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Development of High-Performanced 50nm Bandwidth Rectangular Wave Filter

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Abstract: A method for designing and depositing rectangular wave broadband-pass filter is put forward after a deep study of the nature of the film-filters. A rectangular wave *OD3-A* broadband-pass filter sample is designed and prepared with this method, with its reference wavelength $\lambda_0 = 515nm$ in the working range of 400~1100*nm*. The average transmittance of the sample in its pass-band of $\lambda_0 \pm 25nm$ reaches 92.7%, meanwhile the transmittance in the high-reflective bands of $\lambda \neq \lambda_0 \pm 25nm$ is less than 0.1%. The transmittance of the thin film sample is tested, and the spectrum meet the requirement. It turned out to be a more advanced technology of designing and depositing rectangular wave broadband-pass filter. Compared with the Fabry-Perot Interferometer narrow-band pass filters' films which needs optical-controlling method, and the traditional film which combines short and long pass filters making the coatings very thick and with low transmittance in transition zone. it is more economical, have more wide range of transmission and the transmittance is higher in the range of pass-band.

Keywords: Optical Thin Film, Band-Pass Filters, Rectangular Wave, Optical Density

1. Introduction

Band-pass filter is a kind of optical thin film that cuts off the whole range of wavelength in a most band except for a high transmission middle section. Band-filter can be divided into narrow band-pass filter and the broad band-pass filter. Fabry-Perot interferometer is a typical narrow band-pass filter [1], meanwhile, broadband-pass filter is usually obtained by the combination of long and short wave cutoff coatings. With the increasing use in changing angle of band-pass filters [2], the rectangular band-pass filter attaches more and more attention. Rectangular band-pass filter obviously have the advantages of solving the optical axis offset and temperature changing effect in the process of using the photoelectric instrument.

Rectangular band-pass filter is studied early in aboard [3-7]. The processing technology is researched domestically in recent years. Fei Shuguo, Shen Lin, Yang Jie, Pang Wei studied the F-P narrowband-pass filter [8-11]. This is a typical kind of narrowband-pass filter, its layer-thickness is usually controlled by optical method. More cavity is needed to improve the rectangularity. When depositing narrow band-pass filter, we always need advanced equipment with high stability and consistency and slightly controlling accuracy. In a word, there is always high cost and large limitations in preparing rectangular filters in this way. Qi Jian, Zhu Xinhua, Yue Pengfei and Zhao Huicong et. al. combined the short and long-wave cutoff edge filters [12-15], and got broadband-pass filters using quartz crystal deposition monitor technology. Due to the total thickness of the film and the inherent consistency error by this monitoring method [16], the sample they prepared has a limited scope of application. The rectanglarity and the transmittance in the pass band still needs to be further improved.

In this paper, a rectangular broad band-pass filter depositing on K9 substrate is studied, with its reference wavelength $\lambda_0 = 515$ nm, average transmittance superior to 92% in pass-band $\lambda = \lambda_0 \pm 25$ nm. The spectrum satisfies to the need of *OD3-A* in the rejection zone $\lambda \neq \lambda_0 \pm 40$ nm. The new designing method reduces the sensitivity of every layer and the total thickness of the film on the premise of holding high optical performance. Then the film prepared by quartz crystal deposition monitor technology is tested. The result shows that: its average transmittance reaches 92.7% in the pass-band of 490nm~540nm, the performance in rejection zone meet the need. When comparing with F-P narrowband-pass filters, it overcomes the disadvantages of narrow pass-band width, high cost. And it has thinner total thickness, higher transmittance in the pass-band, superior rectangularity when comparing with the traditional method of combining the short and long wave cut-off filters.

2. Theoretical Analysis

2.1. Spectral Analysis

Optical density (*OD*) specially named in the national standard is the same conception to absorbance and can be convert into each other. The optical density *OD-value* is defined as: the logarithm of the ratio of intensity of the incident light and transmit, it can be written as:

$$OD = \lg^{\left\{ 1/T_{\text{Sample}} \right\}} = \lg(T_{\text{Sample}}) \tag{1}$$

where T_{Sample} is the transmittance of the sample. The *OD-value* determines the transmittance of the band-pass filter in cut-off band. A is the reflective band identifier code with the range of 400nm~1100nm. As is implied above, the spectral of the coating can be written as: in the spectral of 400nm~1100nm, $\lambda_0 = 515$ nm, T≥92% in the pass-band of $\lambda = \lambda_0 \pm 25$ nm, T<0.1% when $\lambda \neq \lambda_0 \pm 40$ nm.

