Coupling light to periodic nanostructures

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CHAPTER 1

Introduction

Already since ancient history, mankind has tried to manipulate light and use it for their purpose. The fact that a piece of glass can be used to manipulate light was known by the ancient Greeks, as reports Aristophanes in his comedy "The Clouds" [1], first performed in 423 B.C.:

> STREPSIADES You know in a chemist's shop... that round thing... clear, like a pretty stone you can see right through... For fires...
>
> SOCRATES You mean a magnifying glass?
>
> STREPSIADES That's it. I'll take one with me in court... Stand behind the clerk with the wax tablets... And when he writes down the fine, melt it away.
>
> SOCRATES That's clever. I like it.

Ever since then, a better and better understanding of light went hand in hand with new inventions, that marked new eras of using and manipulating light. The microscope made it possible to look at ever smaller objects, and the invention of the laser marked the era of using light as an information carrier. A final step was made with the advent of nanotechnology. This technology made it possible to structure materials on a scale of hundreds of nanometers, smaller than the wavelength of light.

On the one hand, this possibility opened new routes for fundamental physics research. The (theoretical) invention of the photonic crystal by John [2] and Yablonovitch [3] paved the way for slowing down and localizing pulses of light [4]. Photonic-crystal defect cavities [5] gave a possibility to combine high-Q resonators with small modal volumes. This boosted the study of new regimes of light-matter interaction [6]. The possibility to engineer the dispersion of light led to studies of nonlinear optics in photonic crystals [7, 8], and even a proposal for a nano-source of entangled photon pairs [9].

On the other hand, a technology-centered route was taken. Plasmonics has taken a renewed interest, because of its promise to focus light on a nanometer scale [10], and multitudes of nanostructures were conceived to steer and guide light [11]. The strong wavelength dependence of several resonant effects inspired people to make photon sorters [12], and the sensitivity for minute changes in refractive index paved the way for nanostructured sensors [13].

1.1 Periodic nanostructures

In this thesis, we study a specific class of nanostructures, that is formed by structures that have a periodic variation of material, and therefore of the refractive index. The simplest example of such a structure is the so-called Bragg stack, a periodic variation of thin layers of different materials. At each interface between two adjacent layers, light is scattered. The reflected waves will interfere, and if the wavelength λ and the lattice vector $\vec{k}$ are tuned, such that all reflected waves add constructively, the reflection can add up to unity, and transmission through the structure is forbidden.

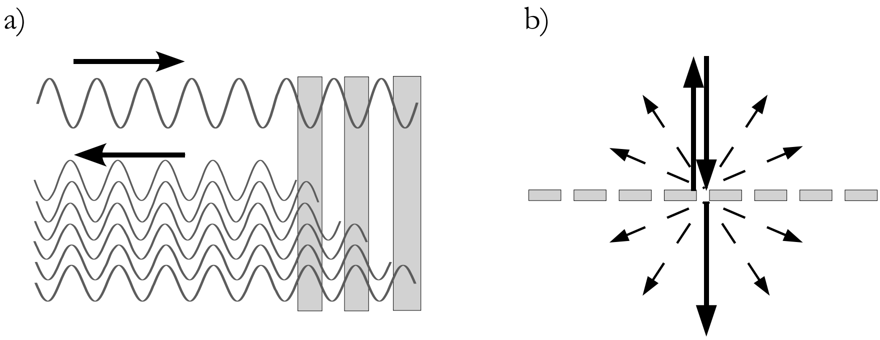

Figure 1.1. (a) Bragg stack. A periodic structure of layers of different refractive index. If the thickness and index difference are tuned right, all reflected waves will interfere constructively and the stack will give unit reflectivity. (b) Diffraction grating. Waves scattered from the periodic structure will interfere constructively in the directions of the dashed arrows. The solid arrows indicate the incident beam and the directly reflected and transmitted beams.

