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Javaoptics simulations: Open-source physics (OSP) library for teaching (or Learning) thin-film optics

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ABSTRACT

To illustrate and broaden knowledge on some aspects of physics at teaching level, that is, university level and higher level, Javaoptics applets was adopted as free software under a GNU General Public License, an open-source license. This applet was used to shows multiple beam interferences from a parallel dielectric thin film and to study the evolution of reflection (or transmission)at normal and oblique incidence of light. Further, the reflection and refraction factors when the index of refraction (may be constant or have a wavelength dependency)and the absorption of the film and the substrate are modified. It was shown that resources can be used as an ordinary course to support material and as the main working tool in an on-line Internet course.

INTRODUCTION

Java is a high-level, third generation programming language (from SUN Microsystem), like C, Fortran, smalltalk[1-7]. It was used to write computer applications that crunch numbers, process words, play games, store data or do any of thousands of other things computer software. Among the different types of programs[3-8] that can be written in Java or other language, are primarily interested is *applets*. These applets introduced in the first version of the Java language in 1995, which required a WWW browser or another Java application to run, so it is an excellent teaching (or learning) language. In the hope of helping in teaching thin-film optics course, we adopt Javaoptics simulations (JOPTICS), as a part of of physics disciplines (physical optics). Javaoptics[4] is an open source software under GNU General Public (GPL)License[9], freely available on the web site, http://www.ub.es/javaoptics/applets/index_app.html"[4]. We believe that the availability of such open-source software is significant advance for the optical coating community.

THEORITICAL BASIS

Multiple beam interference

A plane wave incident from the medium (refractive index 1) onto a thin-film layer with an angle ε and with amplitude E_0, shown in Figure 1. The amplitude of the transmitted wave into the film can be expressed as E_0t_1, where t_1 can be the Fresnel coefficient for each of the two possible polarizations 's' or 'p'. This plane wave propagates inside the thin-film with an angle ε' and undergoes multiple reflections. The amplitude after the first reflection on the film-substrate interface is $E_0t_1r_2$ where r_2 is the Fresnel reflection coefficient from the film to the substrate. At this point, part of the wave is also transmitted with amplitude $E_0t_1t_2$ where t_2 is the Fresnel transmission coefficient from the film to the substrate. After the second reflection inside the film, the amplitude of the reflected wave is $E_0t_1r_2r_1$ where r_1 is the Fresnel reflection coefficient from the film to the incident medium. This wave is then transmitted to the substrate with amplitude $E_0t_1r_2r_1t_2$. Thus, the amplitude of the m-th transmitted wave onto the substrate is[10,11]:

$$E_m = E_0 t_1 t_2 (r_1 r_2)^m \quad (1)$$

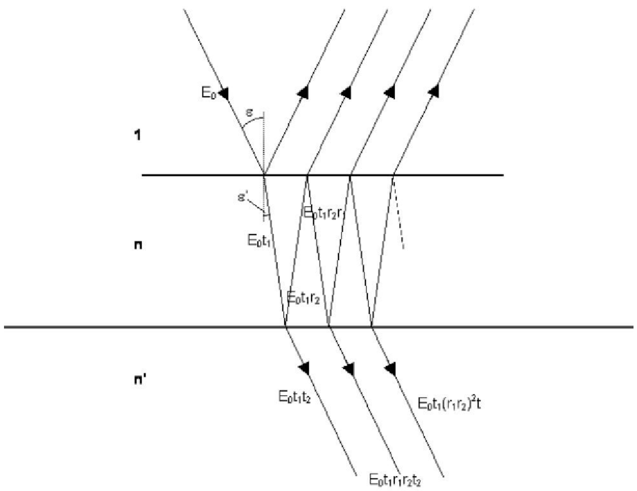

Figure 1 : Sketch of the multiple reflections inside a thin-film layer[10].

To analysis the relative phase of each of the transmitted waves, it is necessary to take two reference points in two consecutive transmitted waves and the these two points are placed on the same plane perpendicular to the propagation direction of the waves, as indicated in Figure 2.

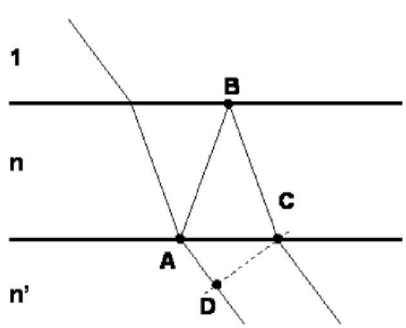

Figure 2 : Optical path difference between two consecutive transmitted waves.

The optical path difference between two consecutive transmitted waves is:

$$\Delta = n(AB+BC) - n'AD = 2nd\cos\varepsilon' \quad (2)$$

The phase corresponding to this optical path is:

$$\delta = \frac{2\pi}{\lambda} 2nd\cos\varepsilon' \quad (3)$$

Thus, the complex amplitude of the m-th transmitted wave can be expressed as:

$$E_m = E_0 t_1 t_2 (r_1 r_2)^m \exp\left(i\cdot m\left[\varphi + \arg(r_1) + \arg(r_2)\right]\right) = E_0 t_1 t_2 (r_1 r_2)^m \exp\left(i\cdot m[\varphi+\delta]\right) \quad (4)$$

The modulus and phase of the Fresnel reflection coefficients r_1 i r_2 have been written separately. The phases $\arg(r_1)$ and $\arg(r_2)$ can be different from 0 in those cases when the refractive index of the substrate is greater than the refractive index of the film ($\arg(r_2)=\pi$) or when the extinction coefficient of the film is not zero ($k\neq0$, $\arg(r_1)\neq0$ and $\arg(r_2)\neq0$).

