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A Detailed Study of a Dielectric Waveguide Structure for an Enhanced Evanescent Wave Atom Mirror

S. Ghezali[1] & A. Taleb[2]

Abstract

We are interested in a coherent atom mirror (specular atomic reflections in vacuum). A resonant dielectric waveguide structure is placed upon the prism so that a large energy is confined into the waveguide which is placed between two mediums of low index medium. The incident laser beam is resonantly coupled to a waveguide mode, through the gap, by frustrated total internal reflection. We obtain a large amplitude evanescent wave in the vacuum above the waveguide. We study the influence of the thickness of the gap and the losses inside the waveguide.

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Evanescent waves generated from the total internal reflection on the surface of a prism [1] play an important role for sub-wavelength resolution. The main applications occur in near field microscopy [2, 3].

We study and optimize the coupling into a thin-film waveguide for the Rubidium line at 780.02 nm for given thicknesses of the layers.

Waveguides are thin films made of high refractive index material embedded between lower index materials. We consider an incident plane wave in the prism. If the light wave introduced into the high index film arrives to the boundary at an incidence angle which is greater than the critical angle of total reflection the light wave is confined inside the waveguide (fig1).

1 Faculty of Sciences. University Saâd Dahlab of Blida. Blida 09000. Algeria. Quantum Electronics Laboratory, Faculty of Physics, USTHB. Algiers. 16000. Algeria. Email: selma_ghezali@yahoo.fr
2 Quantum Electronics Laboratory, Faculty of Physics, USTHB. Algiers. 16000. Algeria.

The multiple reflected wave components interfere with each other. The interference will be constructive if the phase change during traveling across the waveguide plus those due to reflectance from both boundaries of the planar waveguide is integer multiple of 2π. In this case, we observe an accumulation of the energy in the waveguide. The intensity of the evanescent field in the fourth medium (vacuum) is large.

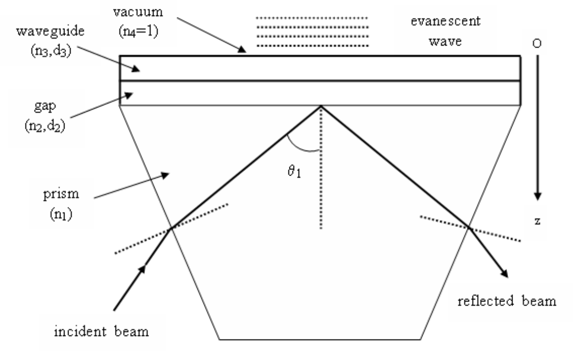

Fig.1: Schematic of the Dielectric Waveguide Structure. The Prism Base and the Gap Layer Have Respectively Index of Refraction N_1=1.893 And N_2 =1.49 .The Characteristics of the Waveguide are D_3=69.7 Nm and N_3=2.387

To study mode excitations in planar dielectric waveguides and the prism coupling technique, we consider the Maxwell formalism combined with continuity equations [4].

The main parameters characterizing waveguides are the refractive index and the low index film thickness, including θ_1, the incident angle on the surface of the prism. This paper reports on the results regarding the optimization of a number of the physical parameters in a double-layer thin film structure [5].

We are interested in the transmittance, i.e. the square of the amplitude of the electric field in the multi layer structure and in the vacuum. The intensity of the electric field is given by:

$$I(z) = I_M(z=0)\exp(\square z) \qquad (1)$$

Where $I_M(z=0)$ is the intensity of the evanescent wave at the surface of the waveguide and □ □□ is the optical thickness. The transmittance T of an evanescent wave generated from a prism coated with a double-layer thin-film structure is defined by the ratio of the intensity at the surface of the waveguide to that of the incident beam [6]:

$$T = I_M\,(z=0)\;/\;I_0 \qquad (2)$$

where I_0 is the intensity of the incident laser beam in the prism.

To obtain total internal reflection at the prism-gap interface, we operate with the incidence angles θ_1 satisfying the Snell-Descartes' relationship:

$$\sin\theta_1 > n_2 / n_1 \qquad (3)$$

The refraction angle in the waveguide θ_3 must also verify the following equation:

$$\sin\theta_3 > n_4 / n_3 \qquad (4)$$

We study the shape of the amplitude of the electric field in the structure for the mode TE m=0 (Fig.2).We note that the maximum of the amplitude of the electric field is located inside the waveguide.

