Advance of the geometrical measurements of the birefringent filter's crystal plates and two-dimensional measurements of Doppler velocity in the solar atmosphere

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ABSTRACT

The process of polishing with simultaneous checking and also spectral and interference methods developed to test birefringent filter (BF) elements gave us possibility to design and manufacture multi-elements BF with extreme parameters for high resolution Doppler mapping of the solar atmosphere.

Keywords: Measurements of geometrical parameters, intelligent measuring devices, optical technology, birefringent filter

1. INTRODUCTION

To study the structure, velocities, and magnetic fields of solar plasma and mechanism underlying their effects, it is required obtaining monochromatic solar images be obtained in the light of spectral lines that form at different levels in solar atmosphere. In the visible and close infrared regions, the main instruments for these investigations are classic monochromatic birefringent filters, which were introduced by Lyot in 1933 [1], and independently developed by Ohman in 1938.[2]

A Lyot filter comprises a sequence of elements (stages), which consist of a birefringent plates each twice as thick as its predecessor installed between polarizers. A thick plate produces a channel spectrum of many thin bands closely spaced , whereas a thin plate produces a channel spectrum of fewer thick bands,witn a larger spacing between them.

Birefringent filters have a number of significant advantages properties over more conventional spectral filtering technique' based on grating Michelson interferometers, Fabry-Perot interferometric filters [3].

-Their primary advantage is wide field of view. The small angle sensivity yelds throughput of collecting light from extented lights. There are some methods for enhancing light - gathering power of BF with wide field elements concluding additional wave plates.
- The passband of the filter can be easily spectrally tuned using Senarmon compensators.
- BF stages can be wide field and tuned the same time.
- To increase BF transparency by using less polarizes, two different stages are combined, the so-called split elements by Ewans[4] but using more crystal elements.
- In meaning transparency BF by Solc[5] gives us the promising design , which use only a few polarizers.
- It's possible to increase the image contrast by adding special contrast (correcting) elements into BF. The purpose of this element is to suppress those theoretically secondary peaks that arise and increase significantly as the passband is displaced across the spectrum in a tuned BF. On some occasion, it is appropriate to design and install an additional contrast-element into the filter upon manufacturing the main stack designed on the basis of measurements of the position and intensity of ghosts in a realistic system. It is necessary to decide what would be better: to narrow the passband with an additional (in multiplicity) stage

or, with the same loss of transmission and with the same consumption of crystals, to add one or two contrast elements.

Summarizing one can say that the possibilities of classical birefringent filters (BF) due to Lyot, Ewans, Solc fall far short of being exhausted. And solar astronomers are very interested in the high contrast and transparency BF with passband less 0.1Å for different lines of the solar spectrum. Theoretically, one may design BF using a lot of different polarization elements. In practice, manufacturing such filter is associated with hard technology of precision optical testing and finishing more then half hundred crystal elements with very strong tolerances.

We describe some techniques of the precise test and finishing of BF crystal elements which were used to modernize crystal stages of a super narrow birefringent filter on the Ba II 4554 Å line. Some demands on thickness, plane parallel and plane tolerances within 0,02-05 by retardance (0.02 m for calcite) were realized to get extremal BF parameters. The super narrow passband and high contrast of BF let us obtain images of two dimension velocity maps in solar atmosphere. The unique speckle interferometry restored patterns of Doppler velocities were taken on Swedish solar telescope together with Holland colleagues.

2. MANUFACTURE OF CRYSTAL ELEMENTS OF BF

One of the main conditions for achieving a high BF contrast is strict adherence to all requirements for design parameters and tolerances in manufactured elements. The polarization stages across the BF field the spectral position of the passband should be kept within an accuracy no less than 0.05 and 0.02 of the band half-width for thick and thin plates, respectively. For calcite crystal plates, tolerances for departures in thickness, parallelism and flatness of surfaces shall not exceed 0.05 m in blue region of spectrum. Such stringent conditions are difficult to maintain with soft crystals treated manually; moreover, treatment is often interrupted by a long-duration optical test. For this reason we developed a technique for mechanical finishing of BF crystal plates with a concurrent optical test to provide the required accuracy of manufacture. Furthermore, this procedure involves a minimum risk of spoilng the thinner plate.

