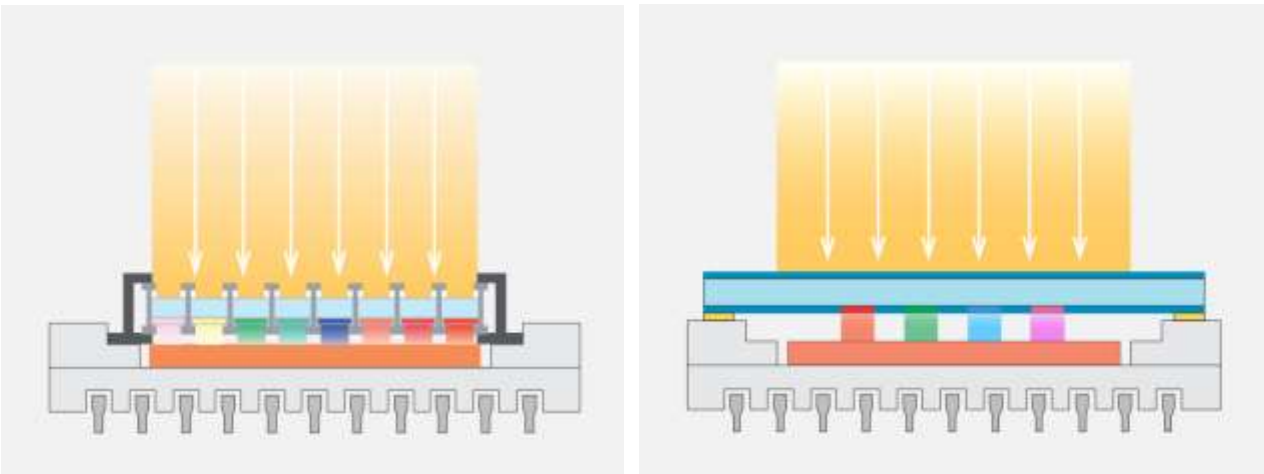

Figure 1. Frame mounted stripe assembly (left) and monolithic filter plate (right) concept

The mounting process requires sophisticated adjustment technologies and a perfect machining of the framing structures which determines the system accuracy. Several materials like titanium metal frames, silicone fillers, black anodized metal apertures and the optical filter glasses have to match and be mechanical stable under the environmental conditions of space based systems like temperature variation, radiation load and vacuum conditions. Otherwise the coating design and the coating technology are independent from the assembly process.

2.1 Monolithic filter plate

Monolithic filter plates consist of one substrate with areas of different coatings on both sides. These can be dielectric optical coatings like band pass, long and short pass filters, spectral blocking and antireflective coatings in combination with metal masks made from chromium of low reflective chromium (LRC) for aperture definition and straylight suppression.

All these coatings are applied in a sequential processing on the same wafer substrate one after the other by micro-structured coating (Figure 2).

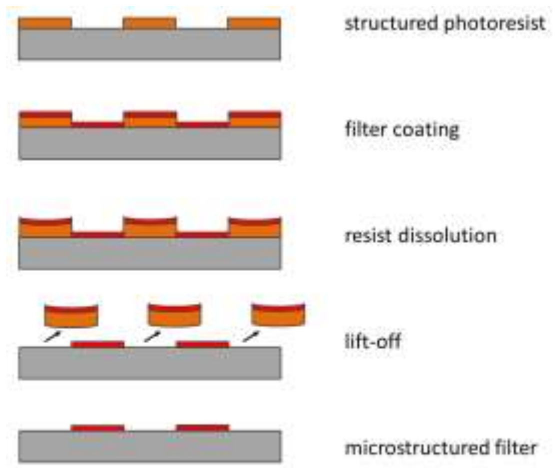

Figure 2. Micro-structured coating - principle process sequence

In principle the position accuracy of this process is defined by common photolithographic processing in the range of few microns by photolithographic masks, commercial mask aligner tools and photoresist lift-off. Alignment marks for exact positioning of the filter channels to each other and for final separation and mounting to the sensor will be integrated. A both-sided structured coating is also possible by back side alignment equipment.

