Resonant Spaces

Part 2: An Introduction to Solid Spaced Etalons and Solar Telescope Technology

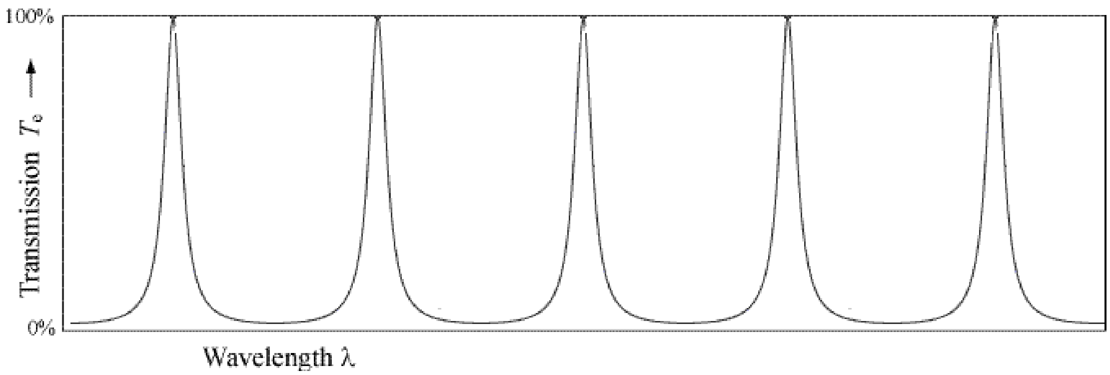
by Colin Kaminski

H-alpha Image by Greg Piepol using a .2A Solar Spectrum Filter

The first Hydrogen-alpha (H-alpha) telescope I ever looked through was a DayStar solid etalon model. It was a good day to be looking at the sun and I was treated to a stunning view. There was a large filament hovering lazily above the disk of the sun and there were many active prominences that were changing every few minutes.

Part one of this article explained the theory of how an etalon works and air-spaced etalons. I think it would be good to review the basic theory very quickly and then we can jump into some solid etalons. If you would like some more background on etalon theory see Part 1.

An etalon, known as a Fabry-Perot etalon, is made from two very precisely made partially reflective mirrors placed very close together forming a cavity. The mirrors set up a resonance condition inside the cavity. If the gap distance divided by the half wavelength of light is an integer, the light is transmitted and if not, it is reflected. If our input source is white light and we look at the spectrum we see spikes that look like a comb. An etalon is also known as a comb filter.



Since we are only interested in one of the spikes we need to provide additional filters to remove the unwanted bands. The quality of an etalon is measured by the parameters of Free Spectral Range (FSR) and Finesse. The FSR controls the distance between the peaks and is primarily controlled by the gap thickness between the two mirrors. Smaller gaps between the mirrors increase the line separation and make choosing a trim filter to block the unwanted peaks (bands) easier and cheaper.

The Finesse controls how wide the bands are and how well the filter blocks off band. A very high finesse (ie 30) makes for a very narrow band. Solar astronomers measure bandwidth as Full Width Half Maximum (FWHM). To measure FWHM we measure the width at half the height of the peak in Angstroms. Solid etalons are sold from .2 A to .7 A in bandwidth. Finesse is controlled by the parameters of surface finish, flatness, parallelism and reflectivity. This is very important and we will get back to it later so remember, for low bandpasses: surface finish, flatness, parallelism and reflectivity.

A very narrow bandwidth (.2A to .4A) shows more contrast on the H-alpha details above the solar disk. It also allows for studies of Doppler shifted gasses moving towards or away from the observer.

One very notable difference between air-spaced etalons and solid etalons is that solid etalons change their center frequency with temperature to a much greater degree than air-spaced etalons. More expensive solid etalons are temperature controlled and can be tuned at or near the ideal frequency without tilting. Un-heated models require tilting the etalon to tune the filter to the H-alpha band at different frequencies.