2.1. Methods of selection and investigation of crystals for BF

To extract from a natural calcite crystal a monoregion suitable for BF, it is necessary to perform a "surgical" operation with a number of technological processes of testing and treatment lest the invaluable, rare raw material be spoiled.

The distribution of inclusions, F-centers and inhomogeneities in the crystal depends on the individual properties of each growth pyramid and is identical for all crystals from the same deposit. The belonging to this pyramid and its boundary are determine from the etch figure. To avoid inclusion of other growth pyramids (which are often strongly intermingled with the selected pyramid) into the element, the crystal is examined throughout its volume in the ultraviolet light after etching or polishing. The boundaries of the growth pyramids are refined from the light scattering of the laser beam within the volume of the plates, which also depends on the individual properties of the growth pyramids. The optical homogeneity of the elements is ultimately determined with the Twyman interferometer from the refractive index in the "O"- and "E"-beams, as well as from the index of birefringence. Refractive indices in the layers of a single growth pyramid and different pyramids sometimes differ by a factor of 510^{-5}. In this case, the blanks must be oriented with respect to the growth layers (Fig.1).
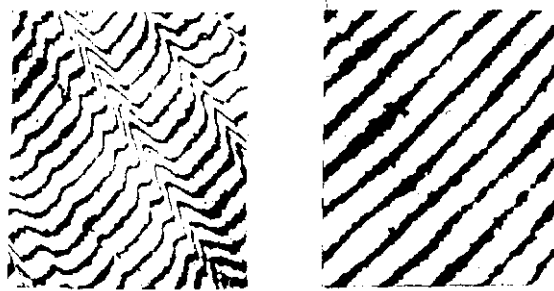
Fig. I The interferograms of the calcite homogeneity oriented across (left) and along the layers of growth (right).

2.2. Methods of testing the optical thickness (from birefringence).

The absolute thickness of one or two reference plates is made with the spectrograph from the transmission spectrum of the polarization stage with respect to spectral lines. The thickness of the other plates is measured with respect to reference plates.

Fig. 2 is a schematic representation of the device for measuring the thickness with the spectrograph. Measurements with this device do not depend on temperature fluctuations. The device consists of light source with lens , polarizing mosaic, collimator, objective lens , and analyzing mosaic at the spectrograph slit. The mosaics contain polaroid film strips with the transmission plane positioned at the angle of 45 to each other. The image of the polarizing mosaic coincides with the analyzing mosaic, and the transmission planes of the coinciding strips are oriented parallel to the mosaic strips. Then the reference and controlled plates become effective in different mosaic strips; therefore, at the focal plane of the spectrograph channel transmission spectra one above the other are simultaneously observed, of both the reference and controlled plate.
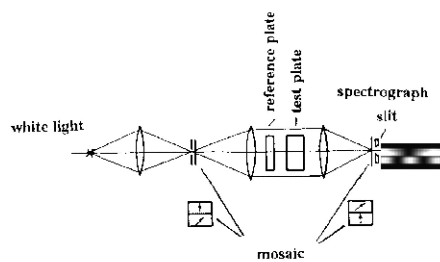

Fig.2. Spectro-interferometric test of thickness with polarization mosaic.

The plate thickness is checked by a visual or CCD measurement of the relative position of the interference fringes on the common boundary of two spectra.

To check the thickness of the BF plates of any order of interference, a quartz wedge is used.

2.3.Combining the processes of working and checking

Finishing of crystal plates consists of two processes: polishing and optical test, which to date, to our knowledge, have been performed separately still after first paper[6]. During polishing, the plate thickness is adjusted. Temperature gradients that arise when polishing an anisotropic crystal give rise to the astigmatic treatment of the surface.

We determined crystal working conditions on a machine where no astigmatic surface bending arises and a high surface quality is ensured. A device was also developed for checking the thickness and plane-parallelism directly during the polishing. Polishing and checking of crystal plates are integrated into a single technological process.

