Input and output terminals used in optical near field technology

In the case of nanophotonic devices operating by using the concept of dressed photons, the given system can be subdivided into two sub systems, namely, one which is the relevant nanometric subsystem and the other, which is the irrelevant macroscopic subsystem that includes the sample and the probe. Input and output terminals are needed to connect the nanometric and macroscopic subsystems. This lecture deals with the above mentioned input and output terminals.

1 Input terminals based on the concept of optical nano fountain

Any input terminal should be capable of converting the conventional propagating light that involves the free photons to the optical near field that involves the virtual photons or the dressed photons which are non propagating. Ohtsu research group have come up with a novel devise known as an optical nano fountain whose principle of operation is analogous to that of biological antennae that are used for trapping light in bacteria which harvest light.

1.1 Principle of operation

The principle of operation of the optical nano fountain is based on the concept of unidirectional exciton energy transfer between two arbitrary quantum dots and is shown as an animation in Figure 1.

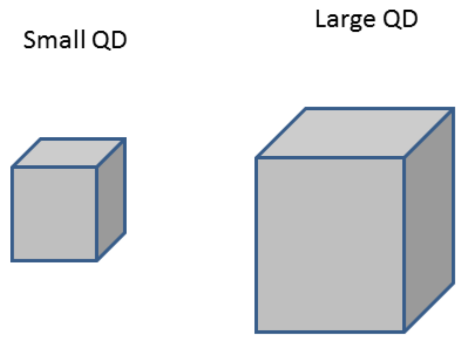

Fig. 1: Unidirectional exciton energy transfer from Small QD to Large QD

Ohtsu research group have considered comparatively small CuCl quantum dots of different sizes that surround a comparatively large CuCl quantum dot. Exciton energy is dissipated via the relaxation process from the quantized upper energy level to the quantized lower energy level in each quantum dot. As the optical near field interaction takes place between the nanometric quantum dots of appropriate sizes and as the subsequent relaxation in each quantum dot is fast, unidirectional exciton energy transfer is guaranteed in each quantum dot. The entire exciton energy from the surrounding smaller quantum dots is transferred to the largest of the quantum dots that is placed at the center of the smaller quantum dots. Finally, from the output of the largest quantum dot, the dressed photons are generated. It is no wonder that optical nano fountain derived its name due to the spurting of light from the largest of the quantum dots after having collected exciton energy in a stepwise manner from all the surrounding smaller quantum dots. As the exciton energy is dissipated only via the relaxation process in each quantum dot, the conversion efficiency from the free photon energy to the dressed photon energy is high. This is a feat that cannot be achieved by any conventional far field optical device such as a convex lens or a concave mirror as it is subjected to diffraction limit which is detrimental for excitation energy transfer. The working principle of an optical nano fountain is as shown in Figure 2.