2.2. Fundamental of Film Filters

The bandwidth of filter either long wave cut-off $(0.5LH0.5L)^S$ or short wave cut-off $(0.5HL0.5L)^S$ can be written as the same equation [17],

$$\Delta g = \frac{2}{\pi} arcsin\left(\frac{n_H \quad n_L}{n_H + n_L} \right)^S \tag{2}$$

In this equation, n_H and n_L indicate the high and low refractive index of layer's material, S is the periodicity of layer. The bigger the ratio of n_H / n_L , the wider the reflectance range and the larger *OD-value*. Splicing some of filters having discrete reference wavelength we will get a filter possessing broad reflective-band.

3. Film System Designing

As is analyzed in 1.1, this is a filter possessing a wide pass-band, hence it can not be designed by the F-P thin film filter. The transition edge changes rapidly and the rejection zone is so wide that it can't be consisted of the short and long cut-off filters, otherwise the coating will be too thick to have a appropriate internal stress. In this research, the rectangular wave wide band-pass filter is obtained by combining a optimized band-pass filter and a long wave cut-off filter composing non-equal thickness periodic film.

3.1. Materials

In the range of 400nm~1100nm, SiO_2 is usually selected as a low refractive index material, and the material acted as a high refractive index material is TiO_2, Figure 1. shows its refractive index dispersion curve,

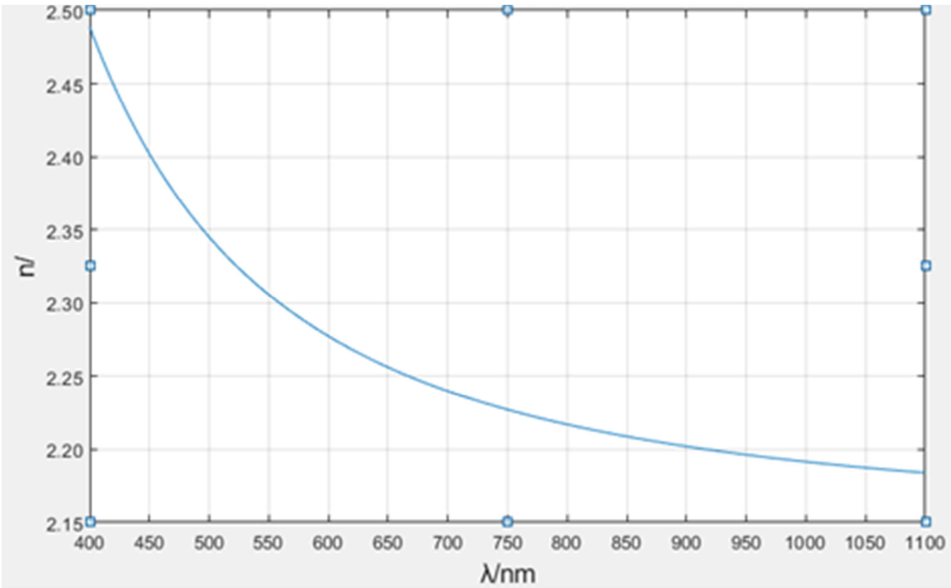

Figure 1. *The refraction index curve of the TiO_2.*

3.2. Band-Pass Film Designing

The band-pass filter in the first side of the substrate is obtained by optimizing the initial system of F-P narrow band filter. Figure 2. shows the simulated transmittance curve.