The total resulting amplitude is the sum of the complex amplitudes of all the transmitted waves:

$$E = \sum_{m=0}^{\infty} E_0 t_1 t_2 (r_1 r_2)^m \exp\left(i\cdot m[\varphi+\delta]\right) = E_0 t_1 t_2 \frac{1}{1 - r_1 r_2 \exp\left(i[\varphi+\delta]\right)} \quad (5)$$

The resulting transmitted intensity is proportional to the square modulus of the total transmitted complex amplitude, i.e.:

$$I = \frac{|E_0 t_1 t_2|^2}{1+(r_1r_2)^2 - 2r_1r_2\cos(\varphi+\delta)} = \frac{|E_0 t_1 t_2|^2}{(1+r_1r_2)^2 - 4r_1r_2\cos^2\left([\varphi+\delta]/2\right)} \quad (6)$$

where the relation $\cos(\varphi)=2\cos^2(\varphi/2)-1$ has been applied. Analyzing the previous expression, the conditions a maximum or minimum of transmitted light can be deduced. For instance, for a dielectric film (with k=0) these conditions can be summarized on the following table:

(m=0,1,2,...)	n<n'	n>n'
Maximum transmitted intensity	$2nd\cos(\varepsilon')=m\lambda$	$2nd\cos(\varepsilon')=(2m+1)\lambda/2$
Minimum transmitted intensity	$2nd\cos(\varepsilon')=(2m+1)\lambda/2$	$2nd\cos(\varepsilon')=m\lambda$

Concerning the reflectance, its behavior is the opposite to the transmittance: where the former is maximum the latter is minimum and vice-versa. In the case when the film is slightly absorbing (extinction coefficient different from 0) the conditions for having a maximum or a minimum in the transmittance are more complex since they have to take into account the phase δ. The

Full Paper

final Reflectance and Transmittance of the sample depend as well on the Reflectance and Transmittance of the second face of the substrate. Since the latter do not depend on the characteristics of the film, this second face does not affect the distribution of R and T maxima and minima.

RESULT AND DISCUSSION

Very short user guide

We first present a very short user guide and the structure of the implementation of Javaoptics. All the functions of Javaoptics are accessible through a graghical user interface (GUI) which is designed so that the vast majority of the information is presented in a single main window, shown in Figure 3.

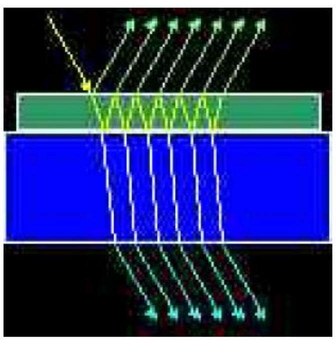

Figure 3 : Applet shows multiple beam interferences from a parallel thin film[5].

(a) Window 'Transmission and Reflection'

This window shows a sketch of the sample with the substrate in blue and the film on its top in yellow. Incident light is represented by a set of beams in green while light reflected is represented in a set of magenta beams. Transmitted light is represented in cyan. The sketch of the sample includes also the values of transmittance (T) and reflectance (R) of the sample. It is worth noting that the light is assumed to be monochromatic and with natural polarization (a uniform superposition of all possible polarization states).

The window "Transmission and Reflection" allows changing the thickness of the layer (d), the wavelength of the incident light (λ), and the angle of incidence (θ). Furthermore, the values of the refractive index (n) and extinction coefficient (k) can be changed by means of the buttons "Change n" and "Change k". These buttons open two windows with the names "Refractive index parameters" and "Extinction coefficient parameters" respectively. These parameters correspond to a mathematical model for the refractive index and the extinction coefficient that follows the expression:

$$n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}; \quad k(\lambda) = k_0 \exp(D/\lambda) \qquad (7)$$

These windows allow changing the values of A, B, C, k_0 and D and show a plot of these indexes against the wavelength as shown in Figure (4-7) for normal and oblique incident of light when dielectric and absorbing materials were used.

(b) Window 'Phase Difference'

This window shows a diagram of the path followed by a beam inside the thin film. For the selected wavelength it shows the value of the refractive index and of the extinction coefficient of the film (n and k on the diagram), as well as the refractive index of the substrate. The window allows changing the thickness of the film (d), the wavelength (λ) the angle of incidence (ε). In addition, the values of the refractive index and of the extinction coefficient can be changed with the buttons "Change n" and "Change k". Figure 7 and 8 illustrate this windows for normal and oblique incidence.

