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Design of a novel TiO_2/airgap-based polarizing micro beam splitter cube

M J Maciel[1], S Pimenta[1], J F Ribeiro[1] and J H Correia[1]

[1]University of Minho, CMEMS-UMinho, Guimaraes, Portugal

mmaciel@dei.uminho.pt

Abstract. Polarizing beam splitters are key elements widely used in different optical instruments. This paper introduces the design and simulation of a novel thin-film multilayer polarizing micro beam splitter based on airgap layers (n = 1.002828 at 400 nm). The negligible absorption coefficient of the air over a wide spectral region ($\kappa \approx 0$ from about 200 nm and higher) satisfies the conditions of a perfect low refractive index material (L). Moreover, using titanium dioxide (TiO_2) as high refractive index material (H), a very high refractive index contrast is obtained. The micro beam splitter optical structure consists in a 7 optimized multilayer of TiO_2 and air, providing a refractive contrast higher than 1.2. The polarizing beam splitter cube is projected in a borosilicate glass substrate (BK7) and the optical multilayer obtained, expressed in multiples of the quarter wavelength optical thickness – QWOT, is 1.6H L 1.1H 1.5L 1.1H L 1.6H. This optical structure ensures the transmission of p- polarization and the reflection of s- polarization, from visible to NIR spectral range, over a bandwidth higher than 170 nm. Additionally, the designed polarizing beam splitter can be fabricated using standard microtechnology fabrication processes.

1. Introduction

Polarizing beam splitters (PBS) are optical components which separate the two orthogonal polarization modes of the light, s- and p- polarizations, into different propagation directions. In these optical components, the two modes of light have the same importance [1,2] and can be processed independently, doubling the traffic bandwidth [3]. PBS are widely used in optical instruments, lasers, electro-optic displays, and optical recording [4,5]. They also play an important rule in liquid crystal displays (LCD), optical communication systems [1] and polarization-based imaging systems, such as a polarization sensitive optical coherence tomography (OCT) systems [6]. The miniaturization of PBS systems will also allow their integration in other applications, such as optogenetic neural probes [7]. Therefore, PBS are imperative optical components from visible to near infrared (NIR) spectral regions.

Multilayer PBS are key polarizing separators, which are based on optical interference thin-films [2]. This type of beam splitters presents very good efficiency (negligible absorption) [8]. Thin-films PBS could be implemented in plate type or cube type configuration. While in plate configuration the layers are deposited on a plane substrate, in a cube configuration the layers are deposited on the hypotenuse face of two prisms [2]. The most convenient PBS reflects one polarization component of light at 90º relatively to the incident light direction, which puts the cube type configuration to advantage [9]. The basic idea of a cube typed PBS is based on fact that when the light is incident at Brewster angle, the p- polarization component of the light will be transmitted at the same direction of the incident light [1].

The implementation of thin-films beam splitters can be done with the deposition of two materials with high and low refractive index, alternately. The refractive index contrast between the two materials in an optical coating determines the optical quality of the beam splitter. The air presents optical properties highly interesting for optical design. Using air as the low refractive index material provides a higher optical contrast compared to all-dielectric filters [10]. Additionally, air has a negligible absorption coefficient over a wide spectrum (k ≈ 0 from about 200 nm and higher).

This paper introduces the design and simulations of an air-gapped based PBS. The air is used as low refractive index material and titanium dioxide (TiO_2) is used as high refractive index material. Wavelength band, reflectance or transmittance of the desired polarization and angular field are the main characteristics of a PBS [2]. These parameters are investigated performing TFCalc (from Software Spectra) simulations from visible to NIR spectral regions.

2. PBS theory

In this paper, the optical theory is adapted to the design of a PBS in a cube configuration. Borosilicate glass substrate (BK7) is the material used as substrate, and it is intended the separation of the two polarization states.

2.1. Optical theory

In the theory of thin-film optical layers, it is crucial to introduce the effective index of refraction, which is the refractive index of the medium relative to the polarization state of the radiation that cross the layer [8,11]. For the two polarization components s- and p-, the effective index of refraction is obtained according to:

$$n_p = \frac{n}{cos\,\theta}, \tag{1}$$

$$n_s = n\ cos\,\theta, \tag{2}$$

where n_p and n_s are the effective refractive indices for p- and s- polarization, respectively; n is the nominal refractive index of the layer, and θ is the angle through which the light passes the layer. This is the angle of refraction, which results from Snell's equation. Using the Snell law, it is obtained:

$$cos\,\theta = \left(1 - \frac{A^2}{n^2}\right)^{1/2}. \tag{3}$$

In equation (3), A is $n_0 sen\theta_0$ (numerical aperture), which is constant in the entire package of thin-film layers; n is the nominal refractive index; θ_0 is the angle of incidence and n_0 is the refractive index of the incident medium. The equations (1) and (2) could now be rewritten using equation (3):

