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(54) **LITHO-AWARE SOURCE SAMPLING AND RESAMPLING**

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G03F 7/20 (2006.01)

(52) **U.S. Cl.**
CPC ***G03F 7/70441*** (2013.01); ***G03F 7/70025*** (2013.01)

(58) **Field of Classification Search**
CPC .. G03F 7/70441; G03F 7/70025; G03F 7/705; G03F 1/36
See application file for complete search history.

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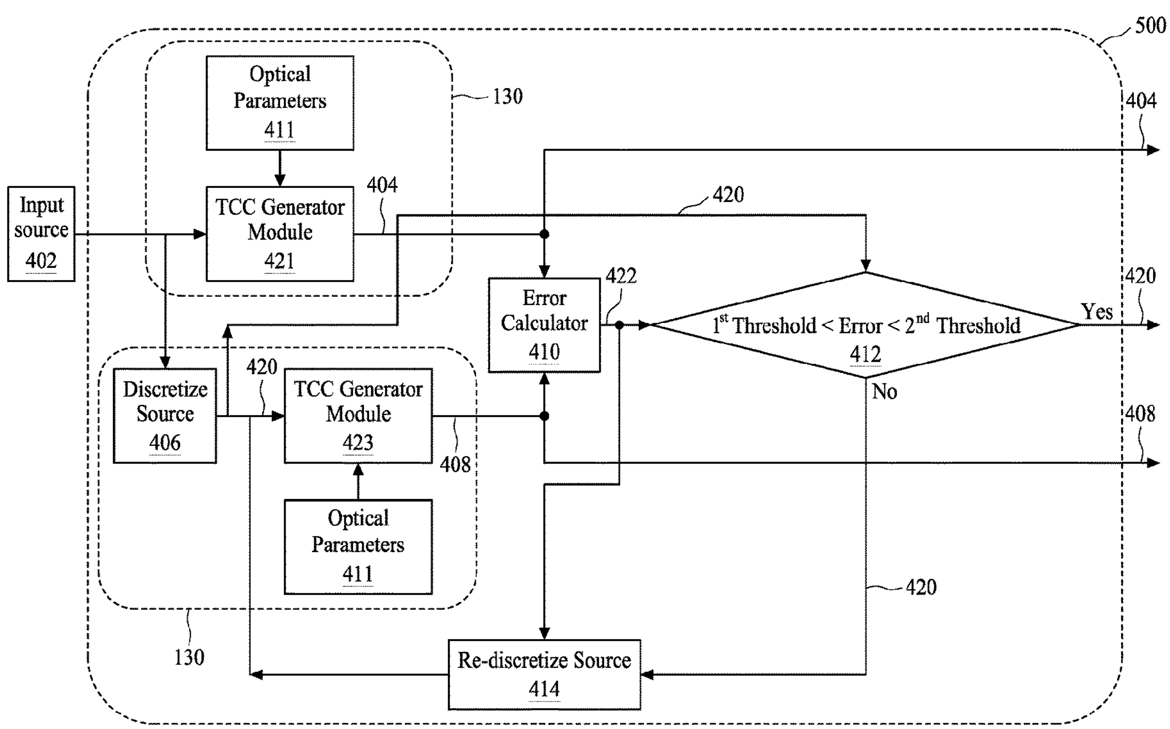
(57) **ABSTRACT**

A method includes determining a first transmission cross coefficient (TCC) operator of an optical system of a lithographic system based on an illumination source. The method includes sampling the illumination source by a first number of sampling points to produce a first discrete source and determining a second TCC operator based on the first discrete source. The method also includes determining an error between the first TCC operator and the second TCC operator. The method includes recursively adjusting the first number of sampling points to re-sample the illumination source and to re-determine the second TCC operator until the error is below a threshold level and a final discrete source and a final second TCC operator is determined.

