Advanced Ultra-Violet and Visible Narrowband Interference Filter Technology Development

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I. INTRODUCTION

Narrowband UV interference filters are a crucial component of many remote sensing technologies ranging from ground-base to airborne to space. Such filters are used to select signals in sun photometers, in air-borne lidars and in space-based systems such as the Hubble Space telescope. Barr Associates is the industry leader in the research and development of narrowband interference filters particularly in the ultra-violet region.

Improved transmittance of an optical filter leads to higher instrument performance, or lower laser power enabling smaller, cheaper lower power instruments to be developed with equivalent performance to current systems.

With this development, Barr has achieved over twice the throughput of previous state-of-the-art performance, while maintaining all other attributes such as out-of-band blocking, size and weight.

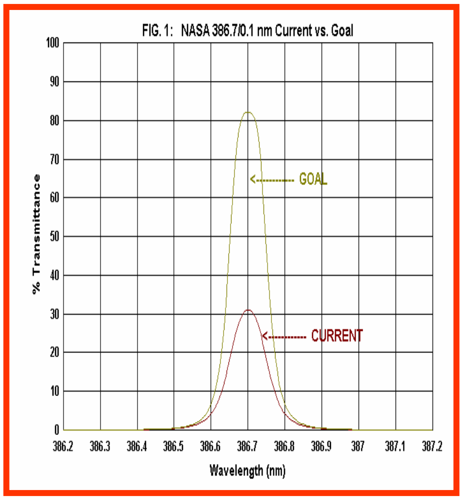
II. TECHNICAL OBJECTIVES

The primary objective of phase I was to develop a process for fabricating UV filters with significant improvement in throughput, then to build a 386.7 nm filter, with a 100 picometer bandwidth with high throughput. One of the challenges was to characterize this filter spectrally; challenging due to its ultra-narrow bandwidth. Discussions between John Potter of Barr and Dave Whiteman of NASA Goddard transpired to determine the goals of phase I. Table I summarizes the performance goals.

Table 1. State-of-the-Art Performance Goals for The UV Ultra-Narrowband Filter Development

Performance Area	**Goals**	**Benefit**
Center Wavelength (CW)	386.68 +,- 0.02 nm	High accuracy benefits all Lidar programs commercial & NASA
Bandwidth (BW)	0.1 +,- 0.02 nm	State-of-the-art
Peak Transmittance	> 60%	Improved instrument performance.
Slope	2 cavity design	Isolation, Improved signal-to-noise
Applications	Longevity	Serves both ground & space based
Blocking	E-8 @ 355 nm, E-6 200-1200 nm	Good background noise reduction, ensure laser line is blocked well relative to signal
Temperature Stability	< 0.002 nm/Deg C	Narrower BW without concern for temperature control
Longevity	Refractory Oxide thin films	5 to 10 year stability
Size	2 inch diameter, uniform	Capture more signal than smaller sizes

Prior to the development effort, the maximum transmittance for a 100 picometer filter was 30 percent. Because the Raman signal at 386.7 nm is weak, any increased filtering performance, would greatly enhance the system performance. Fig. 1 shows the theoretical goal and state-of-the-art prior to this development effort. In addition, fabricating a filter uniform across a two inch diameter area was a challenge. There would be less of a challenge if a one cavity filter was produced, but two cavities is significantly superior in rejecting noise close to the band. Temperature stability and longevity dictated refractory oxides would be the thin film materials of choice.



