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SkyMapper Filter Set: Design and Fabrication of Large-Scale Optical Filters

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ABSTRACT. The SkyMapper Southern Sky Survey will be conducted from Siding Spring Observatory with u, v, g, r, i, and z filters that comprise glued glass combination filters with dimensions of $309 \times 309 \times 15$ mm. In this article we discuss the rationale for our bandpasses and physical characteristics of the filter set. The u, v, g, and z filters are entirely glass filters, which provide highly uniform bandpasses across the complete filter aperture. The i filter uses glass with a short-wave pass coating, and the r filter is a complete dielectric filter. We describe the process by which the filters were constructed, including the processes used to obtain uniform dielectric coatings and optimized narrowband antireflection coatings, as well as the technique of gluing the large glass pieces together after coating using UV transparent epoxy cement. The measured passbands, including extinction and CCD QE, are presented.

Online material: color figures

1. INTRODUCTION

The success of the Sloan Digital Sky Survey[1] (SDSS; e.g., Abazajian et al. 2009) and the immense amount of uniform and precise photometric data made available leads anyone intending to conduct a large-scale survey to consider duplicating the SDSS passbands. However, as much of the SkyMapper (Keller et al. 2007) science case involves stellar photometry, it is advantageous to design the filter set to provide better discrimination of metallicity, effective temperature, and effective gravity in stars than is provided by the SDSS filter set. There are older photometric systems that successfully achieve these goals (see Bessell 2005): namely, the Strömgren $uvby$ system and the DDO system. With these insights we have moved the SDSS u and g bands apart and inserted a violet v band between them, but kept the redder passbands (r, i, and z) largely unchanged.

By shifting the SDSS u band further to the UV, we diminish the contribution of light redward of the Balmer jump, thereby emulating the Strömgren u band. This bandpass is demonstrated to provide good temperature sensitivity in hot stars and good gravity sensitivity in A, F, and G stars. By shifting the blue edge of the g band a little redward, we lessen its metallicity sensitivity and make it behave more like Strömgren b or Johnson V filters. Finally, in the gap between the redefined u and g bands, we introduce a v band similar to the DDO 38 band, which is very metallicity-sensitive, especially at low metallicities.

To facilitate the photometric precision and astrophysical fidelity of the SkyMapper photometric catalogs, it is important that the passbands are consistent across the filter aperture and that their transmission does not change with time. This is especially true in the u and v bands, whose power to accurately discriminate stellar parameters depends on precision photometry. While interference filters can be made in large sizes, they remain very expensive, with uniformity of the passband across the aperture difficult to achieve. To overcome these drawbacks, interference filter manufacturers suggest making a mosaic of smaller filters, rather than a single large filter—something we did not wish to do, given our monolithic focal-plane assembly. There are also problems with wavelength stability of interference filters with time and environment. For all these reasons, we investigated and pursued fabricating large colored glass filters that we have successfully used in the past for long-term photometric programs with single-CCD systems.

In § 2 we will discuss colored glass filters and describe choosing the glasses and sourcing the blanks. In § 3 we will describe grinding and polishing the glass to the required thickness and surface finish, applying the short-wave passband (SWP) and antireflection (V-AR) coatings, and gluing the glass assemblies. In § 4 we will present the resultant passbands, and in the final section we will provide a summary.

2. COLORED GLASS FILTERS

The palette of colored glass filters is quite extensive, although the range of glass types has been reduced since the review article on colored glass filters by Dobrowolski et al. (1977). Much of the discussion in that article is still relevant, but whereas in 1977 there were 13 manufacturers of colored filter glass in six countries, today we have knowledge of only five companies still producing filters, although companies such

[1] See http:www.sdss.org.

as Schott have facilities in several different countries. In addition to a reduction in the range of glass type, the forms of the glass production (size of sheets and thicknesses) and method of production have also changed. The Schott filter catalog[2] provides a good summary of the chemical/physical attributes of the glasses that generate the variety of colors. Briefly, colored glasses are produced in one of two ways, either by ionic coloration or by absorption and scattering from a suspension of colloidal particles that are produced in the glass and controlled in size by heat treatment after an essentially colorless glass is made.

The ionic glasses are made by dissolving particular salts (such as cobalt or nickel oxide) in glass. The ionic coloration of the UG (violet) and BG (blue) series of glasses produces a spectral transmittance curve resembling a bell curve of half-width between 100 and 200 nm, but most of these glasses also transmit red light beyond 700 nm as well, and thus the violet glasses appear purple to the eye.

The second type of colored filter glass is a series of sharp-edged (or short-wave cutoff) filters, the WG, GG (sulfur and cadmium sulfide), OG (cadmium selenide), and RG (gold) series, which absorb light blueward of a quite sharply defined wavelength. The filters are made with their short-wave cutoffs ranging from 400 to 800 nm in steps of 20 nm. To the eye, the WG glasses are essentially colorless, the GG series go from colorless through light yellow to dark yellow, the OG are orange-red, and the RG series are rose to ruby in color. Selecting a thicker piece of glass moves the short-wave cutoff redward.

Schott also make special (nearly) colorless glasses (BG39/40, S8612, and the KG series) that can be used as long-wave cutoff filters; however, these glasses have long-wave cutoffs that fall much more slowly (over about 250 nm) than the short-wave cutoffs rise (over about 50 nm), thus producing an asymmetrical spectral transmittance curve when used together to define a bandpass. An important use for the BG39/40 and S8612 glasses is also as a "red-leak" blocker, absorbing light beyond 700 nm, where most of the blue and violet glasses transmit. The better UV transmission of Schott S8612 compared with BG39/40 makes it the preferred choice to block the red leak of the UG glasses.

