Fabrication of ideal geometric-phase holograms with arbitrary wavefronts

JIHWAN KIM,1 YANMING LI,1,2 MATTHEW N. MISKIEWICZ,1 CHULWOO OH,1,3 MICHAEL W. KUDENOV,1 AND MICHAEL J. ESCUTI1,∗

1Department of Electrical and Computer Engineering, North Carolina State University, Raleigh, North Carolina 27606, USA
2Currently at Apple Inc., Flat Panel Display, Cupertino, California 95014, USA
3Currently at Intel Corporation, Technology and Manufacturing Group, Hillsboro, Oregon 97124, USA

*Corresponding author: mjescuti@ncsu.edu

Received 12 August 2015; revised 9 October 2015; accepted 9 October 2015 (Doc. ID 247820); published 4 November 2015

Throughout optics and photonics, phase is normally controlled via an optical path difference. Although much less common, an alternative means for phase control exists: a geometric phase (GP) shift occurring when a light wave is transformed through one parameter space, e.g., polarization, in such a way as to create a change in a second parameter, e.g., phase. In thin films and surfaces where only the GP varies spatially—which may be called GP holograms (GPHs)—the phase profile of nearly any (physical or virtual) object can in principle be embodied as an inhomogeneous anisotropy manifesting exceptional diffraction and polarization behavior. Pure GP elements have had poor efficiency and utility up to now, except in isolated cases, due to the lack of fabrication techniques producing elements with an arbitrary spatially varying GP shift at visible and near-infrared wavelengths. Here, we describe two methods to create high-fidelity GPHs, one interferometric and another direct-write, capable of recording the wavefront of nearly any physical or virtual object. We employ photoaligned liquid crystals to record the patterns as an inhomogeneous optical axis profile in thin films with a few μm thickness. We report on eight representative examples, including a GP lens with F/2.3 (at 633 nm) and 99% diffraction efficiency across visible wavelengths, and several GP vortex phase plates with excellent modal purity and remarkably small central defect size (e.g., 0.7 and 7 μm for topological charges of 1 and 8, respectively). We also report on a GP Fourier hologram, a fan-out grid with dozens of far-field spots, and an elaborate phase profile, which showed excellent fidelity and very low leakage wave transmittance and haze. Together, these techniques are the first practical bases for arbitrary GPHs with essentially no loss, high phase gradients (∼rad/μm), novel polarization functionality, and broadband behavior. © 2015 Optical Society of America

OCIS codes: (050.1940) Diffraction; (090.2890) Holographic optical elements; (160.3710) Liquid crystals; (310.6860) Thin films, optical properties; (350.5030) Phase.

http://dx.doi.org/10.1364/OPTICA.2.000958

1. INTRODUCTION

Phase shifts in light waves are ordinarily produced via an optical path difference (OPD) known as a dynamic phase effect. However, a change in other light wave parameters can also induce a corresponding phase shift, called a geometric phase (GP) effect [1–3]. This can be caused by optical anisotropy [4,5], plasmonic metamaterials [6–8], propagation evolutions from reflections [9], or adiabatic waveguiding [10]. Elements incorporating these, including polarization holograms [11–13] and metasurface holograms [6–8,14,15], can produce light waves with complex amplitude, phase, and polarization by embodying inhomogeneous attenuation, dynamic phase, and/or GP. In elements wherein only the GP varies spatially, exceptional diffraction and polarization behavior arises—most strikingly, they can theoretically produce nearly any wavefront variation and produce its conjugate just by changing input polarization [Fig. 1(a)]. This should be possible with 100% efficiency [13,16], e.g., when a birefringent layer has half-wave retardation, since the desired phase profile is encoded in the optical axis orientation [Fig. 1(b)]. This allows for continuous optical phase shifts without phase resets [2] in stark contrast to conventional elements, wherein phase profiles are encoded as (usually) discrete OPD variations in refractive index or thickness, limiting performance. We set forth that the class of pure GP elements is most properly designated GP holograms (GPHs), wherein attenuation and dynamic phase are homogenous.

