

Design, assembly and use of a planar guide optical coupling system

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Abstract: Our objective is to design and create a system by which we can characterize and experiment with different types of optical waveguides. We collect the reflection of light through a high index prism illuminated at angles where total internal reflection is expected. Coupling of the evanescent wave, and consequently a reduction of the reflection, can only happen when a system with available optical modes is placed close enough to the bottom of the prism.

I. INTRODUCTION

A waveguide is a physical structure with the ability to propagate electromagnetic waves in a certain area of space. In dielectric waveguides this is achieved by taking advantage of the phenomenon named total reflection (TIR) at the interface between two materials. This confinement phenomenon can only occur when the wave impinges from a material 1 with index n_1 to a material 2 with index n_2 and fulfils the condition that $n_2 < n_1$ and the angle of incidence is equal or greater than the critical angle ($\theta_c = \sin^{-1}(\frac{n_2}{n_1})$). In the field of waveguides, the material with the highest index is usually called core and the materials with the lowest index are called cladding, see FIG. 1.

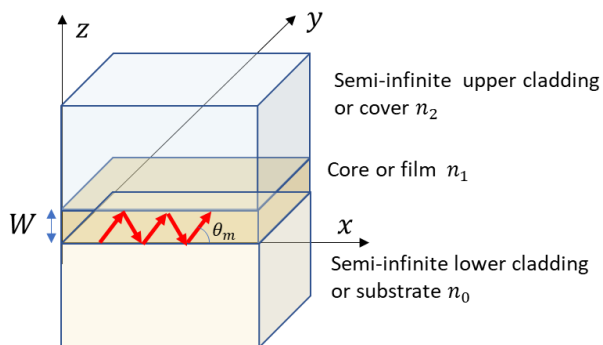


FIG. 1 Propagation of a beam through a waveguide by total internal reflection.

For the propagation of the light in the waveguide to be optimal, the self-consistency condition must be fulfilled, which consists on the fact that after two reflections the wave returns to the same phase as when it entered the guide, so that during its propagation the wave continues to have the same characteristics as when it entered. The angles that satisfy this condition (θ_m) define the guided "modes" of the wave, which are quantized and depend only on the wavelength used and the materials of which the waveguide is made [1].

These propagation modes can be characterised by the propagation constant (β_m) or the effective index defined (N_m) as:

$$\beta_m = n_1 k_0 \cos(\theta_m) = k_0 N_m \quad (1)$$

β_m can be interpreted as the momentum component of the wave parallel to the guide, and N_m can be interpreted as the refractive index that the waves experiences when propagating in a specific mode.

Because of the characteristics of our experiment, we are using an asymmetric planar waveguide, which means that the upper and lower cladding are made of different materials. In our case the configuration is isopropanol (cover), ZnO (core/film) and glass (substrate). In this type of waveguide, the material that limits the modes of the guide is the one that has the refractive index closer to the film one, where the TIR condition will be broken first.

Given a fixed propagation constant β_m , we define the transverse momentum components in each medium as [2], [3]:

$$\begin{aligned} b_1^2 &= (k_0 n_1)^2 - \beta^2 \\ p_0^2 &= \beta^2 - (k_0 n_0)^2 \\ p_2^2 &= \beta^2 - (k_0 n_2)^2 \end{aligned} \quad (2)$$

That we use to calculate the phase accumulated in each reflection and propagation, allowing to write the self-consistency condition in such a waveguide in the following form [3]:

$$2b_1 W - 2\phi_{10} - 2\phi_{12} = 2\pi m \quad (3)$$

Where the first term corresponds to the phase difference experienced by the wave as it travels from one interface to another, ϕ_{10} represents the phase difference when reflecting in the film-cover surface and ϕ_{12} when reflecting in the film-substrate interface, so the sum of the phase differences must

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be a multiple of 2π . It should be noted that the calculation of the phase shifts in the reflections will depend on the characteristics of the light, as the phase shifts are not the same for Transverse Electric (TE) or Transverse Magnetic (TM) polarised light.

