Exploring optical multilevel information storage using subwavelength-sized media structures

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Abstract: Can complex 3-D subwavelength-sized structures molded in plastic optical ROM media be interrogated by a diffraction-limited focused spot for the retrieval of multilevel information? Finite-difference time-domain (FDTD) methods are used to examine the reflected intensity fields from such structures. The results presented show that such information retrieval is possible.

OCIS codes: (050.0050) Diffraction and gratings, (210.0210) Optical data storage, (260.0260) Physical optics

1. Introduction

The general goal behind the data storage concept explored in this paper is the following: the creation of subwavelength media structures whose property, upon reflection/diffraction of a focused laser spot, is the creation of multiple beam paths, each of whose irradiance pattern's centroid position in the lens aperture changes predictably and measurably for the storage of multilevel encoded information.

The author introduced this concept for storing information in subwavelength-sized topographic media features at this conference last year [1]. That paper used geometrical optical arguments for conceiving a high capacity and high transfer rate ROM optical memory system that encoded multilevel information using an array of lithographically fabricated micro-mirrors. A 2x2 array of these mirrors was termed an AO-DVD "optical data element" (ODE). Each ODE is the size of the far-field optical drive's laser stylus spot. For the particular example discussed, each ODE had a square dimension of 780 nm. A DVD track width has this dimension. Leveraging this equivalent track size, an explanation as to how a DVD/AO-DVD cross-compatible system might be implemented was provided. Each of the four micro-mirrors in the ODE has both a tilt and rotation angle associated with its orientation relative to the interrogating laser stylus. These four micro-mirrors hence are intended to split the reflected beam into four independent beam paths, each with a different spatial orientation dependent on its individual micro-mirror angular encoding. The detection sensor for the system incorporated a set of four, spot centroid position sensors for decoding the massively parallel information being reflected from each ODE. Using geometrical analysis, it was shown that a 40X capacity increase for DVD could be obtained. This capacity increase was premised on whether a 2° separation between angular orientation states of the micro-mirrors could be discriminated by the system.

Figure 1 shows some images of a macro-scale AO-DVD concept demonstrator and its associated micro-mirror arrayed media. The image on the right (Fig. 1b) illustrates, using a ground glass detector plane, the nature of the positional encoding of information described above.

(a)

(b)

Fig. 1. Macro-scale concept demonstrator of media structural encoding of information – a) media with quad micro-mirror "optical data elements," b) positional encoding of information by a symmetric "optical data element."

Figure 2 shows a graphic illustration of the general topography of three data tracks of AO-DVD media in the embodiment examined by this paper.