Although the promise of GPHs is great, the principal challenge remaining is their fabrication: achieving precise and pure inhomogeneous GP control for arbitrary patterns at useful wavelengths without detrimental flaws. Most work to date has employed either material anisotropy (e.g., Refs. [12,17,18]) or subwavelength structures (e.g., Refs. [8,19,20]). Nearly all work has focused on a few GP wavefronts with spatial symmetry (i.e., in x, y, r, or Φ), including GP prisms (i.e., polarization gratings) [17,20–24], GP vortex phase plates (i.e., q-plates or vortex retarders) [16,25,26],
and GP lenses [2,27]. Other work has examined more general phase profiles [18,28,29]. So far, experiment essentially matches theory only in the simplest of these elements, the GP prism [23,24] and vortex phase plates [16,25,26], which each have linear phase profiles. In all other cases, experimental results are limited by one or more of the following: low efficiency, high scattering, small clear aperture, spurious leakage, or operation wavelengths outside the visible or near-infrared.

Here we employ two fabrication methods that create truly generalized GPHs that enable highly efficient thin-film GP elements with arbitrary phase profiles, for visible through infrared wavelengths. Two techniques are necessary because phase profiles commonly arise in two different ways: in some cases, a physical object generates the desired wavefront while, in other cases, equations or numerical analyses determine a virtual object description. Both involve creating a linear polarization orientation map that is recorded as an optical axis profile, using a linear photoalignment polymer [30] (LPP) and a polymerizable liquid crystal [17,23] (LC), as illustrated in Fig. 1(b). In what follows, we begin with the theoretical foundation of pure GPHs and then introduce our fabrication methods and results.

2. GEOMETRIC PHASE HOLOGRAM THEORY

The GPHs we study here employ the Pancharatnam–Berry phase [4,5], and may be identified as follows: thin films with an anisotropy defined by an optical axis \( \Phi(x, y) \) varying in the substrate plane, with a strictly constant net linear birefringence/dichroism magnitude (along \( z \)), Hasman et al. [19] were perhaps the first to clearly explain that elements like these output at most three distinct waves (see also Ref. [31]) for each input wave with \( |x_{\text{in}}\rangle \) polarization, \( \delta_{\text{in}}(x, y) \) phase, and unity amplitude:

\[
\begin{align*}
e^{i\delta_{\text{in}}} |x_{\text{in}}\rangle & \xrightarrow{\text{GPH}} \sqrt{\eta_+} e^{i(\delta_{\text{in}}+2\Phi)} |x_+\rangle + \sqrt{\eta_-} e^{i(\delta_{\text{in}}-2\Phi)} |x_-\rangle \\
& + \sqrt{\eta_0} e^{i\delta_{\text{in}}} |x_{\text{out}}\rangle.
\end{align*}
\]  

We identify the output terms as the primary (+), conjugate (−), and leakage (0) waves, where the polarizations \( x \) are always circular and mutually orthogonal, and where coefficients \( \eta_\pm \) are the efficiencies (i.e., fraction of input power coupled into their respective waves). Most interestingly, the primary and conjugate waves gain a phase shift \( \pm 2\Phi(x, y) \) which, in the case of a lens, causes one to converge and the other to diverge [Fig. 1(a)] with a positive and negative focal length, respectively. While the anisotropy may be birefringent and/or dichroic in general, here we study only pure birefringence since it allows for \( \eta_+ + \eta_- = 100\% \), i.e., complete coupling of the input into either the primary or conjugate waves, or any combination selected by \( |x_{\text{in}}\rangle \). In this case, the efficiencies of the primary and conjugate waves are

\[
\eta_{\pm} = \left| \langle x_{\text{in}} | x_{\pm} \rangle \right|^2 \sin^2(\Gamma/2)
\]  

and the efficiency of the leakage wave is

\[
\eta_0 = \cos^2(\Gamma/2),
\]  

where \( \Gamma \) is the retardation. While the simplest layer is uniaxially birefringent and homogeneous in \( z \) [Fig. 1(b)], other anisotropies [22,32] may be employed, resulting in different \( \eta_0 \) but producing the same behavior otherwise [33].

