

Multilayer Thin-Film Holographic Storage: a New Approach

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ABSTRACT

Possibility of data density enhancement of up to $\approx 100 \text{ bit}/\mu\text{m}^2$ is presented in a multi-layer polarization holographic system using thin-film holography and confocal filtering.

1. MULTILAYER HOLOGRAPHIC STORAGE WITH CONFOCAL FILTERING

Advantages of volume holographic storage

- huge storage capacity
- high transfer rate

Volume holographic storage systems require

- 1-2 mm thick storage material
- shrinkage free storage material
- high M# storage material
- high-precision servos with 4-6 degrees-of-freedom for multiplexing
- writing strategy for multiplexed holograms

For more than 30 years there has been no feasible solution for all these challenges at a reasonable price!

Benefits of thin-film polarization holographic data storage

- the data carrier can also work in reflection mode
- the theoretical diffraction efficiency is 100% (measured > 50%)
- only one diffraction order (+1 or -1) is present (except for the 0th order)
- in most cases there is no need for servo mechanisms
- it is possible to read and write with different wavelengths
- holographic encryption of information is possible
- the storage material is 2-10 μm thin (easy fabrication)
- no storage material shrinkage problems even with processing
- volumetric data density can be extremely high: $\approx 1.3 \text{ bit}/\mu\text{m}^3$
- possibility for multiplexing with polarization
- possibility for hologram replication (with half capacity)

Drawbacks of thin-film polarization holographic data storage

Limited multiplexing possibilities: the upper boundary of storage capacity is fully determined by the NA of objective and the wavelength applied.

Our challenge

Instead of multiplexing (using volume holography), is there any other way to increase data density, while retaining the advantages of both thin-film polarization holography and volume holographic storage?

Our solution

Adaptation of the digital volumetric storage concept (multilayer structure and confocal filtering) for the technique of thin-film polarization holography.

Multilayer thin-film polarization holography

The entire multiple-layer material is 1-2 mm thick, containing 10-200 2-5 μm thick storage layers, separated by ≈ 0.01 -0.1 mm rigid spacers. Using special beam separation techniques, the optical system allows for suitable suppression of the reference wave (0^{th} diffraction order) at reading out, while confocal Fourier filtering reduces inter-layer as well as inter-pixel crosstalk to ensure layer and hologram addressing.

Confocal filtering

Reading out is performed by a 6f system, equipped with a suitable spatial filter allowing only that light to reach detector array, which is diffracted from one single hologram located on one specific layer of the storage medium (see Fig. 1). For this purpose, the addressed hologram and the spatial filter are placed in confocal position. Fig. 3 shows an example for filtering out light from a non-addressed layer. Appropriately setting the hologram size, the NA of the object and the layer distance, only one reconstructed image can go through the filter.

Layer addressing

The different layers can be addressed by axially moving the writing and reading sections of the optical head, or alternatively the storage medium (Fig. 6). Optical path variation between the writing/reading objectives and the addressed layer is compensated with a variable thickness plane-parallel plate. The optical thickness of the compensating plane is varied in discrete steps, each of which is equal to the optical distance between the storage layers.