III. MATERIAL APPROACH

A study was performed, comparing candidate deposition materials, useful for fabrication of UV filters; tantalum pentoxide (Ta2O5), hafnium oxide (HfO2) and zirconium oxide (ZrO2). Depositions were made for each of these materials in combination with silicon dioxide, and spectral comparisons were made. These oxides were selected for their unique properties:

a. **Ta2O5** has good physical properties, with a high refractive index (n = 2.284 @ 387 nm), resulting in fewer layers necessary to attain the desired bandwidth and high out-of-band rejection. This material has been the high index material of choice in this wavelength range. The relatively high intrinsic absorption in the ultraviolet (k = 1.6 x 10^{-4}) of Ta2O5 seriously limits the possible transmittance, therefore, process improvement would focus on absorption reduction[2].

b. **HfO2** is a viable alternative to Ta2O5 with similar spectral and physical properties. The refractive index is lower (n = 2.098), requiring more layers to accomplish the same bandwidth and blocking. The bulk intrinsic absorption is lower than Ta2O5 (k = 8 x 10^{-5}), potentially resulting in higher transmittance [3].

c. **ZrO2** has a refractive index closer to Ta2O5 (n = 2.27) and an absorption coefficient closer to HfO2 (k = 1.0 x 10^{-4}), so may be a good compromise.

d. **SiO2** is the low index material to be deposited along with any of the above high index materials. This material is physically compatible with any of the above materials, and has very low absorption in the ultraviolet.

IV. PROCESS DEVELOPMENT APPROACH

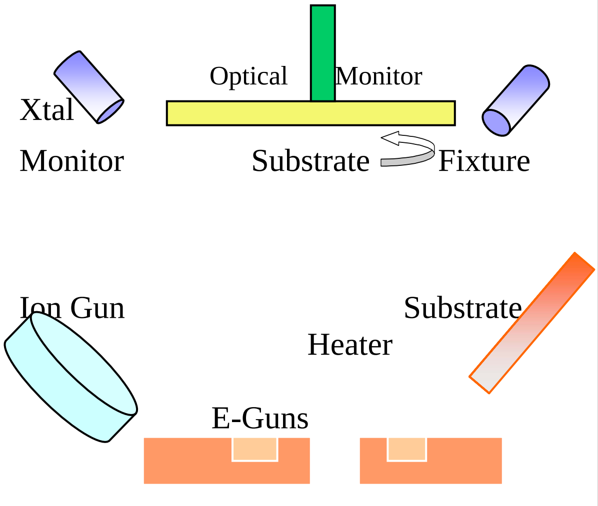
Three deposition processes were utilized in conjunction with the above thin film materials. The focus was on optimizing these processes for minimal absorption, scatter and reflection losses on Fabry-Perot narrowband interference coatings. The following processes were developed and compared spectrally, depositing the above materials:

a. **Electron beam, Kaufman ion assisted deposition (IAD)**, shown in fig. 2, is currently the process used at Barr to produce sub-nanometer bandwidth ultraviolet filters of the highest performance, therefore, this process was the benchmark for comparison of alternative approaches [4]. Due to the many process variables, it is difficult to control the coating uniformity across a 50 mm diameter. The process requires a high substrate temperature during deposition creating problems in control of coating distribution. In addition, the process contaminates the thin films with tungsten from the ion gun cathode and neutralizer. Barr optimized the process by minimizing reflection and absorption losses and reducing thermal effects.

b. **DC magnetron sputtering** is a very consistent process that results in superior coating uniformity compared with e-gun deposition process. This process currently produces thin films of Ta2O5 with higher scatter, hence lower UV transmittance. The scatter losses with HfO2 are minimal, therefore, Barr investigated this material with DC sputtering.

c. **Ion beam sputtering (IBS)** is a process producing smooth films with low scatter losses. An ion beam is created from an RF deposition source, which bombards a target, sputtering the target material onto the substrate. In addition, there is an RF ion beam directed at the substrate for more compact film growth. Currently this process inherently has poorer thickness uniformity than the processes above, so Barr focused attention on improving IBS uniformity, with a goal of less than 0.005% across 50 mm.