For TE it reads [3]:

$$\begin{aligned}\phi_{10} &= \tan^{-1}\left(\frac{p_0}{b_1}\right), \\ \phi_{12} &= \tan^{-1}\left(\frac{p_2}{b_1}\right)\end{aligned}\quad (4)$$

For TM it reads:

$$\begin{aligned}\phi_{10} &= \tan^{-1}\left(\left(\frac{n_1}{n_0}\right)^2 \frac{p_0}{b_1}\right), \\ \phi_{12} &= \tan^{-1}\left(\left(\frac{n_1}{n_0}\right)^2 \frac{p_2}{b_1}\right)\end{aligned}\quad (5)$$

Searching for the zeros of the self-consistency equation it is possible to anticipate the localization of the different modes, as can be seen in FIG. 3.

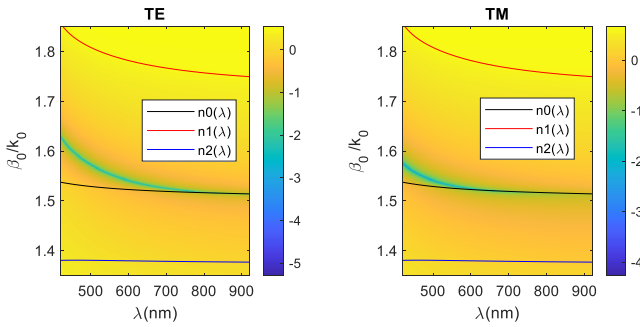


FIG. 3 $\log_{10}|Res|$ as a function of wavelength and effective momentum. *Res* is the residual of the self-consistency equation. Green-blueish lines mark the position of the fundamental mode, located between the index of the film and the highest among the cladding ones (film: ZnO [6]; cover: Propanol [7]; substrate: Glass [8]).

A. PRISM COUPLING

To couple electromagnetic radiation into a waveguide both momentum and frequency must match. We set frequency when we set the light wavelength (λ), momentum in free space is automatically fixed ($k_0 = \frac{2\pi}{\lambda}$) and is smaller than the momentum needed to couple to the guided mode (see equation (1)).

To increase this momentum, we use the prism coupling method which works as follows (see FIG. 2)):

Light enters a prism with a large refractive index tilted with an angle θ_i with respect to the normal, as a consequence the

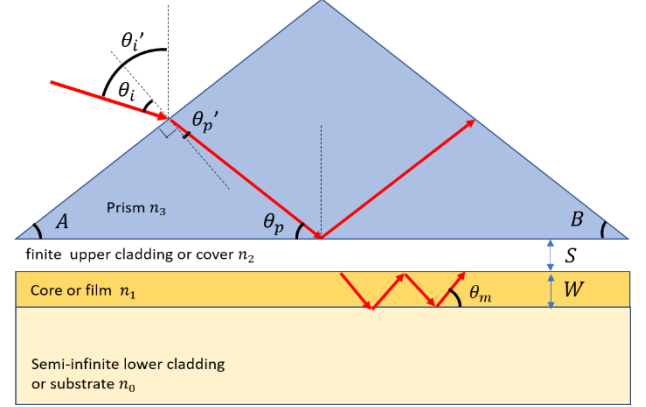


FIG. 2 Prism coupling scheme and angle definition.