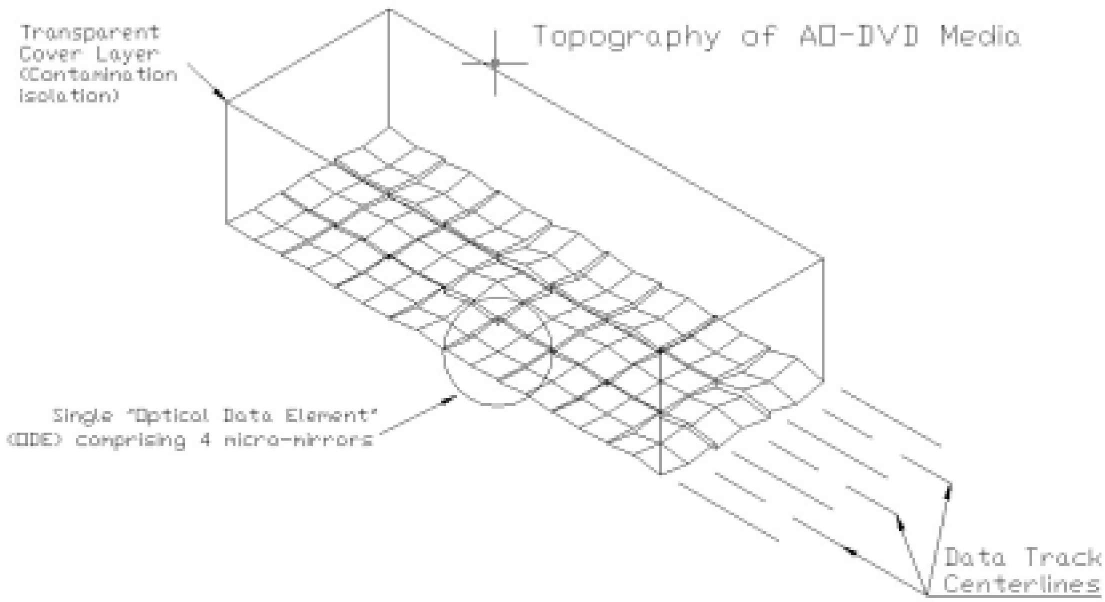


Fig. 2. Topography of subwavelength-sized media structures for multilevel information storage

Some fundamental questions relative to the feasibility of such a system, to actual scale, are readily apparent. These include:

- Can complex 3-D subwavelength-sized structures molded in plastic optical ROM media be interrogated by a diffraction-limited focused spot for the retrieval of multilevel information?
- As the micro-mirror facets become subwavelength in size, does the focused wavefront's interaction with these features produce more than just a scattered blob of light?
- What is the feature size that will produce a diffracted/scattered reflected return versus a specular reflection?
- Is there a transition region of feature sizes that produces a hybrid of both types of reflection?
- Is it possible to split a diffraction limited focused spot into multiple paths with subwavelength media topography?
- Is this just not a complicated way of trying to extract multilevel information from the reflected signal's amplitude S/N excess?

This paper discusses, and most significantly presents, some FDTD modeling results, which address these curious questions.

2. Periodic vs. aperiodic diffractive/reflective structures

Figure 3 shows the periodic structure of a blazed diffraction grating. One will note there are structural similarities to the AO-DVD tilted micro-mirror proposal. Due to the one-dimensional periodic nature of this structure, the prediction of the angular orientation of diffracted orders can be ascertained with the wavefield's expansion in terms of known eigenfunctions. Closed form analytical solutions do not exist in this manner for aperiodic subwavelength structures such as those proposed for AO-DVD ODEs. A numerical electromagnetic technique such as the finite-difference time-domain method (FDTD) must be employed to explore the nature of the reflected field in detail.

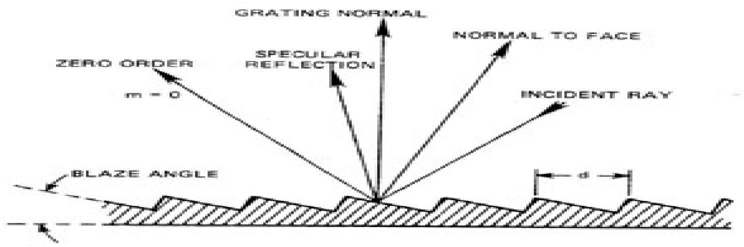


Fig. 3. Periodic blazed diffractive grating structure with diffractive and refractive reflective paths

A measure of insight can be garnered from what is known about blazed grating scalar diffraction theory and empirical observation of reflected returns from such gratings. Most noteworthy are the following facts [2]:

- Blazed gratings are as much as 40% more efficient when the specular reflection is superimposed on the diffractive order by altering the blaze angle.
- The orthongonality of diffracted/reflected polarization is a function of blaze angle.

These facts reveal that light interaction with these types of structures, even in periodic format, produce reflections that are a bifurcated interaction between diffractive and specular phenomena. The blaze angle dependence of reflected polarization further connotes the complicated and possible information-bearing nature of these interactions.

3. FDTD modeling of subwavelength information structures

Recently a FDTD model that is capable of modeling a subwavelength reflective structure such as an AO-DVD ODE has been developed at the University of Arizona. A paper at this conference [3] is being presented that focuses on the validation of that model with other more empirically well-known subwavelength structures such as optical media pits and near-field apertures.

