

Design Optimize Interference Dielectric Edge Filter

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Abstract— An Edge filter is a multilayer coating with a substantial pass-band on either designated side of the stop-band. The Edge filter is meant to have a crisp boundary between wavelength regions that are reflected and those that are transmitted. In this paper, design, optimize, and measurements of an Edge filter is presented. TiO_2/SiO_2 materials system provides a promising solution for realizing low cost lasers, detectors, and optical modulators operating in the telecommunications, by fabricating these devices on Fusedsilica substrates. An extensive comparison of the response obtained from initial design and the final optimization design is presented. In this study results we demonstrate a dielectric multilayer filter. TiO_2 (refractive index $n=2.346$) and SiO_2 (refractive index $n=1.485$) edge filter design with a controlled transmission, reflectivity, absorption, optical admittance, electric field, and dispersion in the wavelength range 300-1000nm.

Keywords— Edge Filter, Long-Pass, Short-Pass, Quarter Wave Stack, Group Delay, Group Delay Dispersion.

I. INTRODUCTION

Filters in which the primary characteristic is an abrupt change between a region of rejection and a region of transmission are known as edge filters. Edge filters are divided into two main groups, long wave pass (LWP) and short wave pass (SWP). The operation may depend on many different mechanisms and the construction may take a number of different forms [1]. Edge filters provide a well-defined transition between reflecting and transmitting regions. Essentially a modified quarter wave stack, the filters use interference effects rather than absorption to isolate their spectral bands. Because Edge filters will shift shorter with an increase in the angle of incidence, they are a good choice for fine-tuning the cut-on/cut-off wavelength, useful for redirecting a particular band of light, provide steeper transition than colour glass filters, and offer coverage over the 400–1000nm range [2]. In long-pass (LP) filter (Fig. 1), the goal is to minimize transmission below a given wavelength and maximize transmission above it.

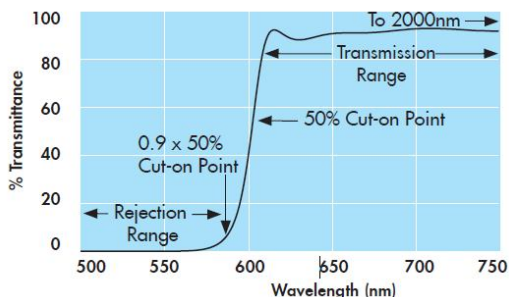


Fig. 1 Long wave pass Edge filter [2]

These designs are usually based on a quarter wave stack, which has a well-defined transition from reflecting to transmitting. Sometimes absorbing materials are used to increase the optical density of the non-reflecting (rejection) band of the filter. Short-pass Edge filters; used as laser clean-up solutions on the laser source side of the system, attenuate wavelengths to ~ 1.3 wavelength edge. They serve as excellent clean-up filters when there are no laser lines or plasma at shorter wavelengths than the primary line being used. Compared to laser line filters, they provide higher transmission and fully block the laser “tail” on the long wavelength side of the laser line.

In short-pass (SP) filter (Fig. 2), the goal is to minimize transmission above a given wavelength and maximize transmission below it.

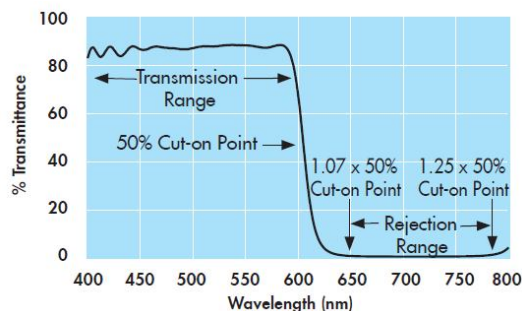


Fig. 2 Short wave pass Edge filter [2]

Long-pass Edge filters are designed to transmit wavelengths greater than the cut-on wavelength of the filter. Long-pass Edge filters are used to isolate portions of the spectrum in a variety of industrial or life sciences applications including microscopy or fluorescence instrumentation. Long-pass Edge filters can be used with short-pass Edge filters to create custom band-pass filters. Certain long-pass Edge filters can also be used as cold mirrors to minimize the heat buildup often caused by infrared radiation.