(c) Window 'Spectrum'

This window shows the Reflectance and Transmittance spectra for the sample with the current configuration. It has to be kept in mind that these values are the result of the transmission and reflection on the film and also on the second face of the substrate. By placing the cursor on the plot, the values corresponding to the position with respect to the coordinate axes on the graph can be read on the lower part of the window. The button "Configure Plot" allows defining the way the plot is presented in Figure 4 and 6. The lower and upper limits of the wavelength represented on the plot can be defined as well as the lower and upper limits of the reflectance and transmittance represented on the plot. These last two values can be assigned automatically with the buttons on the lower part of the window. Thus, the button "R/T Range 0/1" assigns the value 0 to the "Initial T and R value" and 1 to the "Final T and R value". The button "Auto Range" assigns automatically the minimum R/T range that permits representing simultaneously the two spectra. The buttons "Auto

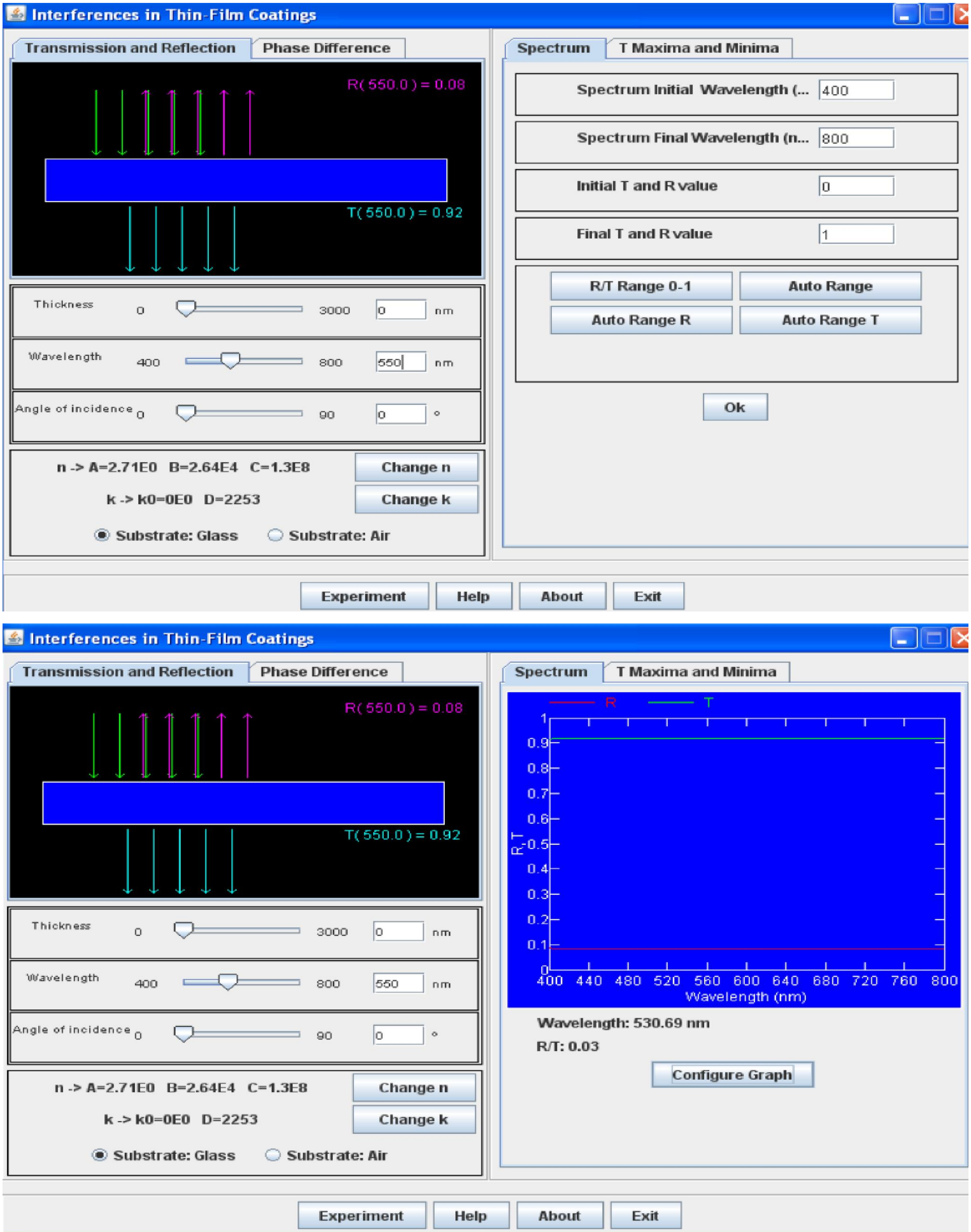

Figure 4 : Main JOPTICS windows showing; (A) The spectrum window, (B) Transmission and reflection window for glass substrate of index n_g=1.52 at λ_0 =550nm.(normal incidence).

