

Article

Novel Multi-Beam Holography for Lithography

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Abstract

From smartphones to artificial intelligence chips, nearly all modern electronics depend on lithography to drive device miniaturization. Realizing nanoscale linewidths and fabricating intricate patterns remain central challenges for lithographic technologies. This work presents a novel multi-beam holography method capable of generating complex patterns for lithography. We demonstrate and systematically analyze the mechanism for the generation of sharp, complex bright fringes within an optical cavity equipped with phase-modulating elements. Through analysis of the types of split-amplitude interference and the position of the localized plane, two practical implementation schemes are established. For each scheme, we examine the key factors governing linewidth performance as well as its fundamental theoretical limits. Numerical simulations confirm the feasibility of our approach, yielding full width at half-maximum (FWHM) values below 1/10 of the wavelength. Theoretical projections further suggest that linewidths narrower than 1/20 of the wavelength are attainable. Requiring only a highly compact optical arrangement, the proposed technique delivers both narrow-linewidth features and sophisticated patterns, highlighting its promise as an alternative lithographic platform.

Keywords: holographic lithography; multi-beam interference; Fabry–Pérot cavity; narrow linewidth; aperiodic

1. Introduction

Lithography is the core process in modern semiconductor manufacturing. It directly dictates the performance and integration density of integrated circuits and constitutes a critical technology that underpins the infrastructure of the digital economy. Achieving narrow linewidth and aperiodic patterns represents two central challenges for lithography in overcoming physical limits and enabling the fabrication of sophisticated devices.

Since the 1950s, three major categories of mask-based lithography techniques have been developed, namely, contact lithography [1], proximity lithography [2], and projection lithography [3,4]. At present, deep-ultraviolet lithography systems account for more than half of global lithography-system shipments and are commonly adopted for chips with processing nodes ranging from 28 nm to 7 nm. Extreme-ultraviolet lithography systems can realize the 7 nm node in a single exposure, and multi-exposure techniques can theoretically push the minimum processing node down to 3 nm. Although these lithography technologies dominate the industry, pattern formation relies on masks, and various resolution-enhancement techniques, including optical proximity correction [5,6] and phase-shift masks [7], are required to compensate for aberrations along the projection system.



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Another mainstream technical route corresponds to mask-free lithography. Direct-write lithography techniques such as electron-beam lithography [8,9] enable arbitrary-pattern writing without masks or sophisticated projection systems. Nevertheless, their point-by-point writing scheme yields low throughput, which makes them more suitable for small-scale sample development in laboratories rather than large-scale industrial manufacturing. Laser interference lithography and holographic lithography are representative interference-based lithographic techniques. Laser interference lithography [10,11] is mainly applied to fabricate periodic structures whose period is constrained by the operating wavelength. Holographic lithography [12–14] employs refreshable wavefront modulators to realize dynamic masks. Such modulators possess high defect tolerance, yet this technique suffers from heavy computational overhead and rough line-edge profiles.

To address these challenges, new lithographic solutions should fully exploit the intrinsic degrees of freedom of light, such as multi-beam interference, to achieve high resolution with minimal manual intervention. The Fabry–Pérot (FP) cavity is an ingenious device. It forms a resonant structure composed of two high-reflectivity mirrors. Relying on multi-beam interference, constructive interference only occurs at positions satisfying the phase resonance condition to yield narrow linewidth [15]. Inserting modulation elements inside the cavity enables customized generation of optical-field parameters and distributions [16–18], and this configuration has been widely adopted in scenarios including precision spectroscopy and optical-field manipulation. But these intracavity-modulation schemes aim at generating a self-reproducing intracavity field and therefore must satisfy the cavity resonance condition, which constrains their output to relatively simple beams.

Despite continuous advances in lithographic resolution, compact methods capable of producing narrow and complex patterns remain urgently needed in both industry and academia. Herein, we propose a pattern-generation method based on the FP cavity, where a holographic optical element (HOE) is inserted into the cavity to produce ultra-narrow aperiodic patterns. This method can generate lines with sub-wavelength feature sizes in a compact and efficient manner. It provides a technical approach for fabricating nanoscale optical devices and exhibits great application potential in the field of photonic integrated circuits.

2. Principles

Figure 1 shows the schematic diagram illustrating the principle of the proposed holographic lithography method. Its core structure is a FP resonant cavity with a built-in HOE. After the collimated incident beam enters the resonant cavity, it travels back and forth multiple times constrained by the high-reflectivity coated mirrors and continuously passes through the HOE to complete phase modulation of the beam. The basic idea of this lithography method is that the constructive-interference condition for multi-beam interference is stricter than that for two-beam interference, which allows the output of extremely sharp bright fringes. Combined with the high design freedom offered by the refractive-index distribution inside the HOE, complex patterns can be generated. Finally, lithographic patterns are produced by this compact sandwich-like configuration in which the HOE is placed between the FP cavity.