The main factor that leads to an astigmatic treatment of plates is the anisotropy of the coefficient of thermal expansion. Only the elimination, within the required limits, of the temperature gradient between the upper, dry and lower (i.e. that being polishing) wet surfaces can do away with the astigmatic bending of the component when treated in separator. Using thermistors placed in the surfaces, we iexamined the appearance and influence of temperature gradients upon the polishing process. When treating the plane-parallel plate of optical calcite of 10 mm thickness and 43 mm in diameter, astigmatic distortions of the surface were found to be about 0.1, with the temperature difference of the lower and upper surfaces less than 0.1 C.
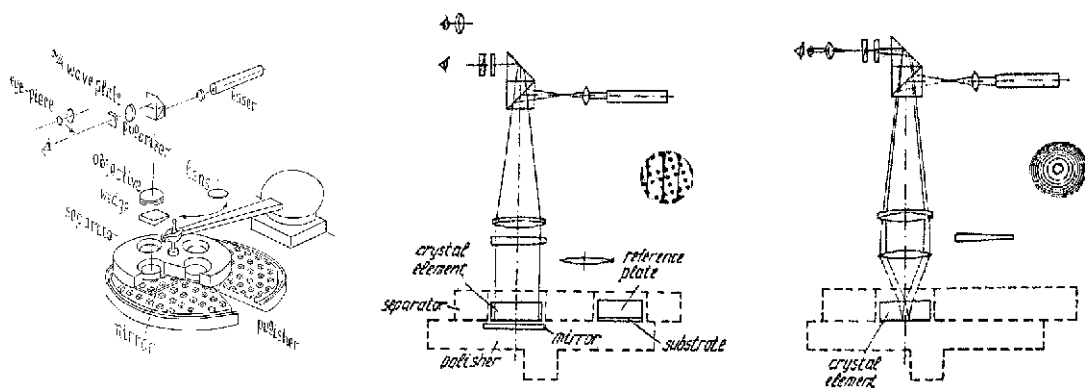

Fig 3.Device for polishing and simultaneous checking of crystal plates.

The fig.3 (left) presents a schematic view of the device for the finishing of plates of birefringent filters. The device includes a polisher with teeth on which abrasive grains within a thin layer of the polishing pitch are secured. The adjusted crystal plates and reference birefringent plate are placed in the holes of the separator. The reference plate is installed on a thin transparent non crystal substrate, which protects it against polisher. The substrate allows the reference plate to take the same temperature as do the adjusted plates. It does not interfere with birefringence measurements. Above the polisher is an optical monitoring device. The device includes a point source of polarized monochromatic light, namely a laser with a microobjective lens, a beam splitter, an auto-collimation objective lens, and a Senarmon compensator (a quarter-wave plate with a polarizer). The system can further incorporate an eye-piece, a crystal wedge, and a lens. The device is designed for measuring the optical thickness of crystal plates in birefringence as well as measuring plane-parallelism in n_o and n_e -beams. Plates are checked during a short -duration stop of the polishing process.

Fig. 3 (middle) shows the scheme for checking the optical thickness. The light from objective lens of collimator passes through the crystal plate being monitored, is reflected by the mirror, passes again through the plate and from the beam splitter enters the Senarmon compensator. Based on the difference in the angles of the orientation of the analyzer to "darkness" for the reference and adjusted plates that are exposed to the same temperature, one decides if subsequent polishing is required. If the plates include the local optical inhomogeneities, then position of "darkness" is determined with low confidence. In this case checking should be carried out with a crystal wedge, which is introduced ahead of objective lens. The wedge, at a combined action with the plate, produces two or three interference fringes of equal thickness whose position depends on the thickness of the plate being processed. Dark circles on interference wedge pattern (Fig. 3) are holes in mirror of polisher.

Plane parallelism of the components in n_e and n_o-beams is monitored with this same autocollimation device from interference fringes of equal inclination (Fig.3, right). The eye-piece and the additional lens are introduced into the system, and the wedge is withdrawn. The plate is put under into device with any

position of the polisher, and no mirror is required for monitoring. Light beams that are reflected from the lower and upper surfaces interfere and produce, in effective focal plane of the device, interference fringes which are observed through the eye-piece. The wedge of the plate is measured in the direction of largest expansion of the fringes when the plate is displaced and it adjusted in the course of polishing. The pattern of equal inclination is also shown here.

3. BA II 4554 Å IMAGING AS SOLAR DOPPLER DIAGNOSTIC

There are different ways to obtain Dopplergrams (radial velocity maps) of structure solar atmosphere. Spectrographs yield full-line profile information for precise Dopplershift evalution but require spatial scanning by the spectrograph slit to derive two-dimensional maps, implying loss of simultaneously across the solar scene and large sensitivity to seeing variations. Filtergraph obtain full field images per exposure but only for one passband at the time, while at least two are needed to derive Dopplerograms through subtraction, which is also sensitive to seeing variations. So we have designed the tuned two passbands filter[7] for very important diagnostic lines Ba II 4554 Å and H. Many interesting observations have been conducted using the BF at the Sayan solar observatory near Irkutsk (Russia). In 25 years some BF parameters have been improved through the use of the technique described herein. An optical sketch and the most recent, very successful BF test combined with post -detection speckle reconstruction to correct seeing degradation[7] are outlined below.

