Design software for stratified optical systems with planar and cylindrical symmetry

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A new software for design and simulation of stratified optical systems is presented. It consists of a modern Java based graphical user interface with an underlying C++/Fortran computational core. The software allows simulation as well as design and analysis of measurements.

1 Introduction

Recent technological developments allow the manufacturing of optical devices based on stratified structures with various practical applications. For optimal application results efficient design methods of the complex structures are required. The presented software tool ATSOS allows the simulation and design of planar and cylindrical multilayer geometries. It comes with features to calculate reflection and transmission and ellipsometric parameters as well as guided and leaky modes in such structures. Materials with complex refractive index like metals or interfaces with high refractive index contrast can be handled exactly. The solver is fully vectorial and allows also complex propagation constants. Future work will aim for providing an interface to hardware for collection of data and building an integrated system for combined measurement/data analysis and design.

2 Theoretical Background

To calculate electromagnetic wave propagation in stratified media in the frequency domain the Helmholtz equation has to be solved.

$$\left(\nabla^2 + k^2\right)A = 0 \tag{1}$$

In the planar isotropic geometry these equation splits into two uncoupled one-dimensional equations for the transverse electric (TE case) and transverse magnetic (TM case) fields.

$$\begin{aligned}\left(\partial_{xx} + k_x{}^2\right)E_z &= 0\\ \left(\partial_{xx} + k_x{}^2\right)H_z &= 0\end{aligned} \tag{2}$$

In the cylindrical geometry the Helmholtz equation can be preferably solved for the two longitudinal fields E_z and H_z which leads to two coupled equations (3), where z is the propagation axis. To find guided modes or reflection and transmission coefficients for a given system, the system has been split into a stack of layers for which analytical field-solutions can be found.

$$\begin{aligned}\left[\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \left(k_0^2 K_j^2 - \frac{\nu^2}{r^2}\right)\right]H_Z^j(r) = 0\\ \left[\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} + \left(k_0^2 K_j^2 - \frac{\nu^2}{r^2}\right)\right]E_Z^j(r) = 0\end{aligned} \tag{3}$$

These are exponential functions for planar geometry and Hankel functions for cylindrical symmetry [1-3]. Fulfilment of the boundary conditions between the layers leads to transfer matrix equations which connect the fields in the outermost layers. From this transfer matrix a characteristic equation can be derived which provides the modal propagation constants. Also reflection and transmission coefficients can be found from this matrix.

3 ATSOS-Software Features

The specific software features can be summarized as follows: (1) Builder for multi-layer systems of planar or cylindrical geometry with unrestricted number of layers; (2) High refractive index contrast and highly absorbing layers (e.g. metals) permitted; (3) Built in material models; (4) Powerful complex mode solver with various parameter scans; (5) Calculation of transmission, reflection and ellipsometric spectra; (7) Exact calculation of hybrid modes and vector fields for cylindrical structures; (8) No artificial calculation windows required; (9) Model library with many examples of guided waves, leaky waves and surface plasmon applications. (10) Intuitive graphical user interface. As future development of the current software data analysis tools with classical and neuroinformatic methods [4] (e.g. Levenberg-Marquard Algorithm and Error Back Propagation Networks) and design optimization tools using gradient methods and genetic algorithms are scheduled.

The application range covers dielectric or metallic multi-layer stacks, optical waveguides, multi-layer- and hollow-core fibers, Plasmon excitation, leaky mode determination, coupling phenomena, ellipsometry, waveguide spectroscopy, and inverse propagation problems.

4 Demonstration Example

To demonstrate the capabilities of the software an example for a fiber that contains metal layer is presented. The selected configuration can be used to detect thin ad-layers or single molecules in the vicinity of the metal cladding [5]. For good detection efficiency the right ratio between core thickness and metal layer thickness has to be selected. To give an idea about the design of such an application, the dispersion characteristic of a metal cladded fiber will be analysed in detail. The cylindrical structure consists of a quartz core coated by a 50nm thick gold layer and is surrounded by air. Material properties were taken from [6]. This fiber should support hybrid plasmon fiber modes. The wavelength is set to 633nm and only the angular mode order one is considered. The radius of the core is varied from 10nm to 1000nm.