$$n_p = \frac{n}{\left(1 - \frac{A^2}{n^2}\right)^{1/2}}, \tag{4}$$

$$n_s = n\left(1 - \frac{A^2}{n^2}\right)^{1/2}. \tag{5}$$

Equations (4) and (5) express the variation of the effective refractive indices according to the nominal index of refraction (n), for p- and s- polarizations, respectively. In the cube PBS configuration, the angle of incidence is 45º and the incident medium is the BK7 substrate ($n_0 \approx 1.52$). From this information results the graphic of figure 1, which represents the variation of effective refractive indices for BK7 substrate.

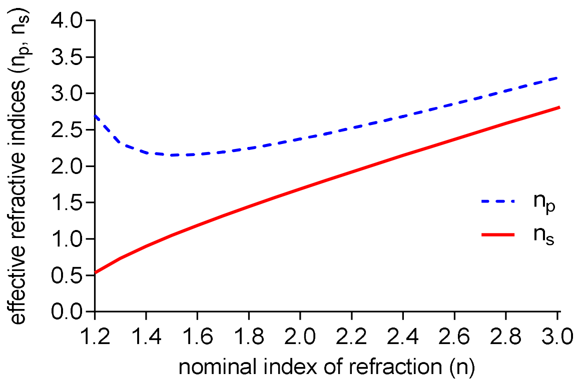

Figure 1. Variation of effective refractive indices for p- and s- polarization according to the nominal index of refraction (n). The angle of incidence is 45º and the incident medium is BK7 optical glass.

2.2. Characterization parameters

The PBS projected in this paper is characterized in terms of polarization degree [2,8], for both s- and p- polarizations. For transmission (T), the degree of polarization (P_T) is obtained according to equation (6), and for reflection (R), the degree of polarization (P_R) is obtained according to equation (7).

$$P_T = \frac{T_p - T_s}{T_p + T_s} \text{ and} \tag{6}$$

$$P_R = \frac{R_s - R_p}{R_s + R_p}, \tag{7}$$

where T_p and T_s represent the transmission of p- and s- polarizations; R_p and R_s represent the reflection of p- and s- polarizations, respectively.

3. PBS design and simulation

By choosing two materials with nominal indices of refraction in one side and other side of the functions n_p and n_s (figure 1), it is expected to obtain a bigger difference between the effective indices of s- polarization (n_s) than between the effective indices of p- polarization (n_p). The total package of thin-films with these two materials will, theoretically, produce a big influence in the s- polarization (maximum reflectivity) and a smaller influence in the p- polarization.

A novel approach is introduced in this paper, which consist on the use of air as a material with low refractive index (n ≈ 1.002828 at 400 nm). TiO_2 was the material chosen with high refractive index (n ≈ 2.4 at 550 nm), providing a high refractive index contrast.

TFCalc simulations were conducted with air and TiO_2. The terms “H” and “L” denotes the material with high and low refractive index, respectively. The optical layers are expressed in multiples of the quarter wavelength optical thickness – QWOT ($\lambda_0/4$). The simulations presented in this section are for visible range (550 nm central wavelength). However, the analysis and characterization for other spectral ranges are presented in the next section.

Two considerations were had in account during the simulations: the optical thin-film package should be symmetrical, and a minimal number of layers is preferable to diminish the optical fluctuation in the total multilayer. After several iterations, a minimal optical structure with seven layers, (BK7) H L H **L** H L H (BK7), allows the quasi-total reflection of s- polarization and the transmission of p- polarization (more than 60%), in the spectral range centered in 550 nm. The next step is to use the optimization function of TFCalc to maximize the p- polarization transmission. The

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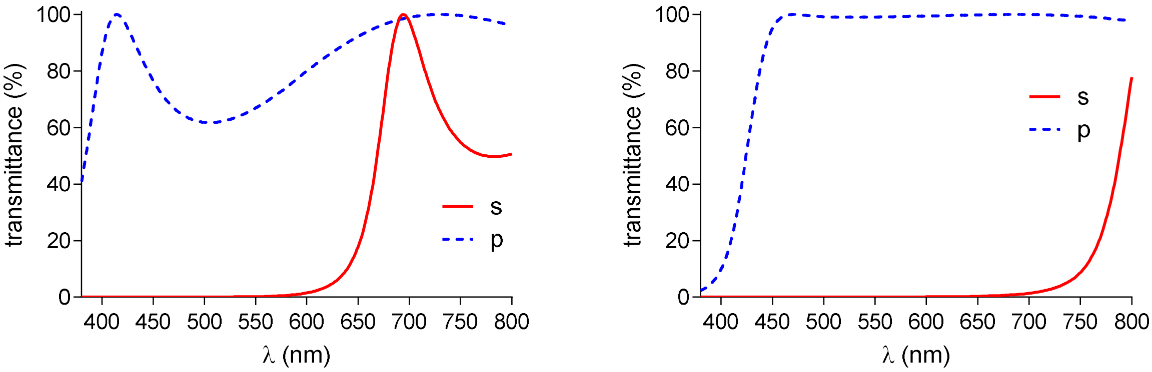
final optimized multilayer is represented in equation (8), and the comparison between the seven thin-film layers before and after optimization is presented in figure 2.