Optics Balzers has realized filter assemblies for various spaceborne remote sensing applications successfully.
Below we present the manufacturing of band pass filter arrays patterned by photolithography as a monolithic filter plate in more detail.

3 MANUFACTURING

As substrate any wafer out of optical glass, fused silica, sapphire, CaF_2 or other material can be used. The wafer size depends from the available equipment, filter size, substrate costs and the required quantity. Typical sizes are 4 to 8”. For reasons of traceability and orientation wafers are engraved with a serial number before processing.

3.1 Sequential processing

Micro-structured coating means a repeated sequence of processes on the same substrate for every filter channel with a channel specific photomask with following steps:

- wafer cleaning and preparation (e.g. adhesion promoter)
- photoresist application and treatment (bake procedures)
- contact exposure, resist developing process, post development treatment (stabilization, inspection)
- thin layer coating (LRC, dielectric filter or antireflective (AR) coating)
- resist lift-off, cleaning, spectral and surface inspection

Figure 3 shows the typical initial process step. By photolithography low reflective chromium (LRC), manufactured by physical vapor deposition is coated and structured. This first coating forms the apertures for the following filter coatings. The channels are separated by masked regions between the free apertures. A tradeoff between sensor array usage (masked sensor pixels) and need of coverage of the filter coating overlap has to be made. Depending on coating complexity (coating thickness) and filter array dimensions this area is chosen typically in the region from 50 to 150 micron.
Annotations, alignment marks for filter mask and back-side adjustment and for final dicing and shaping are set in this first step with highest precision and determine the precision for the following sequence.

Figure 3. Aperture definition by structured coating of a low reflective chromium (LRC) mask

Right after this step or alternatively in a later processing stage a similar structure can be applied to the back side in the same manner overlapping exactly. This double sided black mask reduces cross channel stray light and prevents light leaking between channels and by defect holes appearing on one side.

Figure 4 schematically shows the next manufacturing step - here the RED filter channel. Unlike to the LRC with a thickness in the range of 1 to 2 micron the optical filter coatings require much thicker layer stacks and therefore much longer coating processes. Thus particular attention has to be paid to photoresist stability during the filter coatings.

Figure 4. Filter channel manufacturing by structured photoresist mask, filter coating (RED) and lift of

Chemical adhesion improvement and certain pre- and post-exposure bake steps are applied to stabilize the photoresist for the following coating process. A tradeoff between resist stability, structure edge smearing by pre-treatment, structure stability during plasma processing and keeping sufficient lift-off ability has to be achieved (see Figure 5).

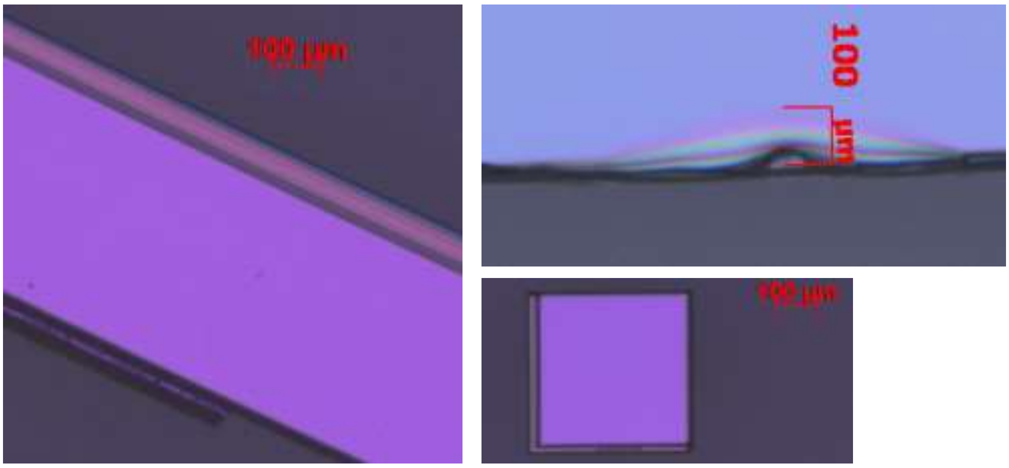

Figure 5. Possible defects: coating residues caused by imperfect lift-off (left), thermally induced resist crinkle and smearing

Notwithstanding to common photolithography optical band pass filters for remote sensing require layer stack thicknesses in the range of several microns. Table 1 compares exemplary designs for a green channel filter with a central wavelength (CWL) of 560 nm and bandwidth (BW) of 75 nm.

