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Introduction: the need for optical antennas

Nanophotonics is a field of research that aims at developing techniques to control and manipulate light at sub-wavelength dimensions, in the nanometer range. Research in this field is motivated by fundamental curiosity about light-matter interactions at the nanoscale and also by a wide variety of potential applications ranging from optical communication and computing to bio-sensing. While light can be routinely manipulated with conventional optical elements such as mirrors and lenses, at the nanoscale alternative approaches are required. Among others, a key element in nanophotonics are optical antennas (OAs) [1]. In analogy to their larger counterparts addressing micro and radio waves, these elements are capable of concentrating free propagating electromagnetic radiation at the antenna's focus (also known as "hotspot"), which can have a volume of zeptolitres, several orders of magnitude smaller than a diffraction-limited focus obtained with conventional lenses. Conversely, OAs are also able to mediate the emission of nano-sized single-photon emitters such as organic fluorophores and quantum dots

placed at the hotspot. In particular, OAs can accelerate and increase the efficiency of the emission and even induce directivity [2]. A sketch of the main functions of OAs is included in figure 1a.

Metallic nanoparticles and localized surface plasmons

Most OAs are based on nano-sized metallic elements [3], though high-index dielectric materials such as Si, Ge and GaAs have also been employed [4,5]. In this report, we will focus on OAs based on metallic nanoparticles. Conduction electrons in metallic nanoparticles present natural oscillation frequencies that depend on the material, shape and surrounding medium of the nanoparticle. If the incident light is in resonance with an eigenfrequency of the nanoparticle's electrons, a strong collective oscillation of the free electrons is induced, which in turn radiates at the same frequency. Then, a coupled electromagnetic-mechanical oscillation is established called localized surface-plasmon polariton, or nanoparticle plasmon for short, that leads to an exceptional polarization of the nanoparticle. OAs are built by one or more