2.1. Narrow-Linewidth Generation

The physical basis for narrow-linewidth realization in the proposed method originates from the phasor superposition induced by multi-beam interference, which is accomplished by the FP cavity. Monochromatic incident light undergoes multiple reflections within the FP cavity and is split into multiple transmitted beams with well-defined phase correlations. Only light satisfying the constructive-interference condition can be amplified during su-

perposition. As the number of transmitted beams participating in interference increases, the constructive-interference condition becomes more stringent, and the resulting bright fringes become narrower.

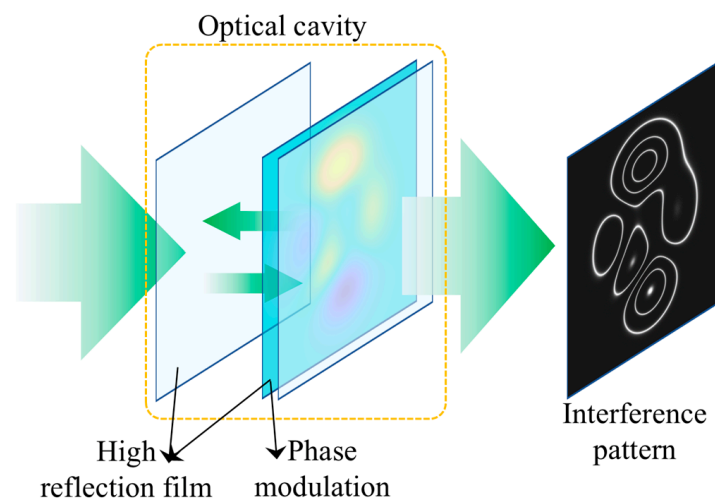


Figure 1. Schematic diagram of multi-beam interference for lithography.

Since the FP cavity serves as the foundation for narrow-linewidth generation, we first quantitatively analyze the influencing factors of linewidth under the condition that no modulation element is placed inside the cavity. Suppose the incident light intensity is I_0 , the initial phase is zero, the reflection coefficient of light at the two inner surfaces of the plate is r , the phase difference between adjacent coherent beams introduced by light propagation inside the plate is $\Delta\varphi$, and the number of beams involved in superposition is N . Under the condition $|r| < 1$, the intensity of the interference field can be expressed as

$$I_T = \frac{I_0 \cdot (1 - r^2)^2 \cdot \left\{ 1 + r^{4N} - 2r^{2N} \left[1 - 2\sin^2(N\Delta\varphi/2) \right] \right\}}{(1 - r^2)^2 + 4r^2 \sin^2(\Delta\varphi/2)}, \quad (1)$$

and with other parameters kept constant, the linewidth narrows and approaches the reflectivity-determined limit as the number of interfering beams increases. When $N \rightarrow \infty$, the above equation can be simplified as

$$I_T = \frac{I_0 \cdot (1 - r^2)^2}{(1 - r^2)^2 + 4r^2 \sin^2(\Delta\varphi/2)}. \quad (2)$$

the phase width of the bright fringe is defined as the interval between the two points on both sides of the bright-fringe center where the intensity drops to half of the maximum intensity, and its expression is $b = 2(1 - r^2)/r$. Given the wavelength λ , cavity thickness d , intracavity medium refractive index n , lens focal length f , and the tilt angle corresponding to the bright fringe i , the linewidth of the bright fringe is given by

$$d_x = \frac{\lambda f \cdot (1 - r^2) \cdot \sqrt{n^2 - \sin^2 i}}{\pi d r \cdot \sin(2i)}, \quad (3)$$

the above formula applies to equal-inclination interference. When the central bright spot appears at $i = 0$, its full width at half-maximum (FWHM) is

$$d_{x0} = 2nf \sqrt{\frac{b}{\Delta\varphi}}. \quad (4)$$

the above formula corresponds to an ideal FP cavity. Physically, the rate of phase detuning governs how rapidly the intensity of the central bright spot decays. It can provide references for parameter selection of systems equipped with modulation elements. This is because the fringe position is determined by the phase difference. Although inserting modulation elements into the FP cavity modifies the phase difference, the resulting system represents a more generalized form of the formula derived for the bare FP cavity. The fundamental analytical reasoning remains consistent, and only the factors inducing phase detuning are altered.

2.2. Complex-Pattern Formation

The characteristics of the interference field produced by the unmodified FP cavity are analyzed in the preceding sections. Although the device ingeniously achieves output with narrow linewidth through multi-beam interference, the spatial intensity distribution of its output is constrained by the phase-difference generation mechanism. Altering the lens surface profile can partially reshape the interference pattern while providing only limited degrees of freedom for modulation. Essentially, the phase difference is coupled with the tilt angle of the incident beam. Therefore, to generate complex aperiodic target optical-field distributions with the FP cavity, the key lies in independent tuning of the phase difference at different spatial positions through suitable variables.

