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Biomedical bandpass filter for fluorescence microscopy imaging based on TiO_2/SiO_2 and TiO_2/MgF_2 dielectric multilayers

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Abstract. We report a design for creating a multilayer dielectric optical filters based on TiO_2 and SiO_2/MgF_2 alternating layers. We have selected Titanium dioxide (TiO_2) for high refractive index (2.5), Silicon dioxide (SiO_2) and Magnesium fluoride (MgF_2) as a low refractive index layer (1.45 & 1.37) respectively. Miniaturized visible spectrometers are useful for quick and mobile characterization of biological samples. Such devices can be fabricated by using Fabry-Perot (FP) filters consisting of two highly reflecting mirrors with a central cavity in between. Distributed Bragg Reflectors (DBRs) 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 stopband of the DBR. This range is usually much smaller than the sensitivity range of the spectrometer range. Therefore a bandpass filters are required to restrict wavelength outside the stopband of the FP DBRs. The proposed filter shows a high quality with average transmission of 97.4 % within the passbands and the transmission outside the passband is around 4 %. Special attention has been given to keep the thickness of the filters within the economic limits. It can be suggested that these filters are exceptional choice for florescence imaging and Endoscope narrow band imaging.

1. Introduction

Thin film optics is well developed technology. Therefore, many devices such as passband filters, stopband filters, polarizers and reflectors are realized with the help of multilayer dielectric thin films [1]. These devices consist of alternating layers of high and low refractive index materials with particular thicknesses with good knowledge of their refractive index and absorption. These devices work on the principle of multiple reflections between high and low index materials interface. Distributed Bragg Reflectors (DBRs) are quarter wave thick of the center wavelength. The high reflection region of a DBR is known as the DBR stopband, and can be obtained by the refractive index contrast between the constituent layers. A broad stopband can be realized by using high index contrast thin films. By inserting a half wave cavity between two highly reflecting mirrors governs an output at the design wavelength [1]. This kind of device is known as Fabry-Perot (FP) filter. DBRs are the most commonly used mirrors in FP filters, due to their high reflectivity. FP has numerous applications in laser line filtering, astronomical observations, fluorescence microscope imaging and spectroscopic instrumentation.

In two photon fluorescence microscopy imaging, a fluorophore absorbs light at its excitation wavelength, and typically emits light at a longer wavelength. The emission spectra of the biological samples has high emission peak at 511 nm which is easy to detect [2, 3, 4]. Therefore, there is a need to develop such filter which can selectively transmit the emitted wavelength and block the excitation wavelength, thus improving the contrast for both sensing and imaging these fluorophores. DBRs consist of alternating layers of high and low refractive index materials. DRBs have high reflectivity for wavelengths around a central wavelength, which is governed by the optical thickness (refractive index x physical thickness) of the constituent layers, and in four times their optical thickness. DBR layers are therefore a quarter-wave thick of the central wavelength.

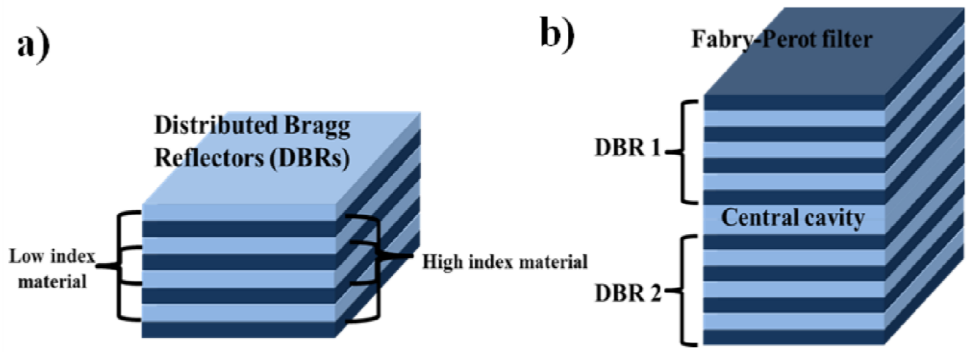

Figure 1. Schematic diagram of (a) Distributed Bragg Reflectors, (b) FabryPerot filter

2. Filter design and discussion

In this work, the designs of Fabry-perot filters based on TiO_2/SiO_2 and TiO_2/MgF_2 are proposed at a central wavelength of 511 nm for biomedical bandpass filter for fluorescence microscopy imaging. We tried to design the filters with less number of layers and high transmission peak at central wavelength with narrow width (FWHM). Open-source software, OpenFilters, is used in this work to design and optimize the required filter.