A 0.60 NA lens is used with 405 nm (blue) circularly polarized laser source to produce a focused spot with an Airy diameter of 0.88 microns. The simulation centers this focused spot on the apex of the four micro-mirror array, which defines a single ODE. Each micro-mirror facet is 0.370 microns square. Three different ODE simulations were run. The angular geometry of the ODEs for these runs is found in Table 1. The relative position of facets A, B, C and D within an ODE is illustrated by Figure 4a. Angle θ is the tilt of the facet relative to the media plane normal to the focused beam, the positive direction being into the plane of the media. Angle α is the angle of rotation (12:00=0° CW=+) in the media plane of the facet's tilt. Alpha (α) is measured rotationally relative to the axis normal to the plane of the media and through the centroid of area of the particular facet. Each tilted micro-mirror is positioned vertically (normal to media) such that its centroid of area intersects the focal plane of the media. ODE surrounding mirrored flat portions of the media also lay in this media focal plane.

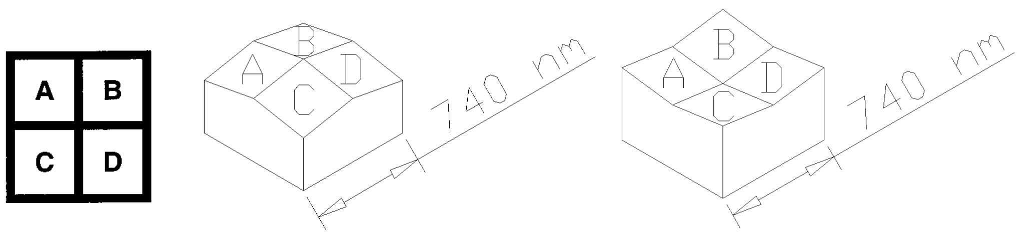
Table 1. Angular orientation of ODE micro-mirror facets modeled with FDTD

Facet >	A		B		C		D	
Angle (deg)	α	θ	α	θ	α	θ	α	θ
Case 1	135	5	45	20	225	12.5	315	20
Case 2	135	20	45	5	225	12.5	315	5
Case 3	315	5	225	20	45	12.5	135	20

Figure 5 illustrates the reflected near-field intensity field and phase plots for both orthogonal polarizations in Case 1. The reflected near-field plots were all computed in the cover layer (n=1.55, thickness=0.6 mm) at a distance of 130 nm above the focal plane of the media. The reflective aluminum layer is 20 nm thick. Figure 6 shows both the intensity field and phase plot for this same reflected signal at the exit pupil of the objective lens. In color versions of this paper, rainbow color scaling is used, with blue as a minimum through red as a maximum. Interpretation of these images in black-and-white is facilitated by the papers descriptions and comments relative to the images. Cases 2 and 3's FDTD modeling results are illustrated in a similar manner with Figures 7 through 10.

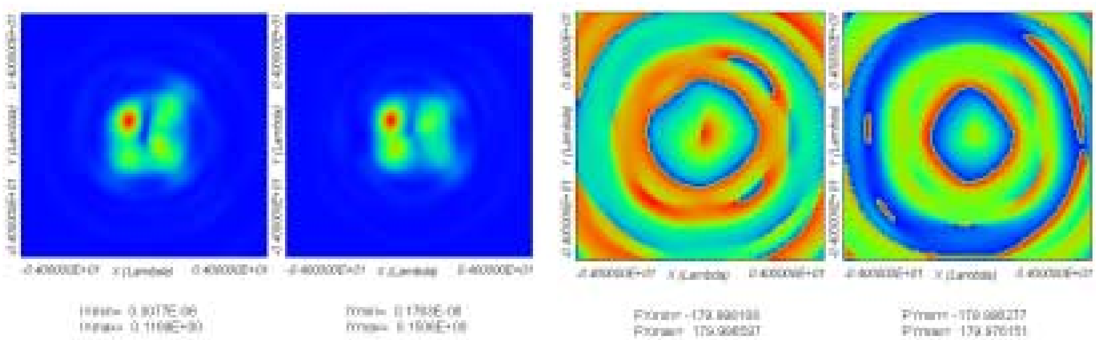
For Case 1, we see that four fairly distinct lobes of light are reflected for the near-field intensity plot (Fig. 5a). The brightest lobe is from the facet with a 5° tilt while the facets with the largest tilt (20°) are the dimmest. As the tilt angles of the facets get larger, there also appears to be a more pronounced difference between the two polarization intensity fields for those quadrants in which the corresponding facets are found. The exit pupil intensity plot (Fig. 6a) illustrates an intensity field that is displaced from the center (right) of the field as well as containing cyclic modulation within this field. Since the exit pupil is the Fourier transform of the final image producable from the original object illuminated (ODE) we see that this exit pupil is indeed information bearing. Case 2, as noted in Table 1, includes two 5° facets. The comments relative to Case 1's near-field intensity field are similar for Case 2 (Fig. 7a), except that the two contiguous 5° facets form a figure 8 pattern of irradiance rather than the more discrete lobes seen in Case 1. The exit pupil intensity plot for Case 2 (Fig. 8a) again shows frequency content as well as a totally different displacement (left) of the intensity distribution then found for Case 1.