3.1. The narrow-band birefringent filter with two passbands

The ame of this part is to describe the tuned BF with passbands for the lines of BaII 4554 Å and *H* which was conceived, designed and manufactured at the ISZF SD RAN. The half-width of its passbands is 0.08 and 0.09Å, respectively.

In our opinion, it would be appropriate to manufacture tunable wide-angle stages and simple stages assembled into Evans's split elements with crossed polarizers

$$\frac{k\lambda}{2} - \frac{\lambda}{2} \quad \frac{m\lambda}{2} \quad \frac{\lambda}{4} \frac{\lambda}{2} \frac{\lambda}{4} \quad \frac{m\lambda}{2} \quad \frac{k\lambda}{2} + \frac{\lambda}{2}$$
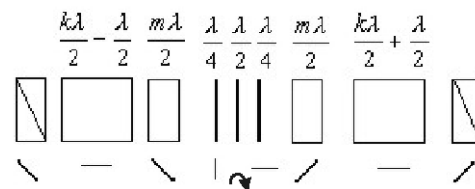
Fig.4.Base BF split element with tuned middle stage.

In BF with polarization prisms (no film polarizers), the astigmatism that they introduce is reduced in cross position. The external parts of the split elements with required thickness additions of different signs, when placed together, can be used as simple stages in other systems of filters.

The BF under consideration consists of twelve polarization stages (1-12) with a linear field of 40 mm combined, according to system into six split elements 1-6, and of two correcting stage 13,14.
The thickness and interference orders are presented in table 1. The BF passband width is determined by the thickest calcite stage of 60 mm, which also has a role of a correcting stage. All subsequent calcite stages, starting from the 32 mm stage, have an optical thickness, each decreased by a factor of two. Calcite stages involve phase adjustment of the passband position. The passband are shifted by rotating the half-wave plates between the fixed quarter-wave plates.
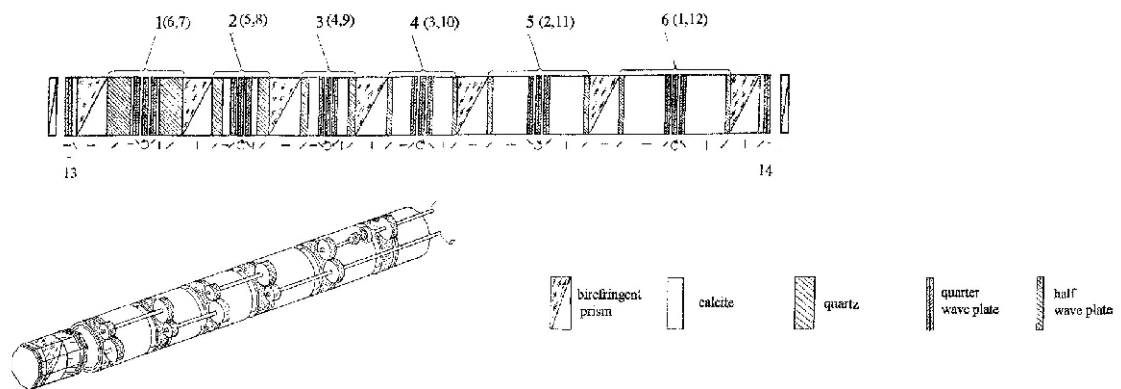
Fig.5. Optical and mechanical sketch of BF.