2. PRINCIPLES OF MULTILAYER THIN-FILM HOLOGRAPHIC STORAGE

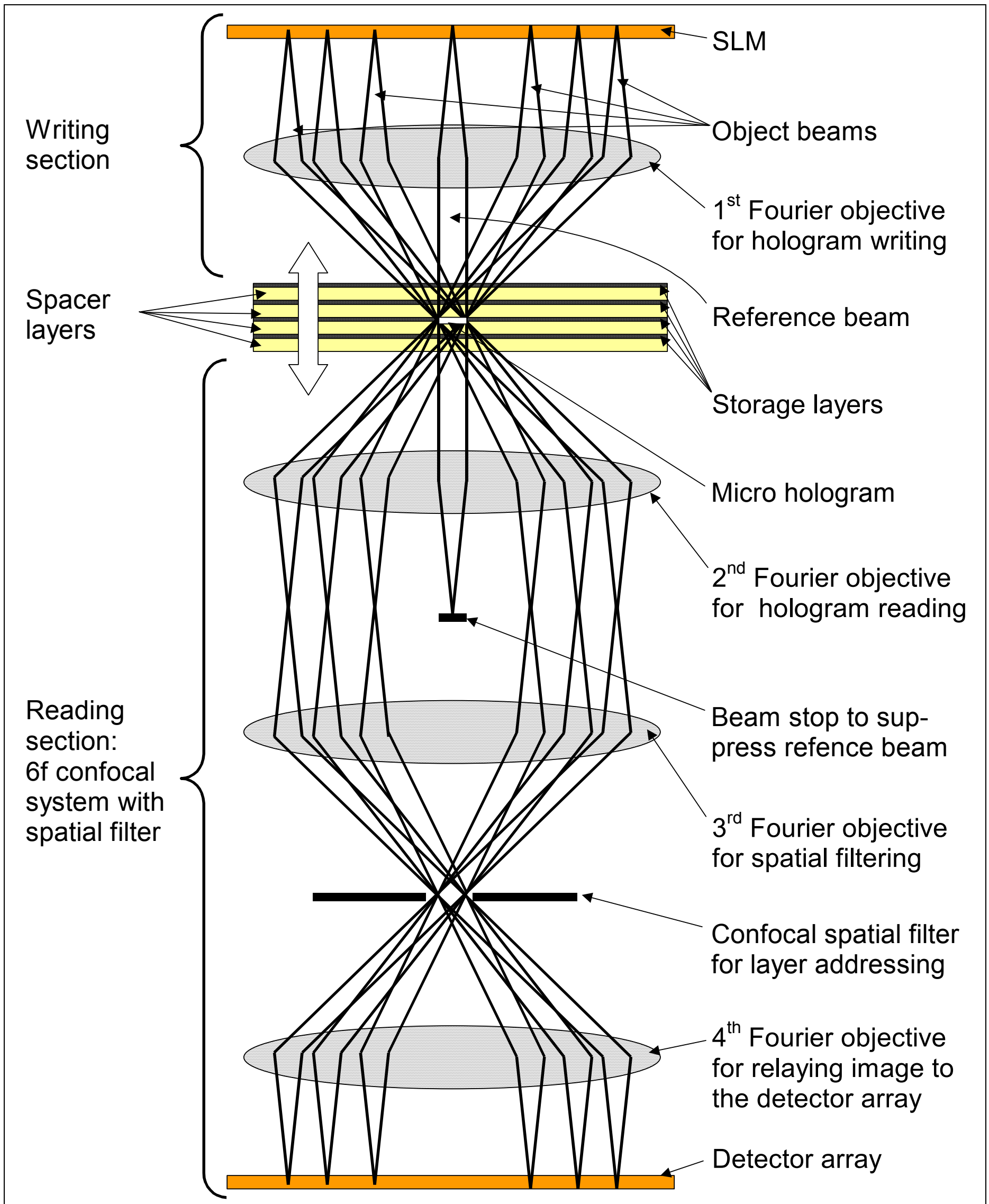


Fig. 1. Optical layout of a prospective implementation of the multilayer holographic storage system (8f linear arrangement) with on-axis reference wave and transmissive storage medium.