Based on the above analysis, a straightforward approach is to convert the original equal-inclination interference into equal-thickness interference. For incident monochromatic plane waves, phase differences can be correlated with spatial positions by introducing deformation of the cavity surface. Nevertheless, this strategy suffers from several inherent drawbacks. First, cavity-surface deformation yields smooth, slowly varying spatial modulation, which introduces strong correlation in phase difference between adjacent spatial positions. Although aperiodic fringes can be produced, there is no guarantee that physically fabricable cavity-surface profiles exist for all target patterns. Second, surface undulation of the mirror alters the propagation direction of reflected light. Even for gently deformed cavity surfaces, the number of beams participating in effective interference decreases, which in turn broadens the resulting bright fringes.

According to the formula $\Delta\varphi = knd$, modifying the optical path difference constitutes the key to tuning the phase difference. Cavity-surface deformation adjusts the optical path by varying the cavity spacing. An alternative strategy modulates the optical path through refractive-index variation. HOEs based on photopolymers serve as well-suited phase-modulation components. After recording, such elements maintain constant material thickness, and phase difference, as well as the resulting intensity distribution, is modified by means of spatially varying refractive-index profiles. Although inserting modulation elements inside the FP cavity raises natural concerns regarding resonant-condition disruption, the influence introduced by the HOE can be reduced to an acceptable level. Resonance deterioration originates primarily from HOE-induced diffraction. When the cavity mirrors tightly enclose the HOE and the feature size of the refractive-index distribution is much larger than the wavelength, diffraction by the HOE can be neglected. Under normal incidence conditions of monochromatic light, the incident light at each spatial position can be approximately treated as the superposition of transmitted beams repeatedly phase-modulated by the local HOE. Accordingly, the phase difference between adjacent beams equals twice the accumulated phase of the HOE along the thickness dimension, namely, $\Delta\varphi = 4\pi d \cdot \Delta n / \lambda$. Here, d denotes the cavity thickness, and Δn represents the refractive-index variation of the HOE at this position relative to the pristine holographic-material refractive index.

Based on the preceding analysis, for the unmodified FP cavity operating under equal-inclination interference conditions, phase detuning arises from variations in the incident-beam tilt angle. After the HOE is introduced, the spatial variation of its refractive-index distribution becomes the source of phase detuning. Consequently, the rate of change of the HOE refractive-index distribution governs the linewidth. Taking the spatial coordinate of an arbitrary point as x_0 , the formula describing how linewidth varies with the refractive-index gradient is given by

$$d_{xh} = \frac{\lambda b}{4\pi d_{\text{hoe}} \left| d\Delta n / dx \right|_{x_0}}, \quad (5)$$

where d_{hoe} denotes the thickness of the HOE. When resonance occurs exactly at the extreme point of the refractive-index distribution, the linewidth formula reads

$$d_{xh0} = \sqrt{\frac{\lambda b}{\pi d_{\text{hoe}} |\Delta n''(x_0)|}}. \quad (6)$$

This equation indicates that steeper variation in refractive index yields narrower linewidth, which provides a basis for parameter selection. Whether such theoretical linewidth can be practically observed depends on the actual cavity finesse after HOE insertion as well as the frequency transfer capability of the detection system.

2.3. Optical Scheme Design

The above analysis clarifies the generation mechanism of narrow fringes and complex patterns. On this basis, the layout scheme of the optical path is designed. The ultimate design objective is to maximize fringe contrast on the plane where the photosensitive material resides, which requires the optical path to be arranged such that the photosensitive material sits at the localization plane. For an unmodified FP cavity operated under equal-inclination interference conditions, transmitted output light consists of parallel beams propagating along distinct directions. Its localization plane lies at infinity, and a lens must be introduced to shift this localization plane to the rear focal plane. For the equal-thickness interference mode under normal incidence conditions of monochromatic parallel light, the output field is theoretically non-localized. That means fringe contrast remains identical at all propagation depths. In an ideal scenario, the photosensitive material can therefore be placed at any position behind the equal-thickness FP cavity. Practical constraints nevertheless come into play. Perfectly parallel incident light is difficult to realize experimentally. Moreover, the introduced HOE brings a certain degree of divergence to outgoing light. When the FP cavity integrated with the HOE is analyzed as an assembly of numerous local wedge-shaped plates, the corresponding localization plane appears in the vicinity of the cavity mirror. Accordingly, the photoresist should be positioned as close to the cavity mirror as physically feasible.

Proximity lithography and projection lithography represent typical technical approaches within conventional lithography. Proximity lithography eliminates the demand for sophisticated optical systems, yet it is limited by diffraction effects and cannot achieve further reduction in feature size. Although projection lithography delivers superior resolution, it relies on complex projection optics. The pattern generation method described here constitutes a physically distinct alternative compared with conventional lithography. To facilitate in-depth understanding of its optical-path configuration and the factors governing fringe width, analogies with conventional lithography schemes are provided.