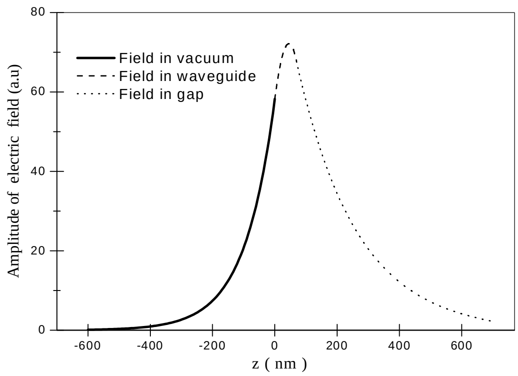

Fig.2: The Amplitude of the Electric Field Function of the Altitude Z for D_2 = 800 Nm And D_3 = 69, 7 Nm

As well, we plot the transmittance as a function of the incident wave wavelength for given values of the thicknesses of the gap and the waveguide and different values of losses in the waveguide (d_2=800nm and d_3=69,7nm). (Fig. 3).

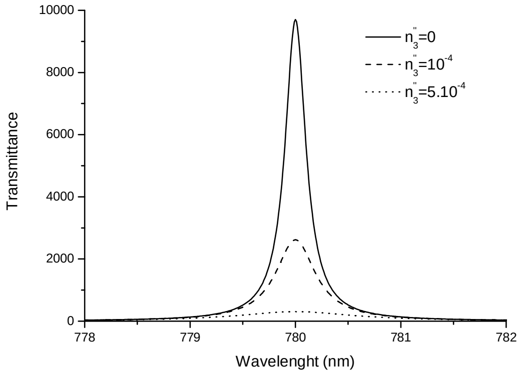

Fig.3: The Transmittance Function of the Wavelength for an Absorbant Waveguide

We see clearly that the transmittance decreases and the resonance becomes wider when we take into account the losses in the waveguide.

The figure 4 shows the transmittance of the structure function of the incidence angle for different values of the thickness of the gap.

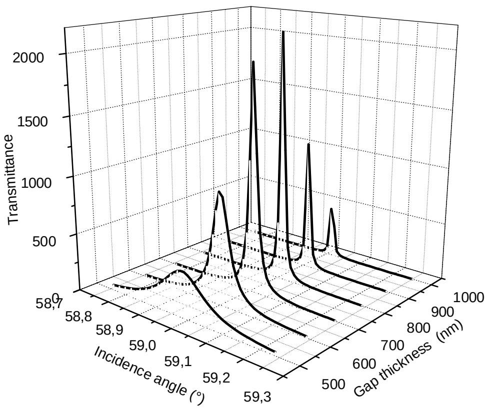

Fig.4: The Transmittance Function of the Incidence Angle Θ_1 and the Gap Thickness D_2 for the Mode TE M = 0, D_3=69.7 Nm and $n''_3 = 10^{-4}$

We notice that the transmission resonance moves to the large incidence angles and becomes narrower when the gap thickness increases [7]. There exists a transmittance peak for a given value of d_2. The incident angle corresponding to the peak approaches a constant when the thickness d_2 of the gap becomes large, which is given by the following resonance condition [8]:

$$2\,k\,n_3\,d_3\cos\theta_3 = \Psi_{34} + \Psi_{321} + 2m\pi \quad (5)$$

for m = 0,1,2, where m is the order of the waveguide mode, $k = \frac{2\pi}{\lambda}$ is the wavenumber of the incident laser beam and Ψ_{34} and Ψ_{321} are the phase changes at total internal reflection on the waveguide-vacuum boundary and on the waveguide-gap boundary respectively [6].In this formula θ_3 is the angle of refraction in the waveguide which is related to θ_1 by the relation $n_1\sin\theta_1 = n_3\sin\theta_3$. We note that the phase changes depend on the polarization of the incident field and the value of Ψ_{321} takes into account the influence of the prism (i.e. it depends on the thickness d_2 of the gap).

A graphical determination of the resonance angle [9] is given by the intersection of the two functions in the equality (5) for d_3 = 69.7 nm and λ = 780.02 nm which corresponds to D_2 line of the atom of rubidium 85. We found θ_3 = 42, 83° for the resonance angle in the waveguide.

For our system, with d_3= 69.7 nm, the only allowed resonance corresponds to the TE mode with m=0. So we study only the transmittance T for this mode.

In the case of lossless waveguide, we observe that the transmittance on resonance increases exponentially with the gap thickness while the widths of the resonance curves decrease when the gap is thicker (Fig 5a).

