A layman’s concept of nanophotonics beyond the diffraction limit

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This lecture purports to the concept of nanophotonics beyond the diffraction limit based on optical near field technology.

1 The inspiring words of Feynman

"There is plenty of room at the bottom"- is the famous statement made by the great scientist Feynman mentioning that when one considers a measurement scale of one micrometer and divides the same into large number of nanometer segments, one will get enormous number of compartments or segments to manipulate during any type of signal processing.

2 Signals and systems perspective of nanoscopic science and technology

Any process occurring in mother nature can be considered as a function of time, thereby pointing either directly or indirectly towards one or another form of signal processing. It is a well known fact that the output signal of any given system is a transformed version of the applied input signal. This transformation from the input signal to the output signal depends mainly on the properties of the concerned system. Thus by manipulating the given system properties, one can obtain the required output. When the behaviour of a system pertaining to its structure, dynamics or properties is subjected to drastic change over its physical dimensions in the scale of 1nm to 100nm, nanoscopic science is born.

Among the various techniques that are used to study mother nature, optical instrumentation is found to prevail in general, mainly due to the ability of man to thoroughly understand the nature of electromagnetic waves at optical frequencies. Thus by using the concept of light as a probe to gain insight into the various structural and dynamic properties of matter present in nature, one can clearly interpret various physical laws and relationships pertaining to nature. This is due to the fact that the energy of light is found to lie within the energy range of electronic and vibrational changes in matter. Hence light can be considered as an effective tool for signal processing in general. It is no wonder that extensive research is being pursued in the study of light.

3 Odyssey of Light

Light is an electromagnetic wave phenomenon encompassing electric and magnetic fields oriented orthogonal to each other. Depending on the spatial dimensions of the given medium through which light is propagating, the phenomenon of light propagation can be explained on the basis of either of the following types, namely, ray optics, wave optics or quantum optics. When the wavelength of light is infinitesimally smaller than the dimensions of the given medium through which light is propagating, the behavior of light can be described by rays governed by a set of geometrical rules. Many optical phenomena can be attributed to a scalar wave theory where light propagation is described by a single scalar function, and therefore, the behavior of light can be explained on the basis of wave optics. When the light wavelength is infinitesimally small, ray optics becomes the limiting case of wave optics. Many optical phenomena can be explained on the basis of the classical concept of electromagnetic radiation. But certain optical phenomena such Compton effect, black body radiation, etc., cannot be described by the classical theory of light and hence one should resort to the quantum mechanical treatment of light known as quantum optics.

Light, with its versatile nature, can interact with matter having various spatial dimensions, thereby paving the way for various modifications in its properties. The study of various photonic devices and nanophotonic devices that can effectively manipulate the properties of light have become the limelight of extensive research.

4 Photonics and Nanophotonics

In a general sense Photonics encompasses the vast field of science and technology that involves the generation of light, absorption of light, emission of light, processing of light in various devices having diverse dimensions. For direct vision, the wavelength of light approximately lies in the range of electromagnetic radiation from 400 nm to 700 nm. Beyond direct human perception, ultraviolet and near infrared regimes falling within the range of electromagnetic radiation from 100 nm to 1 to 2 micrometers are also being explored for many photonic applications. Light has spatial as well as temporal domains. When the dielectric permittivity of the medium of the photnic devices is inhomogeneous, spatial inhomogeneity of light sets in, thereby leading to multiple scattering and interference of light. Thus the propagation of light wave in the medium can be effectively controlled by properly manipulating the spatial inhomogeneities of the given medium. For various photonic application inhomogeneities in the space of the given medium ranging from 10 to 100 nm to a few micrometers, are considered to be important as they are comparable to the wavelength of light.

Electrons play crucial role of information carriers between light and matter in various photonic devices. Electrons have the split personality of wave properties in terms of wavelength and corpuscular properties in terms of mass and charge. Thus by proper manipulation of the interaction of light with matter, information processing speed can be increased substantially. The interaction of light with matter can be effectively modified when the spatial inhomogeneities that are present in the medium of various photonic devices are not negligible when compared to the electron wavelength. Variations in the electric and magnetic fields or inhomogeneity in electronic charge or electronic mass displacement can contribute to the spatial inhomogeneities for electrons.

When the spatial inhomogeneities can be extended to the atomic or sub atomic level, the interaction of light with matter becomes the perrogative of various processes that are involved in the electron subsystem of atoms. The atoms in turn may form molecules and solids. Hence nanophotnics can be characterized as the science and technology of confined light waves in complex media and confined electron waves in various nanostructured solids that in turn determine a plethora of versatile physical phenomena.