There are two main filter manufacturers apart from Schott, Hoya[3] and Nantong Yinxing Optics,[4] both of which have product lines that are are similar to that of Schott. There are also at least two manufacturers in the former USSR (Russia and Ukraine). Nantong Yinxing Optics provides a useful cross-reference of Chinese glasses and other manufacturers, including glasses from the former USSR.[5]

[2] http://www.us.schott.com/english/index.html.

[3] See http://www.hoyaoptics.com/color_filter/index.htm.

[4] See http://www.ygofg.com/Products.htm.

[5] See http://www.ygofg.com/Cross.htm.

2.1. Sources of Large Filter Glass

Two important requirements for SkyMapper filters are their large size, 309×309 mm, and large thickness, 15 mm—or, more precisely, the specific filter-glass thickness (depending on its refractive index) that equates to 15 mm of BK7 glass. Using a thicker filter mitigates ghost intensities and makes fabrication and assembly easier. Unfortunately, Schott, Hoya, and Yinxing production lines currently only fabricate filter glass in strips up to 165 mm wide, with a maximum of 3 mm finished thickness.[6] So we looked to companies in Russia to see whether filter glass was still made in large slabs. Historically, in the former USSR, different-colored glass filters were made in several different plants, but they worked to identical standard formulations and met standard catalog transmission values.[7] A particular added advantage of these GOST glass filters was that their filter range included glasses with a range of concentrations of the colorant, enabling thicker glasses to be specified for the same color as a standard thin Schott filter.

We initially acquired filter glass from a Russian company, MacroOptica, who sourced most of their glass from the companies Krasnyi Gigant (since closed) and LZOS.[8] Since 2008, we have acquired red (RC10), clear ($\mathrm{C3C21} \approx \mathrm{BG40}$), and UV (UVC2) glasses from Potapenko Glass & Filters (PG&F) of the Ukrainian Optical Glass Factory, who consistently delivered glasses of high quality.[9] Stocks of large filter slabs are not usually held, but are made to order. In the case of colloidal colored glasses, special melts require a long lead time, because the processing required to color-strike and anneal large thick slabs of glass uniformly is time-consuming. The LZOS company also offered to make large filters in the yellow, orange, and red glass types of ranges.[10]

Based on transmission values in the GOST 9411-81 catalog we designed glass mixes and thicknesses for the SkyMapper bands after verifying the catalog transmission values against 50 mm samples of the glasses that we ordered. Table 1 lists the filter recipes that we have used. The u-band filter was originally $8\ \mathrm{mm}\,\mathrm{y\Phi C2} + 6.3\ \mathrm{mm}\,\mathrm{BC4}$, but we discovered an optical flaw in the corner of the yΦC2 glass after the filter was assembled and tested on the sky. To expedite the filter fabrication, we then ordered some UVC2 from PG&F and used a piece of Schott B270 that we had on hand to bring the thickness up to 15 mm. Its thermal properties are similar to those of UVC2

[6] Schott is considering making filters up to $350 \times 350 \times 8$ mm again (Doehring et al. 2006). GG, OG, and RG types of glasses can still be made by special melts in large sheets, but still with a limited thickness.

[7] A listing of the GOST 9411-81 standard catalog of USSR glass filters is available from http://www.mso.anu.edu.au/~bessell/FTP/Filters.

[8] See http://lzos.ru/en/.

[9] Links to data sheets of their GOST named filters and a list of equivalences to Schott and Hoya filters are available at http://www.opticalglass.com.ua/en/catalog/filtersheet.htm.

[10] The ranges of the filters from PG&F and LZOS are also given at http://www.mso.anu.edu.au/~bessell/FTP/Filters.

TABLE 1
FILTER GLASSES USED IN SKYMAPPER

Band	Component glasses
u	6.2 mm UVC2 + 8.3 mm B270
v	3 mm yΦC1 + 6.5 mm C3C23 + 5 BC7
g	4 mm GG420 + 5 mm C3C21 + 5.7 mm BC4
r	15 mm BK7 + LWP + SWP
i	6 mm KC19 + 8.5 mm B270 + SWP
z	4.5 mm RG850 + 10.1 mm B270

NOTE.—B270 and BK7 are clear Schott optical glasses used to build up the thickness. SWP and LWP indicate short-wave passband and long-wave passband coatings that were used to define the red and blue sides of the band. The z filter was specially made by Schott.

and its cut-on edge was suitable. The resultant u passband differed slightly from the original formulation, with a small red leak (intensity 0.7%, 250 Å wide, centered at 7170 Å), but with a higher overall transmission of 60%. The r filter was originally designed to use a piece of OC12 (~GG550) from MacroOptica for the short-wavelength cutoff, but on delivery, the nonuniformity (color variation across the aperture) was clearly visible by eye. Due to time and financial constraints, as well as a lower requirement for uniformity in the r band, we decided to use dielectric coatings on BK7 glass for both sides of the passband. The resulting filter has very high throughput, but is less uniform than the glass filters.