Fig. 2 IAD Configuration



V. EXPERIMENTATION

Of the three processes investigated, the Kaufman IAD process proved to be the process giving the best results, achieving what we set out to accomplish. Scatter losses on both the ion beam sputter process and the magnetron sputter process proved to be too great to achieve high throughput on ultra-narrowband UV filters. It was shown by initial experimentation that Zirconium dioxide (ZrO2) had excessive scatter losses, as compared with Ta2O5. These films as they were grown were crystalline instead of amorphous, whether the IBS, IAD or magnetron sputtering process was utilized. The hafnium dioxide efforts looked promising, but the losses were greater than the Ta2O5 losses at 386 nm. This material may prove to be advantages at shorter wavelengths, below 360 nm. The major effort was, therefore, expended in optimizing the results of Ta2O5 in the IAD process. This task was broken down into four separate concerns; improving spatial uniformity, minimizing scatter losses, minimizing reflection losses and minimizing absorption losses.

a. **Wavelength and bandshape spatial uniformity** was addressed with the goal of less than 0.005% change across a two-inch diameter substrate. Rotational uniformity needed to be addressed. It was determined the substrate needed to be flat within 20 microns relative to the source for optimum rotational uniformity. Substrate rotation needed to increase to greater than 500 rpm to minimize rotational variations. The ion gun plume profile needed to be flat across the area, and consistent from run-to-run. To achieve this, the ion gun mechanically needed to be controlled, i.e. the grids consistently cleaned and filaments replaced to within 0.1 mm. The ideal ion gun parameters were determined for each deposition material, minimizing etch rate while maintaining sufficient packing density for stability. The ion gun parameters were coupled with deposition rates, and placed under strict controls. The evaporant plume shape plays a major role in the radial uniformity. We started with a consistent evaporant surface for both the silicon dioxide and the tantalum pentoxide. Calculations were made using uniformity formulae [1]. Then single layer distribution runs were performed, and source geometry adjusted to minimize changes in coating distribution across the two-inch area. Precise tuning of the coating distribution was achieved by fine adjustments to the e-gun sweeping pattern. Thermal effects during the deposition process contributed greatly to the uniformity or non-uniformity. The experimentation lead to three conclusions: There needs to be a consistent substrate temperature during the deposition, a substrate significantly larger than the final size part greatly improves the heat distribution and a clear, large path in front and back of the substrate minimized the thermal effects on optical thickness distribution..

b. **Minimizing scatter** was critical in achieving the maximum throughput. This is particularly important in the ultraviolet region, with very narrow bandwidth filters, because scatter sights are large compared with the filter center wavelength. Coatings were measured with a scatterometer, showing a correlation between scatter and transmission loss. As the bandwidth decreased, the transmittance decreased exponentially as a function of scatter. Barr investigated three areas for potential scatter reduction. The substrate surface is key to low scatter. A series of experiments were performed to determine the effects of the substrate surface on transmittance. For the one-angstrom wide filter, the surface roughness required for maximum transmittance was 10 angstrom (r.m.s.), as shown in table 2. If films grew crystalline, the scatter would increase, therefore it was mandatory the films needed to be amorphous. Substrate temperature, ion beam flux, deposition rates and choice of materials all played a role in minimizing scatter. Minimizing contamination reduces scatter, so extra precautions were taken to ensure the substrate surface and the deposition system did not introduce scatter by contaminants.

Table 2. Substrate Surface Roughness vs. Transmittance

Polished B-270	15.3 Angstroms r.m.s.	43% T @ 371 nm
Polished UV Fused Silica	11.8 Angstroms r.m.s.	56% T @ 371 nm
Float Soda Lime Glass	4.8 Angstroms r.m.s.	73% T @ 371 nm

c. **Minimizing reflection losses** starts with a thin film design where each filter component is matched to its media whereby the reflectance from each surface approaches zero. Errors in the thin films during fabrication as low as 0.005% would increase the reflectance or reduce transmittance by 10 percent. To optimize the accuracy of layer thicknesses, Barr configured a thickness monitor system, specifically designed for the purpose of fabricating ultra-narrow bandpass filters. A state-of-the-art photomultiplier sensitive in the ultraviolet region was used for its superior dynamic range as compared with a silicon detector. Larger monochromators have superior resolution, so a one-meter monochromator was used. A custom blocking filter was placed in front of the monochromator to reduce stray light. The light source was a halogen source, collimated at the substrate, with an iris aperture to control the beam size. The slit width to the monochromator was optimized for maximum signal while maintaining sufficient resolution to fabricate a one-angstrom bandwidth filter. In addition a crystal physical thickness monitor was utilized to control deposition rates and control layer thickness whenever the optical monitor was less accurate.