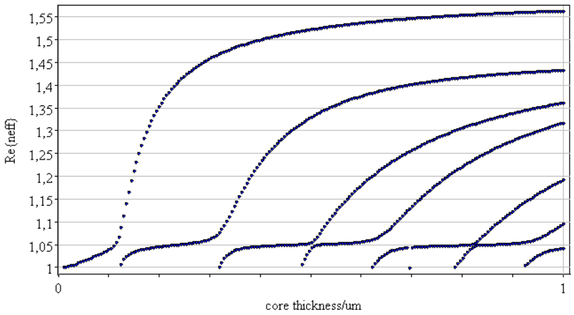

Fig. 1 *Dependence of the real part of the effective refractive index of the guided modes on the core thickness of the fiber. At n_{eff}=1.05 crossing of the core modes and the surface plasmon occur.*

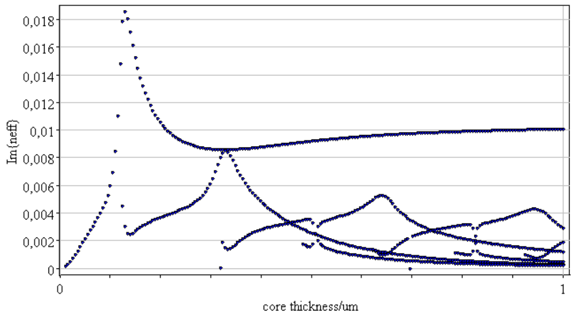

Fig. 2 *Dependence of the imaginary part of the effective refractive index on the core thickness of the fiber. At the positions where the fiber modes couple with the surface plasmon a peak in the attenuation can be observed.*

The real and imaginary part of the effective refractive index n_{eff} is shown in Fig. 1 and Fig. 2 respectively. From the dependence of the effective index on the core radius the behaviour of the fiber can be understood as an interaction of surface plasmons and guided fiber modes. At a low core thickness a surface plasmon at the metal-air interface can exist only. The real part of the effective index for the plasmon appears in Fig. 1 as an almost horizontal flat line at n_{eff}=1.05. This corresponds to the effective index of a surface plasmon supported by a solid metal cylinder. With increasing core radius fiber modes with ascending radial order develop from their cutoff at n_{eff}=1 and cross the effective index curve of the surface plasmon. At each crossing point the wave vectors of surface plasmon and a fiber mode match which causes coupling. As a result modes with symmetric and anti-symmetric fields inside the gold layer occur. These modes are accompanied by a significant increase of the mode attenuation corresponding to peaks in the imaginary part of the effective index (Fig. 2). The detection ability corresponds to strength of the field H_{phi} shown in Fig. 3.

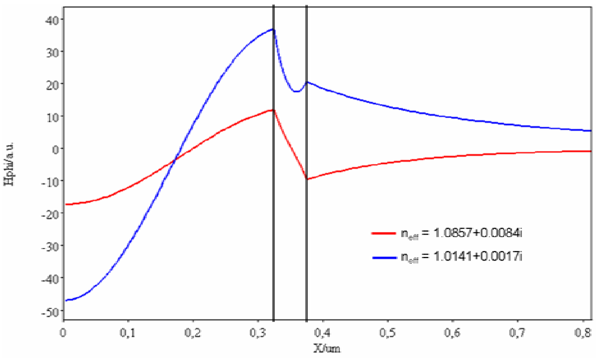

Fig. 3 *Angular magnetic field H_{phi} for a core radius of d=325nm. The position of the gold film is marked with the black vertical lines. The symmetry of the field inside the gold can be clearly distinguished.*

5 Summary

An easy to use software for calculation and design of the electromagnetic properties of planar and circular symmetric stratified optical systems is presented. A demonstration example for a possible sensor application is given. Future work will aim for providing an interface to measurement hardware set-ups und creating tools for the integrated design of stratified optical systems.

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