3. FILTER MANUFACTURE

3.1. Packing and Shipping

Glass is fragile and needs special packing, which is an obvious but important point. When ordering glass, it is important that the shipping container be specified as part of the contract. We recommend supporting the smaller box containing the glass by compressible material within another container. Our preferred method is to pack in bubble wrap inside a corrugated cardboard box that is itself packed in foam in a model 1610 Pelican case.[11]

3.2. Cutting and Polishing

To ensure that the filters do not impinge on the delivered image quality and uniformity of the telescope, we specified standard optical quality in regard to homogeneity, wavelength tolerance, stress birefringence, visible stria, and visible bubbles. We also specified tolerances for the physical dimensions of the glass and for the final polish. The mechanical tolerances on the edge dimension were ± 0.5 mm and on the thicknesses were ± 0.08 mm, and the wedge angle was to be less than $0.0074°/0.04$ mm. Optical tolerances were specified to be less than 0.5 waves peak to valley, transmitted over any single beam footprint of 40 mm diameter within the optical clear aperture; the overall power of each surface was to be less than nine waves at 633 nm; and the surface irregularity was to be less than five waves at 633 nm, with a surface finish of 40–20 SD (scratch and dig).

Our first lot of glasses polished by MacroOptica did not achieve the polishing specifications. To rectify this problem we had the glasses repolished by Bond Optics (New Hampshire).[12] Subsequent glasses from PG&F were ordered in a rough ground state. To assess the optical transmission quality before polishing, we oiled each sheet of ground filter glass and placed it between sheets of plate glass. Selected pieces were sent to Bond Optics for grinding to the required thickness and then polishing. Bond Optics was able to achieve our required specifications.

3.3. Coating the Filters

Rather than use the shallow red cutoffs of the available glasses, we elected to define the long-wavelength edges of the r and i bands by means of a SWP coating (due to the delivered piece of OC12 glass not meeting our specifications, we also elected to define the short-wavelength edge of the r filter with a long-wave passband [LWP] coating). After consultation with a number of manufacturers, we approached ATOC Optical Sputtering Technologies[13] (ATOC/OST; New Mexico), who was able to offer the uniformity runoff across the aperture that we required using modulated reactive DC magnetron sputtering. OST designed and applied the required coatings. They achieved high on-band transmission and, although quite uniform, the filters had somewhat larger fluctuations than anticipated, due to equipment failure during the actual deposition run. OST is also making a narrowband Hα filter (6563 ± 40 Å) and a MgH filter (5142 ± 80 Å) (to distinguish K giants from K dwarfs) on Ukrainian colored glass substrates that will also be used on SkyMapper.

A simple two-layer "V band" (shape of the coating passband) antireflection coating was applied to all the colored glass filters by Optical Coating Associates.[14] The coating process involves heating the substrate to 70–75°C to achieve a good base vacuum, then using ion-assisted deposition to apply the two-layer V-AR coat over a 5–10 minute period. The coating process introduces additional heat, and the chamber registered more than 100° when the coating guns were switched off. In our first attempt, we glued the component glasses together before coating. However, the first filter coated, the g filter, partially delaminated due to the heat absorbed by the middle glass (C3C21 ≈ BG40), which absorbs light at infrared wavelengths.

[11] See http://www.pelican.com.

[12] See http://bondoptics.com.

[13] See http://opticalsputtering.com.

[14] See http:www.opticalcoating.com.au.

FIG. 1.—Gluing the g filter. See the electronic edition of the *PASP* for a color version of this figure.

FIG. 2.—Last Mylar shim in place while gluing the u filter. See the electronic edition of the *PASP* for a color version of this figure.

Subsequently, we decided to make new filters, applying the V-AR coating to the individual glass pieces and gluing the filter assembly together as the final step.

3.4. Cementing the Filters

Schott constructed the SkyMapper z filter using UV-setting cement NOA 61. We could not use this technique on our other filters, as UV-setting cements are incompatible with some colored glass types and also require very uniform large UV light cabinets for processing. The cement also shrinks, causing the glass to bend, which often requires repolishing to recover the desired flatness. We have had much experience successfully gluing smaller filters with UV-transmitting epoxy cement, with the epoxy joints proving to be very stable over time.

We used EPO-TEK 301-2FL,[15] which has excellent UV transmission properties. It is a slow-setting (3 days) optical epoxy that hardens with near-zero shrinkage that puts little strain on the glasses and is easy to work with in a small laboratory environment. This glue has a short shelf life and was ordered as required. As the glue ages, small translucent flecks of material form that do not redissolve on warming.

The technique for successful gluing is straightforward but time-consuming. We elaborate on the procedure here. New dust-free vinyl gloves should be used whenever the filters are handled. The laboratory work area needs to be kept clear of dust, and it is important that the air is filtered and that the temperature is kept at about 26°C. Whenever a new glue run is made, two pieces of plate glass with the same diameter as the filters are glued first as a trial. This enables the correct amount of glue to be better estimated and the uniformity and behavior of the glue layer to be closely monitored. The edges of the filters to be glued need to restrained in a rig to ensure that they stay aligned during the gluing process (Fig. 1). However, access to the edges needs to be available so that any glue that leaks out can be easily wiped off.

