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Achromatic prism-coupler for planar waveguide

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Abstract

We derive the required optical properties of a prism for coupling light achromatically into a planar waveguide. Efficient coupling over a 110 nm spectral bandwidth was experimentally demonstrated with a prism-coupler designed to match the dispersion of a particular waveguide. The design tools described here should be useful in the implementation of broadband attenuated total reflection spectroscopy in the waveguide regime to probe ultrathin and very weakly absorbing molecular submonolayers.

Keywords: Integrated optics; Waveguide; Prism-coupler; Achromatic coupler; Surface spectroscopy

1. Introduction

Attenuated Total Reflection (ATR) in the waveguide regime is a powerful technique for probing molecular monolayers. A long interaction length between guided mode and adsorbed layer on the waveguide surface yields a technique with extremely high sensitivity, usually three orders of magnitude higher than traditional transmission measurements. A major difficulty in implementing broadband ATR spectroscopy in the single mode planar waveguide configuration is the typically narrow bandwidth of conventional waveguide couplers. At a particular launching angle the coupled bandwidth is limited by a mismatch between the dispersive behavior of the waveguide and that of the coupler. Attempts to compensate for this mismatch have led several investigators to introduce an extra dispersing element to cancel the overall dispersion. Spaulding and Morris [1,2] added a transmission grating to both a prism-coupler and a grating-coupler to produce a bandwidth of 41 and 13 nm, respectively. To obtain a 5 nm bandwidth, a holographic optical element was combined with a grating-coupler by Hetherington et al. [3]. Strasser and Gupta [4] employed a grating-coupler with a reflecting grating tilted at a proper angle for a bandwidth of 17 nm. Li and Brazas [5] employed a prism and a pair of gratings to achieve an achromatic coupling of 45 nm. A configuration similar to [5], but with a higher order of dispersion cancellation and a broader bandwidth (70 nm), was implemented by Mendes et al. [6].

To our knowledge only two designs using a single optical component, both employing a prism-coupler, have been proposed for broadband coupling into a planar waveguide. Hammer [7] patented a prism design that would couple light into a waveguide for the whole visible spectrum. However, one can easily demonstrate that his Eq. (2) is incorrect because of a conceptual mistake: the refractive index of the waveguide film was used instead of the effective index of the waveguide. Therefore his prescription for prism and waveguide index of refraction is invalid. Midwinter [8] was able to produce a solution to the waveguide achromatic coupling problem under certain assumptions: (A) waveguide film and prism glass have exactly the same optical properties, (B) different wavelengths of the input beam impinge on the base of the prism-coupler with the same angle of incidence, and (C) the angle of reflection inside the waveguide is stationary with respect to the wavelength at a particular point. Conditions (A) and (B) were assumed for the sole purpose of simplifying the analytical calculations. Once those conditions were assumed then condition (C) was needed for achromatically

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coupling light into the waveguide. However, to simplify the calculations, Midwinter required experimental conditions that are difficult to fulfill. Usually prisms and waveguide films are made of different materials, and even films that could be fabricated from the same optical glass would exhibit different properties from the original bulk material due to differences in packing density and stoichiometry. Although condition (B) is important and useful for another reason that we will explain later, condition (C) is unnecessary and condition (A) is very restrictive and inconvenient. As far as we know, no attempts have been made to experimentally implement this approach.

We present here a generalization of Midwinter's article in the sense that his work is a particular case of our analysis, but we describe a much broader range of solutions. We do not assume Midwinter's conditions and we are able to obtain designs that are easily achievable in practice. Our calculation deals with the practical situation of specifying a prism for broadband coupling into a particular waveguide. For each waveguide structure, as described by the film thickness and the optical properties of the film, substrate, and cover, we derive the prism dispersion characteristics to achieve broadband waveguide coupling. Employing our analysis we designed and fabricated an achromatic prism-coupler, and broadband coupling was experimentally demonstrated.

