

# Design of Linear Variable Optical Filter for Hyperspectral Imaging

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## Research Article

**Keywords:** Thin Film, Thin film devices, induced transmission filter, linear variable optical filter, spectrometry, hyperspectral

**Posted Date:** April 29th, 2021

**DOI:** <https://doi.org/10.21203/rs.3.rs-358928/v1>

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# Abstract

In this paper, the design and simulation of a Linear Variable Optical Filter (LVOF) for the visible and near-infrared (VNIR) 450-900nm region is reported. The design and simulation of LVOF are made based on all-dielectric<sup>[1-4]</sup> and metal-dielectric based induced transmission filter. In the given paper, we have compared the design approach based on all-dielectric and metal-dielectric filters. The LVOF filter based on the metal-dielectric method reduces the design and fabrication complexities and is also cost-effective as it doesn't require any band rejection filters. The minimum spectral transmission of the metal-dielectric filter reported in the paper is 70% with a FWHM of 2-3% of central maxima.

## 1. Introduction

Electro-optical (EO) sensors are finding a wide range of applications in civil and military environments ranging from surveillance to high performance target search, track, and acquisition, guidance and satellite imaging for remote sensing<sup>[5]</sup> applications including detection of military targets. Sensors have been classified in different number of spectral bands such as panchromatic (single band), multi-spectral (more than one band) and hyperspectral (a large number of contiguous bands). Hyperspectral imaging system has very wide capability of spectral discrimination than the multispectral imaging. Hyperspectral imaging combines three different technologies, namely remote sensing, spectroscopy and imaging. Remote sensing is the ability to obtain information without making any physical contact with the objects to be studied. Spectroscopy is the study of spectral component of the electromagnetic spectrum while splitting the light in various small spectral bands. Imaging is done using your conventional optics in combination with suitable detectors.

The hyperspectral imaging system consists of three basic components, fore optics for the collection of radiance, spectral separation device and a detector. These sensors capture the reflected spectrum of the electromagnetic radiation forming a three dimensional data cube, two dimensional in the spatial domain and one in the spectral domain. Hyperspectral Imaging Camera has advanced features of long ranges, wide field coverage, high spatial resolution for better detection and high spectral resolution for better identification capability. Hyper-spectral imaging technology has the potential to provide superior target to background discrimination, when compared to the equivalent spatial resolution broad band devices.

In the present work a linear variable optical filter has been designed for the VNIR (450-900nm) region, which will work as a spectral separation component for the hyperspectral imaging camera which can be used for earth observation satellites and airborne platforms. To satisfy both the requirements of small dimensions and low mass, prism and grating based traditional spectrometers will be replaced by LVOF<sup>[6-8]</sup>. This spectral separation device is proposed in this paper which is designed and simulated on the metal-dielectric based induced transmission filter<sup>[9-14]</sup> and can be fabricated taking advantage of thin film technology like sputtering and e-beam evaporation. In this paper we will be discussing about different design approach for the realization of this linear variable optical filter.

## 2. Linear Variable Optical Filter (Lvof)

In order to have a light weight and miniaturized spectral separation device with no moving parts, a graded transmission filter is proposed.

The LVOF is an optical interference filter whose spectral functionality varies along one direction of the filter, compared to a traditional optical filter whose spectral functionality is intended to be identical at any location of the filter. For a narrow band interference filter there will be a single transmission peak, i.e the coated sample will show same transmission at every part of the sample. However, in the case of LVOF there will be a shift in the transmission peak from one edge of the sample to the other. The LVOF integrated with a CCD will work as a single chip spectrometer, thus opening up a huge potential for spectroscopic and imaging applications.

With a suitable choice of thin film coating materials the LVOF can be fabricated for any spectral band. Since the design and fabrication of this device have its own complexities therefore there are two basic approaches for the fabrication of these devices. The first methodology is using VLSI technology and the second approach is thin film technology using masking.

The first approach is based on the all-dielectric, i.e. the design and fabrication of this filter are based on the concept of the Fabry Perot etalon. The LVOF basically consists of a tapered cavity layer sandwiched between two Bragg reflectors or a dielectric mirror. This type of filter is derived from the concept of Fabry-Perot etalon with a tapering in the cavity layer. However, this filter suffers from a drawback of narrow spectral band<sup>[15]</sup>, and hence can be used only where a limited spectral band is required, i.e. on changing the thickness of the cavity layer, the transmission peak will not be able to cover the entire spectrum (450-900nm). The reason for this is the generation of 3<sup>rd</sup> order harmonics, i.e. we are getting more than one peak at a certain cavity layer thickness which we don't require. Thus in order to design and fabricate this filter in the VNIR (450-900nm) region using the all dielectric approach we need to add many band rejection filter or blocking filters at different positions of the LVOF, thus adding the complexities in fabrication and enhancing the cost of filter as it requires big infrastructure like lithography, dry etching and a e-beam or sputtering system.

The first step is to have an alternate layer of high and low index material and then depositing a cavity layer. The tapering in the cavity layer can be executed with lithography, thermal reflow of the photoresist and dry etching of the cavity layer and further depositing the mirror layer using alternate layers of high and low index material. If the cavity layer is of high index material then the next layer will be of low index material. The substrate in the VNIR region can be borosilicate glass or fused silica or quartz, while the high index and low index material can be TiO<sub>2</sub> and SiO<sub>2</sub> respectively. For a wide transmission band there will be a requirement of band rejection or blocking filters which will suppress the third harmonics generated using the tapered cavity layer. The design and simulation of all-dielectric based LVOF is discussed in the next section.

A second approach to design a LVOF is using metal-dielectric based induced transmission filter. The choice of suitable metallic layer along with the dielectric layer combination will help in getting the desired transmission ( $\geq 70\%$ ) with the wider rejection band. Thus, with this induced transmission filter we will be able to cover a larger spectral band without any blocking filter. Thus the effective cost and overall performance of the filter will be better than all-dielectric based LVOF.