At the start of the procedure, five pieces of Mylar shim of 0.1 mm thickness are placed on top of each other at each corner of the filter. A precise amount of mixed epoxy is weighed and poured in a Z pattern, about 200 mm across, near the center of the lower glass sheet. (The Z pattern is important, at it prevents air bubbles from being trapped in the spreading epoxy.) The second piece of glass is then lowered with a controlled wedge action on top of the first. This is allowed to stand under its own weight, forcing the glue (and any bubbles) slowly across the whole area. After 30 minutes, the first shim is slid out of one corner, slightly lowering the glass on that corner. The other first-level shims are then removed from the other corners in turn over the next hour, gradually allowing the glue to slowly flow/float between the plates out to the edge. The next shim layer is then removed in the same manner as the first layer, with the sequence of removals of each layer continued for 2–3 hr until

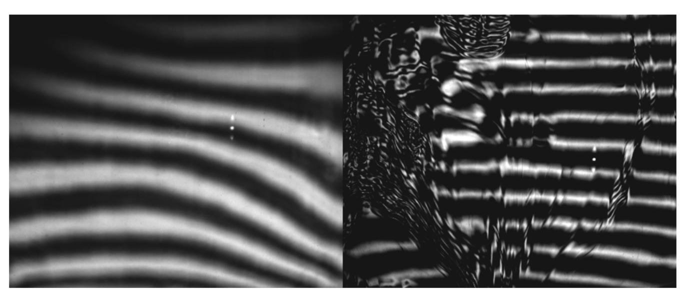

FIG. 3.—Ronchi fringes through good and bad sections of a rejected filter.

[15] See http://www.epotek.com/sscdocs/datasheets/301-2FL.PDF.

the final layer of shims remain—one in each corner, with the glue fully filling the glass all the way to the edge gap over the entirety of the surface (Fig. 2). As the glue slowly thickens (the consistency of thick honey), but is not tacky, the final four shims are removed together in diagonal pairs. Glue continues to slowly leak out for a while, but an even layer of glue—about 30–40 μm thick—remains between the two glasses when finally cured. All glue that leaks from the edges throughout the shim removal process is carefully wiped off, making sure that none touches the surface of the filter. After a 72 hr curing period the

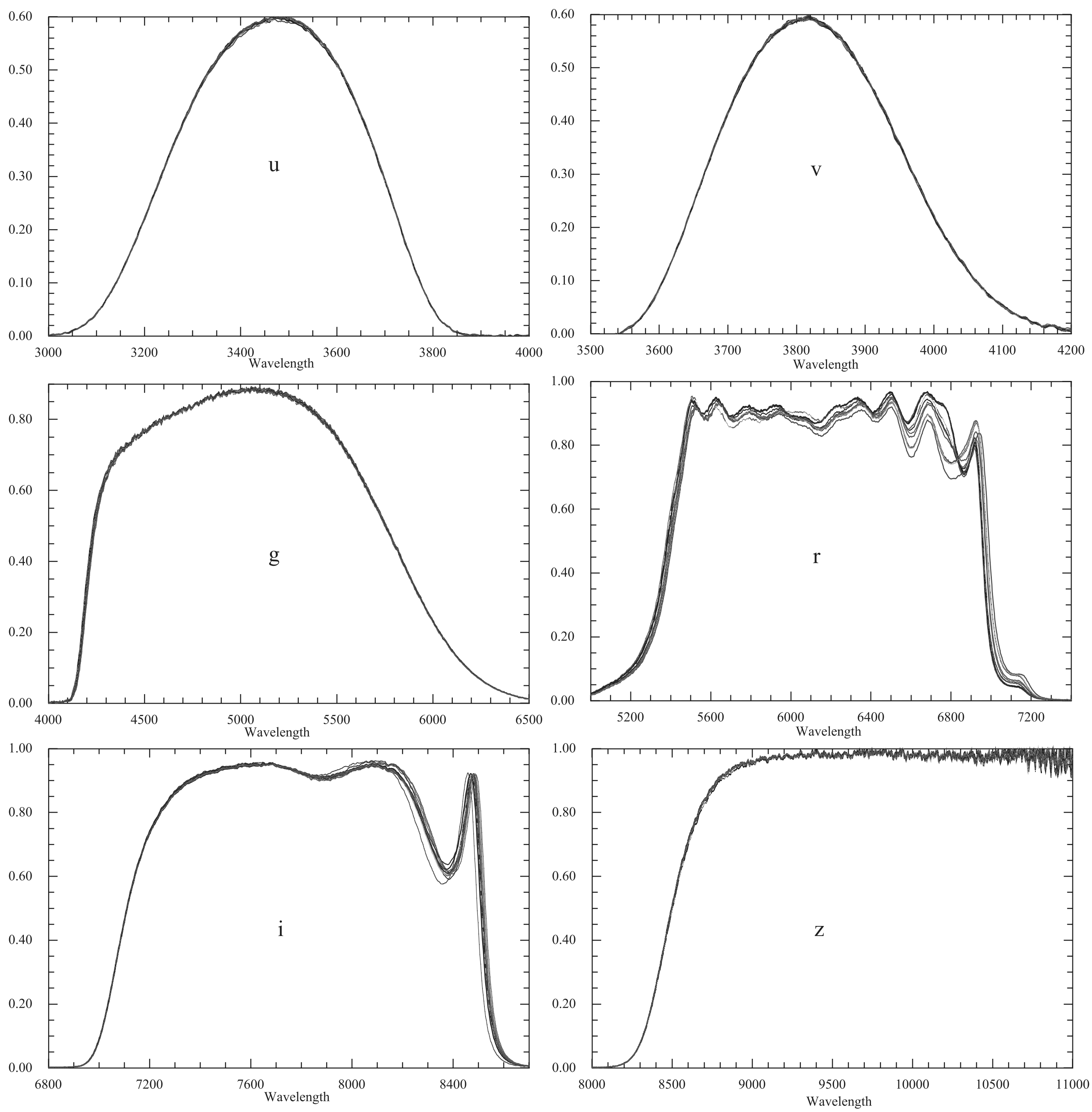

FIG. 4.—Superimposed measured transmissions at 13 points over the aperture. See the electronic edition of the *PASP* for a color version of this figure.

