Isoplanatic Lens Design for Phase Conjugate Storage Systems

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Abstract: A new type of storage lens for holographic data storage systems is introduced that improves phase conjugation. This type of lens is characterized by a large isoplanatic patch. This enables relaxed assembly tolerances, asymmetric reader/writer architectures, and compensation for tilted plate aberrations in the media.

1. Introduction

Angle-polytopic phase conjugate Holographic Data Storage (HDS) systems [1-3] are useful for professional applications and are a leading candidate for 4th generation consumer optical storage. Phase conjugation allows simpler optics to be used due to aberration correction during hologram recovery. This aberration cancellation typically only occurs for the case when the recovered signal retraces the path it experienced during recording, and is limited in the cases of media misalignment or drive to drive interchange, where a completely different optical path is used in recovery. In this paper, we present the isoplanatic lens design concept that cancels aberrations in the presence of media misalignments and interchange between different lenses. This design concept is ideal for Holographic Read Only Memories (HROM) and consumer HDS systems where tolerances lead directly to cost. The design form is especially well suited for HROM system as it allows asymmetric phase conjugate systems [4], holograms recorded with a complex, expensive mastering lens can be recovered and almost perfectly phase conjugated using a different, simpler, and cheaper reader lens.

The design form presented in this paper exploits the principle of isoplanatism or spatial invariance. This means aberrations to the point spread function of the lens do not vary significantly across the field [5]. Almost all lenses have limited isoplanatism due to the tiny "isoplanatic patches" required to linearize the response of the lens and allow it to perform a Fourier transform [6]. The size of these patches is typically slightly larger than the lens point spread function (PSF) [7], typically a few microns square. The lenses presented in this paper have isoplanatic patches on several millimeters square and are thus said to be extremely isoplanatic. The larger the isoplanatic patch, the more a shift of the storage lens with respect to the recorded hologram can be tolerated while phase conjugating the data perfectly.

2. Characteristics of Isoplanatic Lenses

A definition of extreme isoplanatism is readily obtained by extending existing definitions of "infinitesimal" isoplanatism as defined in the literature. Systems with infinitesimal isoplanatism have the following characteristics:

- Infinitesimal translations in object space produce infinitesimal translations in image space without change in quality of the corresponding in image [8].
- Infinitesimal rotations in object space produce infinitesimal rotations in image space without changing the quality of the corresponding image [9].
- Wavefront aberration for a given point in the pupil is constant [10].
- The wavefront aberration corresponding to a given PSF in image space is constant [5].

To extend these definitions of infinitesimal isoplanatism to cover extreme isoplanatism we simply change all infinitesimal rotations and translations to finite and change all instances of the word point to patch. As mentioned in the introduction, extremely isoplanatic patches can be orders of magnitude larger in area than the infinitesimal patches associated with a lens PSF. These definitions, once modified to cover extreme isoplanatism, can be used as design time constraints when optimizing a lens with a modern lens design program [11].

In holographic data storage systems, the most convenient metric to measure the performance of the system is the signal to noise ratio (SNR). Because the SNR is largely a function of the PSF in the recording and recovering systems, we can reformulate the last characteristic of extreme isoplanatism; The SNR in a phase conjugate system is constant in the presence of finite shift or tilt of the system phase conjugation optics.

InPhase Technologies has developed a optical model of holographic storage systems which predicts the recovered page SNR by simulating the PSF using Huygens' method and the k-sphere formulation of volume holography. The model show good correlation with experimental data for media shifts and rotation and has been adapted as a Zemax® plug-in and can be used to simulate the SNR during the design of HDS optics.

3. An Extremely Isoplanatic Holographic Storage Lens

Figure 1 shows an extremely isoplanatic Fourier transforming (FT) storage lens recently designed by InPhase Technologies. The lens was optimized for isoplanatism by constraining the lens performance using the definitions of Section 2. Using the 3rd characteristic of isoplanatic lenses listed above we can directly examine the size of the isoplanatic patches using the changes in Zernike polynomial coefficients or RMS wavefront error as a function of field.

Figure 2 shows the first nine Zernike coefficients as a function of field while Figure 3 shows the RMS wavefront error. The Zernike terms describe the first and third order wavefront properties for a single SLM pixel in the storage system. The slope of these curves can give insight into how the wavefront of the different SLM pixels changes across the lens field. Figure 3 shows how the RMS magnitude of the wavefront error changes across the lens field. An isoplanatic patch is the area where the wavefront shape and magnitude do not change significantly.

To evaluate the size of the isoplanatic patch for this lens, we introduce here the empirical criteria developed by InPhase Technologies of 1/50th wave RMS. While this value is much more stringent than the 1/14th wave Marechal criterion[13] for diffraction limited performance, it has been proven to adequately predict SNR constancy during phase conjugation. Note that this value gives SNR constancy for a SLM with 4.6 micron pixels and may be relaxed when larger pixels are used. Examining Figure 4, we see a large isoplanatic patch between 0 and 1.4 mm of field where there is less than 1/50th wave RMS variation. At the edge of the field the variation corresponds to an isoplanatic patch of 400 microns. We therefore conclude that over neighborhoods of order 400 microns wide, the wavefront shape and magnitude changes of Figures 2 and 3 are insignificant. This has profound consequences on phase conjugation in holographic data storage systems.

