Simulations of an Interference Birefringent Thin-Film Filter Used as a Narrow-Band Polarizer

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ABSTRACT
In this work, it is demonstrated, by means of simulations, the practical feasibility of an interference filter, implemented from a stack of metallic (silver) and birefringent thin films (TiO₂) that can be used as a linear polarizer narrow-band filter. It is shown here, how light can be polarized when it is reflected or transmitted through dielectrics or metals. This feature is highly desirable for polarization-difference imaging systems. Simulations were carried out with a software toolbox package implemented as Matlab™ m-files.

1 – Introduction and modelling

Literature has reported [7] the use of thin films as interference filters, intended to obtain narrow bands centered at specific wavelengths. In addition, the filtering of the polarization state (s or p) has been a matter of intense research [2,3] and several birefringent materials have been proposed for selecting s or p polarization [3].

Light can be understood as an electromagnetic wave whose electric and magnetic fields are perpendicular, one to another, and both to the direction of propagation. As these two fields are related by a proportionality law, if it is known the value of one of them, the value of the other is already determined, so that only one may be specified, for example, the electric one. If the electric vector varies only in a given plane, the light is plane-polarized, but if the electric field varies in a random way, light is said to be unpolarized.

All polarized light can be defined by a composition of two orthogonal components (figure 1-1). Figure 1-1 shows a schematic representation of a composition of a total electric field from two components. Also it is shown a representation for the polarization plane.

The polarization modes can be understood from the figures 1-2 and 1-4 in the following.

Figure 1-2, represents light coming from air and shining on a metal surface. In fig. 1-2 (a), the electric field is parallel to the incidence plane, so, light is said to be p polarized. In fig. 1-2 (b) the electric field is perpendicular to the incidence plane so that light is s polarized.

For both cases, the electric field at the surface must remain unchanged at the lack of surface charges. For normal incidence, there are no differences between the two cases, but for other angle, we will have to consider a cosine term that will affect electric field for p polarization.

Defining the degree of linear polarization by equation 1-1, it is possible to plot the polarization degree against the incidence angle, as can be seen in figure 1-3 for three metals: silver (Ag), aluminum (Al) and gold (Au).
$$IPL^R = \text{abs}\left(\frac{R_p - R_s}{R_p + R_s}\right)$$  \hspace{1cm} (1-1)\\

With the aid of the values shown in the figure 1-3, it can be concluded that metals almost don’t polarize light. The small amount is due to descompensated absorption between the two kinds of polarization for the incident light.

Figure 1-4 shows the case in which light incides on a dielectric medium.

There are two possibilities for linearly polarized light: by transmission and by reflection.

The linear degree of polarization by reflection is given by equation 1-1 as mentioned before, and the degree of polarization by transmission is similarly given by equation 1-2.

$$IPL^T = \text{abs}\left(\frac{T_p - T_s}{T_p + T_s}\right)$$  \hspace{1cm} (1-2)\\

In the following, we see the polarization introduced in the reflected (fig. 1-5) and transmitted (fig. 1-6) light for two dielectrics: (a) TiO$_2$ with high refractive index (2.41) and (b) SiO$_2$ with low refractive index (1.46).

Comparing figures 1-5 and 1-6, it is possible to get the total polarization by reflection if light incides at the polarization angle, (angle at which no reflection occurs for $p$ polarized light).

The reason for this behavior is that at polarization angle, there is no light reflected by $p$ component, but for transmitted light, even for a total transmission at the polarization angle and $p$ polarized light, it is still having a non-null transmission for $s$ polarized light. Therefore, all materials, metals (small) and dielectrics (as great as 100%), polarize light in some degree. This is an important conclusion because imaging systems sensitive to the state of polarization of light (polarization-difference imaging systems) requires that the imaged object have a certain degree of polarization of the light coming from it [4].
In order to obtain polarized light, the polarizers permits one to obtain \( s \) or \( p \) situations. Also, one can get this using birefringent materials instead of isotropic films.

Birefringence is a property owned by certain materials in which the traveling light sees different refractive indexes, depending on the propagation direction. This occurs due to the bulk structure of the material which can be controlled by e-beam, at a given deposition angle, as illustrated in figure 1-7.

![Fig. 1-7: Angular deposition to obtain birefringent materials.](image)

An angle deposited material will exhibit a birefringence degree, which is a function of the deposition angle \( \phi \).

In the next section, it is presented simulations of interference filters implemented with a specific birefringent material, for example, TiO\(_2\) deposited at 56.5\(^\circ\). This angle was chosen because the largest difference between the refractive indexes seen by \( s \) and \( p \) lights at normal incidence occurs.

To define the structure of the filters, it was used the symbols H for a layer of high refractive index, L for low index, P for a layer having a refractive index \( n_p \) for \( p \) polarized light and S for \( s \) polarization. All of these layers are a quarter wavelength in thickness. Symbols “a” and “g” stands for air, as incident medium, and glass for substrate, respectively.

