FABRY-PÉROT INTERFEROMETERS AS NARROW BAND OPTICAL FILTERS

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Abstract. We have constructed solid Fabry-Pérot narrow-band filters that can be used in systems having one arc second or better resolution. Our filters operate at Hα, have a three-inch aperture, and typical transmission of 70%. However, the same technology can be applied to construction of filters as narrow as 0.05 Å at any wavelength from 4200 to 11000 Å.

1. Description of Filters

For the past several years, a group at Harvard College Observatory has been developing narrow-band optical filters that use Fabry-Pérot interferometers as the final wavelength-isolating element. Figure 1 is a photograph of the Sun taken through such a filter; the bandpass was 0.5 Å and the transmission of the package including all necessary prefilters was 50%. The complete filter consisted of a Schott RG1 glass; an all-dielectric, all-deposited thin-film stack with a bandpass of about 6 Å; and a solid Fabry-Pérot having a clear aperture of two inches. At present, however, we are using filters with a three-inch diameter.

The design of the primary Fabry-Pérot in the filter is very similar to that of the common all-dielectric, all-deposited interference filter shown in Figure 2. In other words, the solid Fabry-Pérot interferometer consists of a stack of alternate quarter-wave layers of high and low index material, constituting a mirror; on top of this dielectric stack is a thin piece of fused silica (which for the 0.5 Å filter is about 100 μ thick) and a final mirror stack of high and low index material. A standard interference filter commercially available from any number of manufacturers is built much the same way. Our Fabry-Pérot differs only in that the center layer is made from a polished piece of fused silica rather than vacuum-deposited dielectrics. We use a silica disk because the present state of technology does not allow us to make vacuum-deposited layers of the required thickness and still maintain sufficient uniformity.

Making the silica wafers presents a considerable technical problem since the optical thickness of the disk must be uniform to better than $\lambda/100$, while the total thickness of the disk in the 0.5 Å filter is only 100 μ. At present, 50 μ disks, which will make a 1 Å bandpass etalon, represent the minimum thickness that can be reliably manufactured. Disks as thick as 1000 μ, which will make a 0.05 Å filter, have been made. The thicker disks are relatively easier to manufacture.

2. Advantages of Solid Fabry-Pérot Filters

Once the problem of fabricating the wafer is solved, there are considerable advantages to the solid Fabry-Pérot as compared to the more conventional air-spaced device.

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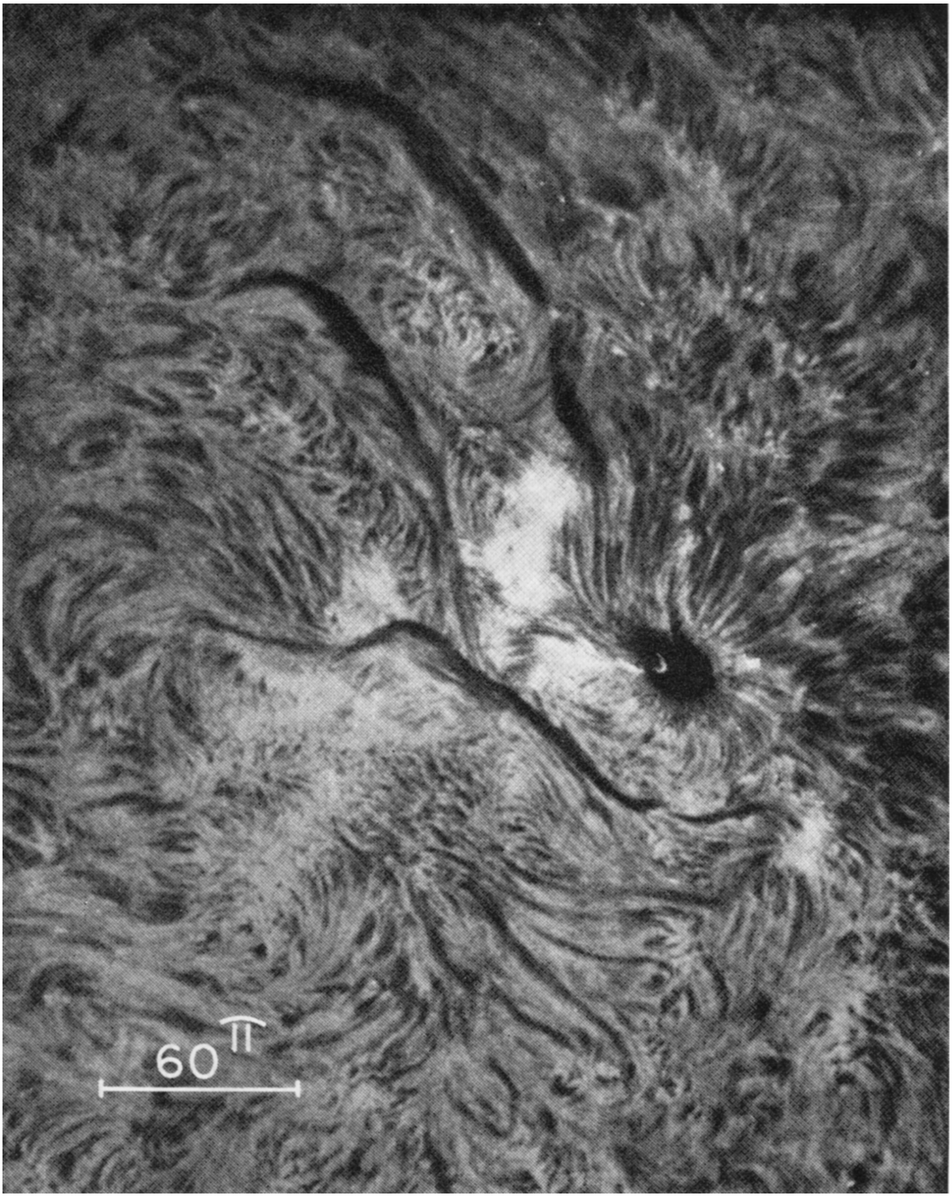

