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# Nonlinear interferometric lithography for arbitrary two-dimensional patterns

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**Abstract.** A new, relatively simple experimental technique for generating arbitrary, two-dimensional patterns with high visibility and higher resolution than allowed by the Rayleigh criterion has been developed. The theoretical and experimental details of the method, based on repeated phase-coherent interference of four beams on a multiphoton absorber, are described. A sample pattern generated by numerical computer simulation of the technique is also shown. [DOI: 10.1117/1.2838591]

Subject terms: nonlinear optics; lithography; interference.

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## 1 Introduction

The constant push in the integrated circuit industry to generate smaller features for next-generation computer chips has caused great interest in improved lithographic techniques. Traditionally, however, it was believed that for a given wavelength used to write the patterns, the ultimate limit to the feature size was given by the Rayleigh criterion.[1] For many years the techniques faced more practical limitations than the physical limitation imposed by Rayleigh's criterion, but technology has now reached the level to meet this limit.[2] Thus, it is commonly viewed that the primary option to reduce feature sizes further involves going to shorter wavelengths. As optical lithography has already approached the lower wavelength limits, this would leave the next alternative seemingly to switch to electron beam or x-ray lithography, both of which are very costly and have many practical drawbacks at this time. Therefore, there is great interest in developing new techniques to bypass the Rayleigh criterion, allowing the integrated circuit industry to continue to make major advances without the costly need to abandon optical lithography on which it is always depended.

In the past several years, such techniques began to be developed, all relying on materials that absorb multiple photons at a time, rather than one at a time as was traditional.[3–13] Although some of the earliest proposals were classical,[3–5] most of the attention has been given to quantum lithography. Although it is interesting because of the special properties it could provide, it does not seem practical for use in industry in the near future. Therefore, working with R. W. Boyd, I previously developed a new classical technique,[14,15] which improved on an earlier method.[3]

In the current study, a simple-to-implement technique has been developed to generate arbitrary, two-dimensional lithographic patterns with a resolution better than that allowed by the Rayleigh criterion. The primary physics behind the technique is based on a one-dimensional method to write fringes developed previously by Boyd and myself, but in the current implementation has been significantly improved for practical use in the integrated circuit industry by allowing for any desired two-dimensional pattern to be written at extremely high resolutions with high production speeds and low production costs. These features could make it of immediate and great interest to the integrated circuit industry.

The technique previously developed[14,15] (on which the new technique to be described here is physically based) was one of one-dimensional, classical, nonlinear interferferometric lithography. The primary idea is to interfere two beams on a $N$-photon absorbing lithographic substrate. This is repeated $M$ times (with $M \leq N$), each time increasing the relative phase between the two beams by $2\pi/M$. This results in canceling the undesired low-resolution features and leaving only features with a resolution $M$ times better than that allowed by the Rayleigh criterion. One initial concern with all of the classical techniques such as this is the resulting pattern visibility. If one lets $M=N$ to achieve the maximum possible resolution enhancement, the visibility quickly degrades beyond a useful level for increasing $N$. However, as long as $N$ is significantly larger than $M$, a high visibility is always possible. Although the original study[14] used harmonic generation to simulate multiphoton absorption due to the lack of high-quality multiphoton absorption, it is important to note that recently the experiment was carried out using true multiphoton absorbers.[16] The technique, as originally described, was limited to one-dimensional patterns (and in fact primarily only to very simple one-dimensional patterns for any practical implementation). The technique developed below introduces a new method that keeps the advantages of the previous technique, but with major improvements that should make it immediately attractive to the integrated circuit industry.

## 2 Method

The method described here makes it relatively simple to write an arbitrary, two-dimensional pattern using nonlinear, classical interferometric lithography. The method creates the pattern using a collection of $M \times M$ "pixel" arrays. You can control which pixels are "on," including turning them only partially on to control relative feature heights, and you can shift them by any amount horizontally and/or vertically from their basic grid location. The defining equation of the resulting electric field for a single $M \times M$ array is

$$E_{s,t} = A_{s,t}[e^{i\delta_{s,t}}(e^{ikx} + e^{-ikx}e^{i\phi_s}) + e^{iky} + e^{-iky}e^{i\theta_t}], \tag{1}$$

where $A_{s,t}$ is the relative strength of the pixels, $k=2\pi/\lambda$ is the wavevector, and $\delta_{s,t}=g+(\phi_s+\theta_t)/2$ is the relative phase between the $x$ and $y$ components, with $\phi_s=2\pi s/M$ and $\theta_t=2\pi t/M$ being the needed phase shifts in the $x$ and $y$ directions, and $g$ is an additional phase factor used to control phases of adjacent $M \times M$ arrays. Even though the phases and amplitudes to be imposed on each of the four beams can be directly seen from Eq. (1), the electric field can also be written as