### 3. Design And Simulation Of Lvof

In the present section we will be presenting the design and simulation of LVOF using all-dielectric and metal-dielectric approach

#### a) All-Dielectric based LVOF:

All-dielectric filter is designed using a combination of high and low index materials  $\text{TiO}_2$  and  $\text{SiO}_2$ . Since these filters have a limited rejection range therefore the filter is split into two spectral bands 450-624nm (LVOF Filter1), 624-880nm (LVOF Filter2) and blocking filters, which is at the back side of the substrate as shown in Fig1. The design for the LVOF filter1 is mentioned in table1 with cavity-layer thickness varying from 400-715nm and subsequently its peak transmission varying from 450-624nm. The transmission curve of the LVOF filter1 with a cavity-layer thickness of 415nm shows peak at 456nm, 565nm with some transmission band (Fig2). Since we require single transmission peak at different positions of substrate therefore, we need to add a low pass filter (Fig3) which will remove peak at 565nm and transmission band as shown in the Fig4. Thus adding a low pass filter1 and band pass filter1 we will get a linear variable optical filter (LVOF filter1) in which the peak transmission varies from 450-624nm as shown in Fig5.

**Table 1 ALL Dielectric LVOF filter 1 (450-624nm), LVOF Filter2 (624-880nm)**

| LVOF Filter 1 |                  |                | LVOF Filter 2    |                |
|---------------|------------------|----------------|------------------|----------------|
| S.No.         | Coating layers   | Thickness (nm) | Coating layers   | Thickness (nm) |
| 1.            | <b>Substrate</b> | BK7            | <b>Substrate</b> | BK7            |
| 2.            | TiO <sub>2</sub> | 56             | TiO <sub>2</sub> | 77             |
| 3.            | SiO <sub>2</sub> | 89             | SiO <sub>2</sub> | 125            |
| 4.            | TiO <sub>2</sub> | 56             | TiO <sub>2</sub> | 77             |
| 5.            | SiO <sub>2</sub> | 89             | SiO <sub>2</sub> | 125            |
| 6.            | TiO <sub>2</sub> | 56             | TiO <sub>2</sub> | 77             |
| 7.            | SiO <sub>2</sub> | 89             | SiO <sub>2</sub> | 125            |
| 8.            | TiO <sub>2</sub> | 56             | TiO <sub>2</sub> | 77             |
| 9.            | SiO <sub>2</sub> | 89             | SiO <sub>2</sub> | 125            |
| 10.           | TiO <sub>2</sub> | 56             | TiO <sub>2</sub> | 77             |
| 11.           | SiO <sub>2</sub> | 89             | SiO <sub>2</sub> | (590-1040)     |
| 12.           | TiO <sub>2</sub> | 54             | TiO <sub>2</sub> | 77             |
| 13.           | SiO <sub>2</sub> | 400-715        | SiO <sub>2</sub> | 125            |
| 14.           | TiO <sub>2</sub> | 54             | TiO <sub>2</sub> | 77             |
| 15.           | SiO <sub>2</sub> | 89             | SiO <sub>2</sub> | 125            |
| 16.           | TiO <sub>2</sub> | 56             | TiO <sub>2</sub> | 77             |
| 17.           | SiO <sub>2</sub> | 89             | SiO <sub>2</sub> | 125            |
| 18.           | TiO <sub>2</sub> | 56             | TiO <sub>2</sub> | 77             |
| 19.           | SiO <sub>2</sub> | 89             | SiO <sub>2</sub> | 125            |
| 20.           | TiO <sub>2</sub> | 56             | TiO <sub>2</sub> | 77             |
| 21.           | SiO <sub>2</sub> | 89             | Air              |                |
| 22.           | TiO <sub>2</sub> | 56             |                  |                |
| 23.           | SiO <sub>2</sub> | 89             |                  |                |
| 24.           | TiO <sub>2</sub> | 56             |                  |                |
| 25.           | SiO <sub>2</sub> | 89             |                  |                |
| 26.           | Air              |                |                  |                |

Similarly, second part of the filter (LVOF filter2 as mentioned in table1) is designed with the transmission peak varying from 624-880nm along with two different band pass filters2 at the back side of the substrate as shown in Fig1. The output of the second part of the linear variable optical filter (LVOF filter2) is shown in Fig6. Thus the combination of LVOF filter1 and LVOF filter2 on a single substrate will work as a linear variable optical filter with transmission peak varying from 450-880nm.

#### **b) Metal-Dielectric based LVOF:**

The design of such filter can be done using two different approaches. In the first method we can use a metal layer as a mirror layer,  $\text{SiO}_2$  as a cavity layer as used in all-dielectric based LVOF. The thickness of the cavity layer when varied from 105-240nm will give transmission peaks at different wavelengths. The design<sup>[16]</sup> of such filter contains Sub/ 35 Ag/(110-240)  $\text{SiO}_2$ / 35Ag/ 220 $\text{SiO}_2$ , the last layer is for protection of silver. This metal-dielectric-metal (MDM<sup>[17]</sup>) filter requires very less number of layers as compared to all-dielectric based LVOF. The combination of metal-dielectric gives the wider rejection band, thus having the advantage of no blocking filters. The only disadvantage using such filters is that the maximum transmission is less than 40% and FWHM is more than 5% of the central maxima. Thus the overall spectral resolution of the filter is poor as compared to induced transmission filter as reported below.

The second approach to design LVOF based on metal-dielectric filter is done using an induced transmission filter having metal-dielectric layers. The selection of metal-dielectric is done in such a way so that we can get a wider rejection band while having the maximum transmission in the required spectral band. The design of such filter is proposed in the paper using a combination of  $\text{TiO}_2$ ,  $\text{SiO}_2$  and Ag layers. The filter designed for the VNIR band (450-900nm) has the minimum transmission of 70% in the entire spectral region with a FWHM ~2-3% of the central maxima.