As already reported [4,6] the spectral bandwidth coupled into a waveguide is limited not only by the broadband matching of the effective index but also by the position at which the light beam impinges on the coupler (either corner of prism, or edge of grating). All designs that add an extra dispersing component to adjust the incoupling angle cause the light beam to be shifted from its optimum coupling position for wavelengths detuned from the center line. Our configuration avoids this problem by setting the angle of incidence for the light beam to be normal to the first prism surface; therefore all wavelengths impinge on the base of the prism at the same spot, which can be adjusted for a high coupling efficiency. Moreover, the absolute coupling efficiency of the achromatic prism-coupler, which theoretically can achieve 80% for a gaussian beam [9], is intrinsically higher than previous schemes [1–6] because the addition of extra dispersing elements generally introduces additional losses. Likewise simplicity favors our approach because the critical alignment necessary for previous schemes is not required here.

2. Theory and design

The effective index of refraction, N, is defined as the projection of the wave-vector onto the waveguide plane divided by $2\pi/\lambda$, for either the waveguide, N_w, or the prism-coupler, N_p. As usual, λ is the vacuum wavelength. The coupling condition can then be written as $N_w = N_p$. Broadband coupling is achieved by requiring that both effective indices have the same dispersion behavior:

$$\frac{\mathrm{d}N_w}{\mathrm{d}\lambda} = \frac{\mathrm{d}N_p}{\mathrm{d}\lambda}. \tag{1}$$

The dispersion of the waveguide is obtained from the characteristic equation

$$\phi(\lambda, N_w) \equiv \frac{2\pi t}{\lambda}\left(n_f^2 - N_w^2\right) - m\pi - \sum_{j=s,c} \tan^{-1}\left[\left(\frac{n_f}{n_j}\right)^{2\rho}\left(\frac{N_w^2 - n_j^2}{n_f^2 - N_w^2}\right)^{1/2}\right] = 0, \tag{2}$$

where $\rho = 0$ for TE and $\rho = 1$ for TM, m is the order of the waveguide mode, and the others parameters are defined in Fig. 1.

From Eq. (2) we can write

$$\frac{\mathrm{d}N_w}{\mathrm{d}\lambda} = a + \sum_{j=f,s,c} b_j \frac{\mathrm{d}n_j}{\mathrm{d}\lambda}, \tag{3}$$

with

$$a \equiv \frac{\partial\phi/\partial\lambda}{-\partial\phi/\partial N_w}, \tag{4}$$

which accounts for waveguide modal dispersion, and

$$b_j \equiv \frac{\partial\phi/\partial n_j}{-\partial\phi/\partial N_w}, \tag{5}$$

which accounts for waveguide material dispersion, and $j = f, s, c$.

The denominator in Eqs. (4) and (5) is calculated to be

$$-\frac{\partial\phi}{\partial N_w} = \frac{2\pi}{\lambda}\frac{N_w}{\left(n_f^2 - N_w^2\right)^{1/2}} t_{\mathrm{eff}}, \tag{6}$$

where t_{eff} is the waveguide effective thickness for the corresponding polarization [10], and the numerator in Eq. (4) is given by

$$\frac{\partial\phi}{\partial\lambda} = -\frac{2\pi t}{\lambda^2}\left(n_f^2 - N_w^2\right)^{1/2}. \tag{7}$$

For the TE polarization, the numerator in Eq. (5) becomes

$$\frac{\partial\phi}{\partial n_f} = \frac{n_f}{\left(n_f^2 - N_w^2\right)^{1/2}}\left[\frac{2\pi t}{\lambda} + \sum_{j=s,c}\frac{\left(N_w^2 - n_j^2\right)^{1/2}}{\left(n_f^2 - n_j^2\right)}\right] \tag{8a}$$

and

$$\frac{\partial\phi}{\partial n_{s,c}} = \frac{n_{s,c}\left(n_f^2 - N_w^2\right)^{1/2}}{\left(n_f^2 - n_{s,c}^2\right)\left(N_w^2 - n_{s,c}^2\right)^{1/2}}. \tag{9a}$$