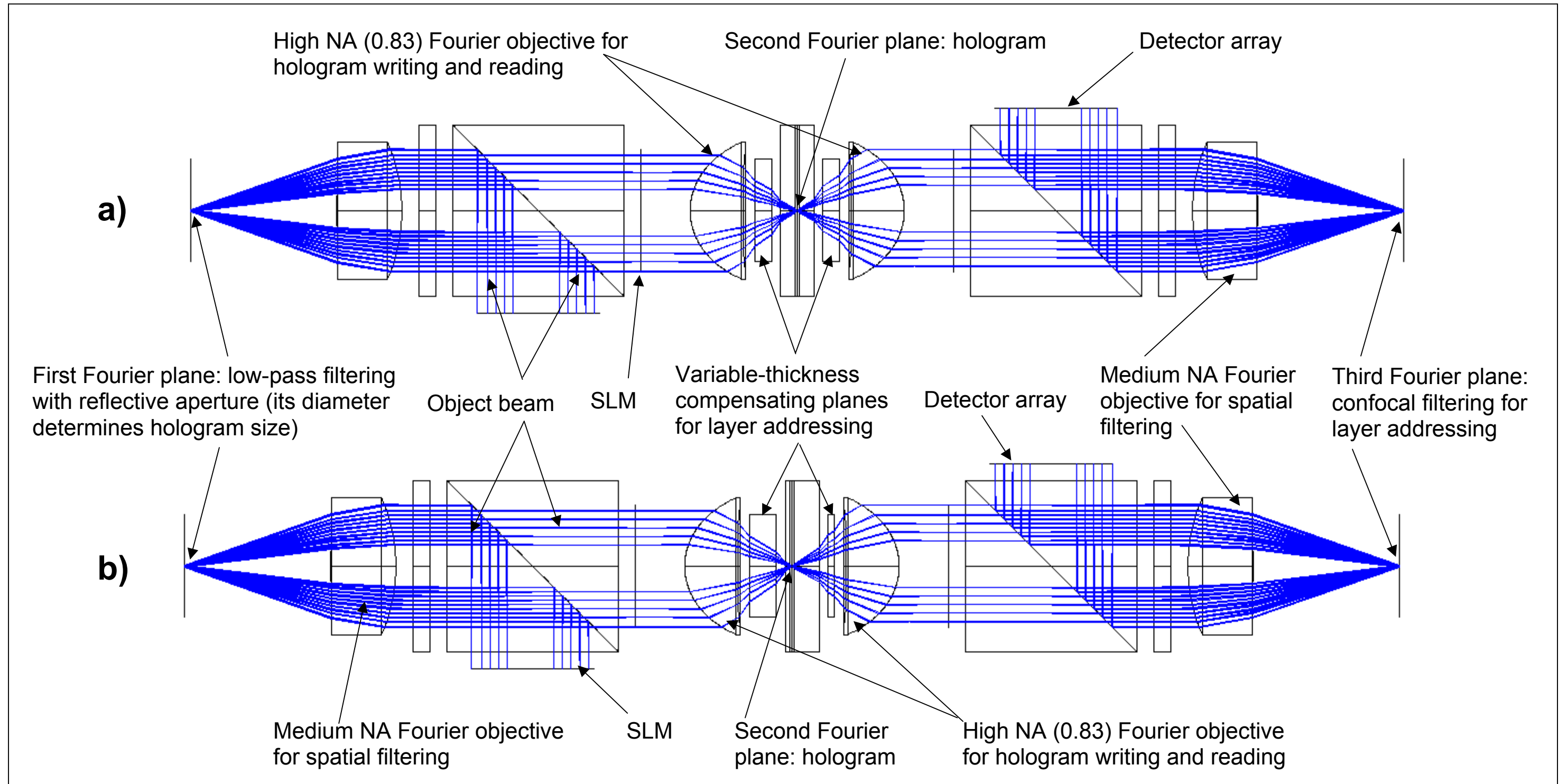


Fig. 2. Optical layout of the multilayer holographic storage system (12f folded arrangement) showing the object beam path. Confocal filtering happens in the third Fourier (focal) plane. Layer addressing is made by changing the compensating plate thickness and by axial positioning of the data carrier. In figure a) the addressed layer is the central plane of the data carrier, while in figure b) a layer near to the surface is addressed.