The design for the transmission peak consists of non-quarter oxide layers and a fixed metal layer (Substrate/ $\text{TiO}_2$ / $\text{SiO}_2$ /Ag/ $\text{SiO}_2$ / $\text{TiO}_2$ / $\text{SiO}_2$ / $\text{TiO}_2$ / $\text{SiO}_2$ / $\text{TiO}_2$ / $\text{SiO}_2$ /Ag/ $\text{SiO}_2$ / $\text{TiO}_2$ / $\text{SiO}_2$ / $\text{TiO}_2$ / $\text{SiO}_2$ /Ag/ $\text{SiO}_2$ / $\text{TiO}_2$ / $\text{SiO}_2$ / $\text{TiO}_2$ / $\text{SiO}_2$ /Air), total 19 layers. The filter's performance at the two extreme ends of the spectral band is shown in the Fig8. The design of the above filter is done using TFCal<sup>[18]</sup> software. The transmission curve of LVOF for the complete VNIR region is shown in the Fig9. The design wavelength in the above design varies from 380-770nm, thus the dielectric layers in the above design vary with wavelength while the thickness of metal layer is kept constant throughout the region. The above mentioned induced transmission filter has an advantage over the LVOF based on all-dielectric filter is that there is no requirement of any kind of blocking filters. The fabrication of such filter can be done at a very low cost as compared to all-dielectric in which there is a requirement of huge infrastructure like lithography, etching and physical vapour deposition (PVD) system. The fabrication of such induced transmission filter can be easily achieved with the masking mechanism in the PVD system, thus having a low cost as in respect of the number of layers and infrastructure required.

## **4. Conclusion**

The design and simulation of a LVOF filter covering VNIR (450-900nm) spectral band for the hyperspectral imaging camera has been carried out using all-dielectric, metal-dielectric-metal and metal-dielectric induced transmission filter. The all-dielectric based LVOF require huge infrastructure like lithography, thermal reflow, masking, etching and PVD for the fabrication. The requirement of additional blocking filters along with a large number of coating layers enhances the cost and complexities in the design & fabrication as well. The MDM based LVOF filter design requires

less number of layers, but with lower transmission and wider FWHM (>5%). The simple and reasonable approach for the design and fabrication of LVOF is based on metal-dielectric based induced transmission filter. This method not only improves the transmission with better spectral resolution, but also reduces the effective cost of LVOF with a wider spectral band. The advantage of this device is wide spectral band coverage with no band rejection filters. Thus a masking mechanism in the PVD system will ease out the fabrication of LVOF without any need of blocking filters and covering the complete VNIR spectral band with a spectral resolution of 2-3% of the central maxima.

## Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgement

The authors wish to acknowledge Director, IRDE for their encouragement in carrying out the above work.

## References

- [1] A. Emadi, "Vertically tapered layers for optical applications fabricated using resist reflow", J. Micromech. Microeng. **19** (2009).
- [2] A. Emadi et.al, "Fabrication and characterization of IC-compatible linear variable optical filters with application in a micro-spectrometer", Sensors and Actuators A, 162 (2010) 400–405.
- [3] A. Emadi, H. Wu, S. Grabarnik, G. De Graaf, and R. F. Wolffenbuttel, "IC-compatible fabrication of linear variable optical filters for microspectrometer", Procedia Chem. 1, 1143–1146 (2009).
- [4] Ph. Nussbaum, R Volkkel, H P Herzig, M Eisner and S Haselbeck, "Design, fabrication and testing of microlens arrays for sensors and microsystems", Pure Appl. Opt. **6**, 617–636 (1997).
- [5] K.Ajay Kumar et.al, "Advances in spaceborne hyperspectral imaging systems", current science vol 108, No. 5 10 March 2015.
- [6] J.P.Coates, New Microspectrometers, *Spectroscopy* **15**, (2000), 21-27.
- [7] S.F. Pellicori, US Patent 4957371 - Wedge-filter spectrometer.
- [8] J.H. Correia, G. de Graaf, S.-H. Kong, M. Bartek and R.F. Wolffenbuttel, "Single-chip CMOS optical micro-interferometer", Sensors and Actuators A82(2000) 191-197.
- [9] P.H.Berning and A.F.Turner "Induced transmission in absorbing films applied to band pass filter design" J. Opt. Soc. Am. **47**, 230-239, 1957.
- [10] H.A.Macleod, "Thin film optical filters", Macmillan Publishing Company, New York 1986.
- [11] H.A.Macleod, "A new approach to the design of metal-dielectric thin-film optical coatings", Optica Acta, 1978, VOL. 25, NO. 2, 93-106
- [12] Lissberger, P. H. (1981), "Coatings with induced transmission," Applied optics, 20, 95–104.

- [13] A.Thelen, “*Design of optical interference coatings*”, McGraw-Hill Publishing Company, New York 1989.
- [14] A. Piegari, J. Bulir, and A. Krasilnikova Sytchkova, “*Variable narrowband transmission filters for spectrometry from space. 2. Fabrication process*”, Appl. Opt. 47, C151–C156 (2008).
- [15] Ronald.R.wiley, “*Practical design and production of optical thin films*”, 2<sup>nd</sup> edition Marcel Dekkar Inc., New York 2002.
- [16] FTG software, [info@ftgsoftware.com](mailto:info@ftgsoftware.com), filmstar free version software licence (1991-2015).
- [17] Calum williams,\* girish rughoobur, andrew j. Flewitt, and timothy d. Wilkinson, “Single-step fabrication of thin-film linear variable bandpass filters based on metal–insulator–metal geometry”, Applied Optics Vol 55, No. 32, November 10 2016.
- [18] TFCalc 3.5, Software Spectra Inc. (2008) <http://www.sspectra.com>.