20 Claims, 18 Drawing Sheets



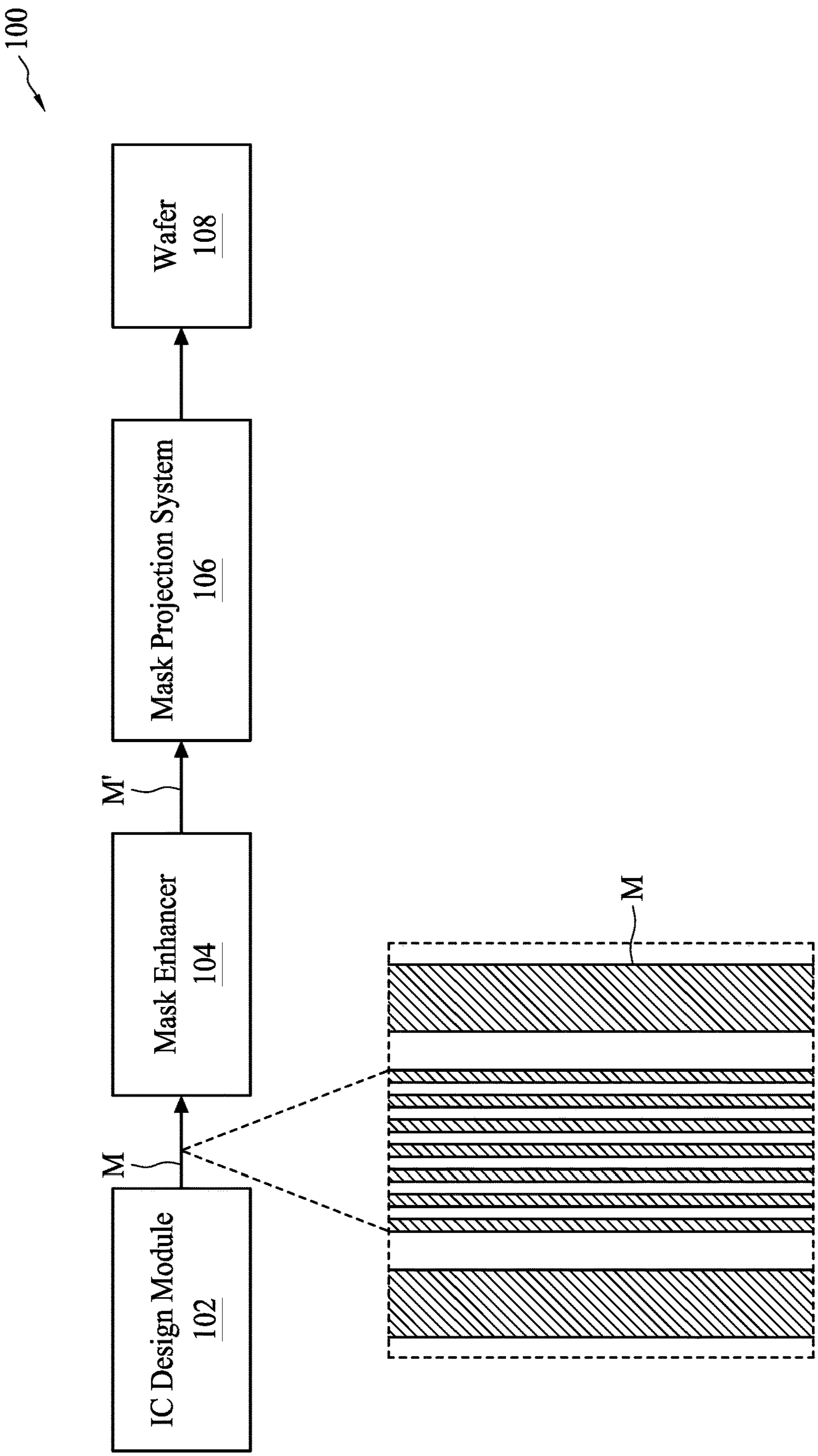

100
IC Design Module
102
M
Mask Enhancer
104
M'
Mask Projection System
106
Wafer
108
M

FIG. 1

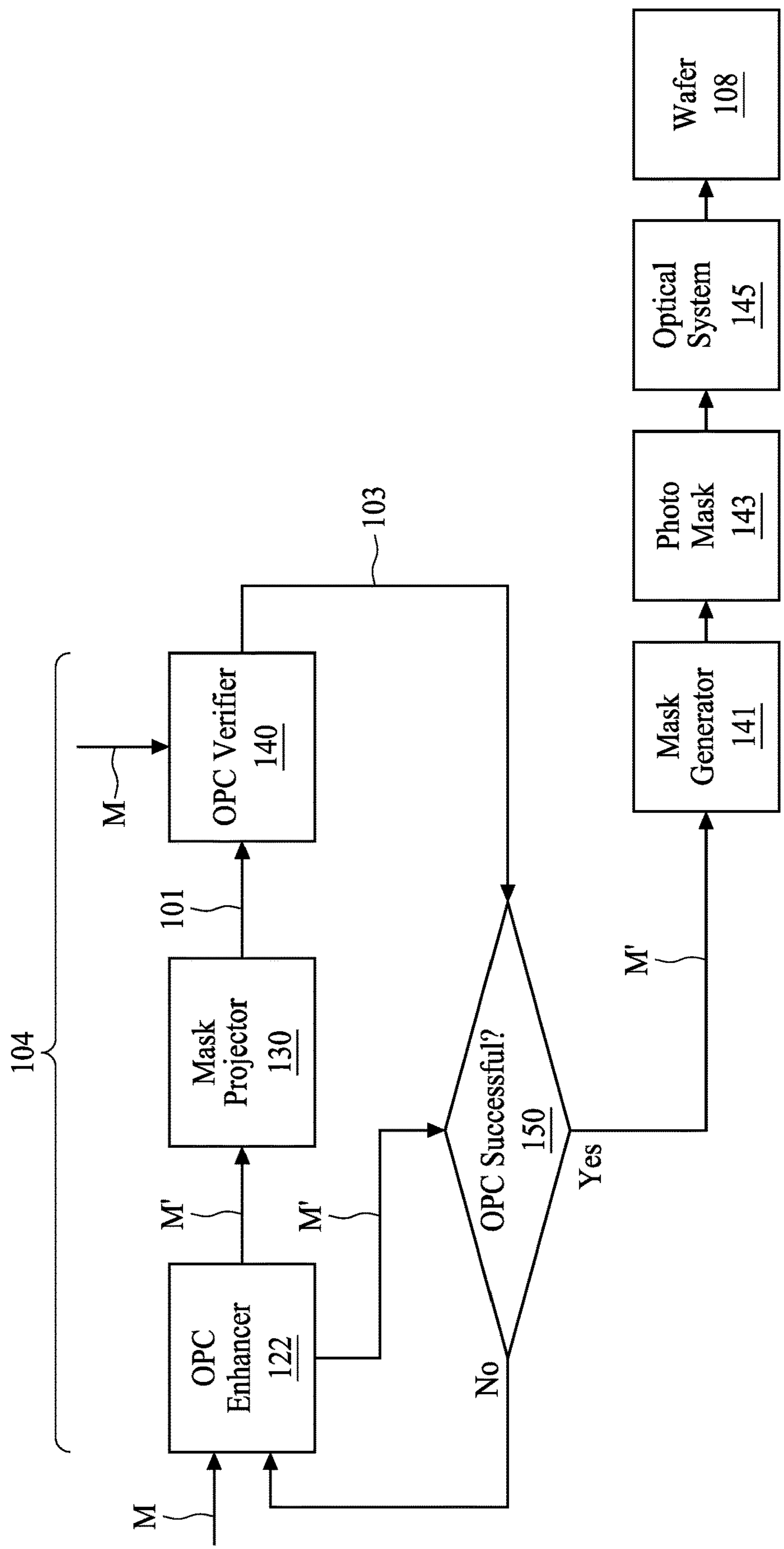

104
OPC Enhancer 122
Mask Projector 130
OPC Verifier 140
M
M'
101
103
OPC Successful? 150
No
Yes
Mask Generator 141
Photo Mask 143
Optical System 145
Wafer 108

FIG. 2A

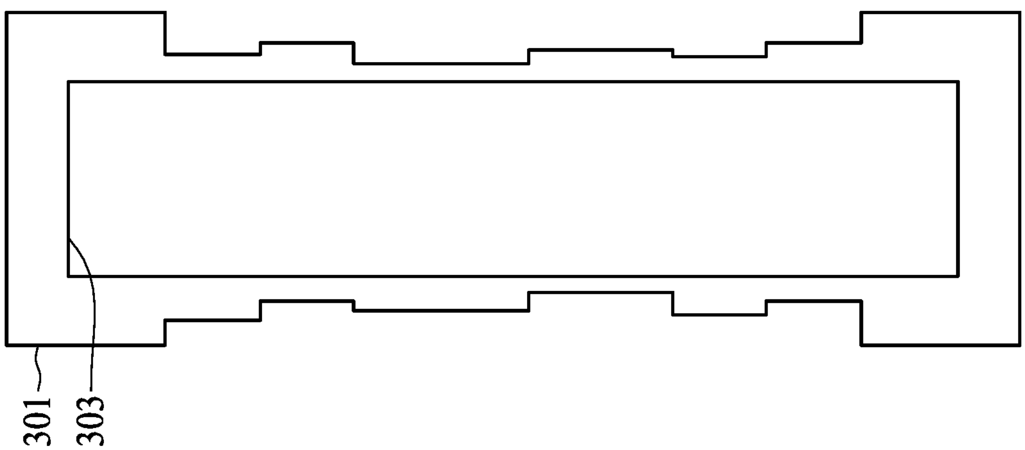


FIG. 2B

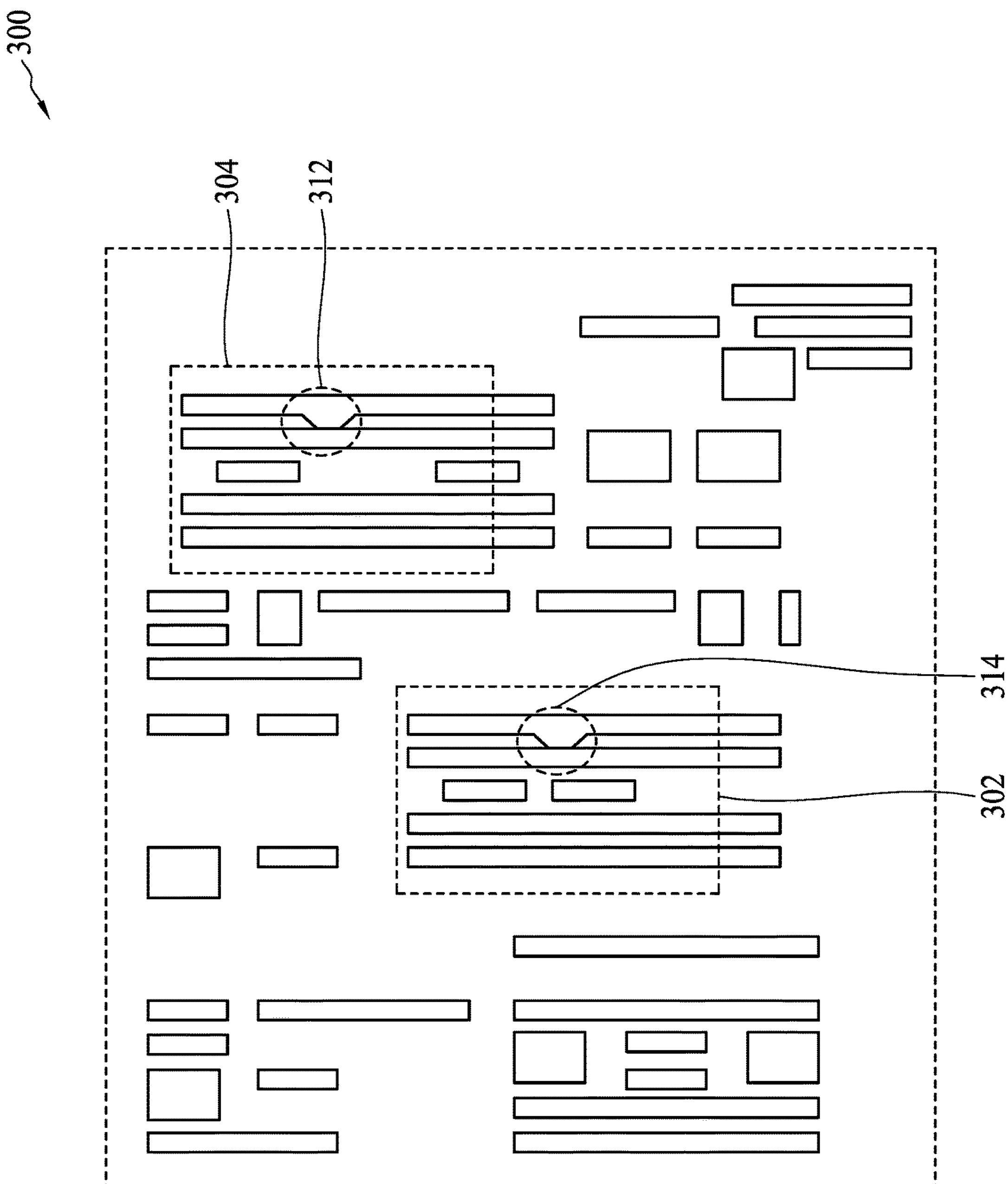


FIG. 3

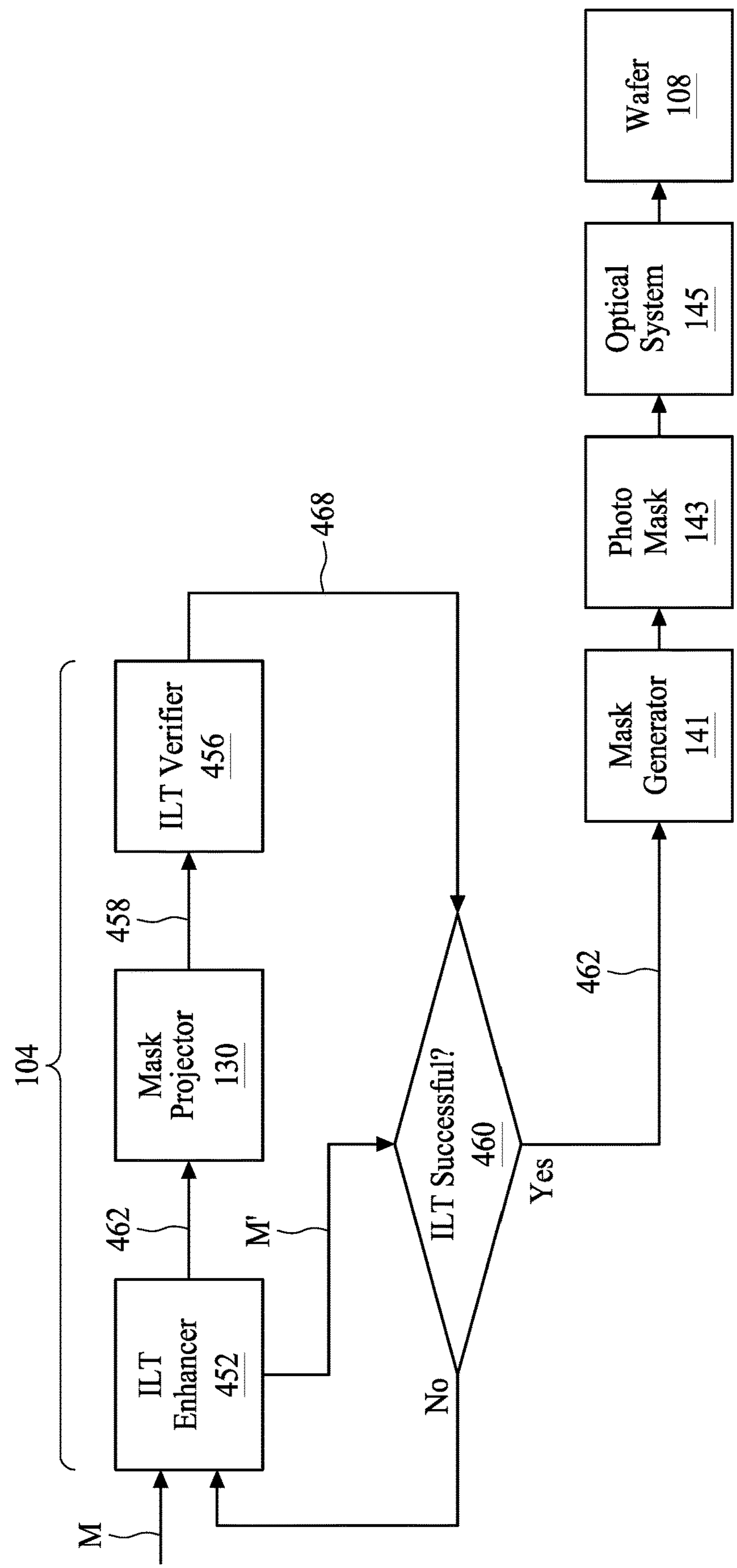

104
M
ILT Enhancer 452
462
Mask Projector 130
458
ILT Verifier 456
468
M'
ILT Successful? 460
No
Yes
462
Mask Generator 141
Photo Mask 143
Optical System 145
Wafer 108

