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Polarizing Beam Splitter

About the Polarizing Beam Splitter

Polarizing beam splitter cubes consist of two right-angled prisms. A dielectric coating is evaporated on the hypotenuse prism surface (see Figure 1). The dielectric coating is designed to transmit the part of the incident wave with the electric field that is polarized in the plane of incidence (p-polarization) and to reflect (in an orthogonal direction) the part of the incident wave with the electric field that is orthogonal to the plane of incidence (s-polarization). Two advantages with the cube design as compared to a plate design, are that ghost images are avoided, since there is only one reflecting surface here; and the translation of the transmitted output beam is very small as compared to the input beam. The latter advantage simplifies the alignment of optical systems using polarizing beam splitter cubes.

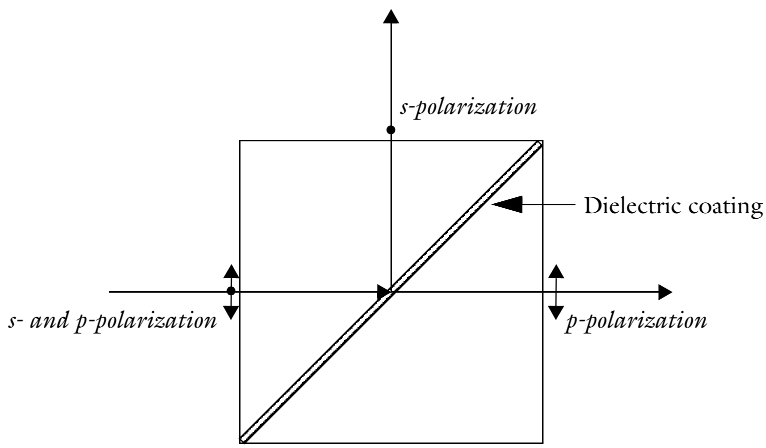

Figure 1: Schematic of a polarizing beam splitter cube consisting of two right-angled prisms and a dielectric coating evaporated on the hypotenuse between the prisms. The incident wave has both s- and p-polarization, indicated by the dot and the double-arrow, respectively. The s-polarized component is reflected upwards, whereas the p-polarized component is transmitted straight through the dielectric stack.

When used with unpolarized sources, the input beam is split into two orthogonally polarized and orthogonally directed output beams with almost the same intensity. When used with a linearly polarized source, the amount of light in the two output beams depends on the angle of the input polarization relative to the plane of incidence.

The dielectric film can be designed to be spectrally broadband or narrowband, making the device useful for either broadband or tunable sources or selected laser lines. The coatings can also be designed for high-power (and/or high-energy) laser applications, with very large damage thresholds (in the J/cm^2 range).

The Polarizing Beam Splitter application demonstrates the basic MacNeille design (*c.f.* Ref. 1). This design consists of pairs of layers having a consecutively high and low refractive index. In the internal dielectric stack, the waves hit the layer boundary at the Brewster angle. Thus, the s-polarization is reflected, whereas the p-polarization is transmitted at each internal layer boundary. A common design is to use zinc sulphide (ZnS) for the high refractive index layers (n = 2.3) and magnesium fluoride (MgF_2) for the low refractive index layers (n = 1.38), and SF5 glass prisms (n = 1.673).

Figure 2 shows a plot for the main rays in a five-layer dielectric stack.

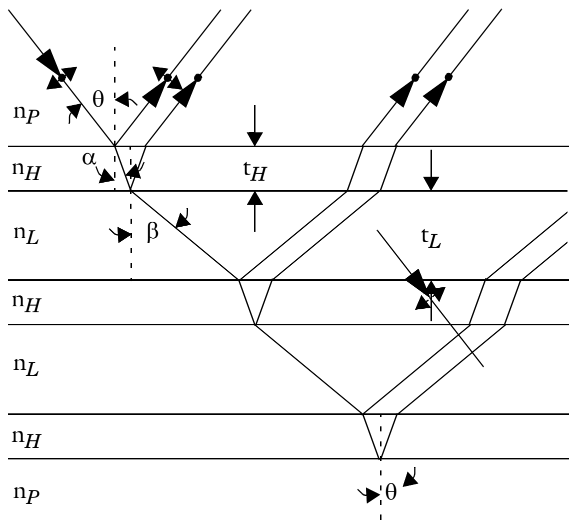

Figure 2: Schematic of the dielectric stack. The angle of incidence, θ, is 45 degrees. The leftmost annotations indicate the refractive indices for the prisms (n_P), the high-index layers (n_H), and the low-index layers (n_L). The propagation angle in the high-index layer is denoted by α and the propagation angle in the low-index layer is denoted β. The thicknesses for the high-index and low-index layers are indicated by t_H and t_L, respectively.