Considering the simplest model, for the unmodified FP cavity operating under equal-inclination interference conditions, although optical components analogous to those in a projection system are required at the output end, the constraint governing its achievable

fringe width differs fundamentally from that of projection lithography. Unlike projection lithography, where resolution is limited by objective numerical aperture cutting off target spatial frequency components, the constraint here originates from the effect of aperture size on the number of beams that participate in interference. This constraint is more lenient in comparison, and it accounts for the favorable capability of multi-beam interference to produce narrow fringes.

For configurations with the HOE embedded inside the cavity, physical behavior becomes more complex. One practical implementation, which may be analogized to proximity lithography, is illustrated in Figure 2a. Here, photoresist is placed in close proximity to the rear surface of the cavity. This configuration remains susceptible to diffraction effects. Even when cavity spacing is reduced to a small value, physical thickness of the HOE sets a lower bound for cavity length. Residual diffraction consequently produces a certain degree of broadening in output fringe width. Nevertheless, this optical layout delivers the most compact and straightforward architecture and represents the best candidate for practical application after optimization. A slightly modified alternative is presented in Figure 2b. A projection imaging system is placed downstream of the FP cavity, shifting the interference plane originally located near the cavity toward the image plane, where photosensitive material is positioned. This architecture shares similarities with projection lithography. Since the HOE is incorporated within the cavity, the system cannot bypass numerical aperture constraints as realized in the unmodified equal-inclination FP cavity. The achievable fringe width is ultimately bounded by the diffraction limit intrinsic to the imaging system. This renders the scheme unsuitable for final practical deployment. Though resolution enhancement techniques could be introduced, such additions would negate the inherent advantages of this method, namely, its compact layout and benefits originating from multi-beam interference. For this reason, this alternative is better suited as an inspection and observation tool for principle verification. A CCD sensor can be placed at the image plane. Repeated physical experiments with photoresist during cavity tuning are no longer required, and approximate evaluation of output optical-field performance can be obtained via imaging measurement.

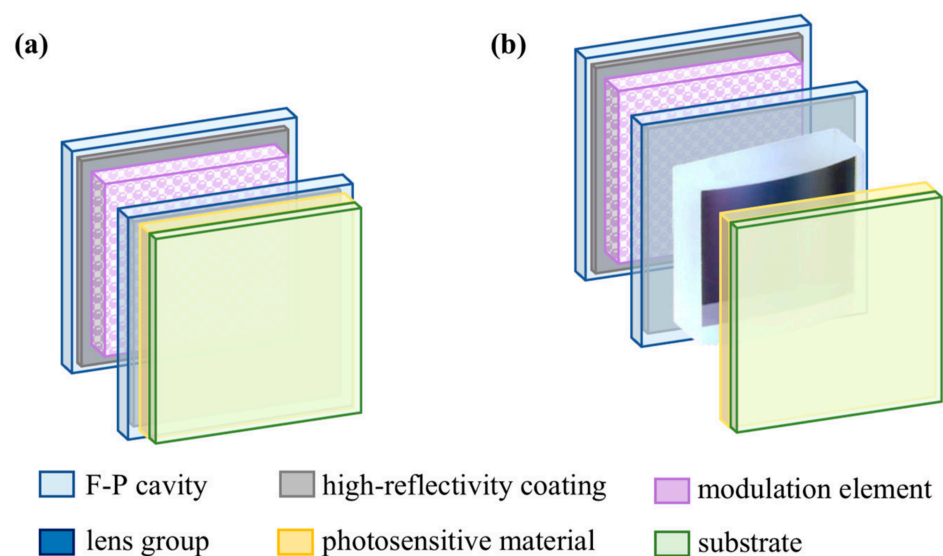


Figure 2. Schematic of optical configuration schemes. (a) Analogy to proximity lithography, where the photosensitive material is placed near the rear surface of the FP cavity. (b) Analogy to projection lithography, where the photosensitive material is located at the image plane of the imaging system.

3. Methods

3.1. Design of Periodic HOE

A local optical setup illustrated in Figure 3a is adopted to record the HOE with periodic refractive-index distribution. Two parallel recording beams strike the holographic material (Beijing Hope-Rainbow Technology Co., Ltd., Beijing, China) at a defined tilt angle, symmetric with respect to the surface normal. Interference takes place inside the material and produces a set of interference fringes oriented perpendicular to the material surface. The holographic material responds to the intensity distribution of these interference fringes and forms a sinusoidal refractive-index profile shown in Figure 3b. It should be specially noted that although the component is fabricated via holographic recording, it does not rely on the Bragg diffraction properties intrinsic to volume holograms. During actual device operation, incident light propagates along the direction normal to the holographic material surface, rather than following the beam angles applied in the recording. Accordingly, the recorded HOE can be interpreted as a periodic phase grating with finite thickness along the beam propagation direction.

