# MODELLING OF MULTILAYER DIELECTRIC FILTERS BASED ON $TIO_2 / SIO_2$ AND $TIO_2 / MGF_2$ FOR FLUORESCENCE MICROSCOPY IMAGING

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### *Abstract*

We report a design for creating 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 and 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. Therefore, bandpass filters are required to restrict the wavelength outside the stopband of the FP DBRs. The proposed filter shows high quality with an average transmission of 97 % within the passbands and the transmission outside the passband is around 3 %. Special attention has been given to keep the thickness of the filters within the economic limits. It can be suggested that these filters are exceptionally promising for florescence imaging and narrow-band imaging endoscopy.

Keywords: Fabry-Perot filter, fluorescence microscopy, dielectric multilayers.

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### *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], [2], [3]. 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, Fig. 1. 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 centre wavelength [4]. 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 desired 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 for specific range of wavelengths. 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 [5] [6] [7].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.

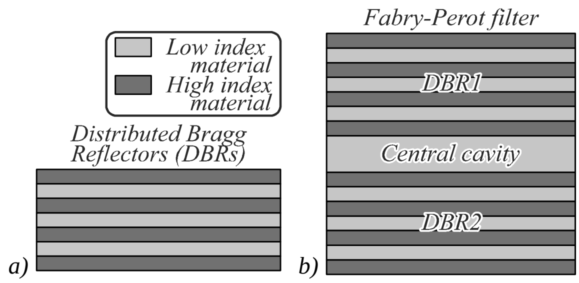


*Fig. 1. Schematic diagram of (a) Distributed Bragg Reflectors, (b) Fabry-Perot filter*

### *Filter design and discussion*

In this work, the designs of FP 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, Fig. 2. We tried to design the filters with minimum number of layers and high transmission peak at central wavelength with high transmission and narrow width (FWHM). Open-source software, Open Filters, is used in this work to design and optimize the required filter, it uses transfer matrix method to analyse transmission and reflection of light from layers based on thicknesses and type of materials [8]. Design are optimized to reduce FWHM and maximum transmission for 511 by nm using needle synthesis method (It adds extra layers (called needle) to the design and each time it add a needle, transmission spectrum of filter is calculated. The optimal position of needle to be added between the layers of a filter is based on derivative of Merit Function with respect to thickness of thin layer. The position where derivative is negative needle is added. Mostly single needle is added and transmission spectrum is calculated. Addition of needle stops at the point where there is no improvement in the target transmission spectrum) [8].

### *A. Material Selection*

Based on refractive indices and absorption coefficient of the materials, $TiO_2$ is selected for its high refractive index at 511 nm, while $SiO_2$ and $MgF_2$ are selected material for its low refractive indices at 511 nm. All three materials have low absorption for 511 nm, Fig. 2.

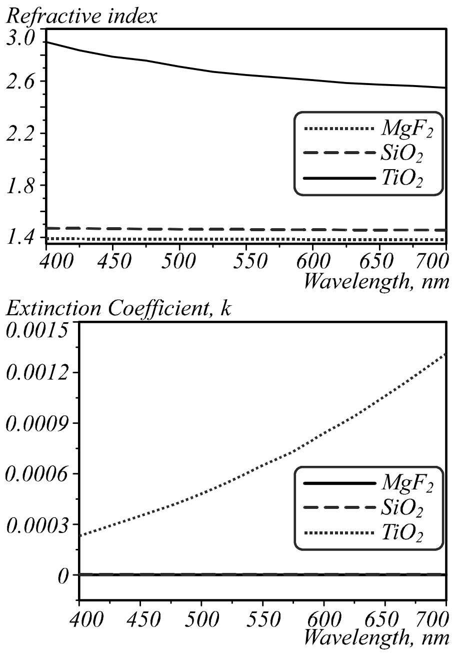


*Fig. 2. Refractive index(a) and extinction coefficient(b) of $SiO_2$, $MgF_2$ and $TiO_2$*

### *B. Filter 1: FP filter design based on $TiO_2/MgF_2$*

$TiO_2$ and $MgF_2$ are chosen as high and low refractive index materials, respectively. As mentioned in section A, the choice of materials is made on the basis of low absorption and high index contrast in the wavelengths of interest. The design was optimized to 97 % transmission at 511 nm and narrow FWHM of 2 nm. The design comprised of 19 layers with thickness of 1457 nm, Fig. 3.

The optimized thickness of each layer is shown in Table 1. The filter design comprises of two DBRs having 9 layers each and a spacer (layer no. 10) is sandwiched between them. The layers thickness is automatically optimized by using needle synthesis method.