Full Paper

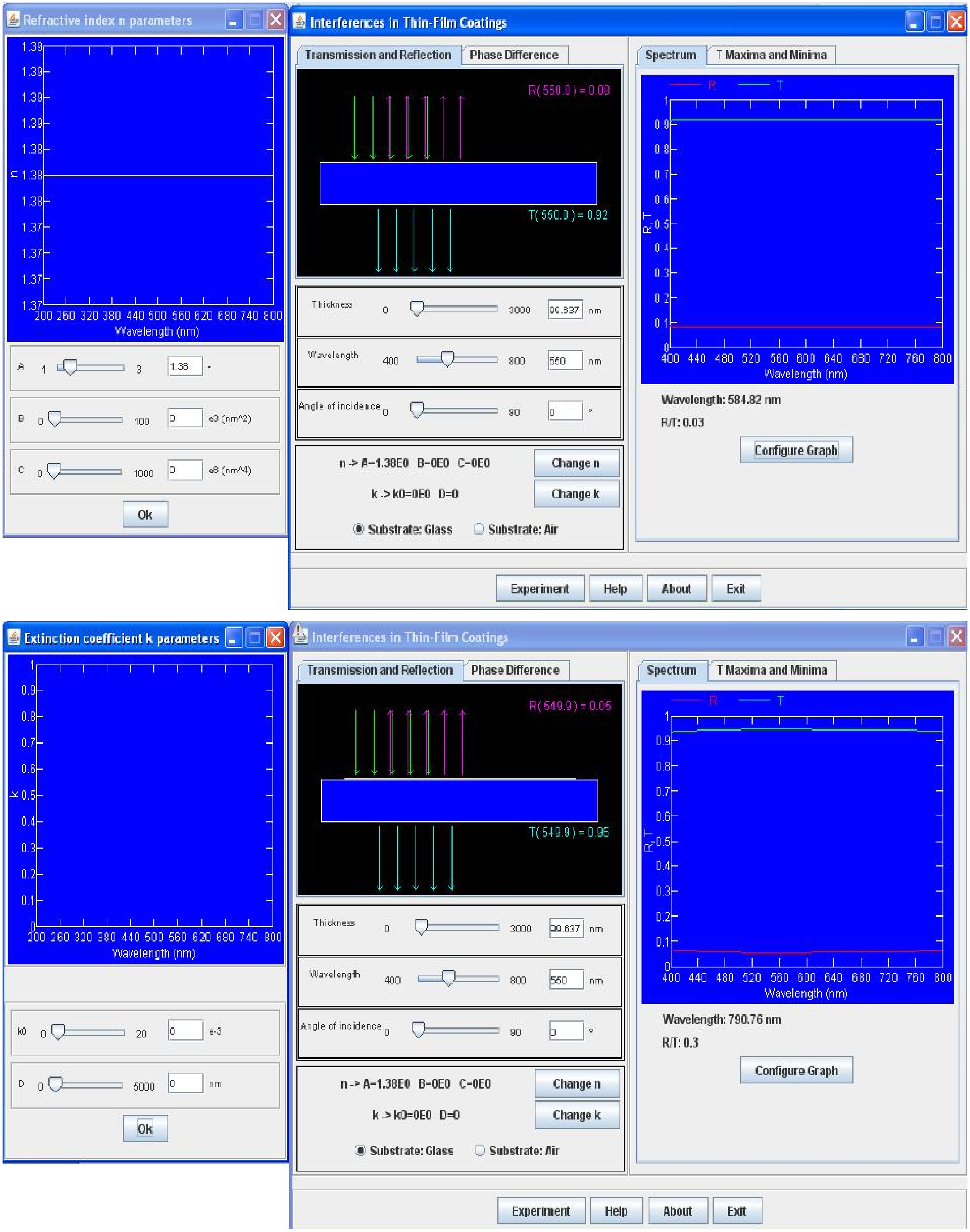

Figure 5 : Joptics windows showing the T and R spectrum (normal incidence) of MgF_2 on glass of geometrical thickness d=99.637 nm at λ_0 =550nm; (A) The refractive index n window, (B) The extinction coefficient k window.