The corresponding expressions for the TM polarization are

$$\frac{\partial\phi}{\partial n_f}=\frac{n_f}{\left(n_f^2-N_w^2\right)^{1/2}}\left[\frac{2\pi t}{\lambda}+\sum_{j=s,c}\frac{n_j^2\left(N_w^2-n_j^2\right)^{1/2}\left(2N_w^2-n_f^2\right)}{\left[n_j^4\left(n_f^2-N_w^2\right)+n_f^4\left(N_w^2-n_j^2\right)\right]}\right] \tag{8b}$$

and

$$\frac{\partial\phi}{\partial n_{s,c}}=\frac{n_{s,c}n_f^2\left(2N_w^2-n_{s,c}^2\right)\left(n_f^2-N_w^2\right)^{1/2}}{\left(N_w^2-n_{s,c}^2\right)^{1/2}\left[n_{s,c}^4\left(n_f^2-N_w^2\right)+n_f^4\left(N_w^2-n_{s,c}^2\right)\right]}. \tag{9b}$$

The effective index of the prism, which is independent of polarization for isotropic materials, is given by

$$N_p=n_i\sin\theta_i\cos\varphi+\left(n_p^2-n_i^2\sin^2\theta_i\right)^{1/2}\sin\varphi, \tag{10}$$

and its dispersion is

$$\frac{\mathrm{d}N_p}{\mathrm{d}\lambda}=c\frac{\mathrm{d}n_p}{\mathrm{d}\lambda}, \tag{11}$$

with

$$c\equiv\frac{n_p\sin\varphi}{\left(n_p^2-n_i^2\sin^2\phi_i\right)^{1/2}}. \tag{12}$$

In Eq. (11) we have assumed no dispersion for the incident medium ($\mathrm{d}n_i/\mathrm{d}\lambda=0$), which is the most common case (air), otherwise it can easily be included. The expressions above would be equivalent to Midwinter's results if we set $n_p=n_f$ and $\theta_i=0$.

At this point we have the equations needed to calculate the dispersion characteristics of waveguide and prism. Depending on the application under consideration, a prism can be selected to match a particular waveguide configuration, or the waveguide parameters can be selected to match a particular prism-coupler, or the characteristics of both components can be allowed to vary to produce a solution to the achromatic coupling problem. In general, each polarization will require its own set of design parameters to satisfy that condition.

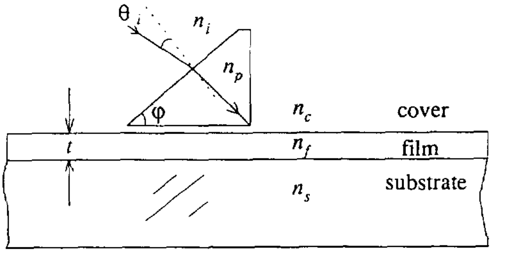

Fig. 1. Schematic representation of the prism-coupler and symbols used in the derivations.

A few conclusions can be drawn from the expressions above:

(a) The modal contribution to the waveguide dispersion is always negative ($a<0$).

(b) Due to the guided mode condition, $n_{s,c}<N_w<n_f$, and under the assumption that $\sqrt{2}N_w>n_f$ for the TM polarization, we have that b_j is strictly positive; therefore the contribution of each material to the overall waveguide dispersion is nonpositive ($b_j\,\mathrm{d}n_j/\mathrm{d}\lambda\le 0$ for $j=f,\ s,\ c$).

(c) The dispersion of the waveguide effective index is negative ($\mathrm{d}N_w/\mathrm{d}\lambda<0$).

(d) The dispersion of the prism effective index is always negative ($\mathrm{d}N_p/\mathrm{d}\lambda<0$).

We have assumed, for conclusions (b)–(d), that all media exhibit normal dispersion ($\mathrm{d}n_j/\mathrm{d}\lambda\le 0$, for $j=f,\ s,\ c,\ p$) in the wavelength range under consideration.

The conclusions above allow us to rewrite Eq. (1) as

$$|a|+\sum_j\left|b_j\frac{\mathrm{d}n_j}{\mathrm{d}\lambda}\right|=\left|c\frac{\mathrm{d}n_p}{\mathrm{d}\lambda}\right|, \tag{13}$$

which shows how strong the dispersion of the prism should be in order to match the modal and material dispersion of the waveguide. If materials with high dispersion are used in the waveguide structure (film, substrate, cover), or if the spectral region of interest is on the short wavelength side, then it is possible that no glass may be available to match the waveguide dispersion.