Case 1 and 2 have geometries that have a general protrusive shape (Fig. 3b) like a pyramid while Case 3's topography is more pit shaped (Fig. 3c). Interestingly, the near-field intensity fields for Case 3 (Fig. 9a) produce a displaced from center, single spot, with a crescent shaped halo to one side. The quadrant that the centroid for this spot appears in seems to be driven by the geometry of the 5° mirror facet.



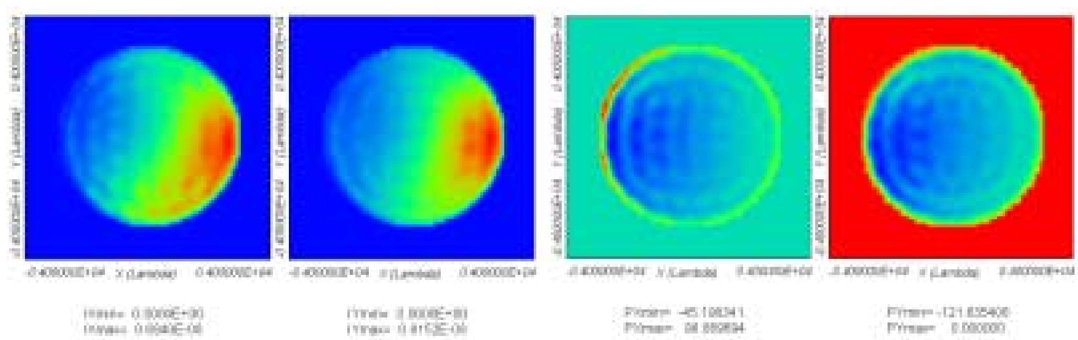
(a) (b) (c)

Fig. 4. FDTD Modeled ODE Micro-mirror facet layout (a) and general protrusive (b) or pit (c) type topography for ODE



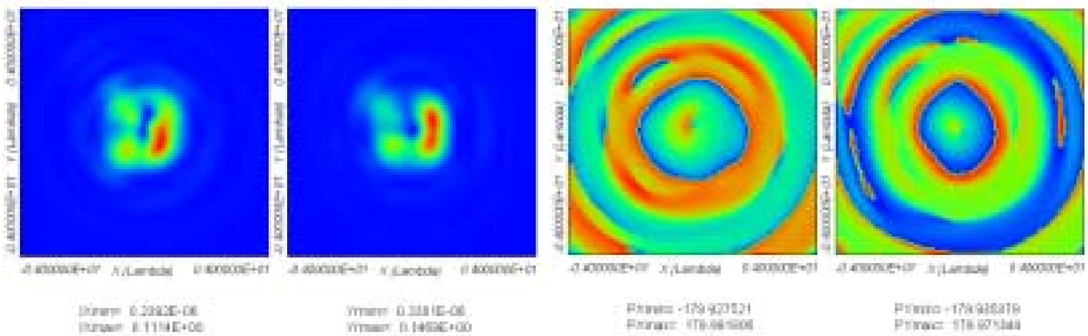
(a) (b)

Fig. 5. FDTD Case 1- reflected near-field (a) intensity field and (b) phase plot results for aperiodic AO-DVD "optical data element"