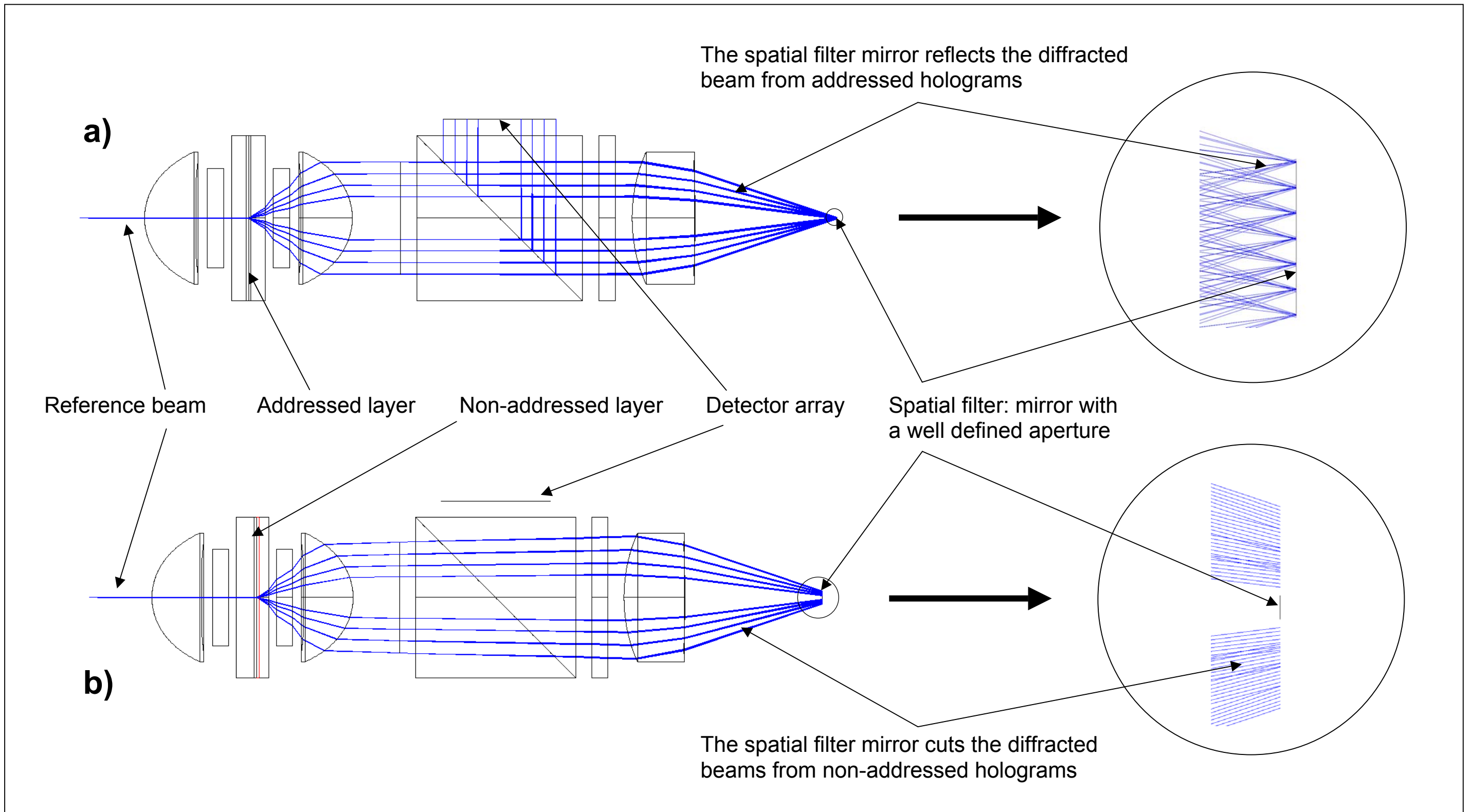


Fig. 3. a) optical scheme for reading-out data (hologram reconstruction); b) an example for filtering out diffracted light from a non-addressed layer (6f folded arrangement with reflective spatial filter).

3. OPTIMIZATION OF RAW DATA DENSITY FOR MULTILAYER THIN-FILM HOLOGRAPHIC DATA STORAGE

$\lambda \equiv 0.000405 \text{ mm}$	laser wavelength
$t_{\text{disk}} \equiv 1.2 \text{ mm}$	total disk thickness
$n \equiv 1.7$	refractive index
$\Theta_{\text{max}} \equiv 53^\circ$	half cone angle of object beam
$A_{\text{disk}} \equiv 10000 \text{ mm}^2$	useful disk area
$t_{\text{layer}} = \tan^{-1} \left[a \sin \left(\frac{\sin(\Theta_{\text{min}})}{n} \right) \right] \cdot d_{\text{holo}}$	layer thickness [mm]
$k = \frac{t_{\text{disk}}}{t_{\text{layer}}}$	number of layers
$N_{\text{pixel}} = \frac{\sin(\Theta_{\text{max}})^2 - \sin(\Theta_{\text{min}})^2}{(1.22 \cdot \lambda)^2} \cdot d_{\text{holo}}^2$	pixel number per hologram
$N_{\text{holo}} = \frac{A_{\text{disk}}}{\left(\frac{d_{\text{holo}}}{2} \right)^2 \cdot \pi} \cdot k$	hologram number per disk
$C_{\text{geom}}(d_{\text{holo}}, \Theta_{\text{min}}) = \frac{N_{\text{pixel}} \cdot N_{\text{holo}}}{8 \cdot 1024^3}$	raw storage capacity in [Gbyte/disk] \approx data density in [bit/ μm^2]

Goal of the optimization: to find optimum number of layers and hologram diameter.