Birefringence

Some materials exhibit a very special optical property called birefringence. Because of the crystalline structure of these materials they have a different index of refraction on one polarization axis from the other. The axis that this effect occurs on is defined as the optical axis. Calcite and Quartz are two minerals that exhibit birefringence and have been in use in solar telescopes for at least 80 years. Mica is also birefringent which is very important to this discussion. Although its birefringence is not utilized the design needs to compensate for it.

Calcite showing the double image due to birefringence.

When you hold a birefringent material over newsprint you will see the image double (like the word Calcite in the image above). If you rotate the crystal one image stays still the other rotates. The image that stays still is defined as the "ordinary ray" the image that rotates is defined as the "extraordinary ray" and they possess opposite polarizations.

Mica

Mica showing terraced cleavage planes courtesy of Jo Edkins

Two of the manufactures of solid etalons use mica as the spacer material and since it has very special properties we should stop and look into them. There are many forms of mica crystal. Exactly what type of mica crystal is used and where it comes from is quite important in optical applications and asking an optical manufacture where they get their mica from is tantamount to asking for their girlfriend's phone number.

Mica has a very interesting property in that it can easily be cleaved into very flat pieces that require no further polishing. In fact when one is highly skilled in the art of cleaving mica it is possible to cleave mica to where there are no steppes in the crystal at all. This perfectly smooth surface is ideal for constructing the spacer for a Fabry-Perot etalon.

Both manufactures of mica etalons offer "Research" or "University" grade etalons. The difference is in the uniformity of the cleaving and coating processes and the homogeneity of the raw mica. If the cleaved surfaces are perfect then the etalon will be on band across the entire field of view at the same temperature. This subtle difference is quite expensive and unless your application really requires this level of perfection a less expensive model will suffice. It must be remembered that in order to make use of very narrow band etalons across the entire field very close attention must be paid to making the optics telecentric.

The original paper on cleaving mica for use as an etalon was written by Dobrowolski and he credits Billings for the idea. Mica was first being used in solar imaging systems made by SpectroLab in 1959 and started with the Dobrowolski method.

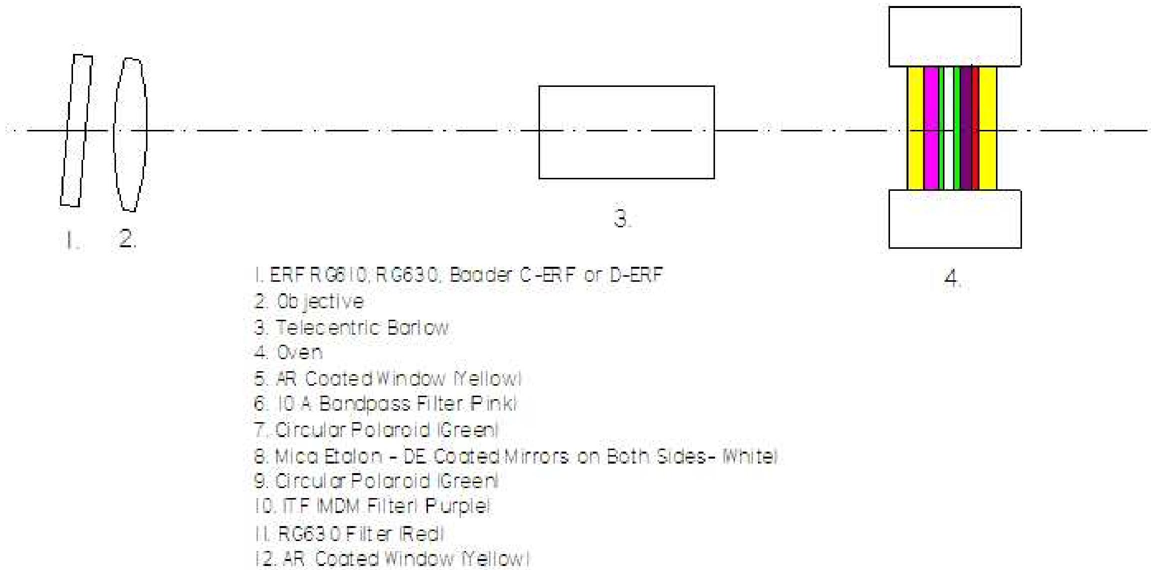
When making a mica etalon for an H-alpha telescope a manufacturer has to either make the mica the exact thickness of a ½ waveplate or place at least one polarizer in the stack to remove one polarization in order to eliminate the extraordinary ray. This results in the loss of at least 50% of the light.