2.1. Filter 1: Fabry perot filter design based on TiO_2/SiO_2

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 FP filter is designed for visible spectrum ranges from 390-700 nm. In our first design, we proposed a spacer (SiO_2) embedded between two DBRs consisting of 7 layers each. The optimized thickness of the layers is shown in table I. The total thickness of the filter is 1117 nm.

Table I. Layer thickness of TiO_2/SiO_2 based Fabry Perot filter with a passband of 511 nm.

Layer no.	Materials	Thickness (nm)	Layer no.	Materials	Thickness (nm)
1	TiO_2	53	9	TiO_2	53
2	SiO_2	85	10	SiO_2	85
3	TiO_2	53	11	TiO_2	53
4	SiO_2	85	12	SiO_2	85
5	TiO_2	53	13	TiO_2	53
6	SiO_2	90	14	SiO_2	85
7	TiO_2	53	15	TiO_2	53
8	SiO_2	178		-	-

2.2. Filter 2: Fabry perot filter design based on TiO_2/MgF_2

TiO_2 and MgF_2 (1.37) 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 FP filter is designed for visible spectrum ranges from 390-700 nm. In our second design, we proposed a spacer (MgF_2) embedded between two DBRs consisting of 7 layers each. The optimized thickness of the layers is shown in table II. The total thickness of the filter is 1171 nm. The transmission spectra in the visible range of the filter shows a characteristic peak with a maximum of 99.4 % at the reference wavelength of 511 nm. The width (FWHM) of the transmission spectra is observed at 3.5 nm.

Table II. Layer thickness of TiO_2/SiO_2 based Fabry Perot filter with a passband of 511 nm.

Layer no.	Materials	Thickness (nm)	Layer no.	Materials	Thickness (nm)
1	TiO_2	53	9	TiO_2	53
2	MgF_2	90	10	MgF_2	90
3	TiO_2	53	11	TiO_2	53
4	MgF_2	85	12	MgF_2	90
5	TiO_2	53	13	TiO_2	53
6	MgF_2	90	14	MgF_2	60
7	TiO_2	53	15	TiO_2	53
8	MgF_2	189		-	-

The transmission spectra of both designs of FP filters are shown in figure 2. Black and red color represents the transmission response of the design 1 design 2 respectively. It can be observed that design 2 provides much broader stopband region in visible region and high transmission peak at 511 nm as compared to design 1 due to high refractive index contrast. The transmission spectra in the visible range of the filter shows a characteristic peak with a maximum of 94.4 % and 99.4 % with width (FWHM) of 4 and 3.5 nm for design 1 and 2 respectively.

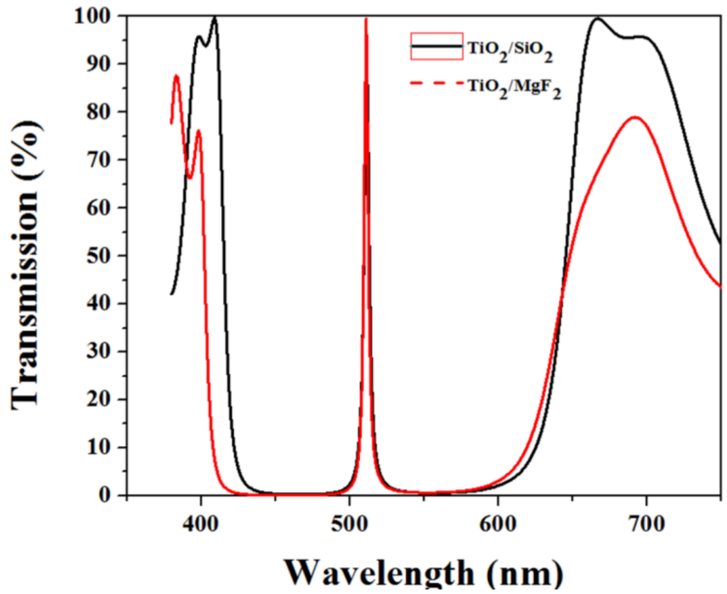

Figure 2. Transmission spectra of TiO_2/SiO_2 and TiO_2/MgF_2 based FP filters.