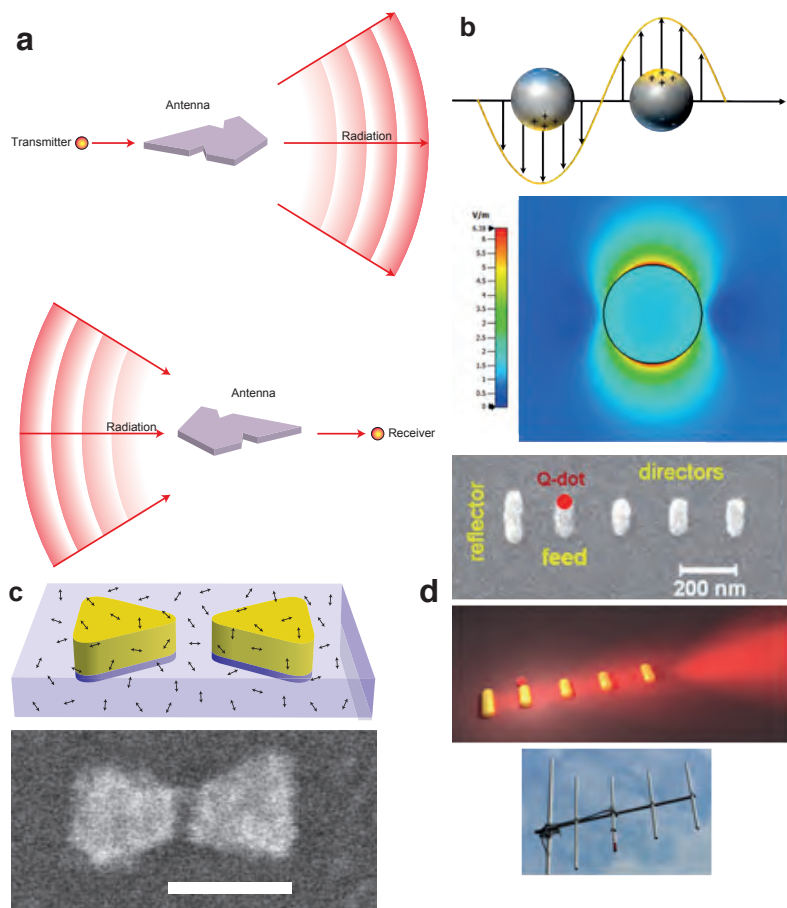


Figure 1. (a) Sketch of an OA mediating the emission (top) and concentrating the incident radiation (bottom). (b) Light can excite localized surface plasmons in metallic nanoparticles (top) leading to a polarization which can enhance the electric field in the nanoparticle's vicinity (bottom). (c) Sketch of an OA dimer composed of two triangular gold nanoparticles forming a bowtie (top) and corresponding SEM image (bottom), scale bar 100 nm. (d) SEM image of an Yagi-Uda OA based on metallic nanorods (top) together with a sketch depicting how the emission is directed (middle). Yagi-Uda antenna operating in the radio frequency range (bottom). Images adapted from [2,6,7].

nanoparticles arranged to form particular resonant modes with hot spots where the local electric field is enhanced by several orders of magnitude with respect to the freely propagating field, see sketch in figure 1b. OAs are useful to manipulate the behaviour of single-photon emitters, such as fluorophores or quantum dots. Single-photon emitters can be modelled as a two-level system, which upon excitation by photon absorption may return to the fundamental level with or without photon emission (of lower energy). A nearby OA alters the photonic landscape for a single-photon emitter. Depending on the OA design, the rates of excitation, radiative decay and non-radiative decay of an emitter can be modified, as well as the emission spectrum and directivity. In this way, OAs are unique in nanophotonic applications because they can be used, among other things, to generate highly intense local excitation rates for photon emitters, to improve their quantum yield, and even to make them emit certain wavelengths in predefined directions.

Optical antennas fabrication: top-down approaches, pioneering examples and challenges

The performance of an OA is determined by its material composition and geometry. Thus, nanophotonics relies on precise nano-fabrication methods, which may be performed in two general ways: top-down and bottom-up. Top-down

techniques are the nanoscale analog of carving a stone block into a sculpture and have been the first and most widely used approach to fabricate OAs so far. Typically, this technique involves evaporating a metallic layer and “carving” the OAs by means of lithography using beams of electrons or ions. Canonical examples include the bow-tie antenna by the Moerner group [6], see figure 1c. This OA was able to achieve an electric field intensity concentration of two orders of magnitude and an overall fluorescence enhancement of 3 orders of magnitude for fluorophores stochastically placed at the OA's hotspot. Another pioneering example is the optical Yagi-Uda antenna by the van Hulst group [7], see figure 1d. The latter, borrowing the design from the 1926 television antenna, was able to direct the emission of quantum dots into predominantly one direction.

Despite the tremendous success in demonstrating the potential of nanophotonics, OA fabricated following top-down techniques often suffer from several shortcomings. First, ion or electron nanolithography are mostly serial processes that involve costly equipment, rendering mass fabrication not viable. Second, the resulting metallic nanostructures have low crystallinity and considerable surface roughness. This affects the quality factor of the plasmonic resonances reducing the OAs' performance and reproducibility. Finally, with this approach it is extremely challenging to fabricate 3D structures and nearly impossible to position single-photon emitters at the hotspot of OAs [2].

Optical antennas fabrication: bottom-up approaches and the DNA origami technique

On the other hand, bottom-up nanofabrication is the nanoscale analog of putting together Lego blocks to build a predefined structure. Of course, one cannot manipulate the blocks one by one, so an automatic self-assembly mechanism driven by molecular interactions is necessary. For example, to fabricate a structure combining three blocks labeled A, B, and C in the following manner, A-B-C, the interactions A-B and B-C need to be significantly stronger than A-C. Thus, a hierarchy of different interactions or forces is required. Such strategy is challenging even for a handful of building blocks because the number of differentiable interactions necessary scales exponentially with the number of elements. In the early 1980s, Prof. Seeman identified DNA as an ideal candidate for the self-assembled bottom-up fabrication of nanostructures [8]. Single stranded DNA (ss-DNA) is built by a chain of nucleotides, A, T, G, and C, each with an extension of approximately 0.34 nm. Two ss-DNAs with complementary nucleotide sequences can hybridize through Watson-Crick base pairing (A-T and G-C) to form a double stranded DNA (ds-DNA) helix with a diameter of approximately 2.5 nm and a persistence length of 50 nm turning ds-DNA into one of the stiffest known polymers.