Up to this point we have allowed the light beam to strike the first surface of the prism at any angle of incidence (θ_i). At oblique angles of incidence, the light beam is refracted at different angles for different wavelengths. As our derivation has included this dispersion, the coupling angle will be automatically satisfied when we solve Eq. (1). However the dependence of the coupling efficiency on the position of the beam with respect to the corner of the prism [9] must be considered. For non-normal incidence, different wavelengths will have the coupling efficiency reduced because the beam is shifted outside its optimum coupling position. To avoid this undesirable effect, from now on, we assume normal angle of incidence ($\theta_i=0$) for the beam at the first surface of the coupler. This can be accomplished using either a prism with a base angle that satisfies the relation

$$\varphi=\sin^{-1}\left(N_w/n_p\right), \tag{14}$$

or a hemispherical lens-coupler.

Under the condition above, let us take the example of identifying the glass material for a prism to couple light achromatically into a waveguide when the region of inter-

Table 1
Effective index of refraction, N_w, and the contribution of each term to the overall waveguide dispersion, $dN_w/d\lambda$, are listed. The waveguide film is Corning glass 7059 with a 424 nm thickness, deposited on a fused silica substrate, and air is the cover medium. The waveguide mode considered is TE_0

N_w	$a\,(nm^{-1})$	$b_f dn_f/d\lambda\,(nm^{-1})$	$b_s dn_s/d\lambda\,(nm^{-1})$	$dN_w/d\lambda\,(nm^{-1})$
1.502	-1.116×10^{-4}	-0.414×10^{-4}	-0.067×10^{-4}	-1.709×10^{-4}

est is the visible part of the spectrum. In this case we relate the prism dispersion to the Abbe number ν by

$$\nu \approx \frac{(n_p-1)}{(\lambda_C-\lambda_F)|dn_p/d\lambda|}, \tag{15}$$

with $\lambda_C-\lambda_F = 170.1$ nm.

Once the waveguide parameters are specified, Eq. (13) determines the required dispersion properties of the prism. Eq. (15) translates this solution into the common terminology found in lens design and glass catalogs to identify the possible glass candidates. As expression (15) is just an approximate relation, the exact prism dispersion should be used to accurately test each available choice.

3. Experimental demonstration

The waveguide used for the demonstration was a Corning glass 7059 film with a 424 nm thickness, deposited on a fused silica substrate. The film deposition process and dispersion characteristics were previously described [6]. The cover and incident media were air ($n_i = n_c = 1.00$). In general, each polarization requires a specific set of design parameters to satisfy the achromatic coupling condition. Only the TE polarization was considered in the experimental demonstration, although the implementation for the TM polarization follows the same procedure to be described below if we use the corresponding expressions derived in the theoretical section.

Table 1 summarizes the calculations of the waveguide effective index and the contribution of each term to the overall waveguide dispersion. Although the values listed there are dependent on the waveguide parameters, on the wavelength, and on the polarization, they are typical numbers that illustrate the relative importance of each term. In Table 2, for each index of refraction of the prism, we list the required Abbe number to satisfy Eq. (15), as well as the range of Abbe number with available materials. There is no optical glass of low refractive index ($n_p \approx 1.6$–1.7) available to satisfy the achromatic coupling condition.

