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Evanescentní vlny v nanostrukturách

Evanescent Waves in Nanostructures

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Současné technologie planárních i periodických nanostruktur umožňují realizaci nových prvků pro sensoriku, elektroniku, fotoniku a spintroniku. K jejich charakterizaci lze využít optické přístupy nabízející prostorové rozlišení v oblasti jednotek nanometrů. Článek shrnuje poznání v oblasti odezvy volných, vedených a evanescentních elektromagnetických vln s definovanou polarizací v nanostrukturách, které mohou být současně anizotropní i absorbující. Zvláštní důraz je kladen na anizotropie vyvolané přítomností spontánního magnetického uspořádání. Z optického hlediska jsou nanostruktury pokládány za stranově, tedy na povrchu dvoudimenzionálně, strukturované multivrstevnaté anizotropní difrakční mřížky. Cílem práce je prezentace přehledu poznatků důležitých pro metrologii anizotropních nanostruktur na základě teoretického i experimentálního srovnání metod optické skaterometrie (zde odpovídající reflexní elipsometrii s proměnnou vlnovou délkou nebo proměnným úhlem dopadu), spektroskopie porušeného úplného odrazu (ATR – Attenuated Total Reflection), reflexní elipsometrie při úplném vnitřním odrazu (TIRE – Total Internal Reflection Ellipsometry) a rezonance plazmonových vln (SPR – Surface Plasmon Resonance) klasická i zahrnující působení magnetizace (MO SPR – Magneto-optical Surface Plasmon Resonance).

Klíčová slova: optika; nanostruktiury; evanescentní vlna; optická diagnostika

The present thesis deals with the experimental and theoretical characterization of anisotropic nanostructures using evanescent waves in the optical spectral region with the special emphasis on the anisotropies induced by magnetic ordering, which can be controlled using external fields. Based on the effect of total internal reflection the following points are considered: Attenuated Total Reflection (ATR), Total Internal Reflection Ellipsometry (TIRE), Magneto-Optical Surface Plasmon Resonance (MO SPR).

Key words: optics; nanostructures; evanescent waves; optical diagnostics

Present technologies of planar and periodic nanostructures enable an implementation of new devices for sensing, electronics, photonics, and spintronics. Optical methods used to characterize such devices offer a spatial resolution of the order of nanometers. This paper is focused on the properties of free, guided and evanescent electromagnetic waves with given polarization in nanostructures that are anisotropic and absorbing. A particular attention is paid to anisotropy induced by spontaneous magnetic distribution. Optically, the nanostructures studied are considered as sidewised, i.e. surface two-dimensionally structured multilayered anisotropic diffraction gratings. The objective is to study properties important for characterization of anisotropic nanostructures by comparing theoretical and experimental methods of Attenuated Total Reflection (ATR), Total Internal Reflection Ellipsometry (TIRE), and Surface Plasmon Resonance (SPR), as well as Magneto-Optical Surface Plasmon Resonance (MO SPR).

Responses of optical waves in material media have been of continues interest since the times of I. Newton, Ch. Huyghens, and later A. Young, A. J. Fresnel, M. Faraday, J. C. Maxwell and others, in the 17th till the 19th centuries. Qualitatively new discoveries came from the works of the 20th century with a birth of the theory of relativity and the quantum theory thanks to J. H. Poincaré, A. Einstein, M. K. E. L. Planck, M. Born, P. Drude and many others [2]. This work that deals with optical methods, such as ATR [11, 12], TIRE [13, 14] and SPR, employs the principles of optical interferometry [2, 3], ellipsometry [4, 5], magneto-optics [6 – 9] and magneto-ellipsometry [10].

Advances in optical measurement methods lead to more accurate results, faster data processing, and their better interpretation, and they enable conducting experiments that used to be either difficult to perform or not possible at all. One of the experimental methods for diagnostics of structures exhibiting anisotropy due to either the structural fabrication or the external fields exploits evanescent waves (ATR and TIRE) in the spectral range of optical surface plasmons. This results in an

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enhancement of resolution up to the order of nanometers. A combination of magneto-optics and surface plasmon resonance was used in the method of MO SPR. Applications of the methods of ATR, TIRE and MO SPR for diagnostics of anisotropic periodic structures require studying electromagnetic wave propagation in anisotropic and bi-anisotropic planar thin and ultra-thin (1–10 nm) layers, multilayers and periodic structures, analyzing the total internal reflection and generation of evanescent waves, and establishing conditions for guided-wave propagation in thin-film waveguides.

