Design of broadband dielectric coatings for near-infrared Fabry-Perot interferometer

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ABSTRACT

Fabry-Perot interferometer has an important effect on near-infrared high spectral resolution spectrograph. In 1896, Ch. Fabry and Alfred Perot designed and used the Fabry-Perot interferometer for the first time. Since then the instruments using Fabry-Perot interference phenomena have been applied broadly to multi-field, such as astronomy, laser, and fiber-optic transmission. Fabry-Perot interferometer has many advantages such as narrow passband, high spectral resolution, high throughput, easy wave-length adjustment, simple structure and large aperture. Comparing with traditional visible light, the solar observation in near-infrared has many advantages: for example, weaker magnetic field strength can be more precisely measured with near-infrared spectrum .So developing the key technology of near-infrared high spectral resolution spectrograph--Fabry-Perot interferometer has become urgent.

For developing near-infrared Fabry-Perot interferometer, there are four difficulties: producing high quality optical plane: peak-to-valley surface flatness better than λ/100; coating Fabry-Perot interferometer plates with broadband multilayer dielectric films(including spectrum performance, thickness uniformity and stress effects); controlling the distance of interference cavity; keeping constant temperature.

In this paper, the process of designing broadband dielectric reflective and antireflective coatings applied in near-infrared Fabry-Perot is described and some problems of designing Fabry-Perot interferometer are discussed: the design of broadband dielectric mirror is described with reflectivity of 93.9±1.0% over spectral ranges from 1.0μm to 1.7μm; by reflective phase shifts in the design of mirror coating, computing the required film thickness uniformity atλ/100 of peak-to-valley surface flatness; degradation of surface figure is perhaps more thanλ/100 even if the soft coating materials-zinc sulfide and cryolite are used, and in order to reduce the degradation of surface figure brought by the stress of dielectric mirror coating, antireflective coating adopts same materials of dielectric mirror coating, ZnS and Na3AlF6, and similar film total thickness.

Keyword: Fabry-Perot interferometer, Broadband reflective coating, Surface flatness, Film thickness uniformity

1. INTRODUCTION

This paper describes the design of broadband dielectric reflective and antireflective coatings for near-infrared Fabry-Perot interferometer and some arguments about designing the Fabry-Perot interferometer.

In recent years, the instruments using Fabry-Perot interference phenomena have been applied broadly to multi-field, such as astronomy, laser, and fiber-optic transmission. In the near-infrared high spectral resolution spectrograph, Fabry-Perot interferometer has an even more important effect.

According to Zeeman splitting of solar spectral lines, Δλ, which is due to solar magnetic field, is proportional to $g\lambda^2B$, where λ is the wavelength of the Zeeman sensitive line, g is the Lande factor of the line and B is the magnetic field intensity. For the Zeeman sensitive lines in the visible spectrum, the Zeeman splitting induced by a sub-kilogauss field is too small to be measured[1]. For example, if λ =5250.2 Å(with g=3) and B=1000G, Δλ≈0.039 Å. But, for the near infrared line, e.g., FeI 15648.5 Å (with g=3), the Zeeman splitting Δλ would be much larger for the same magnetic field. If B=1000G, Δλ≈0.35Å. The Zeeman splitting with infrared line is almost ten times as that with the visible line. Therefore, weaker magnetic field strength B can be more precisely measured with near-infrared lines.

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With the development of the infrared receiver, the solar observation in the near- infrared line is getting more convenient[2]. In the near-infrared high spectral resolution spectrograph, Fabry-Perot interferometer plays a very important role. Comparison between LYOT birefringent filter and Favry-Perot interferometer is in the Table 1.

Table 1. Comparison between LYOT birefringent filter and Favry-Perot interferometer

Filter type	Rationale	Technology difficulty	FOV	Throughput
LYOT filter	Birefringence	Fabrication of crystal	Bigger	Less than 10%
F-P filter	Multiple-beam interference	Fabrication of plane and coating	Smaller	More than 70%
	Material	Stability	Spectral range	Development
LYOT filter	Natural crystal	better	Visible light	Limitation due to material, spectrum and throughout
F-P filter	Fused quartz	good	Visible and near-infrared	rapidly

From the above Table 1, we can see that Lyot filter has bigger field of view, better stability and long life. But with the need of near-IR solar observation and great caliber solar telescope, Fabry-Perot interferometer, having extremely narrow passband, high spectral resolution, high throughput, easy wave-length tenability, simple structure and large diameter, becomes main instrument in the near-infrared high spectral resolution spectrograph.