Fig. 1. Photograph of the Sun through Fabry-Pérot filter with a 0.7 Å bandpass. The picture was taken at Lockheed Solar Observatory.

When a Fabry-Pérot is made from two mirrored flats, a mechanical or electromechanical system must maintain the parallelism to better than $\lambda/100$. In the past, such mounts have been sensitive to temperature, pressure, direction of gravity, and/or condition of electronic systems. A solid Fabry-Pérot, however, is sensitive only to temperature.

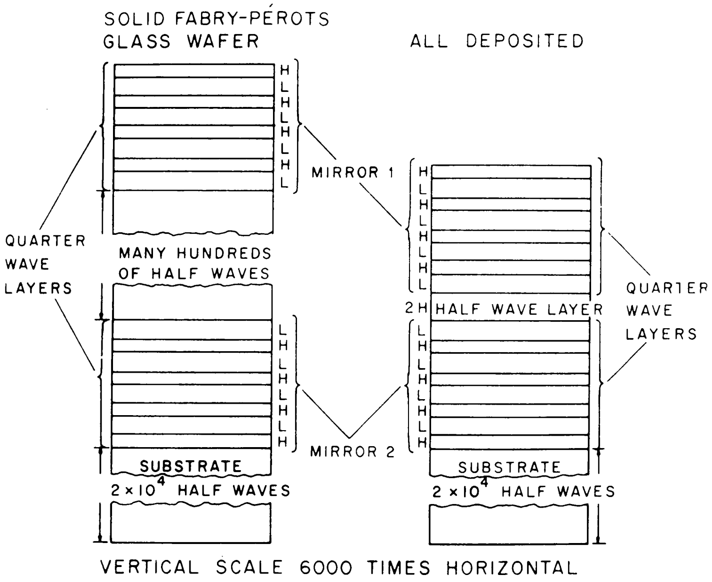

Fig. 2. Typical solid and all-dielectric Fabry-Pérot designs. H indicates a high index quarter-wave layer and L a low index quarter-wave layer.

Temperature affects the interferometer by changing the index of refraction of the fused silica. The temperature sensitivity at Hα is 1 Å for 20 °C. (Shown in Figure 3 is a thermal enclosure for a solid etalon.) Over a three-year period we have discovered no change in transmission characteristics of the solid Fabry-Pérot when the tests are carried out at a standard temperature. That is to say, change in the optical thickness between the mirrors of the Fabry-Pérot due any mechanism other than temperature has been undetectable.