## Figures

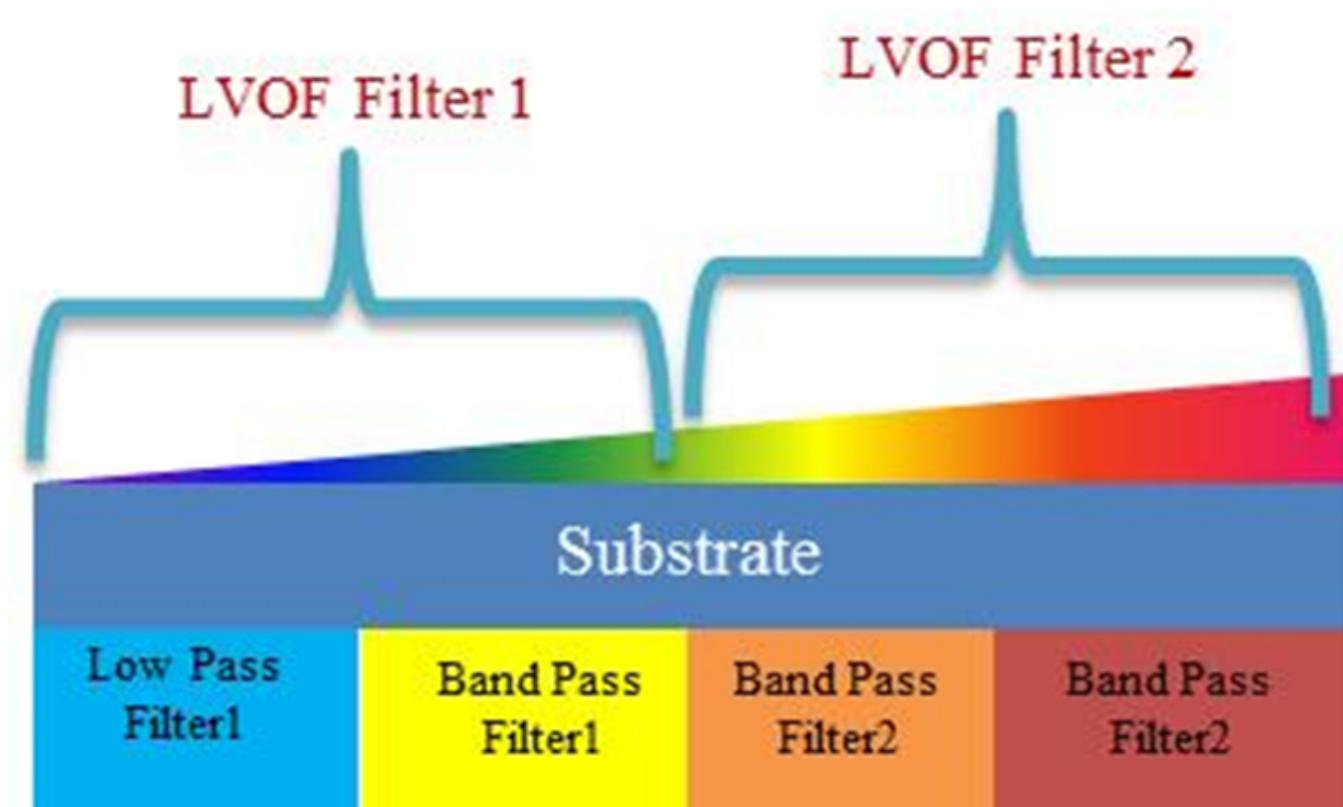


Figure 1

Schematic of LVOF filter based on All-dielectric

Illuminant: WHITE  
Medium: AIR  
Substrate: GLASS  
Exit: AIR  
Detector: IDEAL

Angle: 0.0 (deg)  
Reference: 520.0 (nm)  
Polarization: Ave —  
First Surface: Front

