Holographic data storage at 2+ $Tbit/in^2$

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ABSTRACT

The onslaught of big data continues even as growth in data storage density tapers off. Meanwhile, the physics of holography continues to suggest the possibility of digital data storage at densities far exceeding those of today's technologies. We report on recent results achieved with a demonstrator platform incorporating several new second-generation techniques for increasing holographic data storage (HDS) recording density and speed.

We present data showing the recovery of HDS data at a density of 2 $Tbit/in^2$. Since the highest reported areal densities for hard disk drive products currently hover in the 1 $Tbit/in^2$ range, we have adopted 2 $Tbit/in^2$ as a milestone likely to generate interest in the technology. The demonstrator is based on an advanced pre-production prototype, and so inherits highly functional electronic, mechanical, and optical subsystems. It employs a high-NA monocular architecture with proven angle-polytopic multiplexing.

The demonstrator design includes several second-generation innovations. The first, *dynamic aperture multiplexing*, greatly increases the number of multiplexed holograms. The second, the *DRED™ medium formulation*, provides dramatically higher dynamic range to record these holograms. These two features alone theoretically allow the demonstrator to exceed 2 $Tbit/in^2$. Additionally, it is equipped with the capability of *quadrature homodyne detection*, permitting *phase quadrature multiplexing* (QPSK modulation), and the potential to further increase user capacity by a factor of four or more. The demonstrator has thus been designed to achieve densities supporting the multi-terabyte storage capacities required for competitive products, and to demonstrate the potential for Moore's-Law growth for years to come.

Keywords: holographic data storage, big data, optical data storage, holography

1. INTRODUCTION

The Akonia Holographics AP1 demonstrator platform was designed and constructed to demonstrate several second generation HDS technologies. Development is ongoing, with many key technical features yet to be engaged. Previously, we have reported the recovery of data written at a raw areal density of 1.35 $Tbit/in^2$ using the new DRED™ photopolymer media formulation and dynamic aperture multiplexing [1]. In this paper we report on the incorporation of the coherent channel, including quadrature homodyne detection and phase quadrature multiplexing.

2. AP1 DEMONSTRATOR TECHNOLOGIES

Despite a number of highly publicized efforts, no commercial HDS product has ever been sold to a general market. However, the Bell Labs spin-off, InPhase Technologies, Inc., produced an advanced pre-production HDS drive capable of storing 300 GB on a removable 5 ¼" disk [2]. The InPhase *Tapestry* prototype incorporated typical "first generation" features, including an off-axis architecture recording 320 angle-polytopic [3] multiplexed holograms in a single location, and a direct-detection resampling data channel [4] operating on 1.4 megapixel holographic data pages. The InPhase drive achieved a peak areal density of 512 $Gbit/in^2$ in a photopolymer medium with a 1.5 mm thick recording layer, with read and write data rates of 20 MB/s. Other first generation HDS systems include the monocular [5], collinear [6] and bit-wise architectures, though none were developed to a state nearing commercial readiness.

The AP1 demonstrator was designed to incorporate a set of second generation systems and materials innovations that will increase storage density and speed by more than an order of magnitude. These include:

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1) DRED™ Media Formulation

The DRED formulation represents a significant advance over the two-chemistry recording medium developed by InPhase. The two-chemistry medium is so-named because it consists of two separate, intermixed polymer systems. The first system, the *matrix*, forms the solid recording layer, and the second remains unpolymerized until exposed to light [7]. Akonia has demonstrated a factor of six increase in dynamic range (M/#) using DRED technology, and is currently optimizing it for commercialization.

2) Dynamic Aperture Multiplexing

Dynamic aperture multiplexing fully capitalizes on the shared beam path of a monocular objective lens. Dynamic aperture multiplexing increases the angular scan range by dynamically adjusting the data page size, increasing storage density by over 200%.

3) Quadrature Homodyne Detection

Homodyne detection is the method of blending a coherent reference field with a signal and detecting the interference pattern between the two. This has the effect of amplifying the signal, eliminating nonlinear effects of coherent noise, and allowing the detection of phase as well as amplitude. Akonia has developed a novel algorithm that allows homodyne detection to be performed by combining images taken with changed reference phases. We estimate this will boost the signal to noise ratio enough to more than double storage density, as well as providing a host of other benefits [8].

4) Phase Quadrature Holographic Multiplexing

The ability to detect the phase of a hologram presents another opportunity to increase storage density. A second hologram with a 90° phase difference from the first can be recorded at each reference angle. This technique, *phase quadrature holographic multiplexing*, provides yet another doubling of storage density [9].

