Chapter 1
Introduction

When dealing with light and optics, it is commonplace to constrain our understanding to the visible range of the electromagnetic spectrum, i.e., the narrow interval where the human eye is able to respond. However, this anthropomorphic definition of optics is too narrow. On both sides of the visible spectrum, we find spectral ranges full of interest that also allow an analysis quite similar to that given in the visible spectrum. In the high-energy, high-frequency side, we find that ultraviolet radiation, X-rays, and γ-rays are of use in astronomy, medicine, and technology because of their capability to trigger chemical reactions and generate ionized matter. On the low-frequency, low-energy side, we have witnessed the development of radiofrequency applications in telecom, radar, and microwaves. But, when reaching those portions of the spectrum closer to the visible, the use of millimeter waves, terahertz, and infrared radiation has produced a variety of devices and technologies that have strongly expanded the capabilities to sense nature in a different way. In the infrared, image-forming systems have advanced in accuracy, time response, and analysis capabilities through improved algorithms and by using hyperspectral techniques and sensor fusion. Beyond thermography, infrared image technology already distinguishes chemical compounds, and takes full advantage of the detection of the polarization of light.

Optical antennas, infrared antennas, antenna-coupled devices, rectennas, plasmonic antennas, nano-antennas, resonant elements, frequency-selective surfaces, metasurfaces, metamaterials, etc. — all of these names have been used over the last decades to refer to the analysis and study of the interaction of light, or more generally, electromagnetic radiation, with metallic and dielectric structures having dimensions below, or well below, the wavelength of operation [Fumeaux *et al.*, 1998] [Crozier *et al.*, 2003] [Maier *et al.*, 2003] [Alda *et al.*, 2005] [Muhlschelegel *et al.*, 2005] [Alda *et al.*, 2006b] [Engheta, 2007] [Boreman, 2008] [Bharadwaj *et al.*, 2009] [Novotny & van Hulst, 2011] [Knight *et al.*, 2011] [Berkovitch *et al.*, 2012] [Novotny & Hecht, 2012] [Alù & Engheta, 2013] [Agio & Alù, 2013] [Abadal *et al.*, 2013] [Moddel & Grover, 2013] [Yu & Capasso, 2014] [Zhao *et al.*, 2014] [Chen *et al.*, 2016]. These different names and publications refer to different applications requiring auxiliary elements and subsystems, but all of them share the same foundations when describing their interaction with light. As a matter of fact, this area started drawing increased interest when the possibility of manipulating radiation at the nanoscale was demonstrated using antenna devices. The new elements were usually the natural and miniaturized counterparts of designs that were already proven at radiofrequencies and in the microwave range. However, as the knowledge and understanding of the basic mechanism at work in the optical range improved, the design of new applications ensued, and elements and applications that were optical in nature were proposed.

In this book we have summarized more than two decades of research in this aspect of nanophotonics, even though at the time of our entering in this field, nanophotonics was not fully defined and was lacking some of the elements that now are clearly established. The primary reason to move into the optical antenna arena was the expectation to develop a new kind of detector in the infrared that could improve on the limited technologies that were available back in the 1990s. Thus, we were able to witness and participate in this quest from its inception.

In order to better organize the material in this book, we have divided our analysis into two main types of devices. The first type, which we call infrared or optical antennas, corresponds to those elements that provide an electric signal that is read by external electronics. These devices can be seen as antenna-coupled devices, and besides the resonant elements necessary to collect electromagnetic radiation, they also contain a transducer element that generates a current, a voltage, or a change in some characteristics in the electric circuit that is external to the infrared antenna device. The second type of device, which we call resonant structures, includes those elements that modify some parameters of the incoming radiation: phase, spectral distribution, polarization state, etc. These changes can be observed in the transmitted or reflected radiation. These elements can be considered as passive because they do not provide an electric signal and are not coupled to transducers. However, in some applications involving phase transitions in the subsystems of the devices, some signal inducing those phase transitions can be used.

