Chapter 5

Outlook on valorisation

Optics at the nanoscale attracted much interest due to the fact that it combines fundamental science with the prospect of technological applications. This chapter addresses the possible implications of results obtained in this work from the viewpoint of practical use. The examples outlined here are by no means extensive nor complete in the level of detail about the construction of optical nanodevices. Nevertheless, they highlight some of the possible applications of the particular systems we have studied and the results we have obtained.

5.1 Bistable all-optical switch

All-optical switches are devices whose state can be varied in a step-wise way by an externally applied optical field. Besides their significant role in optical computing, they are also one of the key components in ultra fast optical telecommunication networks. In the latter case, all-optical switches allow direct rerouting of traffic in the optical domain by eliminating several optical-to-electrical-to-optical conversions [147]. This increases the efficiency of the optical communication processes and saves power needed to convert the signals from light to electricity and back.

The key element of a material’s optical response to make it suitable for all-optical switching is that it possesses an abrupt change of state as a function of applied light intensity. This can be achieved by a system having two stable states for a single value of the applied light intensity, a system is known as a bistable system. Increasing or decreasing the applied light intensity around some threshold, one can switch the output from one level to the other. In this way,
such a system represents the binary integers "on" and "off" necessary for optical logic. The concept of optical bistability can be exploited for this purpose [40].

The nanohybrid comprised of a closely spaced SQD and MNP studied in Chapter 2 provides a system that exhibits optical bistability at the nano-scale. We comprehensively analyzed the system’s parameter space (the phase diagram) where bistability may occur and found that the conditions for switching can be fulfilled for real nanomaterials, for instance, a CdSe SQD - gold MNP nanohybrid, thus making this object a prospective candidate for a building block of all-optical nanoscale switches. Further, we studied the time dependent response of the system and discovered that the switching time from the lower to the upper stable state sensitively depends on the excess of the applied field intensity over a certain critical intensity. By contrast, the upper-to-lower state switching time does not exhibit such a peculiarity. Interestingly, by tuning the intensity of the applied field, the switching time between both states, can be lowered to several nanoseconds, which is two orders of magnitude smaller than commercially available all-optical switches [148]. This knowledge is of importance for designing nanoscale all-optical switches.

Although the analysis presented in Chapter 2 has been performed for a single heterodimer, we believe that more complicated clusters, such as an SQD surrounded by several MNPs and a single quantum dot or a grid of quantum dots on top of a metal surface will behave similarly. An MNP or a metal surface plays the role of a resonant mirror and provides a positive feedback on the optical state of the SQD, which is one of the essential ingredients for bistability to occur.

5.2 Tailoring the Fano-like line shape

The adaptability and flexibility of many optical applications, ranging from sensors to slow-light devices [35,149,150], depend on the ability to tailor or modulate the line shape of the optical response. Solving this problem on the nanoscale represents an important task in the design of an optical device. It has been understood that the Fano-like resonances [35], observed in the optical response of materials, may be used in a wide variety of applications, such as the above mentioned ones.

Using as example a hybrid comprised of a quantum dimer emitter strongly coupled to an MNP, we have shown in Chapter 3 that it is possible to tailor its
optical response. In the linear regime, the interaction between the excitons of the
dimer and the plasmons of the MNP results in a dispersive Fano-like line shape
of the system’s absorption spectrum. Interestingly, the line shape appeared
to be strongly dependent on the spectral location of the dimer’s one-exciton
absorption peak with respect to the MNP’s plasmon resonance; in particular, we
found that it is important whether the exciton resonance lies at the low- or the
high-frequency side of the plasmon resonance or at its maximum. In addition, the
line shape is also sensitive to the ratio of the dimer-MNP coupling parameter
to the dimer dephasing rate. Thus, small perturbations, i.e. changes of the
environment and or details of the constituents, may induce a significant shift of
the absorption peak or modify the line shape. Upon increasing the applied-field
intensity, the Fano line shape becomes less pronounced and disappears when
the hybrid gets saturated. All this allows one to tailor the Fano-like shape of
the hybrid’s absorption spectrum by controlling the system’s parameters and by
changing the input power. These properties render the nanohybrid potentially
of interest for applications such as those mentioned at the top of this section.

5.3 Optical ultrashort pulse nanogenerator

Ultrashort light pulses, with durations of the order of picoseconds or less [151]
have a wide range of applications in many fields, such as medical imaging [152],
material processing [153], femtochemistry [154], to name a few. Several ap-
proaches to generate trains of optical short pulses have been proposed and re-
alized. Among them are methods employing multiple-order wave plates and a
linear polarizers [155] and tapered photonic crystal fibers [156].

We have demonstrated in Chapter 4 of this thesis, that the exciton-plasmon
coupling in nanohybrids may give rise to interesting nonlinear optical effects,
one of which is the occurrence of optical self-oscillations. In Chapter 4, we
showed that, when a three-level ladder-type SQD strongly coupled to an MNP
is driven quasi-resonantly by a single continuous wave, sustained oscillations
(self-oscillations) of the SQD’s dipole moment may occur. Most importantly, we
have shown that the period of self-oscillations depends on the amplitude of the
driven field and can be pushed down to sub-picoseconds. Thus, the nanohybrid
in its self-oscillation regime can be viewed as a tunable nanogenerator of trains
of ultrashort pulses. Such a regime can be achieved for a heterodimer system
comprised of a ZnS/ZnSe core-shell quantum dot and a nearby spherical silver
nanoparticle or a heterodimer comprised of an In$_x$Ga$_{1-x}$As/GaAs quantum dot and a triangular silver nanoparticle.