Another well-known example of a periodic structure used to control the propagation of light, is the diffraction grating, that consists of a series of adjacent slits. Each slit act as a line source of radiation that propagates in all directions. In certain directions, where the path length difference between the light emerging from two adjacent slits equals an integer number of wavelengths, the contributions from all slits will interfere constructively. This will lead to a series of diffracted beams emerging from the slits. The directions θ_m in which this occurs are given by the condition

$$d \sin \theta_m = m\lambda, \tag{1.1}$$

where d is the distance between two slits, and m is an integer number defining the *diffraction order*.

The physics of the diffraction grating, or of any periodic structure, can be more easily understood by describing both systems in terms of their properties in reciprocal space. In this space, plane waves of light are described by their wave vector $k = 2\pi/\lambda$, and their angular frequency ω. For light in an unpatterned material, their relation is simply given by

$$\omega = ck/n, \tag{1.2}$$

where c is the speed of light in vacuo, and n the refractive index of the material.

The structure of the periodic lattice can also be described in reciprocal space. The reciprocal lattice of a periodic structure is periodic as well, and is described by reciprocal lattice vectors $\vec{G}$. Each diffraction process can now be described as adding a reciprocal lattice vector to the wave vector of the light, such that

$$\vec{k}_{\mathrm{in}} + \vec{G} = \vec{k}_{\mathrm{out}}, \tag{1.3}$$

where $\vec{k}_{\mathrm{in}}$ and $\vec{k}_{\mathrm{out}}$ are the wave vectors before and after the scattering process, respectively. In the case of the diffraction grating discussed before, at each interface, the component of the wave vector parallel to the interface, is conserved. The perpendicular component of the wave vector is adapted, such that the dispersion relation (1.2) is fulfilled. When $k_{\mathrm{out}} > 2\pi n/\lambda$, with n the refractive index of the medium in which the scattered wave propagates, no propagating solution exists, and the field of the scattered wave will decay exponentially in the direction perpendicular to the interface.

1.2 Bound modes in slabs and at surfaces

In a planar material, that only has variation of material parameters in one direction (the z-direction), solutions of the wave equation can exist, that are bound to a certain region of z-space, but are propagating freely in the two remaining dimensions. Such a bound mode can be parametrized by a propagation constant (i.e. the component of the wave vector in the xy-plane), that has to obey the following condition:

$$\beta > \frac{2\pi n_{\mathrm{amb}}}{\lambda}, \tag{1.4}$$

where n_{amb} is the refractive index of the surrounding material. In this thesis, we study two kinds of bound waves: waveguide modes and surface plasmons.

1.2.1 Waveguide modes

The simplest guided modes in a planar structure are waveguide modes. A waveguide can be constructed by surrounding a high refractive index dielectric by media with a lower refractive index. Light in the high refractive index material is bound to this medium by total internal reflection from the interfaces. In a planar waveguide, the waveguide modes can be classified as having the electric field pointing parallel to the waveguiding plane (TE modes) or perpendicular to this plane (TM modes), and by the number of zeros the field has in the waveguide (the mode number). Figure 1.2(a) sketches the electric field distribution of the two first TE waveguide modes for a planar waveguide [14]. The dispersion relation of the different waveguide modes can be calculated numerically. This is done by imposing a wave solution that is exponentially decaying outside the slab, and sinusoidal inside the slab. Boundary conditions at each interface require that the parallel components of the fields are continuous across the interface, which allows us to numerically find solutions for the waveguide modes.

Figure 1.2(b) shows the dispersion relation of the first waveguide modes for a slab with refractive index $n_{\mathrm{slab}} = 3.4$, surrounded by air. Note that both the frequency and the wave vector axis of this graph are scaled by the thickness d of the slab. This reflects the fact that Maxwell's equations are scale invariant. Three different regions can be identified in this graph. The grey area in this graph shows the light cone. In this region, a continuum of solutions exists for a chosen parallel wave vector $k_{\|}$. These solutions have a propagating component in directions away from the slab ($k_{\perp}$ is real everywhere), and are therefore not bound to the dielectric slab.

