Multilayer dielectric stack Notch filter for 450-700 nm wavelength spectrum

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Abstract

In this work, a multilayer dielectric optical notch filters design is proposed based on TiO_2 and SiO_2 alternating layers. Titanium dioxide (TiO_2) is selected for its high refractive index value (2.5) and Silicon dioxide (SiO_2) as a low refractive index layer (1.45). These filters are conventionally envisioned for overpowering of powerful laser beams in research experiments, to obtain good signal-to-noise ratios in Raman laser spectroscopy. It is precarious that light from the pump laser should be blocked. This is attained by inserting a notch filter in the detection channel of the setup. In addition to spectroscopy, notch filters are also useful in laser-based florescence instrumentation and biomedical laser systems. The designed filter shows a high quality with an average transmission of more than 90% in 450-535 and 587-700 nm bandwidths. And a stop band region between 536-586 nm shows a transmission of 3% only with an optical density of greater than 3, which makes it a promising element to be used as a notch filter.

Keywords: Notch filter; Optical density; Distributed Bragg Reflector (DBR); visible spectrum

1. Introduction

Thin film optics is well-established technology. Many devices such as band pass filters, band-stop filters, polarizers and reflectors are realized with the help of multilayer dielectric thin films [1-4]. Thin films coatings have also been used to increase both colour and energy efficiency of glass and as reflecting mirrors coatings. However the application of single layer thin films has increased, there are a number of applications which require multilayer films that combine the attractive properties of numerous materials. Some of the important applications of multilayer films are in the design of computer disks, optical reflectors, antireflection coating, optical filters, and solar cells among others. An optical filter is an element or material which is purposefully used to change the spectral intensity distribution or the state of polarization of the electromagnetic radiation incident on it. The change in the spectral intensity distribution may or may not depend on the wavelength. The filter possibly will act in transmission, in reflection, or both. Notch filters are usually known as band-stop or band-rejection filters which are designed to transmit most of the wavelengths with the low-intensity loss while diminishing the light within a specific wavelength range to a very low level. These filters are conventionally proposed for overpowering of powerful laser beams in research experiments to obtain good signal-to-noise ratios in Raman laser spectroscopy. It is precarious that light from the pump laser should be blocked. This is attained by inserting a notch filter in the detection channel of the setup. In addition to spectroscopy, notch filters can also be used in laser-based fluorescence instrumentation and biomedical laser systems. They are also used for eye protection and as a camera accessory. These filters contain alternating layers of high (H) and low (L) refractive index materials with precise thicknesses with good knowledge about their refractive index and absorptions. Several multilayer coatings are deposited onto a transparent substrate. Both the multilayer and substrate contribute to the total performance of the filter. Layers made of oxides are, as a rule, harder than those made of fluorides, sulphides or semiconductors. Therefore, they are ideal to be used on unprotected surfaces. Semiconductor materials should be avoided in filters which have to be used over a wide range of temperatures because their optical constants can change considerably. Distributed Bragg Reflectors (DBRs) work on the principle of multiple reflections between high and low index materials interface. It has a $\lambda/4$ thickness of the central wavelength. The high reflection region of a DBR is known as the DBR stopband and can be attained by the refractive index contrast between the constituent layers. A broad stop band can be realized by using high index contrast thin films. The schematic of the DBR is shown in figure 1.

In this work, the design of a Notch filter based on TiO_2/SiO_2 is proposed at a central wavelength of 561 nm with an FWHM of 50 nm. Titanium dioxide (TiO_2) is selected for its high refractive index value (2.5)[5] and Silicon dioxide (SiO_2) as a low refractive index layer (1.45)[5]. TiO_2 is a vital dielectric material with a wide band-gap energy and high refractive index that can make it useful in the fabrication of multilayer thin films due to its high optical properties. For instance, its high transmittance and high refractive index in the visible region (380-760 nm) make it valuable to be employed in the production of the optical filter and window glazing [6, 7].

In the designing of optical filters, the behaviour of the entire multilayer system is anticipated on the basis of the properties of the individual layers in the stack [8]. Hence to attain the optimum performance, it is important to optically characterize and accurately determine the thickness of the individual layers. We designed this filter with a less possible number of layers with high transmission in pass band region and high reflection is obtained in the stop band. Open-source software, Open Filters, is used in this work to design and optimize the required filter. Transmission and reflection properties of interference filters are dependent on materials refractive index and layer thickness of materials. Open filter calculates optical properties of filters. It uses transfer matrix method to calculate the transmission and reflection properties of filters based on the absorption and materials refractive indices [9]. Optimization techniques are available in this software like needle synthesis (Adding an extra layer to give targeted transmission).