Thus, ss-DNA can be employed as the nano-building blocks and an enormous library of hierarchical interactions between these blocks can be established through the length and complementarity between the sequences. Prof. Seeman demonstrated this approach by fabricating a DNA

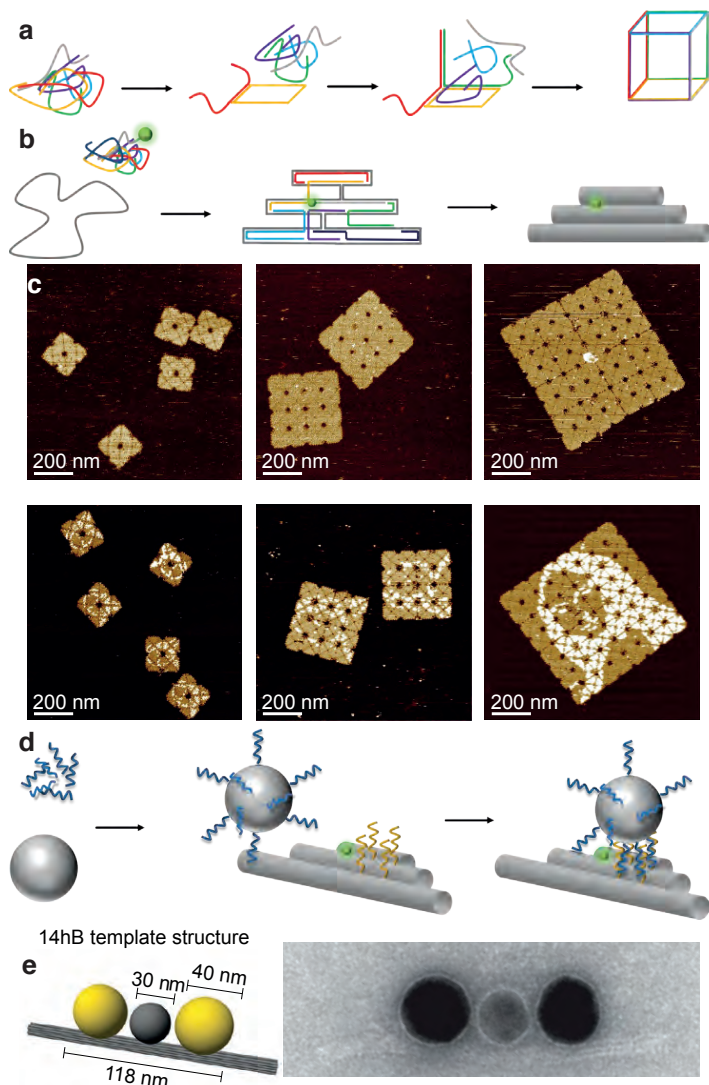


Figure 2. (a) hybridization of ss-DNA sequences for the self-assembly of a DNA nanocube. (b) Sketch of the DNA origami technique. A fluorophore (green sphere) can be directly covalently attached to one of the ss-DNA staples. (c) AFM images of squared shaped DNA origami combined through hybridization to form larger architectures in the micrometer range. (d) Sketch depicting the incorporation of metallic nanoparticles to DNA origami through DNA hybridization. (e) Example of the incorporation of three particles of different materials, gold and silver to bundle-shaped DNA origami (left) with its corresponding TEM image (right). Images adapted from [9,10].

nanocube made of 10 ss-DNA sequences of around 100 nucleotides each with an edge length of about 10 nm [11], see the sketch in figure 2a. Despite the ground-breaking nature of this approach, this technique was not immediately adopted due to the challenges in its implementation. Among other difficulties, ss-DNA sequences had to be incorporated sequentially with precise stoichiometric control, and several purification steps were required. Furthermore, the determination of which sequences to use for each ss-DNA in order to yield a particular nanostructure was cumbersome as computational tools were not readily available. Some decades later in 2006, this idea was revisited by Prof. Rothemund who introduced a key modification [12]. Instead of hybridizing ss-DNA sequences of similar length, nanostructures were fabricated by hybridizing many, around 200 short ss-DNA chains (termed staples, about 40 nucleotides long each) to a much longer, closed ss-DNA chain (termed scaffold, with approximately 8000 nucleotides), see figure 2b. This technique, known as DNA origami, remarkably