2. BASIC PRINCIPLES OF FABRY-PEROT ETALONS

Fabry-Perot interferometer is based on the multiple-beam interference, consisting of a pair of identical transparent plates, having plane-parallel internal faces of high reflectivity R, separated by a uniform spacing d. Peak transmission is attained over a series of orders *m* when

$$2nd\cos\theta = m\lambda, \quad m=0,1,2,3,\ldots \tag{1}$$

Taking into consideration of the losses due to absorption and scattering, the intensity ratio of transmitted to incoming light becomes

$$\frac{I_t}{I_i} = \left[1 - \frac{A}{(1-R)}\right]^2 \frac{1}{1 + \left[4R/(1-R)\right]^2 \sin^2(\delta/2)} \tag{2}$$

Where R is the reflectivity, A is losses by absorption and scattering, and $\delta=4\pi nd\cos\theta/\lambda$ is the phase difference between successive beams.

The Free Spectral Range is defined

$$FSR = \frac{\lambda}{m} = \frac{\lambda^2}{2nd\cos\theta} \tag{3}$$

From the Airy formula, the finesse F is defined as

$$F = \frac{FSR}{FWHM} = \frac{\pi R^{1/2}}{1-R} \tag{4}$$

3. SOME ARGUMENTS ABOUT DESIGN OF FABRY-PEROT ETALONS

Fabry-Perot interferometer consists of a pair of identical transparent plates, having plane-parallel internal faces of wide-band high reflection film .Spectral range is at 1.0 - 1.7μm, reflectivity requires 93.9±1.0% and film uniformity is better than 3‰. The coating materials are ZnS and Na3AlF6[2,3], the plane distortion due to coating stress is less than 1/100 λ.

The finesse is one of the most important parameters in fabry-Perot interferometer, is defined by the ratio of the free spectral range to the FWHM, F=Δλ/δλ.The total effective finesse is defined by the square root of the inverse square sum of the reflectance finesse and the overall defect finesse and approximated by[4]

$$F = (F_R^{-2} + F_D^{-2})^{-1/2} \tag{5}$$

The overall defect finesse is approximated by

$$F_D = \lambda/(2\delta s) \tag{6}$$

δs is the plate deviation from parallel

The reflectance finesse is approximated by

$$F_R = \pi R^{1/2}/(1-R) \tag{7}$$

The total throughput of an etalon system is a function of the etalon defects. The transmission is reduced by approximately a factor $[1+(F_R/F_D)^2]^{-1/2}$ relative to a defect-free etalon. This factor is 0.89 for $F_R/F_D=0.5$ but 0.44 for $F_R/F_D=2$. Therefore the condition $F_R/F_D \leq 1$ must be met in a high throughput system. By formula (7), the needed value of reflective coating can be computed. It is desirable to control the fluctuation in R across the spectral range to values within 1%, so that variations in spectral resolving power of the spectrometer are kept within tolerable limits.

Film thickness uniformity requirements of a coating is given by (δe/e)< t/δ, where λ/δ is the surface figure of the uncoated plates and $t = \lambda / \left|(2\pi)^{-1}(\partial\phi/\partial\sigma) + 2e\right|$, e is physical thickness of the coating[3].

4. DESIGN OF COATING

When the peak-to-valley surface flatness is λ/100, the value of F_D is 50. In a high throughput system the condition $F_R/F_D \leq 1$ must be met, so $F_R \leq 50$. If $F_R = 50$, by $F_R = \pi R^{1/2}/(1-R)$, the value of reflective coating is 93.9±1.0%.

Even using the less stress coating material，ZnS and Na3AlF6, the plane distortion due to coating stress is perhaps more than λ/100. In order to reducing coating stress, the wide-band antireflective film adopts same materials of dielectric mirror coating, ZnS and Na3AlF6, and similar film thickness.

After choosing the coating materials[6], the next is design of the coating. The design base on the character matrix of multilayer dielectric films:

$$\begin{bmatrix} C \\ B \end{bmatrix} = \left\{ \prod_{r=1}^{n} \begin{bmatrix} \cos\delta_r & i\sin\delta_r / \eta_r \\ i\eta_r \sin\delta_r & \cos\delta_r \end{bmatrix} \right\} \begin{bmatrix} 1 \\ \eta_{n+1} \end{bmatrix} \tag{8}$$

$$\delta_r = \frac{2\pi N_r d_r \cos\theta_r}{\lambda} \qquad \begin{aligned} \eta_r &= N_r / \cos\theta_r .....(p) \\ \eta_r &= N_r \cos\theta_r .....(s) \end{aligned} \tag{9}$$

The starting design is: S/HLHLHLHLHLHLHLH/A

S is substrate; H is high refractive index coating material and L is low refractive index coating material ; A is incidence medium--air.

Coating design software was used to optimize the design of the coating and all layers thickness is variable, then fifteen-layer structure shown in:

S/ 1.8302H 1.4461L 1.4468H 1.4321L 1.3269H 1.2489L 1.2083H 1.1775L 1.107H 0.8029L 0.7094H 1.0521L 1.1369H 0.9015L 0.3032H /A

Coating total thickness are: ZnS, 1060.8nm and Na3AlF6,1682nm, calculated reflectance profile is indicated by Fig.1.