Not only are the solid interferometers mechanically and thermally stable, they are also capable of sustaining considerable mechanical and thermal shocks without adverse effects on transmission characteristics. Thus the filters are ideal for use in environments that require high reliability over a long period of time. For these reasons they have been chosen for use in the Skylab Hα telescope, where they will have to operate in space for one year with zero capability of being mechanically adjusted. This filter system can withstand the Saturn 5 launch loads and the thermal characteristics of the space environment. In addition to the Skylab application, a similar filter has been launched on a rocket to produce coincident Hα and X-ray images.

A second advantage of the Fabry-Pérot filter is its high transmission characteristics. Presently the transmission of a full three-inch diameter etalon at the design frequency is about 70%. Because of the channel spectrum of the Fabry-Pérot, it is necessary to use the etalon in conjunction with another blocking filter or combination of blocking filters to eliminate undesired transmission bands. It is therefore not strictly accurate to speak of the transmission of the etalon alone, but of the complete filter. Filters wider in bandpass than 0.3 Å can be blocked by state-of-the-art evaporated dielectric interference filters. Since such filters have a central transmission on the order of 70%, a complete filter assembly, consisting of an etalon and an all-deposited filter, has a transmission of about 50%. To go narrower than 0.3 Å in bandpass, the filter must contain two solid etalons, the second to suppress the transmission channels of the primary etalon closest to the desired wavelength. Filters consisting of two silica etalons accommodate bandwidths as narrow as 0.05 Å. The transmission of a two-etalon complete filter is 70% of the transmission of a complete single filter, or 35%.

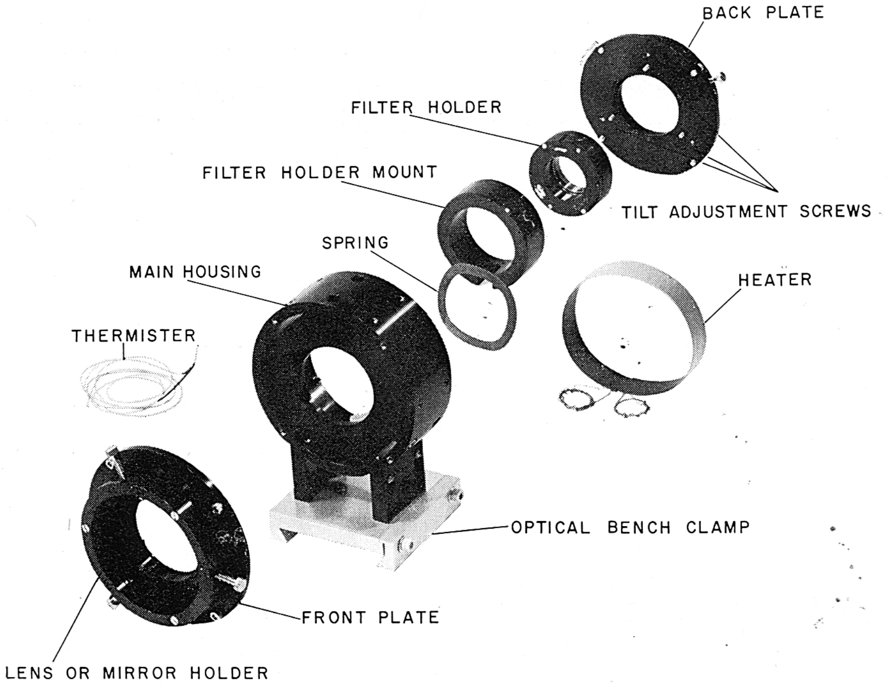

Fig. 3. Exploded view of thermal enclosure for a Fabry-Pérot filter.

A third major advantage of the solid interferometer is the ease with which wavelength tuning can be achieved in a telescope system. This may sound like a contradiction since the wavelength shift with temperature is very small, but there is another mechanism for shifting the wavelengths transmitted by a Fabry-Pérot interferometer: the interferometer can be tilted. The relation between wavelength shift and tilt is given in Equation (1):

$$\Delta\lambda = \lambda/2\,(\theta/n) \tag{1}$$

where n is the index of refraction of the spacer material, $\Delta\lambda$ is the shift in wavelength, and θ is the shift in angle. For spacers of fused silica the shift at λ6563 is 0.5 Å for one degree of tilt. Since the filters are solid they can be tilted at rates up to the point at which inertial loads mechanically damage the wafer.