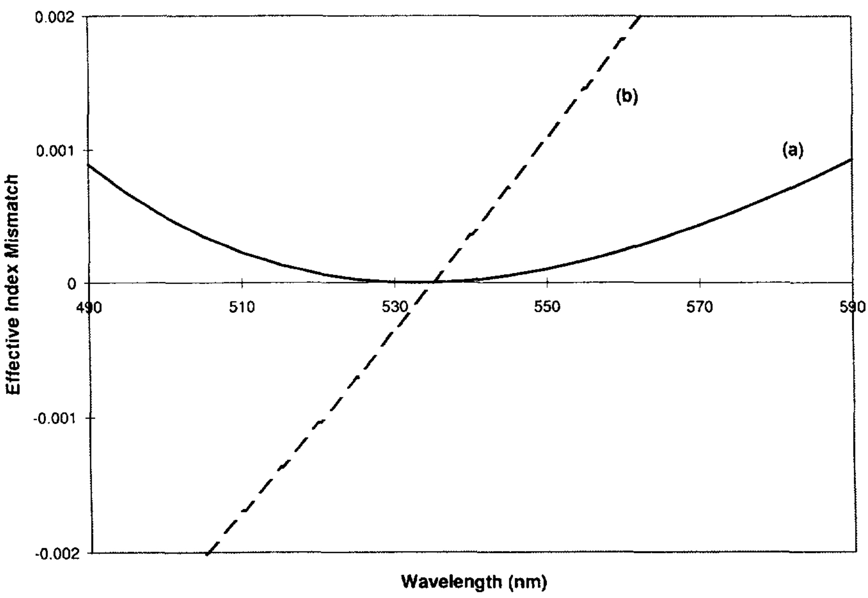

Fig. 2. Mismatch of the effective index of refraction ($\Delta N = N_w - N_p$) for: (a) the achromatic prism-coupler: Schott glass SFL6, $n_p = 1.805$, $\nu = 25.4$; (b) a conventional prism-coupler: Schott glass LaSF3, $n_p = 1.808$, $\nu = 40.6$. Both prisms have the same base angle $\varphi = 56.5°$. Waveguide parameters are the same as described in Table 1.

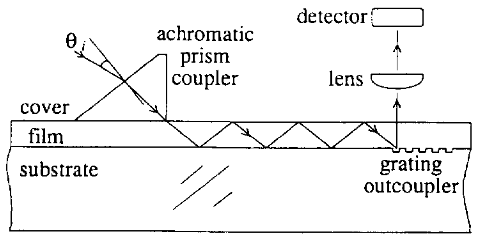

Fig. 3. Representation of the experimental setup used in the characterization of the achromatic prism-coupler.

However, the Schott glass SFL6, with $n_p = 1.80518$ and $\nu = 25.4$, closely matches the solution. The exact description of the dispersion process was then obtained by calculating the effective index mismatch between the waveguide and the prism-coupler, $\Delta N(\lambda) \equiv N_w(\lambda) - N_p(\lambda)$, which was implemented from Eqs. (2) and (10). In Fig. 2, the effective index mismatch between waveguide and coupler is plotted for the achromatic coupler designed above, as well as for a conventional prism-coupler with the same base angle and approximately the same refractive index, but with a different Abbe number, $\nu = 40.6$, to emphasize the importance of the glass material on the process of dispersion cancellation.

In our experiment, a set of six collinear gaussian beams, the 514.5 nm line of an argon-ion laser and five lines (543.5, 594.1, 604.0, 611.9, and 632.8 nm) of a He-Ne laser, were sequentially coupled into the waveguide by the achromatic prism-coupler. As shown in Fig. 3, after propagation along the waveguide the mode was outcoupled by a diffraction grating and a lens was used to focus the beam into a detector. Fig. 4 shows the angle of incidence for the excitation of the TE_0 waveguide mode, at each wavelength. The solid line describing the theoretical prediction exhibits a quadratic wavelength dependence because of the cancellation of the first-order dispersion, with a turning point located at $\lambda = 535$ nm and $\theta_i = -0.25°$.

Table 2
For different values of the prism index of refraction, n_p, we list the required value of the Abbe number, ν, to approximately match the waveguide dispersion described in Table 1. We also list the range of Abbe numbers, $\Delta\nu$, of readily available optical glasses

n_p	ν	$\Delta\nu$
1.60	21	$38 \leftrightarrow 66$
1.70	23	$30 \leftrightarrow 57$
1.80	25	$25 \leftrightarrow 45$

Broadband coupling was confirmed by measuring the relative coupling efficiency against the angle of incidence for a set of wavelengths. The experimental results of the relative coupling efficiency, defined as the outcoupled power divided by its peak value at the angle of maximum coupling, are shown in Fig. 5. A strong overlap between the curves demonstrates that, at a fixed angle of incidence, high coupling efficiency could be achieved for a broad spectral range. In particular, at the turning point angle $\theta_i = -0.25°$, the spectral full-width at half-maxima (FWHM), $\Delta\lambda$, was estimated by the expression

$$\Delta\lambda \cong \left(\frac{2\Delta\theta_i}{\mathrm{d}^2\theta_i/\mathrm{d}\lambda^2}\right)^{1/2}. \tag{16}$$

$\Delta\theta_i$ is the angular FWHM, which was approximately 0.3°,

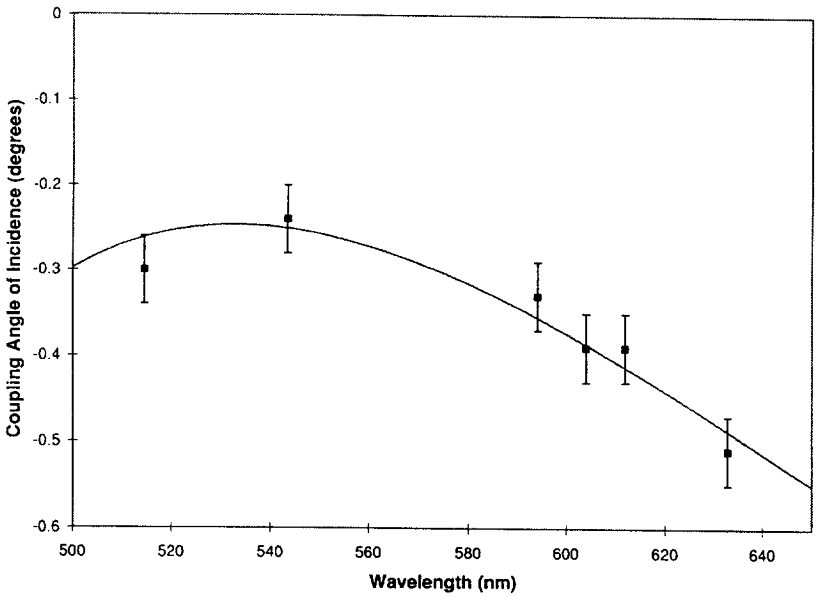

Fig. 4. Experimental angle of incidence for the excitation of the TE_0 waveguide mode by the achromatic prism-coupler for a set of wavelengths. The solid line represents the theoretical prediction. Waveguide parameters are described in Table 1 and the specification of the achromatic prism-coupler is given in Fig. 2.

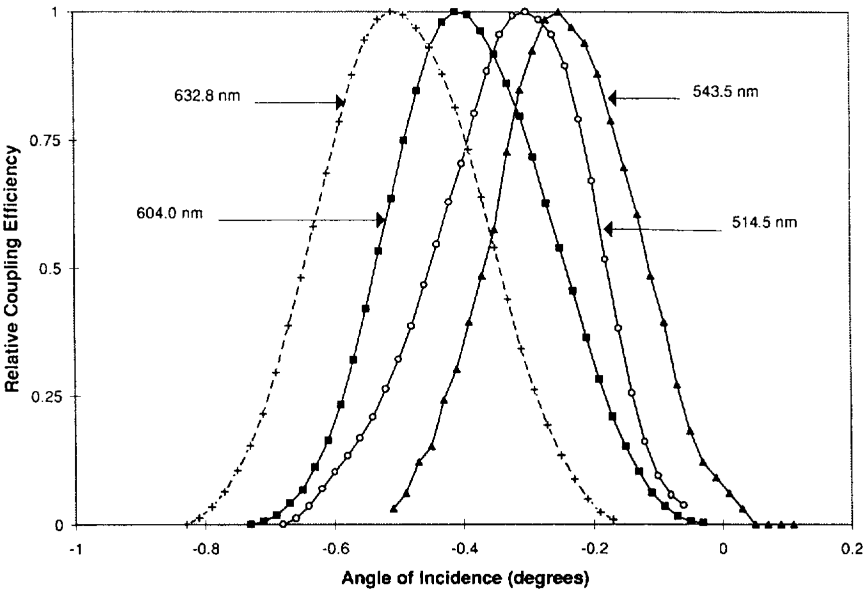

Fig. 5. Experimental relative coupling efficiency against angle of incidence, by the achromatic prism-coupler, for a set of wavelengths. Waveguide parameters are described in Table 1 and specification of the achromatic prism-coupler is given is Fig. 2.