d. **The importance of minimizing absorption** on ultra-narrow bandpass filters for maximum transmittance is shown in table 3. Process improvements were made to reduce the absorption coefficient of tantalum pentoxide (Ta2O5) from 1.6 x 10^{-4} to 2.0 x 10^{-5}. Efforts were concentrated in the area of optimizing the ion gun and e-gun parameters along with the partial pressure of oxygen during deposition. It was also imperative the partial pressure of water was minimized.

Table 3. Transmittance as a Function of Absorption & Bandwidth

FWHM (nm)	Original Process (Transmittance)	New Developed Process (Transmittance)
0.04	7.4%	56%
0.06	27%	77%
0.10	41.2%	83.6%
0.20	59.4%	89.8%
1.4	93.3%	98.2%
3.5	97.9%	98.9%

VI. RESULTS

Three one-Angstrom wide narrowband filters were produced, meeting or exceeding transmittance goals while blocking better than 1 x 10^{-6} from 200 to 1200 nm and better than 1 x 10^{-12} at 354.7 nm (triple YAG laser line). Transmittance on the three filters ranged from 55% to 70%. The rotational uniformity was less than 0.01 nm, and the radial uniformity was less than 0.02 nm over the two-inch diameter. Fig. 3 shows the results of these three filters. These filters were constructed with five components, laminated together with optical epoxy, with the following components:

1. A Fabry-Perot, 0.1 nm narrowband was deposited on Schott B-270 glass, polished to < 10 angstrom r.m.s. surface roughness.
2. A longwave pass filter was designed to block wavelengths shorter than the band and for maximum transmittance at 386 nm, and deposited on B-270 glass, as shown in fig. 4.
3. A shortwave pass filter was designed to block wavelengths longer than the band and for maximum transmittance at 386 nm, and deposited on B-270 glass, as shown in fig. 5.
4. Schott BG-3 and Phila Optic BGG-29 color filter glasses, shown in fig. 6, were used to block the near infrared portion of the spectrum.