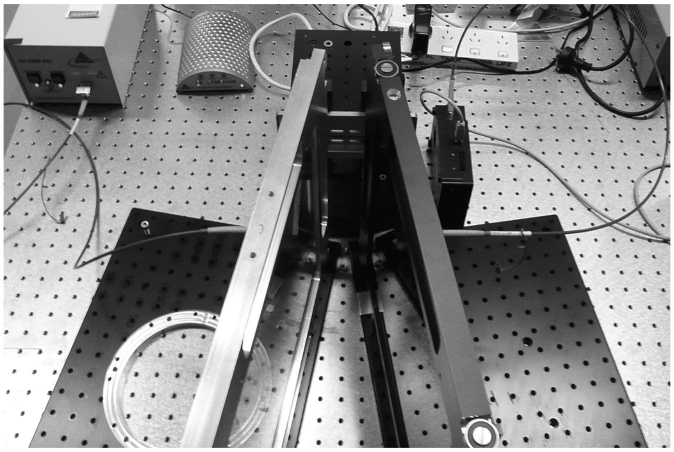

FIG. 5.—Optical setup to measure transmission variation with incident angle. See the electronic edition of the *PASP* for a color version of this figure.

filter is ready for use. This process produces a filter that is extremely stable and can withstand the test of time.

4. FILTER MEASUREMENTS FOR OPTICAL QUALITY AND BANDPASS UNIFORMITY

4.1. Optical Quality Tests

The completed filters were held vertically and the optical quality was assessed qualitatively using a Ronchi screen at the center of curvature of a spherical mirror (radius 3000 mm and 520 mm diameter). All filter and filter-glass components that had been flat-polished were inserted in the beam path adjacent to the spherical mirror, and any local area imperfections in the colored glass filter or distortions of the wavefront (double pass in transmission) were then easily identified by visual inspection of the Ronchi pattern. This is a very simple and sensitive test. Figure 3 shows the fringe pattern through good and bad sections of a rejected filter. A camera was used for the i and z filters, but the u filter could not be tested this way and was instead assembled as spaced components in a filter cell and tested on the sky in SkyMapper. Additional quantitative optical tests were performed with a collimator/camera arrangement with a 30 mm diameter footprint on the filter glass. Here, a perfect object point source was imaged through a specific footprint area of the filter, previously identified in the preceding Ronchi test, the image PSF was analyzed, and the aberration was calculated from those data.

4.2. Wavelength Transmission Uniformity

The wavelength transmission of the filters was measured with an Ocean Optics HR4000 mini fiber optic spectrometer, an Optic DT mini 2GS light source, a pair of 600 μm silica fibers, and a pair of 74-UV collimating lenses. The useful range of the spectrometer is from 250 nm to 1000 nm, and our resolution was about 1 nm. The filter was held vertically on an X–Y slide placed between the transmit and receive fibers, and the X–Y slide moved to enable the probe beam (~4 mm diameter) to measure the wavelength transmission at 25 points across the aperture of the filter to measure the uniformity. The transmissions measured at 13 points over the aperture are shown superimposed in Figure 4. All filters exhibited good uniformity, especially the all-colored-glass filters, which show almost no variation. The dielectric coating on the i filter also showed a small variation top to bottom across the aperture.

4.3. Wavelength Transmission Variation with Angle of Incidence

The filters in SkyMapper are used in the convergent beam and the extreme cone angles of the beams are different for