Mica changes both thickness and birefringence with temperature changes making a temperature controlled oven for the stack very useful. This can be done with a heater or a Thermal Electric Cooler (TEC).

Available Filters

Daystar and Solar Spectrum are using mica as their etalon material. It is clear that they have the ability to change designs on a filter by filter basis. It would not be surprising to find that there have been many design changes to solid etalon filters in the course of the history of each manufacturer. Of course the exact designs and design changes over the years are closely held trade secrets.

Solid Etalon Overview



This figure shows a simple mica etalon with polarizers and blocking filters. It is only intended to be representative of the technology and not an exact design. I think the easiest way for us to understand the function of the filter stack is to examine each element.

Traditionally an energy rejection filter (ERF) made from Schott RG610 or RG630 has been used full aperture to absorb the green, blue and UV light before entering the scope. This reduces tube currents as well as reducing the energy reaching the blockers in the etalon. This red glass is cast and pieces must be chosen to avoid inclusions. The glass is then polished to lamda/4 or better on both sides. Failures in very large sizes have been reported so the practical limit to the aperture is 8” to 10”.

Recently, Baader Planetarium has been making a coated ERF. The C-ERF and the latest version D-ERF are coated to reflect light from 1400nm to UV leaving a narrow band (35nm for the D-ERF) for H-alpha light to pass through. The largest D-ERF available currently is 7”.

The AR windows serve to contain the heat inside the oven that maintains the control of the etalon temperature. They are AR coated to avoid reflections.

The 10 A bandpass filter is chosen to match the FSR of the etalon and blocks the unwanted bands of the etalon.

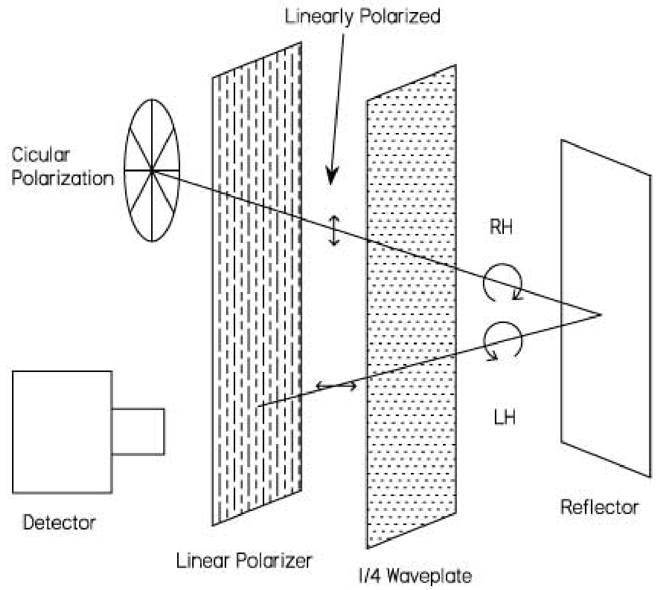


Diagram illustrating the blocking of a back reflection with a circular polarizer. after Edmund Industrial Optics.

The circular polarizers are very important for contrast; however circular polarizers cut a fair amount of the on band light. When the randomly polarized light from the sun passes through the circular polarizer it is reduced in intensity by approximately 50%. It is also converted to circular polarization. Circular polarization is better thought of as a corkscrew and can either be right handed or left handed.

For example if the first pass of the circular polarizer makes the corkscrew right handed, when light is reflected off the reflective surface it changes handedness from right-hand to left-hand. When the left-hand polarization returns to the circular polarizer it is converted to linear polarization but at 90 degrees to the polarizer and is absorbed. This is done to eliminate the ghost reflections from the blocking filters and etalon mirrors without having to tilt the stack.