In the black region, $k_{\perp}$ is imaginary in all regions of space, and no propagating solutions to the wave equation exist at all. Propagation of light is forbidden in this region. In the region in between, light is bound to the slab by total internal reflection, and different waveguide modes exist. The solid curves indicate the dispersion of the TE waveguide modes, and the dashed curves the dispersion of the TM waveguide modes.

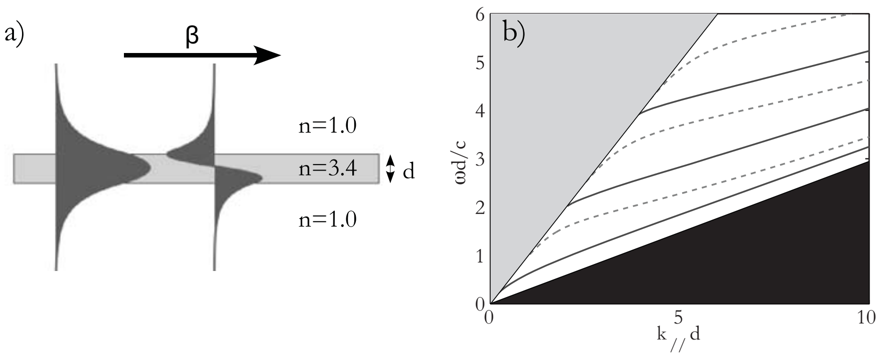

Figure 1.2. (a) Electric field distribution of the first two TE waveguide modes of a slab with refractive index $n = 3.4$, surrounded by air. (b) Dispersion diagram of this structure. The solid and dashed curves give the dispersion of the TE and TM waveguide modes, respectively. The grey area indicates the light cone, were propagating solutions exist that are not bound to the slab. The black area indicates the region where no propagating modes exist at all.

1.2.2 Surface plasmons

On a metal-dielectric interface, another kind of bound wave exists. This is the so-called surface plasmon polariton (surface plasmon for short) [15]. A surface plasmon is a collective oscillation of charges at the boundary between a metal and a dielectric. For a surface plasmon, the magnetic field points parallel to the surface, normal to the propagation vector β. It has a field distribution that is decaying exponentially in both the metal and the dielectric, as is shown in Fig. 1.3(a). Its dispersion relation is shown in Fig. 1.3(b) and is given by

$$\beta(\omega) = \frac{\omega}{c}\sqrt{\frac{\epsilon_{\mathrm{d}}\epsilon_{\mathrm{m}}(\omega)}{\epsilon_{\mathrm{d}} + \epsilon_{\mathrm{m}}(\omega)}}, \tag{1.5}$$

where ϵ_{d} and ϵ_{m} are the dielectric constants of the dielectric and the metal, respectively. Note that, contrary to a waveguide mode, there is no characteristic length scale in this equation, that can be tuned to change the surface-plasmon dispersion. The only length scale is defined by the frequency dependence of the dielectric constant of the gold.

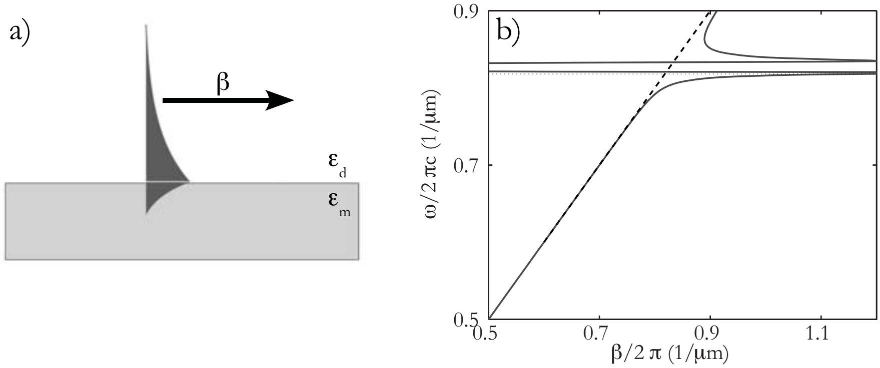

Figure 1.3. (a) Magnetic field distribution for a surface plasmon. (b) Dispersion relation for a surface plasmon on a gold-air interface. For low frequencies, the surface plasmon is close to the light line, indicated by the dashed line. The horizontal dotted line indicates the plasmon frequency.