2.1 AP1 Demonstrator Platform

The AP1 demonstrator was constructed from an InPhase prototype, and hence inherited a high level of functionality from that platform. Components and subsystems incorporated with little or no modification include the SLM and detector, tunable 405 nm laser, electronics and firmware, disk loader, and various actuators and servo systems. Many optical components have also been retained, but the objective lens and reference scanner assemblies have been replaced with a newly designed 0.85 NA objective lens and scanner capable of delivering diffraction-limited planar reference beams over the entire ±60° angle scan range.

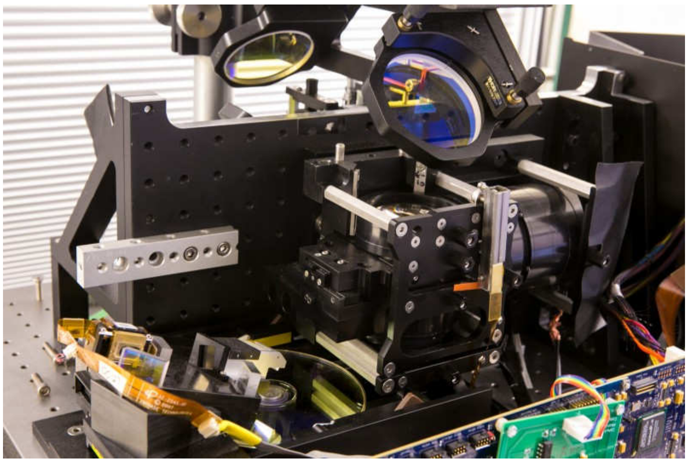

Figure 1. The Akonia Holographics AP1 demonstrator platform.

The completed AP1 demonstrator is shown in Figure 1. The objective lens is housed within the assembly at center, and the disk is visible in the bottom of the photograph. Figure 2 is a schematic, with the main optical paths indicated for both recording and recovery operations. The aperture sharing element (ASE) combines the signal and reference beams, allowing angular regions to be allocated in real time between the two beams for dynamic aperture multiplexing.

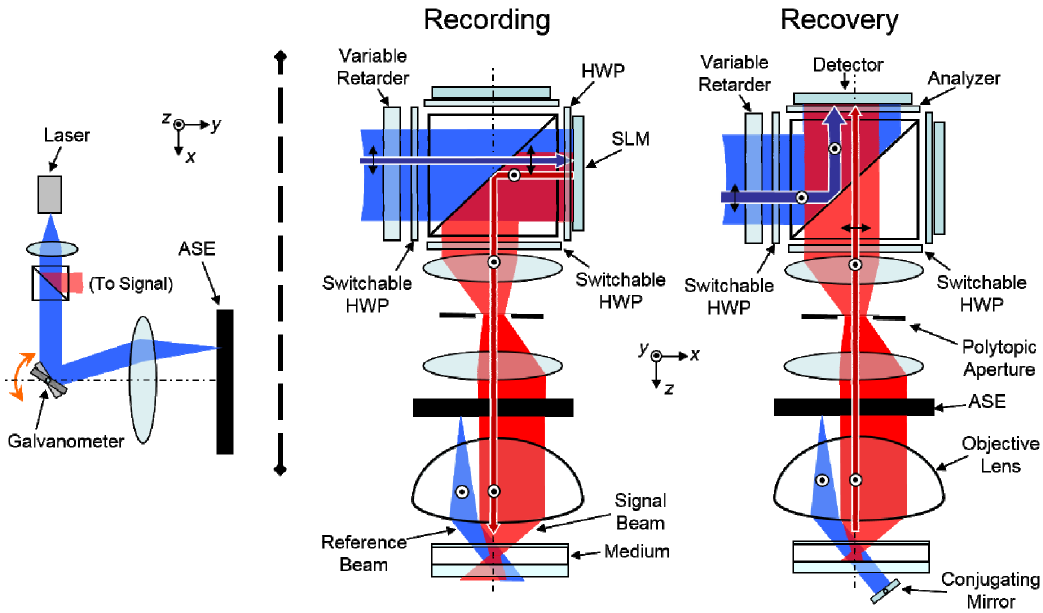

Figure 2. AP1 schematic and beam paths.