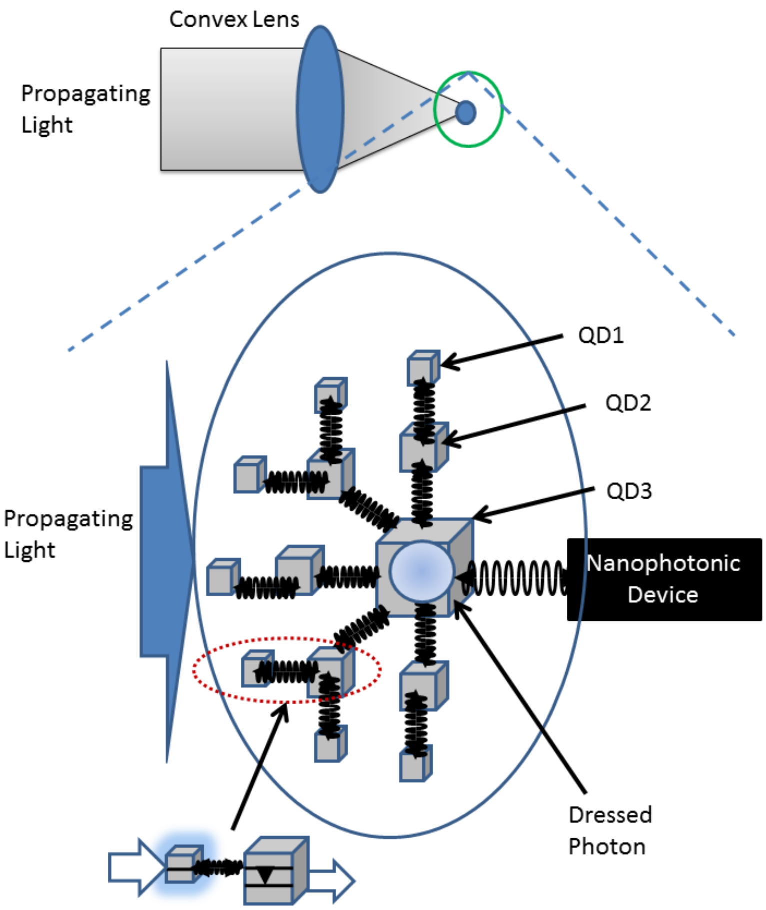

Fig. 2: The working principle of an optical nano fountain

1.2 Room temperature operation of optical nano fountain

By using the principle of molecular beam epitaxy, multi layered InAs quantum dots can be grown at room temperature in a size and position controlled manner. The layer of large quantum dots is surrounded by about thirty layers of small quantum dots. Thus when

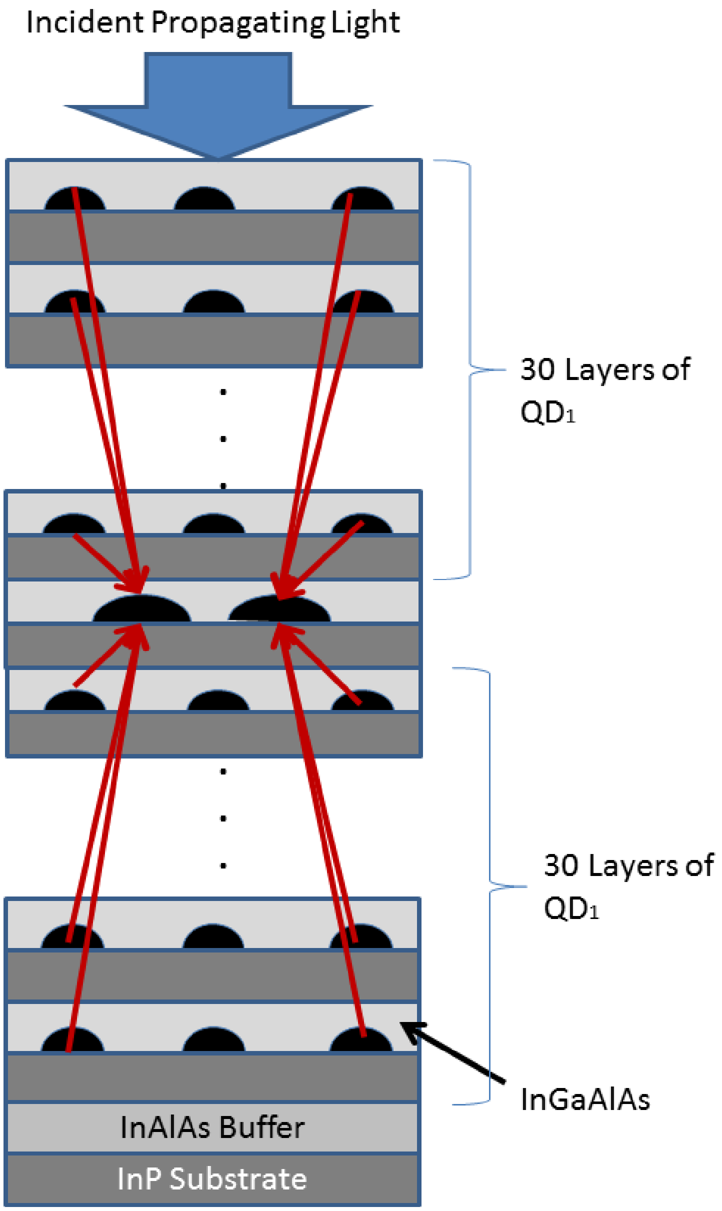

Fig. 3: Room temperature operation of InAs quantum dots as optical nano fountain

the small quantum dots are illuminated with conventional propagating light, the dressed photons are generated form the layer of large quantum dots and is depicted in Figure 3.

2 Plasmon wave guide for optical far to near field conversion

Extensive research work has been carried out by employing nanophotonic wave guides such as photonic crystals, photonic crystal fibers, etc., which use conventional propagating light as the input signal. But this falls under the category of diffraction limited nanophotonics as the alignment of the electric dipole moments are governed by the spatial phase of the incident light. To overcome this deadlock and in order to to connect the conventional diffraction limited nanophotonic devices to the nanophotonic integrated circuits that operated based on dressed photon technology, a nano optical wave guide that can couple the far field and the near field, is very much needed. Ohtsu research group have come up with a novel plasmonic wave guide that can perform optical far field to near field conversion.