The mica etalon is the heart of a solid etalon system. It is cleaved from a large piece of mica much like peeling a label off a beer bottle. Mica cleaving methods for optical uses have been described in the literature since at least the ‘50s. The two preferred methods either use a needle or a razor blade to separate a paper thin piece of mica from a small block. Both faces need to be freshly cleaved and free of scratches.

A perfectly cleaved piece of mica will be as flat as the crystalline structure. In practice there are small terraces left behind. The ability to cleave perfect etalons is a highly refined skill, one of the many arts involved in making a mica etalon. The thickness of the mica sets the FSR and also the temperature that the etalon will be on band. Typical thicknesses range from .010 to .030mm.

Once a scratch free and steppe free piece of mica is cleaved it is then coated with a dielectric mirror on both sides. This mirror must be precisely deposited to have the thickness of the layers even on both sides. Since a thin piece of mica is quite flexible it is very difficult to coat both sides without inducing stresses making the use of "soft" dielectric materials attractive. The reflectivity is tightly controlled to provide the bandpass of the etalon. Higher reflectivities make for lower bandpasses. The evenness of each coating layer sets the evenness of reflectivity. Inaccuracies in coating thickness and reflectivity across the etalon widen the overall bandpass and can create in-homogeneity in the bandpass across the field of view. Dobrowolski had extensive experience in coating technologies before undertaking a mica etalon; in fact he has been publishing papers on coating technologies for 5 decades. This is another one of the art forms in making a mica etalon.

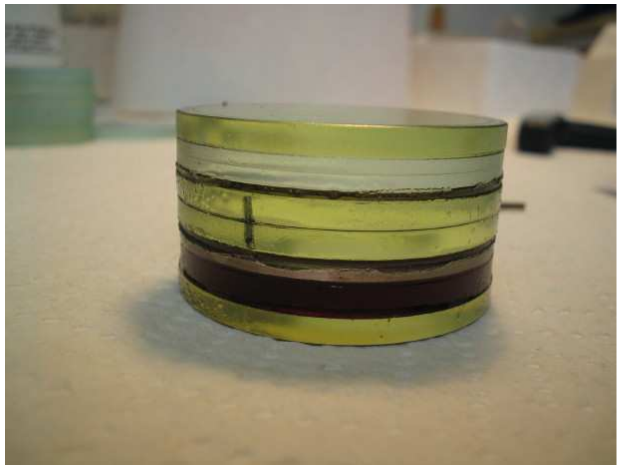
The mica etalon is then placed between two pieces of glass to hold it flat. This is an innovation since Dobrowolski's work and his patent trying to hold the mica in a stress free cell.

The second circular polarizer removes the other ghost from the etalon and further serves to remove the unwanted extraordinary ray from the image. This extraordinary ray can be salvaged if the etalon is precisely the thickness of a ½ waveplate at the H-alpha wavelength but this is not done in practice due to the difficulty of cleaving such a precise thickness and the extra light is not needed because the sun is so bright.

The ITF (MDM) filter blocks IR down to 4000nm. ITF stands for Induced Transmission Filter. This is a safety feature to prevent glassblower's cataracts from long term use of an H-alpha system. It is a polished piece of glass or silica with a layer of silver, a dielectric layer and a final layer of silver (Metal Dielectric Metal). When the thickness of the layers is precisely controlled the filter can pass H-alpha while blocking the IR.

The Schott RG630 is a red colored glass edge filter that passes most of the light below 630nm and blocks the green, blue and UV light. This filter provides safety if the ERF is momentarily left off of the system.

The filter stack is assembled with an index matching fluid so that the reflections between elements are minimized. The assembly of the stack is quite critical and difficult. The rotation of all the elements must be precisely set. Disassembly can damage elements and should not be attempted unless you work for Solar Spectrum or DayStar.



Side View of an assembled Etalon stack. Courtesy of Bob Hess.