total momentum of light increases, $k = n_p k_0$ where n_p is the index of refraction of the prism. For a big range of angles θ_p in Figure (2), the light incidence at the bottom of the prism is a TIR, as it happens between a high index material (prism n_p) and air ($n = 1$). On the surface where we have this TIR an evanescent wave is produced which decays as we move away from the prism surface a distance in the order of the wavelength [1], [2]. If we bring the prism bottom close enough to a system that has a mode with the right frequency (ω), polarization and momentum β_m (equation (1)), light will couple to the propagative mode producing a decrease of intensity in the reflection, a phenomenon known as frustrated TIR evanescent coupling. As the important quantity is the projection of the total momentum k , that can be tuned by varying the angle θ_p the coupling condition can be written as follows [4], [5]:

$$\begin{aligned}\beta_m &= k \cos(\theta_p) = n_p k_0 \cos(\theta_p) = N_m k_0 \\ \theta_p &= \frac{\pi}{2} - A - \arcsin\left(\frac{\sin(\theta_i' - A)}{n_p}\right)\end{aligned}\quad (6)$$

II. EXPERIMENTAL

For the characterisation of the waveguide, our design consists of three parts, the first one where the light that will hit the sample is produced and polarised (FIG 4. Item 1), the second block consists of the coupling of the light in the waveguide through a prism (FIG 4. Item 2), and finally a detection part where the residual light from the coupling is received (FIG 4. Item 3) and analysed (FIG 4. Item 4), with which we will be able to characterise our sample. To be able to detect the different modes, the system is able to vary the angle at which the light hits the prism, this is done by means of stepper motor (FIG 4. Item 5) that rotates the platform

where the prism and the receiver are while keeping the emitter at a fixed position. Their position can be slightly adjusted by means of screws in order to compensate slight deviations. The whole electronic system is controlled by an Arduino board (FIG 4. Item 6) programmed using LabVIEW, in order to easily control the different parameters of the system.

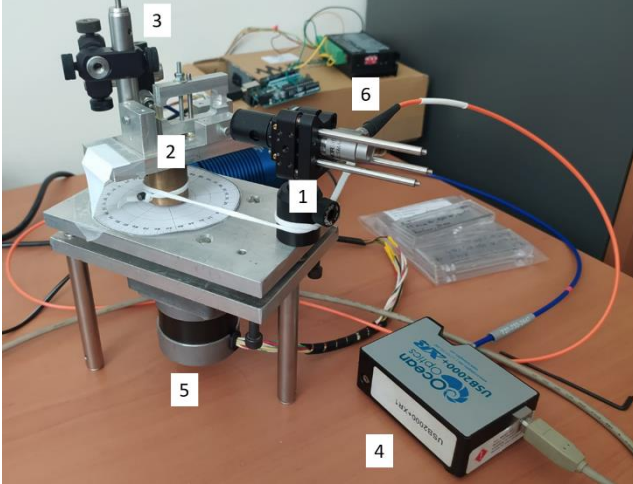


FIG. 4 Parts of the optical system. 1. Light emitting arm 2. TiO₂ Prism 3. Light collector 4. Spectrometer 5. Stepper motor 6. Control system with Arduino

For the experiment to be consistent the system has to be able to meet the following requirements: (a) in order to keep the prism at a constant distance from the sample it has to be pressed down. (b) the platform on which the sample is placed has to adjust the position of the sample to ensure that the sample is fixed in such a way that the whole system is coplanar. (c) the axes of rotation of the light source and receiver must be aligned with the position of the prism and the guide, so that when the angle of incidence is changed, the region where the light is incident is the same.

The prism we have used is made of titanium oxide (TiO₂), this material has the advantage of having a high refractive index [9], thus making the coupling to the guide more effective. One of the main disadvantages of this material is that it is anisotropic, which means that the refractive index of the incident light is strongly dependent on whether the light is incident on TE or TM. The prism has the characteristic that its three angles are different, using Figure 3 as a reference, our prism has $A=44.60^\circ$ and $B=43.45^\circ$, this property is beneficial experimentally, as it prevents multiple reflections inside the prism from altering the experiment in any way.