FIG. 4

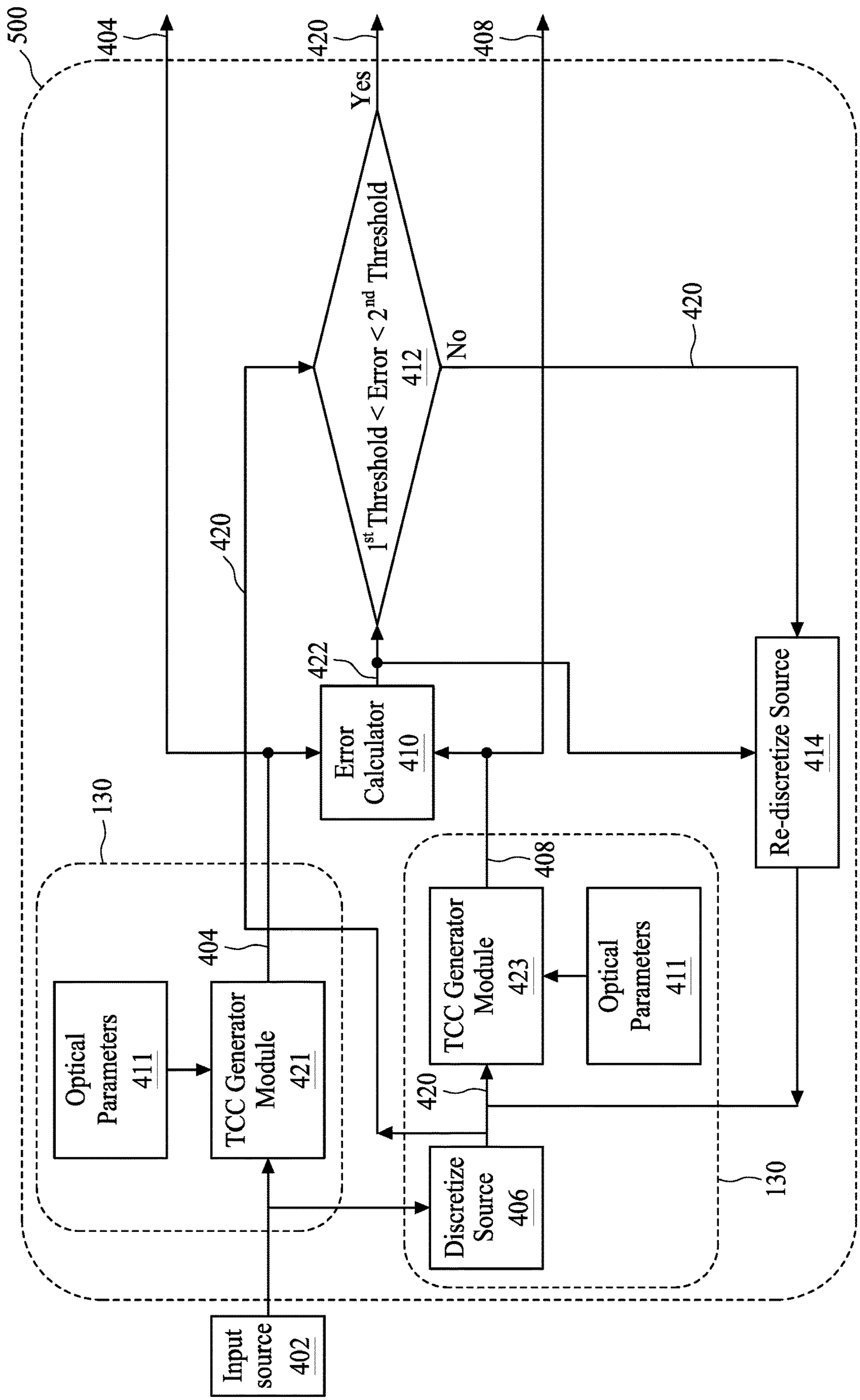

500
404
420
408
Yes
1st Threshold < Error < 2nd Threshold
412
No
420
420
422
Error Calculator
410
Re-discretize Source
414
130
Optical Parameters
411
TCC Generator Module
421
404
408
TCC Generator Module
423
Optical Parameters
411
420
Discretize Source
406
130
Input source
402

FIG. 5

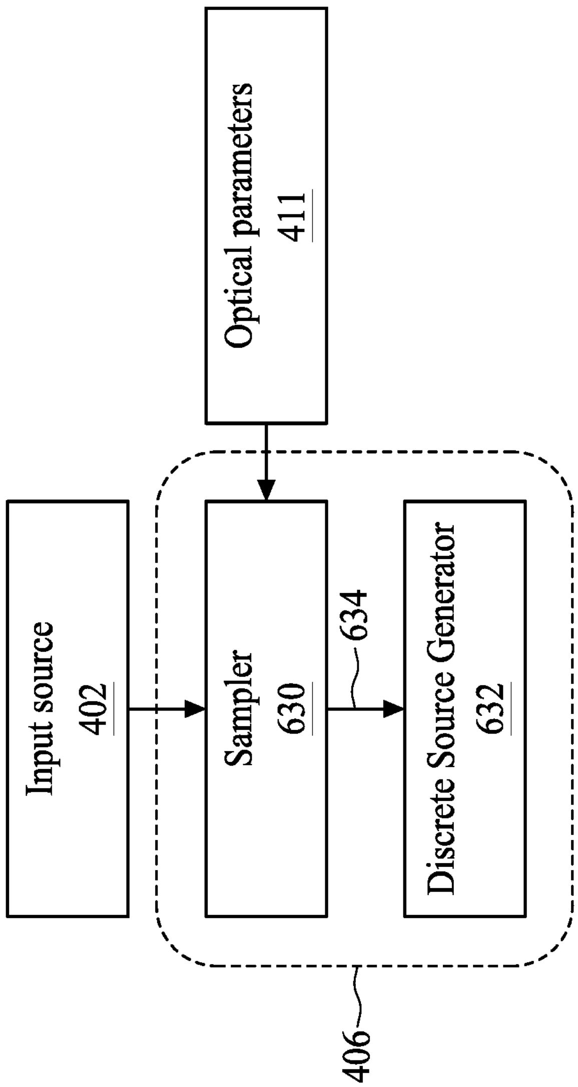

Optical parameters
411
Input source
402
Sampler
630
634
Discrete Source Generator
632
406