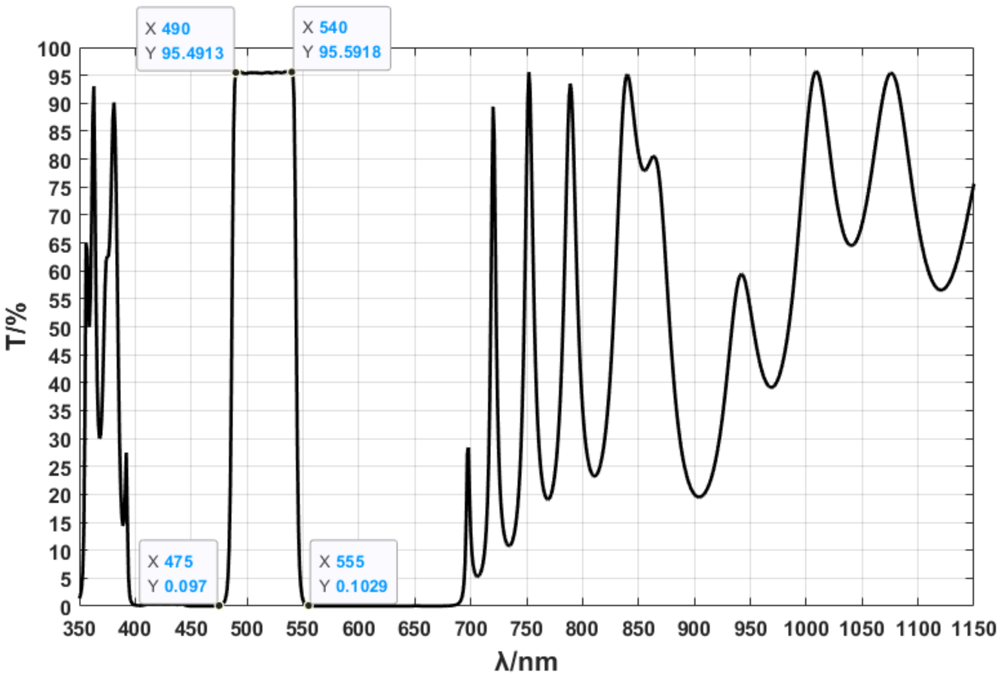

Figure 2. *Simulated spectrum curve of band-pass filter.*

The spectral of the band-pass filter in the first side is: $\lambda = 490 \sim 540$ nm, its transmittance τ >94%, in the rejection zone $\lambda = 400 \sim 475$ nm, $\lambda = 555 \sim 680$ nm, its transmittance τ <0.1%. The total thickness of the filter film is 3.277μm, its thinnest layer is 20nm. The designed film is small in total thickness and low in sensitivity and controlling requirements, the spectral performance meets the requirements.

3.3. Edge Filter Designing

According to the spectrum of the first side and the rectangular wave filter, the coatings matched on the second side should be the spectrum that: high transmission between 490~540nm, cut-off between 680~1100nm, and the transmittance in rejection zone is less than 0.1%. This is a long-wave cut-off filter. Its reflective-band is wide, the transmission-band is exactly in the position "half-wave hole [18]". Designing the long-wave cut-off filter followed by 1.2 will multiply layer thickness leading large internal stress and also can not eliminate the "half-wave hole" effect leading a large decrease of transmittance in the transmission-band [19].