facilitated fabrication as one-pot reactions were possible and no precise stoichiometric control was required. Finally, purification was simplified due to the greater difference in mass between staples, scaffold and the hybridized nanostructure. Currently, DNA origami structures can be routinely designed using an open source software [13] (cadnano.org) by basically sketching the desired nanostructure and selecting which scaffold will be employed (a list of the most common scaffolds commercially available with their corresponding sequences is already preloaded). The software then assesses the feasibility of the design and outputs a list of the required staples, which can be forwarded with one click to place an order in one of the many suppliers of ss-DNA chains. The fabrication process consists of simply mixing the ss-DNA staples with the scaffold strands in a tube at concentrations in the nM range, typically with a significant excess of staples with respect to scaffolds to avoid that a single ss-DNA staple hybridizes with more than one scaffold strand. The mixture is then placed on a thermocycler where a temperature ramp from around 90 °C to room temperature is performed to ensure that staples will hybridize to the portions of the scaffold which are fully complementary. This process can take from two hours to days depending on the complexity of the nanostructure. Finally, the DNA origami can be purified using centrifugation filters or gel electrophoresis. The resulting DNA origami structures have typical dimensions in the 100 nm range (limited predominantly by the size of the scaffold strand) and can be combined with other DNA origami [9], through for example DNA hybridization, to reach the micrometer range, see figure 2c. In the past 15 years, the DNA origami technique was incorporated in dozens of labs around the world thanks to a plethora of available designs and synthesis protocols. But this technique is not only a fascinating nanofabrication approach, it can also be exploited for several applications. Together with Prof. Tinnefeld, we and others identified the potential of the DNA origami technique for nanophotonics [14,15]. This is because both single-photon emitters and metallic nanoparticles can be incorporated into DNA origami structures. Organic fluorophores can be covalently attached at specific positions on the staples. Metallic nanoparticles and other species such as quantum dots can be added by first conjugating the nanoparticle surface with a ss-DNA and designing the DNA origami so that the complementary sequence protrudes at the desired docking locations (this is achieved by extending the sequence of a set of ss-DNA staples), see figure 2d and 2e. In this way, the shortcomings of the top-down fabrication approach can be addressed. First, this constitutes an inexpensive technique with both scaffolds and staples commercially available that can be carried out in standard chemical labs equipped with a thermocycler. In addition, the parallel fabrication by self-assembly yields zillions of structures in one reaction. Second, colloidal metallic nanoparticles are employed. These particles can be synthesized using a variety of metals, sizes and shapes with high degree of homogeneity and crystallinity improving the performance and reproducibility of OAs. Finally, with this technique, both nanoparticles acting as OAs and single photon emitters can be positioned with nanometer precision and stoichiometric control in 3D nanometric geometries. All these advantages were exploited to revisit several light-matter studies at the single-molecule level [16]. In particular, this technique has been employed for surface-enhanced spectroscopies.