Electromagnetic wave responses in anisotropic and bi-anisotropic structures have been intensively studied since the second half of the last century [7, 8, 15]. Among others, works have been described that deal with some selected aspects of interaction, distribution, and propagation of electromagnetic waves in non-isotropic structures and systems. In recent years, the focus has been put on determining guided modes in gyroelectric and gyromagnetic planar structures and structures with circular and elliptic cross-sections [16]. The analysis of guided modes in optical waveguides possessing anisotropy described by non-diagonal elements in materials' tensors is based on employing the characteristics of circularly polarized waves traveling at any angle with respect to the symmetry axes of the studied periodic systems [17, 18]. An interest in such problems is motivated by applications in practical devices, for example in optical isolators that use modulation by an external magnetic field (sweeping of resonant frequencies) or in cylindrical resonators with magneto-optic facets [19]. Design and optimization of devices require vector description of the fields in optical and microwave structures [20, 30]. Non-diffracting beams in 1-D periodic structures consisting of metal and dielectric elements [21] or magneto-optical spectra of assemblies of spherical, as well as non-spherical nanoparticles, are of interest. The latter are usually characterized using the discrete dipole approximation when the particle dimensions are much smaller than the wavelength of the incident radiation [22]. Studies have also been conducted on the behavior of the electromagnetic waves at an interface with a layered bi-anisotropic medium [23, 24, 31] including the periodic homogenization of Maxwell's equations for a scattering bi-anisotropic medium [25]. The description of real interfaces requires an understanding of optical waves scattering on gyromagnetic particles [26, 27]. Optical characterization of materials formed with nanoparticles or an extension of the range of optical frequencies into infrared or terahertz frequencies necessitates investigation of electromagnetic processes in general bi-anisotropic media [28]. For example, it has been shown that when a wave propagates in a bi-gyrotropic medium, the maximum width and amplitude changes of the spectral transfer function are the same for both, the left-hand and the right-hand circularly polarized wave. On the other hand, the shift of the fundamental maximum is different depending on the polarization states [29].

Photonic crystals are one of the important areas of theoretical and experimental research interest around the world. Inhomogeneous photonic structures with random or structured defects have been studied [32, 38]. It has been shown that photonic crystals that contain absorbing materials can display lower losses due to lossy media if a proper geometrical structure is chosen [33]. It has been observed that magneto-photonic crystals exhibit a "unidirectional" effect whereby a wave of a given frequency propagates losslessly in one direction while it experiences a loss in the opposite direction [34, 36, 37]. Anisotropic layers in a resonator based on photonic crystals increase significantly its efficiency [35].

Interaction of optical waves with metamaterials represents a particular area of research [39]. A direct method, based on wave propagation, for extracting effective parameters has been described [40], which is applicable to thick metamaterial layers. A use of metamaterials with negative permittivity and permeability offers a possibility to construct a 1-D hollow resonator with its thickness being much less than $\lambda/2$ [41]. A general method of 4×4 transfer matrices for anisotropic media led to designing a planar metamaterial reflector for an arbitrary control of the electromagnetic wave azimuth [42, 43]. The present state-of-the-art in the theoretical and experimental research on linear and nonlinear optical properties of materials with a negative refractive index is reviewed in [44].

The high resolution of methods that employ the total internal reflection effect (ATR, TIRE, MO SPR) depends on the key element – the optical coupling device – that is made of a denser medium than that of the coupling region. Experimentally, a coupling prism is usually employed [45]. A use of prism coupling in the area of the thin-film optics and optical multilayers dates back to the 60's of the last century [46]. Initially, the prism was used as a coupling element to achieve the phase matching of the longitudinal components when the total internal reflection existed at its interface with the other medium, in which, in turn, guided modes in a planar structure were launched as a result. Determining the angles of incidence corresponding to the guided modes then enabled finding accurately layer thicknesses and their refractive indices, and characterizing optical material anisotropy, the roughness of interfaces, the spectral dependence of optical material parameters, etc., [45, 47]. A number of papers had been published describing the principles of prism coupling for dielectric, as well as metal isotropic and anisotropic structures [48 – 53]. Studies of linear coupling effects have eventually expanded into the areas of the nonlinear optics [54 – 56]. Present theoretical and experimental research activities extend the range of applications of evanescent waves launched at a prism interface as a result of the total internal reflection towards investigations of surfaces roughness and nanostructured material systems while combining this method with, for example, ellipsometric methods (TIRE) [13, 57, 58].