The benefit of the antenna-coupling structure is its spatially compact sensor and a large collection area [Boreman, 1996]. It should be noted that, in the quest for ever-smaller pixel sizes, antenna-coupled sensors provide a platform for denser focal plane arrays as compared to immersion-lens-coupled sensors, which are constrained by the diffraction limit of the radiation impinging on the structure. For a nominally half-wave antenna, the pixel dimension can be distinctly sub-wavelength in spatial dimension. This makes optical antennas the smallest possible detector, being a small fraction of the detected wavelength [Tang *et al.*, 2008]. The main idea from a signal-to-noise ratio perspective is that smaller sensors generate less noise than do larger sensors. Using antenna coupling disconnects the usual dependence of sensor area and collection area. The normal assumption is that noise-equivalent power (NEP) is proportional to the square root of the sensor area. The definition of specific detectivity, $D^* = \frac{\sqrt{A}\sqrt{\Delta f}}{\mathrm{NEP}}$, is such that if NEP is held to a smaller value by a small sensor area, D^* can be referenced to a larger collection (pixel) area, potentially yielding an increased D^*. Over time, we have seen that some of the expectations in terms of performance of optical antennas have not yet been fully realized, but, at the same time, new designs in geometry and material combinations have made possible some other advances. The tiny dimensions of an optical antenna reduces its capability to collect large amounts of energy. Furthermore, impedance mismatches — between free-space, the antenna, and the load in charge of transferring the signal and power to the external circuit — also limit the performance of these devices. One might wonder how an element made of metal, that in its macroscopic form reflects a very large portion of the electromagnetic radiation in the visible and the infrared (the reflectance values are usually well above 90%), can be tailored to couple the incoming energy towards a load. The solution for this issue is not easy and, as we will see, requires a good understanding of the material characteristics and how they can work to improve efficiency and provide useful devices.

Additionally in the infrared (IR), antenna coupling provides an inherent control of spectral response, polarization response, and angular response that is not directly available in classical IR sensors [Schaefer, 1999]. The time response of infrared antennas is limited by the transduction mechanism. When rectification is used, the response is in the range of femtoseconds, allowing a very fast response. The fabrication of optical antennas allows integration with other auxiliary elements of conventional optical systems, diffractive optics, waveguides, and control and acquisition electronics. Additionally, some infrared-antenna-coupled sensors can work at room temperature without the need of sophisticated cooling subsystems that are required in some infrared detection technologies. Beyond the still-to-be-realized gains in responsivity and detectivity, infrared antennas are desirable in some specific applications where their selective capabilities, small footprint, and room-temperature operation are of importance in imaging applications [González *et al.*, 2006] [González *et al.*, 2005].

Since long ago, optical instrumentation has been based on the use of lenses and mirrors. When diffractive elements became available, optical design could merge them with classical refracting or reflecting optics. This fact opened the way to diffractive optics that incorporate Fresnel zone plates, holographic optical elements, etc. When considering the interaction of light with sub-wavelength resonant structures, it is also possible to modify the spectral content (frequency-selective surfaces), the polarization state (polarizers and retarders), as well as the phase front of light beams (reflectarrays). These resonant structures take full advantage of electromagnetism; because their mechanism is based on electromagnetic resonances at optical frequencies, they can be considered as new additions to the optical tool kit in the form of devices that can be grouped under the category of resonant optics. Another field of application of resonant structures controls and tailors the near field around them [Crozier *et al.*, 2003]. In this case, the strong field-enhancement near these devices can be used to boost the emission from a diode laser [Cubukcu *et al.*, 2006], or trigger a spectral response (Raman spectroscopy, fluorescence, etc.) that lowers the limit of detection in some cases [Izquierdo-Lorenzo *et al.*, 2012]. Also, these capabilities can be used to generate optical trapping and confinement.

As shown in this book, the analysis of infrared antennas and resonant structures combines an understanding of the basic interaction between light and matter with the capability to generate devices and elements to detect and control optical radiation in the infrared. Therefore, we are delighted to show how the research in this area is full of challenges and rewards for everyone entering or working in the field.