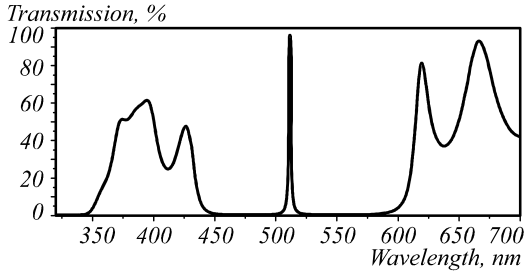


*Fig. 3. FP filter with two DBRs of $TiO_2/MgF_2$ with 19 layers, 97 % transmission at 511 nm and 2 nm FWHM*

*Table 1. Layer thickness of $TiO_2/MgF_2$ based FP filter with a passband of 511 nm*

| Layer no. | Materials | Thickness (nm) |
|---|---|---|
| 1 | $TiO_2$ | 99 |
| 2 | $MgF_2$ | 85 |
| 3 | $TiO_2$ | 53 |
| 4 | $MgF_2$ | 92 |
| 5 | $TiO_2$ | 53 |
| 6 | $MgF_2$ | 94 |
| 7 | $TiO_2$ | 53 |
| 8 | $MgF_2$ | 96 |
| 9 | $TiO_2$ | 53 |
| 10 | $MgF_2$ | 98 |
| 11 | $TiO_2$ | 118 |
| 12 | $MgF_2$ | 61 |
| 13 | $TiO_2$ | 43 |
| 14 | $MgF_2$ | 110 |
| 15 | $TiO_2$ | 53 |
| 16 | $MgF_2$ | 98 |
| 17 | $TiO_2$ | 52 |
| 18 | $MgF_2$ | 94 |
| 19 | $TiO_2$ | 53 |

### *C. Filter 2:FP 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, Fig. 2. The design was optimized to 96 % transmission at 511 nm and narrow FWHM of 2 nm, total layers increased to 21 and thickness of 1351 nm, Fig. 4.

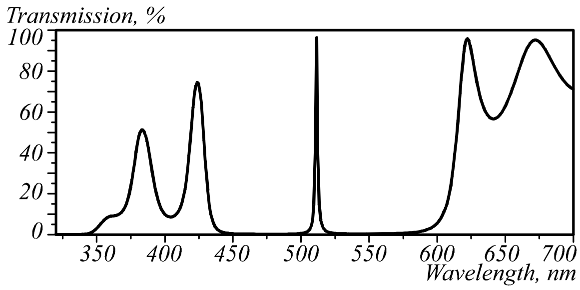


*Fig. 4. FP filter with two DBRs of $TiO_2/SiO_2$ with 21 layers, 96 % transmission at 511 nm and 2 nm FWHM*

The optimized thickness of each layer is shown in Table 2. In this filter design, FP comprises of two DBRs having 11 and 9 layers each and a spacer (layer no. 12) is sandwiched between them. We obtained same results with two DBRs of 11 layers each but in order to reduce the number of layers. We have selected asymmetric DBRs; this can help in reducing the cost of fabrication. The layers thickness is automatically optimized by using needle synthesis method.

*Table 2. Layer thickness of $TiO_2$/$SiO_2$ based FP filter with a passband of 511 nm.*

| Layer no. | Materials | Thickness (nm) |
|---|---|---|
| 1 | $TiO_2$ | 54 |
| 2 | $SiO_2$ | 86 |
| 3 | $TiO_2$ | 54 |
| 4 | $SiO_2$ | 86 |
| 5 | $TiO_2$ | 54 |
| 6 | $SiO_2$ | 86 |
| 7 | $TiO_2$ | 54 |
| 8 | $SiO_2$ | 88 |
| 9 | $TiO_2$ | 57 |
| 10 | $SiO_2$ | 44 |
| 11 | $TiO_2$ | 42 |
| 12 | $SiO_2$ | 46 |
| 13 | $TiO_2$ | 39 |
| 14 | $SiO_2$ | 84 |
| 15 | $TiO_2$ | 55 |
| 16 | $SiO_2$ | 86 |
| 17 | $TiO_2$ | 54 |
| 18 | $SiO_2$ | 86 |
| 19 | $TiO_2$ | 54 |
| 20 | $SiO_2$ | 86 |
| 21 | $TiO_2$ | 54 |

### *D. Filter 3: Bandpass filter design based on $TiO_2$/$SiO_2$*

In order to obtain the desired specific wavelength in full visible region, a bandpass filter was designed based on DBRs. The design approach was based on $(2HL)^n$ layer configuration with central wavelength at 511 nm [9], [10], [11]. $TiO_2$ and $SiO_2$ are chosen as high and low refractive index materials, respectively. The design was optimized using needle synthesis methods; total thickness of bandpass after optimization is 2361 nm with 29 layers. Banspass filter has an average transmission of 95 %, minimum and maximum transmission of 94 % and 96 % within passband, respectively.

