Next generation optical storage systems based on a stimulated emission depletion phenomenon.

Optical data storage systems (implemented mainly as the optical discs and drives for them) had appeared in late 70s-early 80s and became extremely popular in late 90s-early 2000s. The success of optical discs was provided by a relatively high reliability and a capacity that corresponded current multimedia data amounts. Moreover, continuous progress in laser technologies and optical coatings stimulated sequential enhancements in their characteristics while reasonable prices maintained. Thus, in CD-DVD-BD row, disc capacity increased approximately 200-fold whilst drive read rate speeded-up by a factor of 400.

At the same time one can state the fact that to date optical storage evolution practically stopped, and over the past decade we haven't seen anything really new from the leading manufacturers. On the other hand, customers' requirements demanded on the external drives capacities are steadily increasing, and currently significantly outweigh the characteristics of the best available laser discs. There are several explanations for such a fading of the optical storage market. Obviously, it lost the competition with the flash-memory, which now offers higher speeds and capacities, as well as an excellent usage convenience. But this seems not to be a root cause but rather a consequence of the technical restrictions limiting the optical technology development. Let's try to overview these restrictions and hypothesize whether they could be potentially overcome.

Optical disc capacity (disc space) as well as a read/write rate are both determined by a bit density. In turn, bit density depends on a physical size of an elementary data cell. The smaller data cell, the higher bit density can be achieved. The higher bit density, the higher read/write rates and capacities. In optical systems, data cell miniaturization is restricted by a diffraction limit. The principle of the diffraction limit was postulated by the German opticist Ernst Abbe in the late 19^{th} century. In simplified form it can be formulated as: "One cannot distinguish (resolve) two point light sources, if the distance between them is shorter than some critical value". This 'critical value' depends on a refraction index, a numerical aperture of the objective used for detection/focusing and, more importantly, on the light wavelength. Latter factor explains why optical disc drives of the newer generations use lasers with shorter wavelength (e.g. BluRay with violet 405 nm laser). Generally, the diffraction limit in optical drives place a restriction on a laser focusing precision, i.e. on a data cell physical size. In ideal case, resolution of optical system states approximately half of wavelength. But 'ideal case' means first of all perfect objective that is too expensive for consumers' equipment. Moreover, even the best available objective will provide less than 100% increase in resolution (thus, BluRay data cell has a size of approximately 320 nm, while the theoretical limit for the violet laser is circa 200 nm).

Is it possible to overcome a diffraction barrier? To give a definite answer, let's try to overview known approaches to resolution enhancement in different optical systems.

Firstly, one can play with the refraction index using non-air media as the 'spacer' between the surface and the objective. For example, in optical microscopy immersion oil, water and glycerol objectives are widely used. However, this approach seems to be hardly applicable to disc drives and has a modest efficiency (commonly, up to 30-50% resolution enhancement).

Secondly, it is possible to use so-called metamaterials for the next generation optics production. 'Superlenses' made of metamaterials have a negative refraction index, and could potentially overcome diffraction limit[1]. To date 3-fold over limit resolution has been reported, though in these experiments microwave range, that is not relevant to the optical storage systems, was tested. The key problem here is that the progress in metamaterials development (not to mention optics based on them) is quite slow. Even the laboratory prototypes of 'superlenses' are produced rarely and in one-of-a-kind manner. Mass production of 'superlenses' will probably require billions of investments and decades of development.

The third approach underlies a near-field scanning optical microscopy (NSOM/SNOM) technique. In SNOM, sample irradiation is occurred not through the objective, but through the nanometer size aperture. Passing the hole, which is significantly smaller than its wavelength, laser light forms an evanescent field. Evanescent waves cover only several nanometers below the aperture, but within the covered region optical resolution is limited only by the diameter of the aperture. Thus, if the sample is scanned at a nanometer distance, a resolution of 2-20 nm can be reached[2]. In fact, the principles of NSOM were developed in 80s, but to date this technology hasn't been applied to the consumer equipment production, and more than that, it hasn't become a widespread scientific imaging method. This indirectly proves its extraordinary complexity and expensiveness for a real-life utilization.

Finally, substantial success in the sub-diffraction technologies has been achieved in a field of the fluorescent microscopy. Particularly, this refers to stimulated emission depletion (STED) technique, developed in mid-90s by Stefan Hell[3] and awarded by the 2014 Nobel prize in chemistry[4]. The principle of this approach implies fluorophore irradiation by the two lasers. Main laser induces fluorescence excitation, while the secondary laser beam 'surrounds' a focusing spot of the primary laser. The shape of a secondary laser beam can vary, but usually it is donut-like (toroidal). Secondary laser depopulates a pool of the excited fluorophores on a periphery of a primary laser focusing spot, therefore suppressing fluorescence emission there. By that, it limits a physical size of a region emitting light. In STED, a size of the emitting area can be much smaller than diffraction determined one. Resolution of 20 nm has become a *de facto* standard in a sub-diffraction microscopy but potentially one can detect up to 1 nm objects using STED. In contrast to NSOM, STED doesn't require an extremely complex optical construction as well as a nanometer distance between the light source and the object. Also, there is no need to develop the new materials as in 'superlenses' approach. Actually, STED is a well-developed technology already implemented in the commercial equipment, including relatively compact microscopes. There are strong prerequisites for its further cheapening and for a miniaturization of the relevant hardware. Possibly, stimulated emission depletion phenomenon could be used in the next generation optical storage systems.

Certainly, a straightforward implementation of STED into the currently produced optical storage systems is not possible. 'Classical' optical drives rely on a light reflection/diffraction, whereas STED is applied to the fluorophores that absorb and emit light. However, quantum dots and other relatively small fluorophores, immobilized onto a solid surface, could potentially replace the currently used optical coatings.

References

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