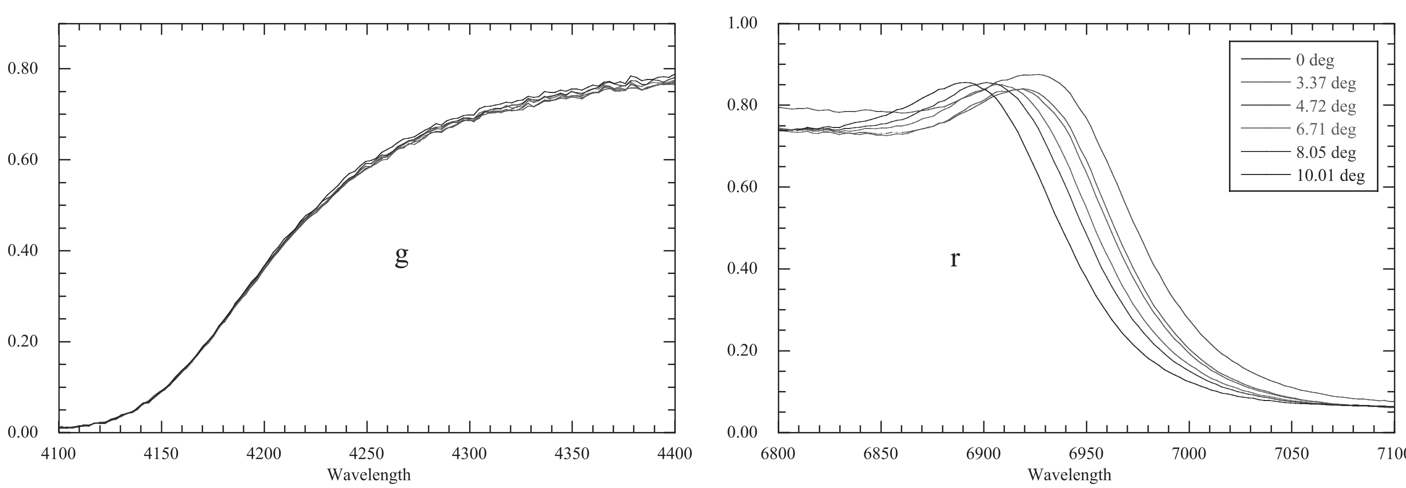

FIG. 6.—Superimposed measured transmissions at six angles of incidence between 0 and 10° of the g and r filters. See the electronic edition of the *PASP* for a color version of this figure.

TABLE 2

NORMALIZED SKYMAPPER RESPONSE FUNCTIONS AND MEASURED FILTER TRANSMISSIONS

Wave	g	g’	Wave	r	r’	Wave	i	i’	Wave	z	z’	Wave	u	u’	Wave	v	v’
4000	0.000	0.001	4800	0.000	0.004	6800	0.000	0.002	8100	0.000	0.003	3000	0.000	0.000	3500	0.000	0.000
4050	0.003	0.004	4850	0.002	0.006	6850	0.001	0.002	8150	0.008	0.006	3050	0.003	0.010	3550	0.009	0.007
4100	0.006	0.007	4900	0.008	0.008	6900	0.003	0.003	8200	0.019	0.015	3100	0.023	0.043	3600	0.121	0.085
4150	0.078	0.087	4950	0.012	0.011	6950	0.015	0.014	8250	0.046	0.035	3150	0.086	0.117	3650	0.370	0.247
4200	0.301	0.326	5000	0.021	0.019	7000	0.087	0.080	8300	0.102	0.078	3200	0.204	0.222	3700	0.648	0.413
4250	0.506	0.537	5050	0.034	0.032	7050	0.262	0.242	8350	0.203	0.153	3250	0.366	0.337	3750	0.879	0.537
4300	0.612	0.637	5100	0.051	0.048	7100	0.480	0.444	8400	0.347	0.261	3300	0.537	0.438	3800	1.000	0.590
4350	0.676	0.692	5150	0.070	0.066	7150	0.633	0.616	8450	0.502	0.383	3350	0.695	0.517	3850	0.996	0.568
4400	0.716	0.722	5200	0.097	0.091	7200	0.707	0.731	8500	0.653	0.508	3400	0.826	0.567	3900	0.873	0.483
4450	0.753	0.748	5250	0.141	0.130	7250	0.777	0.807	8550	0.782	0.620	3450	0.923	0.591	3950	0.664	0.357
4500	0.784	0.768	5300	0.218	0.201	7300	0.851	0.857	8600	0.876	0.710	3500	0.985	0.593	4000	0.421	0.220
4550	0.813	0.786	5350	0.354	0.320	7350	0.934	0.890	8650	0.935	0.778	3550	0.992	0.565	4050	0.234	0.119
4600	0.839	0.803	5400	0.572	0.521	7400	0.980	0.914	8700	0.979	0.837	3600	0.937	0.506	4100	0.107	0.053
4650	0.856	0.813	5450	0.772	0.717	7450	0.993	0.927	8750	0.995	0.876	3650	0.805	0.413	4150	0.039	0.019
4700	0.876	0.827	5500	0.951	0.893	7500	1.000	0.936	8800	1.000	0.909	3700	0.595	0.291	4200	0.015	0.007
4750	0.896	0.839	5550	0.932	0.902	7550	0.936	0.942	8850	0.982	0.927	3750	0.332	0.155	4250	0.000	0.000
4800	0.918	0.854	5600	0.953	0.906	7600	0.709	0.948	8900	0.946	0.944	3800	0.113	0.051	…	…	…
4850	0.939	0.866	5650	0.962	0.926	7650	0.716	0.950	8950	0.845	0.952	3850	0.015	0.006	…	…	…
4900	0.953	0.870	5700	0.926	0.885	7700	0.917	0.946	9000	0.773	0.959	3900	0.000	0.000	…	…	…
4950	0.971	0.880	5750	0.943	0.895	7750	0.959	0.934	9050	0.764	0.968	…	…	…	…	…	…
5000	0.981	0.882	5800	0.947	0.905	7800	0.945	0.920	9100	0.719	0.965	6950	0.000	0.0002	…	…	…
5050	0.990	0.884	5850	0.937	0.895	7850	0.934	0.913	9150	0.699	0.973	7000	0.002	0.0006	…	…	…
5100	0.995	0.883	5900	0.946	0.901	7900	0.927	0.911	9200	0.708	0.974	7050	0.005	0.0014	…	…	…
5150	1.000	0.883	5950	0.947	0.905	7950	0.923	0.916	9250	0.661	0.972	7100	0.010	0.0026	…	…	…
5200	0.997	0.877	6000	0.927	0.891	8000	0.931	0.934	9300	0.493	0.985	7150	0.014	0.0038	…	…	…
5250	0.988	0.865	6050	0.919	0.881	8050	0.929	0.943	9350	0.348	0.980	7200	0.014	0.0042	…	…	…
5300	0.980	0.855	6100	0.898	0.867	8100	0.902	0.951	9400	0.361	0.991	7250	0.011	0.0033	…	…	…
5350	0.960	0.835	6150	0.895	0.858	8150	0.826	0.938	9450	0.350	0.983	7300	0.008	0.0022	…	…	…
5400	0.937	0.811	6200	0.926	0.883	8200	0.784	0.917	9500	0.341	0.979	7350	0.006	0.0016	…	…	…
5450	0.908	0.783	6250	0.945	0.903	8250	0.733	0.854	9550	0.350	0.977	7400	0.002	0.0005	…	…	…
5500	0.874	0.751	6300	0.966	0.919	8300	0.643	0.751	9600	0.368	0.976	7450	0.000	0.0002	…	…	…
5550	0.828	0.710	6350	0.974	0.931	8350	0.565	0.647	9650	0.407	0.986	…	…	…	…	…	…
5600	0.775	0.663	6400	0.947	0.904	8400	0.576	0.627	9700	0.432	0.981	…	…	…	…	…	…
5650	0.719	0.614	6450	0.970	0.909	8450	0.734	0.772	9750	0.424	0.989	…	…	…	…	…	…
5700	0.658	0.561	6500	1.000	0.941	8500	0.554	0.871	9800	0.402	0.990	…	…	…	…	…	…
5750	0.594	0.506	6550	0.928	0.884	8550	0.123	0.216	9850	0.378	0.984	…	…	…	…	…	…
5800	0.524	0.447	6600	0.907	0.835	8600	0.028	0.047	9900	0.355	0.981	…	…	…	…	…	…
5850	0.460	0.392	6650	0.986	0.894	8650	0.009	0.014	9950	0.334	0.980	…	…	…	…	…	…
5900	0.391	0.334	6700	0.990	0.917	8700	0.004	0.006	10000	0.312	0.981	…	…	…	…	…	…
5950	0.329	0.281	6750	0.923	0.853	8750	0.002	0.003	10050	0.291	0.982	…	…	…	…	…	…
6000	0.271	0.232	6800	0.858	0.793	8800	0.000	0.003	10100	0.270	0.981	…	…	…	…	…	…
6050	0.219	0.188	6850	0.782	0.740	…	…	…	10150	0.250	0.987	…	…	…	…	…	…

