Bit-mapped Holograms Using Phase Transition Mastering (PTM) and Blu-ray Disks

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Abstract. Due to recent advances made in data storage, cloud computing, and Blu-ray mastering technology, it is now straightforward to calculate, store, transfer, and print bit-mapped holograms that use terabytes of data and tera-pixels of information. This presentation reports on the potential of using the phase transition mastering (PTM) process to construct bit-mapped, computer generated holograms with spatial resolutions of 5000 line-pairs/mm (70 nm pixel width). In particular, for Blu-ray disk production, Sony has developed a complete process that could be alternately deployed in holographic applications. The PTM process uses a 405 nm laser to write phase patterns onto a layer of imperfect transition metal oxides that is deposited onto an 8 inch silicon wafer. After the master hologram has been constructed, its imprint can then be cheaply mass produced with the same process as Blu-ray disks or embossed holograms. Unlike traditional binary holograms made with expensive e-beam lithography, the PTM process has the potential for multiple phase levels using inexpensive optics similar to consumer-grade desktop Blu-ray writers. This PTM process could revolutionise holography for entertainment, industrial, and scientific applications.

1. Introduction
Computer generated holograms (CGH) are far from new. Ever since the widely referenced paper by Lohmann and Paris in 1967, the potential importance and value of CGH methods have sparked the imagination and challenged the intellect of countless scientists [1-6]. Unfortunately, until recently, limitations in methods of production have restricted their use to a narrow range of applications. In particular, not long ago, limitations in computer memory capacity and processor speeds have stifled the application of CGH to the large surface areas and high information bandwidths commonly found in traditional holograms [28, 29]. In addition, most methods of making computer generated holograms are lacking in continuous phase depth control (are binary) [7-9] or have inferior spatial resolution. These fabrication methods have been limited to very expensive processes such as e-beam lithography or lower resolution photo-reduction techniques. However, in a few narrow applications where low bandwidth can be tolerated or where cost is no object and the effects of binary levels can be tolerated, CGH methods have enjoyed a successful but narrow application. One notable application is for the interferometric testing of aspheric components [10]. Other applications include optical correlation for machine vision [11], and as phase masks in telescopes and microscopes. Along with the limitations of computer speeds and memory constraints, the wide application of CGH had been limited by the lack of any facility to inexpensively mass-produce such holograms with sufficiently high quality. While embossing methods have been around for years and have permitted the cheap mass production of holograms, the lack of phase uniformity and good surface flatness of embossing materials have limited their performance and subsequent use in many potential scientific applications such as holographic optical elements (HOE).
With the advent of compact disk and laser disk technology in the early 1980’s, and DVD technology in the mid to late 1990’s, computer generated holograms have been reconsidered and tested for various applications on these media [10]. However, before Blu-ray disks, the spatial resolution of normal compact disks continued to limit their use. In addition, compact disk and DVD technology continued to be exclusively binary and normal disk recorders lacked the necessary spatial encoding hardware to write holograms directly [12].

Blu-ray disk production, and phase transition mastering in particular, has at last unleashed the potential of mass-producing computer generated holograms for a wider range of applications that demand both high resolution, large surface areas and high-precision phase control [13-21]. At present, there have been few reported attempts to commercialize Blu-ray based holograms [16] and it appears that few if any of the large Blu-ray producers are actively engaged with CGH production. In spite of this lack-luster beginning, it does appear that the PTM process could be ideally suited for CGH mass-production. With the hardware technology already in place for the production of Blu-ray disks, once a CGH has been mastered with PTM, it can be immediately mass-produced in a Blu-ray factory with minimal change to the Blu-ray mass-production process. In addition, while most Blu-ray mastering technologies can only be deployed for binary phase applications, the PTM process has the potential to record multiple phase levels to approximate continuous phase tones.

2. Tera-pixel recording and Terabyte calculations

In many respects, the bit-mapped computer generated hologram is in fact just like any other digital image. The real difference between such a hologram and a standard digital image is the higher spatial resolution of a holographic image. For example, an off-axis bit-mapped hologram could contain 100 million pixels of information for every square millimeter of surface area. This corresponds to a pixel size of 0.1 microns (100 nanometers) or even less. As a result, a hologram that is 100 x 100 mm in size would require a 1 Terabyte of data if each pixel had 256 grey levels. In other words, to capture the same data using a digital camera, one would require a sensor that has one million rows by one million columns.

