Reviews in Physics 1 (2016) 36–51

Contents lists available at ScienceDirect

Reviews in Physics

journal homepage: www.elsevier.com/locate/revip

Magneto-plasmonic nanoantennas: Basics and applications

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ARTICLE INFO

Article history:
Available online 25 March 2016

ABSTRACT

Plasmonic nanoantennas are a hot and rapidly expanding research field. Here we overview basic operating principles and applications of novel magneto-plasmonic nanoantennas, which are made of ferromagnetic metals and driven not only by light, but also by external magnetic fields. We demonstrate that magneto-plasmonic nanoantennas enhance the magneto-optical effects, which introduces additional degrees of freedom in the control of light at the nano-scale. This property is used in conceptually new devices such as magneto-plasmonic rulers, ultra-sensitive biosensors, one-way subwavelength waveguides and extraordinary optical transmission structures, as well as in novel biomedical imaging modalities. We also point out that in certain cases 'non-optical' ferromagnetic nanostructures may operate as magneto-plasmonic nanoantennas. This undesigned extra functionality capitalises on established optical characterisation techniques of magnetic nanomaterials and it may be useful for the integration of nanophotonics and nanomagnetism on a single chip.

1. Introduction

Antennas are important elements of wireless information transmission technologies [1]. In radio engineering, antennas refer to devices converting electric and magnetic currents to radio waves and, vice versa, radio waves to currents [1] [Fig. 1(a)].

In the last decade, the definition of antennas was extended and the concept of plasmonic nanoantennas [Fig. 1(b)] was introduced because of the emergence of a new branch of science known as nano-optics, which studies the transmission and reception of optical signals at the nano-scale [2,3]. Plasmonic nanoantennas are made of specially designed metal (usually gold or silver) nanoparticles and their design visually resembles the existing structures of RF antennas [1]. Similar to RF antennas, plasmonic nanoantennas emit, receive and, more generally, control light with nano-scale (sub wavelength) elements, whose size is much smaller than the wavelength of incident light [2,3].

However, the operating principles of plasmonic nanoantennas and RF antennas are different. The response of nanoantennas to incident light is dictated by collective electron oscillations—plasmons [4]. Plasmons make it possible to control light with subwavelength structures, which is not readily possible with RF antennas whose dimensions are comparable with the wavelength of radio waves. Moreover, nanoantennas not only control light similar to radio waves [Fig. 1(b)], but they also locally enhance optical intensity by many orders of magnitude [2,3]. This effect is achievable because of a strong local field

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http://dx.doi.org/10.1016/j.revip.2016.03.002

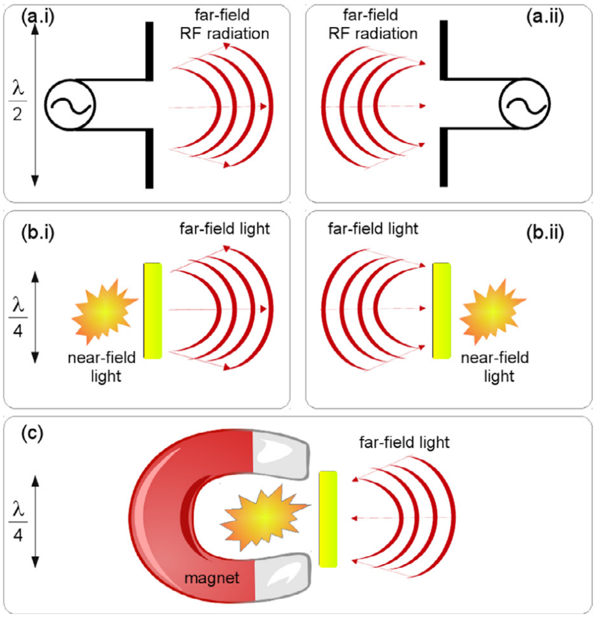

Fig. 1. (a) Illustration of emission (left) and reception (right) of radio waves by a dipole RF antenna. (b) Illustration of emission (left) and reception (right) of light by a dipole plasmonic nanoantenna. In all panels, λ denotes the wavelength of the incident radio waves or light in free space. The double-headed arrows indicate the dimensions of the antennas in comparison with λ. (c) Optical properties of magneto-plasmonic nanoantennas are similar to those of non-magnetic nanoantennas. However, the use of magnetic constituent materials and external magnetic fields adds new degrees of freedom in the control of light at the nano-scale, which allows developing novel devices with unique properties (see the main text). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

confinement near the metal surface of the nanoantenna, and it is used to enhance the extremely small nonlinear optical response of nanoscale materials up to the level achievable with macroscopic nonlinear crystals and optical fibres [3].

Different aspects of plasmonic nanoantennas were discussed in detail in [2,3,5–18]. However, the research direction of plasmonic nanoantennas is very broad and rapidly expanding because of the need to develop advanced optical nanomaterials with previously unattainable functionality, higher performance, smaller footprint and wider application range as compared with the currently available nanostructures. Examples of advanced functionality and applications include, but not limited to, ultra-small on-chip non-reciprocal photonics devices, bio-sensors with increased sensitivity, all-optical data storage and processing at the nano-scale, and different biomedical imaging modalities.

Magneto-plasmonic nanoantennas are novel nanostructures that hold the promise to meet the expectations outlined above. In contrast to conventional (non-magnetic) plasmonic nanoantennas, the constituent materials of magneto-plasmonic nanoantennas are ferromagnetic metals such as nickel, cobalt, iron or their alloys. Magneto-plasmonic nanoantennas can also be made of a non-magnetic metal combined with a magnetic material, which can either be conducting or insulating. External magnetic fields need to be applied to magneto-plasmonic nanoantennas to enable magneto-optical activity [Fig. 1(c)].

Similar to their non-magnetic counterparts, magnetised metal nanostructures may support plasmon excitations—magneto-plasmon resonances [19,20]. Significantly, the strength of magneto-optical effects becomes enhanced due to local electromagnetic field enhancement associated with the magneto-plasmon resonance [19,20]. Thus, magneto-plasmonics allows the development of miniaturised and integrated active magneto-optical devices, which can find applications in, for example, bio-sensing, telecommunications, and imaging. It is noteworthy that plasmon-assisted magneto-optical effects can also be observed in non-magnetic plasmonic nanoantennas [21–23]. However, such structures will not be considered in this work because their operation requires considerable magnetic fields >10 kOe [21], which are readily attainable in laboratory experiments but may not always be adequate for applications in integrated optical circuits and telecommunication systems.

Magneto-optical effects are classified according to the relative orientations of the wave vector of light k and the magnetic field $\boldsymbol{H}$, in which light can either travel along the field direction ($k||\boldsymbol{H}$) or perpendicular to it ($k \perp \boldsymbol{H}$) [20,24]. In these configurations, which are also used in magneto-plasmonics [20], the magneto-optical Kerr effect (MOKE) and Faraday effect are detected as a change in the polarisation state of light reflected from (Kerr effect) or transmitted through (Faraday effect) a magnetised structure. This change arises from the influence of the magnetic field on the dielectric permittivity tensor of the medium ϵ [20,24]: ϵ becomes non-symmetric that results in either polarisation rotation or changes in reflection. Changes in reflection occur in a special case known as the transverse MOKE configuration, in which only the p-component of incident light is affected by the applied magnetic field, but the s-component remains unaffected.

The time is definitely ripe to overview the breakthroughs in the field of magneto-plasmonic nanoantennas. Although different aspects of nano-scale magneto-plasmonics have been discussed in detail in [19,20,25–28], magneto-plasmonic