FIG. 6A

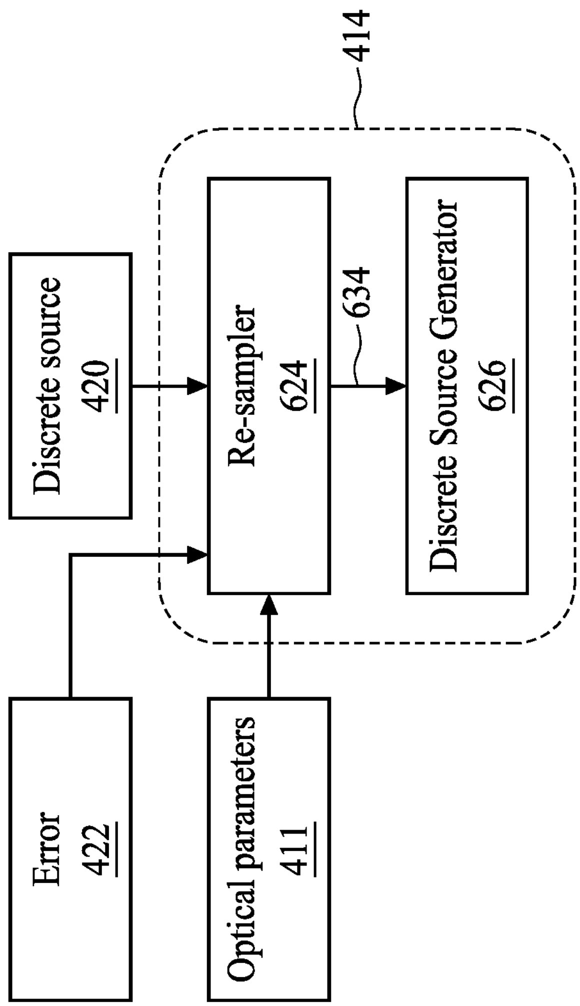

414
Discrete source
420
Re-sampler
624
634
Discrete Source Generator
626
Error
422
Optical parameters
411

FIG. 6B

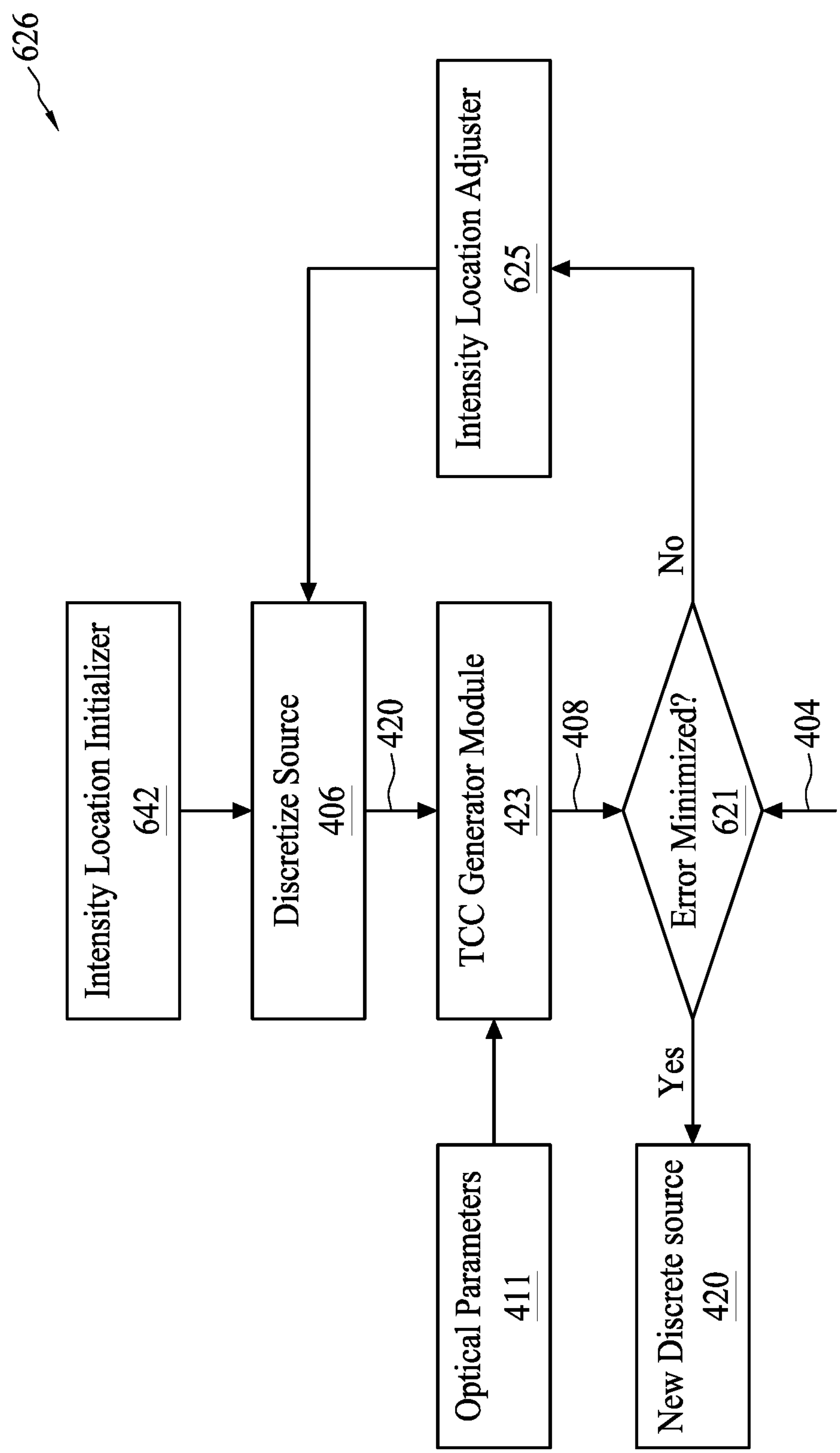

626
Intensity Location Adjuster
625
Intensity Location Initializer
642
Discretize Source
406
420
TCC Generator Module
423
408
Error Minimized?
621
404
No
Yes
Optical Parameters
411
New Discrete source
420

FIG. 6C

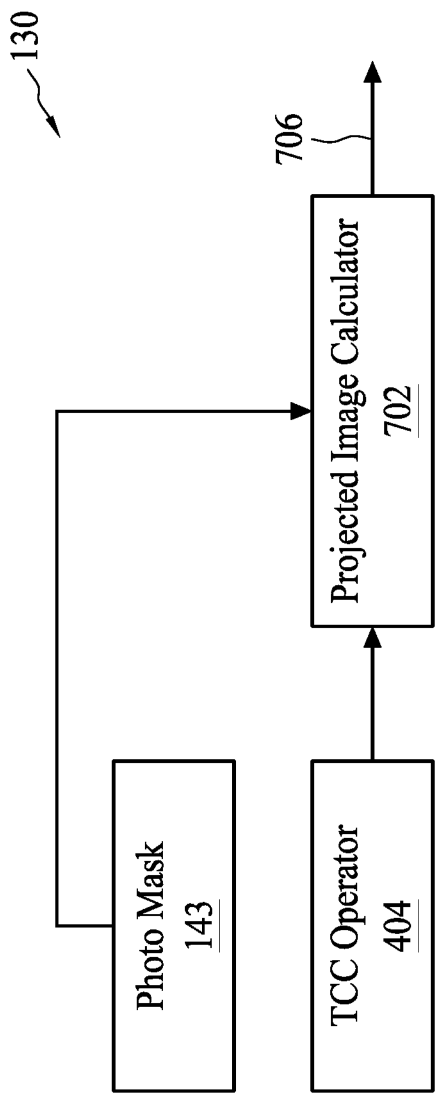

130
706
Projected Image Calculator
702
Photo Mask
143
TCC Operator
404

FIG. 7A

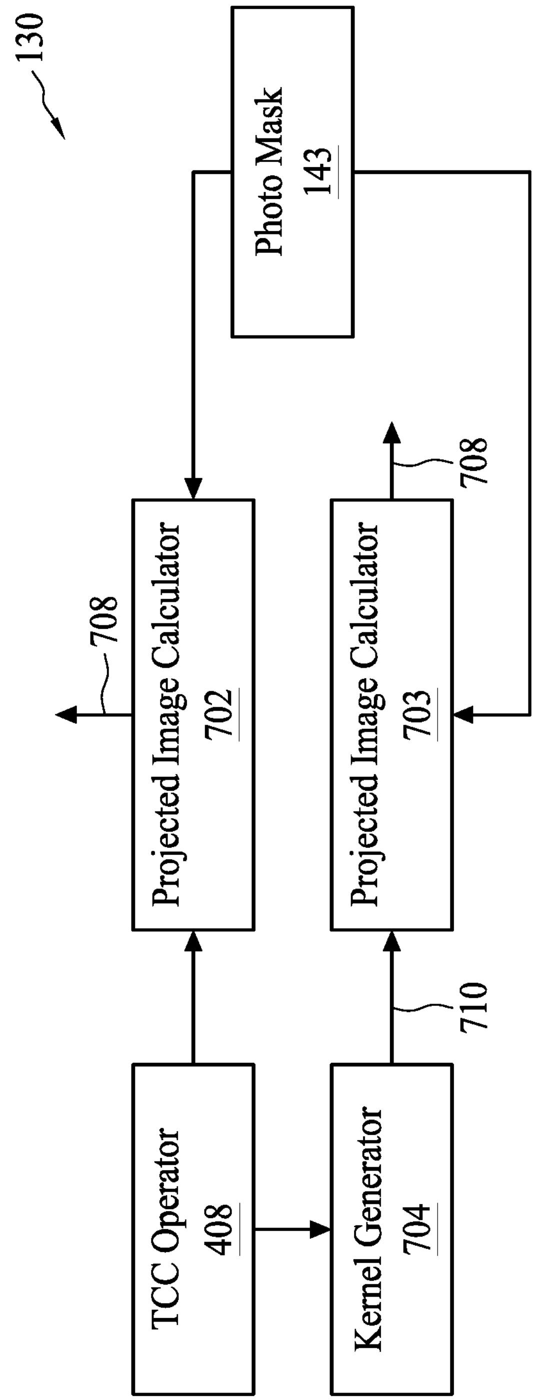
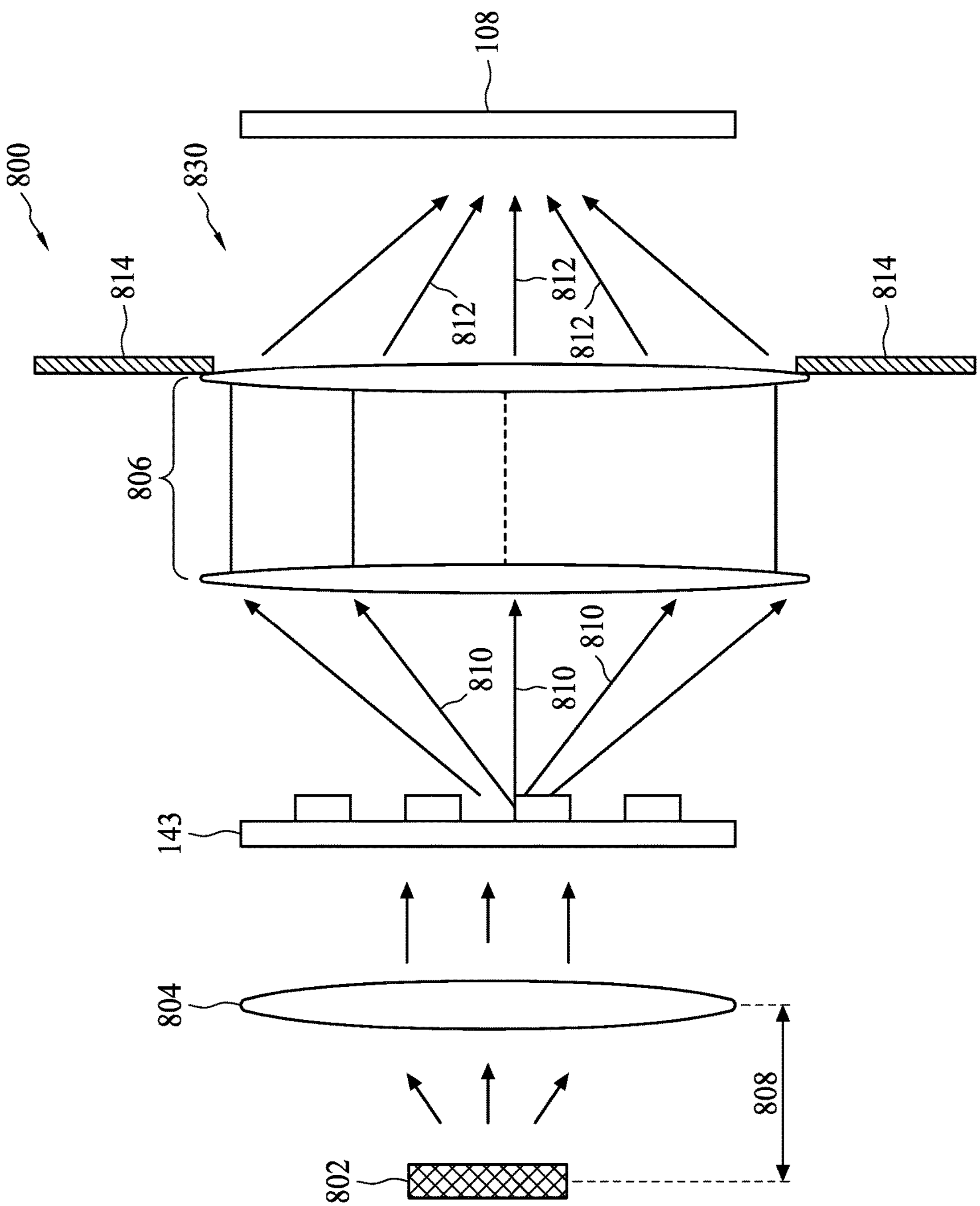