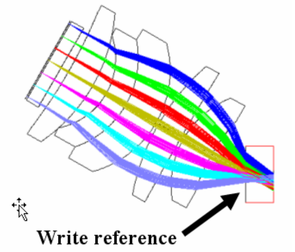

Figure 1. Extremely isoplanatic storage lens with an effective focal length of 2.4 mm and 1.7 mm field

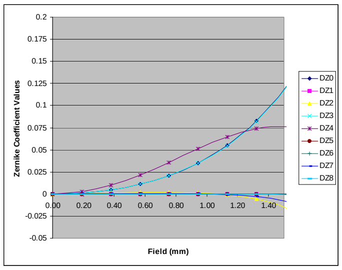

Figure 2. Zernike polynomial coefficients as a function field for storage lens shown in Figure 2.

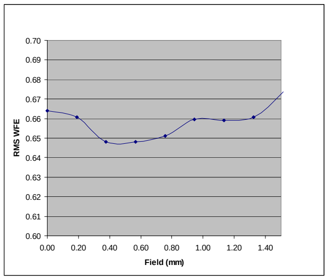

Figure 3. RMS wavefront error vs. Field for the isoplanatic storage lens shown in Figure 2.

4. Examples – Symmetric and Asymmetric Phase Conjugation

In an ideal phase conjugate storage system, the SLM pixels with varying wavefront (see Figure 2 and 3) are recorded into holographic media using a reference beam. The recorded pixel wavefronts are then recovered using a conjugate beam and an identical storage lens. On readout the aberrations in each pixel are negated by reverse propagation through the FT lens resulting in perfect imaging. This is true for any lens, regardless of attributes such as isoplanatism. In practice however, phase conjugation involves an intermediate process where, after recording, the media may shift, tilt, and/or shrink. Additionally, the recording and recovering lens may not be identical due to manufacturing or assembly errors in different storage systems. In these instances, errors do not cancel out and imperfect phase conjugation results. These conditions can be greatly mitigated by using an extremely isoplanatic storage lens

In the first example we consider tilt errors that introduce field shifts of about 400 microns (see Figure 4) in a symmetric phase conjugate system (the recording and recovery lens are identical). Because the tilt induced shift is less than the size of our isoplanatic patch, the performance of the system is still diffraction limited as predicted (see Figure 5). Tilt insensitivity is important when doing wavelength compensation for thermal effects although tilts encountered in a conventional HDS system are much smaller than 9.5 degrees [13].

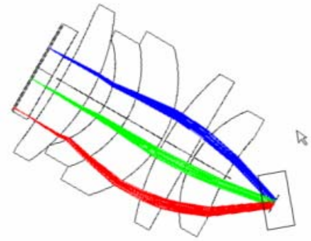

Figure 4. Symmetric readout using the lens in Figure 1 with a 9.5º media tilt.

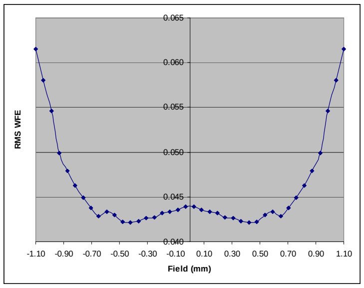

Figure 5. RMS wavefront in a symmetric system with 9.5º tilt error in media position.

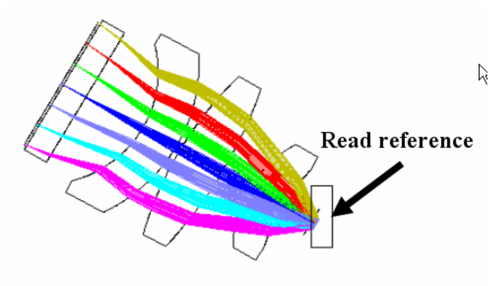

Figure 6. Asymmetric readout using 3 element lens to recover holograms written with the lens in Figure 1.

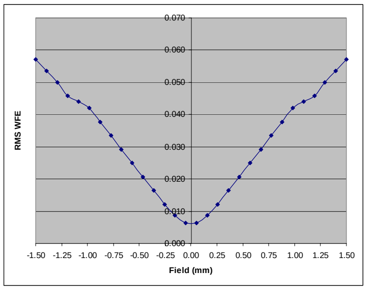

Figure 7. RMS wavefront error vs. field in asymmetric system with 80 µm axial shift in media

In the second example we investigate asymmetric phase conjugation (see Figure 6), where a simple 3 element lens is used to recover holograms written with the 5 element lens in Figure 1. Without media shifts, tilts or rotations the 3 element lens was designed to perfectly phase conjugate the pixel wavefronts recorded by the lens in Figure 2. With a media axial shift of 80 µm, the lens is still diffraction limited over the lens field (Figure 7). This 3 element spherical lens assembly could be further simplified and replaced by a two element aspheric lens assembly without loss of performance.

5. Conclusions

In this paper we have shown a design concept that can be used to create extremely isoplanatic lenses ideal for use in phase conjugating holographic storage systems. This design form can increase the interchange, shift and tilt tolerances of the systems due to extremely large isoplanatic patches where changes in the HDS pixel wavefront shape and magnitude are insignificant. This design concept also allows for the design of asymmetric phase conjugating systems where different lens designs are used for recording and recovering holograms. This property lends itself to HROM systems where the mastering system is made of expensive, near perfect lenses and the readers are built using simple inexpensive molded lenses and consumer HDS where media position tolerances generally lead to higher costs in manufacturing.

6. References

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