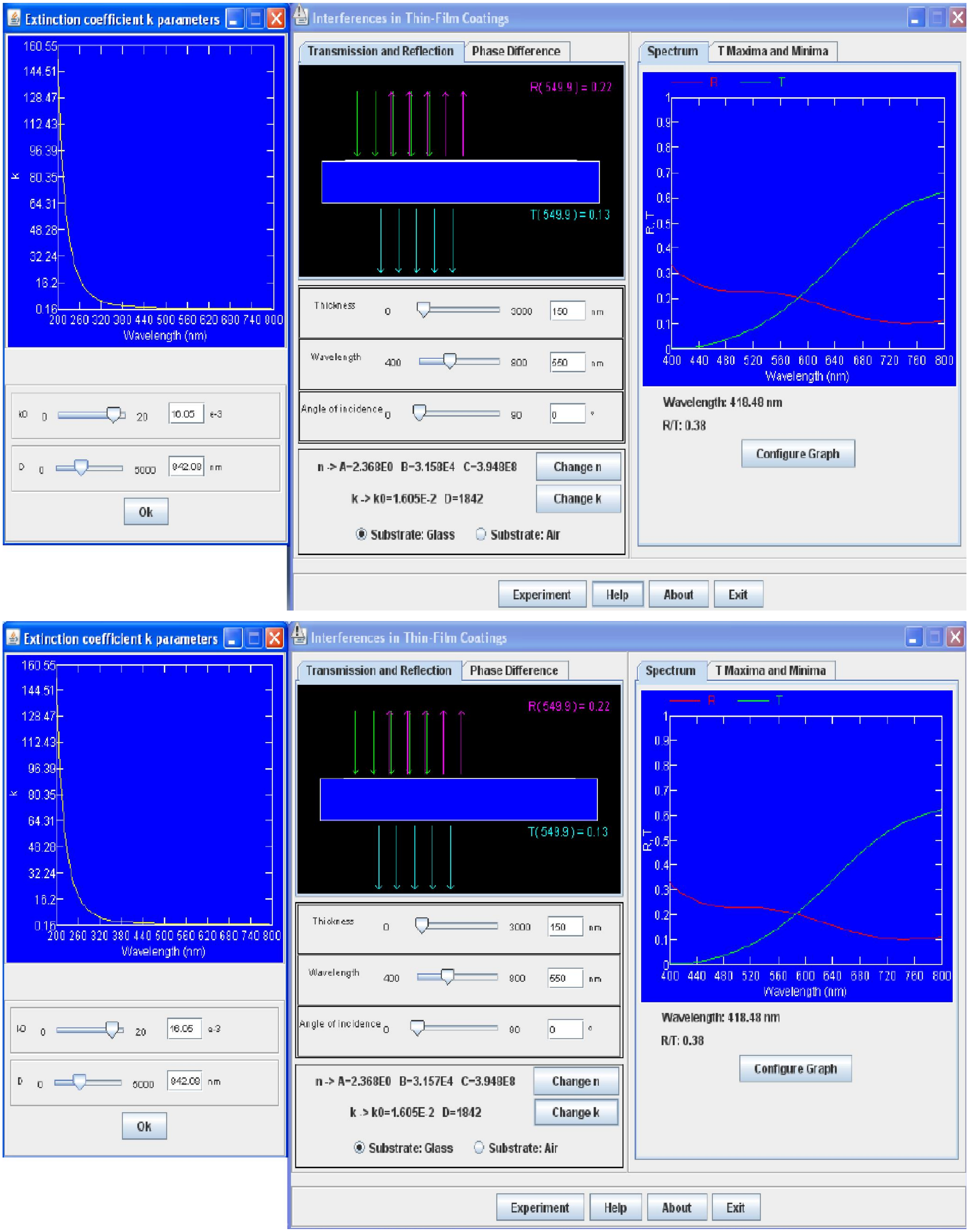

Figure 6 : Joptics windows showing T and R spectrum of absorbing material at normal incidence; (A) The refractive index n window, (B) The extinction coefficient k window.

