Scattering and absorption in 2D optics

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Chapter 1

Introduction

This chapter introduces the reader to light scattering, the central topic in this thesis, and to its role in the nano-optics structures that we studied. With this purpose in mind, we focus our discussion on two recurring themes: optics in two-dimensional structures and optical scattering in random media.
We end with an overview of the content of the main chapters of this thesis.

1.1 Scattering of light: an intuitive picture

Scattering of light is a phenomenon that belongs to everyday life much more than in a dark optics laboratory [1]. Without light scattering we would only be able to see objects that produce light, like the sun or a lamp, or opaque objects that obstruct our sight of a light source. Scattering allows us to see more. When light from a source hits an objects and reaches the eye after changing direction, hence scatters on it, only then does most of vision begin.

Scattering happens in the presence of a change in the environment or at a discontinuity in the optical path of the incident light. Intuition is again supported by an everyday example: a clear slab of glass doesn't disturb light propagation much and it is thus hardly detectable. On the contrary, the slab can easily be seen if there is a scratch on its surface (the discontinuity), or some dirt.

Similarly to how we rely on scattering to interpret the properties of what surrounds us, in the controlled conditions of an optics experiment scattering is a useful tool to investigate the interaction of light with matter, from the macroscopic scale to the single molecule level. The work collected in this dissertation is a study around different examples of scattering of light in the presence of nano-structured materials, i.e. with features in the order of the wavelength of the light, or smaller.

Before presenting an overview of our work, we will address two key ingredients of our research: the quasi-two-dimensional confinement of the light as an effect of the structuring of the materials, and scattering in random media.

1.2 Two dimensional optics

Apart from freely propagating in space, light can also exist in states confined on quasi two-dimensional structures, with dielectric layers [2, 3, 4] and metal-dielectric interfaces [5] as main examples.

The simplest case of a dielectric layer is a thin membrane, surrounded by a material of lower refractive index. One possible example is a thin film of a dielectric or semiconductor of a thickness in the order of the wavelength of light and air on both sides. Under these conditions, Maxwell's equations have a set of discrete solutions, or guided modes, which describe how the electromagnetic field is localized on the structure in the transverse direction, with in-plane propagation only allowed.

The interface between a metal and a dielectric also yields a confined so-

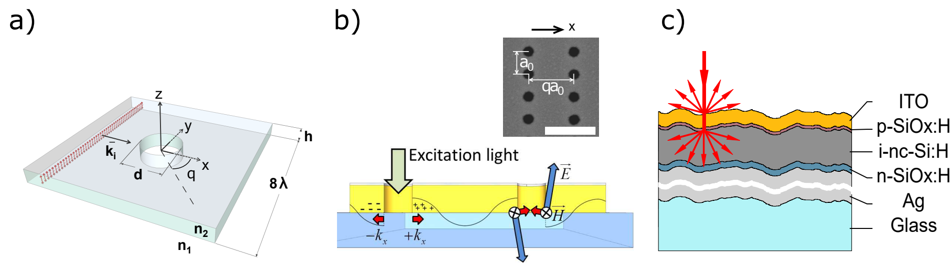

Figure 1.1: The three two-dimensional optical structures studied in this thesis.
a) a single hole in a dielectric slab scatters a waveguide mode propagating in the slab (see Chapter 2). b) a regular array of holes in a metal film on a glass substrate enables the excitation and scattering of surface plasmons (SP) that propagate on the metal-glass interface; the symbols in the lower picture indicate the relevant processes; the scale bar in the SEM picture is 1 micrometer (see Chapter 3). c) a rough thin film Si solar cell scatters the incident light into trapped states inside the quasi two-dimensional structure (see Chapter 5)

lution for the electromagnetic field. This solution is the surface plasmon, for which the electromagnetic (EM) field is coupled to free charges oscillating in the metal, and is tightly confined to the interface [6, 7, 8].

