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Optical antennas for nano-photonic applications

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Abstract
Antenna-coupled optical detectors, also named optical antennas, are being developed and proposed as alternative detection devices for the millimetre, infrared, and visible spectra. Optical and infrared antennas represent a class of optical components that couple electromagnetic radiation in the visible and infrared wavelengths in the same way as radioelectric antennas do at the corresponding wavelengths. The size of optical antennas is in the range of the detected wavelength and they involve fabrication techniques with nanoscale spatial resolution. Optical antennas have already proved and potential advantages in the detection of light showing polarization dependence, tuneability, and rapid time response. They also can be considered as point detectors and directionally sensitive elements. So far, these detectors have been thoroughly tested in the mid-infrared with some positive results in the visible. The measurement and characterization of optical antennas requires the use of an experimental set-up with nanometric resolution. On the other hand, a computation simulation of the interaction between the material structures and the incoming electromagnetic radiation is needed to explore alternative designs of practical devices.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Optical antennas stand for a class of novel optical detectors that have the potential to revolutionize optical inter-connections, imaging, sensing, and related fields by adapting radio wave techniques to the optical regime. This requires a level of miniaturization that became available with the development of electron beam lithography and similar techniques with sub-micron resolution. Optical antennas couple electromagnetic radiation in the visible and infrared wavelengths in the same way that radioelectric antennas do at the corresponding wavelengths [1]. The size of optical antennas is in the range of the detected wavelength: from a few hundred nanometres to a few microns. Optical antennas present proved and potential advantages in the detection of light showing polarization dependence, tuneability, and a potential rapid time response. They also can be considered as point detectors and directionally sensitive.

Antennas have been developed since the very beginning of electromagnetism. Furthermore, one of the first practical designs, the dipole antenna, is still at work in telecom applications. The constant need for increasing the bandwidth of communication links has demanded the use of higher and higher frequencies of the supporting electromagnetic waves. Fortunately, the available fabrication techniques have allowed the realization and demonstration of antenna devices at shorter and shorter wavelengths. However, before antennas could reach optical frequencies in a reliable and practical way, the use of semiconductor detectors made possible the development of lightwave links in free space and along dielectric waveguides (optical fibres). These optical networks use the already available detectors in the optical range mainly based on semiconductor technology [2]. The efforts to improve the performance of these detectors, and the positive results obtained from these efforts, have removed the need to look back toward the antenna designs and make them work also in the optical band for telecommunication applications.

In these previous years we have been watching the development of a new type of detectors in the infrared band: the antenna-coupled detectors. They are derived from the whisker diodes [3, 4] first used for frequency-conversion and frequency-multiplication chains in the astronomy and research on time standards [5]. The uniqueness of this application has hidden the potential of the design for some other broader uses that were anticipated by several research groups [6–8]. A step forward was made when the concept of an antenna for the infrared radiation was totally included in the analysis and design of such devices, specially when taking into account the specific properties of the interaction of light and metals at optical frequencies. Further important progress in the realization of practical devices using antenna-coupled detectors was their fabrication by using electron-beam lithography for the definition of submicron structures [9, 10]. The smoothness of the finished metal structures, along with the spatial resolution of this manufacture technique, has been essential to the feasibility of the devices and to their performance even at visible frequencies [11].

In section 2 of this contribution we show the basic mode of operation of an optical antenna. Here, we will focus on the advantages of this devices and we will point out some of the problems that future research need to solve. Section 3 is devoted to the explanation of some of the immediate and prospective applications of these devices. Finally, section 4 summarizes the main conclusions of this contribution.

2. The optical antenna concept

To better understand how an optical antenna works we present in figure 1 a simple realization of a dipole antenna made of Ni and having a transducer element based on a Ni–NiO–Ni junction. This structure is written by e-beam lithography on a Si wafer coated with an insulating layer of SiO_2. Light is incident onto the wafer perpendicularly and excites currents on the antenna dipole structure. These currents are rectified by the transducer located at the centre of the dipole. The triangular shaped metallic structures are the connection lines in charge of the signal extraction. These lines are typically connected to a voltage divider that produces a signal proportional to the optical irradiance at the antenna plane. At the same time these connectors serve to apply the desired bias voltage to the junction. This detection mechanism is also applicable to antenna devices having microbolometers as transducer elements.