Since AP1 uses the legacy 1.4 megapixel SLM, laser, and electronics from the 20 MB/s InPhase prototype, it cannot directly demonstrate data transfer rates that would be attractive for a commercial product. Akonia has instead developed a model based on a modern 4K-class SLM that supports competitive 200 MB/s recording and recovery speeds, even without the benefit of the coherent homodyne data channel, which would further boost transfer rates.

Fortunately, however, the legacy components *can* support recording densities approaching those achievable with newer components. More media M/# is required since the data payload of each hologram is smaller, but once that is achieved switching to a larger page size will actually result in a system with more margin. Hence, the overarching goal of the AP1 demonstrator is to achieve high density with “no asterisks,” thereby demonstrating the potential of the technology for commercialization with high confidence.

2.2 Coherent Channel Beam Paths

Figure 2 illustrates the optical paths during both recording and recovery for the coherent data channel. During recording, the collimated beam passing though the variable retarder is directed towards the SLM, whereupon the data page to be recorded is composed. The half wave plate (HWP) adjacent to the SLM serves to rotate the polarization of the beam so that phase-modulated, rather than amplitude-modulated, pixel states are produced by the SLM.

The modulated signal beam is then directed downwards through the recording head, which constitutes a 6f lens relay producing a Fourier plane at the middle of the recording medium. A collimated reference beam overlaps the signal beam throughout the recording layer, producing an interference pattern that is recorded in the photopolymer medium.

The reference beam is generated by the scanner assembly shown on the left side of Figure 2. Note the coordinate difference between the left and right sides – the reference beam strikes the aperture sharing element from out of the plane of the figures on the right side. The rotating galvanometer allows the reference beam to be directed towards any point along the aperture sharing element, creating a reference beam at any angle of incidence from –60° to +60° with respect to the medium normal. To achieve 2.0 Tbit/in^2 recording density, 440 holograms may be recorded using approximately 40° of the available reference angle range.

Alternatively, 2.0 Tbit/in^2 may be achieved using only 20° of the reference angle range by employing phase quadrature multiplexing. In this scenario, two separate holographic exposures are performed at each reference beam angle. The variable retarder is used to change the optical path length by one quarter wave between exposures, thereby recording the two independent data pages in phase quadrature.

The right side of Figure 2 illustrates the beam paths during a recovery operation. In this case, a conjugating mirror is used to retro-reflect the collimated reference beam, producing a phase conjugated holographic reconstruction that propagates upwards through the recording head to the detector. This phase conjugate architecture nominally cancels out all optical aberrations of the lenses, producing a high-fidelity image of the data page upon the detector.

The collimated beam entering through the variable retarder is now also shunted towards the detector, where it mixes with the holographic signal to serve as the local oscillator for homodyne detection. The analyzer in front of the detector projects these two beams onto the same linear polarization axis, and also establishes the mixing ratio for the two beams. Typically, the analyzer is aligned to pass 90% of the signal and only 10% of the local oscillator, but the power ratio at the detector is approximately 30:1 in favor of the local oscillator.

For the recovery operation, two or more detector images are collected sequentially, each with a different phase state set by the variable retarder. The images so collected are then processed with the quadrature homodyne detection algorithm to extract the data.

Note that in the AP1 demonstrator the variable retarder function is actually performed by a mirror mounted on a piezoelectric actuator, rather than by a transmissive device as shown in Figure 2.

2.3 DRED Recording Medium

The higher-density AP1 architecture requires considerably more media dynamic range than the Tapestry drive. Density experiments are currently being conducted using a DRED formulation with an M/# of 24 per 200 μm thickness, resulting in a total M/# of 180 in the 1.5 mm thick recording layer. This exceeds the M/# of the InPhase Tapestry formulation by a factor of six. This corresponds to a zero-to-peak refractive index modulation of 0.015. The DRED formulation achieves this level of modulation while maintaining a shrinkage level of less than 0.1%; we estimate that this figure could be improved by a factor of four or more for applications where more shrinkage can be tolerated.

The media is bonded between two 130 mm plastic disk substrates using the InPhase Zerowave™ process [10]. The resulting disk is fitted with a hub and cartridge, and has sufficient recording area for over a hundred automated recording experiments. Akonia owns InPhase manufacturing equipment capable of large-scale media production.

3. EXPERIMENTAL PROGRESS

Density demonstration experiments are performed by recording a grid, typically of 6 × 9 books of angularly-multiplexed holograms spaced at a book pitch of 304 μm. Gridding is necessary because the exposure footprint of each book is considerably larger than the book spacing, so several neighbors are required on all sides of a given book to replicate the hologram overlap conditions that will obtain in a full-capacity medium. In the case of a 6 × 9 grid, the inner 2 × 3 books are so overlapped, and thus “at density.” For a large production medium, only those books at the outer edges of the medium or of a recording partition will not be fully overlapped, and the peak data density will dominate.

