Nanotechnology should not neglect frequency dimension

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Abstract. In considering the packing density of working units of a device the frequency dimension (pixel $\Delta x \Delta y \Delta z \Delta \omega$) should be also taken into account, in addition to the conventional space-only domain characterized by the pixel $\Delta x \Delta y \Delta z$. Persistent spectral hole burning space-and-time domain holography is a spectacular example of usefulness of the frequency dimension in very high density data storage and ultrafast processing.

Nanotechnology has become a key word of magic power to obtain approval and support for studies in solid state physics and technology, in chemistry, biophysics, and molecular biology. This reflects well the present trend in material science. The "nanodimension in spatial coordinates" can to some extent serve as a criterion to tell what seems promising and what looks like out of date. That is reasonable and useful but not sufficient: we must not forget that in physics one more important dimension does exist – the frequency domain.

Consideration in place of the spatial pixel $\Delta x \Delta y \Delta z$ of a more general (and widely used in statistical physics) pixel – the space-frequency domain pixel $\Delta x \Delta y \Delta z \Delta \omega$ (x, y, z are spatial coordinates; ω is frequency) is reasonable and often obligatory for getting an adequate picture of the situation.

Nowadays technology, in the first place the information technology, wants to pack increasingly more and more usable working units on a unit surface (e.g. per cm^2) or in a unit volume (e.g. per cm^3). Let us consider as a quantitative measure for the packing density of working units the packing capacity P as the number of units available for a technological task on 1 cm^2 (P_{sur}) or in 1 cm^3 (P_{vol}) of the material. If the characteristic size is $\Delta x = \Delta y = \Delta z \approx 1$ nm $= 10^{-7}$ cm, we have the estimate $P_{sur} = (\Delta x \Delta y)^{-1} \approx 10^{14}$ cm^{-2} for one nanolayer and $P_{vol} = (\Delta x \Delta y \Delta z)^{-1} \approx 10^{21}$ cm^{-3} for 10^7 nanolayers forming a 1 cm thick block.

Ten atoms lined up make the length of a nanometer. It seems quite unrealistic to exceed considerably the above estimates for P_{sur} and P_{vol} by means of some *spatial* atomic structure.

A promising chapter of information technology is the optical data storage and processing using visible light. Here the addressing is normally performed by means of light waves having the length $\lambda \approx 10^{-4}$ cm. In the case of a usual far-field situation the accuracy of addressing is given by the diffraction limit $\Delta x \Delta y \approx \Delta \lambda^2 \approx 10^{-8}$ cm^2. (We do not consider here the higher, in principle, capabilities of near-field optics.) This is *six orders* of magnitude *below* the nanoscale number $P_{sur} = 10^{14}$. By the only spatial criterion optical devices do not belong to nanotechnology; they seem all out of date.

On the other hand, the optical spectral resolution opens additional ways to increase by several orders of magnitude the number of working units per cm^2 and cm^3. For example, persistent spectral hole burning (PSHB) is a novel high-resolution method of optical engineering (see [1-3] and references therein) which enables one to address and process the optical properties (the coefficient of absorption and the index of refraction bound to it via the Kramers–Kronig relation) at $n \approx \Gamma_{INH} : \Gamma_{HOM} \geq 10^2$–$10^7$ different frequencies at each spatial $\Delta x \Delta y = \lambda^2 \approx 10^{-8}$ cm^2 pixel. Here Γ_{INH} and Γ_{HOM} are the inhomogeneous and homogeneous widths of a zero-phonon line (ZPL), and the typical values for an allowed dipole transition are used: $\Gamma_{INH} = 1$–10^3 cm^{-1}, $\Gamma_{HOM} = 10^{-2}$–10^{-4} cm^{-1}.

If we define now the packing power P taking into account also the frequency domain and take $n = 10^4$, we have

$$P_{sur}(x, y, \omega) = (\Delta x \Delta y \Delta z \Delta \omega)^{-1}$$

and get the following numerical estimate:

$P_{sur}(x, y, \omega) \approx (10^{-4} \cdot 10^{-4} \cdot 10^{-4})^{-1} = 10^{12}$ per cm^2 and per one absorption band.

This is the same order of magnitude achieved in spatial-only nanotechnology with linear accuracy of 5 nm. Considering the spatial coordinates only, we face a totally wrong conclusion that visible light is completely impotent in nanotechnology.

For three spatial dimensions we get

$$P_{\text{vol}}(x, y, z, \omega) = (10^{-4} \cdot 10^{-4} \cdot 10^{-4} \cdot 10^{-4})^{-1} = 10^{16}$$ per cm^3 and per one absorption band.

Let us point out:

1. The number of working frequencies in PSHB in one band can be somewhat higher than 10^4 because of $n > 10^4$ (recently $n \approx 10^8$ has been achieved) and also several bands of absorption, introduced by implanting different impurities, can be used. Thus, if needed, the frequency domain can comprise 10^6 and even more frequency sites and add 10^6 to the number of units and raise the packing power really high:

$$P_{\text{sur}}(x, y, \omega) \approx (10^{-4} \cdot 10^{-4} \cdot 10^{-6})^{-1} = 10^{14}$$ per cm^2 and per several absorption bands, and

$$P_{\text{vol}} = (10^{-4} \cdot 10^{-4} \cdot 10^{-4} \cdot 10^{-6})^{-1} = 10^{18}$$ per cm^3 and per several absorption bands.

2. Scanning in the frequency domain is more convenient and addressing more accurate than scanning in the spatial domain.

3. Single impurity molecule spectroscopy is a fine example of how very high spectral resolution in combination with decent or even low spatial resolution helps to address single molecules (see [4] and references therein).

4. I think we should begin to consider the ZPL-based very high spectral resolution studies – single impurity molecule spectroscopy, PSHB, and their applications, especially PSHB data storage and processing (see [2] and references therein) – as a new chapter of nanotechnology.

I think that we at the Institute of Physics of the University of Tartu, as one of the initiators of ZPL-based very high spectral resolution studies and applications, are obliged to promote this chapter of nanotechnology.

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Nanotehnoloogia ei tohiks ignoreerida sagedusdimensiooni

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Spektraalsälkamise aegruumholograafia põhjal on näidatud, et arvestades elementide paigutuse tihedust seadmes on nii mõnigi kord, eriti optikas, vajalik arvesse võtta lisaks ruumilisele tihedusele veel sageduste järgi tihedust.