Applications of dressed photon technology in communication networks and systems

Digital optics plays a very crucial role in enhancing the system performance in order to cope up with the demand for handling huge data and also to satisfy various tasks imposed by industry and society. When using conventional propagating light as the input signal, optical digital signal processing technology suffers a severe problem in the form of diffraction limit of light. Thus one has to live up with poor integrability of optical devices as one is forced to operate an optical device around $1\mu m$ which is very large when compared to the gate width of conventional silicon VLSI hardware.

Nanophotonic devices employing dressed photon technology, do not depend on the wavelength of light. Rather they depend only on the size of the nanophotonic device, thereby aiding ultrahigh-density integration. Hence one can realize both qualitatively and quantitatively novel features that are not present in conventional optical and electronic nano devices.

This lecture purports to the optical excitation transfer in a crystal mixture comprising of semiconductor quantum dots of various sizes that are networked on the basis of optical near field interaction.

1 Principle of optical excitation transfer in an optical quantum dot network

When one considers a nanometric quantum dot system consisting of two or more quantum dots of appropriate nanometric sizes in multiples of side length a, the energy eigen values corresponding to the exciton energy levels represented by the quantum numbers (n_x, n_y, n_z) can be written as

$$E_{n_x,n_y,n_z} = E_b + \frac{(n_x^2 + n_y^2 + n_z^2)\pi^2\hbar^2}{2m_{eff}a^2}, \tag{1.1}$$

where E_b is energy of the bulk exciton and m_{eff} is its effective mass.

Based on Eq. (1.1), one can have resonance between appropriate exciton energy levels of the quantum dots, resulting in optical near field coupling between the quantum dots. Hence optical exciton energy transfer takes place from one quantum dot to another quantum dot. When there exists a sublevel energy relaxation which is faster than the optical near field interaction, uni directional signal transfer is guaranteed.

An optical network, comprising of several quantum dots of appropriate sizes that are connected with each other via optical near field interaction due to the steep electric field that exist within the vicinity of the quantum dots, can thus be perceived. An important aspect due to optical near field interaction is that even conventional forbidden energy levels contribute to the exciton energy transfer. One can hence examine and determine an efficient autonomous optical network topology via optical near field interaction.

2 Optical network topology via optical near field interaction

One can consider a nanometric quantum dot system comprising of multiple smaller quantum dots denoted as S_i coupled to one large quantum dot L via optical near field interaction.

Interdot interaction also is possible between adjacent smaller quantum dots. The main aim of this optical network topology is to maximize the transfer of excitons from each smaller quantum dot to the sole larger quantum dot.

As the smaller quantum dots have limited radiation lifetime, the entire initial excitation cannot be transferred to the large quantum dot. Hence when there are many smaller quantum dots surrounding the larger quantum dot, loss in energy transfer takes place from the smaller quantum dots to the larger quantum dot due to the presence of too many excitations in the smaller quantum dots.

Hence one has to arrive at an optimal combination of smaller and larger quantum dots in order to maximize the exciton energy transfer from each of the smaller quantum dot to the larger quantum dot.

3 Experimental demonstration of optical network topology

Ohtsu research group demonstrated an optimal optical network topology consisting of two kinds of quantum dots. One set consists of $CdSe$ quantum dots of that form the core and ZnS quantum dots that form the shell, each having a diameter of $2nm$. The other set comprises of the same type of above mentioned quantum dots, but having a diameter of $2.8nm$. After being dispersed in a matrix comprising of tolune and ultraviolet curable resin, they were spin-coated on one half of the surface of a silicon photodiode. The other half of the silicon photodiode was coated with the same resin but without the quantum dot mixture. Each area of the photodiode was selectively radiated with input light and the generated photo current was noted down. It was observed that there was a marked increase in the photo current when input light was radiated on the area containing the quantum dot mixture. They attributed the increase in photo current due to the optical excitation transfer through which the input light wavelength was red shifted to wavelengths where the photo detector was more sensitive. The maximum increase in the photo current was recorded when the ratio of the number of smaller quantum dots to the larger ones was $3:1$, which very much agreed with the theoretical optimal ratio.

Thus one can conclude that by appropriately manoeuvering the ratio of the number of smaller and larger quantum dots, it is very much possible to increase the output signal. Hence by proper engineering of the optical network topology between the various quantum dots, the output can be increased.

4 Different types of quantum dot optical network topologies

One can consider an $S2-Ll$ optical network topology consisting of two smaller quantum dots and a larger quantum dot. Figure 1 illustrates various state transitions arising from eleven basic states occurring in the $S2-Ll$ system comprising of two smaller quantum dots QD-A and QD-B and a larger quantum dot QD-C. Assuming that there are two excitons present in the given nanometric system, the following transitions can take place:

1. A sublevel energy relaxation denoted by ‘R’ with respect to the larger quantum dot QD-C by which the exciton goes from sublevel 2 to sublevel 1.
2. A radiative transition ‘rL’ by which the exciton in the larger quantum dot QD-C gets radiated.
3. A radiative transition ‘rS1’ by which the exciton in the smaller quantum dot QD-A gets radiated.
4. A radiative transition ‘rS2’ by which the exciton in the smaller quantum dot QD-B gets radiated.
5. An inter-dot interaction between the smaller quantum dot QD-A and the larger quantum dot QD-C denoted by ‘NS1L’ which can take place from QD-A to QD-C and viceversa.
6. An inter-dot interaction between the smaller quantum dot QD-B and the larger quantum dot QD-C denoted by ‘NS2L’ which can take place from QD-B to QD-C and viceversa.
7. An inter-dot interaction between the smaller quantum dot QD-A and the smaller quantum dot QD-B denoted by ‘NS1S2’ which can take place from QD-A to S_2 and viceversa.

From the above animation, it is clear that a single process of optical excitation transfer is more energy efficient than conventional electrical devices. From the quantum master equation discussed in Lecture 26 entitled ‘Quantum master equation’, one can finally calculate the population of the larger quantum dot, the time integral of which yield the output signal.

5 Applications for information and communications systems

The most important aspect of the optical network topology is that in spite of not having a cental controller in the systems, efficient transfer of optical excitations can be realized, which addresses the autonomous behaviour of optical excitations. This can lay the foundation for the realization of a self-organized and distributes complex information and communications technology based systems on internet scale. On using a distributed and autonomous network system, unbalanced traffic load and energy consumptions can be avoided. One can also ensure overall durability and reliability as the above mentioned network topology no longer depends on single points of failures. Moreover, as the output signal can be increased due to degraded optical near field interactions robustness against errors can be achieved.

Finally with regard to the energy efficiency of optical excitation transfer, one can say that it is of the order of 10^5 times more efficient than conventional electrical devices. Thus on employing the above mentioned nanophotonics technology, one can easily handle the huge demand in data transfer with more energy efficiently, robustness, overall durability and reliability.

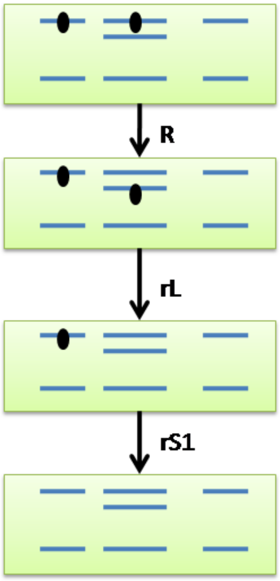

Figure 1: Schematic representation of all the possible transitions for the nanometric $S2 - Ll$ system comprising of QD-A, QD-B and QD-C.

6 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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