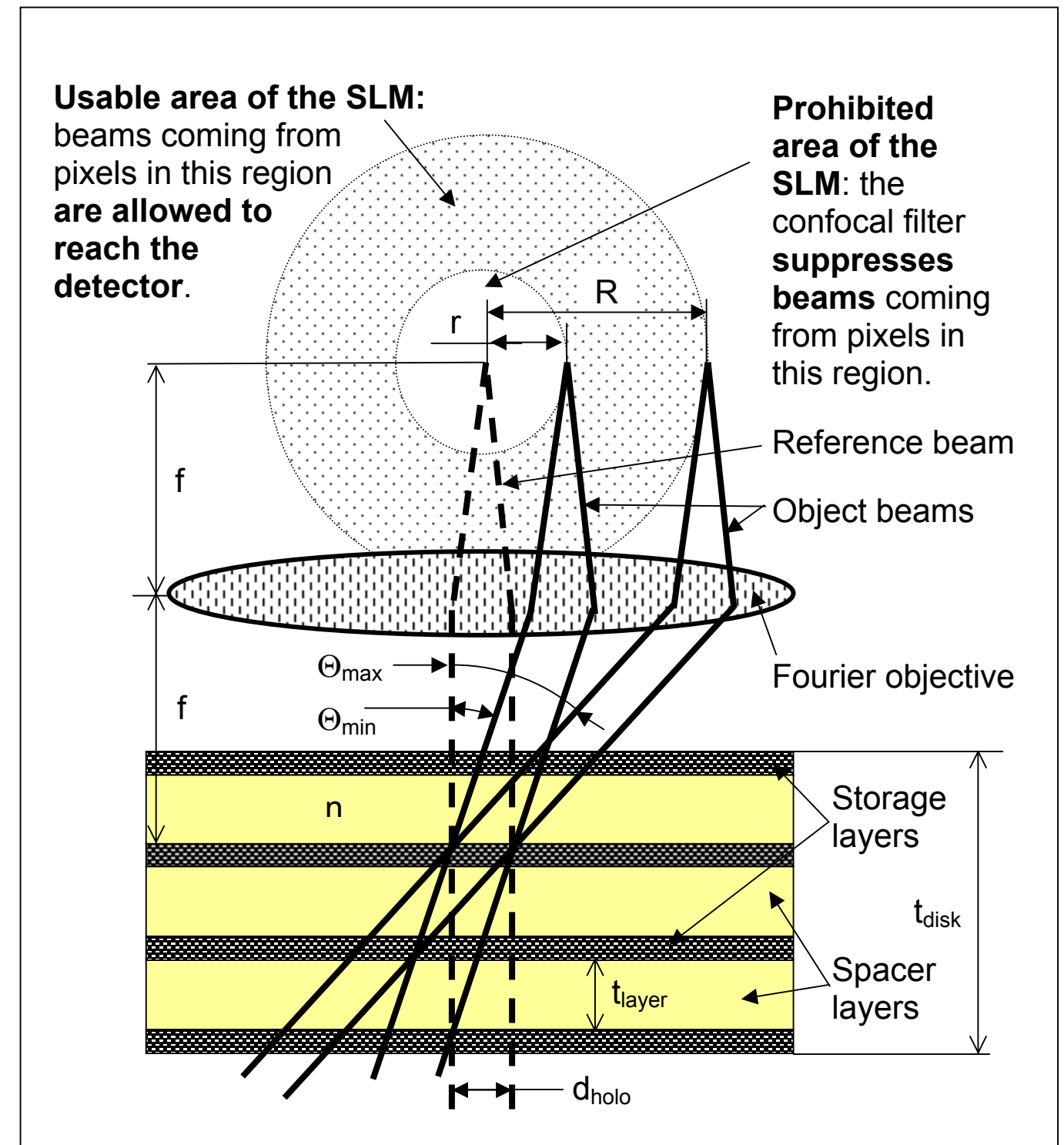


Fig. 4. Scheme for calculating raw storage capacity.

The model reveals that disc capacity grows monotonically when the hologram size is reduced (see Fig. 5,6). The limit of this model is the case when the reconstructed pixel diameter equals to the width of storage ring. (R-r, see Fig. 4). In this case the pixel number in a single hologram is 6 pieces. The achievable storage capacity is about 400 Gbyte/disk.