While 20 years ago, an optical scientist would have no chance of working with such large sums of data in any format, such data today is almost trivial to obtain and only slightly less trivial to calculate, particularly with today’s graphics cards and Cloud computing options. The next step is how to print such a digital hologram? Enter the Blu-ray disk: with its high spatial resolution and high quality optical characteristics that essentially match the requirements for a good CGH. At last, with this last piece in place, perhaps the age of the CGH can finally arrive!

3. Benefits of bit-mapped computer generated holograms

For a number of years, a category of computer generated hologram has existed that does not directly use bit-mapped data, but rather depends on the local mixing of a reference beam with the object-space frequency spectrum across an array of holographic “voxels” on the hologram surface. Such a system was pioneered at MIT and has been successfully deployed by Zebra Imaging to make large format display holograms [23]. Related approaches have also been used with great success to make holographic storage by companies such as In-Phase [24]. Such systems do have some important advantages over bit-mapped holograms in terms of larger hologram formats, reduced hologram write-times, reduced image processing, and reduced memory overhead requirements. In addition, the voxel approach is able to write volume gratings that support “thick” Lippmann-type holograms in photopolymers instead of the “thin” holograms used with bit-mapped holograms. Nevertheless, the incoherent bit-mapped CGH described in this paper do offer a number of significant advantages that are not available with interference-based methods. In particular, the bit-mapped approach can offer better performance for holographic optical elements (HOE). In addition, the bit-mapped hologram can be mass produced either in the Blu-ray disk format or as an embossed hologram. Furthermore, aberrations, distortion, and diffraction efficiency can all be improved in a bit-mapped hologram.
4. Noise Reduction

There is an important advantage with incoherent writing of a hologram pixel by pixel that needs further discussion. This advantage is the reduction (and even elimination) of intermodulation noise, which is also known as cross-talk.

In classic interference-based holography, intermodulation noise occurs as a result of the interference between the different scattering points from the surface of an illuminated object. In particular, coming from an object are a very large number of wavefronts (or angular frequency components) from each scattering point in the object space. Instead of considering all possible scattered wavefronts from an arbitrary object, as shown in Figure 1, the effects of intermodulation noise can be most easily observed if we restrict our attention to three such wavefronts that we label as A, B, and C. At the hologram plane H, these wavefronts interfere with a reference wavefront, R, that creates an interference pattern which gets recorded by the holographic film and defines the holographic grating used during holographic reconstruction.

![Figure 1: Interference between 3 wavefronts A, B, C and reference wavefront R at H](image)

We can next write an equation to represent this process of recording and reconstruction of a holographic image. In particular, during the recording, all of the coherent wavefronts interfere with each other at the holographic film plane, H. This interference is really the summation of the amplitudes of each wavefront multiplied by their complex conjugates that gives the intensity distribution [6]. This is shown in equation (1).
I = (R + A + B + C) (R* + A* + B* + C*)  \hspace{1cm} (1)

After algebraic expansion, the result is:

I = RR* + RA* + RB* + RC* + AR* + AA* + AB* + AC* + BR* + BA* + BB* + BC* + CR* + CA* + CB* + CC* \hspace{1cm} (2)

Of all of these 16 terms found in equation (2), only 3 terms relate to the desired holographic image formation:

I[image] = A R* + B R* + C R* \hspace{1cm} (3)

while three other terms are related to the phase conjugate image:

I[conjugate image] = RA* + RB* + RC* \hspace{1cm} (4)

The remaining 9 terms shown in equation (5) relate to intermodulation noise and bias components:

I[noise] = RR* + AA* + CC* + AB* + AC* + BB* + BC* + CA* + CB* \hspace{1cm} (5)

With classic interference-based holography, the bias and noise terms are unavoidable and inherent in the process. However, with the method of incoherent bit-mapped recording, the intermodulation noise and bias terms are not generated and it becomes possible to directly eliminate these issues. By using multiple phase levels to write a blazed hologram profile, it may also be possible to eliminate the conjugate image terms as well.