TABLE 2 (*Continued*)

Wave	g	g'	Wave	r	r'	Wave	i	i'	Wave	z	z'	Wave	u	u'	Wave	v	v'
6100	0.173	0.148	6900	0.849	0.787	...	...	...	10200	0.225	0.977	...	...	...	...	...	...
6150	0.135	0.116	6950	0.631	0.676	...	...	...	10250	0.203	0.975	...	...	...	...	...	...
6200	0.103	0.088	7000	0.210	0.249	...	...	...	10300	0.181	0.976	...	...	...	...	...	...
6250	0.077	0.066	7050	0.093	0.096	...	...	...	10350	0.159	0.973	...	...	...	...	...	...
6300	0.057	0.049	7100	0.071	0.065	...	...	...	10400	0.134	0.967	...	...	...	...	...	...
6350	0.042	0.036	7150	0.052	0.056	...	...	...	10450	0.112	0.963	...	...	...	...	...	...
6400	0.031	0.026	7200	0.017	0.023	...	...	...	10500	0.091	0.970	...	...	...	...	...	...
6450	0.020	0.017	7250	0.006	0.008	...	...	...	10600	0.048	0.981	...	...	...	...	...	...
6500	0.014	0.012	7300	0.000	0.004	...	...	...	10700	0.000	0.989	...	...	...	...	...	...
6550	0.012	0.010	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
6600	0.007	0.006	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
6650	0.005	0.004	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
6700	0.000	0.002	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

different parts of the field (e.g., Elliott & Meaburn 1976; Parker & Bland-Hawthorn 1998) and the large secondary obscures the low-angle incident rays. To assess the resultant wavelength shifts for the SkyMapper filters, we measured the wavelength transmission variation with angle of incidence (AOI) using the preceding measuring setup, but with the filter and an identical clear (compensation plate) inserted in the measurement space, as shown in Figure 5. The AOI was varied by changing the angle of the "V" arrangement of the filter and compensating plate. Spectral data were collected for a range of AOI out to approximately 12°. A function describing the wavelength shift with AOI was then derived at the sample points across the aperture, and these data were used to reconstruct the shift for the telescope cone beams in angle steps.

The dielectric coatings showed larger nonuniformities with viewing angle compared with the colored glasses. Figure 6 shows, for example, a comparison of the variation of transmission with angle of incidence for the GG420 cut-on of the g filter and the SWP cutoff of the r filter. We computed for the i filter that the red edge of the i band for the axial cone shifts 13 Å to the blue compared with the measured normal incidence ray. The shift is a further 3 Å for the edge and 6 Å for the corner of the field. The blue edge of the i band, being colored-glass-defined, scarcely moves. For the r filter, the blue and red edges of the axial cone shift blueward by 12 Å and 6.5 Å, respectively. To the first order, these variations in the wavelength transmissions of the r and i filters will be accounted for by the flat field, although in principle, systematic differences can arise for objects with large spectral changes near the edges of the passbands. As noted earlier, this would be of much more concern for the u, v, and g bands, whose power to accurately discriminate stellar parameters depends on precision photometry. However, these three colored glass filters show exceptional angular and spatial uniformity.