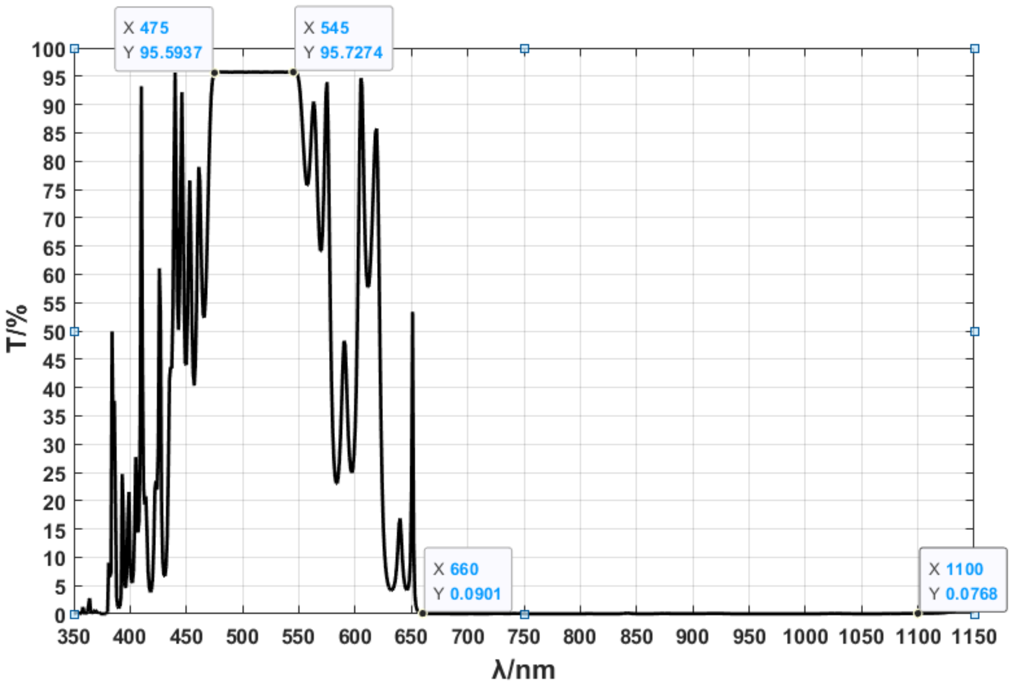

Figure 3. *Simulating curve of long-wave cut-off filter.*

Using non-normalized periodical film $(mHnL)^S$, which has more than one reflective-band, Dong Ying design coatings avoiding the "half-wave hole" effect and reducing the total thickness, improve the transmittance in its transmission-band [20]. Learning from this approach, the long-wave cut-off coating is designed, Figure 3. shows the simulated transmission curve.

Total thickness of the coating is 7.3μm, in transmission-band $\lambda = 470 \sim 560$ nm, τ >95%, in its rejection zone $\lambda = 660 \sim 1100$ nm, τ <0.1%. The requirements of the whole spectrum for the film on the second side is met.

3.4. Global Film Designing

Combining the layers on the first and the second side, a rectangular wave broadband-pass filter is obtained, Figure 4. shows the simulated transmittance curve of the filter:

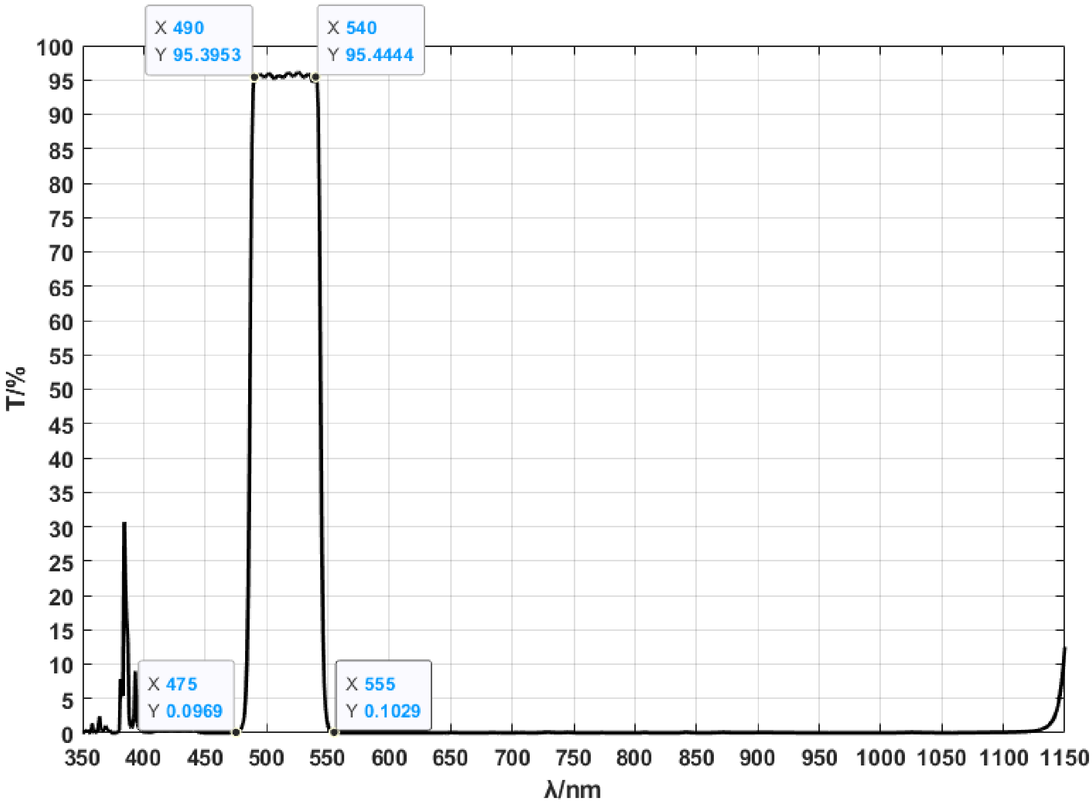

Figure 4. *Simulating curve of rectangular wave broadband-pass filter.*

According to the theoretical design and simulation, the central wavelength of the rectangular wave filter is λ_0 =515nm, the average transmittance $\bar{\tau}$ ≥95% in the transmission band 490~540nm, in the rejection zone 400~475nm and 555~1100nm, the highest transmittance τ_{max} <0.1% or *OD*>3, FWHM=546nm-486nm=63nm. Obviously, all the optical indicatrix containing transition zone, transmittance in pass band and reflective band meet the requirement.

4. Preparing and Testing

The sample is manufactured by a ZZSX-800M vacuum coating equipment with INFICON 5 quartz crystal controller. Band-pass filters, cut-off films and the final rectangular wave wide band-pass filter is deposited separately on substrate K9 for a convenient testing.

The most important factor we should take into account for the band-pass filter on the first side is the thinnest layer. It has the highest sensitivity. Moreover, temperature-drift is also significant as the central wave length and the transition zone has a very demand. All the rest layers is simple to control. It is relatively complex to placing the long-wave cut-off film. There must be some duplicate experiments to remove the effect of the crystal controlling consistency because of the thickness of the coating reaching 7.3μm, consuming much more material.

All the transmittance curve of the band-pass filter, the cut-off filter and the final rectangular wave wide band-pass filter is tested separately using a LAMBDA900 spectrophotometer. The transmittance curve of one-side band-pass filter, one-side cut-off filter and the final rectangular wave broadband-pass filter is successively shown in Figure 5, Figure 6 and Figure 7.

As can be seen from Figure 7, the rectangular wave wide band-pass filter designed and manufactured by the essay mentioned method has a cut-off area λ =410~475nm and λ =555~1100nm, the average transmittance $\bar{\tau}$ =92.7% in its transmission zone λ=490~540nm.

The optical density OD-value curve of the rectangular wave wide band-pass filter is calculated from equation (1). Figure 8. shows the *OD-value* curve of the rectangular band-pass filter,