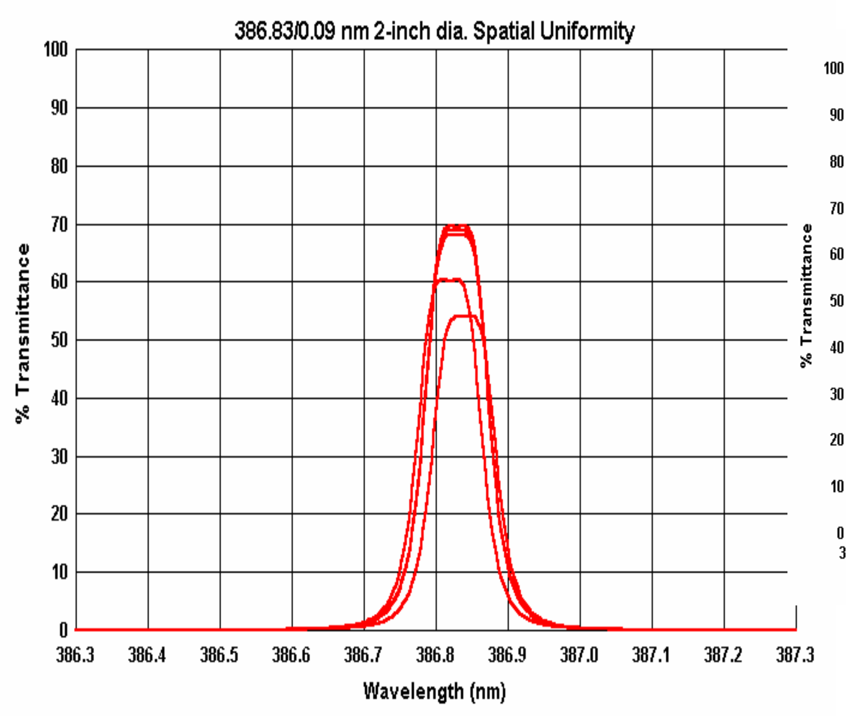


Fig. 3. Spatial Uniformity of the three filters

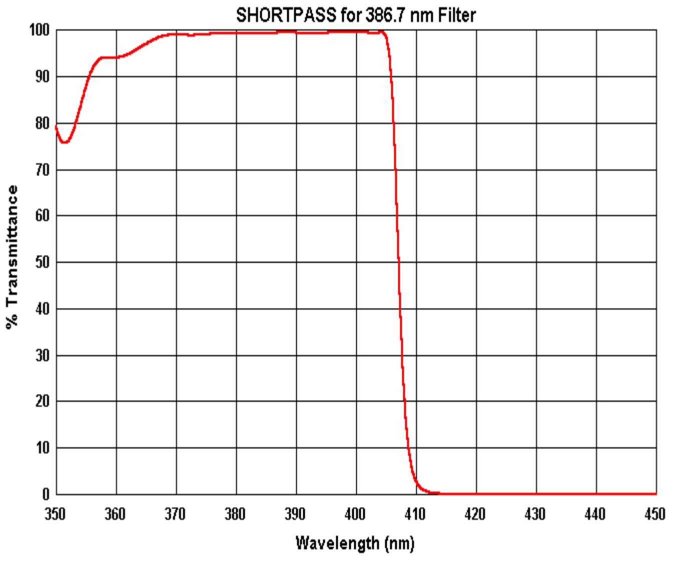


Fig. 5. Shortpass Blocking Filter for the 386.7 nm Filter, Blocking the Long Side on the Band

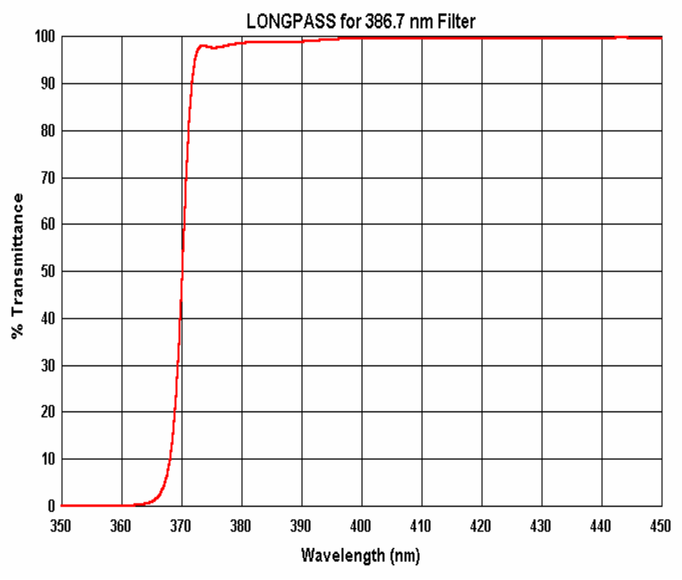


Fig. 4. Longpass Blocking Filter for the 386.7 nm Filter, Blocking the Short Side of the Band