One of the elements that we have had to design is the arm through which the light coming from the source is redirected,

(FIG 4. Item 1). This element has the characteristic that it is capable of decoupling the weight of the source from the setup, as it has an entrance for fibre optics, thus avoiding that the light source has to be in the movable structure of the system. This device has a parabolic mirror inside in order to collimate the light coming from the fibre, a mirror is used and not a lens, because even if a lens can be used to collimate the beam, it is very difficult for the material to keep its refractive index constant for the whole range of frequencies we want to analyse (chromaticity), contrary the mirror is based on reflection and not refraction, ensuring that for all frequencies the resulting beam is collimated (achromaticity).

The range of frequencies that we can analyse is limited only by the spectrometer, since the source is an incandescent bulb that emits white light in a broader range. In this case, we have used the Ocean Optics spectrometer, which allows us to capture information from a wide spectrum of wavelengths (400-950 nm). The data generated by the spectrometer are transmitted via a USB to a computer where they are processed and managed in such a way as to obtain analysable results.

A. CALIBRATION AND MESURAMENTS

For the calibration of the system, we measured the refractive index of a reference liquid for the whole range of wavelengths. The material we have chosen is isopropanol which is an alcohol with a considerable refractive index. To obtain the results we have obtained two spectra, one without sample, which means that the change of medium is between prism and air, and the other spectrum with a sample containing isopropanol. The range of angles we have analysed is from 8° to 20° , named θ_i' in our reference system, defined taking the origin at the tip of the prism, see FIG. 3.

The spectrum with the air measurement allows us to have a reference of the intensity received in all this range of frequencies and angles when we have total internal reflection, in this case the condition of critical reflection is always fulfilled thanks to the fact that the air has a very small index and the prism has a very high one.

In FIG. 5. what is being represented is the ratio between the intensity of the experiment with iso-propanol (Signal) and that of the experiment with air (Reference), which theoretically corresponds to a normalized reflection. In the spectra with isopropanol we see that for angles close to 20° reflection is almost 1 for all wavelengths. Decreasing the angle has no effect for small wavelengths, but as wavelength increases we see for different angles a change in the reflection coefficient, that abruptly goes from approximately

1 to 0.5. This change is due to the crossing of the critical angle, since when this angle is passed starts transmitting.

In the figure two zones can be highlighted, the zone with a constant shade of blue corresponds to the fact that the ratio mentioned above is 1, which indicates that in this region the two spectra are indistinguishable and we are in the critical reflection zone. In the second zone we see that the values are moving away from 1, which indicates that for these wavelengths in this range of angles they are not yet experiencing total reflection.

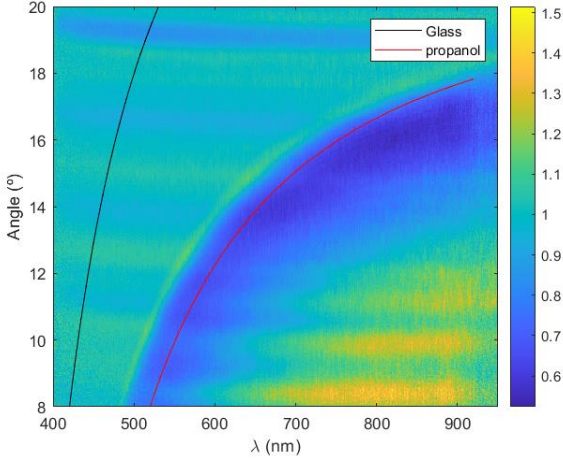


FIG. 5 Representation of the normalized reflection (Signal/Reference) as a function of the angle of incidence and wavelength in mode TM, the red and black lines indicate where the critical angle of isopropanol [7] and microscope slide glass [8] would theoretically be.