$$E_{s,t} = 2A_{s,t}[e^{ig}\cos(kx - \phi_s/2) + \cos(ky - \theta_t/2)], \tag{2}$$

with the resulting intensity (for single-photon detection) being

$$\begin{aligned} {}_1I_{s,t} = A_{s,t}(2 &+ \cos(2kx - \phi_s) + \cos(2ky - \theta_t) + 2\cos(g) \\ &\times\{\cos[k(x-y) - \phi_s + \theta_t] + \cos[k(x+y) - \phi_s - \theta_t]\}). \end{aligned} \tag{3}$$

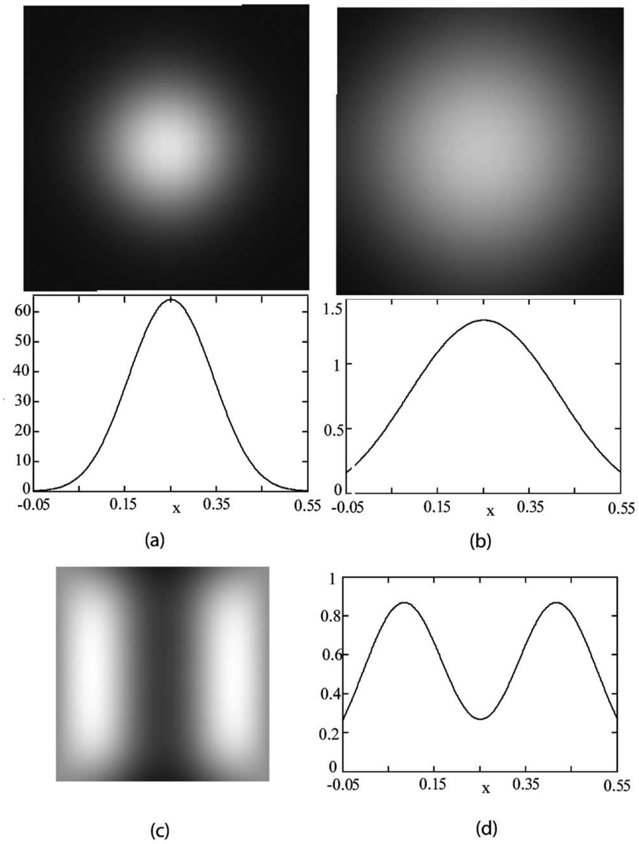
Thus, well-defined pixels are generated due to the overlap of four peaks at the desired location (not two as you would have with incoherent $x$-$y$ addition). The total deposition on a $N$-photon absorber is given by a two-dimensional sum over the grid

$$I(x,y) = \sum_{s=1}^{M}\sum_{t=1}^{M}[{}_1I_{s,t}]^N. \tag{4}$$

Note that this method is not merely a combination of two one-dimensional patterns. It is truly a coherent interference of the two dimensions. Simply adding intensities in two dimensions by the technique described in Ref. 14 would lead to low visibilities and reduced resolutions. The coherent interference, however, produces localized points, or the pixels of the pattern to be created. Thus by specifying the coefficients, one can create an arbitrary, high-resolution pattern pixel by pixel.

## 3 Results

Figure 1 explores the resolution and visibility possible by the method described above through the results of numerical simulation. To show the increased visibility, in Figs. 1(a) and 1(b), the smallest resolvable spots possible with this technique (for $M=3$) are compared to the smallest possible spot possible with standard interference (i.e., $M=1$). It is clear that the spot in Fig. 1(a) is much sharper, with the graph showing the full width at half maximum of the spot generated by the current technique being 1.7 times smaller than that generated traditionally. This implies that for two dimensions, the density of elements can be increased by a factor of 3. The visibility possible with the technique is shown in Figs. 1(c) and 1(d). Two $1 \times 3$ lines are shown, with a visibility of 53% and a separation that is much smaller than that possible for standard Rayleigh-limited interference (approximately the 1.7 shown possible above).



(a) (b)

(c) (d)

**Fig. 1** Demonstration of resolution and visibility of technique with simulated patterns with $M=3$. Horizontal scales shown are in fractions of a wavelength. (a) Smallest resolvable spot with technique (top) and one-dimensional graph (bottom). (b) Smallest resolvable spot without nonlinearities (top) and one-dimensional graph (bottom). The pattern in (a) has 1.7 times higher resolution than the pattern in (b). (c) Two $1 \times 3$ lines with standard spacing. (d) Graph of pattern in (c), showing a visibility of 53%.