The combined effect of filter 1 (FP filter $TiO_2$ / $MgF_2$) with filter 3 (Bandpass filter $TiO_2$ / $SiO_2$) and combined effect of filter 2 (FP Filter $TiO_2$ / $SiO_2$) with filter 3 fulfill 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 bandpass filter is shown in table 3.

The transmission spectrum of the resulting filters (filter 1 + filter 3) is shown in fig. 5. It is well noted that the overall transmission spectra in the visible range of the spectrum shows a characteristic peak at 511 nm with a maximum of 96 % and a small peak at 433 nm. FP filter and pass band filter can be fabricated on same substrate in the form of single optical element with high characteristic peak at 511 nm.

*Table 3. Layer thickness of bandpass filter based on $TiO_2$ / $SiO_2$*

| Layer no. | Materials | Thickness (nm) |
|---|---|---|
| 1 | $TiO_2$ | 126 |
| 2 | $SiO_2$ | 54 |
| 3 | $TiO_2$ | 46 |
| 4 | $SiO_2$ | 59 |
| 5 | $TiO_2$ | 45 |
| 6 | $SiO_2$ | 55 |
| 7 | $TiO_2$ | 36 |
| 8 | $SiO_2$ | 71 |
| 9 | $TiO_2$ | 44 |
| 10 | $SiO_2$ | 78 |
| 11 | $TiO_2$ | 129 |
| 12 | $SiO_2$ | 47 |
| 13 | $TiO_2$ | 85 |
| 14 | $SiO_2$ | 37 |
| 15 | $TiO_2$ | 141 |
| 16 | $SiO_2$ | 18 |
| 17 | $TiO_2$ | 180 |
| 18 | $SiO_2$ | 103 |
| 19 | $TiO_2$ | 85 |
| 20 | $SiO_2$ | 111 |
| 21 | $TiO_2$ | 74 |
| 22 | $SiO_2$ | 95 |
| 23 | $TiO_2$ | 77 |
| 24 | $SiO_2$ | 112 |
| 25 | $TiO_2$ | 76 |
| 26 | $SiO_2$ | 107 |
| 27 | $TiO_2$ | 74 |
| 28 | $SiO_2$ | 100 |
| 29 | $TiO_2$ | 97 |

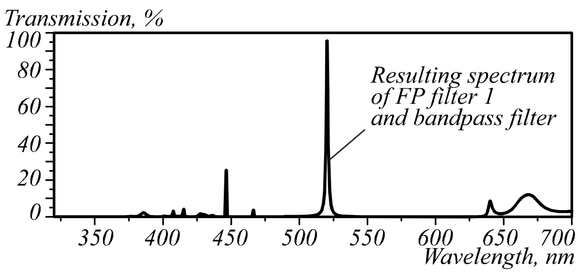


*Fig. 5. Resulting spectrum of filter 1 and filter 3 with 3 % transmission outside passband*

The transmission spectrum of the combined filters (filter 2 + filter 3) is shown in fig. 6. It can be seen that the overall transmission spectra in the visible range of the spectrum shows a characteristic peak at 511 nm with a maximum of 96 %. FP filter and pass band filter can be fabricated on same substrate in the form of single optical element with high characteristic peak at 511 nm.

## *Conclusions*

In this work, we presented two FP filter designs based on $TiO_2$ / $SiO_2$ and $TiO_2$ / $MgF_2$ combined with two band-pass filters based on $TiO_2$ / $SiO_2$. These filters provide a peak transmission of 96 % and 97 % at 511 nm. By combining two DBRs with FP filter, the transmission outside the passband reduced to 3 %. The combined effect of 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.

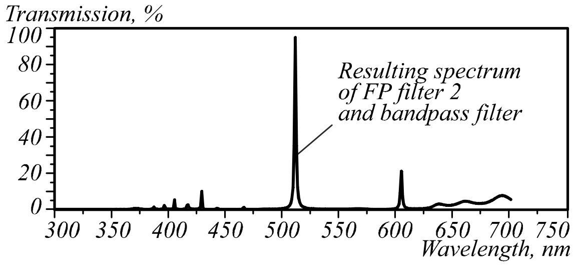


*Fig. 6. Resulting spectrum of filter 2 and filter 3 with 3 % transmission outside passband*

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