3.1 Dynamic Aperture Density Demonstration

Dynamic aperture multiplexing was first demonstrated on AP1 in direct-detection (non-homodyne) mode. For this experiment, 360 holograms were recorded in each book of the 6 × 9 grid. The data region of the pages averaged 610,700 pixels, so the raw areal bit density was

$$\frac{610{,}700\ \text{bits} \times 360\ \text{pages}}{(304\ \mu\text{m})^2} = 1.53\ \text{Tbit/in}^2 . \qquad (1)$$

The data pages were recovered using the 4:3 oversampling data channel of the InPhase Tapestry [4]. The channel uses known “reserved block” pixel patterns embedded within the page to determine a quality metric,

$$\text{SNR} \equiv 20\log_{10}\left(\frac{\mu_1 - \mu_0}{\sigma_1 + \sigma_0}\right), \qquad (2)$$

where μ_1 and μ_0 are the means, and σ_1 and σ_0 are the standard deviations of the detected ones and zeros, respectively. Figure 3 shows a typical detector image of a hologram recovered at density, along with the sampled reserved block SNR map of the page.

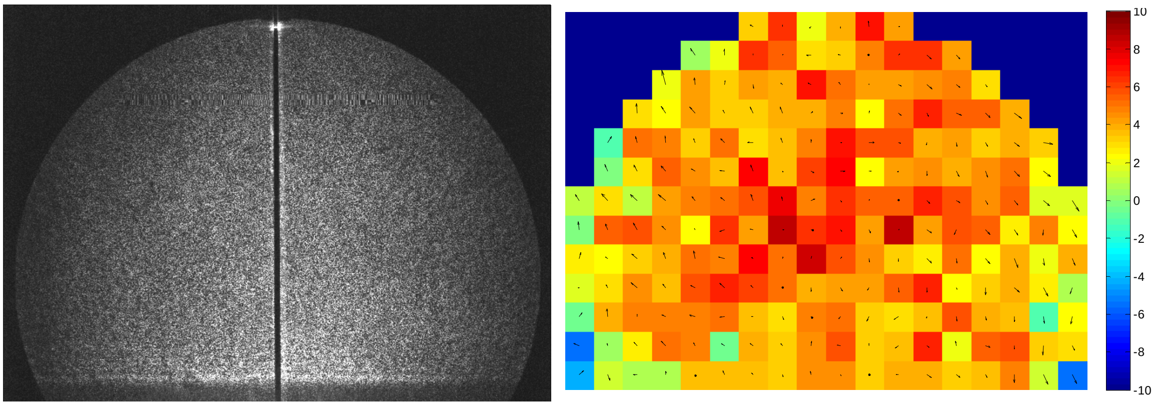

Figure 3. Left: Detected data page recovered at density; Right: Regional SNR map of data page.

Figure 4 shows the aggregate SNR for each hologram in the first density book within a grid written at 1.53 Tbit/in^2. The average SNR of the holograms in the book is 2.6 dB, sufficient for the book to decode without error using the Tapestry data channel with an extremely high degree of confidence. Also shown is the diffracted power of the holograms, demonstrating the uniform peak and trough (between hologram) signal levels.

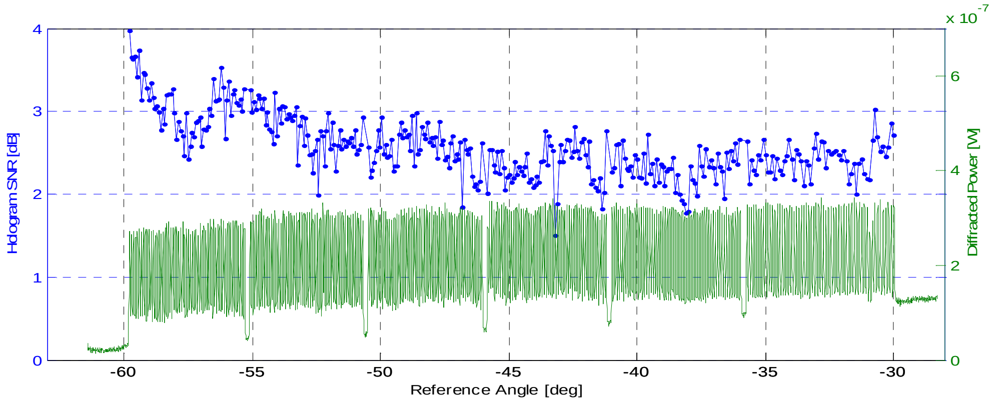

Figure 4. SNR and diffracted power of holograms recovered at an areal density of 1.53 Tbit/in2.