3. Use of Solid Fabry-Pérots in Telescopes

When the interferometer is in the collimated section of an optical system, a change in wavelength occurs across image plane. This wavelength shift is radially symmetric with the optical axis and moves toward the blue with distance from the axis. The magnitude of the wavelength shift is determined by the angle formed by the rays for a particular image point and the optical axis in the collimated section (Equation (1)). Note that the angle shift can be minimized by looking at narrow fields.

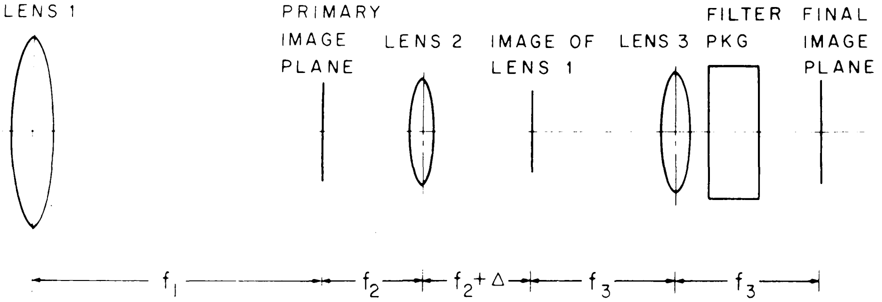

Fig. 4. A telecentric optical design. Behind lens 3, which collimates the objective, the angular distribution of all ray bundles is the same.

If a wavelength shift across the field is unacceptable, then it is possible to use a telecentric design, that is, an optical system in which all the image points have the same ray distribution through the interferometer. In such a system the wavelength distribution is the same for all points in the image plane. Figure 4 shows a typical telecentric design. To prevent significant widening of the profile, the focal ratio in the telecentric section must be 45 or greater for a 0.5 Å filter and 130 or greater for a 0.05 Å filter. (The photograph shown in Figure 1 was taken through a telecentric system.)

4. Comparison of Fabry-Pérot and Lyot Filters

Currently, the Lyot filter is the standard device for taking solar filtergrams. The Lyot has somewhat different bandpass characteristics than the Fabry-Pérot, so it is useful to compare the transmission characteristics of the two instruments.

Near a wavelength of maximum transmission, λ_0, the transmission profile of a single Fabry-Pérot is given by

$$T_{\mathrm{FP}}(\Delta\lambda) = T_{\max}[(1 + \Delta\lambda/\Delta_{1/2}\lambda)^2]^{-1} \tag{2}$$

where $T_{\max}$ is the transmission at λ_0, and

$$\Delta_{1/2}\lambda = \lambda_0 - \lambda_{1/2}$$

where λ is the wavelength, and $\lambda_{1/2}$ is the wavelength at half transmission, and $\Delta_{1/2}\lambda$ is the half-width at half-maximum. The corresponding equation for an N-element Lyot is

$$T_{\mathrm{NL}}(\Delta\lambda) = T_{\mathrm{NLmax}} \prod_{k=1}^{N} \cos^2\left(\frac{\pi\Delta n d}{\lambda_0^2}\,\frac{\Delta\lambda}{2^{k-1}}\right) \tag{4}$$

where T_{NLmax} is the transmission at λ_0, d is the length of the longest element and Δn is the difference in the indices of the birefringent elements. When two Fabry-Pérots are used in a filter, they usually have a half-width ratio of 3 to 4. Near a peak, the transmission of such a combination is

$$T_{2\mathrm{FP}}(\Delta\lambda) \approx [1 + (\Delta\lambda/1.08\Delta_{1/2}\lambda)^2]^{-2} \tag{5}$$

where $\Delta_{1/2}\lambda$ is the half width of the narrower filter.