130
Photo Mask
143
708
Projected Image Calculator
702
Projected Image Calculator
703
708
TCC Operator
408
Kernel Generator
704
710

FIG. 7B



800
830
108
814
814
812
812
812
812
806
810
810
810
143
804
808
802

FIG. 8A

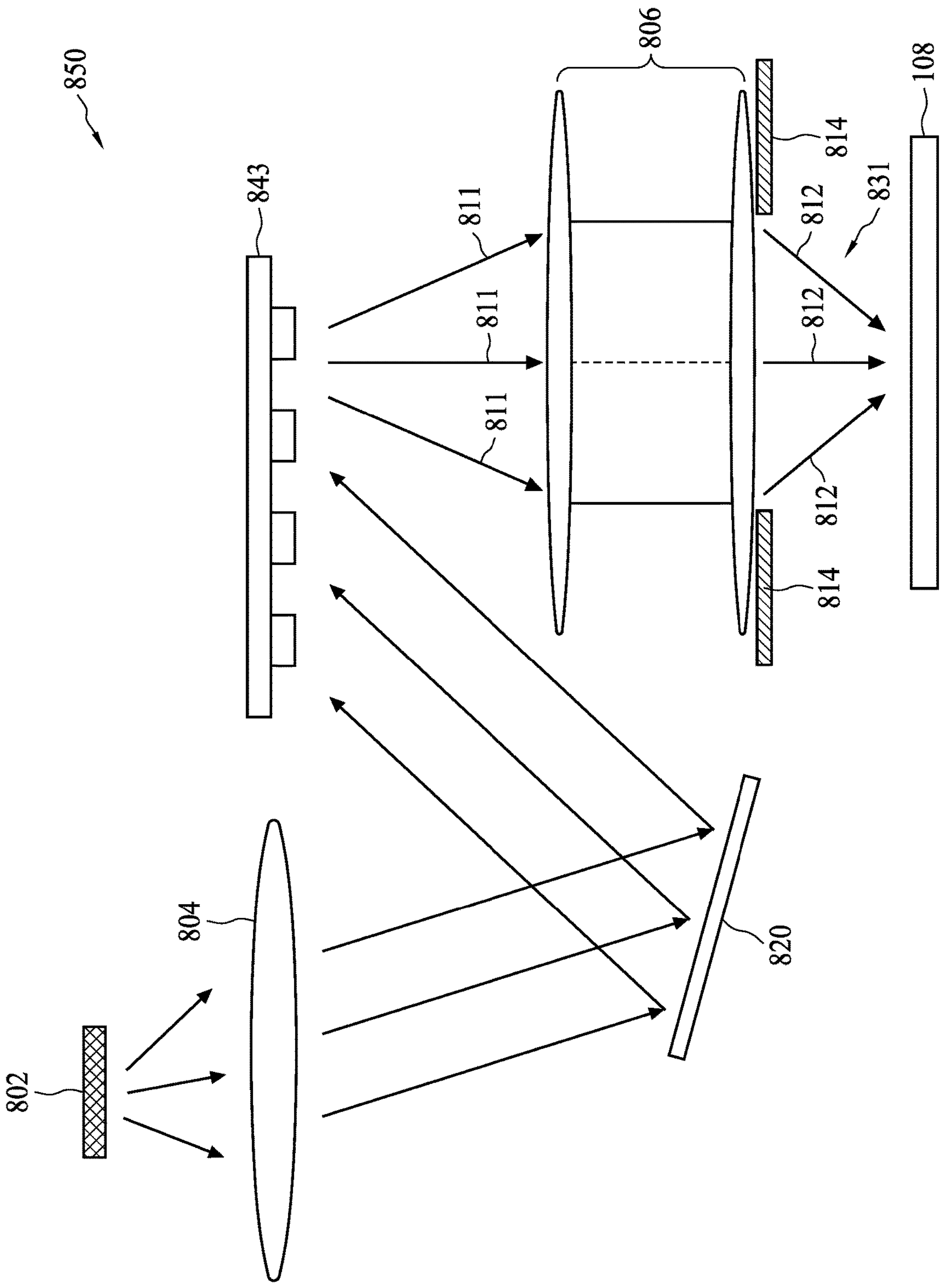


FIG. 8B

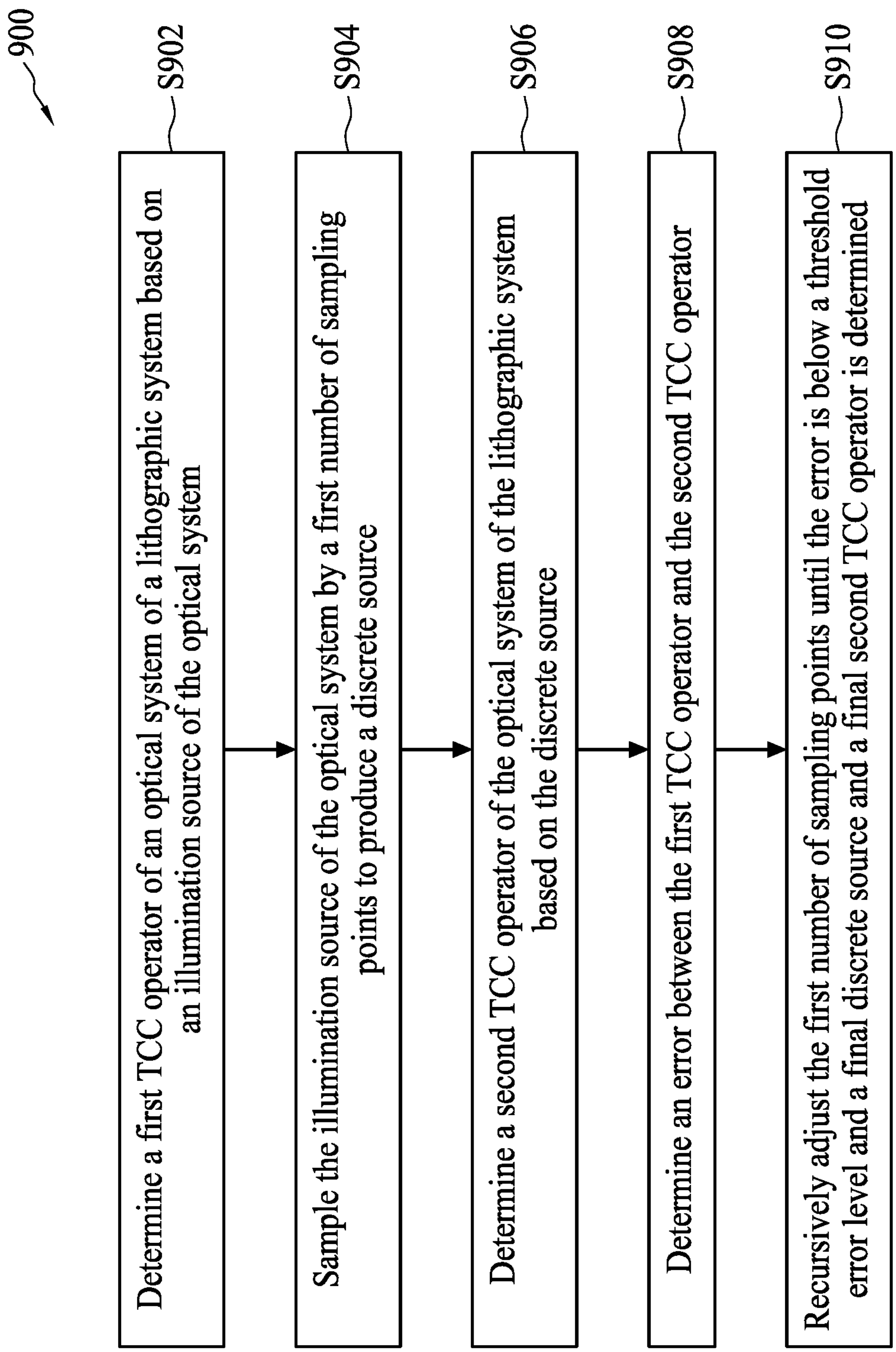

900
S902
Determine a first TCC operator of an optical system of a lithographic system based on an illumination source of the optical system
S904
Sample the illumination source of the optical system by a first number of sampling points to produce a discrete source
S906
Determine a second TCC operator of the optical system of the lithographic system based on the discrete source
S908
Determine an error between the first TCC operator and the second TCC operator
S910
Recursively adjust the first number of sampling points until the error is below a threshold error level and a final discrete source and a final second TCC operator is determined