3.2 Quadrature Homodyne Detection Density Demonstration

In another demonstration, a Tapestry drive was configured to implement quadrature homodyne detection. This involved the removal of the SLM illumination phase mask, and the inclusion of optical elements necessary for PSK modulation and homodyne detection (see Figure 2). Recovered images were saved for processing off-line in software rather than using the drive's ASK hardware channel. Data was recorded and recovered at the nominal density of the Tapestry drive, i.e., at 500 Gbit/in^2 in books of 320 holograms each.

Figure 5 shows screen shots of a typical page recovered at this density, demonstrating the ability of the quadrature homodyne channel to operate without a phase mask at a performance level exceeding that of the original ASK channel. At the left is an image map showing the local SNR and alignment of the hologram. The aggregate SNR of the page is 9.4 dB. At center is a bit error map showing the locations of erroneously detected pixels. The raw bit error rate (bER) of the page is 1.6×10^{-3}. At right is a map showing the phase difference between the hologram and the local oscillator beam used to recover it. This map is generated during the quadrature homodyne detection process, and the algorithm is designed to accommodate many waves of phase difference that may occur due to misalignments and other tolerances.

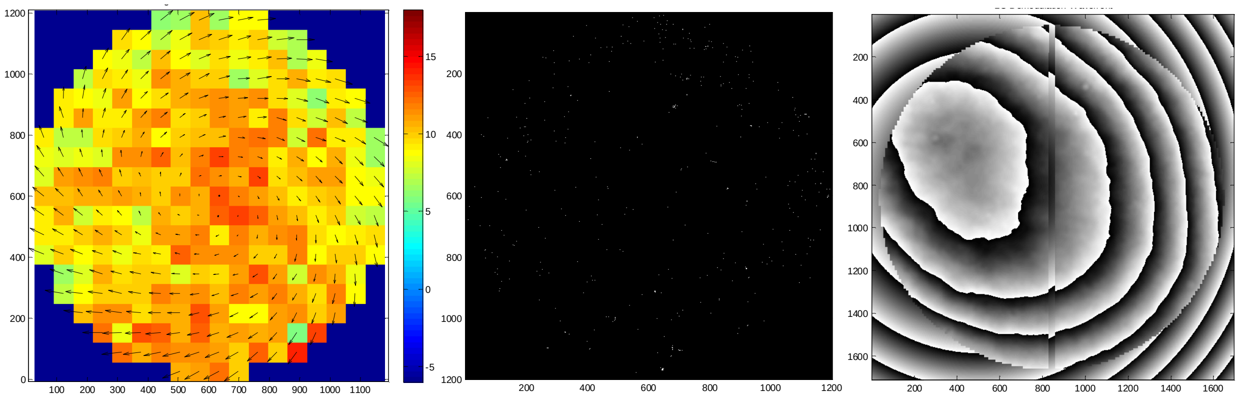

Figure 5. SNR map, bER map, and homodyne wavefront for a BPSK hologram recorded at density on the Tapestry drive.

3.3 Phase Quadrature Holographic Multiplexing Density Demonstration

In the next demonstration, the Tapestry drive used for the previous quadrature homodyne demonstration was used to implement phase quadrature holographic multiplexing. This is accomplished by recording a second hologram at each reference angle with the variable retarder (see Figure 2) changed by 90^{o}. This results in a recording density of 1.0 $Tbit/in^2$ on the Tapestry drive. Figure 6 shows screen shots of the recovery of a hologram recorded at this density. At left is the SNR and alignment map of the I phase of the hologram, and at center is the Q phase. Each has an aggregate SNR of 6.9 dB, and a raw bER of 1.3×10^{-2}. At right is a phase map showing the measured local phase difference between the I and Q quadratures. The mean value of the difference is 84.9^{o}, and the standard deviation is 3.8^{o}. Since the ideal phase difference is 90^{o}, this small difference may contribute to the slight degradation in SNR and bER compared to the recovery of Figure 5.