1.1 Historical Background

Since ancient times, the word “antenna” has been related to the protuberances that insects have developed to sense their surroundings using mechanical, thermal, and olfactory terminations. The first appearance of this term defining these apparatus was perhaps given as a translation of Aristotle from the word “keraiai” into the Latin “antenna” by Theodorus Gaza in 1476 [Aristotle, 4th century BC]. When electromagnetism began its journey in modern science and technology, Hertz demonstrated the emission and reception of electromagnetic waves through air using a spark generator and a metal ring that acted as emitter and detector antennas. This happened in 1887, and in 1895 Marconi rediscovered the findings of Hertz and began to use the word antenna to refer to the metallic structures used to generate and receive electromagnetic waves, which we now know as radio waves. Since then, electromagnetism and electronics have adopted the term antenna for the part of a circuit that interfaces between the freely propagating wavefront that moves through the space and the electronic circuit that performs the generation or detection functions.

Antenna theory has become one of the most interesting parts of electromagnetism because it has combined geometries that are able to harness charge carrier oscillations to produce the desired patterns of radiating fields in a variety of angular, spectral, and polarization combinations. The quest for higher frequencies in the emission and reception of electromagnetic waves has been boosted by bandwidth hunger and by the need to sense objects and elements beyond the visible range. Telecommunication and radar have provided solutions that have become more optical as they have approached and surpassed the terahertz band. Nowadays antennas are pervasive and ubiquitous in daily-use technologies. From the most common case of radio stations to the implementation of radiofrequency identification (RFID) tags in products, credit cards, and documents, antennas are part of the technology that we use every day. As a very common example, any current smartphone contains a plethora of antennas specialized for dedicated tasks and bands: Wi-Fi, GPS, near-field communication, radio stations, and of course telecom bands (3G, 4G and beyond). An adequate design of these antennas is key to improving performance, avoiding mutual interference between bands, and obtaining a longer battery life. These designs are much more sophisticated than the simple dipole antennas used in the first radio stations at the end of 19^{th} century, and they are flat and printed on flexible substrates. At the same time, microwave, millimeter band, and terahertz devices have demonstrated a very good adaptation to the new requirements of modern security, surveillance, and remote sensing applications.

These advances in antenna design and understanding have been made during the 20^{th} century when electronics have been driving most of the cutting-edge advances in technology. In the last quarter of the previous century, we saw how new fabrication tools opened the way to the manufacturing of tiny structures already in the nanoscale. Then, the unstoppable push towards higher and higher frequencies in antenna design reached the optical domain, first in the infrared and finally in the visible range. When this happened about 30 years ago, it was common for optical antennas to be considered as any element able to capture optical radiation, and by extension to radioelectric astronomy, an optical telescope was also considered as an optical antenna. However, actual optical antennas, seen as the natural extension of their lower-frequency counterparts, were already on the scene for some exotic applications and ideas. It is interesting to point out that a leap forward in the development of optical antennas was made when nanoscale resolution fabrication was available in the form of electron-beam lithography. Designs capable of being printed as flat metal geometries were made to work and began to produce the first results for the reception of light waves. However, much earlier than these nanofabrication tools were commonly applied, some other technologies had already gained their place as photodetectors. Among them are those based on the photoelectric effect, which became fully developed with the use of semiconductor materials. Over the decades, semiconductor detectors, based on the development of the semiconductor industry, were refined to improve their performance in terms of spectral response, cut-off frequency, responsivity, and size. Thermal detectors, either thermoelectric or bolometric, were also used when semiconductor elements were not applicable for a given case. In the 1980s and 1990s infrared detectors were facing some issues related to their performance in terms of cooling requirements and signal processing [Dereniak & Boreman, 1996]. This is when infrared antennas offered an innovative option that could use the intrinsic beneficial features of microwave and radioelectric design. At this time optical antennas were seen as a possible option with good added value in terms of selectivity in polarization, spectral response, short time response, and directivity. Unfortunately, the one drawback of these devices, their low responsivity, reduced their ability to challenge the already well-established technologies. Some decades after those first steps, the response of optical antennas has improved in terms of better impedance matching and improved transducers. However, response is still an important issue that will deserve significant attention in the years to come. The delay in the dissemination of this detection technology is mainly due to the behavior of metals at optical frequencies. The characteristics of a perfect conductor are lost in the infrared, and electromagnetic radiation thus penetrates the antenna structure, producing dispersive effects that change differently for each metal. Thus, optical antenna design differs from radioelectric antenna design. In optics, it is not only the geometry that is important; also, the shape and dimension of the resonant structure must be combined with a proper choice of metal to fabricate the structure without neglecting the effect of the surroundings of the antenna. Moreover, the coupling of the antenna with the transducer and the transducer efficiency become key factors in the development of a good optical antenna device [Boreman, 1996]. Up to now, we have described optical antennas as light detectors that use the currents generated in metallic resonant structures to produce a signal in the read-out external electronics. In addition, optical antennas have been proposed as energy harvesters when coupled to high-frequency rectifiers, mimicking the good results obtained in the radioelectric and microwave bands, and adapting the designs and constituent parts to the optical regime [Moddel & Grover, 2013]. Also, when thinking of optical antennas as emitters, optical antennas excited by optical radiation have made possible their use in nanoprobing devices that sense molecules in the near field with nanoscale resolution. Thus, optical antennas are at the core of a wide array of nanophotonic applications and devices [Novotny & Hecht, 2012] [Agio & Alù, 2013].