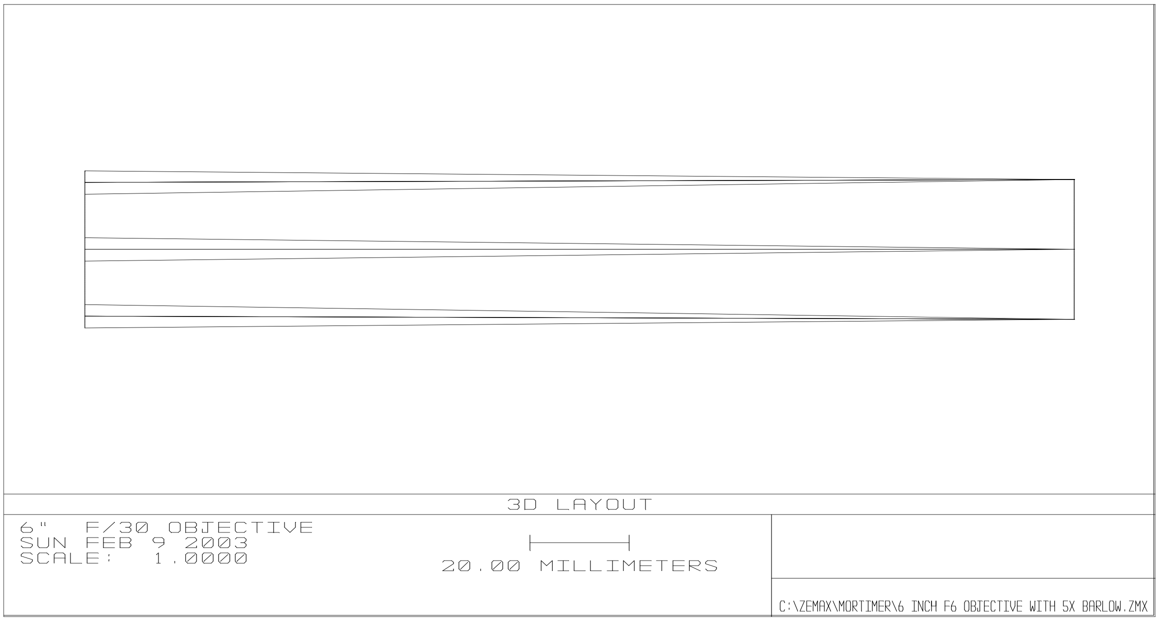
Properties of Solid Etalons

The wavelength change due to tilt is less sensitive in spacer materials of higher index of refraction making solid mica spacers more tolerant of being placed in a converging light cone than an air spaced etalon. The disadvantage to tilting the etalon is tilting mica etalons can increase scatter, lower contrast and widen bandpass. Tilting an etalon can also create a sweet spot that allows one side of the etalon to be on band when the other side is not. The lower the bandpass is the more important this becomes.

Since the bandpass of a mica etalon is sensitive to both temperature and to tilt these factors can be used to look for Doppler shifted events on the solar surface. The useful sweep range for a very narrow band H-Alpha filter is 2A into the blue and .5A into the red. The reason blue shifting is more useful is motion towards us is blue shifted while motion away from us is red shifted. Things moving away from us usually deposit material on the photosphere unless we are looking at the limb. Tilting allows rapid changing of the center frequency in some designs like the T-Scanner. Changing the center frequency with an oven is slower but very precise velocity measurements can be made. Solar Spectrum filters for example use a TEC and can be changed .5 A in 45 seconds.

Installing a Solid Etalon

The peak transmission falls in a converging beam of light and the bandwidth is broadened. DayStar and Solar Spectrum design their etalons to be placed in an f/30 telescope. This can either be obtained by designing an f/30 system, by placing a telecentric Barlow ahead of the filter or stopping the aperture of a large telescope making the focal ratio higher. Since a 4” f/30 scope would be 120” long one of the latter methods is usually chosen by the amateur astronomer.



Courtesy of Mark Wagner.