II. QUARTER WAVE STACK INTERFERENCE EDGE FILTERS

The basic type of interference Edge filter is the quarter wave stack. Quarter wave stack is used as a basic building block for many types of thin film filters. It can be used as a LWP filter, a SWP filter, a band-stop filter, a straightforward high reflectance coating, for example in laser mirrors, and as a reflector in a thin-film Fabry–Perot interferometer, which is another basic filter type. This brief description has neglected the effect of multiple reflections in most of the layers and, for an accurate evaluation of the performance of a filter; these extra reflections must be taken into account. This involves extremely complex calculations and an alternative, and more

effective, approach has been found in the development of entirely new forms of solution of Maxwell's equations in stratified media [1].

A classical optical stretcher consists of a stack of layers of thicknesses d_i and indices of refraction N_i between an incidence and an exit media of indices of refraction N_{inc} and N_{ex} , respectively. To calculate the optical properties, the i th layers are represented by [3]:

$$M_i = \begin{bmatrix} \cos \phi_i & i/\eta_i \sin \phi_i \\ i\eta_i \sin \phi_i & \cos \phi_i \end{bmatrix} \quad (1)$$

Where:

$$\eta_i = \begin{cases} N_i \cos \theta_i & s - polarization \\ N_i^2 / N_i \cos \theta_i & p - polarization \end{cases} \quad (2)$$

is the pseudoindex of the layer, $\phi_i = (2\pi/\lambda)N_i d_i \cos \theta_i$ is the phase shift of the wave inside the layer, θ_i is the angle of propagation in the layer, and λ is the wavelength of light in vacuum.

According to the Snell law $N_i \sin \theta_i$ is constant. The pseudoindices and phase shift can be calculated using [4]:

$$\eta_i = \begin{cases} \sqrt{N_i^2 - \alpha^2} & s - polarization \\ N_i^2 / \sqrt{N_i^2 - \alpha^2} & p - polarization \end{cases} \quad (3)$$

$$\phi_i = \frac{2\pi}{\lambda} \sqrt{N_i^2 - \alpha^2} d_i \quad (4)$$

The characteristic matrix describing the multilayer is:

$$M = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = \prod_{i=q}^1 M_i \quad (5)$$

where q is the number of layers, and the product is taken in reverse order since the matrices of upper layers must be multiplied on the left. The amplitude reflection and transmission coefficients of the multilayer are [5]:

$$r = \frac{\eta_{inc} m_{11} - \eta_{ex} m_{22} + \eta_{inc} \eta_{ex} m_{12} - m_{21}}{\eta_{inc} m_{11} + \eta_{ex} m_{22} + \eta_{inc} \eta_{ex} m_{12} + m_{21}} \quad (6)$$

$$t = \frac{2\eta_{inc}}{\eta_{inc} m_{11} + \eta_{ex} m_{22} + \eta_{inc} \eta_{ex} m_{12} + m_{21}} \quad (7)$$

Where η_{inc} and η_{ex} are the pseudoindices of the incidence and exit media, respectively. The reflectance and transmittance are:

$$R = rr^* = |r|^2 \quad (8)$$

$$T = \frac{Re N_{ex} t t^*}{Re N_{inc}} = \frac{Re N_{ex}}{Re N_{inc}} |t|^2$$

Where, Re is the real part and $*$ denotes the complex conjugate. The absorptance is simply: $A = 1 - R - T$.

When dealing with a rapidly changing signal, such as a pulse train, one also needs to know the dispersive properties of the multilayers. The global phase shifts on reflection and transmission modulo 2π , and ϕ_r are the angles made by r and t in the complex plane so that [5]:

$$\phi_r = \arg r = \arctan \frac{Im r}{Re r} \quad (9)$$

$$\phi_t = \arg t = \arctan \frac{Im t}{Re t} \quad (10)$$

Where, Im is the imaginary part and the signs of the numerator and the denominator must be evaluated separately [5].