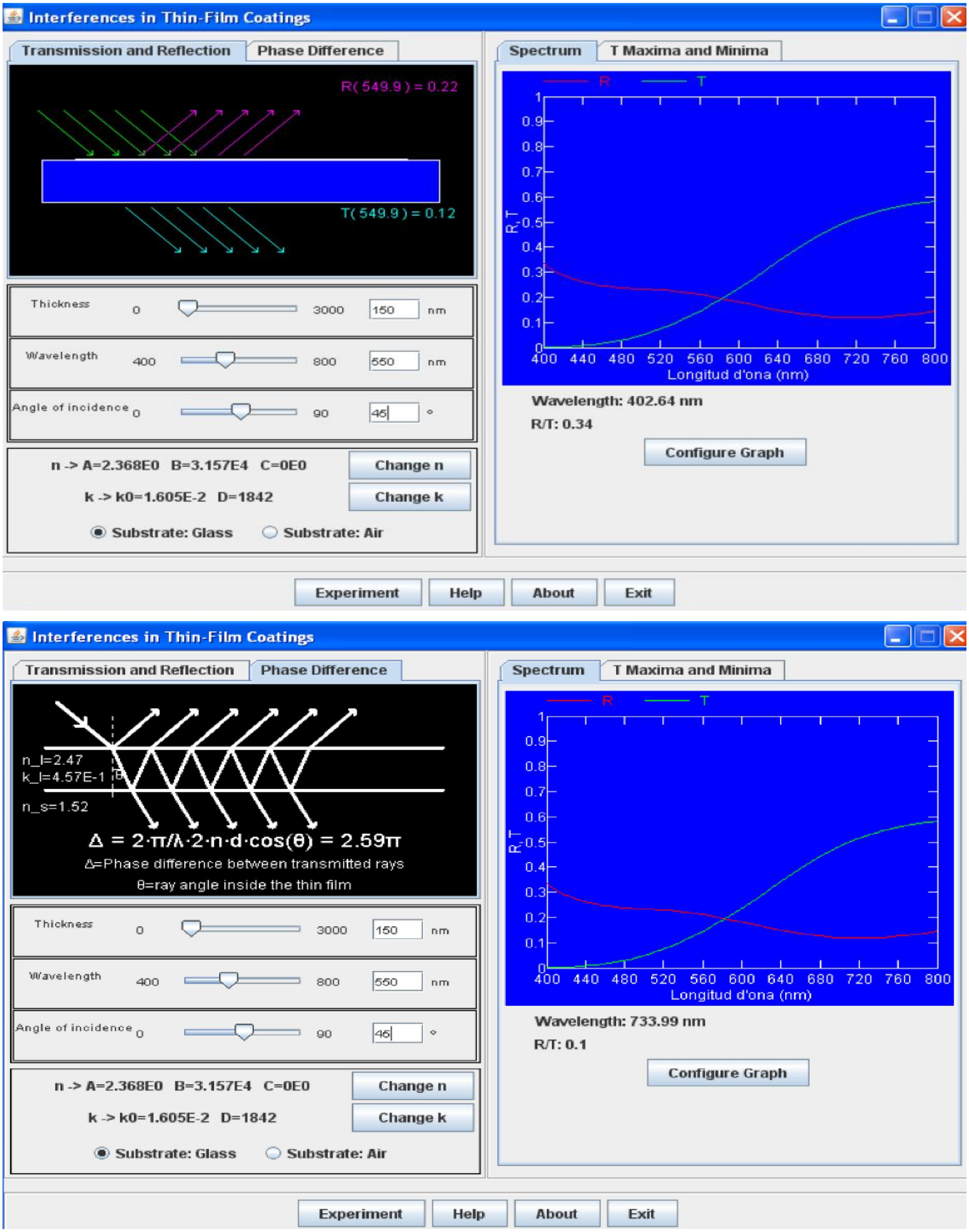

Figure 7 : Joptics windows showing; (A) T and R spectrum of absorbing material at oblique incident of light, (B) phase difference of light from absorbing material at oblique incident of light.

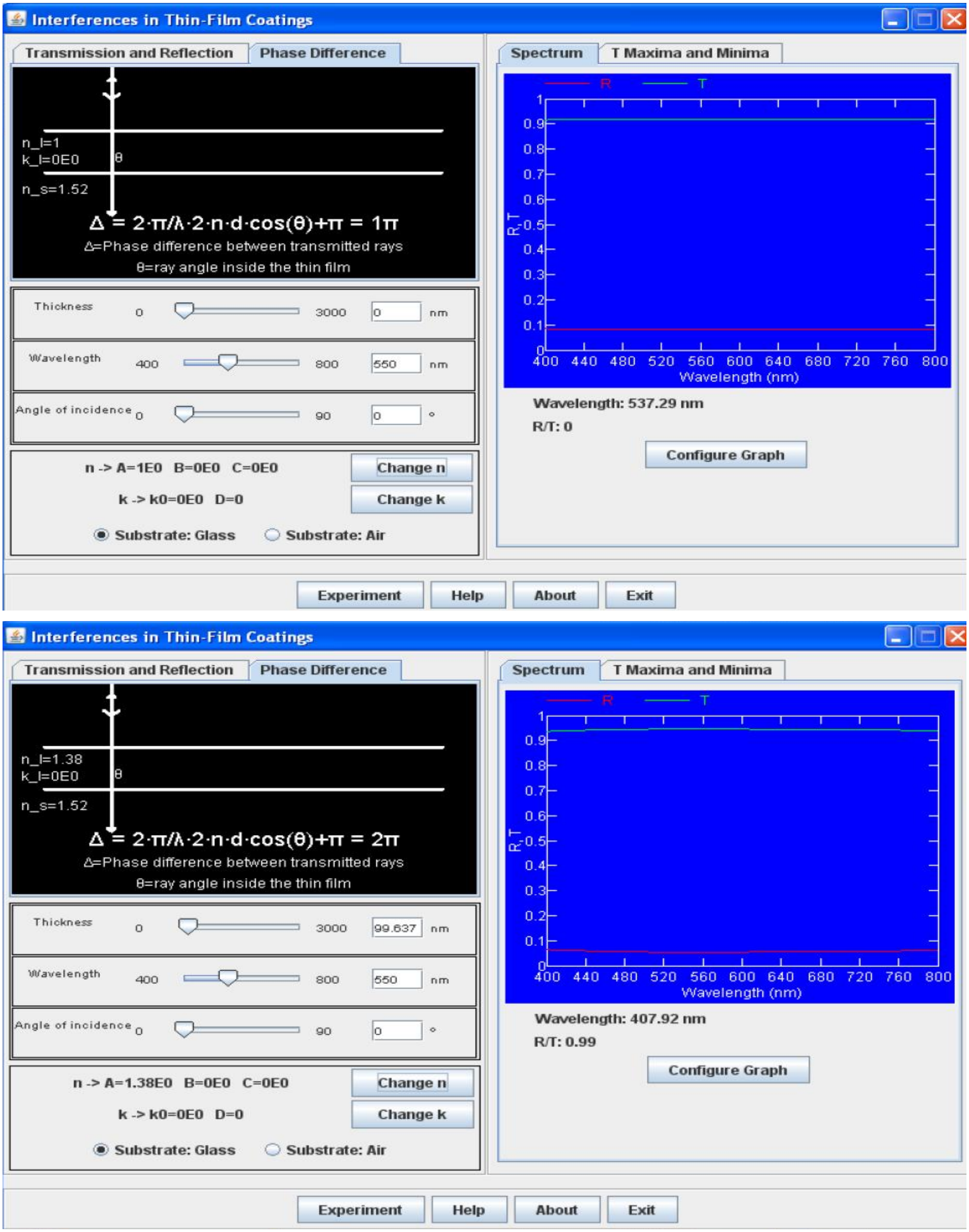

Figure 8 : Joptics windows showing the the phase difference (normal incidence); (A) glass substrate, (B) MgF_2 on glass of geometrical thickness d=99.637 nm at λ_0 =550nm.