By separating the element coupling radiation, the antenna, from the transducer element it is possible to design and manufacture devices having the advantages of an antenna and producing a signal fast enough to be used in a variety of demanding applications. Until here we have focused our attention on the metallic structure defining the antenna. However, the second part, but not less important, of an optical antenna is the transducer element. It provides a signal, typically an electric signal that is processed by an external circuit. There are two types of material structures that have shown capabilities to perform this task: the metal–oxide–metal diode, and the microbolometer. Both of them rectify the currents generated in the antenna structure by the incident radiation. These mechanisms are sensitive to the heating of the material structures (substrate, connectors, bond pads, etc) surrounding the antenna. However, the microbolometer transducer is, by its mode of operation, much more sensitive to this effect. With respect to its time of response MOM diodes are faster than microbolometers. The theoretical limit for MOM is given by the tunnelling effect through the junction, and it is around 10^{-15} s. The experimental value of the time response of these devices is around 100 ns. On the other hand, practical devices containing microbolometers have shown response times of 350 ns. This fast response for the bolometric transducer is possible because of the very small volume of the microbolometer itself that produces a very low thermal inertia.

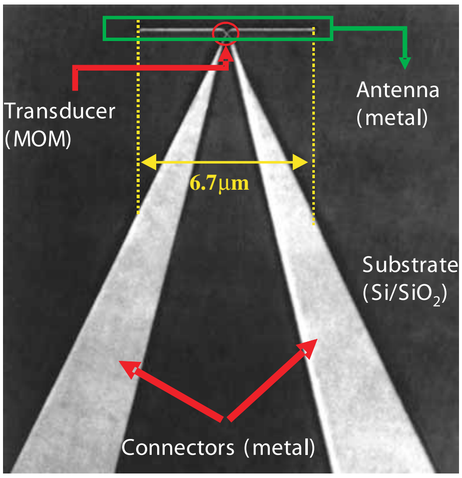

Figure 1. Electron microscope photography of a dipole antenna on a Si–SiO_2 substrate. The metallic structure forming the antenna is located on the top of the figure. The triangular shaped structures are connection lines for biasing and for the extraction of the signal. Light is incident perpendicularly to the plane of the wafer.

The main advantages of optical antennas can be summarized as follows.

- Optical antennas are point detectors having a detection area of about the square of the detected wavelength [12].
- Optical antennas couple the radiation into tiny volumes to create currents in the wire that are detected with a small rectifying element having a volume of about 0.02 μm^3. This small amount of material allows us to obtain a very fast response. Preliminary estimations of the response time for non-optimized devices are about 100 ns [13]. However, one of the practical rectifying mechanisms used in the detection of the signal is based on a tunnel effect having response times of about 10^{-14}, 10^{-15} s [14].
- Optical antennas are polarization-sensitive detectors in the same way as their radioelectric versions are [11, 12, 15].
- Optical antennas can be tuned to a specific wavelength. Due to the lossy character of the metallic structures at optical frequency, resonances are expected to be broadened, maybe limiting the tuning capability [16, 17].
- Optical antennas are directionally sensitive depending on the design of their metallic structures and the addition of external optical devices [16].

- Optical antennas can be monolithically integrated with read-out electronics and auxiliary optics.

To complete the optical antenna panorama we should include some weak points of these devices. The currents generated on the metallic structure tend to be dissipated due to the losses on the metal at optical frequencies and also due to the thermal dissipation on the substrate structures. The measured values of the responsivity are around $0.1\ \mathrm{V\ W^{-1}}$ for optical antennas having impedances of about $100\ \Omega$ and using microbolometer transducers. These values are one order of magnitude below those corresponding to high-speed avalanche photodiodes and metal–semiconductor–metal diodes. Based on the same material limitation, the tuning capabilities of optical antennas are compromised, allowing only a broadband tuning. Another issue related to the performance of optical antennas is the large time of response of optical antennas in comparison with the values obtainable with existing detection technologies [18]. This gap should be reduced by improving the thermal isolation from the substrate.