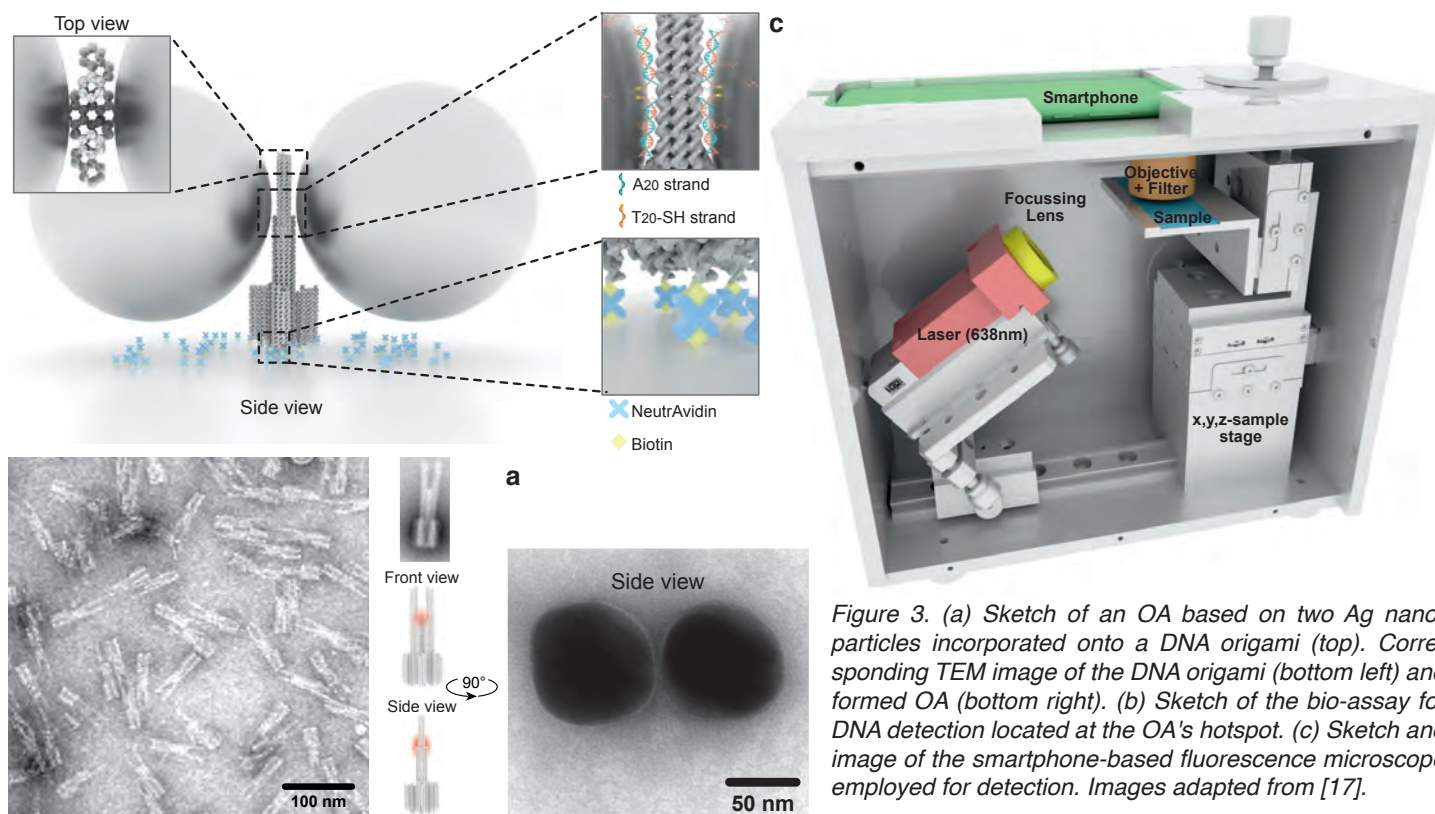


Figure 3. (a) Sketch of an OA based on two Ag nanoparticles incorporated onto a DNA origami (top). Corresponding TEM image of the DNA origami (bottom left) and formed OA (bottom right). (b) Sketch of the bio-assay for DNA detection located at the OA's hotspot. (c) Sketch and image of the smartphone-based fluorescence microscope employed for detection. Images adapted from [17].