The EM field of both waveguide modes and surface plasmons decay exponentially away from the 2D structure on which they are confined. Both modes don't exchange energy with the outside in either direction when unperturbed. A consequence of this is that their creation and detection require particular geometries or the presence of nanostructures. The easiest nanostructures widely used in two-dimensional structures are subwavelength cylindrical holes. In Chapters 2 and 3 we study how light interacts with single holes for a dielectric waveguide (Fig. 1.1 (a)) and for surface plasmons (Fig. 1.1 (b)), respectively.

1.3 Random scattering

Complex media are literally everywhere and comprise materials like paint or fog [9, 10], but also cells and bone tissues [11, 12]. This makes them particularly interesting to study and extensive research exists on the control of light propagation in random scattering media in different fields [13, 14]. Research on scattering finds applications in the technological improvements of devices that emit or absorb light, like LEDs and solar cells [15, 16, 17].

Scattering materials are made of randomly arranged scattering elements. The main effect of this on light is to scramble its propagation direction, making it impossible to look through them. When illuminated with coherent light, the reflection of random scattering media has a complex structure that depends on the internal structure of the medium and is named speckle-pattern [18].

In Chapters 4 and 5 we present two experimental studies on the reflected speckles from respectively 3D scattering media and a 2D scattering solar cell. Both studies are based on the deterministic nature of random scattering and its linear relation between input and output EM field.

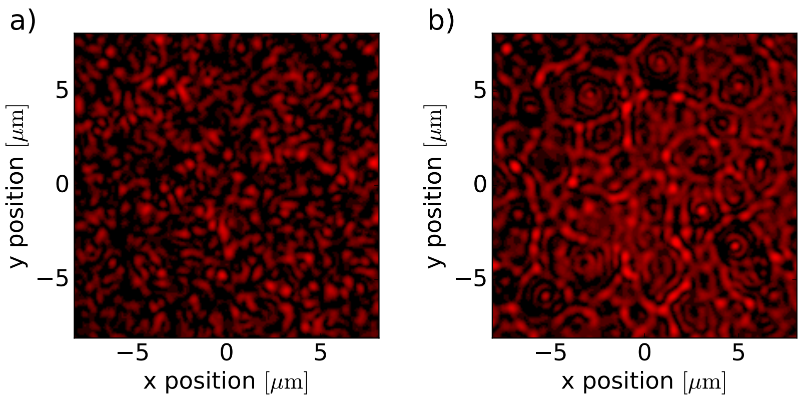

Figure 1.2: Two example of reflected intensity patterns from a 3D scattering medium like (a) a 3D scattering medium in form of white paint and (b) a two-dimensional rough thin film Si solar cell. In both cases the intensity shows a speckle pattern but with a very different structure for the two cases, and with a resemblance of the sample morphology in the case of the solar cell.

1.4 Overview of this thesis

This thesis is divided into four main chapters, and it concludes with a summary of the presented results.

In Chapter 2 we consider the scattering of waveguided light on a single cylindrical hole in a thin dielectric membrane. We use numerical simulation to calculate the properties of the scattering process, separating the in-plane scattering from the radiative loss induced by out-of-plane scattering at the hole.

In Chapter 3 we investigate how surface plasmons scatter on nano-holes in gold. We study this experimentally for extended arrays of holes with spacing in the order of the wavelength of the surface plasmons, and multiples thereof. We exploit interference effects to effectively use the arrays as optical gratings, and reconstruct the far field profile characteristics of the light scattered by a single hole.

In Chapter 4 we demonstrate a new method to measure scattering and absorption properties of a complex medium like white paint. We employ a wavefront shaping technique to modulate only the optical phase of the illumination on the sample. We record its effect on the reflected speckle pattern and interpret it using a simple diffusion model. This method can be applied to any complex medium for which light transport can be modelled statistically.

In Chapter 5 we study the scattering properties of a rough thin Si solar cell under coherent illumination, i.e. different from the condition under which solar cells usually operate. This experiment provides valuable information on how light enters the cell and reflects from it. Our study brings a nano-photonic approach to the study of thin-film solar cells. Our aim is to provide a physical picture of the processes of light propagation and absorption, up to the point where we can use wavefront-shaping techniques to increase the in-coupling of light in a solar cell and improve its performances. Chapter 5 presents the first steps in that direction.

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