At this point of research in optical antennas some other facts should be taken into consideration for further investigation. For example, optical antennas develop currents that respond to the incident electric field. The transducers used today for extracting the signal rectify these currents. This procedure wastes the capabilities of the antenna to map the polarization of an incoming light beam. Besides, when optical antennas are used as a stand-alone metallic structure without optical-to-electrical transducer, the excitation and confinement of optical radiation may trigger observable changes in tailored chemical or biochemical substances such as dyes or photoluminescent materials. An advanced step in the research and analysis of optical antennas is also being developed under the nano-antenna topic. The use of carbon nanotubes to implement passive antenna structures able to resonate at visible frequencies opens the way to build new devices by an alternative fabrication technique allowing nanoresolution features.

3. Optical antenna applications

In this section we itemize three different fields of application of optical antenna devices: infrared and multi-spectral imaging, near-field optics, and sensors.

3.1. Infrared and multi-spectral imaging

Nowadays, antenna-coupled infrared detectors are becoming a more mature technology with unquestioned advantages with respect to conventional detectors in the infrared, and with some other technological challenges that need to be solved. The geometry and arrangement of these devices are about the same as those used in the classical antenna design and include structures having dipole antennas, microstrip and micropatch antennas, bow-tie antennas, spiral antennas, arrays of antennas, etc. As was pointed out before, when optical and infrared antennas are used to image a scene consisting of incoherent emitters, the amount of irradiance reaching the detector area is quite small. At the same time, the goal in the design is the fabrication of a focal plane array formed by adjacent pixels containing infrared antenna detectors (see figure 2). These antennas have to be separated by a given distance to preclude crosstalking and coupling between adjacent pixels. This fact, along with the necessary matching with the read-out electronics, dimensions the pixel to about 10^3–10^{-4} $\mu\mathrm{m}^2$. The antenna is written in the centre of the pixel and has a receiving area of about 10^1–10^2 $\mu\mathrm{m}^2$ for an incoming wavelength of $10\ \mu\mathrm{m}$. The filling factor is quite poor and the corresponding irradiance actually producing the signal is small. In order to improve the characteristics of the individual pixel we have attached a binary Fresnel zone plate lens to the pixel (see figure 3). These diffractive elements have shown their potentials in a variety of wavelength ranges and applications [19, 20]. By using this added optics we could measure an improvement in the responsivity of two orders of magnitude [21]. This improvement has compensated the losses due the small filling factor of the focal plane array.

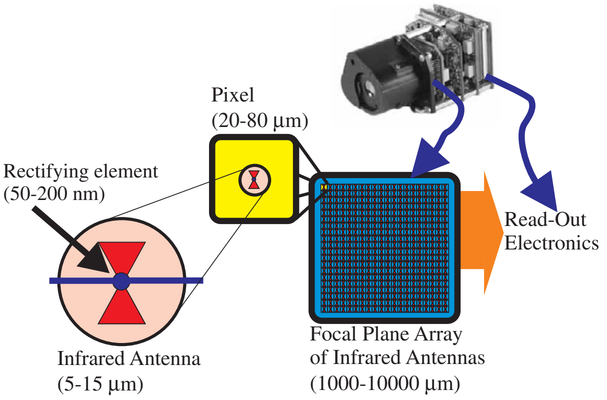

Figure 2. Schematic representation of a focal plane array composed of infrared antennas. The dimensions presented in the figure illustrate the low filling factor of this kind of arrangement.

Infrared imaging is moving towards multi- and hyper-spectral imaging. Different kinds of approaches have been proposed for it [22]. In this field we proposed the use of optical antennas with fractal geometry of the same type as already proved in the radioelectric spectrum. Figure 4 shows a fractal antenna having five different sizes of bow-tie antennas.

3.2. Near-field optics

Another stream of interest in antennas working at optical frequencies originates from the field of near-field optics (NFO). NFO can be considered a branch of nanometre-scale science and technology concerned with the optical properties of material structures less than about 100 nm in size (and down to molecular dimensions) as well as optical processes occurring on that scale [23–25]. Among these, the excitation and properties of surface plasmon polaritons (SPs) play a prominent role [26, 27]. At optical frequencies, these oscillations are of primary importance for the induction of antenna currents as well as for the propagation of signals along wires. The existence of SPs is closely related to the poor conductivity of most metals at optical frequencies but it also opens up opportunities for the design of electric components that will be specific for the optical regime. Therefore, the combination of antenna resonances and SP resonances holds promise for giant localized field enhancement. Optical frequency radiation can be confined to dimensions considerably less than 100 nm only by material