The phase shifts do not provide much information about the behaviour of the design. One is usually more interested in the delay introduced when a pulse is reflected or transmitted, the group delay (GD), or in the deformation of a finite bandwidth pulse caused by the variation of GD with the wavelength, the group delay dispersion (GDD). The group delay is defined as the negative of the derivative of the phase response with respect to frequency [6], [7], GD, also known as "Envelope Delay" [8]. Group delay dispersion is a ubiquitous, and often irritating, phenomenon in ultrafast laser labs. When ultrashort pulses propagate through dispersive media, their frequency components emerge at different times due to GDD, causing the resulting pulse to be chirped and stretched and reducing the pulse's peak power. This effect can be compensated by using a pulse compressor, which can introduce negative GDD [9]. The standard method for computing the GDD is to compute complex reflection coefficients using the transfer matrix technique and then take successive finite difference over frequency [10]. GD and GDD are obtained from the phase using:

$$GD = -\frac{d\phi}{d\omega} \quad (11)$$

$$GDD = -\frac{d^2\phi}{d^2\omega} \quad (12)$$

Where, $\omega = 2\pi c/\lambda$ is the angular frequency and c is the speed of light in vacuum. There are analytical formulas to calculate the GD and GDD, but it is impossible to calculate them analytically from the characteristic matrix of a multilayer. The solution appears as a very elegant product of 2×2 matrices, each matrix representing a single film. Unfortunately, in spite of the apparent simplicity of the matrices, calculation by hand of the properties of a given multilayer, particularly if there are absorbing layers present and a wide spectral region is involved, is an extremely tedious and time-consuming task. The preferred method of calculation is to use a computer. This makes calculation so rapid and straightforward that it makes little sense to use anything else. The matrix method itself brings many advantages. In the design of a thin-film multilayer, we are required to find an arrangement of layers which will give a performance specified in advance, and this is much more difficult than straightforward calculation of the properties of a given multilayer.

There are two basic multilayer designs that are currently used for Edge filters. One design has the pass-band on the high wavelength side of the stop-band, the other on the low wavelength side. The designs are the following:

$$\text{Medium} / \left(\frac{L}{2} H \frac{L}{2} \right)^m / \text{Substrate} \quad \text{"Low } \lambda \text{ pass"}$$

$$\text{Medium} / \left(\frac{H}{2} L \frac{H}{2} \right)^m / \text{Substrate} \quad \text{"High } \lambda \text{ pass"}$$

The designs are illustrated below [11]:

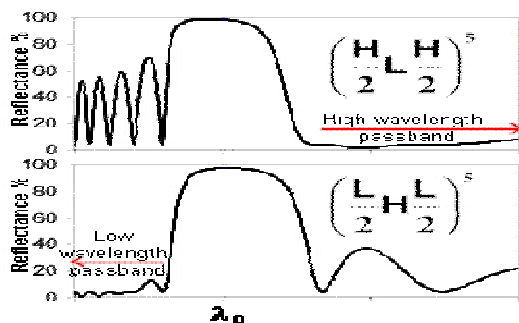


Fig. 3 Edge filter designs [11]

III. RESULTS AND DISCUSSION

It is often difficult, or even impossible, to manually design a filter respecting all the specifications for a given application. However, it is possible to optimize a filter using refinement [12]. In this method, the designer provides a starting design whose properties are sufficiently close to the specifications. Then, an optimization algorithm is used to adjust the thickness of the layers and eventually their index of refraction. In addition to the starting design, the designer must provide targets describing the specifications. The targets can be any property computable from the parameters of the filter; usually, these are the reflection, the transmission, phase properties, or the polarization and angle of incidence. Depending on the application, it may be necessary to define a target at a single wavelength or over a range of wavelengths. In the latter case, the target must in fact be discretized and defined at a finite number of wavelengths.