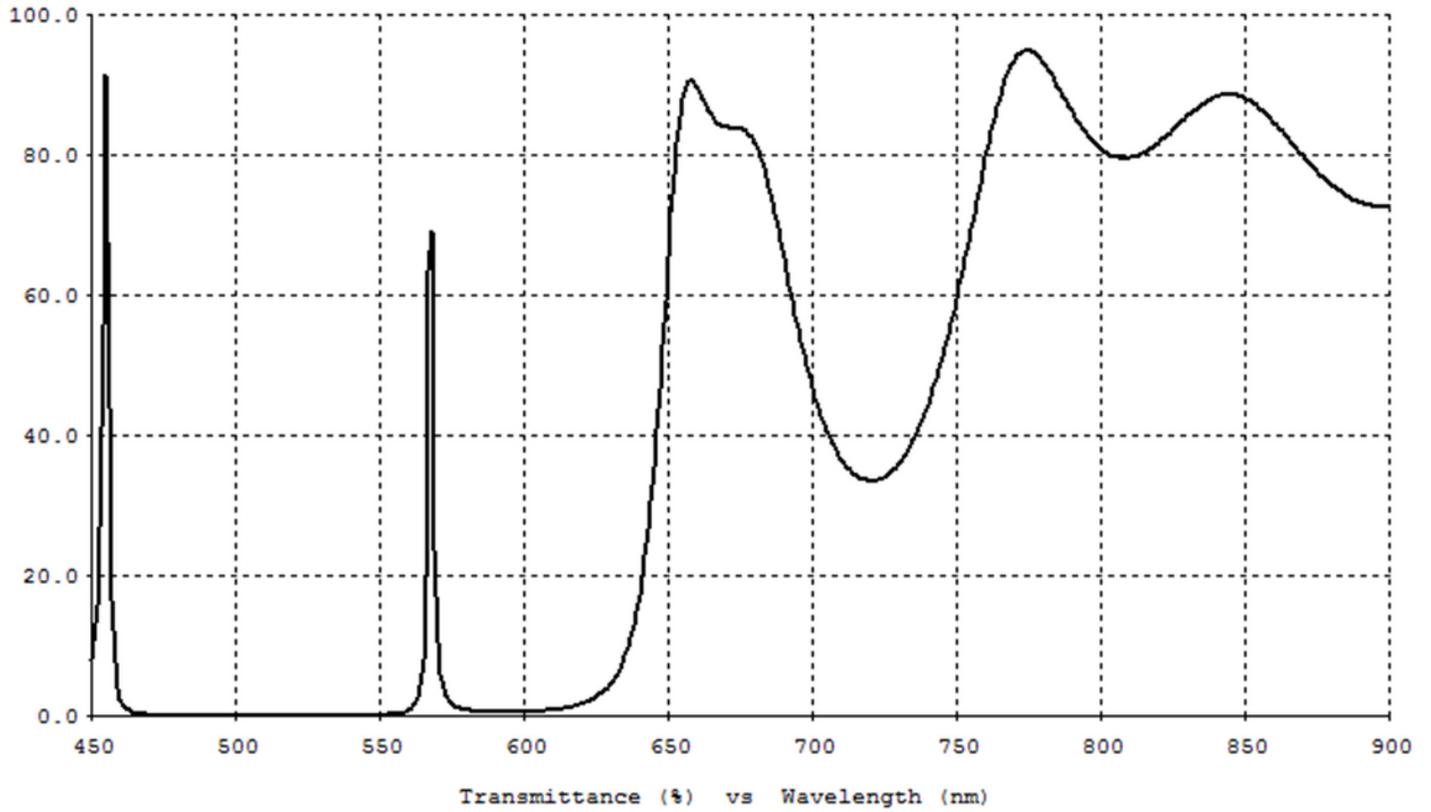


Figure 2

Transmission curve at a cavity thickness of 415nm

Illuminant: WHITE  
Medium: AIR  
Substrate: BK7  
Exit: AIR  
Detector: IDEAL

Angle: 0.0 (deg)  
Reference: 675.0 (nm)  
Polarization: Ave —  
First Surface: Front