2.3. Filter 3: DBR filters design based on TiO_2/SiO_2

In order to obtain the desired specific wavelength in full visible region, two DBRs with 9 layers each were designed to stop the undesired band of wavelengths. TiO_2 and SiO_2 are chosen as high and low refractive index materials, respectively. The total thickness of DBR 1 and DBR 2 is 455 and 832 nm respectively. The combined effect of all three filters fulfills the requirement of fluorescence microscopic imaging and can transmit the excitation wavelength while suppressing all the wavelengths outside the stopband of the FP DBRs. The optimized layer thicknesses of both DBRs are shown in table III.

Table III. Layer thickness of bandpass filters based on TiO_2/SiO_2.

DBR1: Stopband below 450 nm			**DBR2: Stopband above 550 nm**		
Layer no.	Materials	Thickness (nm)	Layer no.	Materials	Thickness (nm)
1	TiO_2	25	1	TiO_2	83
2	SiO_2	70	2	SiO_2	86
3	TiO_2	35	3	TiO_2	93
4	SiO_2	70	4	SiO_2	103
5	TiO_2	45	5	TiO_2	93
6	SiO_2	70	6	SiO_2	98
7	TiO_2	30	7	TiO_2	85
8	SiO_2	90	8	SiO_2	103
9	TiO_2	20	9	TiO_2	88

The transmission spectrums of the combined filters (filter 1 + filter 3) and (filter 2+filter 3) are shown in figure 3. Black and red color represents the transmission response of (filter 1+ filter 3) and (filter 2 + filter 3) respectively. It is well noted that that the overall transmission spectra in the visible range of the spectrum shows a characteristic peak at 511 nm with a maximum of 92.4 % and 97.4 % .These combined filters reduced the transmission outside the passband up to 4%.

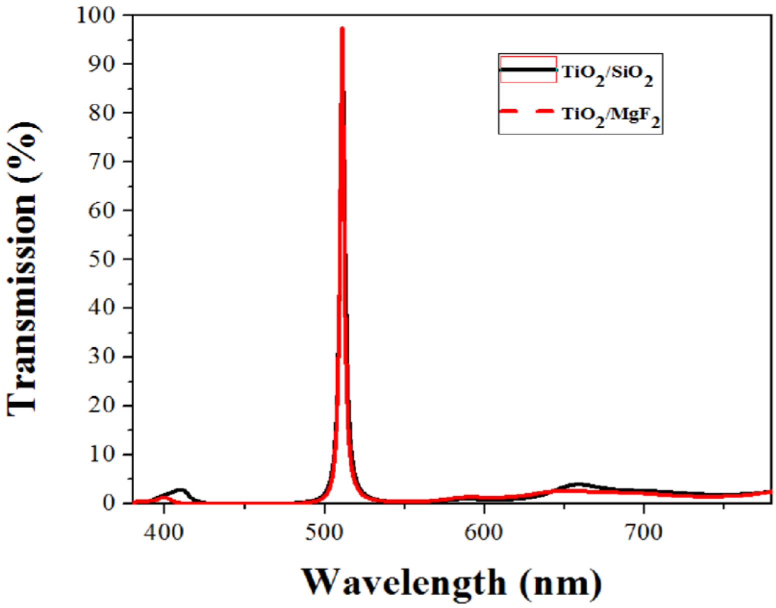

Figure 3. Over all transmission spectra of (filter 1+ filter 3) and (filter 2 + filter 3) indicating a peak at 511 nm in full visible spectrum.

3. Conclusions

In this work, we presented two FP filter designs based on TiO_2/SiO_2 and TiO_2/ MgF_2 combined with two DBR filters based on TiO_2/SiO_2. These filters provide a peak transmission of 92.4 and 97.4 % at 511 nm. By combining two DBRs with FP filter, the transmission outside the passband reduced to 4 %. The combined effect of all three filters fulfils the requirement of fluorescence microscopic imaging and can transmit the excitation wavelength while suppressing all the wavelengths outside the stopband of the FP DBRs.

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