Table 1. Components of birefringent filter

Stage
Crystal
Thickness,mm
Interference order

Ba II comp.
Ba II stage
H stage

1
quartz
0.694
0.668
13.75
14.25
28.0
26.01

2

quartz

1.010

1.034

20.75

21.25

42.0

39.01

3

quartz

2.032

2.056

41.75

42.25

84.0

78.03

4

quartz

4.015

4.101

83.75

84.25

168.0

156.06

5

quartz

8.165

8.189

167.75

168.25

336.0

312.2

6

quartz

16.342

16.365

335.75

336.25

672.0

624.24

7

calcite

1.6229

640.0

1280.0

1183.96

8

calcite

3.2539

1280.0
2560.0
2367.91

9
calcite
6.5079
2560.0
5120.0
4735.82

10
calcite
13.0157
3120.0
1024.0
9471.64

11
calcite
26.0314
10240.0
20480.0
18943.28

12
calcite
30.0988
11840.0
23680.0
21903.17

13
calcite
1.5886

625.0
578.10

14
calcite
1.0853

428.0
395.88

/4
quartz
1.312
1.300

0.25.0

/2
quartz
1.324
1.300

0.5

Phase adjustment of the order of interference makes it possible to center the passbands of the calcite stages on the lines of Ba II 4554 Å and H and to cause them to shift within 1.5 Å. However, the optical properties of quartz did not permit the non-adjustable quartz stages (the thickest of them 30 mm thick) to be accurately "set" on the two lines. For that reason, for eliminating the ghosts that remain when tuning to the H line using only phase adjustment of the calcite stages, it is necessary to use the correcting stage 13 ,14 by introducing the external polarizers and to raise the filter temperature by 2 in order to accurately "set" the quartz stages on the H line. When observations are switched over to another passband, the dielectric interference filters of pre-monochromatization are changed.

Polarization elements 1-6 are placed within sleeves in such a manner that the quarter-wave plates lie on the outer side. The half-wave plates of elements, placed in the gear mounts include a kinematics constraint the 1:2 reduction ratio and can be rotated by a single shaft . The half-wave plate in element 6 can be rotated by a separate shaft or together with the other plates by shaft by means of the disconnectable clutch . Independent adjustment of the thickest calcite plate makes it possible to change the form of the passband. Because the quarter-wave plates are aligned as shown in Fig. 5, as the passband is shifted, the half-wave plates of the adjacent elements rotate in the opposite direction thus significantly simplifying the kinematics design.

We now consider the requirements to be met by the BF, and the steps that were taken in this regard.

T r a n s p a r e n c y. The narrow passband of the filter of width less than 0.1 Å, which must let pass a very small portion of solar radiation in the line with 20% residual intensity, imposes more stringent requirements on the BF light transmission. Based on this, we manufactured birefringent prisms, one of the wedges of which as from calcite, and the other from glass, so that on the calcite surface perpendicular to the optical axis it is difficult to obtain a good surface finish. With 4554 Å wavelength, the refractive index of STK-3 (super heavy croun) glass coincides to the third decimal place with the refractive index of calcite for the ordinary ray; this leaves the prism with almost no deviations. The transmission of the birefringent prisms for 4554 Å averaged 81% (uncorrected for reflection).

Largely because of reflection, 180 surfaces of the optical components of the BF decrease its transparency, even though they are in immersion usually used in optics. We investigated the new kinds of silicon oils. The highest BF transmission was obtained when diphenyldixylene xysilane with $n_d = 1.58$ was used (average crystal index is 1.57).

O p t i c a l   i n h o m o g e n e i t y   a n d   t h e r m o s t a t t i n g. For the operation of the BF, it is necessary to maintain a given temperature with an accuracy of 0.03C and to ensure the absence of these same temperature differences in a radial and longitudinal direction. Longitudinal gradients were measured from the relative position of the bands of the channel spectrum of two identical plates placed in the middle and near the end of the optical cylinder heated to the working temperature. The measurements were made with the polarization mosaic in the configuration described above. We detected no difference in the spectral transmission of the two plates, hence no appreciable longitudinal gradients.

To investigate the radial gradients, the optical cylinder of the thermostat with the mounts inserted without crystals was filled with immersion. Radial gradients (the optical homogeneity of the stack along the field of view) were measured interferometrically with the thermostat turned on.

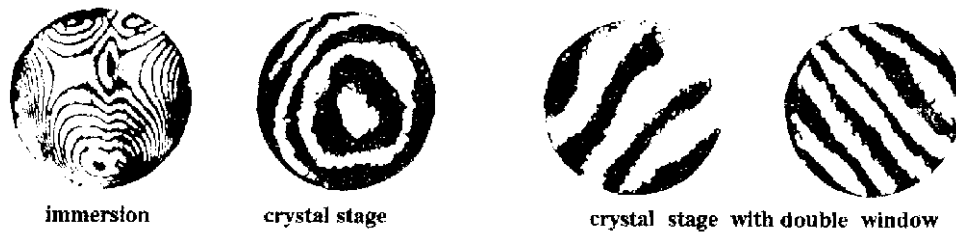immersion   crystal stage   crystal stage with double window

Fig.6. Interference pattern of BF stack.