5. Polychromatic performance

With classic holographic methods based on interference, the reconstructed hologram is dependent on the wavelength of the laser used to write the hologram. The holographic recording process is formed from interference between each of the laser wavelengths present with their corresponding reference beam. After development, the fringes formed during exposure from each laser is converted into a diffraction grating at a carrier frequency that corresponds with the laser wavelength used to record it.

As such, in order for multi-wavelength reconstruction to occur for a classic hologram, it is necessary either to use multiple laser wavelengths during the recording step or a careful arrangement of the recording optics to compensate for the resulting distortion, magnification, and loss of diffraction efficiency that would otherwise occur at the different shifted wavelengths during reconstruction. In both situations fore-mentioned, the recording geometry has an increased complexity for multiple wavelength reconstruction. In contrast to this, with the CGH method of writing the hologram pixel by pixel, there is no increase in complexity or change in the recording optics to accommodate multiple wavelengths.

6. Light scattering through non-interferometric origins

With bit-mapped computer generated holograms, it is no longer necessary to create the sinusoidal grating structures found in interference-based holograms. A diffraction grating produced by classic interference methods typically has a sinusoidal shape to its surface profile. In contrast, the ruled blazed grating used with spectroscopic measurement has existed since the nineteenth century and has been historically created on a ruling machine which physically cuts the grating by a knife edge. In this case, the grating has a sawtooth profile. Such a grating has advantages for achieving a higher diffraction efficiency in a particular direction or diffraction order.
When writing bit-mapped holograms with multiple phase levels, it becomes possible to create analogous structures that are computer optimized profiles for specific applications. These shapes might have a non-smooth profile (as in the case of the blazed grating), be asymmetric or even aperiodic. The designs of such shapes need not be governed from interference considerations and may even be calculated using electromagnetic simulations of the scattering boundary conditions. Some novel surface profiles might even be fractal in nature or mimic the nano-structure on a butterfly wing to create iridescence. The key point is that light scattering profiles can have many different shapes other than the standard sinusoidal-based profile exhibited from interference recording.

7. CGH on Blu-ray disks

The Blue-ray disk technology was developed by Sony and their partners as the next step beyond DVD technology. While the DVD uses a 658 nm laser wavelength, the Blu-ray is based on the 405 nm wavelength. With a 320 nm track pitch and a 150 nm minimum pit length, a single layer Blu-ray disk is capable of storing 25 GB of data on a single layer [13]. Such numbers however do not reveal the true information density available on a Blu-ray disk. In particular, the Blu-ray disk is designed for serial digital read-out of data and is composed of a spiral of tracks in an analogous fashion to CD’s, DVD’s, and even the old fashioned vinyl LP records. The electronic hardware used with personal Blu-ray writers and players depend on these tracks for recording and read-out purposes.

For CGH applications, the normal tracks found on Blu-ray disks serve no purpose and only add diffraction noise to the reconstruction. In addition, these tracks are arranged with a 150 nm gap between them. These gaps are needed for serial digital read-out in order to prevent optical cross-talk between the tracks. With CGH, it becomes possible to completely fill-in the space on the disk surface and eliminate the tracks altogether. In addition, with Phase Transition Mastering (PTM), it is also possible to reduce the size of the recorded spot from 150 nm down to below 70 nm. This is due to the remarkable nonlinear behavior of the PTM process that enables spots to be recorded at super-resolution (smaller than the diffraction limit (NA = 0.85)). While the diffraction-limited spot-size of the laser focus optics is about 0.4 micron, the PTM advantage gives it less than 0.1 micron by thermal threshold. Taken together, a single Blu-ray disk layer can store a Terabyte of data or a CGH filled with a $10^{12}$ pixels. In fact, holograms aside, Sony has already successfully produced Blu-ray ROM disks containing a Terabyte of data [27].