Radar and microwave techniques have also been beneficial for extending the use of metallic resonant structures to the optical regime. Frequency-selective surfaces, wire grids and retarders based on resonant elements, and reflectarrays were part of the technology commonly used in defense and security applications. Those advances pioneered the field of metasurface band-gap structures and photonic crystals. As has happened with the optical antenna designs that inherited the good results already proved in the microwave band, these passive resonant elements used designs that modified, using the current generated in the metallic shapes written on typically flat surfaces, the spectrum, the polarization, and the phase of the incoming wavefront. We may say that, as occurred with the use of diffraction and interference in optical design, these additions to the optical tool kit paved the way to a new realm that can be called resonant optics [Puscasu, 2001] [Tharp, 2007] [Ginn, 2009] [Yu & Capasso, 2014] [Yu *et al.*, 2013]. With resonant elements being considered for enhancing near-field phenomena and promoting easier excitation of transitions, Raman spectroscopy, associated with near-field measurement techniques, makes possible important advances in the detection and analysis of molecular and biomedical substances. Finally, many of the results in nanophotonics have used resonant elements in the form of nano-antennas to reveal phenomena or modify the electric field distribution of light waves propagating at the nanoscale.

1.2 Organization of the Text

Before delving into the actual findings described in the book, we provide a short introduction to the basics of electromagnetism applicable to the interaction of light with metallic structures having a size comparable to the wavelength. The special behavior of metals deserves attention, to which Chapter 2 is devoted. The next three chapters are organized according to the manner in which we have made our contributions to this area. Chapter 3 explains how to model, design, and validate the proposed geometries through simulation. Chapter 4 describes techniques used for fabricating the most promising device designs. The fabricated devices are then tested and characterized to assess their actual performance and support the expected characteristics previously modeled or numerically evaluated. A variety of characterization techniques are described in Chapter 5. Chapters 6 and 7 describe the two main types of devices that we have developed: those producing an electric signal (antenna-coupled devices) and those changing the parameters of the light incident on the resonant elements (resonant optics). Finally, we close the book (Chapter 8) with a description of actual and future challenges that are currently being addressed or that will be met in new lines of research and future devices.

Upon completion of the book, the reader will know how optical antennas and resonant structures work, what their limitations and special characteristics are, and how the current technology and state of the art has provided some interesting devices that are applicable to a variety of fields in optics and photonics.