$$\text{BK7 1.6H L 1.1H } \mathbf{1.5L} \text{ 1.1H L 1.6H BK7} \tag{8}$$



(a) **(b)**

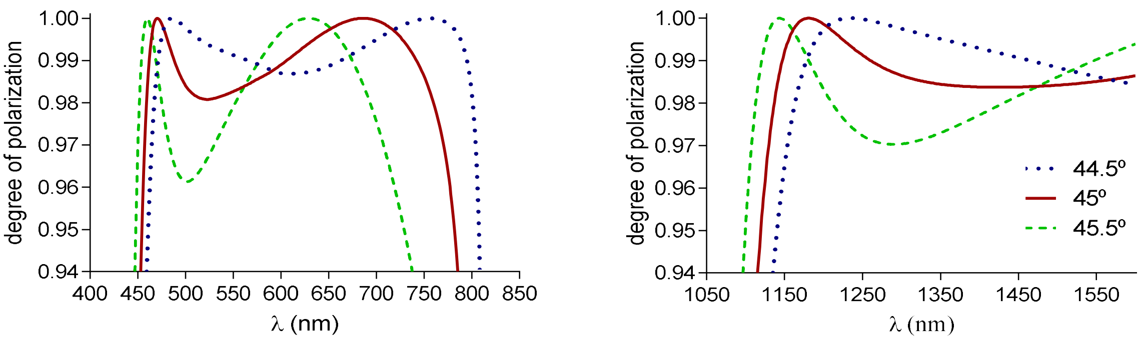
Figure 2. Optical transmittance for s- and p- polarizations: (a) before and (b) after TFCalc® optimization. An incident angle of 45º and a central wavelength of 550 nm was defined in the optical environment.

4. PBS characterization

The PBS is now analysed and characterized from visible to NIR region of the electromagnetic spectrum. A polarization degree higher than 0.95 was used as the optical criterion [2] and an angle variation between 44.5º and 45.5º (Δθ = 1.0º) was considered for PBS characterization, due possible fluctuations during the PBS fabrication process. For each central wavelength defined in the optical simulation, the bandwidth of operation of the PBS was calculated considering the optical criterion.

Figure 3 represents the degree of polarization in reflection for (a) 550 nm and (b) 1350 nm central wavelength, which was used to define the operation bandwidth of PBS. In all simulations, the degree of polarization in transmission – equation (6) – is higher than the degree of polarization in reflection – equation (7).

Table 1 summarises the results for PBS design, with the individual thickness of TiO_2 and airgap layers. The optical package of the PBS cube assures a bandwidth of operation higher than 170 nm, which increases from 550 nm to 1350 nm central wavelength.



(a) **(b)**

Figure 3. Degree of polarization in reflection for (a) 550 nm and (b) 1350 nm central wavelength. An angle variation of 1.0º was used to calculate the optical bandwidth of the PBS.

Table 1. Physical thickness of the different layers (TiO_2/air) and bandwidth operation of the simulated PBS, for different spectral ranges.

*The bandwidth of operation was determined according to the optical criterion degree of polarization higher than 0.95 and for an angle variation 44.5-45.5º.

λ_0 (nm)	TiO_2 **1.6H** (nm)	Air **L** (nm)	TiO_2 **1.1H** (nm)	Air **1.5L** (nm)	TiO_2 **1.1H** (nm)	Air **L** (nm)	TiO_2 **1.6H** (nm)	Bandwidth* (nm)
550	92.24	137.46	63.42	206.19	63.42	137.46	92.24	461-639 (178)
650	111.25	162.45	76.49	243.68	76.49	162.45	111.25	547-753 (206)
850	147.25	212.44	101.23	318.66	101.23	212.44	147.25	715-985 (270)
1050	182.67	262.43	125.59	393.64	125.59	262.43	182.67	885-1215 (330)
1350	234.88	337.40	161.48	506.11	161.48	337.40	234.88	1141-1559 (418)

5. PBS fabrication process

The micro PBS fabrication will be based on conventional MEMS fabrication technologies. TiO_2 layers will be deposited by RF sputtering. A sacrificial layer of chromium (Cr) will be deposited, by dc sputtering, according to the design specifications of the airgap layers. The PBS layers will be patterned to obtain physical apertures which will allow the wet etching of Cr layers. Figure 4 presents the different steps of the proposed fabrication process.