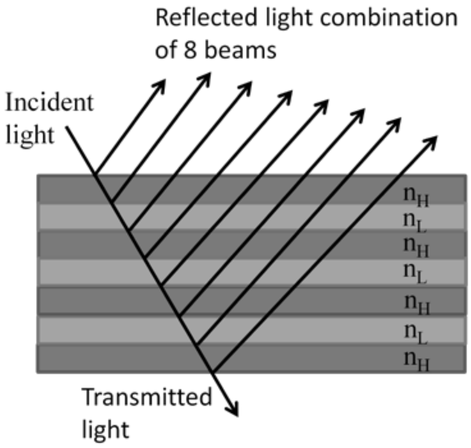

Fig. 1. Schematic of Distributed Bragg Reflector (DBR).

2. Optical density of the notch filter

A filter plate made of an isotropic material with smooth and parallel surfaces, the transmittance depends on the thickness, optical constants of the material, the angle of incidence and polarization state of the incident light, and the degree of coherence between multiple reflected waves [10, 11]. Optical density (OD) is used to see the blocking specification of a filter and is associated with the amount of energy transmitted through it. It uses a logarithmic scale to describe the transmission of light through a highly blocked optical filter, particularly useful when the transmission is extremely small. A high optical density value indicates very low transmission of light and low optical density indicates high transmission. For instance, OD=1 relates to a transmittance value of 0.1, and OD =8 corresponds to a transmittance value of 10^{-8}. It can be expressed as [12]:

$$T(transmission) = 10^{-OD} x\, 100$$

$$OD = -\log\left(\frac{T}{100}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.eq \qquad (1)$$

For the filters having OD ≥ 3 the effects of multiple reflections are insignificant because of the low reflectance and strong absorption of the filter.

3. Filter design and discussion

Multilayer thin films have an extensive wavelength tunability which gives an optical response that is desired for a specific application. Distributed Bragg Reflectors (DBRs)[13,14] consisting of alternating high and low refractive index material pairs are the most commonly used mirrors in FP filters, due to their high reflectivity. However, DBRs have high reflectivity for a selected range of wavelengths known as the stop band of the DBR. Its reflectance usually depends on the constructive or destructive interference of light reflected at consecutive boundaries of different layers of the stack. The performance of the multilayer devices highly depends on the interface formed between the alternating layers. Therefore an appropriate sequencing of the layers of suitable dielectric materials and their thicknesses is critical for achieving the desired spectral response and application. Therefore, it is important to optimize the coating conditions in the designing process [15, 16]. In our previous work, we proposed multilayer dielectric filter based on TiO_2 and SiO_2 materials because of their excellent optical properties [17]. Therefore, TiO_2 and SiO_2 are chosen as high and low refractive index materials, respectively. The choice of materials is made on the basis of low absorption and high index contrast in the wavelengths of interest. The notch filter is designed for visible spectrum ranges from 450-700 nm with FWHM of 50 nm. The optimized thickness of the layers is shown in table 1. The total thickness of the filter is estimated to be 3627 nm with a total of 27 alternating layers of TiO_2 and SiO_2 deposited on a substrate.

Table 1. Layer thickness of Notch filter based on TiO_2/SiO_2.

Layer no.	Layer name	Thickness (nm)	Layer no.	Layer name	Thickness (nm)
1	SiO_2	548	15	SiO_2	147
2	TiO_2	11	16	TiO_2	164
3	SiO_2	28	17	SiO_2	149
4	TiO_2	280	18	TiO_2	127
5	SiO_2	153	19	SiO_2	165
6	TiO_2	124	20	TiO_2	42
7	SiO_2	151	21	SiO_2	25
8	TiO_2	164	22	TiO_2	116
9	SiO_2	148	23	SiO_2	80
10	TiO_2	123	24	TiO_2	16
11	SiO_2	153	25	SiO_2	39
12	TiO_2	52	26	TiO_2	120
13	SiO_2	153	27	SiO_2	227
14	TiO_2	122	-	-	-

The transmission spectrum of the designed notch filter shows a stop band at 536 nm to 586 nm with a central wavelength at 561 nm. The line width which is measured at half of the maximum transmission is around 50 nm. The transmission in pass band regions 450-536nm and 586-700nm is more than 90% as shown in figure 2. The transmission of such filters can be improved by increasing the number of the layers. Whereas this designed filter has only 27 layers which can be implemented economically.