1.3 Periodic guiding structures

When a planar material that contains guided modes, is patterned with a periodic structure, diffraction will allow light that is incident, to couple to the guided waves, and vice-versa. This is most easily visualized by considering the dispersion relation of the guided wave, and imposing the periodicity of the lattice to the dispersion relation. Figure 1.4 shows the dispersion diagram of the first two waveguide modes from Fig. 1.2, where a one-dimensional periodicity with reciprocal lattice vector G was imposed by repeating the dispersion relation.

A few things can be noticed in this figure. First, by repeating the dispersion relation every reciprocal lattice vector, the frequency ω of a particular mode with well-defined $k_{\|}$ is not uniquely defined anymore. Moreover, different waveguide modes cross. At the crossing of two waveguide mode lines in this diagram, interaction between the modes can induce an avoided crossing between the curves, leading to a more complicated dispersion relation. This interaction is caused by the Fourier component of the dielectric function, at the reciprocal lattice vector that links the two crossing curves.

Finally, guided modes show up above the light line (grey area). Where this happens, diffraction from the periodic structure allows light that would otherwise be confined to the waveguide, to propagate away from the waveguiding

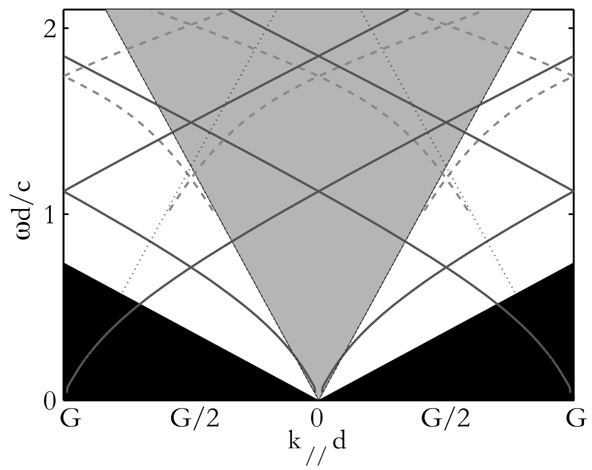

Figure 1.4. Construction of the dispersion relation of the dielectric waveguide of Fig. 1.2, that is patterned with a one-dimensional array of infinitesimal lines. The lattice period $a = 2.5d$, where d is the thickness of the slab. Only the two first waveguide modes are shown. The grey area indicates the light cone. The dash-dotted lines indicate diffraction orders into the surrounding air.

layer. The condition for such a resonance to occur is given by

$$\vec{k}_{\|} = \vec{\beta} + \vec{G}, \tag{1.6}$$

where $\vec{k}_{\|}$ is the parallel component of the wave vector of the incident light. Although this equation gives the frequencies at which resonances occur, the coupling strength, and therewith the width of the resonance, is determined by the Fourier spectrum of the dielectric function.

Just as a Bragg stack has certain wavelengths for which no reflection occurs, the reflection and transmission from a periodic nanostructure bears the signature of the resonances. There are two channels through which light can be transmitted (or reflected) through a patterned structure. First, there is a direct channel, where the light is just reflected or transmitted. Furthermore, there is a resonant channel, in which light is resonantly coupled to the leaky modes, and diffracted back again. Usually, the non-resonant channel is independent of, or slowly varying with, frequency. The reflection or transmission due to the resonant channel is sharply peaked at the resonance frequency, as shown in Fig. 1.5(a). The total transmission or reflection will be the coherent addition of the fields of the two channels, which results in an asymmetric peak shape as in Fig. 1.5(b). The asymmetry of the peak will be determined by the relative phase of the two channels.