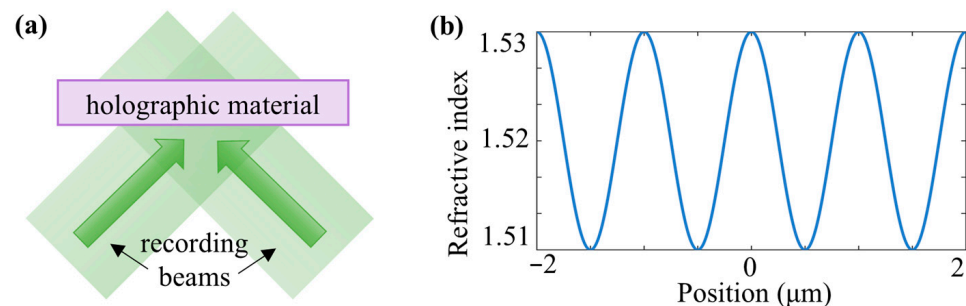


Figure 3. Schematic of the design procedure for the periodic HOE. (a) Partial schematic of the recording optical path for the periodic HOE. (b) Cross-sectional view of the refractive-index distribution inside the HOE.

During grating recording, phase modulation depth represents the most critical parameter. This quantity directly governs the total accumulated phase of light across the medium thickness, which in turn defines the positions where bright fringes form within the system. Phase modulation depth is primarily tuned by adjusting exposure time. At constant exposure power, the total exposure dose is determined by exposure time, and refractive-index modulation depth varies accordingly. Within the visible spectral range, the relationships between refractive-index modulation depth and the exposure dose follow a uniform trend for various working wavelengths, whereby refractive-index modulation depth increases gradually as the exposure dose rises. Once the exposure dose exceeds a certain threshold value, the growth of refractive-index modulation depth slows down and gradually approaches saturation. Experimental calibration of such curves is required under conditions of the practical optical setup.

3.2. Design of Aperiodic HOE

The design principle for the aperiodic HOE matches that of the periodic HOE, where specific refractive-index distributions within the medium are constructed according to target patterns. The holographic material can be treated as a volume of finite thickness, with refractive-index patterns oriented overall perpendicular to the material surface. Within each plane of the material cross-section, the spatial intensity distribution of the pattern sets the positions for constructive interference, while the target fringe width governs the gradient of refractive-index distribution. Both aspects together form the fundamental design principles.

As illustrated in Figure 4a, this process takes target intensity distribution as input to inversely compute the required refractive-index distribution, and multiple valid solutions can exist for one given intensity profile. Distributions within non-resonance regions allow room for optimization, where relevant regions can be adjusted to improve metrics such as contrast or uniformity. For preliminary design, however, the results derived from the two aforementioned basic design principles together with spatial continuity constraints can serve directly as initial values, with optimization reserved for subsequent processing steps. Since refractive-index distribution inside a photopolymer correlates with exposure intensity, designing the target refractive-index profile is equivalent to defining the corresponding exposure intensity. For convenience in numerical computation, the three-dimensional target intensity distribution is decomposed into successive two-dimensional slices, which are used to calculate the phase patterns loaded on a spatial light modulator (SLM) so that the expected three-dimensional intensity distribution can be reproduced within the optical setup shown in Figure 4b. Phase patterns loaded onto the SLM are optimized via the iterative algorithm presented in Figure 4c, with the physical model and optical layout as follows. A phase-only SLM (3840×2160 pixels, pixel pitch $3.74 \mu\text{m}$, Jasper Display Corp., Hsinchu, Taiwan, China.) is placed at the front focal plane of a $4f$ system, and a frequency-domain filter is placed at the Fourier plane; the $4f$ filtering is described by a Fourier-transform relation combined with spectrum multiplication. Light propagation, both in free space and inside the HOE, is modeled with the angular-spectrum method, where the refractive index of air is taken as 1 and the average refractive index of the HOE as 1.51. The HOE, $13 \mu\text{m}$ thick, is uniformly divided into 7 cross-sections along the z direction, with the sampling grid matched to the SLM pixel number. The target intensity is generated from the contour of a Chinese character, with a line profile consisting of a flat plateau and cosine-gradient edges. The layer intensities are compared with the target through a weighted total loss: $L = w_t \cdot L_{\text{target}} + w_z \cdot L_z + w_{bg} \cdot L_{bg}$, where L_{target} is the squared error between the layer intensities and the target, L_z quantifies the intensity uniformity among the layers, and L_{bg} suppresses the background in the dark regions. The optimization is initialized by 5 iterations of the multi-plane GS algorithm and then proceeds with the Adam optimizer (learning rate 0.04), with a fixed number of iterations used as the stopping criterion.

