Computation of high-stability DC balancing scheme for ferroelectric liquid crystal on silicon holograms using graphics processing units

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Spatial light modulators based around liquid crystal on silicon have found use in a variety of telecommunications applications, including the optimization of multimode fibers, free-space communications, and wavelength selective switching. Ferroelectric liquid crystals are attractive in these areas due to their fast switching times and high phase stability, but the necessity for the liquid crystal to spend equal time in each of its two possible states is an issue of practical concern. Using the highly parallel nature of a graphics processing unit architecture, it is possible to calculate DC balancing schemes of exceptional quality and stability. © 2011 Optical Society of America

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The use of spatial light modulators (SLMs) in telecommunications requires a degree of stability in the holograms they display that few other holographic applications demand. The phase stability and fast switching time of ferroelectric liquid crystals make them attractive in the context of telecommunications [1–6], but the requirement that the liquid crystals see no net DC field is a practical concern that must be considered. While a ferroelectric liquid crystal can switch from one state to another on the order of microseconds, which is effectively instantaneous for applications such as holographic video projection, it is all but an eternity for a 10 Gb/s data stream. As the switching time is orders of magnitude slower than the rate of the data it is controlling, any single change on the path to complete DC balance of all pixels must have negligible effect on the quality of the replay field it is creating, at least in the area of interest near the photodetector or fiber. In applications such as modal conditioning of multimode fibers, the spatial resolutions required of the SLM have been shown to be very small [3–5]. Consequently, with only a few total pixels generating the replay field, a change in any single pixel can be of significant influence and, hence, requires special consideration.

For telecommunications purposes, the hologram displayed on the SLM in the near field produces the replay in the far field in which photodetectors or fibers are positioned. Fiber coupling is sensitive to the intensity and phase distribution of the field incident on the core, while photodetectors are concerned only with intensity. The absolute phase offset is irrelevant to both and is, after all, an arbitrarily defined value in this context. This degree of freedom is exploited to DC balance simple gratings described analytically for beam steering [2] or more complicated arbitrary holograms [1], but controlling the absolute phase of light near the center of the replay field is difficult, especially when the SLM is underilluminated.

The binary nature of a ferroelectric SLM is less of a hindrance in the context of adaptive mode conditioning of multimode fibers when compared to other applications, such as beam steering. The replay field due to a binary hologram must exhibit conjugate symmetry. Typically, this is undesirable and would result in at least 3 dB of loss due to the unwanted conjugate twin. However, the eigenmodes of an optical fiber are real-only functions with Fourier transforms that resemble scaled versions of the original eigenmodes. This means they have virtually binary phase and are conjugate symmetric in both the near- and far-field planes. Consequently, a mode can be generated at the center of the replay field with no 3 dB symmetry penalty. Unfortunately, unlike when the pattern is offset from the center, where the absolute phase in the far field can be incremented gradually [1,2], when centered, there are only two absolute phase possibilities and techniques, such as [1] breakdown, as they attempt to change the state of a large proportion of the pixels simultaneously, effectively randomizing the hologram.

However, while there is little flexibility in the absolute phase of the centered mode being generated, the rotational orientation of the modes are arbitrary for a perfectly symmetric fiber. All but the LP_{0x} family of modes consist of angularly separated lobes, which are out of phase with their adjacent lobes. Hence, rotating the replay field by the angular separation of these lobes will DC balance the hologram while maintaining excitation of the desired mode, as shown in Fig. 1(b).

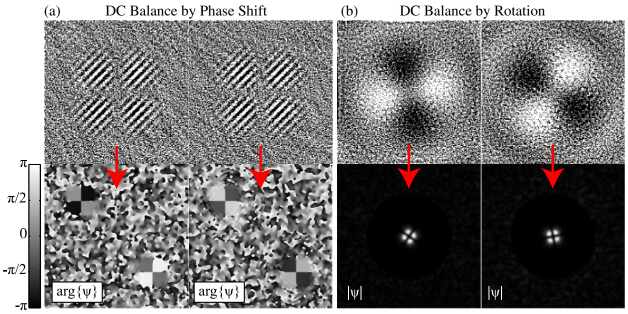

Fig. 1. (Color online) Binary phase $[0, \pi]$ holograms (top) maintain DC balance by (a) shifting the absolute phase for offset patterns or (b) rotating the replay field for centered patterns.