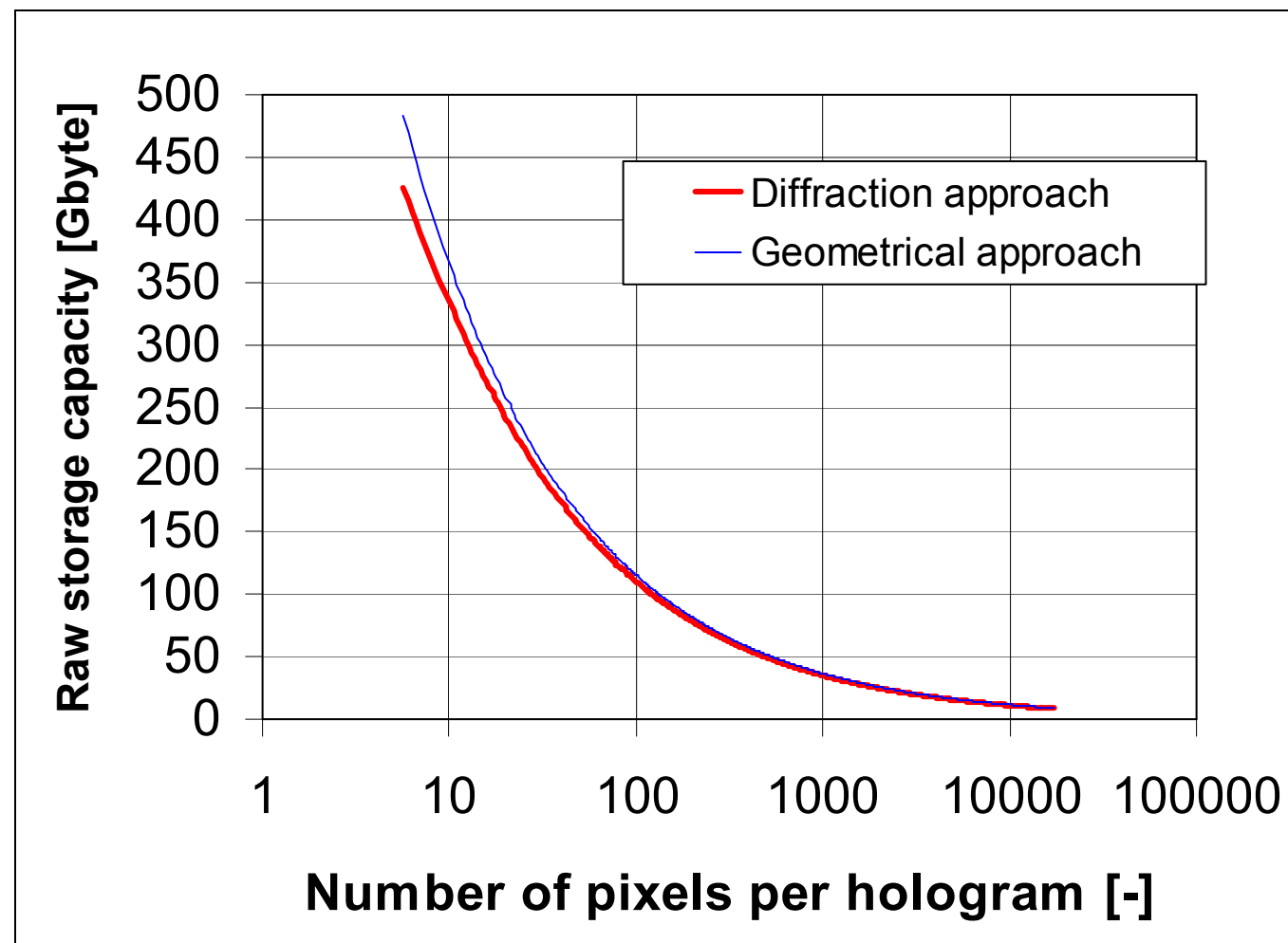


Fig. 5. Theoretical raw storage capacity versus pixel number per one single hologram.