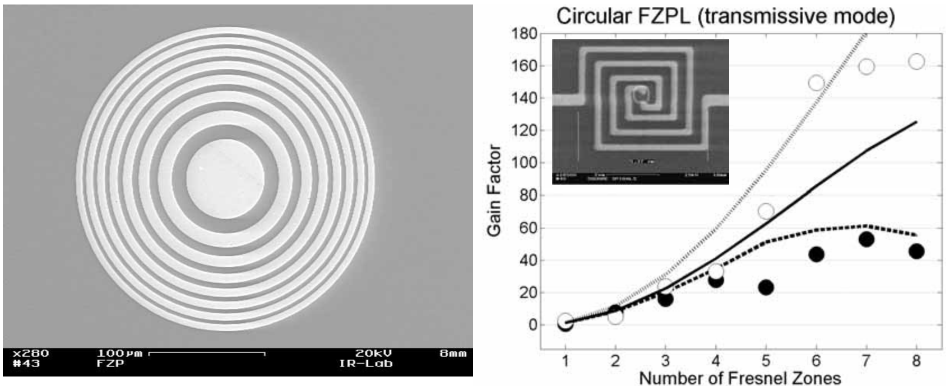

Figure 3. The coupling of Fresnel zone plate lenses located in front of the antenna improves the responsivity of the device. The measured responsivity with the Fresnel zone plate is two orders of magnitude larger than the responsivity without Fresnel lenses when the number of involved Fresnel zones is large enough. The antenna used in this study is a square spiral antenna having a microbolometer as its transducer element.

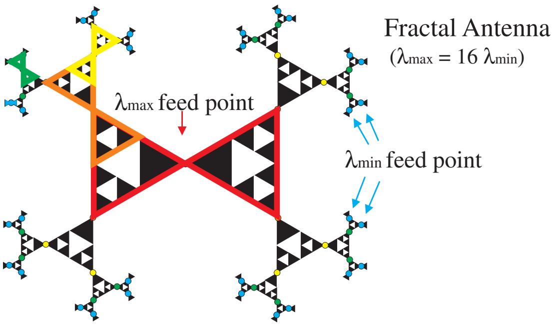

Figure 4. The use of fractal geometries may provide multi-spectral capabilities to devices working as infrared and millimetre imagers. This design has five scales having a relation of $\lambda_{\max} = 16\lambda_{\min}$.

structures of similar size, e.g. small apertures and scattering particles. Such structures have been used already for optical imaging beyond the diffraction limit by means of scanning near-field optical microscopy (SNOM) [28]. In a generalized sense, such structures are antennas, the confinement volume corresponding to the feed point region of the antenna. Apertures and small spheres, however, are not necessarily optimal shapes for the field confinement needed in some practical applications. For this reason, scientists studying NFO recently have become interested in the properties of radiowave antennas and their potential for downscaling into the optical regime [29].

3.3. Optical antenna sensors

Based on the same advantages as already used in the design of optical antennas for infrared imaging application, we anticipate the use of optical antennas for replacing cooled semiconductor and infrared detectors. The absence of cooling subsystems allows an easy integration. The capabilities of optical antennas to detect polarization will be fully integrated in new designs of sensors for spectroscopic applications.

4. Conclusions

Optical antennas are becoming a competitive alternative for some applications currently addressed by semiconductor and photoelectric detectors. The metallic structures are written using e-beam lithography and lift-off techniques. The spatial dimensions are of the order of the detected wavelength. Among the proposed applications for optical antennas, probably the most advanced now is that dealing with infrared imaging systems. These new systems will benefit from the polarization sensitivity properties, the absence of cooling mechanisms and the easy interface with read-out electronics and auxiliary optics. Here, the specifications for the time response are not very demanding, and the obtained results with microbolometers are sufficient for complying with the expectations. Near-field optics will use optical antennas as probing devices for enhancement of physical phenomena occurring at the nanoscale level. The optical antennas typically used here are not connected to any external circuit. Then, the information provided by the antenna needs to be read by some other measurement line in the optical set-up. In the very near future the introduction of carbon nanotubes acting as dipole antennas will make possible the excitation of new phenomena.

Summarizing, optical antennas, and the downscaled versions known as nano-antennas, are moving from the basic research activity to be part of the solution for a wide variety of nanophotonic applications.

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