3. TWO DIFFERENT FABRICATION METHODS

A. Interferometer Approach

The first method enables the recording of nearly any wavefront as a GPH from a physical element, using a specialized interferometric principle. In conventional (intensity) interference, when a primary (or "object") wave with phase \( \delta(x,y) \) is superimposed with a similarly polarized and coherent reference wave, then \( \delta(x,y) \) is incorporated into the amplitude of the standing wave. In more general interference, however, where the primary and reference polarizations are not the same, the resulting standing wave has a complex distribution of both amplitude and polarization [13,34–36]. More specifically, when the two waves are orthogonally circularly polarized, then a special situation results: the standing wave is approximately linearly polarized everywhere, with in-plane orientation \( \psi(x,y) \). While this principle has long been used for polarization grating fabrication [17,21,23,24] with two plane waves leading to \( \psi(x,y) = (\Delta k \cdot r)/2 \), where \( \Delta k \) is the wavevector difference, this also applies in general for nearly any nonplanar object wave. When the object wave has phase \( \delta(x,y) \), then the polarization map is substantially linearly polarized, with \( \psi(x,y) = (\delta(x,y) + \Delta k \cdot r)/2 \). While this principle was hypothesized by Marrucci et al. [16] and employed to some extent by Ruiz et al. [37], neither they nor anyone else has yet proposed or demonstrated a general implementation.

The approach introduced here is the first to enable interferometric holographic recording of an arbitrary physical object’s wavefront as a pure GP phase element. We employ a modified Mach–Zehnder interferometer [Fig. 1(c)] to achieve this \( \delta(x,y) \rightarrow \psi(x,y) \) recording principle. The first polarizing beam splitter (PBS) separates the object/primary (O) and reference (R) arms into orthogonal linear polarizations, which are then recombined by a second PBS. A quarter-wave retarder transforms the...
beams into orthogonal circular polarizations. The object to be recorded must be placed before the second PBS so that its wavefront interferes with the reference, as illustrated for a lens in Fig. 1(c). For objects with wavefronts that diverge rapidly, lenses may be placed immediately before and after the second PBS to relay the object’s wavefront to the recording plane (not shown). Note that both O and R waves can be arranged parallel and collocated at the hologram plane. These constraints ensure that $\Delta k = 0$, allowing the often preferable elimination of the diffraction grating term ($\Delta k \cdot r$). Nearly any transparent and reflective dynamic phase object can be recorded in this way.

Photoaligned LC materials are especially well suited to GPH recording because of several unique properties [30]. These include: (i) any modest variation in the intensity of the standing wave will be eliminated and not recorded because the response of LPP is the same beyond a threshold fluence; and (ii) LPP is able to record only the polarization orientation angle and not its ellipticity.

B. Direct-Write Approach

The second fabrication method involves directly writing a virtual wavefront (i.e., nearly any inhomogeneous phase shift) via continuous scanning of a focused laser beam, partially introduced in Ref. [38]. At least three degrees of freedom are needed to record an arbitrary GPH, two for the spatial scanning and one for control of the anisotropy orientation. Most of the previously studied scanning methods employ only two, typically one spatial and one orientational [26,39–41]. Of the prior scanning methods that use three degrees of freedom [18,29,42], all employ a pixel-by-pixel discrete scan approach, a beam size not greater than those pixels, and one-shot exposure in each pixel, which altogether make smoothly varying and continuous phase profiles unattainable. Conversely, we postulate (and here demonstrate) that a continuous scan in all three dimensions achieves continuous optical axis profiles and thus continuous phase profiles. Furthermore, any residue of the scan contours themselves can be eliminated if they at least partially overlap and the recording material responds to the average polarization—as occurs in the photoaligned LC. The LC to LPP interaction also makes it possible to create features smaller than the writing beam size, exceeding the resolution limits found in the prior scanning approaches. We implement this principle with a direct-write system consisting of a polarization rotator and a 2D translation system for spatial scanning as shown in Fig. 1(d).

4. RESULTS

These two techniques in principle enable the embodiment of nearly any phase change as a GPH. To demonstrate this range of possibilities, we highlight eight representative experimental examples. The resulting quality and complexity significantly exceed all prior GP elements.

A. Interferometer Results

In the first GPH example, we fabricated a GP lens [Fig. 2(a)], using the modified Mach–Zehnder interferometer and a refractive spherical lens. Its clear aperture diameter is 16 mm and it has a focal length of 36 mm at 633 nm. The ideal phase shift [Fig. 2(a.i)] and its crossed polarizer texture [Fig. 2(a.ii)] are well matched by the corresponding experimental results [Figs. 2(a.i) and 2(a.iii)]. The unique GP lens characteristic behavior is easily observed in Fig. 2(a.iv), where a positive or negative focal length may be selected by changing input polarization.