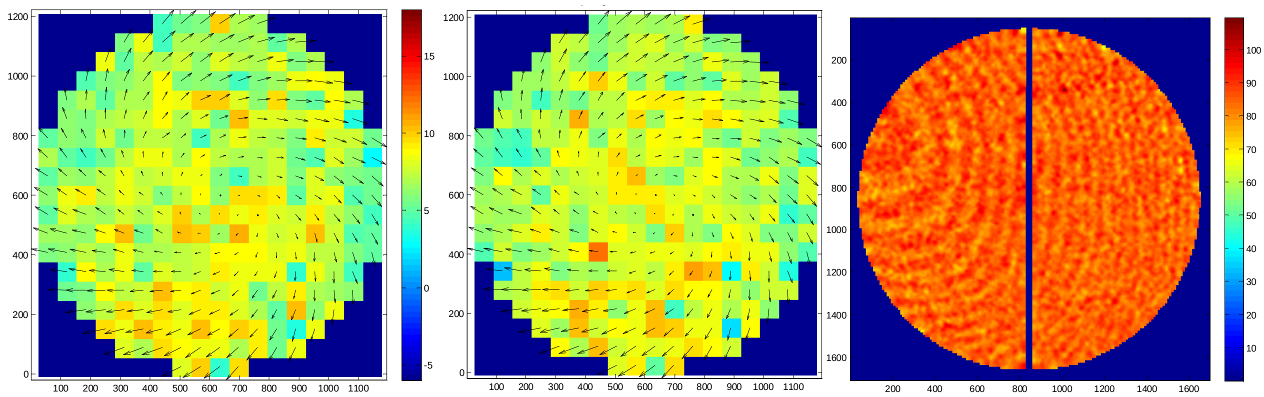

Figure 6. SNR maps for I and Q QPSK holograms and phase difference map.

3.4 2 $Tbit/in^2$ Density Demonstration

The AP1 demonstrator was next reconfigured to perform quadrature homodyne detection and phase quadrature multiplexing. Holograms were recorded and recovered at a raw density of 2.004 $Tbit/in^2$ in a grid of 6×9 books of 440 data pages each. The holograms were recorded at 220 separate reference angles, employing phase quadrature multiplexing to store two data pages at each angle. Figure 7 shows the SNR and diffracted power of one of the interior books within the grid. The mean SNR of the holograms is 2.4 dB, and the recovery shows adequate SNR margin to be recovered without error. Thus, we have successfully demonstrated the holographic storage of data at the 2 $Tbit/in^2$ level.

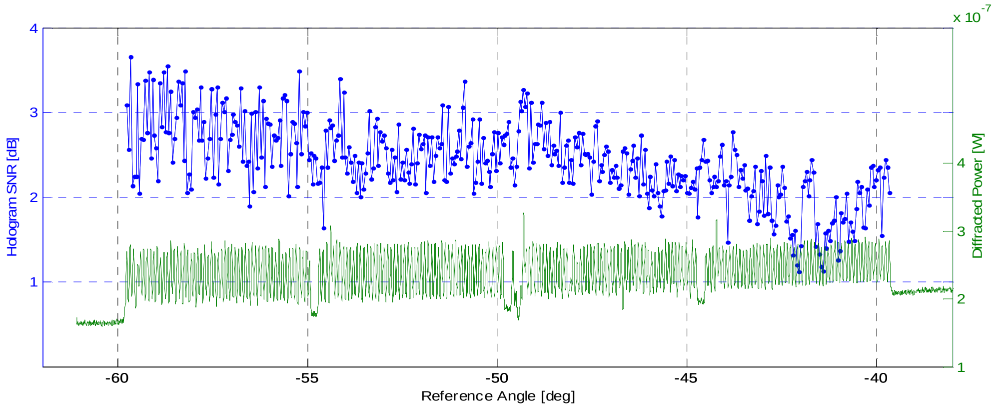

Figure 7. SNR and diffracted power of holograms recovered at an areal density of 2 Tbit/in^2.

CONCLUSION

We have presented experimental results from a second-generation holographic data storage demonstrator platform. The demonstrator has achieved a world-record raw areal bit density of 2 Tbit/in^2 utilizing several new second-generation technologies.

Successful demonstration of these second-generation innovations will spark a renaissance in holographic data storage. The big data storage tsunami is generating enormous opportunities for cold storage, archival storage, and near-line storage of the sorts that will be the target of initial HDS commercial offerings. These second-generation innovations not only leap-frog the capabilities of competing technologies, they lay the foundation for Moore's-Law growth for years to come.

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