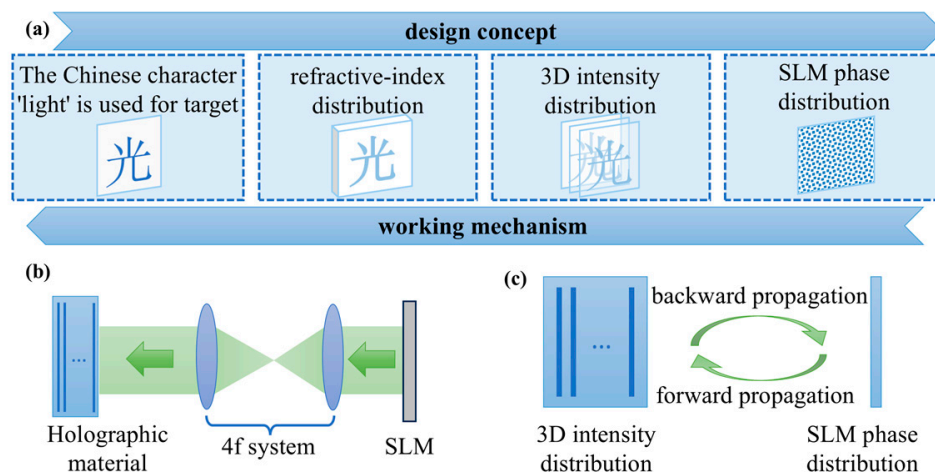


Figure 4. Schematic of the design procedure for an aperiodic HOE. (a) Design concept for aperiodic HOE. (b) Recording optical setup for aperiodic HOE. (c) Optimization algorithm for phase-distribution design.

4. Results

4.1. Verification Optical Setup

To verify the effectiveness of the above-described method, an experimental scheme together with its corresponding optical setup was devised. The overall layout of this optical path, as shown in Figure 5a, shares the same configuration introduced in Figure 2b. It aims to deliver approximate observation of output fringe width during preliminary cavity design by means of the imaging system. The core of the experimental optical setup consists of a sample holder mounted on a translation stage, with a microscopic imaging system assembled downstream comprising an infinity-corrected objective lens and a tube lens. A CCD is positioned at the output end of the tube lens for image acquisition. Collimated light serves as the input illumination for the sample. Different components can be loaded onto the sample holder. Relying on this single hardware configuration, the system can switch between distinct operating modes to fulfil a series of separate test functions.

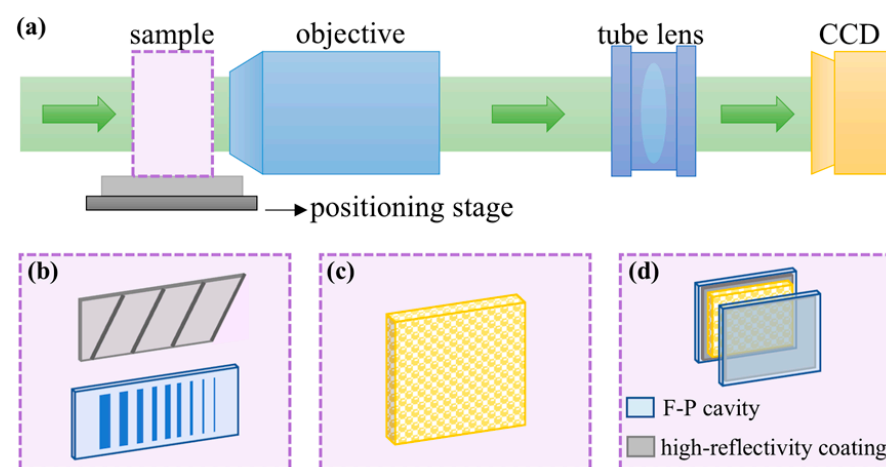


Figure 5. Schematic of the verification optical setup. (a) Overall observation optical path. (b) Blade and calibration target required for the calibration mode. (c) HOE sample required for the HOE observation mode. (d) FP cavity inserted with a HOE required for the fringe observation mode.

Optical components deployed in different operating modes are presented in Figure 5b–d, among which Figure 5b shows the blade and calibration target used for calibration mode, Figure 5c the HOE sample required for HOE observation mode, and Figure 5d the FP cavity with an embedded HOE for fringe observation mode. In calibration mode, multiple measurements are performed with a calibration target of known fringe width to generate response curves for determining the practical magnification of the complete microscopic imaging system. The HOE observation mode acquires structural information regarding the refractive-index distribution inside the element. Even though the HOE functions as a phase-only device, the rate of intensity change along the propagation direction is governed by phase gradient according to the transport-of-intensity equation, from which the phase structure can be retrieved using captured intensity distributions. In fringe observation mode, the fully assembled FP cavity is introduced into the optical path to characterize the practical fringe width produced by the cavity. As a microscopic imaging system is incorporated within this test setup, its intrinsic point-spread function (PSF) broadens the true fringe width, as discussed in earlier sections. The PSF can be obtained either experimentally via the knife-edge method or through numerical simulation, and the measured results can be processed by PSF subtraction or deconvolution. Fringe width obtained with this approach provides a reasonable estimate of true physical fringe width and reduces time overhead from physical photoresist experiments during cavity tuning. Meanwhile,

the microscopic imaging system magnifies native fringe features so that intrinsically fine fringes span multiple CCD pixels and prevent loss of fine details.