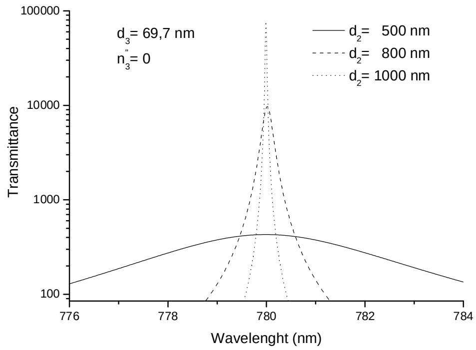

Fig.5a: The Transmittance Function of the Wavelenght for Three Values of D_2 and Lossly Waveguide

To understand the increase of the amplitude of the evanescent wave we use an analogy with a Fabry-Perot cavity. The gap layer acts as the input mirror with a transmission factor proportional to $\exp(-2\kappa_2 d_2)$ where d_2 is the thickness of the gap layer and□□$_2$ is the inverse of the penetration depth of the evanescent wave in the gap layer. Because of the total internal reflection, the interface waveguide/vacuum acts as an output mirror with a reflectivity equal to unity. As the thickness of the gap is increased, the transmission factor of the input mirror decreases, the finesse of the Fabry-Perot cavity increases and the transmittance on resonance becomes greater and the resonance sharper.

The linear fit (Fig.5b) shows that the transmittance on resonance increases as $\exp(2\kappa_2 d_2)$ for a lossly waveguide with $\kappa_2 = 51370\,\text{cm}^{-1}$ near theoretical value which is given by

$$\kappa_2 = k\sqrt{n_1^2 \sin^2\theta_1 - n_2^2} \qquad \text{where} \quad k = \frac{2\pi}{\lambda}$$

For the multi-layer structure given in reference [5], $\varkappa_2 = 51753\ \text{cm}^{-1}$.

We conclude that, in the case where the waveguide is free from losses, the transmittance on resonance increases indefinitely as d_2 is increased.

In general small losses exist always in the medium of the waveguide. We take into account these losses in our calculation by adding an imaginary part n_3'' to the index of refraction of the waveguide layer.

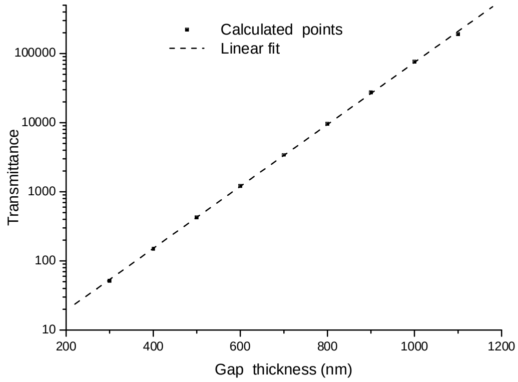

Fig.5b: The Transmittance on Resonance Function of the Gap Thickness for A Lossly Waveguide

In this case the transmittance on resonance reaches a maximum value for an optimum thickness of the gap which depends of the value of the losses (Fig.5c).

The optimum thickness is reached when the injected energy is equal to the losses in the waveguide.

The smaller the losses, the greater optimum thickness of the gap, the higher the transmission on resonance.

In the case where the losses are equal to $n_3'' = 10^{-4}$, we obtain T_{max}=2500.

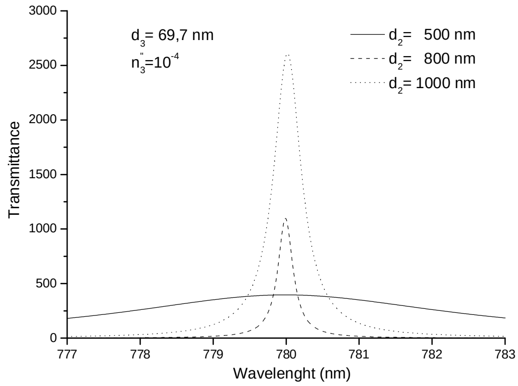

Fig.5c: The Transmittance Function of the Wavelength for Three Values of D_2 and Loss $n_3^{"} = 10^{-4}$

For given values of thickness and losses of waveguide (d_3=69.7 nm and $n_3^{"} = 10^{-4}$), we have calculated the transmittance on resonance for different values of the gap thickness d_2 from 300 to 1300 nm (Fig.6a).

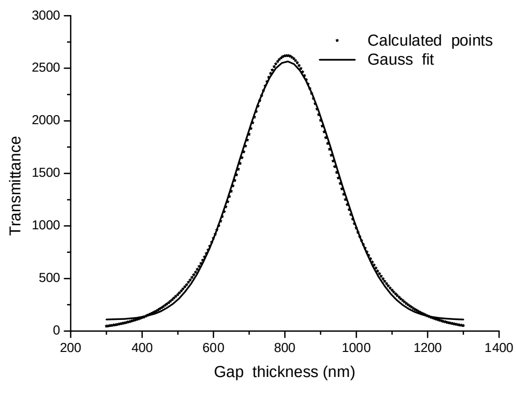

Fig.6a: The Transmittance on Resonance Function of the Gap Thickness

We plot the transmittance on resonance for low values (from 300 to 600 nm) and high values (from 1100 to 1400 nm) of d_2. (Fig. 6b and 6c)

For low values of the thickness of the gap, the energy injected by frustrated internal total reflection in the waveguide is greater than the losses of the waveguide.