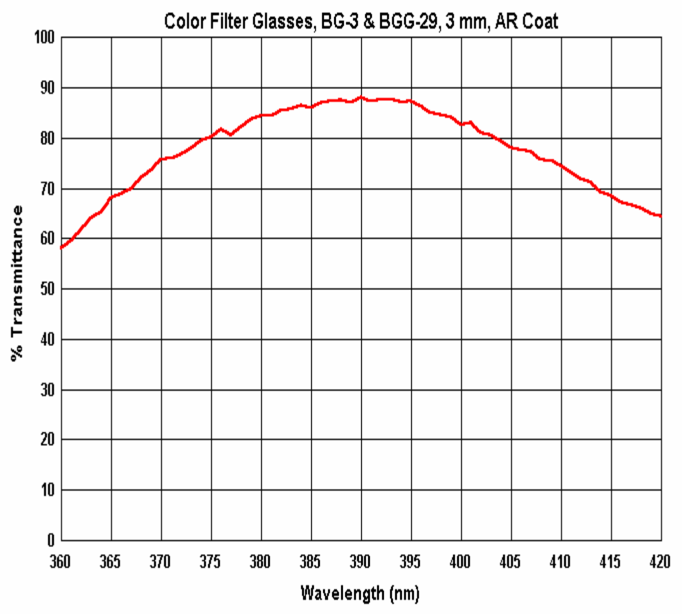


Fig. 6. Color Filter Glasses used in the Construction of the 386.7 nm Filter, to Block the Near Infrared Spectral Range

VII. CONCLUSIONS

Barr has exceeded the goals of greater than twice the throughput on ultra-narrowband (100 picometer bandwidth) filter, 2-cavity design without sacrificing blocking, size or weight. This was repeated, fabricating three filters with even greater throughput, verifying the process has merit in a production setting. Fig. 7 shows the spectral background of these filters from 300 to 1100 nm. The uniformity across 2-inch diameter shows high performance in terms of center wavelength and transmittance consistency. This was accomplished by process improvements focusing on reduction in scatter, reflecting and absorption, and by process improvements in the deposition system to improve coating uniformity. Spectral measurements were performed on these filters at Barr and at NASA Goddard with excellent correlation in respect of bandwidth and transmittance with reasonable correlation in center wavelength (<0.02 nm).

VIII. FURTHER STUDY

Development in multi-cavity (4, 5 or 6 cavity) filters in the UV and at 532 nm, are an obvious extension of this work. There is a need in Raman spectroscopy to have very steep slope, ultra-narrowband filters close to the laser lines, at 532 and 355 nm. The absorption of tantalum pentoxide at 355 nm may be prohibitive, therefore, further development of hafnium dioxide is natural. Since there was a discrepancy between Barr's and NASA's center wavelength measurements, further study is warranted to improve this correlation.

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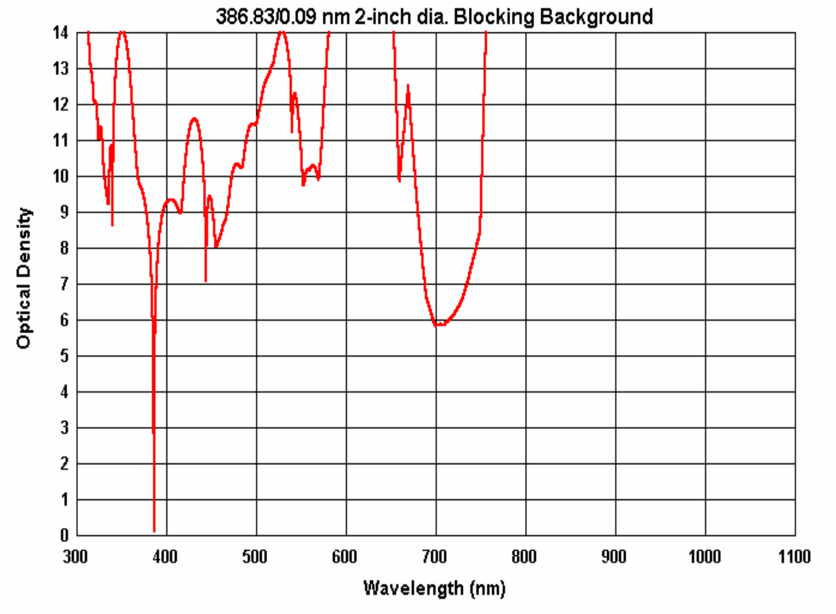

shows greater than OD 6 300 to 1100 nm, and greater than OD 12 at 354.7 nm.

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