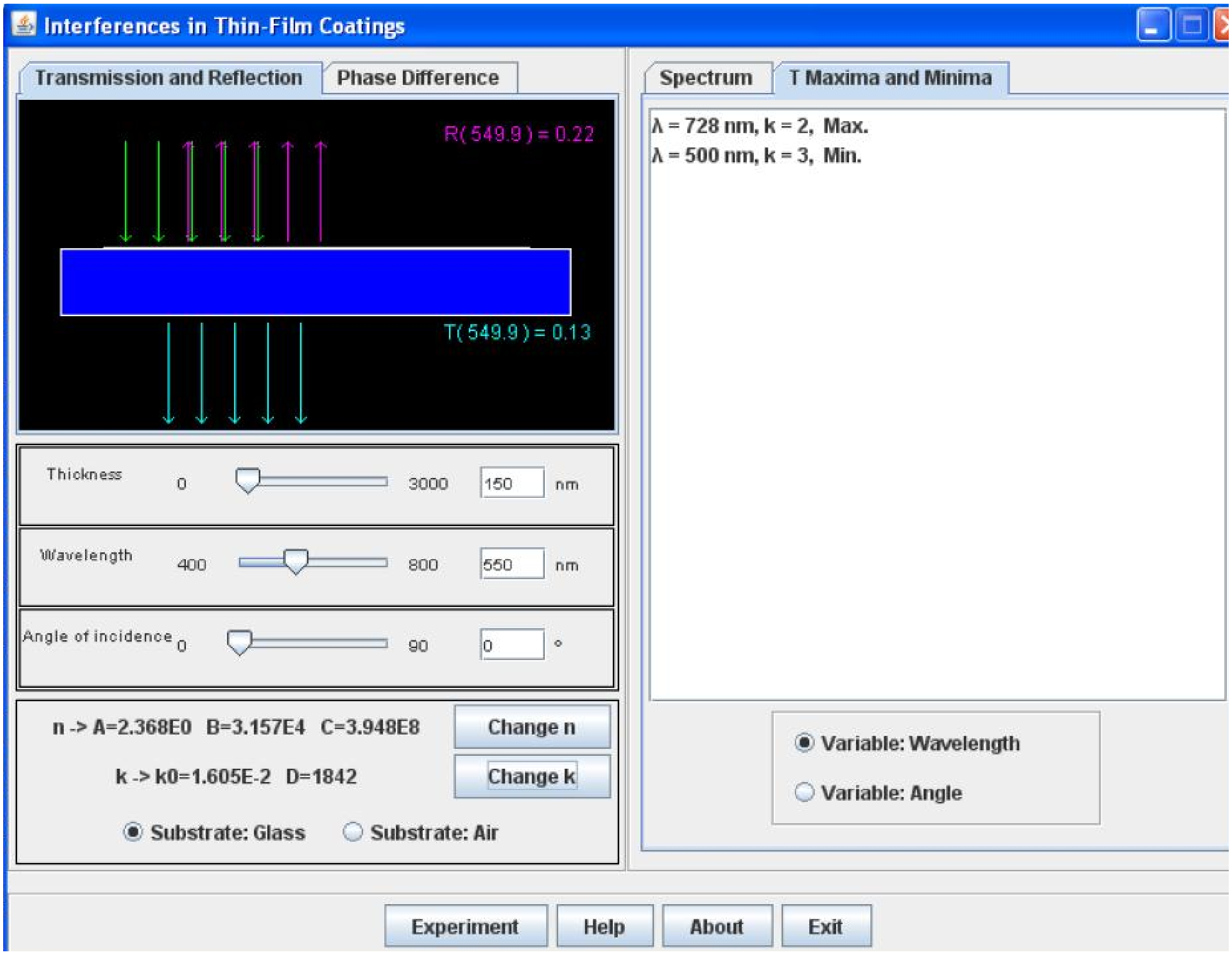

Figure 9 : Joptics windows showing $T_{max\ and\ min}$ window of absorbing material at normal incidence.

Range R" and "Auto Range T" assign automatically the minimum R/T range that permits representing the spectra of R or T respectively as shown in Figure 4-a.

(d) Window 'T Maxima and Minima'

This window shows a list of the Transmittance maxima and minima that can be seen in the spectrum plot. The option "Variable: Wavelength" lists the maxima and minima as a function of the wavelength. This list is calculated for the values of n(λ), k(λ) and thickness of the film and for the selected angle of incidence. The option "Variable: Angle" the list is calculated as a function of the angle of incidence for the wavelength selected on the left window, shown in Figure 9.

(e) The virtual experiment: the button 'Experiment'

The button "Experiment" simulates an experimental situation where a sample composed of a substrate with a transparent (k=0) thin-film coating on top of it. The thickness and refractive index of the thin-film are unknown and they have to be deduced from the analysis of a spectrum taken witn a spectrometer. The window "Spectrum" shows two spectra (in blue and in yellow, R exp and T exp) that correspond to the unknown sample and two spectra corresponding to the model with the current selected values. The virtual experiment consists of finding out the values of thickness d and of the variables A and B which characterize the spectral behavior of the refractive index. To change the values of A and B the button "Change n" should be used. The procedure to find the correct values is that of trial and error: 1) try to change the value of one of these parameters, 2) check whether the theoretical spectra fit better or not the experimental ones and 3) decide if the change in the parameter is in the right sense or not. This can be shown in Figure 10.