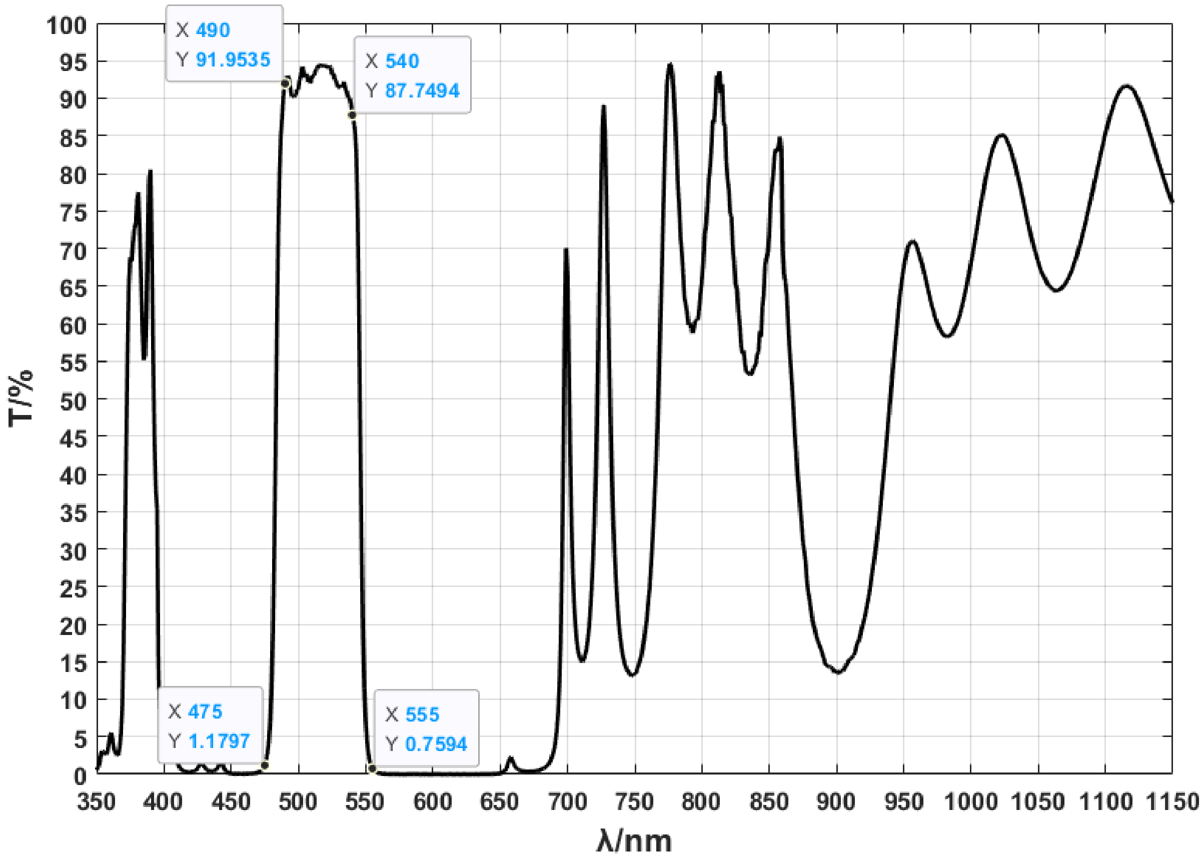

Figure 5. *Testing curve of broadband-pass filter.*

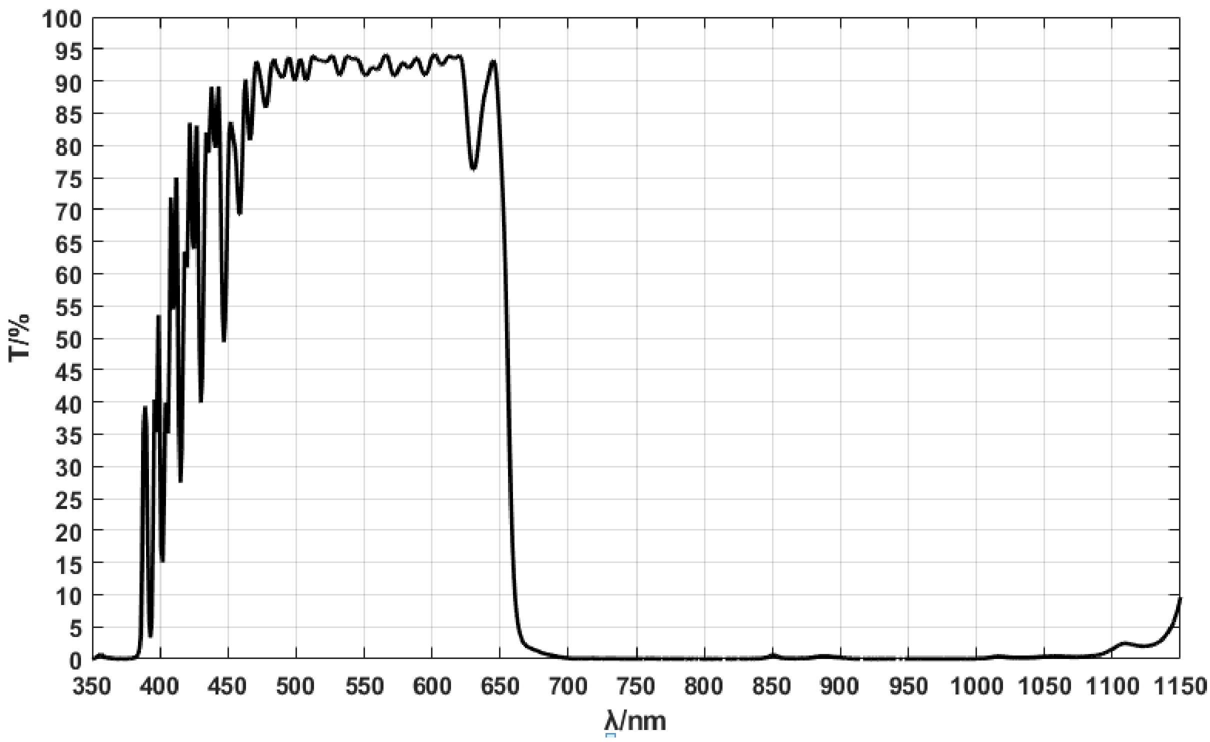

Figure 6. *Testing curve of long-wave cut-off filter.*

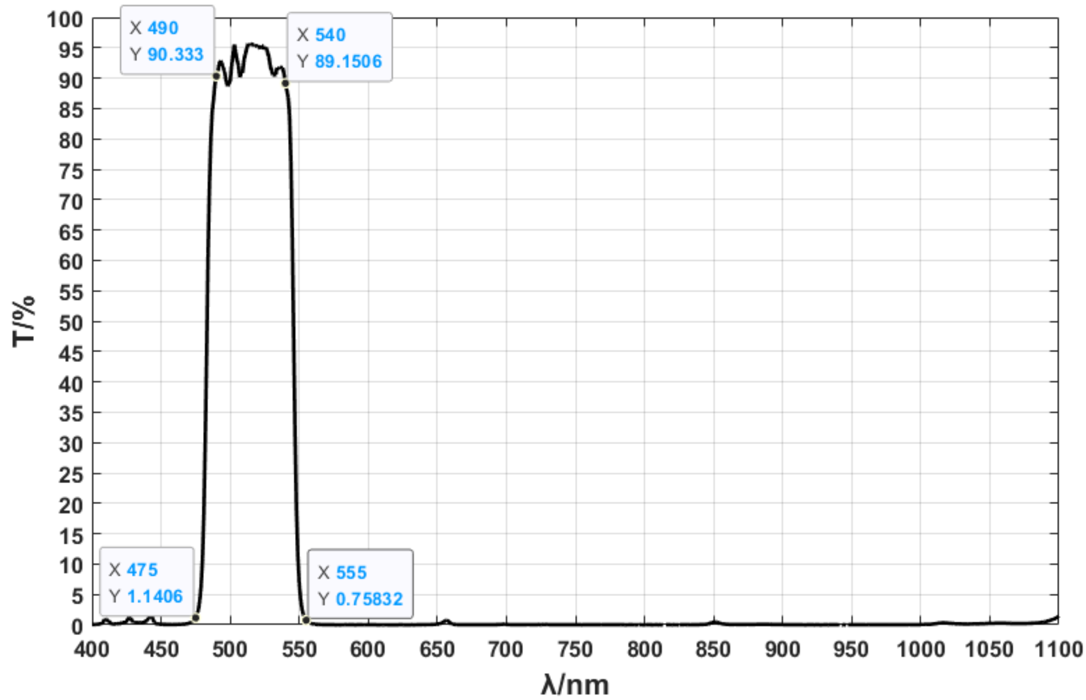

Figure 7. *Testing curve of rectangular wave broadband-pass filter.*

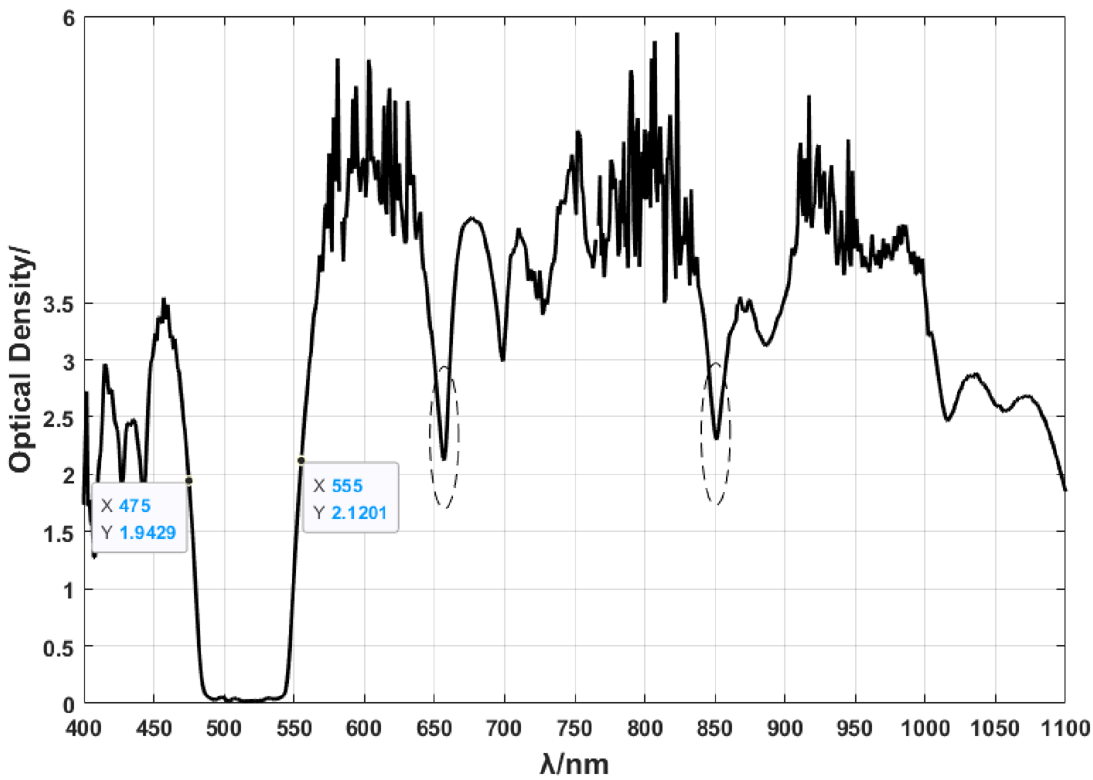

Figure 8. *Calculating curve of the rectangular wave broadband-pass filter.*

Undeniably, there are some imperfections for the rectangular wave filter. Firstly, for the range of 400~410nm in the rejection zone, it still transmit some energy or its transmittance is relatively a little high. This is caused by large dispersion effect of TiO_2 and the different packing density between the single layer and multi-layer film [21, 22]. Secondly, at the wavelength λ =655nm and λ =850nm, when the wavelength stay neighborhood of the point, there are some deficiencies in the transmittance, or to say that there is a deviation in the splicing of the rejection zone, because the temperature drift between the band-pass coating and long-wave cut-off filter is discrepant [23]. All the two problems mentioned above can be solved by repeated processing experiments [24].

5. Conclusion

A new method for designing and depositing a rectangular wave *OD3-A* broadband-pass filter is proposed by studying the properties of it. The total thickness of the film designed by this method is smaller, the sensitivity of the film is lower, the required monitoring accuracy is poorer, and the manufacturability is more practical. A rectangular wave *OD3-A* broadband-pass filter with a bandwidth of 50nm and the central wavelength λ_0=515nm is designed and prepared. The testing result shows that the spectrum of the prepared sample meets the requirement. By analyzing, it can be proved that some defects about the spectrum of the sample can be eliminated. It is proved that this is a practical economical efficient and advanced method for design and depositing this kind of rectangular wave *OD3-A* wide band-pass filter.

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Biography

Dong Ying: PhD student in Xi'an Institute of Applied Optics, mainly engaged in optical thin film process, optical processing process and other technology research work, PhD student period mainly study the tolerance design of optical system.