However, there is a severe deadlock imposed on the miniaturization of nanophotnic devices as long as conventional propagating light is used. This deadlock is imposed by the diffraction of light known as the diffraction limit. For example, when conventional propagation light is passed through a small aperture, a diverging spherical wave is formed leading to diffraction. This diffraction is detrimental for focusing the spot size of the light below a certain value λ/NA, where λ is the wavelength of the propagating light and NA

is the numerical aperture of a conventional convex lens for focusing the spot size, the spot size on the local plane cannot be smaller than λ/NA termed as the diffraction limit. Thus it is impossible to resolve the images formed by a conventional convex lens on the focal plane, when two point sources of light are placed at a distance nearer than the diffraction limit λ/NA

5 The demands imposed on the nanophotonics industry

In the present scenario, the nanophotonics industry has to satisfy three major demands- namely

1. Enormous data transmission rate;
2. Novel optical fabrication technology and
3. High optical memory storage density.

5.1 Enormous data transmission rate

Trans oceanic fiber optic caller have been deployed in the Pacific and Atlantic oceans for long distance communication technology. They are also being used as local area networks. Thus owing to the speed by which various data types can be sent from one place to another with minimal loss, electronic technology has been replaced by photonics technology. Photonic integrated cicuits are devices that are similar to electronic integrated circuits which integrate multiple photonic functions. Photonic integrated circuits are replacing electronic integrated circuits owing to their higher capability and performance in signal processing. This can be attributed mainly due to high switching speeds offered by photonic integrated circuits. Hence with photonic integrated circuit technology, one can achieve high-speed data processing with an average processing speed of the order of tera bits per second. Extensive research work is being carried out in the miniaturization of photonic integrated circuits in order to achieve enormous data transmission rates.

5.2 Novel optical fabrication technology

Optical dynamic random access memories are devices that are capable of providing more than hundred giga bytes of storage capacity with which one can achieve data access times of femto seconds. They are fabricated using photolithography for patterning parts of a thin film or the bulk of a substrate. In photolithography, focused light is used for processing the material surface. This ultimately results in a transfer of geometric patterns from a photo mask to a light sensitive photo resist on the substrate material. For fabrication of dynamic random access memories that are capable of having a storage capacity, a novel optical fabrication technology, which can provide inexpensive and practical fabrication tools, is very much needed.

5.3 High optical memory storage density

An optical disk memory has the capacity for storing enoromous amount of digital signals in numerous small pits present on its surface, where each pit stores one bit of data. The stored digital signals are read by illuminating the disk surface by a focused laser beam and by detecting the laser light reflected from the disk surface. It is estimated that high optical memory storage density of the order of tera bytes per squared inch is very much needed for future optical disk memory devices.

Thus nanophotonic devices, that are capable of large-scale data storage and processing and thereby lay the foundation for the fabrication, measurement, control and functional requirements of novel optical science and technology, are very much called for.

6 Drawback of conventional nanophotonic devices

Conventional nanophotonic devices use propagating light as the input signal. Whenever propagating light is used, the ensuing electric dipoles induced near the surface of the nanophotonic devices, align periodically depending on the spatial phase of the incident light, thereby rendering the nanophotonic devices diffraction limited. This can be illustrated with an example: diffraction of a wave can be attributed to the apparent bending of the wave around obstacles and spreading out of the wave past infinitesimal openings. In that sense, for the case of nanophotonic waveguides, for better integration with electronic devices, the size of the nanophotonic device should be made as small as the electronic device. This is not possible due to diffraction limit of propagating light.

In the case of optical fabrication technology, the size of the narrow patterns cannot be reduced beyond a certain value due to diffraction limit. Even though high frequency sources like synchrotron radiation X-rays, etc., can be used, they cannot be technologically feasible owing to their want of large cost, large size and high energy consumption. Thus for optical disk memory devices, the storage and the read out of pits cannot be reduced beyond the diffraction limit.

The above mentioned facts point out that as long as conventional propagating light is used as the input signal, the miniaturization of nanophotonic devices is not at all possible beyond the diffraction limit, thereby leading to diffraction limited nanophotonics

7 Diffraction limited Nanophotonics

Diffraction limited nanophotonics, as a broader perspective, encompasses photonic crystals, plasmonics, silicon photonics and quantum dot lasers, that employ conventional propagating light.