It is interesting to note that in the immersion occupying the volume of the cylinder of the thermostat (the side surface of which has no gradients) two circulating flows arise caused by the outflow of heat from the cylinder ends. This is illustrated by leftmost photograph of Fig.6 showing the interferogram of the optical homogeneity of the immersion, which fully fills the volume of the cylinder, with the crystal stages withdrawn. But the temperature dependence of the refractive index of the crystals is lower when compared with the immersion. Next photograph shows the interferogram of the stack 500 mm long, with crystals and immersion filling the interfaces between elements (these interfaces total 20 mm in length). The deformation of the front into three rings is caused by thermal gradients in the air near the filter windows. By introducing an air lock, it would be possible to eliminate all interference sources (two photograph on the right). It is evident that the entire optical stack causes a distortion of the wave front not exceeding 0.25. Excellent homogeneous crystals, quality treatment, and no radial gradients! This is corroborated by the absence of a marked shift of the passband along the field of the filter on the spectrogram obtained with a tall slit, with the filters illuminated by a parallel light beam.

The passband and ghosts of the filter were investigated with the spectrograph having a focal length of 6 m, in the fifth order of spectrum with the 600 lines/mm grating. The half-width of the filter's band for the Ba II line is 0.08 Å, and the nearest principal maximum at a distance of 95 Å are cut off by pre-monochromatization filters. The half-width of the principal maximum centered on the H line, is 0.09 Å. Ghosts surrounding this maximum are stronger than in Ba II because of the chromatizm of the half-wave and quarter-wave plates, but they are "pressed together" by the correcting elements. The band is shifted by 1Å without the appearance of strong ghosts.

3.2. Observations testing the Dopplergram capability of narrow-band Lyot filter in the Ba II 4554 Å line

The reason we choose the BaII 4554Å barium resonance line for BF fine structure observations is that line is formed in the week investigated solar atmosphere- lower chromosphere. According to spectral data, supergranulation in the velocity field reaches a maximum visibility in this line; it clearly shows oscillations, as well as limb spicules are detectable. In the altitude range between the sodium and magnesium level (0-200 km) and H (1200-1500 km) there are few lines (except for 4554) which are suitable for magnetic field measurement. Many lines form too low or in the spectral region not convenient for measurements.

A major advantage of Ba II resonance line is that barium is very heavy atom making the thermal contribution to Dopplerwidth small. Resulting steepness of the line wings brings large Doppler sensitivity. The line is from ground state of the dominant ionization stage and line strength is therefore insensitive to the radiative overionization. This makes interpretation relatively straightforward.

The observation were done on July 15, 2000 with the Swedish Vacuum Telescope on La Palma by DOT and ISZF teams[8]. CCD camera (Hitachi KP-F1, 768x572 px) and data acquisition system (8-bit frame grabber running at 8 frames/s) were used to obtain sufficient speckle frames with sufficient S/N per speckle burst.
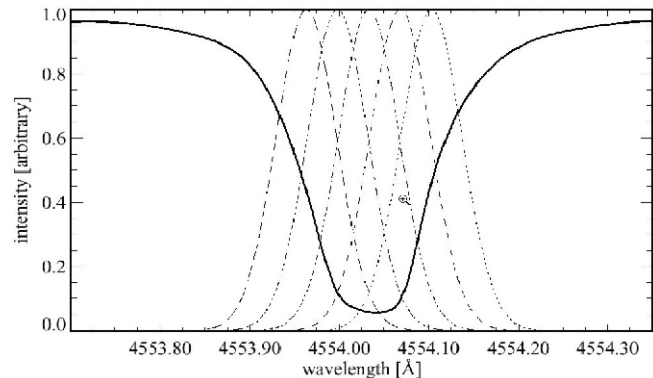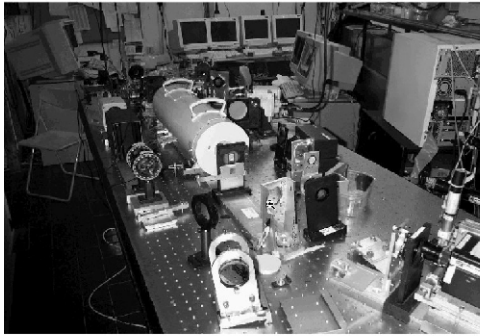
Fig.7.BF in prime focal plane of SVST and setting of BF passband (P. Sütterlin's photo)

