Why Nanotechnology?

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Smaller objects in nature are not just scaled replicas of similar big objects

Galileo was the first to notice that smaller objects in nature are not just scaled replicas of similar big objects. He got this insight from examining animal bones as one can see in figure 1.

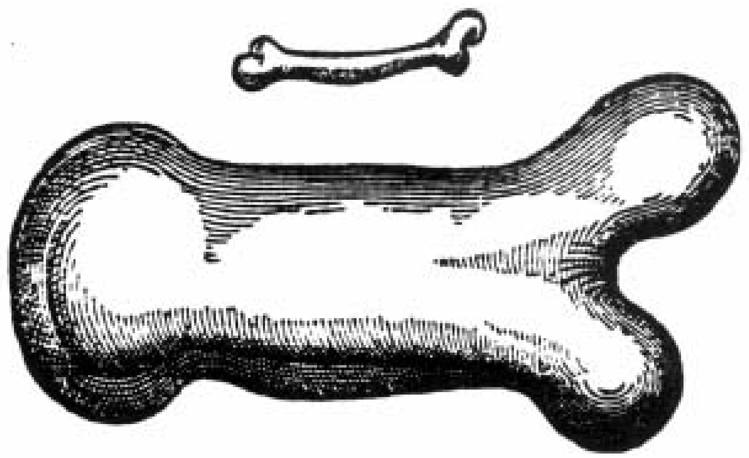

Figure 1: The scaling of bones. (From Galileo, Dialogue Concerning Two New Sciences, 1638)

He noticed that the weight a bone carries is proportional to the animal volume (length^3) whereas the strength of this same bone is proportional to its cross section area (length ^{2}). A simple dimensional analysis shows that if an animal is larger, Its bone should expand transversely more than it expands longitudely in order to carry the weight. This explains why a giant animal cannot have the same proportions as its smaller model (Fig. 1).

From animal bones to silicon chips.

The same fundamental idea also applies for NanoElectronics, since heat generation is proportional to the volume (length ^{3}) whereas the heat removal is proportional to the surface area (length ^{2}). If one makes a chip 10 times smaller the heat removal:generation ratio is 10 times better. Smaller is also faster. For example, the pendulum cycle time is proportional to the square root of its length which is why the fastest mechanical oscillator [1] (oscillating 10^9 times in one second) is only 100 Nanometer long. This is why NanoStructures and Nanooptics are not just about making conventional devices smaller in dimensions.

NanoStructures can perform tasks that can not be achieved with conventional techniques

NanoStructures are much more than doing things faster, with less heat generation and with less power consumption. NanoStructures can be used to make novel materials and novel devices which perform tasks that can not be achieved with conventional techniques. One of the most important problems in photonics is sub-wavelength imaging. Conventional optics does not allow sub wavelength imaging (according to the more than 100 years old Rayleigh limit). In spite of this limit, NanoStructures can image objects several order of magnitude smaller then wavelength.

The intuition behind this striking phenomenon is as follows. If one uses conventional optics, it is well known that image resolution is limited to the wavelength of light. When one tries to image a sub-wavelength object, he will find that even if he makes his imaging system symmetric (e.g. a 4f system) still the image will not be the same as the object. What breaks the symmetry and blurs the image? The reason is the evanescent waves [2]. A regular lens cannot reconstruct the evanescent waves. Without the evanescent waves, details smaller than the wavelength are lost in the image. So, is the only solution for finer images is to go deeper into the UV? The answer is no! It was proven that the old limit on sub-wavelength imaging can be violated by using a lens made of a perfect (slab) lens with index of refraction = -1 [3]. This perfect lens will reconstruct the evanescent waves (as well as the "propagating waves") and will enable one to get sub wavelength image as shown in figure 2.

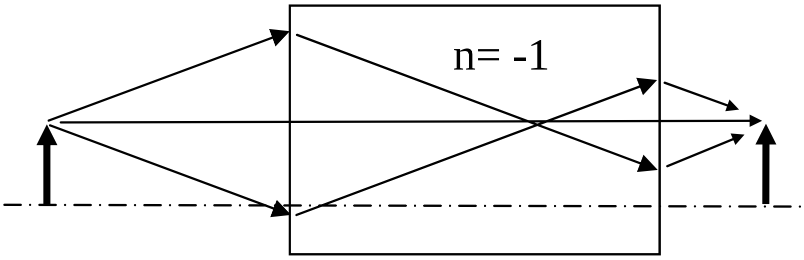

Figure 2: A perfect lens, slab of -1 refractive index is a perfect lens; ray tracing according to Snell law is shown.

The theoretical prediction of a negative refractive index laid dormant for more than 30 years until it was proven experimentally [4] for the millimetric waves part of the electromagnetic spectrum. Moving forward and making -1 refractive index medium for the optical part of the spectrum has now become doable. To do this, one has to scale down the "millimetric waves" structure to a Nanometer scale. Because this structure should be in Nanometer scale only Nanostructure can answer this problem (attempts to do such materials by following the chemical rules of stable compounds were failed). It is important to note that optical lenses are one of science's prime tools. Improving the traditional image resolution limit by several orders of magnitude will have an enormous impact on all fields of science and engineering. The ability to image a single atomic dipole, improving lithography resolution, and enabling the concentration of radiation energy in an extremely small area, are only few examples for new applications using these perfect lenses.