The portion of the method described above is for generating one $M \times M$ array. However, any number of these arrays can be generated in parallel by impressing the amplitude and phase factors to appropriate portions of the beam (that is, use spatial modulation across the beam, with each region of modulation becoming one area in which a $M \times M$ array will be created). In total, one generates an array of arrays. Although there are many ways one could impress the amplitude and phase structure on the beam, if it is desired to implement this in a fast, repeatable method with a large number of arrays generated in parallel across the beam, spatial light modulators (SLMs) could be an ideal choice.

Figure 2 shows a basic configuration for implementation of the beam preparation portion of the method. First, the amplitude structures for the first pixels ($A_{s,t}$) are imposed on each of the spatial regions by SLM1. The beam is then split into two, with one to carry the horizontal ($x$) information, and the second to carry the vertical ($y$) information. The relative phase between the $x$ and $y$ components ($\delta_{s,t}$) is imposed on the $x$ beam with SLM2. Each of the beams is then again split in two. (Note that the $y$ beam is split vertically rather than horizontally.) For one of the two $x$ beams

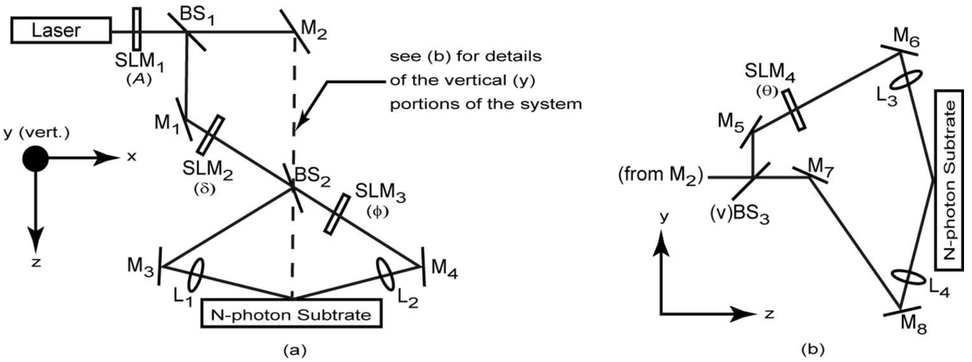


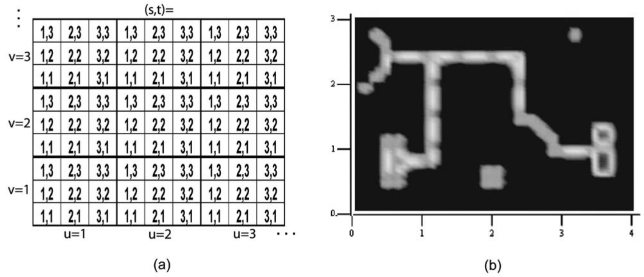
**Fig. 2** (a) Basic configuration of the technique. SLM=spatial light modulators, BS=beamsplitters, M=mirrors, and L=lenses. The dashed line denotes the overlapping *y* beams and components, shown in (b). Details are described in the text. (b) The vertical beams and corresponding components of the system configuration.

and one of the two $y$ beams, the final phase factors ($\phi_s$ for $x$ and $\theta_t$ for $y$) are imposed with SLM3 and SLM4. Throughout this preparation stage, the beam can be large and the spatial regions can correspondingly be large (with current SLM technology having resolutions on the order of microns). Each of the four beams is then imaged onto the multiphoton absorbing material in which the pattern is recorded. The $y$ beams are brought in to interfere in a vertical manner, and the $x$ beams in a horizontal manner, with each of the four beams reaching the recording material at the same point and time. The multiphoton absorbing substrate is placed in the $x$-$y$ plane, with $z$ being the depth into the substrate. The imaging is such that each spatial region is as small as allowed by diffraction, or approximately 0.5 wavelengths. This will result in maximum resolution. (Note that the resolution of each $M \times M$ area is independent of the imaging; it is only the "tight-packing" of the array of these arrays that is determined by the imaging, thus affecting the overall pattern-writing capability.) The above process is repeated $M^2$ times (for each combination of $s$ and $t$) such that all pixels are written for each array.