Table 1. Coating stack examples for different green channel designs.

	process	blocking [%] 420-520nm 620-900nm	high index material	number of layers	thickness [µm]
BP560-75	PIAD	> 0.1 (OD3)	TiO_2	87	7.5
BP560-75	PIAD	> 0.01 (OD4)	TiO_2	95	8.8
BP560-75	PIAD	> 0.001 (OD5)	TiO_2	131	11.0

It’s obvious that the thickness changes with the required blocking level. For other spectral bands this coating stack thickness varies proportionally with the wavelength region of the filter and choosing other high index materials with lower refractive index also requires thicker stacks.

For the photolithography process currently established at Optics Balzers photoresist thicknesses up to ~10 µm are processed routinely and allow layer stack designs with thicknesses in the same scale. This limits the suitability of this filter manufacturing approach to visible up to near infrared spectral ranges.

Figure 6 shows an example of the dimensional transformation of a structured aperture from photoresist over the edge rounding during mask stabilization treatment up to the final shape of the coated filter region after lift-off for a 9µm filter design.

The particular transformation depends (amongst others) on total dimensions, substrate heat conductance, surrounding structures, coating design and process conditions. Thus already during the mechanical and optical design of such a filter array the micro-structuring process constraints have to be considered.

Figure 6. Dimensional transformation of a ~9µm photoresist/coating system from resist (left), treated resist (center) to final filter after coating and lift-off (right)

3.2 Ion assisted deposition (IAD) with optical broad band monitoring (BBM)

The production of optical filters with high accuracy requirements to central wavelength, bandwidth and edge steepness demand latest deposition technology. Structured filter plates are manufactured at Optics Balzers by using SyrusPro box coaters equipped with Advanced Plasma Source (APS) by ion assisted deposition. This technology has proved to achieve stable thin-film optical filters since the end of the last century [7].

In contrast to conventional e-beam evaporation PVD the plasma assistance allows coating at low process temperatures and induces a compaction of the coated layers. Those coatings will not change their optical properties in ambience after the vacuum process by moisture penetration and temperature change (vacuum/air shift).
The relatively low process temperatures (<90°C) allow the coating of photoresist covered substrates for several hours. In the case of extreme conditions (very thick layer stacks, high content of high index material) coating has to be interrupted to cool down.

Standard layer thickness control by quartz crystal monitoring achieves maximum accuracies of about 1-2%. For production of filters with high requirements to wavelength, bandwidth and edge steepness this uncertainness is not tolerable.
Filter plate manufacturing by sequential micro structured coatings requires a series of coating runs with no opportunity for optimization or recurrence of certain runs. Whenever a single step fails, the whole sequence has to be started from the beginning.

The combination of plasma assisted e-beam evaporation with broad-band spectra photometric thickness monitoring is a useful technology for the manufacturing with an affordable yield. Layer thickness control during deposition is done by optical broad band monitoring (BBM) in the wavelength region from 420 to 1020 nm [8,9].
With this monitoring technique the optical thickness control of the multilayer stack is performed directly on the calotte close to the substrates position. The measurement is carried out intermittent on a monitoring glass per single calotte rotation (0.5Hz). The growing layer thickness is calculated by comparison of the modeled with the measured spectra.

The accuracy for the thickness control is in the order of 0.5 nm as absolute value over the complete deposition process under stable conditions. Of course the generation of difficult coatings requires accurate knowledge of optical material constants. The design of the coatings is based on experimentally determined material data. In real production situation that values vary for different operating conditions (coating parameters), chamber maintenance status or even during deposition. The in situ monitoring in combination with thin film design software allows re-optimization during coating run. With the BBM manufacturing can be carried out direct from design data without the necessity of validation runs.