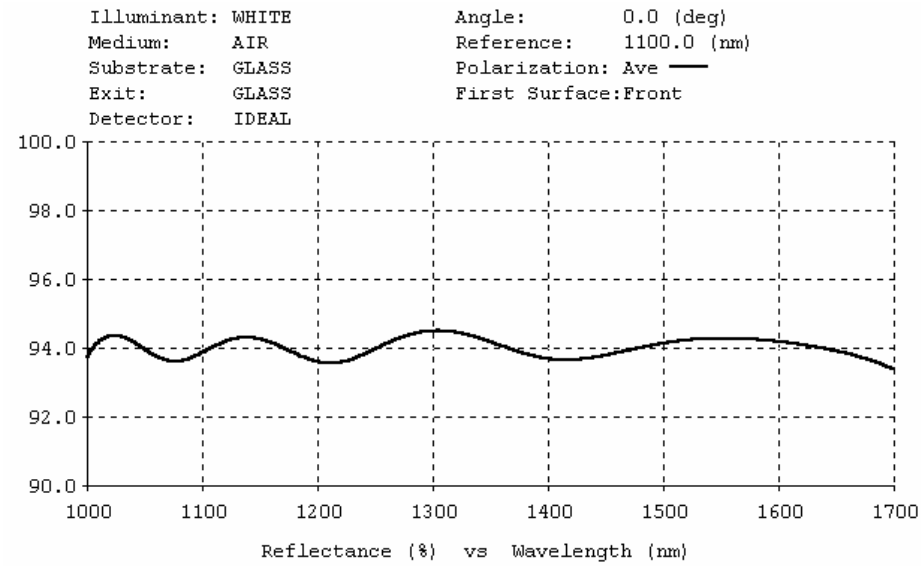

Fig.1. Calculated reflectance profile of the reflective coating

Antireflection coating design used Synthesis method for the improvement of design performance and the same coating materials- ZnS and Na3AlF6 are used. The optimize targets are reflectance magnitude and thickness, then gained single surface transmittance profile, as indicated by the data in Fig.2.

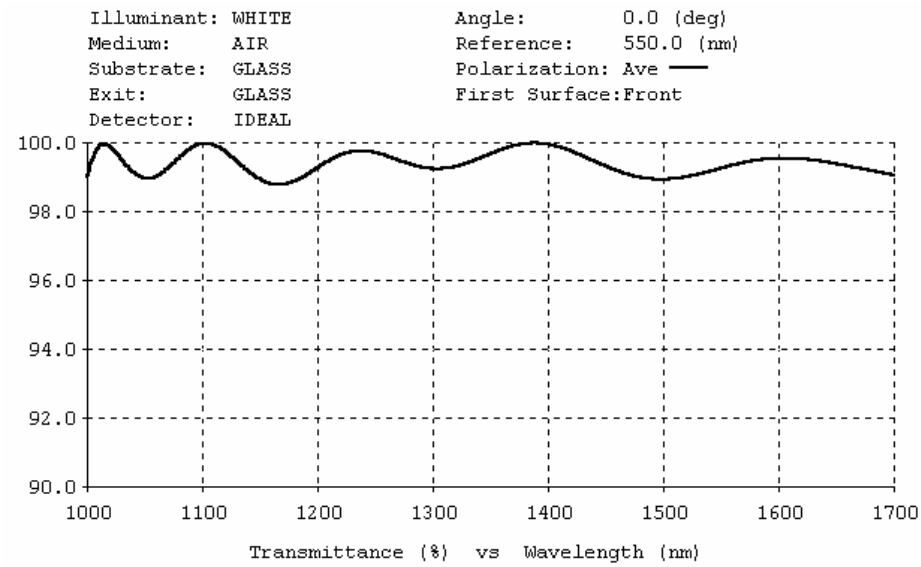

Fig.2. Calculated transmittance profile of the antireflective coating

Ten-layer antireflection coating obtained the better wide-band antireflective effect. Its aim is ensuring antireflective effect, then adopts same materials of dielectric mirror coating, ZnS and Na3AlF6, and similar film thickness , and thereby reduces the degradation of surface figure brought by the stress of dielectric mirror coating. Antireflection coating total thickness are: ZnS, 1060.8nm and Na3AlF61682 nm.

From the reflectance phase shifts of the reflective coating, the computed thickness uniformity requirement must be held to values less than 3‰ with peak-to-valley surface flatness within λ/100 at 1560nm.

5. DISCUSSION

In this paper, some of difficulties existing in developing near-infrared Fabry-Perot interferometer are brought out, some of the practical problems associated with the wide-band dielectric coating have been considered in detail and the design of broadband dielectric coating is described. Before patterns of coatings can be successfully produced, more work is required including controlling film uniformity, reducing the coating stress, controlling the distance of interference cavity and improving environment stability of Fabry-Perot interferometer and so on.

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