<table>
<thead>
<tr>
<th>i</th>
<th>ii</th>
<th>iii</th>
<th>iv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase (rad)</td>
<td>$\Phi(x, y)$</td>
<td>Microscope X-pol</td>
<td>Far-Field</td>
</tr>
<tr>
<td>GP Lens</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GP Axicon</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GP Prism [PG]</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 2.** Interference GPH. (a) Lens. (b) Axicon. (c) Large period prism (i.e., polarization grating). Columns: i, Simulated (curve) and measured (circles) primary (magenta) and conjugate (cyan) phases, where measurement error is less than ±0.02 rad. ii, Theoretical optical axis profile, with simulated cross-polarizer texture. iii, Measured polarizing optical micrograph under crossed polarizers. iv, Far-field result. Scale bars in column iii indicate 500 μm.
Additionally, we measured spatial power distribution at the focal plane of the spot produced when the GP lens focuses a Gaussian laser beam [Fig. 3(a)]. The resulting focused beam shows almost no deviation from \( I(r) \propto \exp(-2(x^2 + y^2)/w_0^2) \), where \( w_0 \) is the beam waist, indicating that the wavefront of the refractive lens was well captured by the GP lens (cf., Ref. [43]).

This result exceeds all prior diffractive lenses (e.g., etched-surface Fresnel [44] and previous GP [37,39] types) with regards to efficiency, bandwidth, and scattering. In our results, 99% of incident light is directed into the converging and/or diverging waves, depending on input polarization. Because we used the two-layer broadband LC structure from our work with PGs [45] and multitwist retarders [32], this high (real-world) transmittance appears across the whole visible spectrum [Fig. 3(b)]. The lack of spurious leakages can be directly attributed to the continuous nature of the geometric phase change embodied in the anisotropic layer, and the lack of defects or other degradation [Fig. 2(a.iii)]. Note that while the transmittance is achromatic, the focal length manifests chromatic dispersion [shown in the inset of Fig. 3(b)] as with all diffractive lenses.

Indeed, this feature enables fabrication of fast [i.e., low F-number \((F/#)\)] lenses. For example, a parabolic GP lens profile will have \( f = \pm \Delta_{\text{min}} D/(2\lambda) = \pm \pi D/(4|\delta|_{\text{max}}) \), where \( D \) is the lens diameter and \( \Delta_{\text{min}} \) and \( |\delta|_{\text{max}} \) are the extreme values at the lens edge of the local grating period and the magnitude of the phase shift gradient, respectively. Even though this GP lens replays at 633 nm with \( F/2.3 \), the refractive lens used for the recording at 325 nm was \( F/4.5 \) (i.e., a lens with focal length 100 mm illuminated with a beam of 22 mm). The \( F/# \) upon replay will be scaled by the ratio of the replay to recording wavelengths, in this case \( (633 \text{ nm})/(325 \text{ nm}) \approx 2 \). In Fig. 3(c), we calculate the relationship in general: GP lenses that replay fast at visible and infrared wavelengths may be recorded (in the UV) using much slower physical lenses. Furthermore, as Ref. [46] highlights, GP lenses offer practical removal of lens aberration.

This GP lens also manifests excellent imaging properties. In Figs. 3(d) and 3(e), we arranged the GP lens and a circular polarizer between a picture of our university logo on a computer screen and a digital camera, where one polarization leads to a reduced apparent size while the orthogonal polarization magnifies the logo (where pixels are clearly resolved).

We also fabricated a GP axicon [Fig. 2(b)] and GP prism [Fig. 2(c)], which both showed highly linear phase in the radial and horizontal directions, respectively. In the far field, the GP axicon produces the expected ring [Fig. 2(b.iv)] for \( \chi_+ \) with \( \sim99\% \) transmittance, and the GP prism manifests \( \sim99\% \) transmittance in both primary and conjugate waves. Note that the small plateau in the apex of the axicon, as seen in the phase [Fig. 2(b.i)] and the crossed polarizer image [Fig. 2(b.iii)], arises directly from the rounded region at the tip of the physical axicon that was recorded. It is also worthwhile to note that the GP prism (i.e., a polarization grating) in Fig. 2(c.iii) has a very large grating period \( (\lambda = 0.56 \text{ mm}) \), something difficult to accomplish otherwise. Its interferogram [Fig. 2(c.iv)] captured a few mm from the element and analyzed by a linear polarizer, shows that the primary wave is propagating at a small angle from the leakage wave, and that the wavefronts are highly uniform.