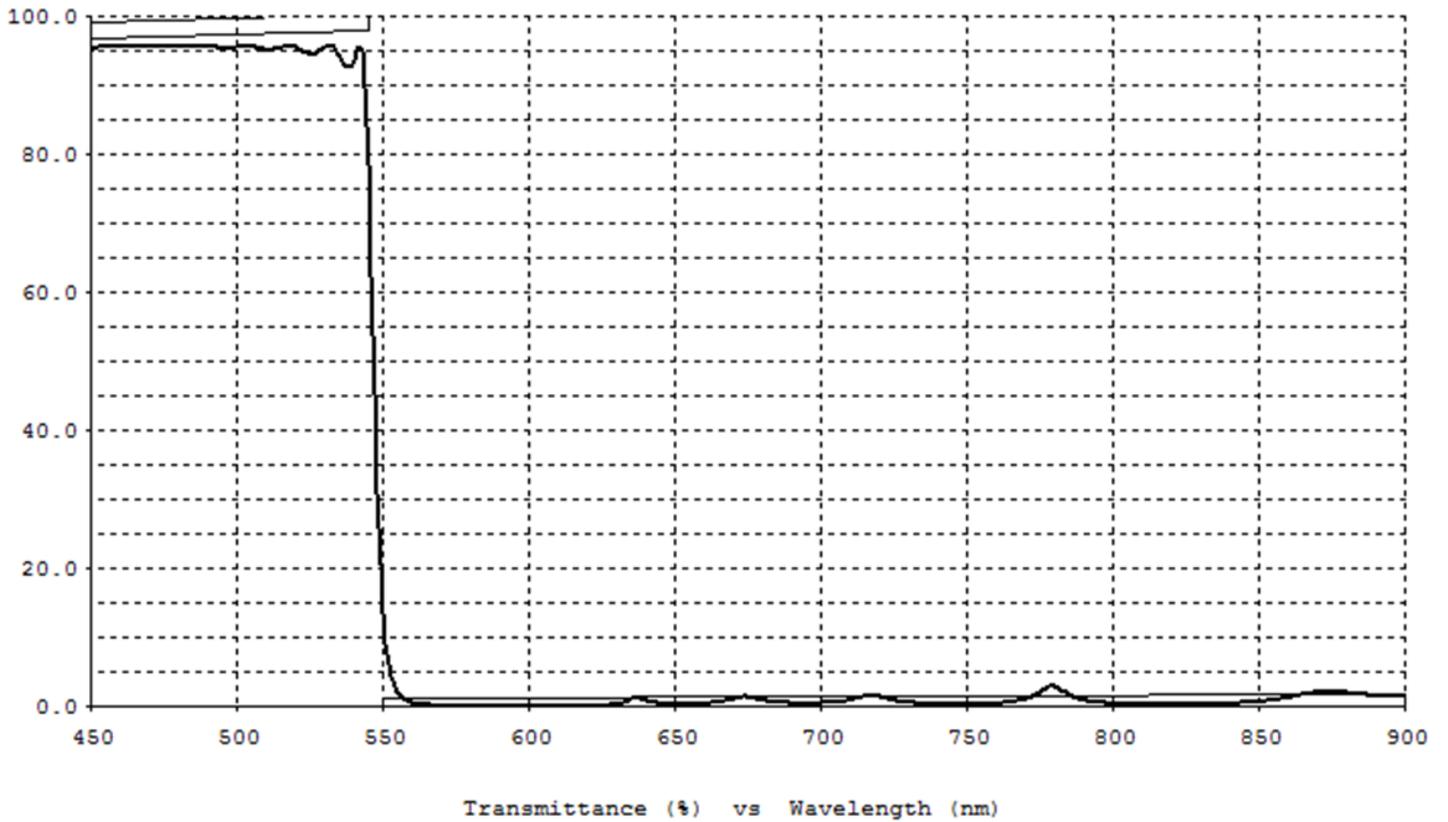


Figure 3

Bandrejection filter: low pass filter 1



# LVOF Filter 1

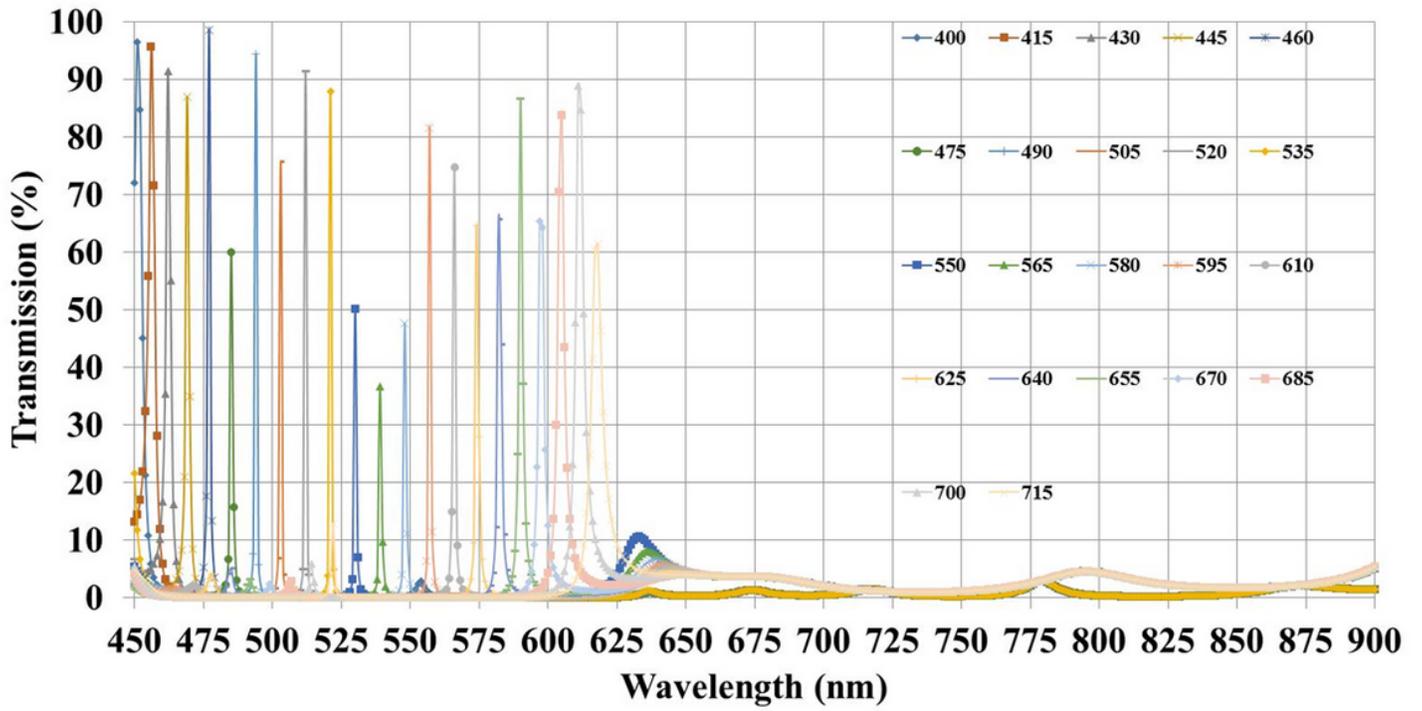


Figure 5

Transmission curve of LVOF Filter1 with cavity thickness varying from 400-715nm