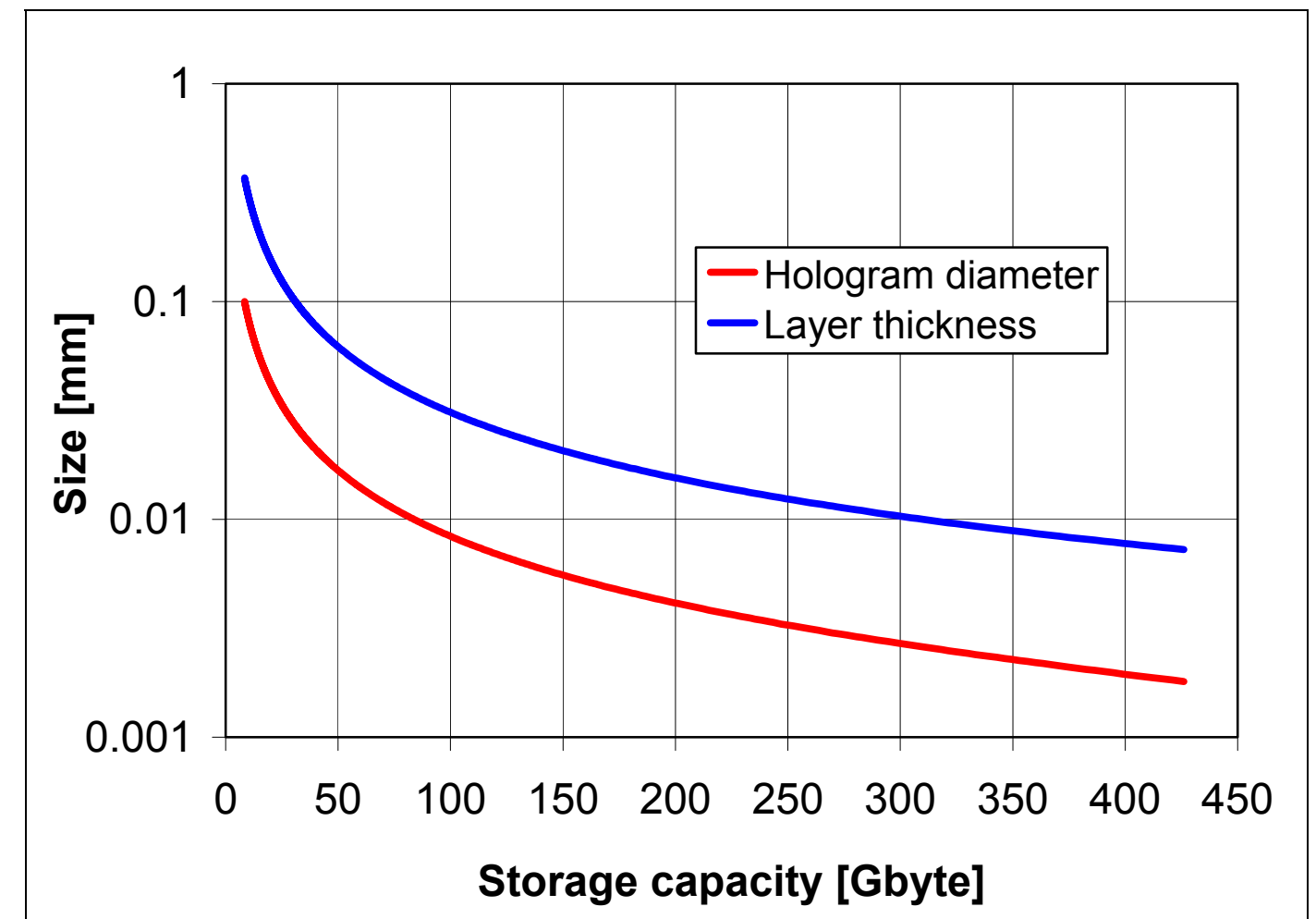


Fig 6. Hologram diameter and layer thickness versus disk raw capacity. (Diffraction approach.)

4. NEXT STEPS

- Experimental proof of concept
- Wide hologram size range gives nearly optimal data density, thus further optimization is possible for
 - signal-to-noise ratio
 - mechanical, optical tolerances
- Reading/writing speed calculations/optimizations
- Optimization of white-rate and coding
- Exploiting the possibilities of low number (2-10) multiplexing