FIG. 9

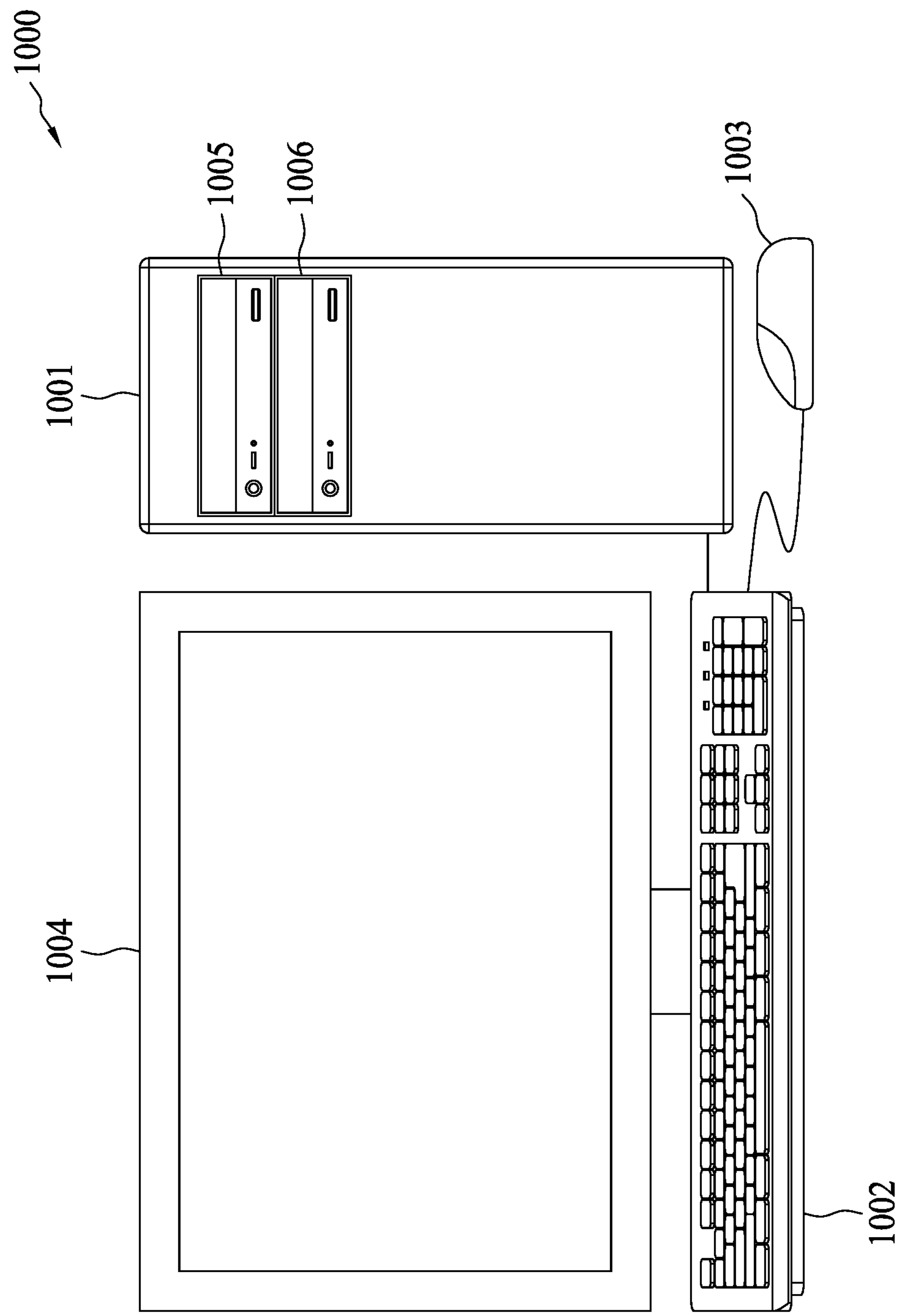


FIG. 10A

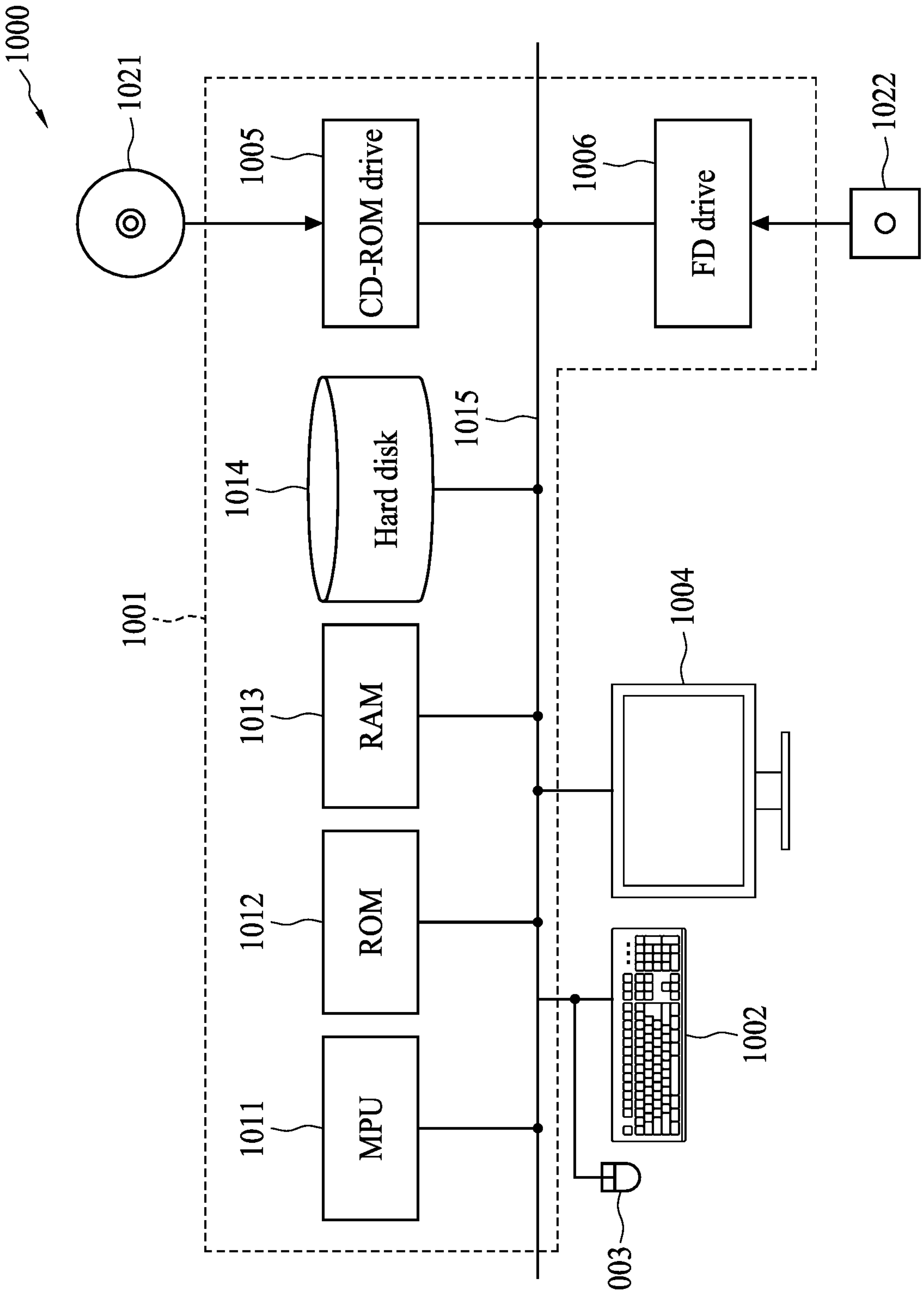

1000
1021
1001
1005
CD-ROM drive
1006
FD drive
1022
1015
1014
Hard disk
1013
RAM
1012
ROM
1011
MPU
1004
1002
1003