In this study, we designed Edge filter using Titanium Dioxide (TiO₂) and Silicon Dioxide (SiO₂). The structure composed (21) layers of TiO₂ (refractive index $n=2.346$) and SiO₂ (refractive index $n=1.485$), wavelength rang 300-1000nm, and design wavelength=550nm has been used in calculations. Fig. 4 and Fig. 5 represent the relationship between the quarter wave stack layers depth and the refractive index for the initial and final filter design.

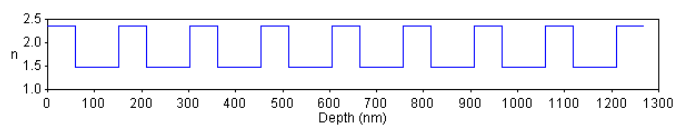


Fig. 4 Depth versus refractive index for the initial Edge filter design

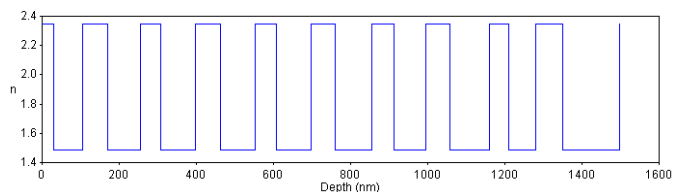


Fig. 5 Depth versus refractive index for the final Edge filter design

Fig. 6 and Fig. 7 show the phase behave before and after the optimization processe. In order to consider the properties of

the filter, it is common to consider the phase shift as a function of ω . The phase change ($\phi_r(\omega)$) of the reflected wave can be developed by using the propagation matrices that are obtained from Maxwell's equations.

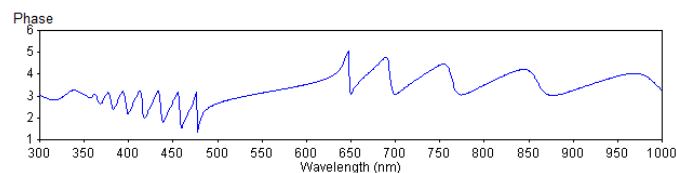


Fig. 6 Phase versus wavelength for the initial Edge filter design

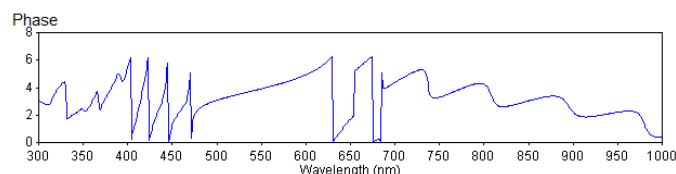
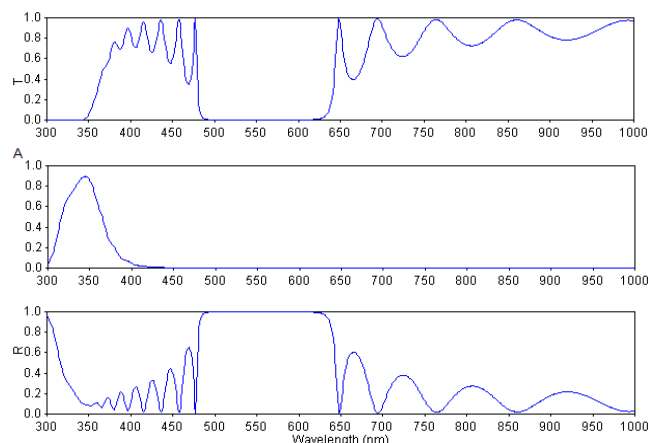
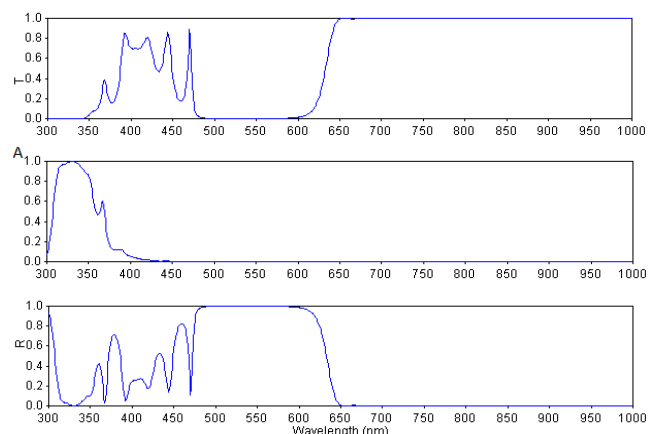