8. Quality control and mass production of Blu-ray disks

While Blu-ray technology enables recorded resolutions that are comparable with the best holographic films, it is the incredible perfection of the Blu-ray quality control during mass production that makes it ideally suited for CGH production. Unlike other methods used to produce CGH media, with Blu-ray mastering each pixel can be tested to accurately ensure that the intended phase level at each pixel has been obtained. In addition, once a Blu-ray master has been created, the subsequent mass production of Blu-ray disks from the master has already been carefully fine-tuned by the Blu-ray industry to deliver copies that are optically flat to a fraction of a wavelength with high fidelity reproduction of the phase information.

9. Overview of the PTM process

The PTM process was originally developed by Sony in 2003 [14]. By 2009, of the 400 million Blu-ray disks produced world-wide, 94% were created with Sony’s PTR-3000 BD Mastering System.

PTM operates by depositing a layer of imperfect oxides of transition metals on an 8 inch silicon wafer substrate. More specifically, the deposited layer consists of imperfect oxides of tungsten and molybdenum. Originally, the deposited layer is amorphous. Because the material is non-transparent, it absorbs the blue laser light (405 nm). Sudden increases in temperature (where the light is absorbed) cause oxidation with oxygen from the surrounding environment. This results in a change from an amorphous to a crystalline structure. There are also chemical changes in the material. When the
material is immersed in an alkaline developing solution, only the areas crystalized through exposure to the blue laser are dissolved [22].

The silicon wafer substrate also plays an important role in the mastering process by ensuring an optically flat surface as well as conducting the heat from the exposed region more quickly than the glass substrate used traditionally with DVD production. This increased heat transfer permits smaller write zones than otherwise possible by dissipating the heat away from neighboring unexposed regions.

10. Features of PTM
The Phase Transition Mastering process (PTM) is only one of several competing processes developed for Blu-ray mastering [13]. However, for the purposes of CGH mastering, it appears to be superior to other methods.

11. PTM vs e-beam lithography
With PTM, the mastering equipment costs are extremely low compared to e-beam lithography. In addition, the time required to create a BD master is greatly reduced over e-beam. In particular, e-beam mastering requires 12 processes and takes approximately 11 hours to write a 25 Gigabyte layer [21]. With PTM, there are only 5 processes and the total write time required for a single 25 GB layer can be as short as 40 minutes for a 3x write speed or as long as 80 minutes for the more standard 1.5 x write speed. When making a Terabyte CGH recording, this could translate to an overall mastering time of 24-100 hours depending on the mastering write speed [27]. Another advantage with PTM is that the areas crystallized through exposure to blue laser light are slightly raised compared with other areas. This means that error checking can be carried out at the same time as mastering, leading to 100% error-free masters [21]. Finally, e-beam lithography has traditionally been deployed as a binary process. However, e-beam writing has recently been used by researchers to create nano-structures in materials such as PMMA. It would appear that the PTM process can also be harnessed in a similar fashion.

12. Phase depth control
With PTM, the pixel depth can be controlled to deliver a maximum phase modulation of $2 \pi$ radians for greatest diffraction efficiency. For reflective Blu-ray disks, this corresponds to a profile depth of 0.5 wavelength/refractive-index. This means that for the visible wavelength range, a pixel depth of less than 200 nm is needed to achieve $2 \pi$ radians of phase modulation in the reflected beam. While the standard PTM mastering system is designed for binary phase operation, the Sony PTM process has the potential to support multiple phase levels. This is due to the fact that the Sony PTM process is a positive process in which the exposed surface is removed during chemical development and can increase the phase depth through increased exposure at different regions across the CGH bit-map.

While the several other PTM mastering technologies now exist that compete with Sony’s PTM, these competing methods are generally lower resolution and based on negative processes in which the unexposed surface regions are removed. In contrast to positive PTM, negative PTM processes have no ability to increase the phase depth through increased exposure and the resulting spot size is larger. While positive PTM has the potential to write multiple phase depths, this property has not been exploited by the current PTM control software nor has it been reported for CGH production by other researchers. Instead, all reported CGH research using PTM has been exclusively binary phase to date [12, 14, 16]. However, PTM has been successfully applied by Sony to write different phase levels for the creation of both Blu-ray and DVD masters (which have different phase depth requirements) and there is a limited capability in some PTM control software to program the pit depth up to 100 levels. Before it can be fully exploited, further development will likely be required to add support for multiple phase levels on current PTM machines [27].
13. **Electroplating from PTM**

The PTM process creates a master that is electrically conductive. This enables nickel stamps to be electroplated directly on the PTM master without the additional metal sputtering step required for traditional photoresist or non-conductive, glass-substrate based disk mastering techniques, thereby simplifying the production cycle.