4.2. Simulation of Linewidths

To verify the pattern-generation capability of the proposed method, Figure 6 presents the simulation results for patterns produced by an optical cavity embedded with a HOE. Among these plots, Figures 6a–c and 6d–g correspond to the simulation results for periodic and aperiodic fringes, respectively. Figure 6a,e show cross-sectional views of the refractive-index distribution inside the HOE. Figure 6d presents the designed target of the aperiodic pattern. Figure 6b,f illustrate cumulative phase profiles of the HOE along the light propagation direction. Figure 6c,g give intensity distributions of patterns formed at the rear surface of the FP cavity after the HOE is inserted into the cavity.

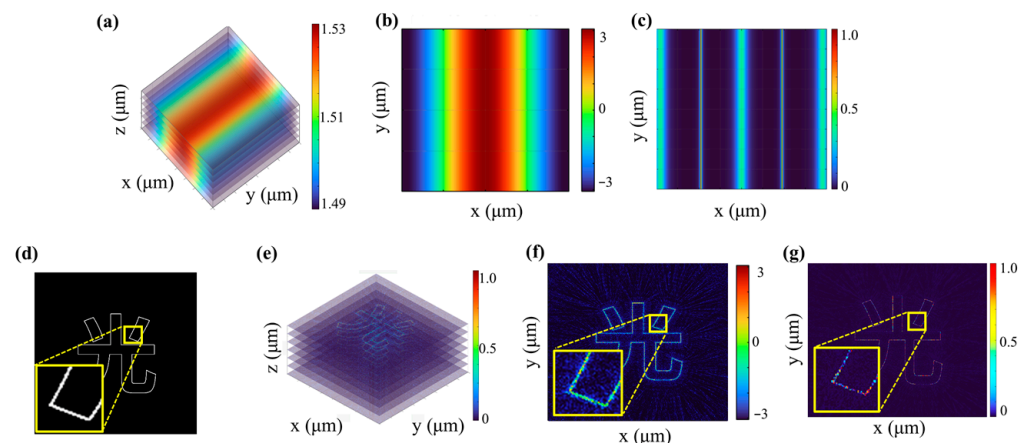


Figure 6. Simulation results of patterns generated by the optical cavity embedded with a HOE. (a) Cross-section view of the internal refractive-index distribution of the periodic HOE. (b) Accumulated phase of the periodic HOE. (c) Generated pattern after the periodic HOE is inserted into the FP cavity. (d) Target pattern. (e) Cross-section view of the internal refractive-index distribution of the aperiodic HOE. (f) Accumulated phase of the aperiodic HOE. (g) Generated pattern after the aperiodic HOE is inserted into the FP cavity.

Assuming an optical wavelength of 532 nm and cavity-mirror reflectivity of 90%, the physical length of the cavity matches the thickness of the holographic material, with 50 beams participating in interference, all of which can be obtained experimentally and remain coherent. For periodic fringes, the simulated fringe width reaches 41.9 nm, less than one-tenth of the operating wavelength. It is also worth noting that the theoretically achievable fringe width can be further reduced by raising cavity reflectivity and the effective number of interfering beams. Given sinusoidal refractive-index distribution $n(x) = \bar{n} + n_1 \cos(2\pi x/\Lambda)$ together with specified average refractive index $\bar{n} = 1.51$, refractive-index modulation depth $n_1 = 0.02$, wavelength $\lambda = 532$ nm, holographic-material thickness $d_{\text{hoe}} = 13$ μm and fringe spatial period $\Lambda = 3.39$ μm , the fringe width at the position of maximum phase gradient can be calculated to be approximately 18.5 nm according to Equation (5), which is the minimum fringe width obtained when the resonance occurs exactly at this position. This theoretical value is smaller than one-twentieth of the operating wavelength and defines the asymptotic lower bound for fringe-width reduction with current parameters in both simulation and experiment. Practical experimental fringe width is additionally affected by multiple factors, including loss introduced by the inserted modulation component, inter-mode coupling, accuracy of phase modulation depth, and the transfer function of the observation system. For aperiodic patterns, which are characterized by spatially varying and intricate structures, the structural similarity index measure (SSIM)

is introduced to objectively evaluate the reconstruction fidelity between the reconstructed intensity and the target outline. Over the entire reconstructed region, the SSIM is obtained by window-wise evaluation over all sliding windows. The resulting SSIM of approximately 0.34 is primarily attributed to intensity fluctuations in the background, rather than to poor reconstruction of the patterned features. When the target strokes are used as a binary mask to exclude the background, the SSIM computed within the strokes rises to approximately 0.95. The high masked value indicates that the reconstructed strokes themselves reproduce the target structure faithfully, whereas the lower full-field value is attributable to residual background intensity fluctuations rather than to errors in the pattern. Suppressing these background fluctuations through further optimization is identified as a direction for future work.