Fig. 7 Phase versus wavelength for the final Edge filter design

Figs. 8 and Figs. 9 represents the relationship between wavelength with transmission (T), absorption (A), and reflection (R) respectively for the initial design and the final optimized design. After the optimization processes, we can



notice the high wavelength pass-band.



Figs. 8 Transmission, absorption, and reflection respectively versus wavelength for the initial Edge filter design

Figs. 9 Transmission, absorption, and reflection respectively versus wavelength for the final Edge filter design

Almost as important as the transmitting optical components are to reflect a major portion of the incident light. In the vast majority of cases the sole requirement is that the specular reflectance should be as high as conveniently possible, although, there are specialized applications where not only should the reflectance be high, but also the transmitting and absorption should be extremely low.

Fig. 10 and Fig. 11 show the group delay versus the wavelength. It is clearly seen; the very small oscillations in the group delay are visible over design wavelength 550nm after the optimization process in the final Edge filter design.

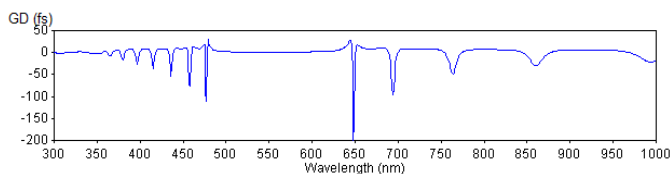


Fig. 10 Group delay versus wavelength for the initial Edge filter design



Fig. 11 Group delay versus wavelength for the final Edge filter design

Fig. 12 and Fig. 13, show the group delay dispersion versus the wavelength. Of course, the same behaviour can be found for the GDD.

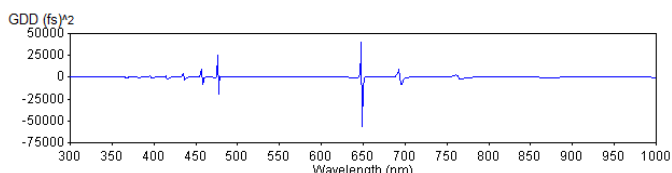


Fig. 12 Group delay dispersion versus wavelength for the initial Edge filter design

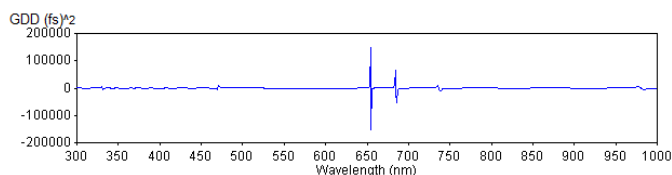


Fig. 13 Group delay dispersion versus wavelength for the final Edge filter design

When thin-film optical coatings are illuminated by light, standing wave patterns form which can exhibit considerable variations in electric field amplitude both in terms of

wavelength and position within the coating. The electric field distribution, Fig. 14 and Fig. 15, profile of electric field intensity for radiation incident on a multilayered system for the Edge filter design, also are plotted in this study.

It can be observed that strong electric field intensity occurred at the first layer and the electric field intensity starts to diminish after it has passed the layer region.