To see if the obtained results corresponded to the real ones, we have calculated the critical angle that we should observe from the real refractive index of isopropanol [7], with the following formula that is obtained by imposing the critical reflection condition on the angle ratio of equation (6).

$$\arcsin\left(\frac{n_{iso}}{n_p}\right) = A + \arcsin\left(\frac{\sin(\theta'_i - A)}{n_p}\right) \quad (7)$$

It is important to note that there is an area that does not correspond to what we would expect theoretically, specifically the area with yellowish colours, as the value obtained is higher than one, which theoretically does not make sense, as the intensity received in the experiment should always be greater than or at most equal to the intensity with propanol. We believe that this anomaly could be due to the stray light (unwanted scattered light from the source in to the holders that should be blocked makes it to the detector) or to ambient light (since even though the measurements

were made in the dark, there is always some noise coming from the instruments or screens). Another possible source of error could be the lack of rigidity in the receiver of the reflected light, as it could have been displaced a little, causing some of the data to be altered.

III. CONCLUSIONS

Due to time constraints, we have not been able to analyse the modes of a waveguide, but the system has proved capable of analysing a basic experiment with sufficient accuracy to give consistent results, and has the ability to manipulate the necessary parameters to accommodate future experiments. The LabView software is flexible enough to be able to adapt to future changes in the different parts of the system, and has a clear and easy-to-interpret interface.

The system can still be improved, with a little more time some features could have been improved that would extend the parameters and increase the accuracy of the results, such as the stiffness of the part that holds the fibre that collects the light, the inclusion of servomotors in both the receiver and the emitter for better adaptability to the experiment.

Acknowledgments

First, I would like to thank my tutor Dr. Jordi Gomis Bresco for all his support and dedication to this project. I would also like to thank my family for the advice and help they have given me throughout the project.

IV. APPENDIX

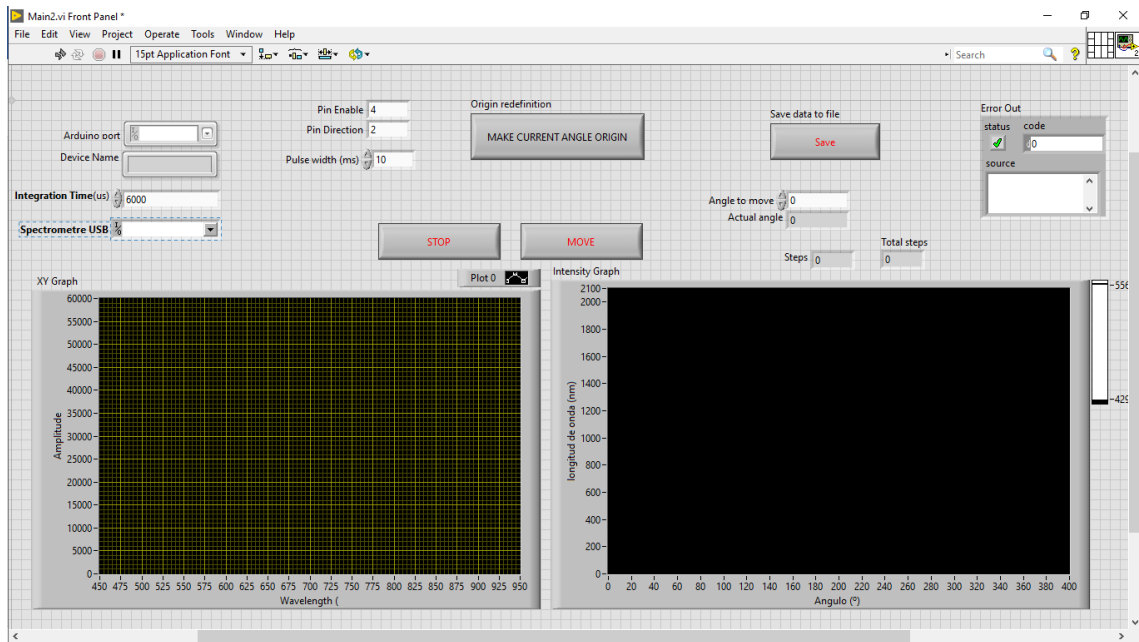


FIG. 6 LabView program interface for angle control by stepper motor and analysis of the data from the spectrometer.

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