The narrower the bandpass is the more care must be taken to keep the light as parallel as possible in the etalon in order to maintain the lower bandpass. With a traditional Barlow and a very narrow band etalon you can get something called the “Ring Effect”. There is a ring (fringe) that is on band and the rest of the field is off band. When the light cone is telecentric this ring can be shifted to the center to become a spot and still be large enough to fill the entire field of view.

Choosing a Telescope

When choosing a way of getting an F/30 system you start to have a compromise between getting full disk views and getting high resolution. It is easier to illustrate with a couple of examples.

Example 1:

Starting with a TV-85 with an 85mm objective and a f/30 system you have a focal length of 2550mm. This creates an image of the solar disk (2550/108) 23.6mm without prominences. Since the etalon is likely not placed at the exact focal plane and we need room for prominences a 30mm etalon will be slightly too small for a full disk view. This would also require a 4.3x telecentric Barlow which is not available so you would choose a 4x Barlow and end up with f/28 which is pretty close.

Example 2:

Starting with a NP-127is with a 127mm objective and a f/30 system you have a focal length of 3810mm.This creates an image of the solar disk (3810/108) 35.3mm. With a little extra room we quickly exceed the largest available mica etalons to get a full disk view.

Example 3:

Starting with C-14 with a 355mm objective and a f/30 system would have a focal length of 10650mm! This creates an image size of 98mm and is far outside the range of available etalons. The solution is to mask down the aperture with an off axis aperture mask. This also allows us to use a smaller ERF. We could limit the aperture to 5" and not use a Barlow for an image size of 36mm. This is much more reasonable.

The problem we have is now the light cone is off axis to the optical axis of the scope and an adaptor needs to be fashioned to match the angle. This angle will be different for each off axis design. Usually the off axis mask is designed to match an existing adaptor angle.

If we don't care about getting a full disk view then we can use very large apertures as long as we can create an ERF large enough to protect the etalon.

It is also important to consider where the etalon is relation to the focal point of the objective. If it is moved too close to the objective (up into the light cone) it will vignette the image. If it is placed so the focal point lies inside the etalon, the etalon may be damaged by the heat.

Maintenance

The life expectance of the blocking filters in a DayStar or Solar Spectrum filter is from 5 to 10 years. When the blockers fail there is a loss of contrast but there is no safety concern. The filters are designed so the factory can replace the blockers and this is considered part of the maintenance. Under no circumstances should a user try to disassemble a mica etalon. Even if one is able to disassemble the assembly without damaging the very fragile mica, reassembling the stack without any dust and in the proper rotations is not worth the small amount of money charged by the factories.

DayStar

Daystar was founded in 1975 by Del Wood and has made filters for amateurs, professionals and custom designed filters for dedicated instrumentation. Del sold the company to Vic and Jen Winters in 2006 and they continue to manufacture similar designs with some modern updates. They make etalons in 32mm or 50mm aperture.

T-Scanner

The T-Scanner is DayStar's most affordable H-Alpha filter. It is un-heated and incorporates a tilting mechanism to keep it on band at different temperatures. This has the advantage of there being no warm up time. Omitting the oven makes the system more affordable and also eliminates the requirement for power.

The disadvantages of this system are it is designed for a smaller ambient operating range and tilting is not the ideal way to keep the full field on band.

The T-Scanner is offered in .8 A to .3A bandwidths with a 30mm aperture.

Quantum SE

The new upgraded ATM filter. The Quantum features the latest oven from DayStar. It is tuned at the factory to be on band with an internal set temperature usually around 40 C to 50 C. The digital readout reads out the exact frequency at any moment by using the relation that shifting the temperature 9.33 C shifts the etalon 1 A. When one is looking to shift blue or red there is a blue and red button provided that changes the oven temperature and the digital readout reads the new frequency. The Quantum ovens operate on 12 volts making it more portable that the older 120 volt systems. An international adaptor is supplied.

The SE/ATM filters are offered in .8A to .3A bandwidths.

Quantum PE

The PE is the new oven and has replaced the University series of filters. The PE/University filter has a nearly perfect band pass across the entire field of view. In order to manufacture a mica etalon to this level of accuracy takes time and very sophisticated testing. (How would you measure flatness in the range of lamda/200?) Of course this is reflected in the price as it is the highest level of art form in making a mica etalon.