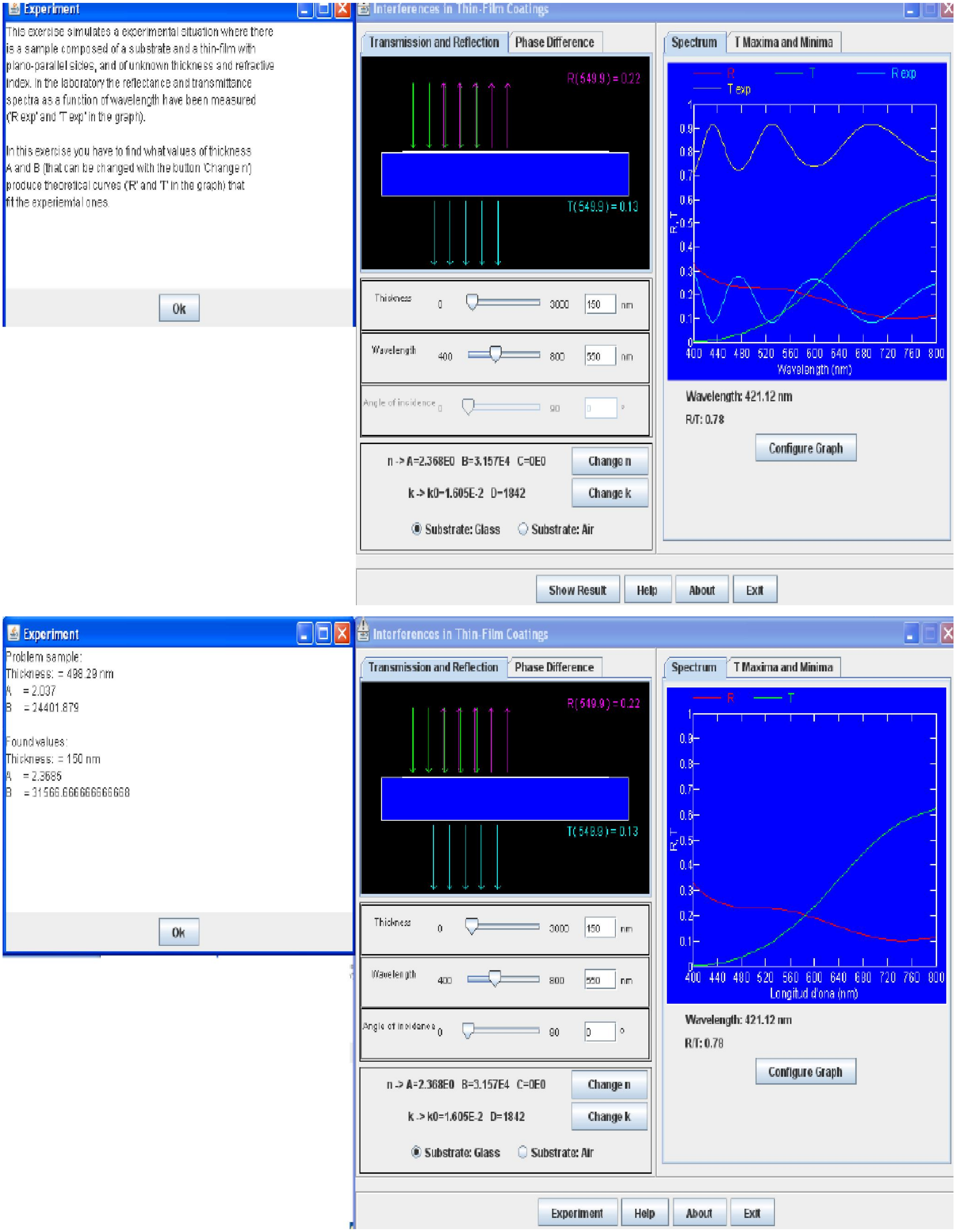

Figure 10 : Joptics windows EXPERIMENTAL window of absorbing material at normal incidence.

Examples

To illustrate Joptics applets, normal and oblique incident of light on thin film material were consider as an examples taking into account the followings:

- Choosing glass as substance with index n=1.52 at λ_0 =550nm.shown Figure 4
- Choosing MgF_2 as dielectric material with index n_f=1.38 at λ_0 =550nm, with optical thickness of quarter-wavelength (geometrical thickness d_f=99.64 nm).as in Figure5
- Absorbing material taking in to account dispersion of n and k.Figure 6.
- Phase shift due to reflection. shown in Figure 7 and 8.
- R_{exp} and T_{exp} of unknown thickness and refractive index in laboratory.shown in Figure 10.

CONCLUSION

There are at least many ways that Java applets can be used in education:

1. teachers can perform classroom demonstrations involving real-time computations, bringing more realism to the subject matter.
2. Can encourage asynchronous distance learning and thus help overcome the limitations (involving both time and space) inherent in traditional instructional techniques.
3. when used in a classroom, can bring a stronger integration between (already existing) theoretical and practical aspects of the subject.
4. This applets may be consider as :
   - informational applets which are similar to the Help files in Windows-based programs where by clicking on a tab or choosing an item from a pull-down menu, the user can obtain more information on the topic.
   - concept illustrating applets.
   - Computational Applets, can serve as examples of concepts being learnt as well as illustrating a phenomena. They can have the capability of user-interactive visualization of results and with a built-in graphical user interface (GUI) to facilitate experimentation by manipulating various parameters which can be “hard-wired”.
5. The applet can be used either in an ordinary course as support material or as the main working tool in an on-line Internet course.

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