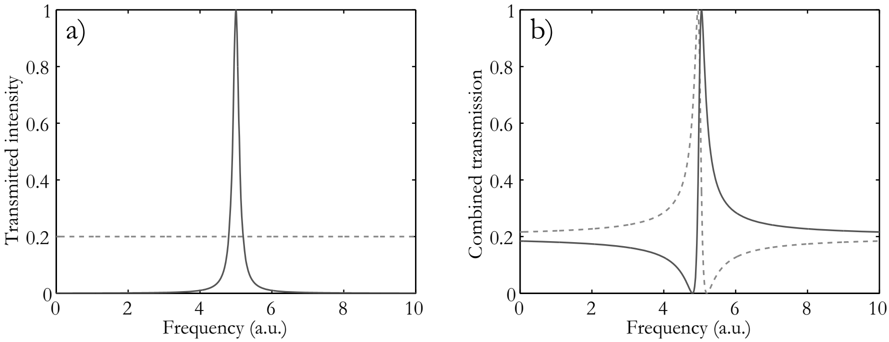

Figure 1.5. (a) Transmission intensity as function of frequency, for the direct (dashed line) and resonant (solid curve) transmission channel. When the two channels are combined, an asymmetric line shape arises due to the coherent addition of the two channels (b). The relative phase of the direct and resonant channel determines the asymmetry of the peak, either red-tailed (dashed curve), or blue-tailed (solid curve).

1.4 This thesis

In this thesis, we investigate how light couples to periodic nanostructures. We study different structures, and start out with dielectric structures. In chapter 2 we discuss the fabrication and reflection spectra of two-dimensional photonic-crystal slabs. We discuss the resonances in terms of a Fano model, and show that light can be coupled resonantly to waveguide modes in the slab. In chapter 3 we discuss the line shape of these resonances, and show that the line shape changes when the angle of incidence is tuned. In chapter 4 we study one of these resonances in more detail. For this, we change to a direct-imaging scheme, which allows us to show the propagation of the light through the resonant modes.

Chapters 5-7 describe experiments using metallic structures. The bound waves in these structures are surface plasmon polaritons, that propagate on either the gold-air or the gold-substrate interface of the hole arrays. Chapter 5 describes an experiment where a dielectric pillar was placed in each of the nanoholes. These pillars act as antennas and increase the coupling to specific surface plasmon modes. In chapter 6, we use a dielectric glass layer on top of the metal hole array to achieve index matching. Besides degenerating the surface plasmon modes, this dielectric layer acts as a waveguide, which gives rise to extra resonances in the transmission spectra. Finally, in chapter 7, we study surface plasmon modes on both sides of the hole array, that are made degenerate by immersing it in an index-matching liquid, and discuss the coupling that is a result of this degeneracy.

The last two chapters discuss the optics of a new kind of single-photon detector, that consists of a very thin superconducting meander. We study the polarization dependence of these detectors in chapter 8, and we describe the absorption of light in this thin meander in terms of an optical impedance model. In chapter 9, we show that the absorption in a metallic film of only a few nanometers thickness can be as high as 95%, for one single polarization. Besides that, we extend these results to the geometry of the single-photon detectors, and show that it is equally possible to make a detector with such a high absorption efficiency.

1.5 Polarization convention

Throughout this thesis, I tried to consistently use the following classifications for the polarization of light in experimental setups and for the polarization of different modes. When a mirror symmetry is present, modes will have a profile that is either even or odd with respect to this symmetry plane. The polarization is also defined with respect to these symmetry planes:

- s- and p-polarization define a polarization with respect to the scattering plane of a reflection. Light that has its electric field perpendicular (*senkrecht*) to this plane (i.e., parallel to the reflecting surface) is denoted with s-polarization, whereas light that has the electric field parallel to the scattering plane, is denoted as being p-polarized.

- TE and TM polarization have another meaning. In two-dimensional periodic structures, they define the polarization with respect to the third dimension. When the electric field is perpendicular to the direction of translation symmetry, i.e. in the plane of the reciprocal lattice vectors, it has TE (transversally electric) polarization, otherwise it has TM (transversally magnetic) polarization. For slab waveguides, TE and TM are defined with respect to the waveguiding layer. TE waveguide modes have the electric field in the plane of the slab waveguide, whereas TM waveguide modes have the magnetic field in the plane of the slab.