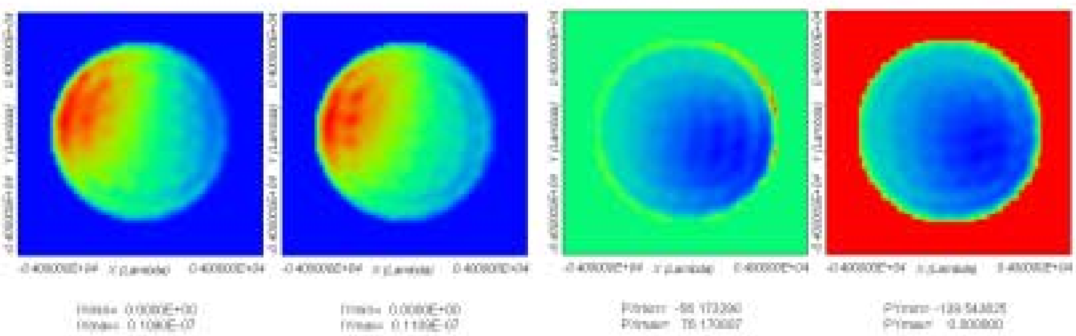
(a) (b)

Fig. 6. FDTD Case 1- reflected objective lens exit pupil (a) intensity field and (b) phase plot results for aperiodic AO-DVD ODE



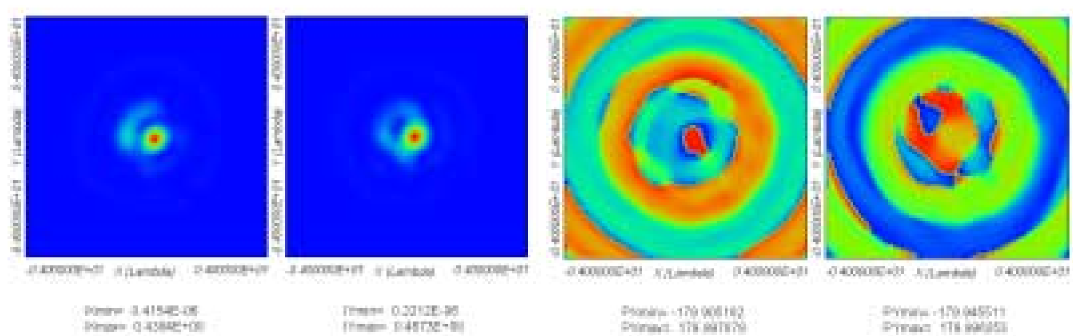
(a) (b)

Fig. 7. FDTD Case 2 - reflected near-field (a) intensity field and (b) phase plot results for aperiodic AO-DVD "optical data element"



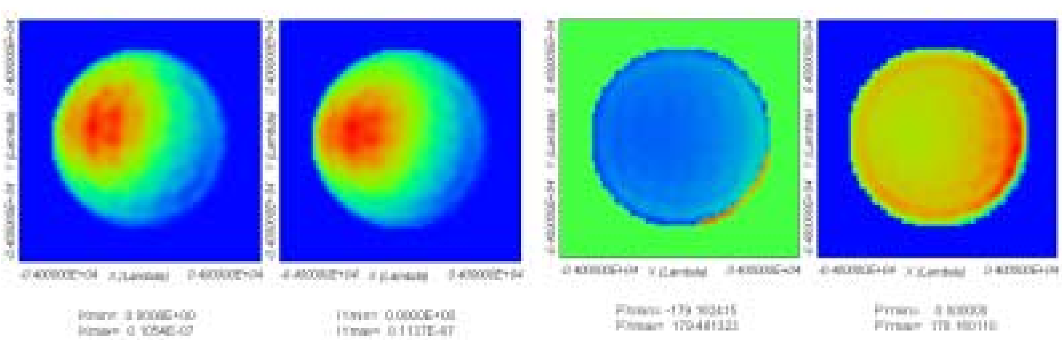
(a) (b)

Fig. 8. FDTD Case 2 - reflected objective lens exit pupil (a) intensity field and (b) phase plot results for aperiodic AO-DVD ODE



(a) (b)

Fig. 9. FDTD Case 3 - reflected near-field (a) intensity field and (b) phase plot results for aperiodic AO-DVD "optical data element"



(a) (b)

Fig. 10. FDTD Case 3 - reflected objective lens exit pupil (a) intensity field and (b) phase plot results for aperiodic AO-DVD ODE

Looking at the exit pupil intensity plot for the pit shaped Case 3 shows a more pupil centered intensity distribution than found in Cases 1 or 2. The modulation of the field for this case is indicative again of spatial information content being extracted from the ODE. These three FDTD modeled cases in summary, illustrate that information from an array of subwavelength reflected media structures can be extracted simultaneously with a single focused optical stylus (spot).