Figure 3(a) shows the basic layout of the "pixels within pixels" created by the technique described above. The regions of a particular $u$ and $v$ combination correspond to a given element of the SLM, and thus the only limit to the number of large pixels is the number of elements in the SLM (and increasing this number does not add appreciable time or complexity, because they are processed in parallel). Notice that, effectively, the $3 \times 3$ subpixel array shown (for $M=3$) is generated by the interferometric technique described, but the combination of these arrays is a "quasi-mask" technique, using the various regions of the SLMs as programmable masks. Thus at the interface of these elements the limit is diffraction, but due to the multiphoton absorption these features are also sharpened. An example of the type of pattern that can be created is shown in Fig. 3(b). The pattern shown is 4λ wide by 3λ high. Notice that lines, small spots, and even diagonals are trivially possible with the method. Also, because the SLMs have very fast response times, a complete pattern such as the example shown in Fig. 3(b) could be written thousands of times each second. Figure 3(c) gives the values of the $A$ coefficients [in the matrix form given in Fig. 3(a)] needed to generate the pattern shown.

## 4 Conclusions

A technique is presented that allows for generation of arbitrary, high-resolution two-dimensional lithographic patterns in an inexpensive and simple-to-implement method. It is important to note that the technique, though it requires precise alignment as does any critical imaging technique, does



| ⋮ | (s,t)= | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1,3 | 2,3 | 3,3 | 1,3 | 2,3 | 3,3 | 1,3 | 2,3 | 3,3 |
| v=3 | 1,2 | 2,2 | 3,2 | 1,2 | 2,2 | 3,2 | 1,2 | 2,2 | 3,2 |
| | 1,1 | 2,1 | 3,1 | 1,1 | 2,1 | 3,1 | 1,1 | 2,1 | 3,1 |
| | 1,3 | 2,3 | 3,3 | 1,3 | 2,3 | 3,3 | 1,3 | 2,3 | 3,3 |
| v=2 | 1,2 | 2,2 | 3,2 | 1,2 | 2,2 | 3,2 | 1,2 | 2,2 | 3,2 |
| | 1,1 | 2,1 | 3,1 | 1,1 | 2,1 | 3,1 | 1,1 | 2,1 | 3,1 |
| | 1,3 | 2,3 | 3,3 | 1,3 | 2,3 | 3,3 | 1,3 | 2,3 | 3,3 |
| v=1 | 1,2 | 2,2 | 3,2 | 1,2 | 2,2 | 3,2 | 1,2 | 2,2 | 3,2 |
| | 1,1 | 2,1 | 3,1 | 1,1 | 2,1 | 3,1 | 1,1 | 2,1 | 3,1 |
| | | u=1 | | | u=2 | | | u=3 | · · · |

(a)

(b)

$$\begin{pmatrix}
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&1&0&0&0&0\\
0&0&1&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&1&1&1&1&1&1&1&1&1&1&1&1&0&0&0&0&0&0&0&0&0\\
0&0&1&0&0&0&1&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0\\
0&1&0&0&0&0&1&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0\\
1&0&0&0&0&0&1&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&1&0&0&0&0&0&0&0&1&0&0&0&0&0&0&0&0&0\\
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0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0\\
0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0&0
\end{pmatrix}$$

(c)

**Fig. 3** (a) A schematic showing how the "pixels within pixels" are arranged for $M=3$. Each small $3 \times 3$ region (particular $u$ and $v$) is $0.5\lambda \times 0.5\lambda$, as the images from Fig. 2, with the subpixels being $\lambda/6 \times \lambda/6$. The $(s,t)$ values are limited from 1 to $M$ and are stepped through serially, and the $(u,v)$ values are only limited by the SLM and are processed simultaneously in parallel for each $(s,t)$. (b) Example of an arbitrary simulated pattern from the described method for $M=3$. The scales are in number of wavelengths. A $8 \times 6$ spatial array of the $3 \times 3$ subarrays was used, generating an overall pattern of $24 \times 18$ pixels ($4\lambda \times 3\lambda$) total for the image shown. (c) The values of the $A$ coefficients for the pattern of (b) in a matrix form as defined in (a).

not require any nonstandard equipment beyond multiphoton absorbers. Also, no complicated algorithm is needed to determine the needed phase and amplitude coefficients for any given pattern—it is simply a trivial mapping of pixel information from a desired pattern. The most difficult experimental challenge is expected to be maintaining proper alignment of what is effectively a four-beam interferometer. The ultimate limiting factor of the technique is the availability of appropriate multiphoton absorbing materials, but these are continually being engineered.[16,17] Due to these qualities, it is believed that unlike previous proposals, this technique could be useful for implementation by the integrated circuit industry.

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