2.1 Principle of operation

In order to couple efficiently the converted optical near field to the quantum dots, a plasmon wave guide has a sub 100nm width of a guided beam. Also in order to prevent the direct coupling of the conventional propagating light to the nano dots, it requires a super wave length propagation length. Moreover, it should have high conversion efficiency.

The plasmon wave guide comprises of a silicon-wedge which is coated with a thin-metal film. The conversion from the far field to the near field is three stage process. In the first stage, the incoming far field light is transformed into a two dimensional surface plasmon mode on the slanting surface of the wave guide. At the second stage, the two dimensional surface plasmon mode is converted into a transverse magnetic plasmon mode at the edge between the slanting surface and the plateau, owing to the scattering coupling at the edge. The plateau is coated with a metal film with sufficient thickness such that the plateau on the plasmon wave guide performs as a metal core waveguide. The presence of the 100nm nano dots at the edge of the plateau convert the one-dimensional transverse magnetic plasmon mode to the optical near field.

2.2 Fabrication of the plasmon waveguide

The glass substrate on the plasmonic waveguide was coated with a (100) oriented silicon wafer by anodic bonding. The patterned rectangular mask of the plasmon waveguide was tilted at an angle of 30° with respect to the (110) crystal orientation of silicon. A mixture of 40g of KOH, 60g of water and 40g of isopropyl alcohol at 80°C was used for fabricating the silicon wedge by anisotropic etching. Finally, the silicon wedge was given a 50nm thick coating of gold layer after removing the SiO_2 layer.

2.3 Advantages of the plasmon wave guide

The plasmon wave guide devised by Ohtsu research group has the following advantages:

Conversion from the two-dimensional surface plasmon mode to the one dimensional surface plasmon mode can be achieved efficiently due to the high conversion efficiency of the plasmon mode, mainly because of scattering coupling. As the plasmon waveguide does not have a cutoff, the beam width can be made as rainbow as $1nm$ by appropriately decreasing the core diameter. Last but not the least, the one dimensional transverse magnetic plasmon mode has got a sufficiently long propagation length so the it can be converted to the optical near field by effective coupling with the nano dots.

3 Metallic pyramidal silicon probe

The generation as well as the detection of an optical near field can be achieved using a metallic pyramidal silicon probe, which has been devised by the Ohtsu research group.

3.1 Fabrication of metallic pyramidal silicon probe

The pyramidal silicon probe has a refractive index of 3.67 at $830nm$ and is coated with an aluminium film. It has 180 cells along the Y-direction and 150 cells along the z-direction. The four sidewalls of the pyramidal silicon probe are forwarded by the (111) silicon crystal planes. A scanning probe with a glass core having a refractive index of 1.53 is used for detecting the optical near field energy on the probe tip. The scanning probe has a conic angle of $30°$ and is coated with a gold layer of $1\mu m$ thickness. The aperture of the scanning probe has a diameter of $50nm$.

The glass substrate is bonded with a (100) oriented silicon wafer by anodic bonding. The scanning probe is fabricated by anisotropic etching consisting of $40g$ of KOH $60g$ of water and $40g$ of isopropyl alcohol maintained at $80°C$. The scanning probe is coated with an aluminium layer having a thickness of $20nm$ after removing the SiO_2 layer.

3.2 Principle of operation

The metallic pyramidal silicon probe has high refractive indices for the core and the metallic thin film. As a result, the conventional propagating light is converted into a surface plasmon mode at the metallic tip. As the metallic probe does not have a cut off, the beam width can be made as narrow as $1nm$ by reducing the cone diameter. The peak energy of the metallic pyramidal silicon probe is very large. Hence optical near field excitation is very much effective mainly due to localized surface plasmon resonance.

4 Output terminal

A metallic nanoparticle placed in the close proximity of the large output quantum dot serves as the output terminal of the nanophotonic device. The matallic nanoparticle is governed by large electric dipole and the fast relaxation process involving the phase and energy. Hence a scattered free photon is generated at the output terminal constituting the metallic nanoparticles when the dressed photon, that is generated from the output of the large quantum dot, is transferred to the metallic nanoparticles. For room temperature operations, gold nanoparticles are placed in the close proximity of the two-dimensional arrays of InAs quantum dots. Hence energy is converted in an efficient manner from the dressed photon to the free photon. This is due to the fact that the impedance owing to the fast relaxation process of phase and energy from the large quantum dot layer to the gold nanoparticles is exactly matched to that of free space.

5 Additional reading and references

1. M. Ohtsu, K. Kobayashi, T. Kawazoe and T. Yatsui, Principles of Nanophotonics (CRC Press, New York, 2008).

2. M. Ohtsu (Ed.), Progress in Nanophotonics 1 (Springer-Verlag, Berlin, 2011).

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