At the Brewster angle, the in-plane polarization for the refracted ray is polarized in the same direction as the propagation direction for the reflected ray. Thus, the condition on the angles becomes

$$\alpha + \beta = \frac{\pi}{2}. \tag{1}$$

Using Snell's law, the internal Brewster angles become

$$\alpha_B = \operatorname{atan}\left(\frac{n_L}{n_H}\right) = 31^\circ \tag{2}$$

and

$$\beta_B = \frac{\pi}{2} - \alpha_B = 59^\circ. \tag{3}$$

The angle of incidence, θ, is 45 degrees. However, the Brewster angle between the prism and the high-index layer is given by

$$\theta_B = \operatorname{atan}\left(\frac{n_H}{n_P}\right) = 54^\circ. \tag{4}$$

Thus, at this interface, the reflected wave will not be perfectly s-polarized.

To maximize the intensity of the s-polarized reflected wave at each interface, the wave reflected from the next layer must be in phase with the incident wave. To achieve this, the physical thicknesses must be set to

$$t_H = \frac{\lambda}{4\sqrt{(n_H^2 + n_L^2)/n_H^2}} \tag{5}$$

and

$$t_L = \frac{\lambda}{4\sqrt{(n_H^2 + n_L^2)/n_L^2}}. \tag{6}$$

In the application, the user inputs the refractive indices or the materials for the prisms and the high- and low-index materials. Then, the application calculates the layer thicknesses from Equation 5 and Equation 6.

The MacNeille design is sensitive to the angle of incidence. The larger deviance from normal incidence on the prisms, the less contrast between the two polarizations. Thus, the application also allows the user to sweep the spot radius for the incident Gaussian beam, thereby varying the angular spectrum distribution for the incident beam.

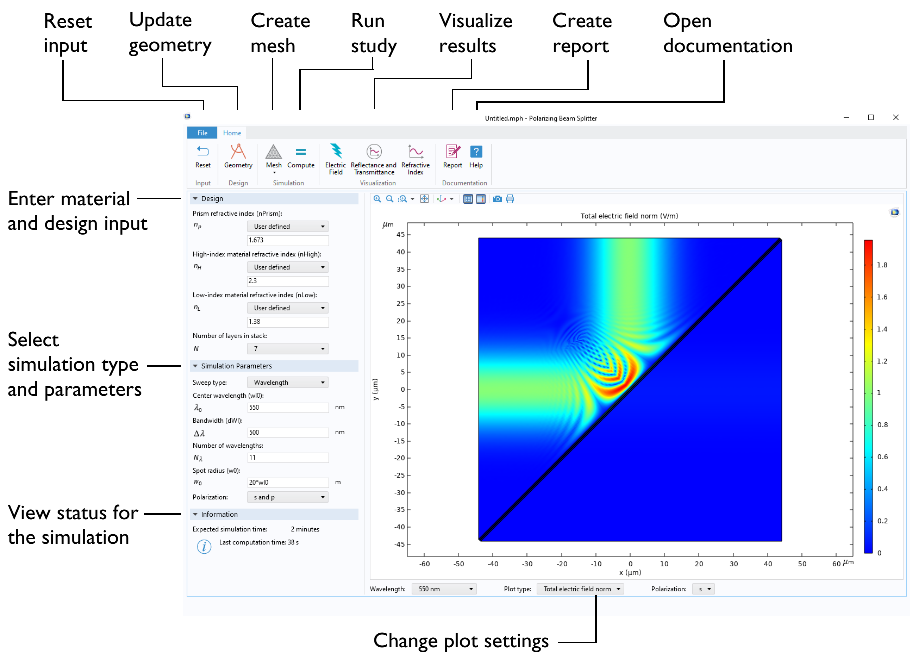

Figure 3: The user interface of the Polarizing Beam Splitter app.

By clicking the **Reset** button in the **Input** section of the ribbon, the design and simulation parameters are set to the default parameters. Click the **Geometry** button in the **Design** section to display the current geometry. If a **Spot radius** sweep has been performed, it is possible to select the spot radius for which the geometry should be displayed.