Photograph on Fig 7 (left) depicts the optical setup: the Ba II filter was put immediately after the prime focus. Filter was manually tuned to the five wavelengths covering the Ba II line at 35 mÅ intervals as indicated in Fig**.**7 (right)**.** At each wavelength setting, a speckle burst was taken within 12 seconds, well within the solar change time (30 s per 0"3 resolution at 7 km/s sound speed). The exposure per speckle frame was 20 ms, sufficiently short to freeze atmospheric seeing but yet yielding sufficient S/N for speckle processing even with the 80 mÅ bandpass. A full scan covering the line with five sequential wavelength setting took approximately 130 s.

The target was a part active region AR 9077. The field of view is shown on two speckle-reconstructed images (Fig.8, upper) resulting from two setting of one scan. It contains sunspots with high-structured penumbra in the right-hand part, plage with small pores at center, and more or less quiet Sun at the left.

The differences between the two line wings are striking. In the the red wing granulation is very prominent, whereas the granular contrast is low in blue wing. This is consequence of the granular velocity-intensity correlation: the gas moves upward in bright granules and downward in dark lines. The situation reverses when there is an inverse brightness - intensity correlation, i.e. when bright structures contain downward motion. This in the case for many small, bright features seen in the blue-wing image. Their blue-wing brightness implies downdrafts in and/or around these.

The subtraction of two images of one scan gives Doppler maps of which one is shown in Fig. 8 (low)**.** It quantifies that blue-wing bright points exibit downflows of 1-1.5 km/s. The Doppler map also reveals an extended bright region with an average redshift of approximately 400 m/s. The pores in the plage area generally have adjacent high-speed downdrafts at small sites in their perimeter. The pores themselves contain lower-speed downdrafts in complex patterns. The active region shows much filamentary contrast, indicating the presence of bi-directional mottle flows in alternating arrangement.
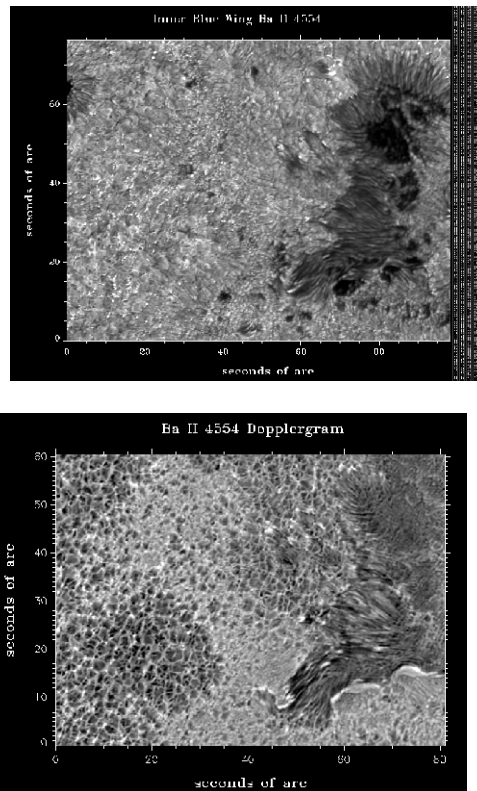
Fig.8. Solar atmosphere in Ba II 4554 Å line.

CONCLUSION

Creation BFs with extremal parameters is faced with serious problems because of strong tolerances and technology capabilities required.

Besides our effort to resolve this problem, we scrupulously design and improving experimental methods, choose crystal well and go other,. in first glance, small improvements.

A test done at the SWST in summer 2000 demonstrated the tantalizing science capability of the tunable filter operating in the Ba II 4554 line that was developed at ISZF. Superb angular resolution obtained by speckle processing and large sensitivity of the Ba II line to the motions due to the combination of very large atomic mass and insensitivity of the line opacity to temperature variations.

For parameters perhaps Ba II 4554 BF is one of the most successful and still unique instrument in practice designing filter.

ASKNOWLEDGEMENTS

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