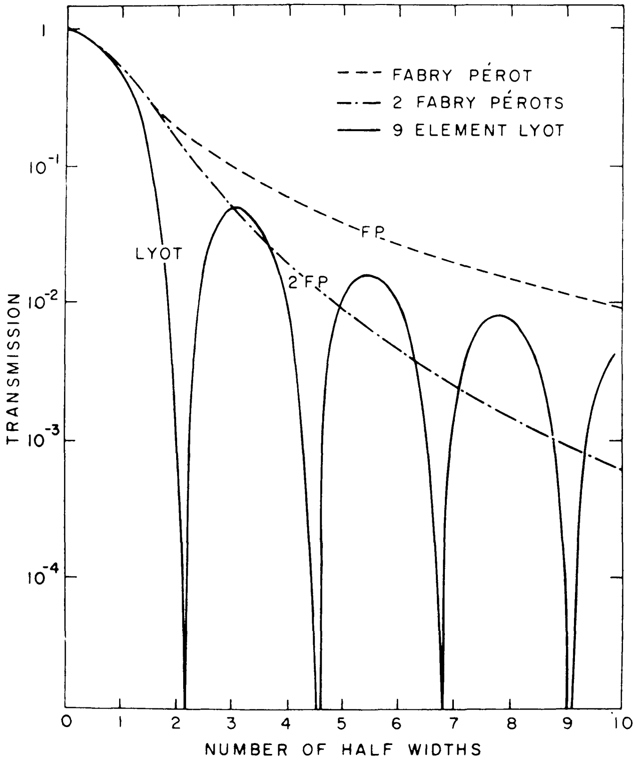

Fig. 5. Transmission profiles of nine-element Lyot, Fabry-Pérot, and a pair of Fabry-Pérots. Maximum transmission is normalized to unity.

Shown in Figure 5 are the transmission profiles of a nine-element Lyot, a single Fabry-Pérot, and a pair of Fabry-Pérots with 3:4 spacing ratio. The curves are plotted in units of the half-width of the complete filter and are normalized so that the maximum transmission is unity. It is clear that the double Fabry-Pérot system is quite comparable to the Lyot filter.

5. State of the Art

At present, it is possible to construct 0.05 Å filters with transmission of 35% for wavelengths of 4200 to 11000 Å. Such filters consist of two solid etalons of 1000 μ and 750 μ thickness, respectively, and an all-deposited interference filter. Such a filter would have transmission profiles near a wavelength of maximum transmission of

$$T(\Delta\lambda) = 0.35\left[1 + (\Delta\lambda/0.038)^2\right]^{-2} \tag{6}$$

A unit consisting of a single dielectric filter and a pair of glass etalons can be tuned over a range of 30 Å by a combination of tilting the blocker and heating or cooling the glass etalons. The dielectric mirrors on the solid glass Fabry-Pérots are efficient within ±500 Å of their design wavelength, so by merely changing the temperature of the etalons and using a new all-dielectric filter, the complete filter can be used at any wavelength in a 1000 Å range. Further, the mirror coating can be stripped and the glass etalons recoated to investigate a different 1000 Å range.

6. Solar Applications

From the preceding sections it should be clear that a Fabry-Pérot filter can be made with a profile similar to a Lyot's. However the Fabry-Pérot has a peak transmission greater than the Lyot's by an order of magnitude. Further, a Fabry-Pérot-based filter can easily be made an order of magnitude narrower than the narrowest available Lyots. Increasing the transmission an order of magnitude implies that exposures can be an order of magnitude shorter. For solar observations, then, fewer seeing fluctuations have to be averaged over.

A Fabry-Pérot with a 0.05 Å bandpass represents the first filter to be competitive with spectroheliographs, which seldom are operated with bandpasses of less than 0.05 Å. In exposure time, the advantage of the solid filter over a spectroheliograph is not one, but three to four orders of magnitude. Thus, any experiment requiring a spectroheliograph can be accomplished with a three to four orders of magnitude shorter exposure using a Fabry-Pérot system.

Some spectroheliographs have beam splitters in front of the entrance slit and multiple-exit slits to simultaneously obtain spectroheliograms at varying wavelengths. Similar results can be obtained with interferometers by including an appropriate mirror or prism system to feed multiple beams to the filter. Alternately, the interferometer can be fed a single beam, allowing a secondary optical system to produce filtergrams in as many wavelengths as desired; that is, images can be obtained simultaneously in all the wavelengths over which the primary etalon is efficient.

Acknowledgements

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