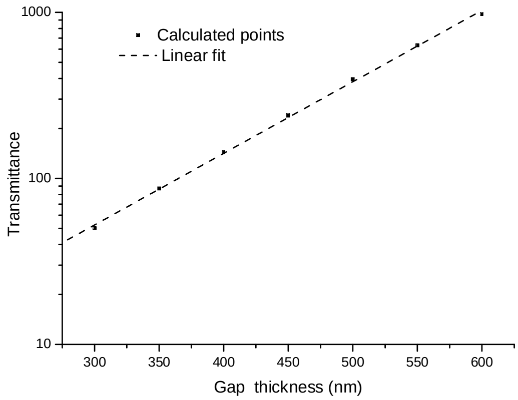

Fig.6b: The Transmittance on Resonance Function of Low Values of the Gap Thickness

For high values of the thickness of the gap, the losses of the waveguide are greater than the injected energy.

Between these two cases we have an optimal value of the thickness of the gap where the losses in the waveguide are equal to the injected energy.

In our system the optimal value is d_2 = 800 nm.

At last, we examine the influence of the thickness of the waveguide.

We notice that the transmittance in vacuum increases when the waveguide is narrowed (Fig. 7). For each value of d_3, we look for the value of d_2 which optimizes the transmittance in vacuum.

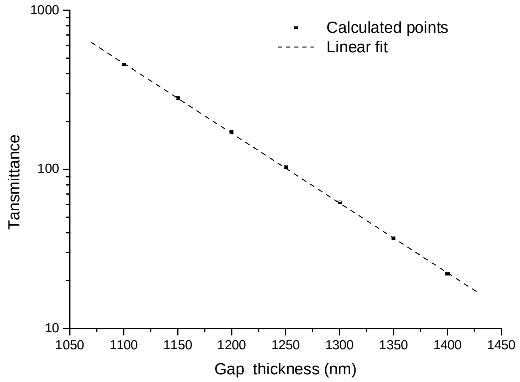

Fig.6c: The Transmittance on Resonance Function of High Values of the Gap Thickness

We observe that the transmittance on resonance increases linearly when the thickness of the gap decreases.

The energy density increases linearly in the waveguide when its thickness decreases.

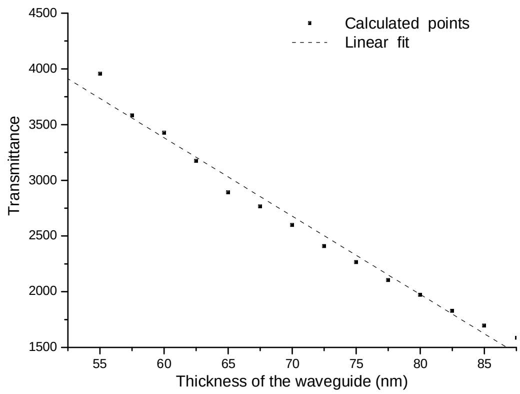

Fig.7: On Resonance Transmission Factor against the Waveguide Thickness D_3 for Losses in the Gap $n_2'' = 10^{-4}$

Conclusion

For the same high of fall, the probability of spontaneous emission during the reflection is much lower in the case of a multilayer structure than in the case of a bare atom mirror (in general a factor ten between the two cases).

As the probability of spontaneous emission during the reflection is inversely proportional to the intensity of the evanescent wave [8], it is important to increase the intensity of evanescent waves to obtain coherent atomic mirror. For that, it is more interesting to use a resonant structure instead of a bare mirror. For incident intensities on the prism of the order of $40W/cm^2$ [9], atoms can be dropped at an altitude z = 2cm for a simple atom mirror. For a detuning of 1 GHz, we have one spontaneous emission by bound for a bare atom mirror. With a multi layer film above the prism, we have to go 100 times further for the detuning to increase the number of bounds (1 spontaneous emission each 100 bounds) when the intensity of the evanescent laser wave in vacuum is increased by a factor 100. This allows to maintain the coherence of the guided structure atom mirror.

We have shown how the coupling through the evanescent field of the prism to a thin-film waveguide comes about, and how it depends critically upon the laser beam parameters, particularly the incidence angle $□_{□□}$ and the film parameters. We notice that the evanescent wave is enhanced for a given value of the incidence angle $□_{□c}$. We observe an enhancement of the evanescent wave in vacuum when the thickness of the gap is around 800 nm.The enhancement factor is about 1600 (see figures above) for the parameters of the structure taken in [5].

It is hard to get an enhanced evanescent wave when the thickness of the gap becomes larger. Also, we have to take into account the losses in the structure. When the loss of the double-layer stack is reduced, we can gain in the evanescent wave intensity.

Acknowledgments

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