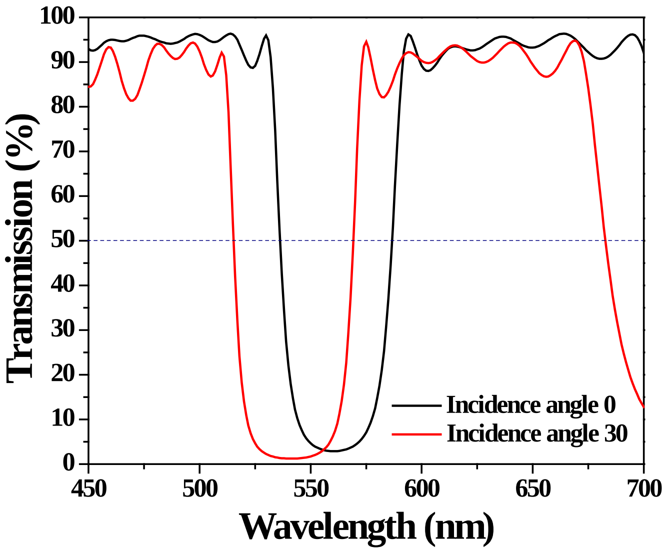

Fig. 2. The transmission spectrum of a notch filter at 0º and 30º of incidence light.

The designed filter has maximum transmission of 3% in the stop band. The OD of the filter is calculated by using an eq. (1) which provides a value greater than 3.5 (Transmission is 0.0003%). It shows a promising result for the notch filter. The optical density of the notch filter is plotted in figure 3.

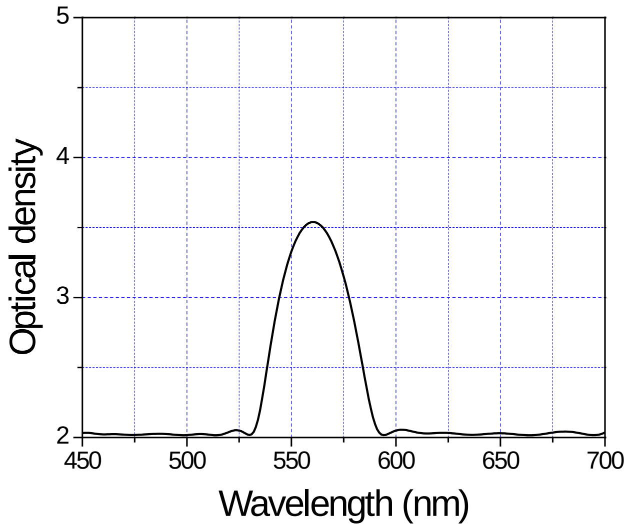

Fig. 3. The optical density of the designed notch filter.

4. Effect of the angle of incidence of light on the central wavelength and FWHM

In all dielectric stack filters, the transmission depends on the angle of incidence. The central wavelength of the blocking region shifts to shorter wavelengths and FWHM increases as the angle of incidence is increased. It can be seen from figure 2, when the angle of incidence of light increases, a noticeable increase in the FWHM of the bandwidth of stop band is seen which shifts towards smaller wavelength. And an increase in the OD is also noticed which is around 3.9 with a slight decrease in the transmission of the band-pass region. Table 2 summarizes the effect of the incidence angle of light on the filters FWHM and central wavelength.

Table 2. Central wavelength and FWHM of the notch filter at different incident angles.

Angle of Incidence (Degrees)	Central wavelength (nm)	FWHM (nm)
0	561	50
30	542	53

5. Conclusion

In this work, a multilayer dielectric optical notch filter design is presented which is based on TiO_2/SiO_2 alternating layers. These filters provide an average transmission of more than 90% in region 450-535nm and 587-700 nm. The transmission of the stop band 536-586 nm is around 3%. The OD of this filter is greater than 3.5 which shows the high blocking specification of a filter and is associated with the amount of energy transmitted through it. With an increase in the incident angle of light, the central wavelength of the notch filter shifts toward smaller wavelength.

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