Water is the only material, today, that allows ice skating;
other anomalities include negative heat capacity and negative stiffness

The index of refraction is not the only constant that can possess arresting qualities. Materials possessing unexpected properties like for example water anomaly, materials with negative heat capacity [5], and materials with negative stiffness that expand under pressure [6] have always caught the attention of the scientific community. Anomaly of water causes ice to liquefy under the pressure of the skater blades and makes it the only material which enables ice skating. Such skating is impossible with other materials. In the same manner materials with other unexpected properties such as negative permeability, permittivity, refractive index [3], heat capacity [4] and stiffness [6] will allow effects which are impossible with conventional materials. The perfect lens mentioned above is just one such example.

Unfortunately, the laws of chemistry almost never allow one to make a material with such negative constants. We are lucky enough though, that when making a crystal, one does not have to rely only on chemistry. As long as the unit cell of this artificial crystal is smaller than some physical constant (e.g. smaller than the wavelength for optics) it does not matter whether the unit cell is a single molecule or a mechanical entity like a wire, a ring, or a spring. When connecting these artificial unit cells in a periodic array, one is not limited to the chemistry rules of stable compounds but can use “screws”, glues, welding, or even an optical periodic trap to hold these NanoStructures together. This freedom of choice enables one to design artificial materials with properties that cannot be achieved with conventional materials.

Few examples for such applications:

1) <u>Perfect lenses for the visible part of the spectrum</u> by means of negative refractive index slab.
2) <u>Photonic crystals of Unit cells (e.g. colloid) trapped in a periodic optical trap</u>. Engineering the fine structure of the periodic optical potential can be done by means of Fourier decomposition of sine traps. Each one of the sine traps is prepared by simple interference of two plane waves and employing light pressure. The light pressure is negligible in daily life. However, the light force can not be neglected in very small scales. This is because the optical force is proportional to the colloid cross section area ($\sim r^2$) while other forces on this colloid (e.g. gravity) are proportional to its volume ($\sim r^3$). Hence, the force of the trap normalized to other forces in the system is proportional to 1/r. Consequently, scaling down our system means effectively increasing the optical trap force (light pressure).
3) <u>Photonic crystal of Unit cells trapped in a passive matrix</u>. Initially, arranging the unit cells can be done using a periodic optical trap and then “freezing” will be done with a curable matrix material. The optical trap will be turned off when curing is achieved.
4) <u>Nonlinear materials possessing huge nonlinearities based on the toggle effect</u>. Some springs have two stable equilibrium states (e.g. see figure 3), NanoStructure made of toggle unit cells will function as nonlinear material that support huge (~1) nonlinear light induced change of their refractive index (For comparison: in traditional materials the index change is only about 0.001).

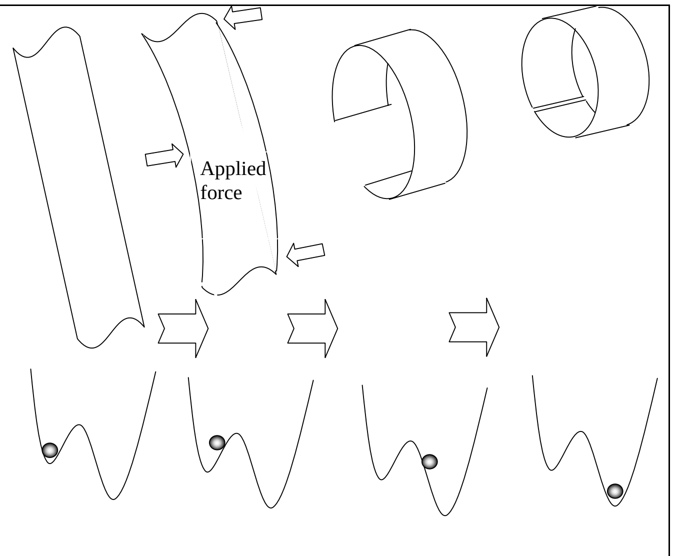

Figure 3: A mechanical toggle; a piece of metal with internal stress may be in the high energy stable equilibrium state as shown on the left side (the longitude fold holds the piece straight). When external force is applied, the piece can move to the other stable equilibrium state. Those two states are extremely different in character. An array of such toggles can function as an optical medium that can toggle between two extremely different indices of refraction.

To conclude, one of the greatest challenges in today's physics is to create NanoStructures with novel optical properties like -1 refractive index and Nonlinear optical properties upon demand. Such novel Nanostructures will allow measuring of fundamental photonic and electronic properties. In addition such structures can be used to measure and image very small objects in biology, materials science, etc.

<u>Refrences</u>

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