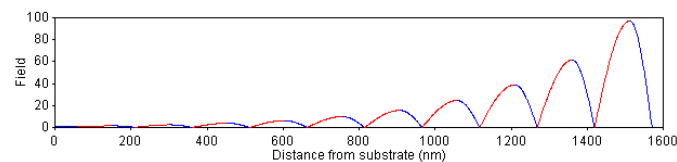


Fig. 14 Electric field versus distance from the substrate for the initial Edge filter design

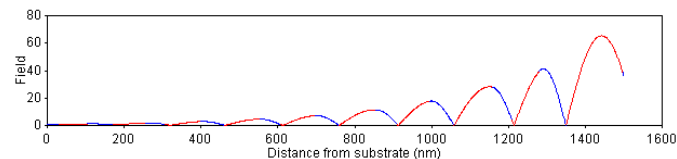


Fig. 15 Electric field versus distance from the substrate for the final Edge filter design

The admittance diagram Fig. 16 and Fig. 17 permits a simple technique for assessing these amplitude variations and from them deductions about losses can be made, sometimes with surprising results. In this discussion we limit ourselves to normal incidence.

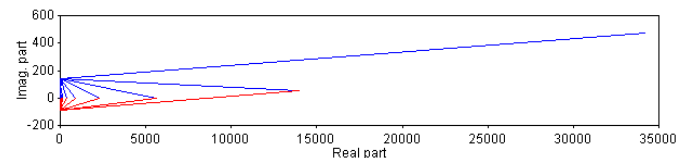


Fig. 16 Optical admittance diagram to real and imaginary part for the initial Edge filter design

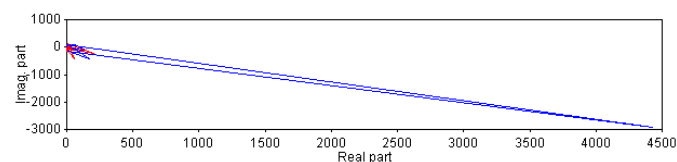
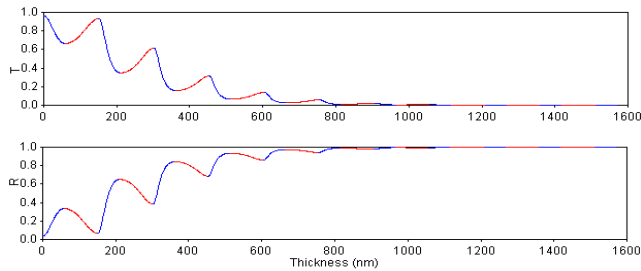


Fig. 17 Optical admittance diagram to real and imaginary part for the final Edge filter design

Finally, the transmission and reflectance versus thickness are shown in Figs. 18 and Figs. 19. It was obtained after several optimization processes.

Fig. 18 Transmission and reflection versus thickness for the initial Edge filter



design

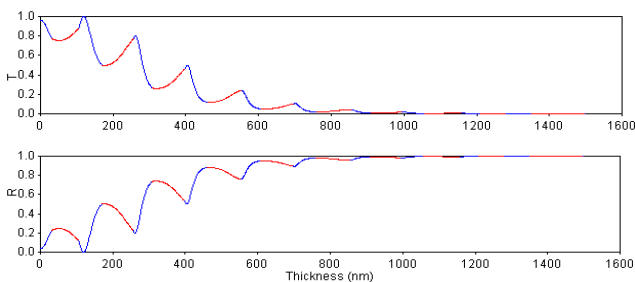


Fig. 19 Transmission and reflection versus thickness for the final Edge filter design

IV. CONCLUSIONS

In view of the simulation results presented in this study, the main contributions of this research can be summarized below: The $\text{TiO}_2/\text{SiO}_2$ materials system offers great promise for use in optoelectronic devices operating in the 300–1000nm wavelength range. Lasers, detectors, and modulators operating in this range are important for telecommunications and optical interconnects. Because Edge filters will shift shorter with an increase in the angle of incidence. The Edge filters used interference effects rather than absorption to isolate their spectral bands. In the case of high reflectors, a combination of materials with the highest refractive index ratios n_h/n_l is usually preferred since the higher the ratio, the higher the theoretical reflectance and bandwidth of standard quarter wave stacks. To design, optimize, or synthesize an Edge filter, we must define targets, single wavelength and spectral reflection, absorption and transmission targets. We can optimize an existing filter using refinement, synthesize a filter using the needle or step methods, or design one using the Fourier transform method.

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