5. THE SKYMAPPER PASSBANDS

The mean of the filter traces was used as the filter passband. For the r and i bands, we used the computed axial cone values. The primed values in Table 2 are the measured transmission values of the filters. Figure 7 shows and Table 2 lists the normalized passbands, including the mean QE of the E2V CCD44-82 devices and one air mass of atmospheric extinction for Siding Spring Observatory (including mean telluric H_2O and O_2 bands). The CCD responses shortward of 4000 Å are more poorly determined than at longer wavelengths, so it is likely that the calculated SkyMapper passbands in Table 2 will need slight adjustment after on-sky observations are made of our primary spectrophotometric standard stars. As mentioned previously, the u filter has a small red leak that is also given in Table 2.

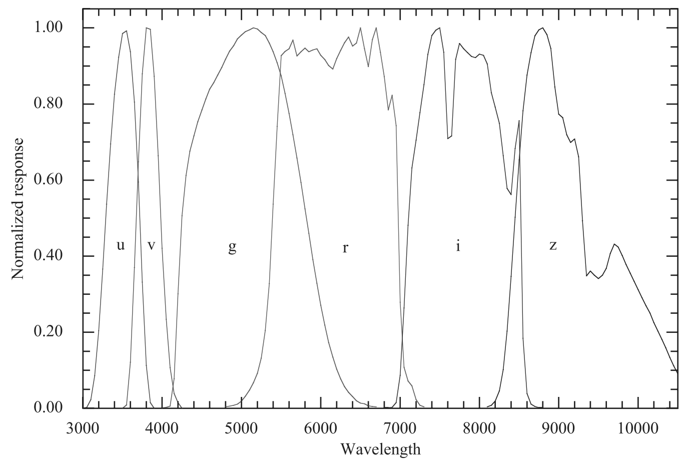

FIG. 7.—Normalized SkyMapper response functions. See the electronic edition of the *PASP* for a color version of this figure.

5.1. Stability of Passbands

The transmission passbands of the ionic glasses in the u and v filters are stable with temperature, but their surfaces have low chemical oxidation properties. However, as their surfaces are protected by the V-AR coating or by the epoxy cement, this feature should not be an issue. The wavelength transmission of the other colored glass filters do change with temperature, but the shifts are small for the expected summer-winter variations. It is important to note that some of the colloidally colored glasses (e.g., GG, OG) can have their bandpasses permanently altered by application of moderate amounts of heat, and such treatment (which occurs, for example, when attaching filters with molten pitch for polishing or in some methods of AR coatings) needs to tested. The V-AR coatings are hard but can be damaged by moisture. Our filters are stored in dry air, and during an exposure dry air is continually blown through the filter and corrector assembly. The LWP and SWP coatings on the r and i filters are dense, low-absorption, low-scatter, high-energy laser optical coatings deposited by modulated reactive DC magnetron sputtering and exhibit much-improved environmental stability and durability compared with more porous coatings produced by conventional multilayer evaporative coating processes. We anticipate excellent wavelength stability from these coatings, but we will monitor any transmission changes over time via SkyMapper calibration procedures.

6. SUMMARY

Obtaining large-sized interference filters that are both uniform and high in their transmission in bands spanning the ultraviolet to the far red remain challenging and very expensive. Using a combination of colored glass and dielectric coatings, we have produced a highly uniform set of filters for the SkyMapper telescope for moderate cost. Reliable sourcing of colored glass was the principal difficulty we encountered, but the Ukrainian-based Potapenko Glass & Filters company appears to be able to consistently supply the requisite glass in a timely manner. In addition, Schott is considering making large-dimension filters again. Since we believe we are the first group to attempt to make large-format glass filters, we have shared our experiences to make the process easier for others in the future.

We wish to thank Thorsten Doehring of Schott AG (Germany) for specially making a large sheet of the unique Schott glass RG850 and constructing the z filter for SkyMapper; Ross Zhelem, who very ably assisted with the original filter designs and verified the transmissions of the Russian glasses; and the late Al Collins (Collins & Associates), Serge Potapenko (Potapenko Glass & Filters), Bill Doherty (Bond Optics), Reed Schmell and Andres Rael (Optical Sputtering Technologies), and David Baker (Optical Coating Associates) for the extra care and interest that they took in working with us to make the excellent SkyMapper filters.

REFERENCES

Abazajian, K. V., et al. 2009, ApJS, 182, 543
Bessell, M. S. 2005, ARAA, 43, 293
Dobrowolski, J. A., Marsh, G. E., Charbonneau, D. G., Eng, J., & Joesphy, D. 1977, Appl. Opt., 16, 1491
Doehring, T., Loosen, K.-T., & Hartmann, P. 2006, Proc. SPIE, 6273, 26
Elliott, K. H., & Meaburn, J. 1976, Ap&SS, 39, 437
Keller, S. C., Schmidt, B. P., Bessell, M. S., Conroy, P. G., Francis, P., Granlund, A., Kowald, E., Oates, A. P.et al. 2007, PASA, 24, 1
Parker, Q. A., & Bland-Hawthorn, J. 1998, PASA, 15, 33