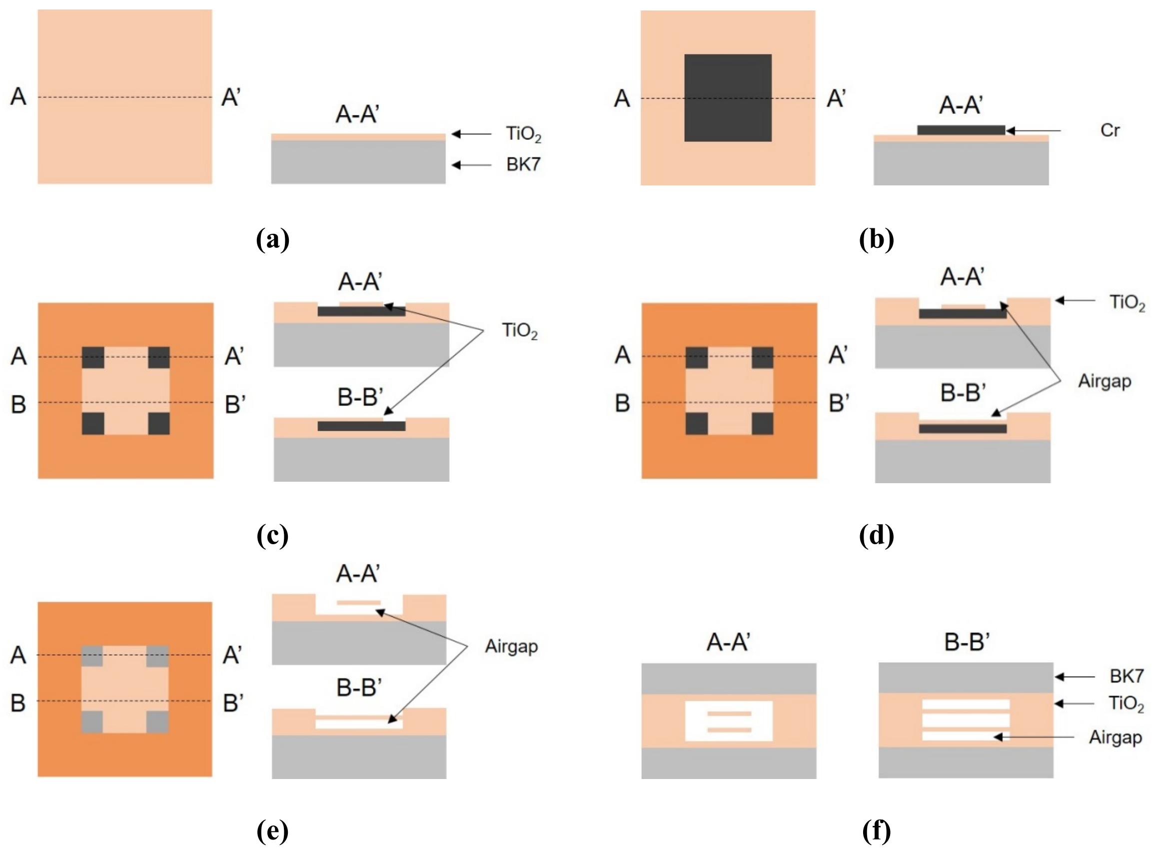


Figure 4. Proposed micro PBS fabrication process: top and cross section view of (a) TiO_2 bottom layer deposition, (b) Cr sacrificial layer deposition, (c) and (d) TiO_2 top layers deposition, (e) Cr wet etching; (f) the final structure with TiO_2 and airgap layers (two symmetrical parts are coupled).

6. Conclusions and future guidelines

This paper introduces a novel thin-film polarizing beam splitter, based on the use of air as a low refractive index material. By combining with TiO_2 layers, this thin-film package provides a high refractive index contrast. The PBS was designed for a cube typed configuration, using borosilicate glass (BK7) as substrate. An optical multilayer based on only 7 thin-films was optimized and allows the separation of the two polarization states of the light. The optical structure is adapted to spectral ranges from visible to NIR, allowing an operation bandwidth higher than 170 nm.

The optical design presented in this paper is now being implemented through MEMS technologies, namely the thin-film deposition with a sacrificial layer, which will be removed by wet etching. The advance in PBS miniaturization and MEMS technologies compatibility will allow the integration in new applications, such as optogenetic neural probes.

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