**B. Direct-Write Results**

In the first example of direct writing, we fabricated a set of GP vortex phase plates which produce optical vortices with topological charges of \( m = 1, 2, 4, \text{ and } 8 \). For each, the target phase profile [Fig. 4(a.i)] was continuously scanned by a small Gaussian beam (diameter \( 2w_0 = 4 \mu \text{m} \); uniform linear polarization) in a spiral pattern [Fig. 4(a.i)] with arms \( 2 \mu \text{m} \) apart, starting at a radius of \( \sim2 \mu \text{m} \). The angle \( \Phi(x, y) \) was varied according to the ideal optical axis profile [Fig. 4(a.ii)]. This led to substantial overlap between neighboring scans, causing every location in the LPP to be exposed multiple times, with different polarization angles and intensities, often from the peripheral parts of the Gaussian.

![Fig. 3](image)

**Fig. 3.** Detailed Results from GP Lens. (a) Measured (dots) focused beam profile of GP lens (blue) and recorded lens (red), compared with perfect Gaussian result. (b) Measured transmittance of primary + conjugate (solid) and leakage (dashed) waves; inset: chromatic dispersion of focal spot. (c) Predicted replay versus recorded \( F/# \); dot indicates the GP lens reported here. (d) Imaging through the GP lens with \( \chi_+ \) polarization, showing positive focal length. (e) Same as (d), but with \( \chi_- \) polarization, showing negative focal length.
beam. This results in two important consequences. First, the scan pattern is not observable in the LC orientation profile because the local nematic director aligns along the average polarization direction of the multiple exposures, equivalent to $\psi(x, y)$. The LC alignment is smoothly varying [Fig. 4(a.iii)], without pixels or discontinuities, and a continuous geometric phase profile is produced. Second, the singularity is small because only the center point is equally exposed to all linear polarizations, which results in null averaging. Remarkably, the size of the central defect in each case is significantly smaller (i.e., 0.7, 1.6, 5, and 7 μm, respectively) than the best reported [26,47,48], and smaller than or similar to the beam diameter used to record the pattern. As a result, the far-field vortex beam intensities [Fig. 4(a.iv)] show excellent purity in each case.

In our second example of direct writing, we fabricated a lensless GP Fourier hologram (with image focus at infinity). The target far-field intensity was a fan-out grid with 63 spots of roughly equal intensity (~1.5% of the input) in the shape of an “E” offset from the incident direction and a vertical line of 27 spots on axis with half this intensity, shown in Fig. 4(b.i). This corresponds to half of the similar grid in Ref. [49], and was chosen to emphasize the unique features of the GP Fourier hologram. Using the Gerchberg-Saxton algorithm [50,51], we calculated a $64 \times 64$ pixel tile of the optimum phase shift [shown in Fig. 4(b.ii)], and arranged this into an $8 \times 8$ array to form the overall target $512 \times 512$ hologram. The GPH was recorded with a pixel spacing of 4.4 μm and a 6 μm beam diameter, using a continuous-motion raster scan [Fig. 4(b.i)].

The target [Fig. 4(b.ii)] and experimental [Fig. 4(b.iii)] crossed polarizer textures correspond overall, but notably, the experimental result is smooth and largely continuous despite the discrete nature of the target. Nevertheless, when illuminated with a 2 mm diameter 633 nm laser with $\chi_2$, the primary wave intensity matches the target very well [Fig. 4(b.iv)], at least qualitatively. The leakage wave transmittance is low (~1%) and scattering is minimal due to the largely continuous nature of the recorded phase, both dramatically improved over prior Fourier GPH (cf., Refs. [6,8,14,29,39,52]). As expected, the conjugate wave (illuminated by $\chi_1$) is rotated 180°. Interestingly, when both the primary and conjugate waves are illuminated using a linear input polarization, the output is the full fan-out grid (cf., Ref. [49]), a superposition of both waves simultaneously [directly predicted by Eq. (1)].