In the **Simulation** section of the ribbon, click the **Mesh** button to display the mesh menu, then select one of the available mesh element size items to generate a new mesh. If you select the mesh element size that is currently used, the mesh is not regenerated, only displayed. If a **Spot radius** sweep has been performed, the mesh quality is displayed for the selected spot radius. Click the **Compute** button to perform a simulation, using the provided design and simulation parameters.

Display the result plots by clicking the buttons in the **Visualization** section. The buttons are enabled when a solution is available. Click the **Electric Field** button to show the norm of total electric field, the electric field for the first wave, or the electric field for the second wave, for a given **Wavelength** or **Spot radius** and **Polarization**. Click the

Reflectance and Transmittance button to show the reflectance and transmittance for the polarizations for which the simulation was performed. For a **Wavelength** sweep, clicking the **Refractive Index** button shows the refractive index versus wavelength for each material or the spatial refractive index profile across a cut-line over the prisms and the dielectric stack. For a **Spot radius** sweep, clicking the **Refractive Index** button only shows the spatial refractive index profile. Finally, in the **Documentation** section, click the **Report** button to generate a Microsoft® Word® report containing the input data and the results of the simulation. Clicking the **Help** button shows this help text.

In the leftmost panel, use the **Design** section to enter refractive indices for the prisms and the layers in the dielectric stack. Enter a refractive index by selecting **User defined**, or select a material from the material list via **From material**. Click the **Plot** button that appears next to the material list to show the refractive index spectrum for the selected material. The **Number of layers in stack** can be chosen from the list.

Choose **Sweep type** in the **Simulation Parameters** section. If **Wavelength** is selected, enter the **Center wavelength**, **Bandwidth**, **Number of wavelengths**, and **Spot radius**. If **Spot radius** is selected, enter **Center wavelength**, **Smallest spot radius**, **Largest spot radius**, and the **Number of spot radii**. For both sweep types, select the **Polarization**(s) for which the simulation will be performed.

The **Information** section displays the current status of the application.

The Embedded Model

The geometry consists of two right-angled prisms (polygons) and a Thin-Film Stack part. The base lengths of the prisms are determined from the center wavelength and the spot radius, so the geometry is automatically scaled given those two parameters. The relation says that the base length should be wide enough for a Gaussian beam having propagated a base length. The relation is

$$a = 8w_0\sqrt{1+(a/z_0)^2}, \tag{7}$$

where a is the prism base length and the Rayleigh range z_0 is defined by

$$z_0 = \frac{\pi n_P w_0^2}{\lambda_0} \tag{8}$$

and n_P is the prism refractive index, w_0 is the spot radius, and λ_0 is the center wavelength.

From Equation 7, the base length a can be solved for, giving

$$a = \frac{8w_0}{\sqrt{1-(8w_0/z_0)^2}}. \qquad (9)$$

To prevent a zero denominator in Equation 9, a requirement is that

$$8w_0 < z_0 \qquad (10)$$

or

$$w_0 > \frac{8\lambda_0}{\pi n_P}. \qquad (11)$$

Thus, the entered spot radius parameter must fulfill Equation 11.

The **Electromagnetic Waves, Beam Envelopes** physics interface includes the default **Wave Equation, Electric** domain feature and **Matched Boundary Condition** features for the input and output facets of the prisms. To prevent reflections at the thin-film boundaries in the upper-right corner for tightly focused beams, a **Scattering Boundary Condition** feature is used there.

To automatically calculate continuous phases, used by the **Electromagnetic Waves, Beam Envelopes** interface, a **Global ODEs and DAEs** interface is added. Each defined global equation ensures that the phase functions are continuous across the boundaries between different materials in the thin-film stack.

The **Maximum element size** field in the **Mesh 1>Size** settings is set to resolve the minimum spot radius in the domain.

The **Results** node contains plots of the electric field norm, the reflectance and transmittance and the refractive index along a cut-line crossing the prisms and the dielectric stack.

Notes About the Implementation

The Polarizing Beam Splitter application demonstrates how the phase functions required by the **Electromagnetic Waves, Beam Envelopes** interface can be defined using variables and global equations from the **Global ODEs and DAEs** interface. The variable definitions and the global equations are modified dynamically as the number of layers in the dielectric stack are changed.

Reference

1. S.M. MacNeille, *Beam Splitter*, U.S. patent 2,403,731, published 1946-07-09.

Application Library path: `Wave_Optics_Module/Applications/polarizing_beam_splitter`