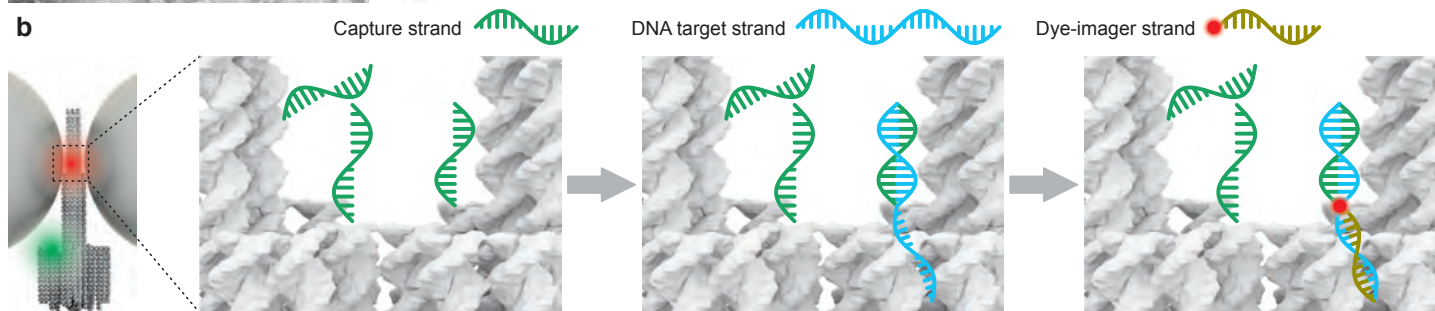


Figure 4. (a) Sketch of the self-assembly of a bow-tie OA based on two Au triangular plates. Two rectangular DNA origami are first hybridized to form the support structure. At the hotspot, a Raman active single molecule is positioned. (b) Corresponding TEM image. Images adapted from [18].

Examples of self-assembled optical antennas

Recently, we have fabricated DNA origami structures capable of hosting two 100 nm silver nanoparticles forming a dimer OA (figure 3a) [17]. We took advantage of the versatility of DNA nanotechnology to place a fluorescence bio-assay for DNA detection exactly at the OA hotspot located in the gap between the two nanoparticles (figure 3b). In the presence of the target DNA sequence, fluorophores could dock at the OA's hotspot where the fluorescence was am-

plified by a factor of up to 500x and could be detected with portable devices such as a smartphone-based fluorescence microscope (figure 3c). This experiment represents a clear step forward in the development of point-of-care diagnostic platforms.

Another remarkable example includes the self-assembly of anisotropic metallic nanostructures. Ding's group has recently fabricated bow-tie antennas by incorporating and orienting gold nanoplates onto two rectangular DNA origami structures [18], see figures 4a and 4b. Compared to the structures fabricated with top-down nanolithography (figure 1c), smaller and more homogenous gaps between the elements can be achieved. However, the unique advantage of this approach is that single Raman active molecules (Cy3 and Cy5) could be placed at the hotspot of the bow-tie antenna in order to demonstrate single-molecule SERS.

Finally, DNA origami structures can also be designed to undergo conformational changes upon for example the incorporation of additional ss-DNA sequences. The groups of Liu and Lindfors have recently exploited this technique to fabricate an OA dimer based on two gold nanoparticles where a single fluorophore can "walk" in a controlled manner across the gap (figures 5a and 5b)

rectangular DNA origami are first hybridized to form the support structure. At the hotspot, a Raman active single molecule is positioned. (b) Corresponding TEM image. Images adapted from [18].

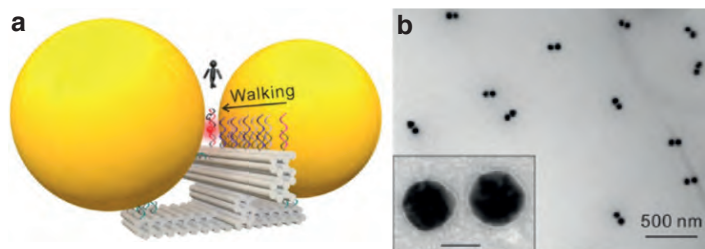


Figure 5. (a) Sketch of an OA dimer designed to allow controlled stepwise motion of a fluorophore across its hotspot. (b) Corresponding TEM image. Images adapted from [19].

[19]. In this way, the effect of the OA on the fluorescence at the hotspot could be fully mapped.

Conclusions and outlook

Over the last decades, an increasing number of researchers have resorted to DNA nanotechnology for nanophotonic applications. In particular, the DNA origami technique enables the bottom-up fabrication of 3D nanostructures capable of hosting both single-photon emitters and nanoparticles with unprecedented stoichiometric and positional control facilitating light-matter studies at the single-molecule level with defined geometries. Furthermore, this technique is flexible, inexpensive, and can be readily implemented in conventional chemistry labs. Future developments currently under investigation include the control of the orientation of single molecules in DNA origami [20], as well as the consolidation of this approach in other fields such as sensing [21], nano-electronics [22] and super-resolution microscopy [23].

Acknowledgements

G. P. A. acknowledge financial support by the SNF through grant 200021_184687.

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