### LVOF Filter 2

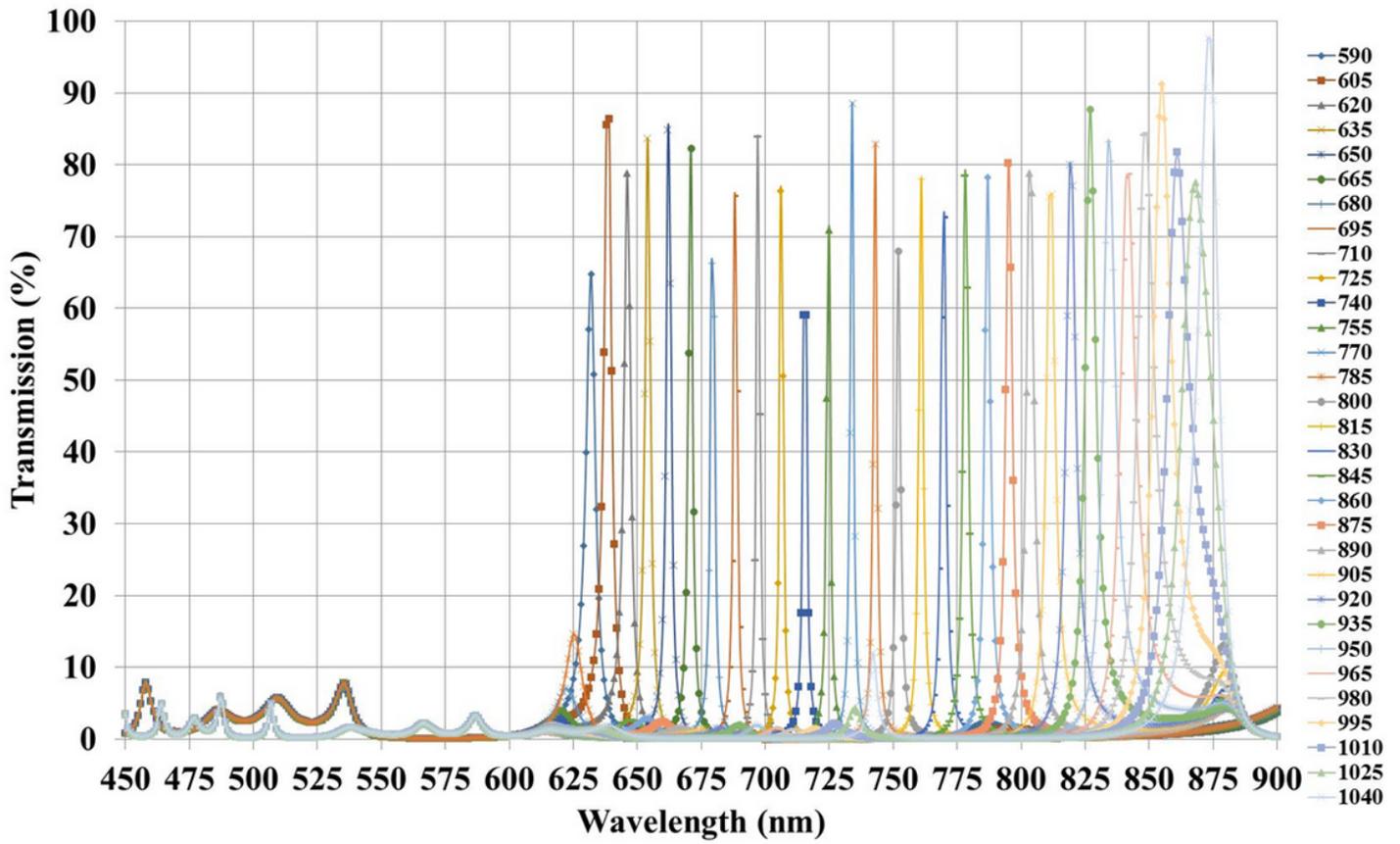


Figure 6

Transmission curve of LVOF Filter2 with cavity thickness varying from 590-1040nm

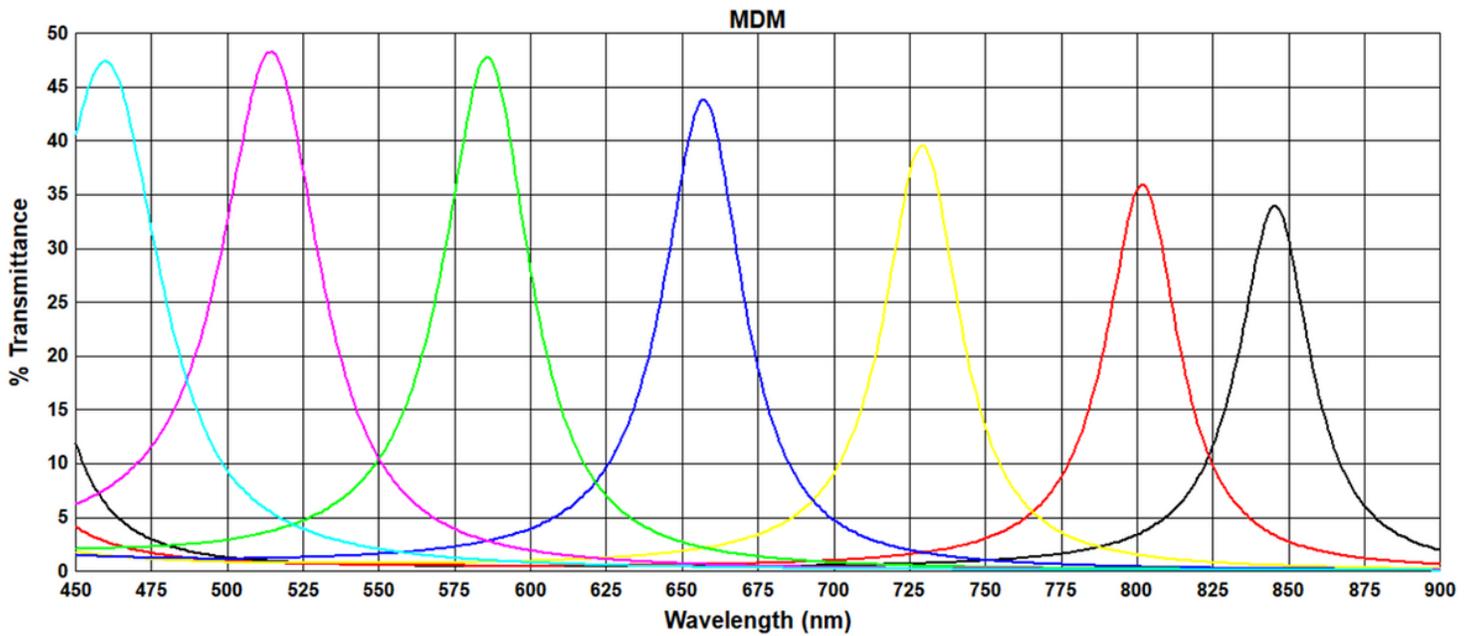


Figure 7

Transmission curve of Metal-Dielectric-Metal (MDM) based LVOF