In addition spectral accuracy of the filter channels is monitored by test wafers on comparable chamber positions with the same micro-structure. So every single filter position can be monitored by intermediate spectral measurements during the coating sequence.

After completion of the filter coating sequence the wafers have to be singularized by a dicing step (figure 7). The alignment marks applied during the first photolithography step allow an accurate positioning. A chamfer can be applied to prevent edges from damage during further processing.

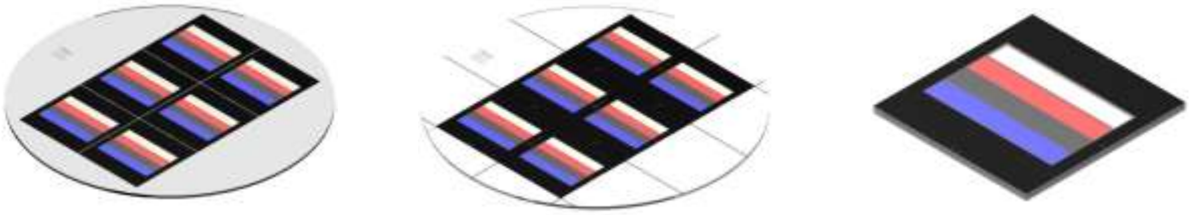

Figure 7. Final packaging: wafer dicing, filter plate chamfering and inspection

An essential step is the final inspection of the multi spectral filter plates. Typical yields achieved at Optics Balzers for a 4 channel filter plate with backside AR coating may vary from 40 to even 80% depending on the complexity of the coating and the production numbers.

4 RESULTS

Several band-pass filter arrays based on micro structuring have been realized at Optics Balzers for remote sensing applications over the last decade.

Figure 8 shows measured filter channel transmission data of a 5 channel MSI on fused silica manufactured by IAD technology.

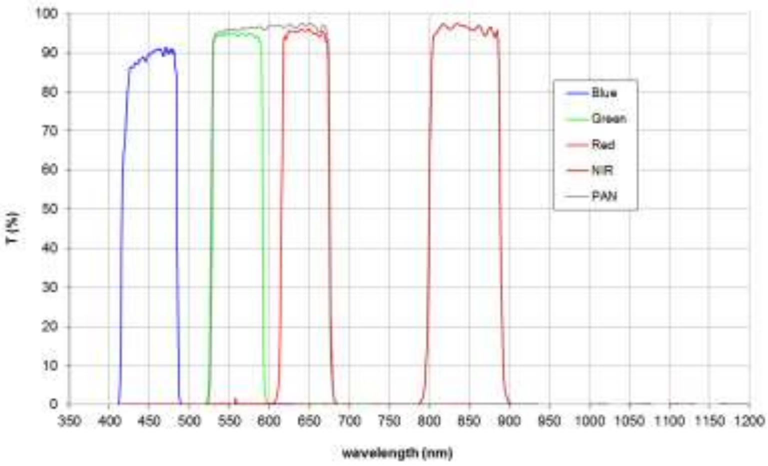

Figure 8. Measured spectral characteristic of a five channel MSI filter plate

Figure 9 demonstrates coating homogeneity over a 4” wafer for a green channel filter (BP510) compared to design data.

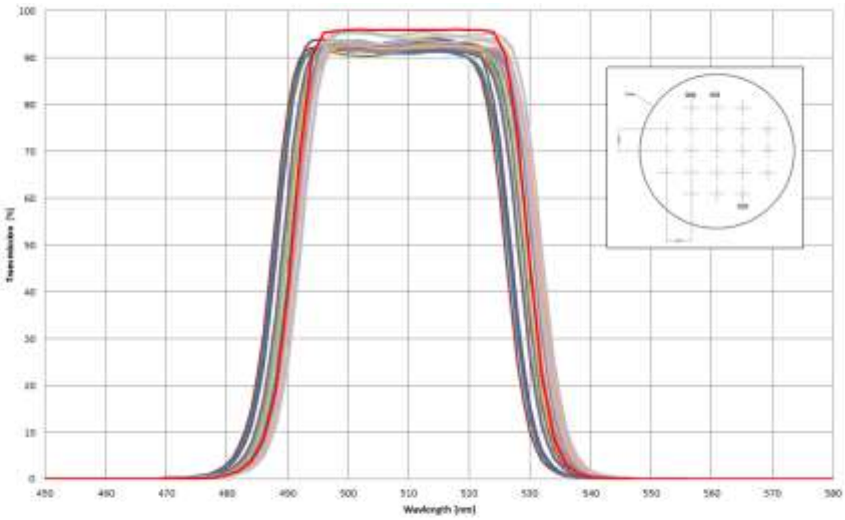

Figure 9. Coating homogeneity for a green channel filter on a 4” test wafer (design data in red)