This Letter investigates maintaining DC balance by flipping individual pixels one at a time in an order decided by a highly parallel steepest-descent search for the best permutation of the N pixels of the SLM. Both shifting of the absolute phase in the far field for offset patterns as in Fig. 1(a) and rotation of the replay field for centered patterns as in Fig. 1(b) are investigated with both methods attempting to keep the area of the replay field in the vicinity of the fiber constant in terms of coupling quality and efficiency.

The search is in effect a variation on the classic "travelling salesman problem" [7]. Finding an exact optimal solution for this problem is intractable for nontrivial resolutions. However, the high level of parallelism present in modern graphics processing units (GPUs) makes acquiring a good solution by steepest-descent methods possible for holograms where a DC balancing scheme is not required in real time and can be precomputed. The strategy is simple: if there are N pixels in the SLM to balance, each pixel will be responsible for shifting the absolute phase of the replay field by approximately π/N for offset patterns or rotating the replay field by θ/N (where θ is the separation between lobes) for centered modes, and the remaining as yet unchanged pixel that best generates this shift will be chosen at each iteration. When a pixel is flipped, it is removed from the list of available pixels until every pixel has changed state exactly once. Hence, the decision with regard to which of M remaining pixels to flip requires evaluating the replay field M times. To compute the full sequence for N total pixels requires k evaluations of the replay field:

$$k = \sum_{i=0}^{N-1} (N - i). \tag{1}$$

It is a daunting proposition in that even for a relatively low-resolution hologram consisting of an array of only 256 × 256 pixels, more than 2 billion replay field evaluations would be required. Fortunately, most proposed applications of holography in telecommunications require only limited resolution [3–5]. The implementation of the search in the GPU architecture is essentially as outlined in [8]. However, this instance has parallelism in two dimensions, not just simultaneously calculating many replay pixels due to a single hologram pixel change, but computing all M potential pixel flips with their respective replay fields concurrently. The metrics used to evaluate the quality of a solution at each iteration where $T(\theta)$ is a set of n pixels defining the desired target distribution at an orientation of θ in an area of interest near the fiber within the total replay field and R defines the actual replay field in that same area due to the current hologram are

$$\mathrm{Re}[e^{i\phi}\langle T(0)|R\rangle]^2 = \mathrm{Re}\left[e^{i\phi}\left(\sum_{i=0}^{n} T(0)_i R_i\right)\right]^2, \tag{2}$$

when DC balance is to be maintained by shifting of the absolute phase (ϕ) of the replay field for offset patterns. For an optimal value, this metric requires T and R to have the appropriate phase relationship. Alternately, the quality may be calculated as

$$|\langle T(\theta)|R\rangle|^2 = \left|\left(\sum_{i=0}^{n} T(\theta)_i R_i\right)\right|^2, \tag{3}$$

when DC balance is to be maintained by rotation of the replay field by the angle θ for centered modes. For an optimal value, this metric requires T and R to be structurally the same but without regard for any overall phase offset between them. It is the power coupling coefficient. While the two methods use Eqs. (2) and (3) respectively to choose which pixel to change at each iteration; inside the algorithm, the final quality is always measured by Eq. (3). That is, without regard for any overall phase shift between the target field T and the actual replay field R. If T and R are respectively normalized to unity power, this will result in a possible error range of 0 to 1. The available pixel, which maximizes the quality at each step while keeping the total power of R at or above the initial value, is chosen.

Two resolutions will be examined here, a 32 × 32 hologram with an area of interest in the replay field consisting of 16384 pixels and a 256 × 256 hologram with an area of interest of 65536 pixels [8]. Computation times are approximately 25 s and 6 h, respectively, using an nVidia GTX 260 GPU. In both instances, the target field is an LP_{21} optical fiber mode. For reference, the simulated results are compared with those obtained by the binarization method in [1], where the number of subframes has been set to the number of pixels and the error calculated by Eq. (3). This implementation of [1] differs slightly in that the original full-phase holograms have been generated using simulated annealing [8,9] rather than Gerchberg–Saxton. As only the portion of the replay field near the fiber is to be optimized [8], in order to maximize the quality of the hologram after binarization for offset patterns, background noise is suppressed in the area $(-x,-y)$ where the pattern is at (x,y). To ensure the validity of any comparison, the overall efficiency of the hologram for the steepest-descent and binarization methods are kept the same.