It should be noted that the present work is positioned as the proposal of a new concept, which is verified by simulation. Owing to the diffraction limit inherent to a microscopic imaging system, it cannot provide direct experimental verification of the achieved sub-wavelength linewidth; the optical setup described above therefore serves to confirm the correctness of the proposed idea during the parameter-tuning stage. A more direct verification would be to record the patterned field onto a high-resolution photoresist or a silver-halide dry plate, rather than imaging it through a microscope. The corresponding experimental results will be reported in our follow-up work. Lithography is inherently difficult to implement in practice, and the contributions of this work are to propose a new lithographic scheme, provide a detailed physical description and analytical derivation, and demonstrate by simulation that narrow linewidths on the order of one-tenth of the wavelength are achievable. The main advantage of this scheme is that, by exploiting multi-beam interference, it bypasses the diffraction-limited linewidth bottleneck inherent to other lithographic approaches. Although process refinement is still required, the associated optimization effort is substantially less demanding than that of conventional lithography.

5. Discussion

Driven by the urgent demand for narrow-linewidth performance in lithography, we propose a multi-beam holography approach based on an FP cavity. A HOE is introduced inside the FP cavity as a phase-modulating element. Linewidth compression of output fringes is realized through multi-beam interference, and target complex optical-field patterns can be generated by custom-tuning the internal refractive-index distribution of the HOE. The method presented in this paper operates under a principle distinct from conventional holographic lithography. In conventional computer-generated holography, the holographic mask and the target output pattern follow a many-to-many coupled mapping. A single pixel on the mask simultaneously modulates the light intensity at numerous positions in the target plane. Conversely, the optical field at any point on the target plane originates from the superposition of contributions from a large number of mask units. Although this strong coupling characteristic delivers a certain defect tolerance, it intrinsically limits design accuracy and makes noise suppression challenging. Furthermore, outputs from conventional computer-generated holography are constrained by light propagation. Whether adopting a projection optical path or free-space propagation, low-pass filtering effects eliminate high-frequency components of the optical field. Since target patterns are composed of diverse spatial-frequency components, the loss of high-frequency information induces critical degradation of key metrics such as linewidth. By contrast, the FP resonant-cavity scheme with an integrated intra-cavity HOE physically decouples the strong coupling between the mask and the target optical field. Relying on the divided-amplitude multi-beam interference mechanism of the FP cavity under weak diffraction conditions, the frequency-domain design problem is transformed back into the spatial domain. Linewidth broadening caused

by propagation is suppressed, and the spatial field can be modulated independently and with high precision at every point on the output plane.

For the proposed scheme, the key issue is how many output beams effectively participate in the interference, which calls for a discussion of several practical limitations. Multi-beam interference requires the successive output beams to remain mutually coherent, which is the physical basis for achieving narrow linewidths. Since the cavity spacing is on the micrometer scale, the longest path traveled by the interfering beams does not exceed 1 mm, which is far below the coherence length of typical solid-state lasers. More critical than this, however, is controlling the intracavity loss so that as many output beams as possible have comparable intensities, thereby increasing the number of beams that contribute to high-contrast interference. The HOE loss is the dominant source of intracavity loss, arising mainly from absorption by the material and substrate and from modulation by the internal microstructures of the material. If the single-pass transmission coefficient of the HOE is denoted by τ , the round-trip factor changes from r^2 to $r^2\tau^2$ compared with an ideal FP cavity, and the effective reflectivity can be defined as $r\tau$. This means that the HOE loss is equivalent to a reduction in the mirror reflectivity, which lowers the cavity finesse and broadens the linewidth. Nevertheless, the proposed method exhibits favorable expandability. On the basis of the core concept, the HOE can be replaced by other novel elements to further reduce intra-cavity loss and increase modulation degrees of freedom. Dynamic modulation elements can also be deployed for batch generation of diverse patterns, laying a foundation for scanning and stitching of large-area patterns. Even the cavity itself may be substituted by static or dynamically modulated components with sufficiently high reflectivity to further simplify system configuration. Benefiting from its compact optical layout and low cost, the proposed scheme provides a promising practical route for lithography applications.

6. Conclusions

In summary, we demonstrate an effective strategy for generating lithographic patterns based on the principle of multi-beam holography. The main innovation of this work lies in a compact optical cavity. Phase modulation is introduced by inserting a HOE inside the high-reflectivity coated cavity mirror. It enables non-periodic patterns with controllable line positions while achieving sub-wavelength linewidth, breaking the periodic limitation of conventional holographic interference lithography. The core idea that opens up a new route for lithography originates from the unique beam-modulation properties of the FP cavity. This approach exploits the intrinsic physical properties of light with minimal modulation effort to achieve remarkable performance, rather than manually intervening in every pattern-generation step. This constitutes the physical basis for system simplification in the proposed scheme. This work presents a novel optical control strategy for lithographic pattern generation, featuring a compact optical layout and high integration level. With further advances in optical devices and materials, it offers an entirely new route to high-precision patterning, with promising applications in advanced manufacturing such as integrated circuits.

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Abbreviations

The following abbreviations are used in this manuscript:

FP	Fabry–Pérot
HOE	holographic optical element
FWHM	full width at half-maximum
SLM	spatial light modulator
PSF	point-spread function
SSIM	structural similarity index measure

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