### 2 - Simulations

It was simulated a few types (table 2-1) of interference filters that can be used as a linear polarizer pass-band filter, intended to reject the \( s \) component.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Metal?</th>
</tr>
</thead>
<tbody>
<tr>
<td>FP1c</td>
<td>Fabry-Perot type with 1 cavity</td>
<td>—</td>
</tr>
<tr>
<td>FP2c</td>
<td>Fabry-Perot type with 2 cavity</td>
<td>—</td>
</tr>
<tr>
<td>FPm1c</td>
<td>Fabry-Perot type with 1 cavity and metallic films</td>
<td>✓</td>
</tr>
<tr>
<td>FPm2c</td>
<td>Fabry-Perot type with 1 cavity and metallic films</td>
<td>✓</td>
</tr>
</tbody>
</table>

The first ones use only dielectric materials while the others use both, metallic films and dielectric birefringent films.

The chosen metal for the filter implementation was silver (Ag) because it exhibits lower optical losses (by absorption) and high transmission for a thickness larger than that required by aluminum. This is important to avoid stress, poor adherence and low reproductibility.

The structure of the filters follows the Fabry-Perot principle, that is a resonant cavity surrounded by two high-reflexive layers. For FP1c and FP2c, the reflexive layers are made of dielectric [HL] layers, and for FPm1c and FPm2c they are implemented with silver films.

#### 2.1 – Simulations for dielectric filters

The following simulations concern to FP1c and FP2c filters. The simulation results can be seen in figures 2.1-1 and 2.1-2.

![Fig. 2.1-1: Transmittance for FP1c filter.](image)
The structure of FP1c can be represented as follows:

\[ a \ H \ [L \ H]^2[P \ P] \ [H \ L]^2 \ H \ g \]

where the exponent numbers represent a layer repetition.

In figure 2.1-1, BP and BR stands for band pass and band rejection respectively, and they represent merit figures when analyzing the filter behavior.

The simulated structure in fig. 2.1-2 was:

\[ a \ [H \ L]^2[P \ P]^2[L \ H]^2 \ C \ [H \ L]^2[S \ S]^2[L \ H]^2 \ g \]

Again, the exponent numbers represent the number of repetitions of the layer, and C stands for a spacer layer, equal to an L layer.

Obviously, one cavity filter is inefficient in cancel out the s component response, what can be done only with 2 cavities filters.

The problem, in this case, is the total thickness of the filter and the high transmittance exhibited for wavelengths inside the visible spectrum.

### 2.2 – Simulations for metallic filters

These simulations were carried out for equivalent versions of FP1c and FP2c but with metallic films instead of [HL] layers.

Figures 2.2-1 and 2.2-2 shows the behavior for the birefringent filters FPm1c and FPm2c.

The structure of the FPm1c filter is:

\[ a \ [40 \text{ nm Ag} / 87 \text{ nm S} / 40 \text{ nm Ag}] \ g \]

The structure of the two cavities Fabry-Perot filter is:

\[ a \ [35 \text{ nm Ag} / 225.2 \text{ nm S} / 70 \text{ nm Ag} / 233.8 \text{ nm P} / 35 \text{ nm Ag}] \ g \]

The main problem here is the peak transmittance that is as low as \( \sim 56\% \). The presence of a spurious peak at 370 nm is not important because it is outside the visible spectrum range (390 – 770 nm).

### 2.3 – Simulation conclusions

Table 2.3-1 shows a comparative review of the simulated filters:
Tab. 2.3-1: Comparative review of the filters.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Thickness [nm]</th>
<th>Peak trans.</th>
<th>s comp. rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>FP1c</td>
<td>863.5</td>
<td>1.0000</td>
<td>1.10</td>
</tr>
<tr>
<td>FP2c</td>
<td>1,865.0</td>
<td>1.0000</td>
<td>4.83</td>
</tr>
<tr>
<td>FPm1c</td>
<td>167.0</td>
<td>0.5668</td>
<td>0.98</td>
</tr>
<tr>
<td>FPm2c</td>
<td>599.0</td>
<td>0.5267</td>
<td>12.19</td>
</tr>
</tbody>
</table>

Where $s$ component rejection is the ratio of the transmittances for $p$ and $s$ components.

So, we can see that filters with metallic films have a lower peak transmittance but are less thick and have higher rejection for the $s$ polarization.

This leads us to the obvious choice of FPm2c as the best structure, here presented, for the implementation of polarizer pass-band filters.

3 – Conclusions

In conclusion, light exhibits a given polarization degree for several materials and for a large range of illumination angles. This effect is due to the difference between the behaviors of the two orthogonal polarization states of the light: $p$ and $s$. This result is important for polarization-difference imaging systems \([4]\) and, consequently, for the progress of this work.

It was shown that an efficient polarizer using metallic (silver) films in together with birefringent material (TiO$_2$ at 56.5°). This loss in the transmission intensity of the filter can be, in principle, compensated by an increase of the sensor area.

This set of simulations and results are important both, to demonstrate the possibility of getting a linear polarizer interference pass-band filter and also to obtain some practical values, like thicknesses and deposition angles, to be used in the fabrication of prototypes.

References: