

Ellipsometric retrieval of the phenomenological parameters of a waveguide grating

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Abstract: Ellipsometry gives access to the phenomenological parameters of a grating coupled slab waveguide structure and permits its functional modeling without a priori knowledge of the geometry of the structure. The evidence is shown by comparing with the exact electromagnetic modeling of a sliced cross-section of a singlemode grating waveguide biosensor chip cut by FIB and analyzed by SEM.

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References and links

1. G. A. Golubenko, A. S. Svakhin, V. A. Sychugov, and A. V. Tishchenko, "Total reflection of light from a corrugated surface of a dielectric waveguide," *Sov. J. Quantum Electron.* **15**(7), 886–887 (1985).
2. B. T. Cunningham, P. Li, B. Lin, and J. Pepper, "Colorimetric resonant reflection as a direct biochemical assay technique," *Sens. Actuators B Chem.* **81**(2-3), 316–328 (2002).
3. Y. Fang, A. M. Ferrie, N. H. Fontaine, J. Mauro, and J. Balakrishnan, "Resonant waveguide grating biosensor for living cell sensing," *Biophys. J.* **91**(5), 1925–1940 (2006).
4. N. M. Lyndin, V. A. Sychugov, A. V. Tishchenko, O. Parriaux, N. Athanassopoulou, P. Edwards, C. Maule, and J. Molloy, "Enhanced visibility grating waveguide biosensor," in *Proceedings of 5th European Conference on Optical Chemical Sensors and Biosensors EUROPT@ODE V*, Lyon, France, ed. (Elsevier, 2000), p. 63.
5. B. A. Usievich, V. A. Sychugov, J. K. H. Nurligareev, and O. Parriaux, "Multilayer resonances sharpened by grating waveguide resonance," *Opt. Quantum Electron.* **36**(1-3), 109–117 (2004).
6. T. Clausnitzer, A. V. Tishchenko, E.-B. Kley, H.-J. Fuchs, D. Schelle, O. Parriaux, and U. Kroll, "Narrowband, polarization-independent free-space wave notch filter," *J. Opt. Soc. Am. A* **22**(12), 2799–2803 (2005).
7. I. Abdulhalim, "Optimized guided mode resonant structure as thermo-optic sensor and liquid crystal tunable filter," *Chin. Opt. Lett.* (to be published).
8. V. A. Sychugov, and A. V. Tishchenko, "Ray optics philosophy in the problem of corrugated-waveguide-excitation with an external lightbeam," *Photon. Opto.* **1**, 79–89 (1993).
9. D. Pietroy, A. V. Tishchenko, M. Flury, and O. Parriaux, "Bridging pole and coupled wave formalisms for grating waveguide resonance analysis and design synthesis," *Opt. Express* **15**(15), 9832–9842 (2007).
10. K. Vedam, "Non-destructive depth profiling of multilayer structures by spectroscopic ellipsometry," *Mater. Res. Soc. Bull.* **12**, 21–23 (1987).
11. M. Nevrière, "The homogeneous problem," in *Electromagnetic Theory of Gratings*, R. Petit, ed., (Springer Verlag Berlin, 1980), pp. 123–157.
12. D. Neuschäfer, W. Budach, Ch. Wanke, and S. D. Chibout, "Evanescent resonator chips: a universal platform with superior sensitivity for fluorescence-based microarrays," *Biosens. Bioelectron.* **18**(4), 489–497 (2003).
13. W. Lukosz, and K. Tiefenthaler, "Directional switching in planar waveguides effected by adsorption-desorption processes," *IEEE Conf. Publ.* **227**, 152–155 (1983).
14. K. Schmitt, K. Oehse, G. Sulz, and C. Hoffmann, "Evanescent field sensors based on tantalum pentoxide waveguides – a review," *Sensors* **8**(2), 711–738 (2008).
15. H. Mukundan, A. S. Anderson, W. K. Grace, K. M. Grace, N. Hartman, J. S. Martinez, and B. I. Swanson, "Waveguide-Based Biosensors for Pathogen Detection," *Sensors* **9**(7), 5783–5809 (2009).
16. A. M. Popa, B. Wenger, E. Scolan, G. Voirin, H. Heinzelmann, and R. Pugin, "Nanostructured waveguides for evanescent wave biosensors," *Appl. Surf. Sci.* (to be published).
17. B. H. Cheong, O. N. Prudnikov, E. Cho, H. S. Kim, J. Yu, Y. S. Cho, H. Y. Choi, and S. T. Shin, "High angular tolerant color filter using subwavelength gratings," *Appl. Phys. Lett.* **94**(21), 213104 (2009).
18. N. Lyndin, "MC grating: diffraction grating analysis," <http://www.mcgrating.com>.
19. <http://www.sopra-sa.com/5-spectroscopic-ellipsometer-se.php>.

20. J. H. Liu, C. W. Liu, K. J. Huang, T. Y. Li, M. C. Chiu, J. J. Hong, C. Chung-Ping Chen, C. S. Jao, and L. Wang, "Efficient and accurate optical scatterometry diagnosis of grating variation based on segmented moment matching and singular value decomposition method," *Microelectron. Eng.* **86**(4-6), 999–1003 (2009).
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1. Introduction

A slab waveguide grating placed on the path of a free space beam gives rise to interesting and possibly useful effects when the incidence conditions and structure parameters correspond to waveguide mode excitation. The best known and often used effect is that of abnormal, or resonant reflection first identified and analyzed by Sychugov et al. [1]. This theoretically 100%, very selective reflection effect is now widely used in biosensors [2–4]. Its wavelength selectivity is advantageously used under normal incidence in laser mirrors to narrow down the emission linewidth as well as to control the polarization of laser emission, for instance the direction of the linear polarization of a microchip laser or the electric field orientation in the radially polarized mode of a high power laser. In association with a second mirror of the multilayer type, this resonant reflection effect is changed to a resonant transmission thanks to the Fabry-Perot resonance taking place between the standard and resonant mirrors [5]. It can also be used to (de)multiplex narrowly spaced wavelength channels when made polarization independent [6]. It can give rise to frequency agile devices if the waveguide index can be modulated as in the case of liquid crystal waveguides or electrooptical polymer waveguides [7].

This list of applications is not exhaustive, but it expresses the diversity of optogeometrical configurations and of possible structural material implementations. Numerical modeling can easily calculate such resonances and a number of codes are available. Nothing however replaces physical intuition for analyzing and inventing new optical functions or devices. The basis for physical intuition is a modal representation with a restricted number of physically meaningful phenomenological parameters [8]. These are the radiation coefficient α of the mode used in the resonance effect, its propagation constant β in the corrugated waveguide, the coupling coefficient κ_c between the incident wave and the mode, and the diffraction efficiency η_c of this mode into the incident medium. The product of κ_c and η_c define the compound phenomenological parameter called the coupling constant $a_p = -j\kappa_c\eta_c$ where $j = \sqrt{-1}$. Although these phenomenological parameters give a full understanding and quantification of the resonance, they are not related with the optogeometrical parameters in a simple fashion. The link between the former and the latter can be established analytically under some hypothesis, for instance by means of the Rayleigh-Fourier method; however this is valid only under the assumption of a shallow grating corrugation. The polar representation of a single resonance in the reflection function permits to find out the phenomenological parameters from numerical modeling and, more importantly, the latter can be retrieved from experimental quantities which are rather simple to measure; plotting the measured complex reflection coefficient upon a scan of the incidence angle or of the wavelength results in a circle in the complex plane from where the phenomenological parameters can be extracted meaningfully as shown in [9]. Such measurement can very suitably be made by means of an ellipsometer as demonstrated in the present paper on high quality corrugated waveguide structures used in biosensing. The aim of the present paper is to show experimentally that the operation and the properties of a waveguide grating coupler can all be determined by a simple ellipsometer scan. The key for this is the link that was established in [9] between the restricted number of meaningful waveguide grating phenomenological parameters α , β and a_p and the specific features of the reflection coefficient of the incident wave on the structure.

2. Phenomenological parameters retrieval

We have shown in [9] that, in the neighborhood of a mode coupling resonance, the locus of the reflection phasor $r(k)$ in its polar representation $r(k) = r_0 + \frac{a_p}{(k - \beta) - j\alpha}$ in the complex plane in the presence of waveguide resonance is a circle upon a variation of the compound in-plane spatial frequency parameter k as reminded in Fig. 1 for a typical high-index grating waveguide structure propagating the TE₀ mode.

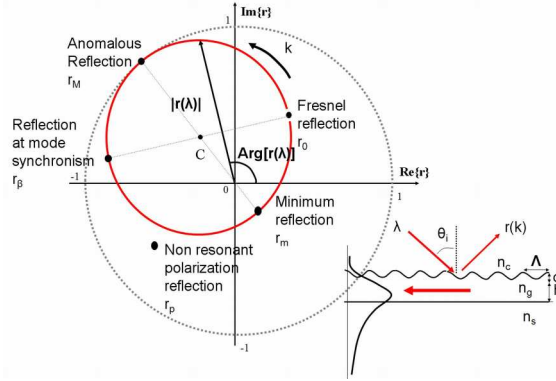


Fig. 1. Complex plane representation of the features of the reflection coefficient with k as a parameter. The insert represents a typical waveguide structure under -1 st order mode coupling. All quantities are defined in [9].

As a preparation to the next section on the ellipsometric measurement it is interesting to point out that the scan of k in the absence of resonance would ideally be represented as a point in the complex plane as shown in Fig. 1. In fact it is a curve limited within a small area of the complex plane as shown later in Fig. 4. This point will also be discussed in section 6.

The analysis undertaken in [9] on the polar expression $r(k)$ of the reflection coefficient of a waveguide grating has provided analytical relationships between the wave coupling phenomenological parameters and these experimentally measurable values of the parameter k describing the circle. α , β and a_p are respectively given by expressions (21), (23) and (14) in [9].

3. Ellispometric measurement methodology

Ellipsometry is an optical technique commonly used to analyze a surface or to determine the thicknesses and refractive indices of a multilayer structure [10] for example. It is based on the analysis of the polarization state of the reflection from a sample. The polarization state is described by the ratio $\tan\Psi$ between the reflection coefficient modulus of the p-polarized and s-polarized (TM and TE respectively) components and to their phase difference Δ . Thus, the s-polarized reflection coefficient phase φ_s and modulus $|r_s|$ can be written as a function of the ellipsometric parameters Ψ and Δ , and also of the phase φ_p and modulus $|r_p|$ of the reference p-polarized reflected wave:

$$|r_s| = \frac{|r_p|}{\tan\Psi} \quad (1)$$

$$\varphi_s = \varphi_p - \Delta$$

The characterization of the resonant reflection from a grating coupled waveguide is well adapted to ellipsometric measurement since it is a 0th order effect in the direction of the Fresnel reflection mediated by the first order mode coupling of the grating. The polarimetric

measurement made by an ellipsometer allows to measure the phase and amplitude of the polarization experiencing the resonance relative to the orthogonal polarization which experiences no waveguide mode resonance in the scanning domain of the parameter k . In the absence of resonance the reflection coefficient of a grating waveguide varies only slowly and can therefore be considered as essentially constant in phase and amplitude and can be used as a reference. Let us now assume that the s-polarization experiences resonant reflection and that the p-polarization is taken as reference. That the essentially constant amplitude and phase of the reference are unknown is not a matter of concern for the retrieval of the phenomenological parameters α and β since an unknown but constant phase offset on the resonant s-polarized reflection amounts to a simple rotation of the complex plane of Fig. 1 leaving the relative positions of the points r_m , r_M , r_β and r_0 unchanged. Similarly, an unknown but constant modulus of the p-polarized reflection amounts to an homothety in the complex plane of Fig. 1 leaving ρ given in expression (20) of [9] identical. Thus, using ellipsometric measurement and expression (1), $|r_s|$ will be inversely proportional to $\tan\Psi$ and scaled by $|r_p|$, and $\varphi_s = \arg(r_s)$ will be the opposite of Δ shifted by $\varphi_p = \arg(r_p)$:

$$\begin{aligned} |r_s(k)| &\propto \frac{1}{\tan\Psi(k)} \\ \varphi_s(k) &= \varphi_p - \Delta(k) \end{aligned} \quad (2)$$

Therefore, as the radiation coefficient α and the propagation constant of the mode β only depend on a spatial frequency term and on a function of ρ according to (21) and (23) of [9], their retrieval won't be affected by the ellipsometric scaling with the factor r_p . This is very valuable information for the design or optimization of a resonant functional element. This might however not be sufficient under the circumstances where one has to go back to the coupled wave Eq. (11) for a complete modeling of some coupling problem. In such case the third phenomenological parameter a_p , the coupling constant, must be known in amplitude and phase. This implies, according to expression (14) of [9] where all terms in the bracket scale with r_p , that both phase and amplitude of the reflection coefficient of the p-polarization at the waveguide grating surface must also be known. The measurement of the modulus $|r_p|$ is an easy matter. However, the absolute phase of a reflection coefficient is less easy to measure; it can for instance be determined as follows as an add-on to an ellipsometer: a transparent plate comprizing a few binary etched zones at different depth is placed in hard contact on the surface under study. The range of depths is of the order of a few wavelengths. Each zone represents a Fabry-Perot cavity operating in the first order range. The analysis of the sampled reflection modulation gives access to the sole unknown of the problem: the phase and amplitude of the surface reflection coefficient.

4. Experimental and exact modeling verification

The relevance of achieving the full functional modeling of a resonant waveguide grating structure on the basis of the sole phenomenological parameters without a priori knowledge of the structure optogeometrical data will now be shown by considering an actual grating waveguide used as a biosensor [12]. This choice is motivated by the fact that biosensing was the first [13] and has been the most important application field for grating coupled slab waveguides. The hardware of such sensors is usually very simple, comprising a corrugated glass substrate coated by a uniform high index layer. This layer is quite often Ta_2O_5 as reviewed in [14]. Several excitation and detection schemes can be used. References [2–4] use the very resonant reflection peak as the measurand. Other groups use one grating for beam coupling and a second grating for outcoupling [15], and there are also variations in the interrogation technique as for instance wavelength tuning [16]. Another application of resonant reflection could have been chosen as a test structure instead of a biosensor chip, for

instance color filters for LCD [17], but such application is still at the R&D stage, and the detailed structure and materials are by far not fixed yet.

An ultra-thin slice of this biosensing element was cut orthogonally to the grating lines by focused ion beam (FIB) and its profile analyzed by SEM. From this scan the geometrical parameters are determined and with the knowledge of the different refractive index an exact electromagnetic modeling is made which also gives the phenomenological parameters α and β . The results of the exact analysis will be compared with those obtained by ellipsometry without knowledge of the structure geometry.

The waveguide grating submitted to ellipsometric characterization is made of a corrugated glass substrate with a high index tantalum pentoxide film deposited onto an essentially binary corrugation. With a period Λ of 360 nm, a depth σ smaller than 40 nm, the corrugation at the cover side of the slab of 120 nm thickness should be conformal to the substrate corrugation. Conformal waveguide layer deposition on a corrugation is a very tolerant waveguide grating excitation scheme since the local thickness of the waveguide, therefore the local modal effective index, are constant, therefore the resonance position does not depend on the grating imperfections which usually in a single-sided waveguide corrugation is the main cause of non-uniformity of the resonant structure. The narrow slice of the 40 nm deep grating waveguide is represented by its SEM scan in Fig. 2. It shows a slight difference between the two undulations: the substrate corrugation is 47 nm deep in glass with a fill factor of about 0.4. The top corrugation has a slightly larger fill factor of about 0.6 and is only 40 nm deep. The Ta_2O_5 layer is 127 nm thick. The microstructured sensor platforms were fabricated by Unaxis (now supplied by Optics Balzers AG, Liechtenstein).

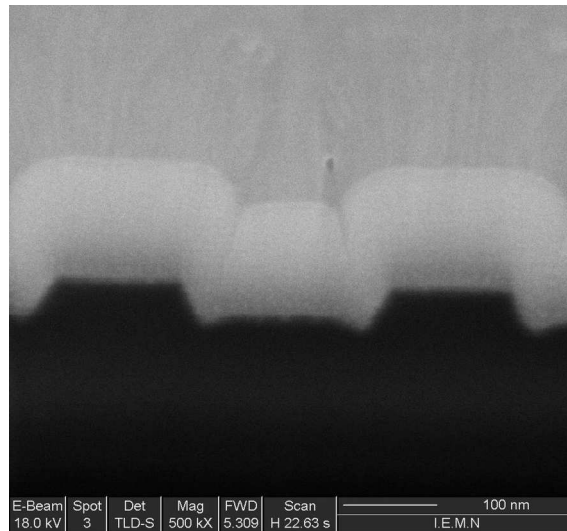


Fig. 2. SEM picture of a slice of the Ta_2O_5 -coated glass corrugation cut by focused ion beam.

The real structure, assumed to be binary, was numerically modeled using a commercial software [18] based on the true-mode method: the modulus and phase of the reflection coefficient are presented in Fig. 3 (dotted line). The scattering matrix of the structure gives access to the characteristics of the excited mode by studying its pole [11]. Thereby, a TE mode is found to be excited under an incidence angle $\theta_0 = 25.12^\circ$ by a s-polarized wave at a wavelength λ_0 of 764 nm. This mode is characterized by a propagation constant $\beta = 13.97 \mu\text{m}^{-1}$ and a radiation coefficient $\alpha = 0.84 \mu\text{m}^{-1}$.

5. Phenomenological parameters retrieval by ellipsometry

The ellipsometric measurements were performed using a Sopra GES5E Ellipsometer [19] with the rotating polarizer method. The k -parameter is scanned at constant wavelength by varying the incident angle across the TE_0 mode resonance. The light source is a short arc xenon lamp. The 764 nm line was used with a spectral width of 0.2 nm. The beam divergence was limited by injecting the light into a 200 μm core fiber whose output beam was collimated by a 130 mm focal lens resulting in a beam divergence about 0.1° . The final spot diameter impinging onto the samples was about 2 mm. The amplitude and phase $|r_s(k)|$ and $\phi_s(k)$ of the reflection coefficient of the resonant polarization were calculated from the measured ellipsometric data using expression (2). However, expression (2) only gives the shape of the amplitude response of the structure. To obtain the absolute reflection modulus, $|r_p|$ must be known to scale $r_s(k)$ according to expression (1). To that end, $R_p = |r_p|^2$ was measured using a large spectrum supercontinuum source sent through a monochromator to filter a narrow band centered at 764 nm which is the wavelength of the line chosen for the ellipsometric measurement. The monochromatic output beam is then p-polarized and directed onto the waveguide grating. Making the ratio of power after and before the grating plane gives the power reflection coefficient $R_p = 9.8\%$. Thus, $|r_p|$ is 0.313 and all experimental values of $|r_s(k)|$ are scaled according to (1).

These experimental data permit to determine the off-resonance r_0 , the resonant (maximum) r_M and the minimum r_m values of the TE reflection coefficient. The phenomenological parameters were then retrieved using the methodology of [9] succinctly referred to in section 2. These parameters were finally injected into expression (11) of [9] to calculate the reflection coefficient so that experimental and retrieved reflection coefficient curves can be compared.

The experimental measurements presented in Fig. 3 (crosses) first give access to the off-resonance reflection coefficient taken as the mean of the reflection coefficient values at the limits of the scanning range: $r_0 = 0.356\exp(-3.043j)$. The resonant reflection occurs at an incidence angle $\theta_M = 25.4^\circ$ corresponding to a spatial frequency $k_M = 13.93 \mu\text{m}^{-1}$ using (2) of [9] and the reflection coefficient takes the value $r_M = 0.992\exp(-2.430j)$. The minimum of reflection occurs at an incidence angle $\theta_m = 22.8^\circ$ corresponding to a spatial frequency $k_m = 14.27 \mu\text{m}^{-1}$ using expression (2) of [9] and the minimum reflection coefficient takes the value $r_m = 0.235\exp(-2.481j)$. Using expression (23) of [9], the propagation constant is determined: $\beta = 14.11 \mu\text{m}^{-1}$ which means an error of 1% between numerical and experimental results. The experimental radiation coefficient is also calculated using expression (21) of [9] and is found to be $\alpha = 0.91 \mu\text{m}^{-1}$: the relative error between numerical modeling presented in section 4 and experimental determination is less than 10%. It is however important to note here that if a slightly different layer thickness (120 nm instead of 127 nm) is considered for the corrugated waveguide, the numerical calculation of α and β performed in section 4 leads to values much closer to the experimental ones. This means that the error affecting the experimental retrieval of the phenomenological parameters can mainly be attributed to a slight difference between the real and the modeled structure i.e. to the grating shape which is not perfectly binary and also to the error made on the opto-geometrical parameters of the structure (refractive index and thickness) mainly determined on the basis of the SEM picture (Fig. 2). Finally, the coupling constant a_p was calculated using expression (14) of [9]: $a_p = 0.524\exp(2.835j) \mu\text{m}^{-1}$. The reflection coefficient is then calculated by injecting the phenomenological parameters just obtained by ellipsometric measurement into the polar expression of the reflection coefficient (11) of [9]. The results are represented in Fig. 3 for the amplitude and phase response as well as in Fig. 4 for the complex plane representation of the reflection coefficient.

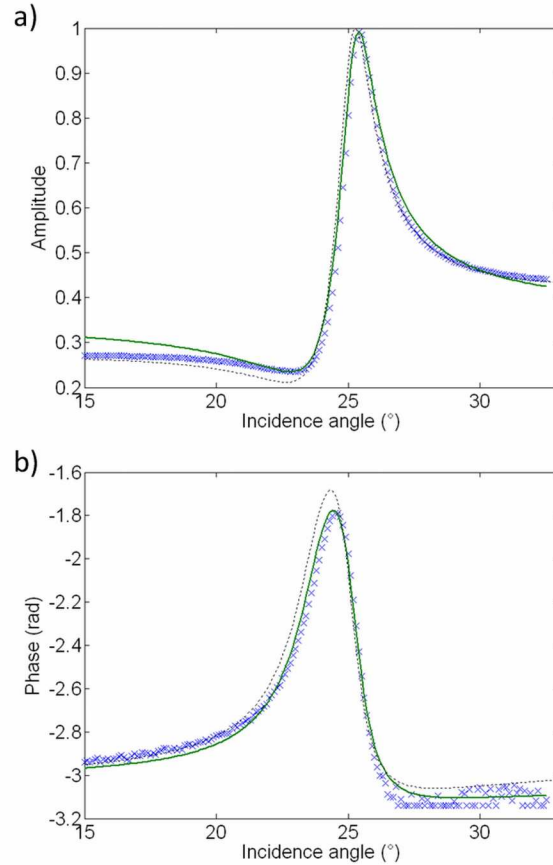


Fig. 3. Ellipsometric measurements (crosses), phenomenological retrieval (solid line) and numerical modelisation (dotted line) of the amplitude (a) and phase (b) of the reflection coefficient upon incidence.

In order to ease the graphical comparison between the numerical and experimental phase dependences of Fig. 3, the numerical curve was angularly shifted close to the experimental curve by about 5.6 rad. This phase shift actually reveals to be the phase of the non-resonant reflection coefficient r_p calculated numerically and represented in Fig. 4. The slight discrepancy at the edges of the scanning range between the ellipsometric measurement and the phenomenological retrieval model is due to the approximation made on the off-resonance reflection coefficient r_0 . In the phenomenological approach, r_0 is considered as a constant over the scanning range while it does vary slowly as shown in Fig. 3 from the exact electromagnetic model. In Fig. 4 is also represented the numerically calculated reflection coefficient r_p of the non-resonant p-polarization in the same scanning range. This brings the evidence that it can be considered as essentially constant and therefore can be taken as a reference for the resonant s-polarization, as anticipated on the sole basis of theoretical modeling in Fig. 1.

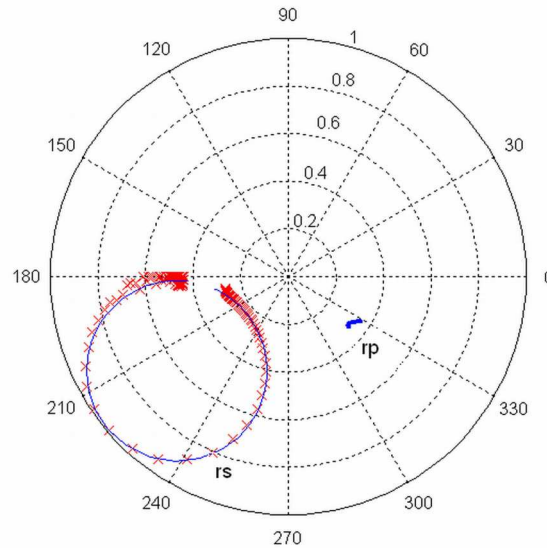


Fig. 4. Representation of the reflection coefficient r_s of the TE resonant polarization in the complex plane: ellipsometric measurements (crosses) and phenomenological retrieval (solid line). The small cloud of points at about 325 degree azimuth represents the numerically modeled reflection coefficient r_p of the non-resonant TM polarization.

6. Validity domain and usefulness of the phenomenological approach

Reference [9] gave the basis for connecting the optogeometrical parameters of a grating coupled slab waveguide with the phenomenological parameters, and the present paper makes the experimental demonstration that the phenomenological parameters retrieved by means of an ellipsometer account for the characteristics of resonant reflection as well as an exact code does on the basis of the accurately, but destructively measured optogeometrical parameters. Two issues will be discussed in the present section. The first one is on the validity domain of the phenomenological approach relative to the number of waveguide modes and of diffraction orders, the second issue is on the assumption that the non-coupled polarization can be considered as a reference for the ellipsometric measurement. We will then conclude on the usefulness of the approach.

The statement that in the phenomenological modelling of the resonant structure no a priori knowledge of the structure geometry is needed must be associated with validity conditions. A multipole case with more than one mode and/or more than one diffraction order can still be tentatively described by a sum of polar expressions. However, the number of phenomenological parameters increases proportionally with the number of poles whereas the number of optogeometrical parameters remains the same. The intelligibility which a mode coupling approach permits quickly transforms to a more complex problem as soon as the mode number of each polarization is larger than 1 or 2; large period/wavelength ratios still lead to resonance characteristics which can be understood with the same vision, but a quantitative representation is practically beyond reach, and particularly useless. As a matter of fact, most applications using the effect of resonant reflection need high efficiency in the 0th order, therefore impose a suppression of the second diffraction order, and even if possible the + 1st order. Besides, it is in the single mode regime that the radiation coefficient of a grating waveguide mode is maximum, and, by the way, also the sensitivity of an evanescent wave waveguide grating sensor. Therefore, the domain of validity, and the usefulness, of the phenomenological representation match well with the conditions of optimal use of such resonant structures.

The second issue to be discussed is on the correctness and generality of the hypothesis that the non-coupled polarization (the TM polarization in the chosen example) can serve as an amplitude and phase reference upon the scan of k in the scanning domain. The reflection coefficient of a non-coupled polarization is in most cases of interest that of a dielectric layer on a transparent substrate with the corrugation slightly degrading the reflection at the interface where it is located. The only reflection variations which can occur in such structure upon a variation of k come from the Fabry-Pérot filter effect in the waveguide layer. In a single mode layer the Fabry-Pérot effect is an extremely slow effect versus k (i.e. versus the wavelength or the incidence angle) since it is in the region of the first order and, furthermore, its contrast is very small except in cases where the layer is made of silicon as in a SOI structure for instance. Of course one first has to check that there is no mode of the reference polarization excited in the scan domain; those familiar with the art of waveguide resonances will easily check on this knowing that the TE and TM resonances of a thin high index slab waveguide of small mode number are far apart. Considering that the scanning range of k just has to frame a little more than the resonance peak of the mode coupled polarization, it can reasonably be admitted that the non-coupled polarization may be used as a phase and amplitude reference in an ellipsometric measurement. As shown numerically in Fig. 4, the locus of r_{TM} is a little cloud of restricted area in the complex plane of 5% extent in amplitude and 10 degrees in phase. r_{TM} is however not strictly constant and taking it as a reference inevitably leads to an error. The question which matters is what is the impact of this error and is it larger than an alternative method. By judging from how the results of Fig. 3 and 4 fit, the error is remarkably small. Besides, the optogeometrical parameters of a grating coupled waveguide can at any rate not be measured precisely and non-destructively, and furthermore no method exists for the time being to precisely quantify the long range uniformity of the resonant corrugation. Under such circumstances, the interest of the phenomenological approach is to offer a reasonably precise quantitative measurement method and, most importantly, to enable the measurement of functional parameters which are close and relevant to the very *modus operandi* of the element, and also to account for its long range characteristics such as the uniformity of the depth and duty cycle of the grating. The only possible alternative to the ellipsometric technique proposed here is scatterometry associated with a solution of the inverse problem [20]. The scatterometry of gratings is now widely used in microelectronic process control. To the best knowledge of the authors it has not been used for the characterization of resonant diffractive structures yet.

7. Conclusion

We have shown that the phenomenological parameters of a grating coupled slab waveguide can be determined by means of ellipsometric measurement without a priori knowledge of the waveguide and grating optogeometrical parameters provided the waveguide propagates a few modes only and the number of diffraction orders propagating in the adjacent media is no more than 1 or 2. The accuracy on the retrieved characteristics is rather high and no smaller than what can be derived from a destructive SEM scan of a FIB-sliced waveguide cross-section or/and from an AFM scan of the corrugation. This characterization method can be used regardless of the waveguide and grating technology, for instance the waveguide and grating can be of the graded index type like ion exchanged or in-diffused or else photomodified structures where AFM and SEM techniques are of no help. This method does not lead to an analytical tool, but rather to a contactless and non-destructive characterization tool permitting the quantitative on-line testing of the optical function of resonant elements of a definite type. The most notable contribution of the present paper is to permit the non-destructive and contactless functional characterization of resonant diffractive elements by means of the very instrument which is already widely used for the test of structures and process control in microelectronics.

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