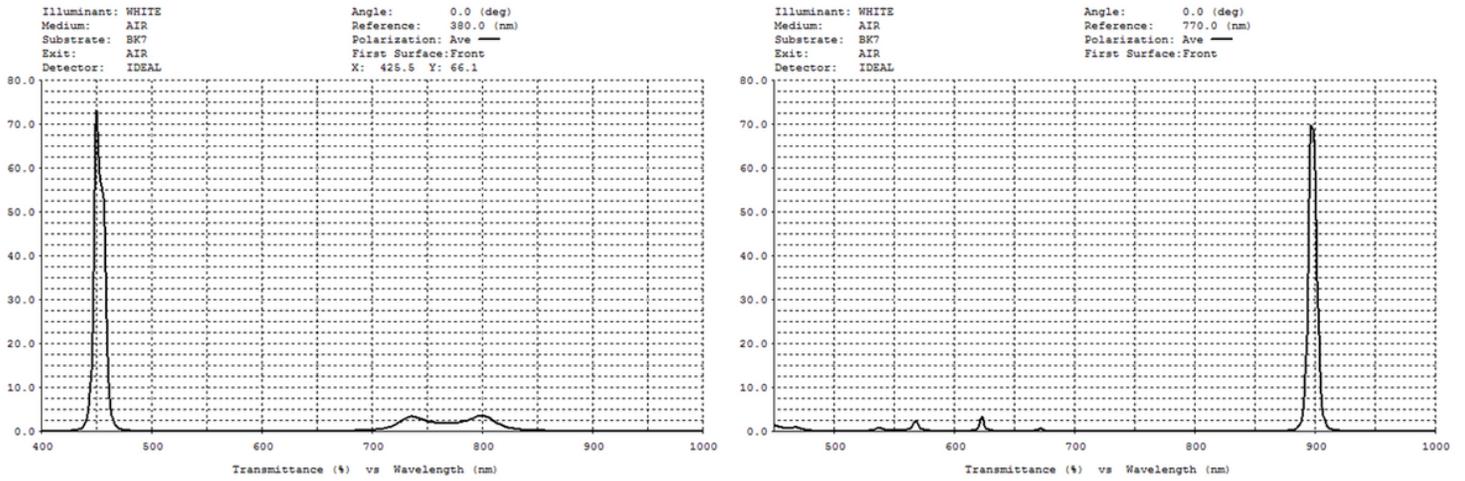


Figure 8

Transmission curve of the LVOF based on Metal-Dielectric at 450nm&900nm wavelength

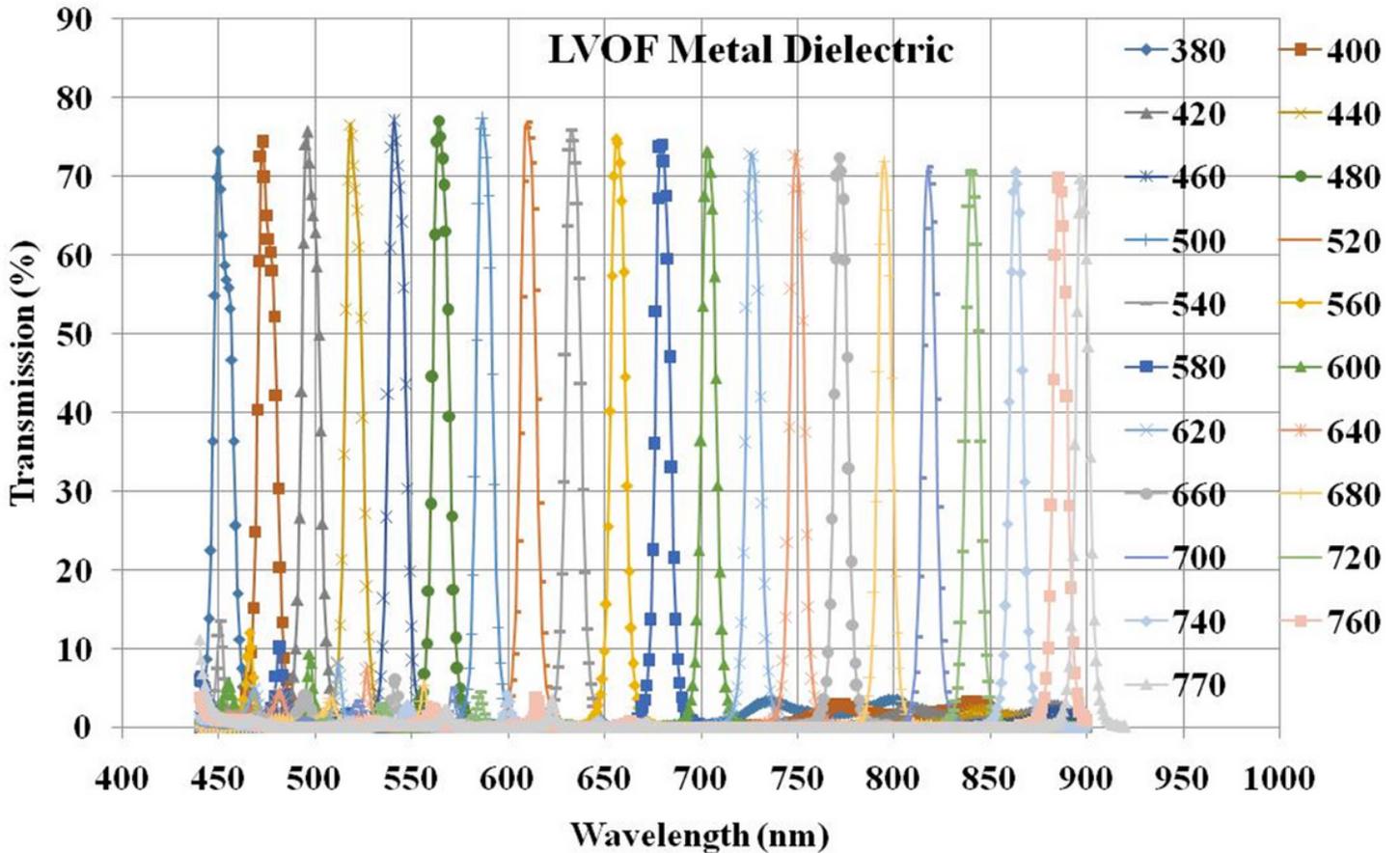


Figure 9

Transmission curve of the LVOF based on the Metal-Dielectric