14. **CGH with PTM**

In traditional holography, the object and reference beams interfere at the holographic plate by means of standing wave patterns in intensity. This interference pattern is recorded by chemical changes in the photosensitive medium. Because the light is spread out over an area on the holographic plate, the intensity or energy density at the film surface is greatly reduced. As a consequence, the photosensitive medium must have a certain degree of sensitivity to chemically capture and amplify the impact of the interference fringe intensity. For example, traditional media will have a sensitivity that ranges between 50 micro-Joules/cm$^2$ for silver halide and >2 mJ/cm$^2$ for photopolymers.

In the case of phase transition mastering, the recording media has no chemical sensitivity toward light because the physical processes involved are phase changes due to heat. This can only happen with light that is tightly focussed to a very small spot with very high power density. The spatial scale of the heat zone can be less than 100 nanometers. As such, traditional methods of holographic recording will not work with PTM. Instead, the hologram must be synthesized pixel by pixel (or point by point) into a composite structure to diffract the light during holographic reconstruction.

15. **Thin versus thick holograms**

PTM holograms are generated in a single diffractive surface rather than being distributed within a diffractive volume. This is the classic difference between a “thin” hologram and a “thick” hologram. It is also the reason why holograms created with PTM can be mass-produced by the same methods as either Blu-ray disks or classic embossing. In particular, the “thin” quality of holograms made by PTM allows their features to be stamped into a plastic substrate or foil.

The thin nature of the PTM-based holograms permits diffraction to occur with equal efficiency across a broad range of wavelengths and angular frequency inputs. This property can be very useful in the application of holographic optical elements (HOE).

16. **Applications**

Bit-mapped holograms with the PTM process could revolutionise holography for entertainment, industrial, and scientific applications. In particular, Blu-ray mass production could enable high quality holograms to be mass-produced for the first time at an affordable cost. By using the standard Blu-ray disk mass-production process, the manufactured cost of each Blu-ray CGH can be less than one dollar.

17. **HOEs**

The low cost and high performance make Blu-ray HOE’s viable for many new and previously unrealised applications. Today, the true potential of HOE devices has been left untapped because of insufficient performance characteristics combined with inadequate means for mass-production. With Blu-ray CGH production, this could change. In particular, with the right performance characteristics in place, HOE components could displace current optical systems that now cost many thousands (and even hundreds of thousands) of dollars. The most critical characteristics include a sufficiently high diffraction efficiency and sufficiently low aberrations and wavefront distortion. Of course the precise limits of acceptable performance varies with the application. For some applications, a diffraction efficiency approaching 100% could be necessary, while in other applications a diffraction efficiency of 50% might be perfectly acceptable. In some cases, the high diffraction efficiency may be far less critical than minimizing all distortion, while the requirements may be reversed in other cases.
Here is a partial listing of potential HOE applications:

- Laser beam-shaping
- Toys and entertainment
- Sign projections for advertising and displays
- Laser welding
- Light collection systems
- Architectural lighting systems
- Three-dimensional shape measurement and shape validation
- Solar energy concentrators
- Spectroscopy
- Bio-medical instrumentation optics
- Imaging lens optics
- Integrated circuit fabrication validation
- Aspheric and free-form optic characterization
- Head-up displays
- Three-dimensional displays
- Space-born and military optics
- Astronomy
- Microscopy.

**18. Display Holograms**

Display holograms have different requirements from HOE applications. In general, display holograms do not require high diffraction efficiencies and can tolerate greater aberrations and distortion than for HOE applications. Here is a partial listing of some specific display hologram applications:

- Blu-ray disk movie cover-art
- Watermarks [16]
- Anti-counterfeiting
- Embossed hologram masters
- Holographic “postcards” of venue-specific material (including landscapes and landmarks)
- Advertising and product promotion
- Artistic display holograms.

