Coupling light to periodic nanostructures

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Summary

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In this thesis, the interaction of light with a variety of periodic nanostructures is studied. These nanostructures consist of material that is patterned on a (sub)wavelength scale. The periodicity of the pattern can cause a more efficient coupling to a guided or bound mode in the nanostructure. Alternatively, the anisotropy of the individual periods of the structure can cause strong polarization dependence of the optical properties. The thesis consists of three parts, in which these effects are studied in different kinds of periodic nanostructures.

In the first part (Chapters 2–4), so-called photonic-crystal slabs are studied. These slabs, that support at least one guided mode, consist of a high refractive index dielectric material, perforated by an array of holes. In Chapter 2, the reflection spectra from such slabs are discussed. The spectra contain several asymmetric resonances, on top of a slowly-varying background. The line shape of the resonances is explained in terms of a Fano model. In this model, there are two contributions to the reflection spectrum: a direct contribution, in which light is reflected by Fresnel reflection from the layered structure, and a resonant contribution, caused by coupling to a leaky waveguide mode in the slab. These two contributions interfere, which leads to the asymmetric line shape of the resonance. To quantitatively describe measured reflection spectra, loss needs to be included in the model, by adding a loss channel. This gives a model with the loss rate, escape rate, and resonance frequency as adjustable parameters. To predict the resonance frequency, a waveguide model that uses an effective refractive index for the photonic-crystal slab, is introduced. Numerical calculations show that resonances disappear when the refractive index of the substrate underneath the slab is increased. This is explained by the cut-off condition of higher-order waveguide modes, given by the waveguide model.

The asymmetry of the line shape is determined by the relative phase of the resonant and the direct contribution of the reflection. In Chapter 3, this phase is changed experimentally, by changing the angle of incidence. For p-polarized light, the measured line shape of the resonance changes, from red-tailed asymmetric, to symmetric, to blue-tailed asymmetric, when the angle of incidence is increased from $20°$ to $80°$, across Brewster's angle. With the Fano model of Chapter 2, it is shown that this change of asymmetry originates from a change in sign of the direct reflection, at Brewster's angle.

In Chapter 4, a particular resonance is studied in more detail. A strongly focused beam of monochromatic light is used to illuminate a photonic-crystal slab, and the reflection is measured both in real space and in k-space. A polarization analysis of the k-space images reveals that the resonance is caused by coupling to the TM_0 waveguide mode of the slab. In the real-space images, the resonant and direct contributions to the reflection are spatially separated. Due to this separation, the decay length of the resonance can be determined. This decay length varies with wavelength, and measures up to 7 μm. Combined with the information obtained from the reflection spectrum at normal incidence, this gives an estimate of the group refractive index $n_g = 2.6$, and the phase index $n_{eff} = 1.5$ of the resonant waveguide mode.

The second part of the thesis (Chapters 5-7) discusses experiments with metal hole arrays. These arrays consist of an optically thick gold layer, perforated by a regular array of holes. In the transmission spectra of these structures, resonances are observed that are caused by coupling to surface-plasmon modes on either side of the gold layer. In Chapter 5 the effect of placing a dielectric pillar in each of the holes is studied. Angle-dependent measurements of the transmission spectrum are compared to measurements where these pillars are removed. The pillars enhance the transmission, as well as the interaction between different surface-plasmon modes. The enhanced interaction causes a frequency splitting of 6% for modes on the pillar side of the hole array.

In Chapter 6, the metal hole array is covered with a thin layer of glass. This glass layer diminishes the asymmetry of the structure, and causes the resonances that are caused by coupling to surface plasmons on either side of the structure to become degenerate, when the glass layer is sufficiently thick. Besides the surface-plasmon resonances, a number of sharp dips is observed in the transmission spectra. These dips are caused by coupling to waveguide modes that are contained in the glass layer on top of the hole array, and their angular dispersion is reproduced in calculations of these modes.

The transition from an asymmetric to a symmetric structure, where the resonances caused by surface plasmons that propagate on either side of the metal layer are frequency-degenerate, is studied in Chapter 7. This is done by immersing the metal hole array in liquids of increasing refractive index. When the index contrast is reduced, an avoided crossing is observed between the surface-plasmon modes on the liquid and glass sides of the metal hole array. Moreover, the line width of one of the resonances increases at the expense of the other, such that there is only a single resonance left when the modes are index matched. A coupled-mode theory with both conservative and dissipative coupling gives a phenomenological description of these observations.

The last part of this thesis describes the absorption of light in a superconducting single-photon detector. This type of detector consists of a meander of very thin, absorbing metal, niobiumnitride. In Chapter 8, the polarization-dependent detection efficiency of such a detector is studied. The parallel-wire structure of the detector induces a strong polarization dependence, which is caused by a higher optical absorption for light that is polarized parallel to the metal wires. A theoretical study of the absorption properties of the meander as a function of film thickness shows that the absorption for parallel-polarized light can be as high as the absorption of a closed film, when the product of filling factor and film thickness is kept constant. By illuminating the detector from the substrate side, the calculated absorption is increased by a factor equal to the refractive index of the substrate.

The final Chapter 9 discusses the absorption of a thin film of NbN as a function of angle of incidence. The measured absorption for s-polarized light approaches 100% when the film is illuminated at the critical angle for total internal reflection. The absorption for p-polarized light at the same time vanishes. This effect is to design a superconducting single-photon detector which has a calculated broadband absorption coefficient of $> 90\%$ for wavelengths from 700 to 1600 nm, for s-polarization.