7.1 Photonic crystals

Photonic crystals are mainly used for controlling optical interference and light scattering by devicing a sub wavelength-sized periodic structure in the photonic device material. Hence they are mainly used as filter device. The principal laying behind the working of a photonic crystal is that at the center of the device material, constructive interference occurs between scattered light. Thus optical energy is concentrated. In order to filter out the scattered light, it is made to interference destructively at the edge of the device material. Constructive interference is maintained at the center of the device material only when the rim of the material is made sufficiently larger than the wave length of the conventional propagating light. Otherwise, light that is concentrated at the center leaks to the rim, thereby playing a spoil sport for constructive interference to occur. As photonic crystals employs conventional propagating light and as its size cannot be reduced beyond a certain values, the spatial dimensions of the photonic crystal is limited by diffraction.

7.2 Plasmonics

In plasmonics technology, by exciting free electrons, resonant enhancement of light takes place in a metal. As a result of strong interaction with the free electrons, optical energy gets concentrated on the metal surface in the form of a surface plasmon, which represents in general, the quantum mechanical picture of plasmon oscillation of free electrons on the metal surface. But this quantum mechanical picture is lost as the plasma oscillation of electrons has a short phase relaxation time. Hence plasmonics is essentially governed by wave optics in the metal and hence is limited by diffraction.

7.3 Silicon Photonics

In silicon photonics, narrow-striped optical wave guides that use high-refractive index silicon crystals are employed to confine light effectively. As wave optics is solely responsible for this light confinement, this is essentially an application of wave optics in silicon and hence is limited by diffraction.

7.4 Quantum dot lasers

Nanometer-sized semiconductor quantum dots are used as the gain media in a quantum dot laser. Large number of quantum dot lasers are required in order to confine light effectively because semiconductor quantum dots are much smaller than the wavelength of light and hence an individual quantum dot cannot be employed for effective light confinement due to scattering and diffraction. This again leads to the scenario that the device size becomes limited by diffraction.

Thus all the above mentioned cases are based on diffraction limited wave optics. Also, even if nanometer- sized materials are used for the above mentioned cases in the future, as long as conventional propagating light is used, the size of these photonic devices cannot be reduced beyond the diffraction limit. Hence to go beyond the diffraction limit, the only other option left is to use non-propagating or stationary nanometer-sized light to induce primary excitations in a nanometer-sized material such that the spatial phase of the excitation is independent of that of the incident light.

8 Concept of an Optical near field

In order to go beyond the barricades of diffraction limit, Ohtsu research group came up with a novel technology known as optical near field technology or dressed photon technology.

In optical near field technology, the input signal is taken as the non-propagating optical near field. The concept of the optical near field can be explained on the basis of classical electromagnetism as follows: when a nanoparticle is illuminated with conventional propagating light, free photons can be emitted from the electrons constituting the nanoparticle. These free photons form the conventional scattered light propagating to the far field. In addition to the free photons, an independent set of photons are also emitted from the electrons which are re-absorbed by the nanoparticle within a short duration. These set of photons engulf the nanoparticle and remain in the proximity of the electrons constituting the nanoparticle, thereby forming the non-propagating optical near field. As these virtual photons can couple with the electrons, they are also known as dressed photons.

The concept of an optical near field thus introduced raises lots of questions such as

- What is the theory one should adopt in explaining the principles of optical near field technology ?
- How can one generate optical near field in reality ?
- How can one detect the presence of an optical near field ?
- How does an optical near field help in making nanophotonic devices operate beyond the diffraction limit ?
- What are the various applications of optical near field technology ?

This course work makes an attempt to provide answers to the above mentioned questions mainly by adhering to the research works of Ohtsu research group.

9 Nanophotonics (Beyond the diffraction limit) in a nutshell

The course work is arranged as follows: Module One entitled as ‘Introduction to Nanophotonics (Beyond the diffraction limit) gives a general introduction to the macroscopic and microscopic theory of electromagnetics, the concepts of diffraction limit and optical near field. Module Two entitled ‘Mathematical Foundations of Quantum Mechanics’ pertains to the mathematical treatment of quantum mechanics . The mathematical aspects of many body systems, time independent perturbation theory, P space and Q space and density operators are presented in Module Three entitled ‘Advanced Quantum Mechanics’. Module Four entitled ‘Quantum Treatment of Light-Matter Interactions’ is centred around the operator formalisms of photons, excitons and polaritons. Module Five entitled ‘Quantum Treatment of Optical Near Field’ contains the optical near field approach, effective operator and effective interaction and the concept of dressed photons. Module Six entitled ‘Principles of Operation of Semiconductor Quantum Dots’ explains the operating principles of semiconductor quantum dots based on optical near field and derivation of the quantum master equation. Module Seven entitled ‘Applications of Optical Near Field Technology’ concentrates on the applications of optical near field in the formulation of logic gates, communication network and systems, information security, data summation, broadcast interconnects, energy up conversion, photochemical vapour deposition, photolithography and in repairing surface roughness.

10 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).