In these modeled cases the Airy illuminated area of any single micro-mirror facet is 0.130 microns^2. The square-root of this area is hence, 0.36 microns. The ratio of this micro-mirror dimensional metric to the wavelength of the focused light (0.405 microns) can be computed, and is 0.89 (0.36/0.405). From this ratio the claim of subwavelength-sized media structure illumination is supported.

4. Multilevel signal-to-noise (S/N) discussion

Both multilevel recording, as practiced by Calimetrics [4] in the form of gray-level encoding and run-length limited (RLL) recording as practiced in conventional optical drive technology, are techniques that extract, in large part, more information from excess signal-to-noise in the “amplitude domain.” Gray-level encoding is purely “amplitude domain” dependednt while RLL encoding uses excess signal amplitude to extract higher information density from the “temporal domain.” The AO-DVD concept is different in that it explores the extraction of information from the spatial orientation of reflected subwavelength media features. This is a different signal domain. AO-DVD exacts information from the “spatial domain.” This approach provides a new dimension or domain for multilevel signal extraction from a pre-fabricated optical ROM media. Hence, the question posed earlier in this paper, “Is this just not a complicated way of trying to extract multilevel information from the reflected signal’s amplitude S/N excess?” can be answered, “No, it is not.” It is a fundamentally different multilevel optical data encoding technique.

To make the assertion of above more tangible and clear, the following example is provided. RLL, gray-scale (Calimetrics) and AO-DVD encoding for a signal amplitude-limited case are explored. Figure 11 is provided to help illustrate this example for all three cases. In all cases a focused laser spot illuminates the data track. The reflected intensity of the spot for fully reflective media (100% reflection) at each of the drive’s detection planes has a normalized power value of two (2). In each case the noise-equivalent power (NEP) of a detector has a value of one (1). For the sake of the discussion, the detection threshold of a signal in each of the systems will require a S/N level of two (2:1). This is met in all three cases for a fully reflected spot (100% reflection).

Now, let’s first look at “Case 1” illustrated in Figure 11 for RLL encoding. A simple reflectance modulated system (CDR, CDRW) rather than a pit depth modulate ROM format is presented to make the discussion more straight forward while not sacarficing the validity. Three different laser spot positions (A1, B1 & C1) are shown relative to two dark (0% reflection) RLL marks on the media. This encoding method uses the transition edges between bright and dark marks to detect the transition time between spaced marks on the media. One approach to this edge or “temporal domain” detection is to set a threshold for the signal at about 50% of the full dynamic range between bright and dark marks. When the laser spot is in position A1, the full signal is reflected and its 2:1 S/N at the detector can be detected. As the spot transitions to B1 (50% signal) to C1 (no reflection), no difference in the detected signal can be ascertained since in both cases the detected signal has fallen below the required detection threshold.

RLL encoding uses the distance between RLL marks to increase the capacity for data storage. This is achieved by being able to discriminate RLL marks, which are closer than a full laser spot width apart. In practice this fairly complicated temporal convolution of the focused guassian spot with the transition edge requires an amplitude excess to noise on the order of at least 10:1. A more direct correlation with this temporal jitter “noise” is obtained by measurement of the carrier-to-noise ratio (CNR), but discussion of this difference adds little to this basic discussion. Hence, to ensure that discretely different encoded states, which are closer than one spot diameter, do not “jitter” or overlap in time with other encoded RLL states with a very high probability, then a S/N or CNR with significant excess to the 2:1 S/N illustrated here are required. In this manner “temporal domain” encoding (RLL), takes advantage of excesses in reflected signal amplitude to provide for sub-spot size recording resolution. In the signal-limited case shown in Figure 11, this is not possible because there is no excess S/N in the “amplitude domain.”