**19. PTM for embossed hologram mastering**

PTM mastering could revolutionize the embossed hologram industry. Many embossed hologram masters are produced one at a time by a highly skilled artist in a holographic studio. This is a delicate and expensive endeavor which limits the types of subject matter that can be produced in the hologram. While the PTM process is currently only used to create Blu-ray masters, it is naturally suited to produce embossed hologram masters since it already generates nickel replicas for stamping. With PTM-based hologram masters, the subject is always computer generated and the resulting embossed holograms can include any subject without limitation. Finally, PTM-based hologram mastering can be a turn-key process with predictable production time-lines.

**20. Embossed versus photopolymer versus Blu-ray holograms**

For a number of years both embossed and photopolymer materials have been used to mass-produce holograms. These methods of hologram production have different strengths from Blu-ray holograms. Both embossed and photopolymer holograms are usually created in a flexible material. With embossed holograms, a metalized-mylar film is bonded to a substrate such as paper, plastic, or card stock. Photopolymers are inherently pliable and are often produced in flexible film. Blu-ray disks, on the
other hand, are rigid. This has the result of the Blu-ray disk preserving the optical phase integrity more accurately than embossed or photopolymer media. For holographic display applications, this phase flatness is not a big issue. However, for HOE applications, phase front flatness can be extremely important. For such applications, the Blu-ray disk is a far superior vehicle for CGH production.

21. Blu-ray mastering versus Blu-ray disk burning
This paper has placed a particular emphasis on the Blu-ray mastering process for making computer generated holograms on the Blu-ray disk format for mass production. In particular, Blu-ray mastering is a process that occurs in a Blu-ray factory to create a master used for the mass-production of Blu-ray disks. However, there also exists the potential of using the hardware from an inexpensive personal Blu-ray burner to make computer generated holograms. In particular, the laser optics associated with a Blu-ray writer is essentially the same as those found with Blu-ray mastering hardware. The difficulty lies in the absence of the necessary spatial encoding hardware required to accurately print the bit-map pixel locations. In contrast, the Blu-ray mastering systems normally found in a Blu-ray factory can be readily configured with optical encoders to provide positional feedback for the direct printing of bit-mapped holograms.

In addition, the recordable Blu-ray disk used in personal Blu-ray writer is based on a different material process from PTM (the details of which are beyond the scope of this paper). It appears that this recordable material could also be used to make computer generated holograms, but such disks usually get pre-imprinted with spiral recording tracks at the time of disk manufacture. For CGH, the presence of these tracks creates noise in the reconstructed image.

While it could be possible to adapt a personal Blu-ray writer for CGH production, it will require significant modifications to the writer hardware and software to make this possible. This could be worthwhile if the end-goal is to construct an inexpensive prototype holographic printer, but it will require significant costs and risks of additional research and development to adapt such hardware. By using an existing mastering facility at a Blu-ray factory, the research and development risks are greatly reduced and the resulting CGH masters made with PTM will be optimized for immediate mass production.

22. Mass-production versus custom printing
With the development of digital cameras that can capture fully three-dimensional pictures, such as the Lytro camera [25], there is likely to be a very significant market for custom printed display holograms taken by ordinary people. In theory, this could be a very good application of bit-mapped holograms printed on Blu-ray disks. However, the inherently longer process times of a bit-mapped printed hologram (24-100 hours) is much slower than alternative holographic print techniques, such as offered by Zebra Imaging. This might not be a problem for custom HOE applications since they often cannot function well in competing formats. However, for custom display hologram applications, other faster hologram print methods can be better suited.

23. Conclusion
The holography business needs a heavily invested industry to “piggy-back” onto. At the same time, with millions of dollars already invested into Blu-ray production and stiff competition from video streaming and digital downloads, the CGH market could provide a much needed source of revenue for the Blu-ray industry. The synergy between standard Blu-ray and CGH production could become an ideal partnership. In fact the technical requirements of Blu-ray already closely match CGH technical requirements and any enhancement made to the Blu-ray mastering process will immediately improve CGH production capabilities as well.

While PTM bit-mapped holograms are inherently slower to record than many other computer generated hologram methods, it appears to be the best option for the mass-production of both HOE’s and display holograms on Blu-ray disks.
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