FIG. 10B

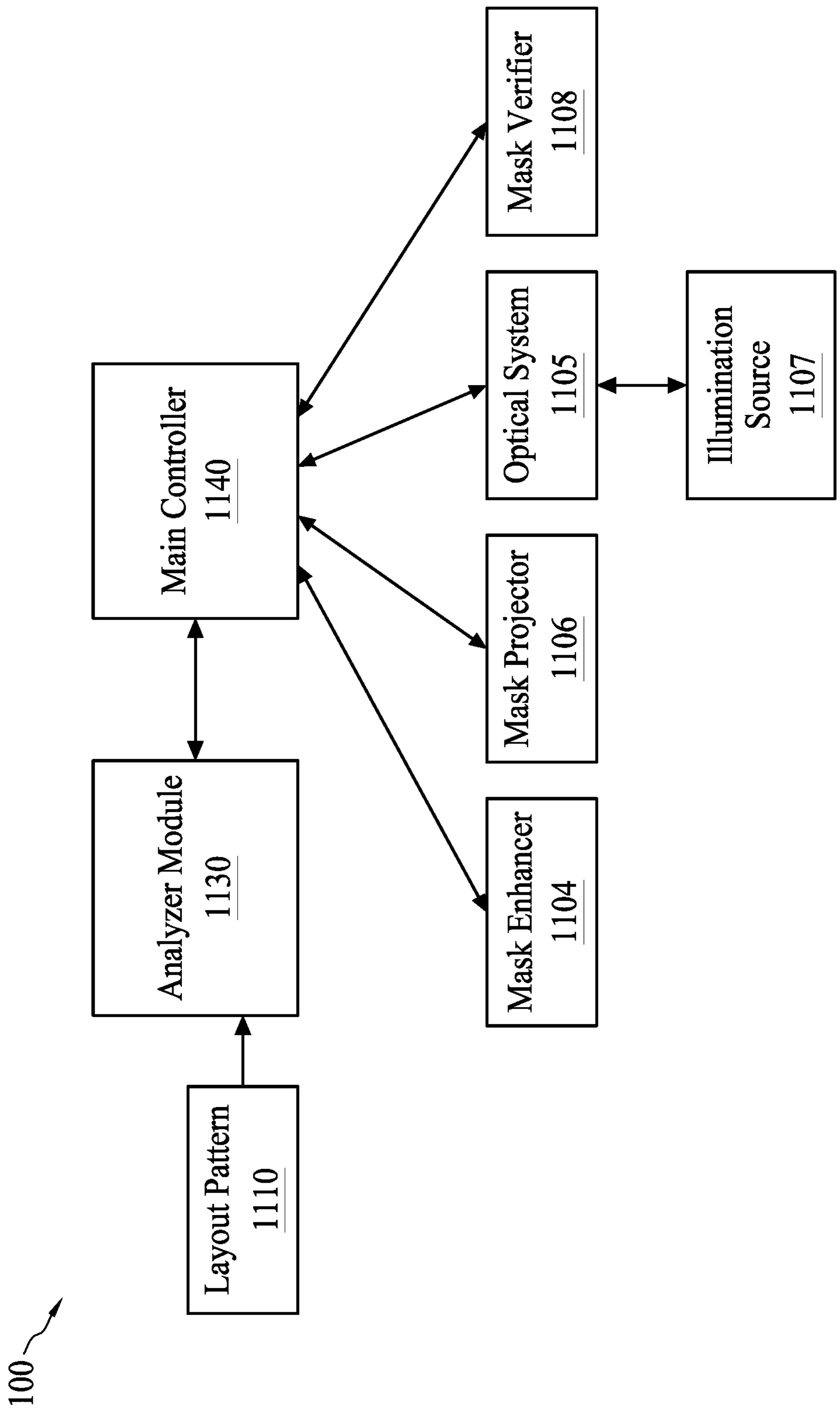

1100
Layout Pattern
1110
Analyzer Module
1130
Main Controller
1140
Mask Enhancer
1104
Mask Projector
1106
Optical System
1105
Mask Verifier
1108
Illumination
Source
1107

FIG. 11

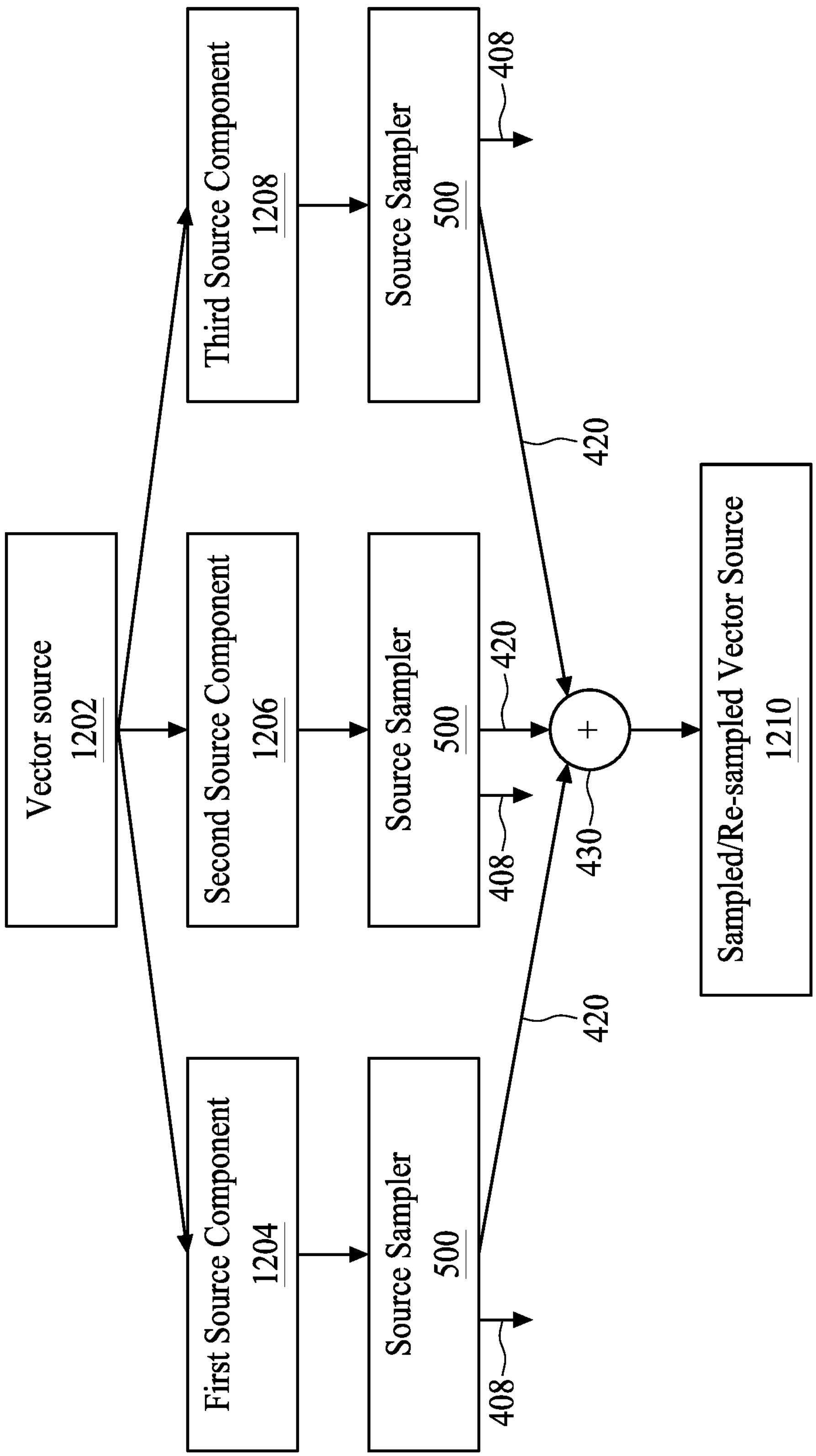

Vector source
1202
First Source Component
1204
Second Source Component
1206
Third Source Component
1208
Source Sampler
500
Source Sampler
500
Source Sampler
500
408
408
408
420
420
420
430
+
Sampled/Re-sampled Vector Source
1210

FIG. 12

LITHO-AWARE SOURCE SAMPLING AND RESAMPLING

An optical lithography process transfers a layout pattern of a photo mask to the wafer such that etching, implantation, or other steps are applied only to predefined regions of the wafer. Transferring the layout pattern of the photo mask to the resist layer on the wafer may cause resist pattern defects that are a major challenge in semiconductor manufacturing. An optical proximity correction (OPC) operation may be applied to the layout pattern of the photo mask to reduce the resist pattern defects. The OPC may modify the layout patterns of the photo mask before the lithography process to compensate for the effect of the lithography process. In addition, inverse lithographic transformation (ILT) may be performed on the layout patterns of the photo mask to further compensate for the effect of the lithography process. An efficient OPC or ILT operation on the layout patterns of the photo masks is desirable.

BRIEF DESCRIPTION OF THE DRAWING

The present disclosure is best understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale and are used for illustration purposes only. In fact, the dimensions of the various features may be arbitrarily increased or reduced for clarity of discussion.

FIG. **1** illustrates a schematic diagram of an exemplary integrated circuit (IC) fabrication flow.

FIGS. **2**A and **2**B illustrate a schematic diagram of an exemplary photo mask enhancer and an OPC enhanced layout pattern associated with a target layout pattern.

FIG. **3** illustrates exemplary layout contours having two defective areas.

FIG. **4** illustrates a schematic diagram of an exemplary layout corrector.

FIG. **5** illustrates a schematic diagram of an exemplary source sampler system for optimizing a transmission cross-coefficient (TCC) operator.

FIGS. **6**A, **6**B, and **6**C illustrate schematic diagrams of exemplary systems for sampling and re-sampling an illumination source and generating a TCC operator.

FIGS. **7**A and **7**B illustrate schematic diagrams of exemplary systems for calculating projection images using a TCC operator in accordance with some embodiments of the disclosure.

FIGS. **8**A and **8**B illustrate schematic diagrams of exemplary optical systems of an optical system of a lithographic system.

FIG. **9** illustrates a flow diagram of an exemplary process for enhancing a photo mask in accordance with some embodiments of the disclosure.

FIGS. **10**A and **10**B illustrate an apparatus for enhancing a photo mask in accordance with some embodiments of the disclosure.

FIG. **11** illustrates an exemplary system of enhancing a photo mask in accordance with some embodiments of the disclosure.

FIG. **12** illustrates a schematic diagram of an exemplary source sampler system for optimizing a TCC operator for vector optics.

DETAILED DESCRIPTION

The following disclosure provides many different embodiments, or examples, for implementing different features of the provided subject matter. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. For example, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed between the first and second features, such that the first and second features may not be in direct contact. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed.

Further, spatially relative terms, such as "beneath," "below," "lower," "above," "upper" and the like, may be used herein for ease of description to describe one element or feature's relationship to another element(s) or feature(s) as illustrated in the figures. The spatially relative terms are intended to encompass different orientations of the device in use or operation in addition to the orientation depicted in the figures. The apparatus may be otherwise oriented (rotated 90 degrees or at other orientations) and the spatially relative descriptors used herein may likewise be interpreted accordingly. In addition, the term "being made of" may mean either "comprising" or "consisting of" In the present disclosure, a phrase "one of A, B and C" means "A, B and/or C" (A, B, C, A and B, A and C, B and C, or A, B and C), and does not mean one element from A, one element from B and one element from C, unless otherwise described.