5 OUTLOOK

In order to satisfy the demand for improved block-band performance (OD4 and beyond) of band-pass filters increasingly thicker multi-layer coatings are required. Therefore, thickness limitations in the existing micro-structuring technology need to be overcome. These are the enhanced thermal and radiation stress on the photoresist during thick coating processes which cause thermally-induced deformations and complications in lift-off processing (see figure 5).

Alternative resist systems with improved thermal stability and lift-off behavior are currently under assessment. Dielectric protection layers to reduce thermal and radiation stress could be deposited in a low-stress process. Also a direct monitoring of the sample temperature during deposition process is requested to interrupt deposition process in a controlled manner.

Edge steepness and smearing depend significantly on stripe geometry and require process modifications and trials for each individual filter array and coating design. These effects will be investigated more systematically to improve prediction and to shorten development time and costs.

Recently OBJ delivered first MSI filter assemblies based on an alternative design approach. This technology combines the freedom of coating design and technology (thickness restrictions) and the opportunity of inter-channel separation of the mounted filter arrays with the accuracy and small feature size of the monolithic multi-channel filter plates.

For this semi monolithic approach elementary coated stripes are cemented edge-to-edge to form a single substrate (like a butcher block). An opaque material can be used as a light barrier between the channels to improve cross channel image suppression inside the filter plate.

Subsequent a LRC aperture mask has been applied on both sides of this block by an adapted microlithography and coating process. Besides the application of the (originally only wafer shape matching) micro lithography equipment to a rectangular filter plate the main challenge is to deal with the (unavoidable) filter stripe displacement tolerance within the block. Although this difference in height between the channels can reach the scale of the resist thickness itself, a successful micro-structuring of a double sided aperture mask has been performed. The aperture mask serves as reference for final dicing and chamfering steps and carries reference marks for the assembly to the sensor.

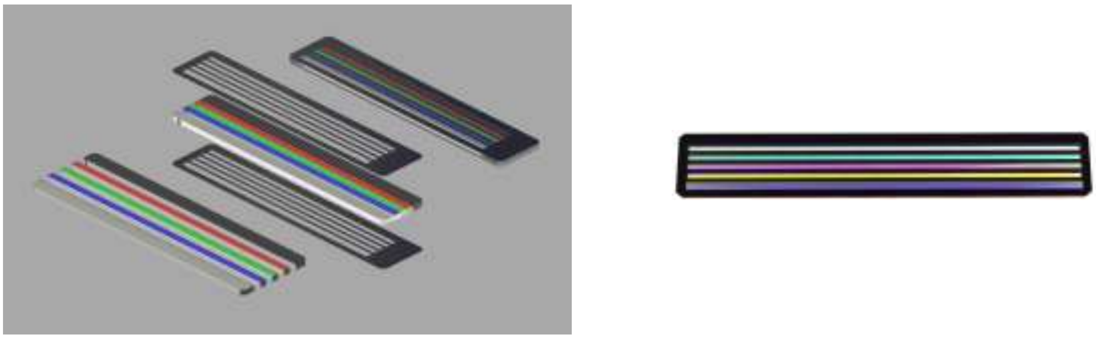

Figure 10. Principal approach and realized customer-specific 5 channel filter array (about 15mmx80mm)

5 CONCLUSIONS

In this paper we have demonstrated the realization of high-performance bandpass filter arrays by micro-structuring processes at Optics Balzers. Applying plasma-IAD technology and broad-band monitoring allows direct from the design data manufacturing and reliable sequence processing of several coatings on the same substrate with affordable yield.

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