mainly due to the angular width of the incident gaussian beam. The spectral bandwidth then obtained was $\Delta\lambda = 120$ nm. The relative coupling efficiency against the wavelength, at an angle of incidence fixed to a value of $\theta_i = -0.24°$, is shown in Fig. 6. Although the experimental results are limited to a few spectral lines, a similar spectral bandwidth, $\Delta\lambda = 110$ nm, was obtained from a gaussian fit. The maximum absolute coupling efficiency, even though it was not a point of major concern in the present demonstration, was above 10% and certainly can be increased by fine adjusting the prism–waveguide air gap and the spot size of the incident light beam [9].

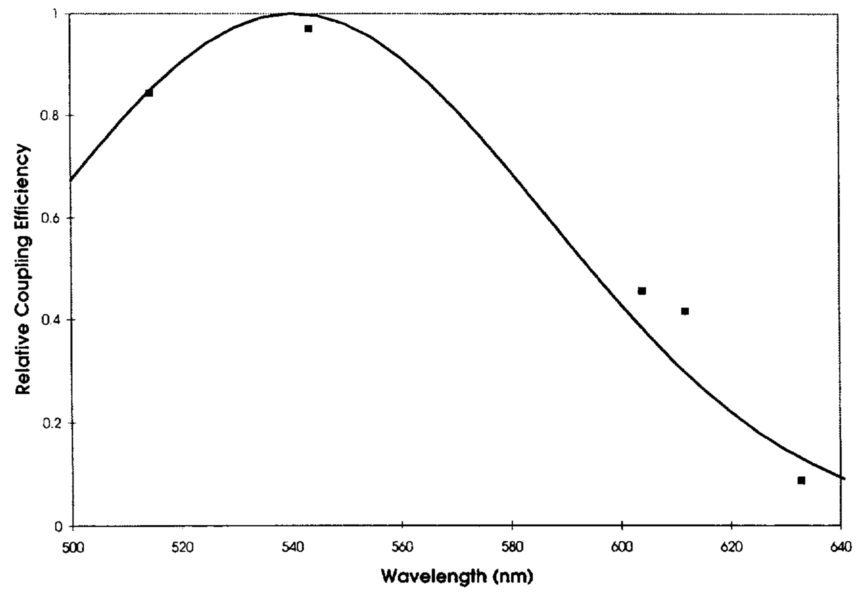

Fig. 6. Experimental relative coupling efficiency versus wavelength using the achromatic prism-coupler, for a set of wavelengths and at a fixed angle of incidence. The corresponding gaussian curve fitting is also shown. Waveguide parameters are described in Table 1 and specification of the achromatic prism-coupler is given is Fig. 2.

4. Conclusions

Analytical expressions have been derived to describe the wavelength dispersion of a waveguide. The modal contribution to the overall dispersion as well as the contribution of each waveguide element (film, substrate and cover) are described by straightforward relations. A prescription for designing a prism that achromatically couples light into a waveguide has been established and experimentally tested showing a bandwidth of 110 nm.

The approach proposed here for broadband coupling, although it does not guarantee the existence of an optical glass that matches the dispersion of any given waveguide, eliminates the use of extra dispersing elements, avoids elaborate alignments and simplifies device fabrication, in all cases when it can be applied. Most important, the limitation on the coupled bandwidth, present in previous works, by beam shifting at the edge of the coupler has been eliminated.

The results above should prove useful in the implementation of broadband attenuated total reflection spectroscopy in the single mode planar waveguide regime. Indeed, spectral characterization of an adsorbed protein submonolayer (thickness $t \approx 3$ nm, extinction coefficient $k \approx 10^{-3}$) has been recently demonstrated in a multichannel ATR waveguide spectrophotometer [11], using an earlier and more complex achromatic coupler than the one just described here. This novel type of achromatic coupler will certainly find extensive applications in ATR waveguide spectroscopy, a technique that should be valuable in the fields of chemical sensing, and in understanding the properties of adsorbed films on surfaces.

Acknowledgements

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