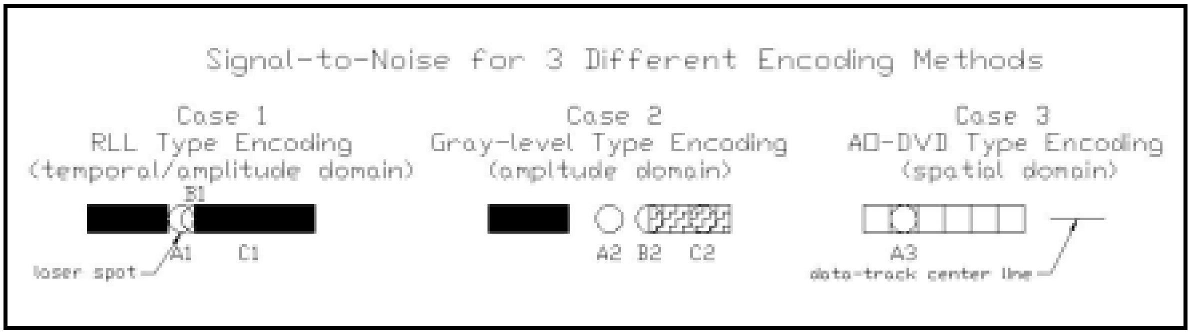


Figure 11 – Multi-level encoding "domains"

"Case 2" in Figure 11 illustrates this same amplitude signal-limited case for gray-level (Calimetrics) style encoding. Again three focused laser spot positions are shown. At position A2 the spot is fully reflected by the media and the 2:1 S/N is detected. Two different gray-level type marks are shown in the Figure. The mark to the left is a dark mark (0% reflection) and to the right a gray mark (50% reflection). Laser spot positions B2 and C2 respectively show the laser spot partially illuminating the gray mark and fully illuminating the gray mark. These intermediate levels of reflection upon which gray-level type encoding extracts multiple states (>2) from and hence its higher information density, will not work here. This is because, again, for this signal amplitude-limited case, there is not enough excess S/N to make the technique applicable. Only two levels or data states can be recorded here.

The final example is "Case 3" where AO-DVD type encoding is shown. For simplicity, each AO-DVD optical data element (ODE) to be considered is a single micro-mirror facet, rather than the 4 element arrays explored in the FDTD modeling section of this paper. The illustration shows six (6) such ODE arranged in serial fashion on a data track. Each ODE is a fully reflective mirror (100% reflection). Only one laser spot is illustrated (A3) which falls fully on a single AO-DVD ODE. This ODE can have a multitude of angular orientation states. If this ODE can be tilted to about 20 degrees relative to the media plane and rotated through a full 360 degrees one sees that the number of detectable orientations states is dependent upon the ability of the system to resolve between states. If one assumes here that a 2.5-degree resolution in tilt and rotation of each ODE is possible, then over 1024 states (2^{10}) are encodable within this spot-sized ODE. Each of these orientations is reflected back to an array of 32x32 detectors each with a normalized NEP of 1. This reflected signal has a power of 2 (i.e. 100% reflection) and hence is detected by one of the individual detectors (1024 total detectors). For this signal amplitude-limited case, the AO-DVD encoding method was hence able to provide another order of magnitude of recording density and transfer rate without the need for further excess signal amplitude. This was not achievable in the RLL and gray-level encoding cases.

The example hopefully provides the insight required to understand that the AO-DVD technique opens a new signal "domain" for optical recording not provided for by more traditional multi-level encoding techniques such as RLL and grey-level encoding. This new "domain" is the spatial domain. By combining AO-DVD encoding with RLL encoding, by varying individual ODE element lengths, there is the potential to tap both the amplitude, temporal and spatial signal domains in optical data recording. The result could be increases in areal density and transfer rate of orders of magnitude for low-cost ROM distribution media.

5. Conclusions

Subwavelength aperiodic reflective structures in media are shown by FDTD modeling to be capable of separating the interacting focused laser beam into four separate beam paths upon reflection/diffraction. This was not an apparent result predictable from known classical closed-form theory on the topic. The exit pupil intensity fields for these subwavelength structures show both spatial frequency content as well as significantly differing positional distributions within that field. These FDTD modeling results demonstrates that information can be extracted from the reflected intensity distributions of subwavelength-sized optical ROM media structures. Further modeling using the FDTD methods described is required to better understand the practical potential of the concept described.

6. Acknowledgements

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7. References

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