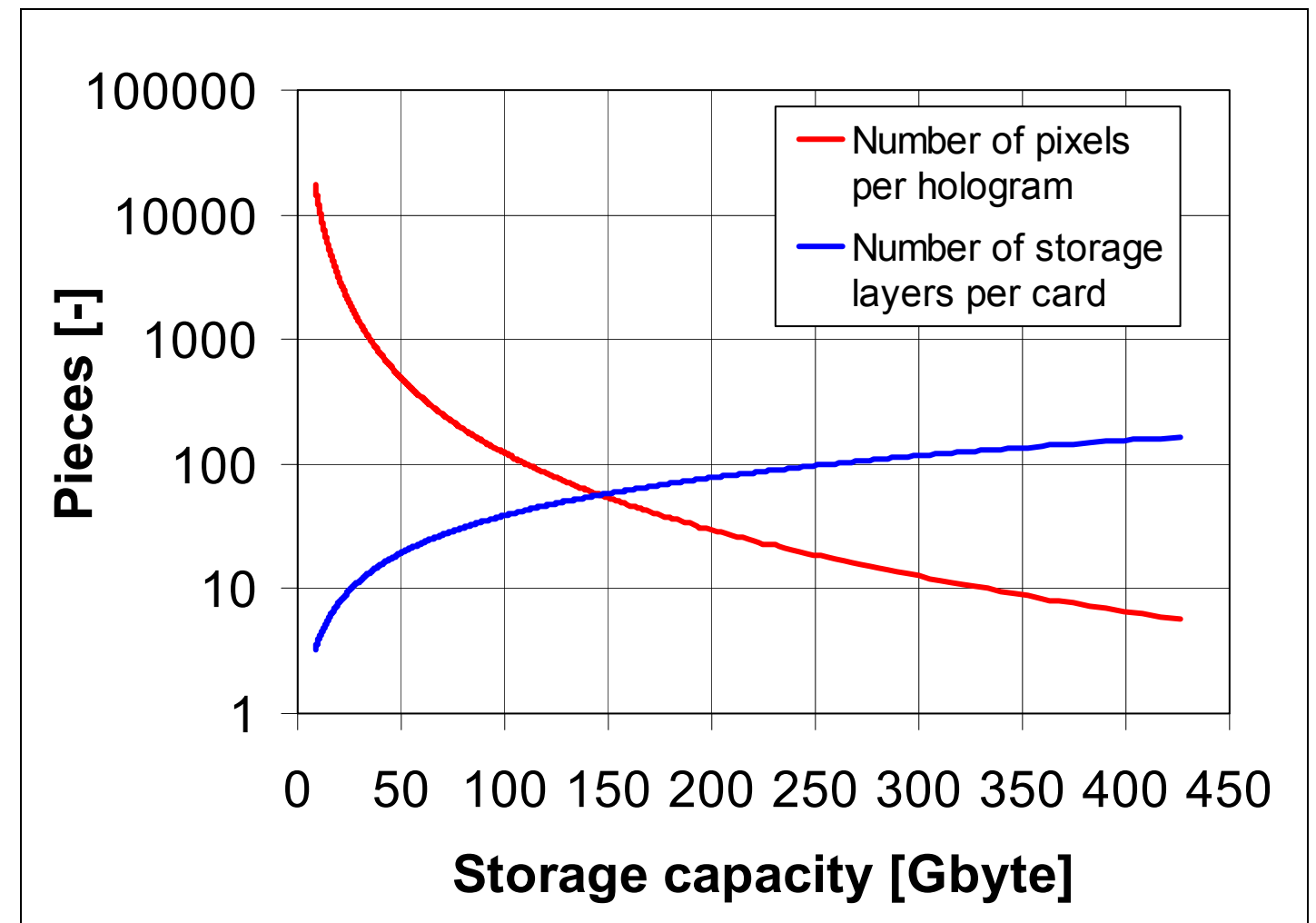


Fig 7. Number of pixels per hologram and number of layers per disc versus raw storage capacity of the disk (diffraction approach).

5. COMPARISON OF DIFFERENT VOLUME OPTICAL STORAGE METHODS

	Volume hologram, multiplexed	Multilayer thin film polarization hologram	Multilayer digital storage
Disk capacity [Gbyte]	300 - 400	400	200 - 400
NA / λ	0.8 / 405 nm	0.8 / 405 nm	0.75 / 405 nm
Servo requirements	$\Delta\Theta_x, \Delta\Theta_y \approx \pm 0.005^\circ$ and / or $\Delta x, \Delta y, \Delta z \approx \pm 0.1 \mu\text{m}$	$\Delta x, \Delta y, \Delta z \approx \pm 1 \mu\text{m}$	$\Delta x, \Delta y, \Delta z \approx \pm 0.1 \mu\text{m}$
Storage material	shrinkage-free	no shrinkage problem	no shrinkage problem

Conclusion

Theoretical raw data capacity of multilayer thin film holographic storage methods is comparable with other volumetric optical storage techniques.

Open questions

- Is it possible to make simpler servos for multilayer storage than for thick multiplexed holographic storage systems?
- Is it easier to make multilayer storage material than thick, shrinkage-free storage material?
- Where is the real SNR limit?