SolaRedi

The SolaREDi is DayStar's latest entry into the H-Alpha field. It is a dedicated scope with a 35mm clear aperture etalon and a 60mm objective. It is unheated and is tilted to tune on band. The back end is offered with many different adaptors making imaging with almost any conceivable camera possible. This complete scope is being offered at a low price making it a good entry level scope for mica etalons. It is available in .7A, .5A and .3A models.

Solar Spectrum

Marc Wagner worked with Del Woods and in 2002 branched out on his own and founded Solar Spectrum. The filters appear very similar with the exception that Mark incorporated a TEC unit so the filters could be both heated and cooled making the operating temperature closer to ambient without fear that the ambient temperature would exceed the operating temperature of the etalon and allowing them to come to temperature quickly.

Solar Observer 1.0

This is Solar Spectrum's entry level solid etalon. The small aperture makes the cost very affordable especially in the .7 A model. It has a 19mm Clear Aperture and is available in bandpasses from .7 A to .3 A.

Solar Observer 1.5

The Solar Observer 1.5s larger aperture allows for a larger field of view making is useful on longer focal length scopes. It has 25mm clear aperture and is offered in bandpasses from .7 A to .3 A.

Advanced Solar Observer 1.5

The Advanced Solar Observer is the finest system available from Solar Spectrum. With its large 32mm clear aperture and with very even bandpass and transmission it designed for doing research involving consistent full field views. It is offered in bandpasses from .7 A to .2 A.

<u>Lunt Solar Systems</u>

The designs for the Lunt solid etalons are still very new. It would be fair to say they are still in pencil. Instead of the mica technology Andy Lunt has opted for a fused silica spacer optically contacted to two mirrors. This etalon will be temperature controlled and it has not been decided in what Lunt models it will be used. While this requires four very precision polished optical surfaces Andy believes it will be easier to mass produce than mica etalons.

Fused silica does not have any birefringence and therefore does not require a polarizer to eliminate the birefringent ghost.

Conclusion

Daystar and Solar Spectrum both offer good choices for people using an existing scope to view the sun in H-alpha. The choice between solid and air spaced designs perplexes newcomers to solar viewing. In small apertures and in grab and go situations air spaced etalons are more cost effective and provide passbands down to .5 A (although the recently introduced SolaREDi is blurring this line).

In larger apertures solid etalons are more cost effective, however to utilize the larger apertures you compromise the field of view. Some solid etalons require power and the ones that don't have limited temperature ranges. While all the current offerings are run on 12V DC some older systems will need 120V AC to operate.

Solid etalons offer the possibility of .3A and narrower bandpasses from a single etalon while air spaced etalons are limited in practice to .5A in a double stacked configuration. Such a narrow bandpass opens many interesting lines of study. For example, while providing breathtaking disk views while on band they can be tuned to see only ionized hydrogen moving towards or away from the observer. Also, having the bandpass adjustment close to the eyepiece is much more convenient than having to go to the end of a long telescope and make an adjustment.

Only time will tell what will come of the solid etalons from Lunt Solar Systems but the community is eagerly awaiting new products from Lunt.

With all of the buzz about Lunt’s new air spaced designs one should not overlook the tried and true technology of DayStar and Solar Spectrum. These very refined designs have been providing H-alpha views to professional and amateur astronomers for nearly 50 years.

Further Reading:

"Mica Interference Filters with Transmission Bands of Very Narrow Half-Widths" by J. A. Dobrowolski

"Thin-film Optical Filters" by Hugh Angus Macleod

"Procedures in Experimental Physics" by John Strong

"Optics" by Hect

US Patent 03039362

"Lectures on Solar Physics" by H.M. Antia, A. Bhatnagar, and P. Ulmschneider

http://www.company7.com/library/daystar/DayStarManualU-1804.doc.p.pdf

"A Telescope for Lovers of the Sun" by Michael Olshausen