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Such a combination offers qualitatively new results since the method of attenuated total reflection (ATR) makes it possible to vary the thickness of the interaction region (evanescent waves penetration depth) of the studied material with a resolution higher than that obtained with classical plane waves. One of the main advantages of the TIRE method is its ability to determine otherwise unavailable input parameters. This results in a reduction in a number of free parameters when signals reflected from, for example, thick gratings are to be interpreted. More complete geometrical and material characteristics can then be used in interpretations of spectral ellipsometric measurements. A lower number of free parameters when analyzing ellipsometric data makes it thus possible to increase the accuracy in the metrology of nanostructured systems.

An interest has grown over the last ten years in structures and material systems exploiting resonances of surface plasmons (SPR) [59]. A great deal of interest has been devoted to the optimization of coupling conditions and thicknesses of metal layers for the generation of surface plasmon polaritons (SPPs) [60 – 67]. One of the successful experimental techniques is ATR that yields a very good agreement between theoretical assumptions and experimental data [68-70]. Studies have shown that the interface (Au or Ag layer or layers in multilayer systems) roughness plays a significant role in the generation of SPPs. Surface roughness determines the SPPs' propagation distance, controls the angle dependence of the plasmon resonance, and affects the effective dielectric constant of the metal layer [71]. Research groups focus not only on problems of planar structures that support SPPs, but they also study coupling conditions for exciting SPPs in periodic and non-periodic systems. Attention is being paid to exciting plasmon resonances of metal particles embedded in dielectric layers [72 – 73], a scattering of light by thin wires during the plasmon resonance [74], and scattering by layered nanospheres [75]. Specific properties of SPPs have also been demonstrated in dielectric waveguides with metal coatings [76 – 77], in grating waveguides [78], and in waveguides with a crossectionally structured core [79]. Plasmonics has also been introduced into areas of nanoantennas [80] and photonic metamaterials [81]. SPPs find applications in new experimental approaches for microscopy and ellipsometry [82 – 85]. Thanks to a high sensitivity of plasmon resonances to changes in surrounding media (i.e. refractive index, thickness, surface roughness, etc.) [86-88], applications of SPR-based systems are found in sensing, namely in biology and medicine [89-93]. An interesting application (mostly from the economic point of view) exists in the recording disc technology whereby an optical beam is affected by the plasmon resonance [94 – 95]. The enormous interest in surface plasmon problems is testified by many books published, describing theoretical aspects, mathematical modeling, and applications [96 – 101].

Efforts to increase the sensors' sensitivity using resonant states of the generated surface plasmons led to combining magneto-optical effects with SPRs [102]. An attention has been paid to strengthening the MO Kerr and Faraday effects in plasmonic structures [103 – 106], in a plasmon-induced magneto-optical activity in systems with gold nanodiscs [107], in composites containing structured nanoparticles [108], and in periodically layered structures [109]. Studies of magneto-optical effects in structures satisfying the conditions of exciting surface plasmons (MO SPR structures) show a promise for a use of sandwiched structures (or multilayers) where the metal layer supporting SPPs is in contact with a layer possessing magnetically induced anisotropy [110 – 111]. Such a combination makes it possible to achieve a multifold increase in sensitivity when compared to a system having just one non-magnetic metal layer [112].

Theoretical and experimental research has recently focused on magnetoplasmonics of nanocavities, nanowires, dots, one- and multi-component nanoparticles, and applications of these structures [113 – 120].

In the work reviewed here, we deal with a relatively narrow area of optics of nanostructures that are implemented with anisotropic materials whereby the anisotropic properties are induced via an external magnetic field. This research direction has a practical motivation; anisotropic nanostructures are promising for applications in both linear and nonlinear optics. Studies of nanostructures with magnetic properties by optical methods are motivated by the possibilities of their applications in magnetophotonic crystals where functionalities that cannot be realized with isotropic materials (e.g. non-reciprocal propagation of optical signals, isolators, circulators, optical modulators, etc.) are possible, in recording media, in medicine, and others.

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