### 5. DISCUSSION

A primary feature of GPHs is the lack of a physical difference between phase shifts of 0 and $2\pi p$ for any integer $p$ due to the cyclical nature of the optical axis orientation. Conversely, phase shifts in thin-film dynamic phase elements (e.g., SLMs, conventional diffractive optics) are frequently embodied with $2\pi$ resets in the OPD, corresponding to discontinuities in physical quantities such as thickness or refractive index. These discontinuities result in unwanted diffracted light, reducing efficiency and introducing artifacts. The lack of such discontinuities [2] in the GPHs described here allows them to embody high-fidelity continuous phase shifts, resulting in high efficiency. Consequently, their primary limitation is not the phase shift $\delta$ range, but rather the phase shift gradient $|V\delta|$ since the latter is linked to physical parameters. In our materials, $|V\delta|$ is limited principally by the elastic deformation of the LC molecules, and we currently consider the maximum extreme to be at least $|V\delta|_{\text{max}} \leq \pi$ rad/μm, since we reliably fabricate polarization gratings [53] as small as $\Lambda_{\text{min}} \sim 2$ μm.

The reader may fairly ask, “Why introduce a new name for this class of elements?” Indeed, the elements qualifying as pure GPHs have been called patterned retarders, space-variant Pancharatnam–Berry phase optical elements [16,31], plasmonic metasurfaces [6–8], or any one of at least half a dozen different names already in the literature (e.g., Refs. [11,13,15,18,25,26,29,33]). We offer
three reasons supporting “geometric phase” as the proper name beyond simple semantics: First, the diversity of terminology for the same photonic effect is evident of at least some confusion on the physics fundamental to them all, hindering effective comparison and dissemination; second, this name all at once provides the clearest distinction for a general audience from conventional holograms (both amplitude and dynamic phase types) and from polarization holograms, of which GPH is a distinct subclass; and third, only the three output waves in Eq. (1) are possible in all embodiments of inhomogeneous pure geometric phase, including all those other than anisotropy (e.g., Refs. [2,7,10,15,33]).

Because the same LC and LPP materials used in the display industry may be employed, these elements are immediately viable for real-world use. For the same reason, GPH of nearly any δ can be created with $\eta_+ + \eta_- \approx 100\%$ efficiency across wide bandwidths in the visible and infrared using multiple chiral LC layers [32]. Furthermore, GPH can be both individually made with switchable LCs [17,53,54] and/or stacked with switchable polarization selectors so that exponentially many multistate wavefronts [55] can be nonmechanically generated based on the addition and subtraction of each element’s geometric phase shift (e.g., a lens assembly with multiple focal lengths). Finally, note that while predominantly continuous $\Phi(x,y)$ are reported here, discrete domains with boundaries on the order of a few μm are also feasible.

6. CONCLUSION

We have described and validated two novel methods that enable the fabrication of pure GPHs with essentially ideal properties. As a result, the phase profile of nearly any (physical or virtual) object can now be embodied as a smoothly varying inhomogeneous optical axis in a thin film, functioning as a highly efficient hologram with unique polarization sensitivity. The first method, based on a modified Mach–Zehnder interferometer, is capable of recording a physical object’s wavefront. As the primary example, we fabricated a high-quality GP lens with $F/2.3$ (at 633 nm), 99% diffraction efficiency across the visible spectrum, and phase properties matching the refractive lens used during recording. We also report on a GP axicon and GP prism (i.e., polarization grating), which manifest highly linear phase in the radial and horizontal directions, also with 99% transmittance in both primary and conjugate waves. The second method, employing a direct-write laser scanner, is capable of generating holograms with arbitrary wavefronts from a virtual object description (e.g., equations or tabular data). Using this method, we fabricated a set of GP vortex phase plates with excellent modal purity and remarkably small central defect size (e.g., 0.7 and 7 μm for topological charges of 1 and 8, respectively). We also made a GP Fourier hologram, a fan-out grid with 63 far-field spots, and an elaborate phase profile, which showed excellent fidelity and very low (~1%) leakage wave transmittance and haze. These fabrication techniques transform the compelling behavior of GPH from a curiosity to a robust capability in the photonics toolbox, viable for a wide range of applications across many disciplines.

Funding. ImagineOptix Corporation; National Science Foundation (NSF) (NSF PECASE ECCS-0955127).

Acknowledgment. The authors are grateful to Dr. Ravi Komanduri for helpful discussions throughout this work.

See Supplement 1 for supporting content.

REFERENCES