As can be seen in Fig. 2(a), which corresponds to the method shown in Fig. 1(a), for both resolutions, the steepest-descent algorithm outperforms binarization both in

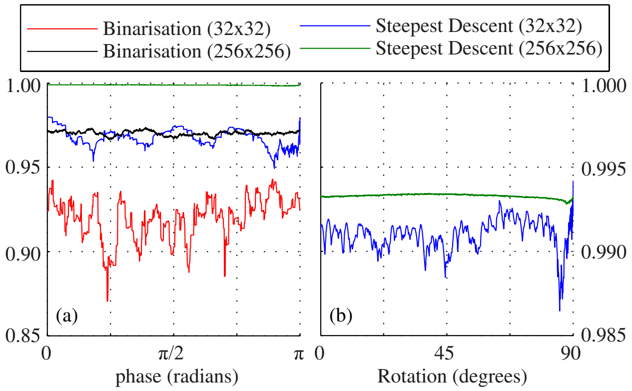

Fig. 2. (Color online) (a) Comparison of DC balancing by phase shifting for binarization of a full-phase hologram [1] and by steepest-descent search for an offset pattern. (b) DC balance by rotation of a centered fiber mode.

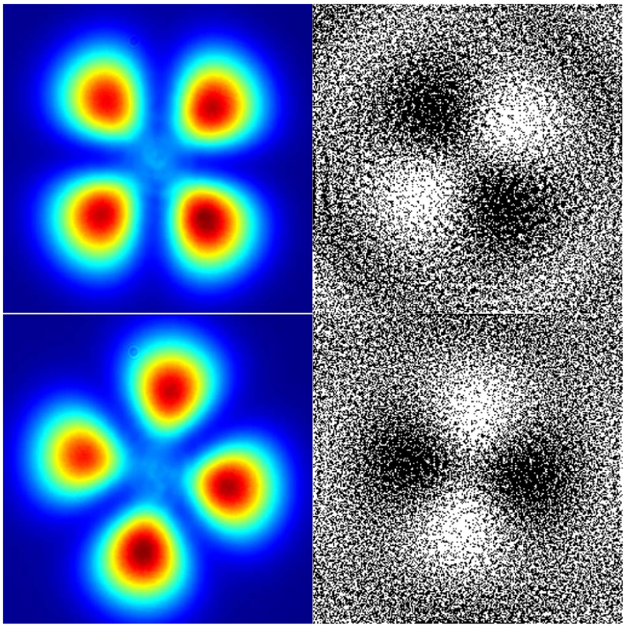

Fig. 3. (Color online) Far field at the output of the fiber (left) where the input is excited by a hologram (right) undergoing DC balance by rotation.

terms of the absolute quality of the replay field and the stability under DC balance. Working natively in binary phase rather than quantizing a full-phase hologram obviously has the advantage of avoiding information loss, which leads to a higher-quality hologram. This steepest-descent method also takes into account the distribution of the beam illuminating the SLM, which is not considered by simply quantizing the phase. Both methods perform better as the resolution increases, but the steepest-descent results for a 256×256 hologram are virtually perfect.

The results of Fig. 2(b) illustrate the stability and quality of a DC balance performed by rotation of the replay field as per Fig. 1(b). As mentioned above, where the majority of the replay power is near the center, it is not possible to DC balance the hologram by shifting the absolute phase. Rotation of the replay field provides a solution for achieving DC balance of a hologram where the majority of the power is concentrated at the center of the replay field. However, this requires the target to be identical under rotation except for a 180° phase shift. This is relevant to multimode fiber launch, but could also be used for beam steering by replacing what is typically a Gaussian–Sinc-like spot, which would be incident upon a photodetector, with something resembling an LP_{11} mode.

To demonstrate DC balancing by rotation, an LP_{21} fiber mode at 660 nm is excited holographically at one end of a 1-m-long SMF-28e fiber and a CCD camera observes the far field leaving at the other end. The SLM used is capable of about 2000 frames per second and so as DC balance of its 65536 pixels takes place over a convenient time scale, pixels are flipped 64 at a time. In Fig. 3, it can be seen how the LP_{21} mode rotates as the SLM undergoes DC balance, consistently exciting the desired mode at different rotations.

Maintaining DC balance of a low-resolution ferroelectric SLM using steepest-descent search has been shown to produce superior quality and stability to existing methods, albeit at a large computational expense. This makes it appropriate for telecommunications where holograms are precalculated, low resolution, and have very tight temporal stability requirements.

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