In some embodiments, one or both of the OPC operation or the ILT operation is applied to the layout pattern of the photo mask to reduce resist pattern defects. In some embodiments, both OPC and ILT operations are iteratively performed. The OPC and the ILT modify a layout pattern of the photo mask, the modified layout pattern of the photo mask is projected, by an optical system of a lithographic system, as a pattern on the resist material layer on a wafer. The projected pattern on the resist material is compared with a target layout pattern and an error between the projected pattern on the resist material and the target layout pattern in calculated. Depending on the calculated error and/or existence of some defects, e.g., a bridge or a narrowing, the layout pattern of the photo mask is further modified by the OPC and/or ILT operations. The iterative method is repeatedly applied until the defects are corrected and/or the calculated error is below a threshold level. In some embodiments, the projection of the layout pattern of the photo mask on the resist layer of a wafer is performed by a simulated projection and the projected pattern on the resist layer of the wafer is calculated. In the simulated projection, the illumination source, e.g., light source or laser source, of the optical system of the lithographic system is sampled by a sampling grid. A resolution of the sampling grid directly affects the complexity and accuracy of the simulated projection. If the illumination source sampling is performed with low resolution, the simulated projection may be fast but the simulated projection may lose accuracy. Conversely, if the illumination source sampling is performed with high resolution, the simulated projection may be slow and time consuming but the simulated projection may be more accurate. Thus, the resolution of the illumination source sampling defines the speed of the OPC and ILT operations and the accuracy of the OPC and ILT operations. Therefore, finding a suitable resolution for sampling the illumination source is desirable.

FIG. **1** illustrates a schematic diagram of an exemplary integrated circuit (IC) fabrication flow **100**. The IC fabrication flow **100** begins with an IC design module **102** that provides layout patterns M, e.g., target layout patterns, that will be produced as a resist pattern of an IC product on the wafer. The IC design module **102** generates various layout shapes, e.g., geometrical patterns, based on the specification of the IC product for different steps of processing the IC product. In some embodiments, the layout patterns M are presented by one or more data files having the information of the geometrical patterns. In some embodiments, optically projecting the layout pattern of the photo mask to the wafer in the lithographic process degrades the layout pattern of the photo mask and generates pattern defects on the resist layer on the wafer. An optical proximity correction (OPC) operation may be applied to layout patterns of the photo mask to reduce the pattern defects on the wafer. The OPC may modify the layout patterns of the photo mask before the lithography process to compensate for the effect of the lithography and/or etching processes. The IC fabrication flow **100** also shows a mask enhancer **104**. As will be described in more detail below with respect to FIG. **2**A, the mask enhancer **104** performs the OPC in some embodiments. The mask enhancer **104** creates an OPCed (e.g., a corrected or enhanced) layout pattern M' on the photo mask. In some embodiments, the enhanced layout pattern M' is presented by one or more data files having the information of the enhanced geometrical patterns.

The IC fabrication flow **100** further shows a mask projection system **106**. In some embodiments, the mask projection system **106** produces the enhanced layout patterns M' on the photo mask. In some embodiments, the mask projection system **106** performs two functions. As a first function, the mask projection system **106** uses the data files of the enhanced layout pattern M' and uses an electron beam to generate the enhanced layout pattern M' on a mask blank (not shown) to produce the photo mask for the ICs. In addition, and as a second function, the mask projection system **106** optically projects the enhanced layout pattern M' of the photo mask on the wafer **108** to produce the IC layouts on the wafer **108**.

FIGS. **2**A and **2**B illustrate a schematic diagram of an exemplary photo mask enhancer and an OPC enhanced layout pattern associated with a target layout pattern. FIG. **2**A illustrates a schematic diagram of the mask enhancer **104** that receives the target layout pattern M at an input of an OPC enhancer **122** and produces the enhanced layout pattern M' at an output of the step **150**. The mask enhancer **104** performs an iterative process. In some embodiments, the mask enhancer **104** includes an OPC enhancer **122** that receives, from the IC design module **102**, the target layout pattern M that will be produced on the wafer **108**. The OPC enhancer **122** performs enhancements on the target layout pattern M and produces the OPCed (e.g., the corrected or enhanced) layout pattern M'. As described, OPC is a lithography technique that is used to correct or enhance the layout pattern M and to add improved imaging effects to a target layout pattern M such that the OPCed layout pattern M' reproduces, on the wafer **108**, the target layout pattern M. For example, OPC is used to compensate for imaging distortions due to optical diffraction. In some embodiments, the target layout pattern M is a data file having the information of the geometrical patterns to be produced on the wafer **108**, and the OPC enhancer **122** modifies the data file and produces a corrected data file representing the enhanced layout pattern M'. In some embodiments, the target layout pattern M and the enhanced layout pattern M' are represented by the vertices of the layout patterns in the data files. Thus, in some embodiments, the rounded corners and the bends are represented by a curvilinear shape having multiple vertices and multiple line segments connecting the vertices and the curvilinear shape is represented by the multiple vertices in the data file.

FIG. **2**A further shows a mask projector **130**, e.g., a simulator for mask projection, that is applied to the enhanced layout pattern M' to produce a projected resist pattern **101** on the wafer. In some embodiments, the enhanced layout pattern M' is a data file and the mask projector **130** simulates the projection of the enhanced layout pattern M' on the wafer and produces the simulated projected resist pattern **101**. The projected resist pattern **101** is inspected by an OPC verifier **140** for errors. In some embodiments, the OPC verifier **140** receives the target layout pattern M in addition to the projected resist pattern **101** and compares the projected resist pattern **101** with the target layout pattern M to find errors between target layout pattern M and the projected resist pattern **101**. In some embodiments, the OPC verifier **140** verifies the enhanced, e.g., OPCed, layout pattern M' when the error between the target layout pattern M and the projected resist pattern **101** is below a threshold level and there are no defects, e.g., a bridge or narrowing shown in FIG. **3**, in the projected resist pattern. In some embodiments, after verifying the enhanced layout pattern M', the OPC verifier **140** generates and sends a verification signal **103**. In some embodiments, the OPC verifier **140** stores the enhanced layout pattern M' in a database. In some embodiments, instead of a simulated result, a photo resist pattern is formed by using a photo mask fabricated with the enhanced layout pattern M' and the shapes and dimensions of the resist patterns are measured and are fed back to the OPC enhancer. The mask projector **130** is described in more details with respect to FIGS. **7**A and **7**B.

The verification signal **103** is tested at step **150** and if the verification signal **103** is not successful, e.g., the error is above the threshold level or defects exist in the projected resist pattern **101**, iterations continue by applying further OPC enhancements by the OPC enhancer **122**. The iterations continue until the verification signal **103** is successful. When the verification signal **103** is successful, the enhanced layout pattern M' is provided as the output of the mask enhancer **104**. In some embodiments, the error between the target layout pattern M and the projected resist pattern **101** is defined as a distance between the boundary of the target layout pattern M and a boundary of the projected resist pattern **101**.

As shown, in addition to the mask enhancer **104**, FIG. **2**A includes a mask generator **141** and an optical system **145**. In some embodiments, the enhanced layout pattern M' is sent as a data file to the mask generator **141**. The mask generator **141** produces the enhanced layout pattern M' on a mask-blank to generate a photo mask **143**. In some embodiments, the photo mask **143** is used by the optical system **145** of a photo lithography system to produce a resist pattern on a resist layer of the wafer **108**.

FIG. **2**B illustrates the target layout patterns **303** and the OPC enhanced, e.g., corrected, layout patterns **301** of a connection line. In some embodiments, the OPC enhanced layout patterns **301** of FIG. **2**B is formed on a photo mask and the photo mask is projected onto a wafer, e.g., the wafer **108**, by the mask projection system **106** of FIG. **1**.

FIG. **3** illustrates exemplary layout contours having two defective areas. FIG. **3** shows the resist pattern **300** having two defective areas **302** and **304**. The resist pattern **300** may be produced by the mask projector **130** when the corrected mask layout M', after being OPCed, is projected on the resist layer of the wafer **108**, disclosed herein. As shown, both of the defective areas **302**, **304** respectively include a bridging **312** and a bridging **314** (e.g., short circuits) that are connections between adjacent layout lines in the middle of the defective areas **302** and **304**. In some embodiments, the defective areas **302** and **304** are back projected to two corresponding hotspot regions in the corrected mask layout M'. In some embodiments, the ILT operation is performed on the corrected mask layout M', e.g., on the hotspot regions in the corrected mask layout M', to correct the corresponding defective areas **302** and **304** of the resist pattern produced in the resist layer of the wafer **108**.

FIG. **4** illustrates a schematic diagram of an exemplary layout corrector. FIG. **4** is configured to perform an ILT enhancement. FIG. **4** shows the mask enhancer **104** that receives the target layout pattern M at an input of an ILT enhancer **452** and produces an enhanced mask layout **462** at an output of the step **460**. In some embodiments, the ILT enhancer **452** receives the corrected mask layout M' after the OPC operation. Either the corrected mask layout M' or the target layout pattern M includes a hotspot region corresponding to a defect on the resist layer when the corrected mask layout M' or the target layout pattern M is projected on the resist layer of the wafer **108**.

The ILT enhancer **452** performs an enhancement, e.g., a constrained inverse filtering operation, on the hotspot region of the corrected mask layout M' or the target layout pattern M and produces the iteration result, the enhanced mask layout **462**. The enhanced mask layout **462** is projected by the mask projector **130** on the resist layer of the wafer **108** to create a projected resist pattern **458**. In some embodiments, the mask projector **130** performs a simulated projection and is consistent with the operation performed by the configuration of FIG. **7**A. The projected resist pattern **458** is inspected by an ILT verifier **456** for defective areas. A verification outcome **468** is tested at step **460** and if the verification outcome **468** is not successful, e.g., defective areas exist, the iterations continue by modifying the layout enhancement at the ILT enhancer **452**. The iterations continue until the verification outcome **468** is successful and the projected resist pattern **458** does not have any defective areas. When the verification outcome **468** is successful, the enhanced mask layout **462** is provided at step **460**.

As shown, in addition to the mask enhancer **104**, FIG. **4** includes the mask generator **141** and an optical system **145**. A described above, the mask generator **141** generates the photo mask **143** from the enhanced mask layout **462** and the optical system **145** of the photo lithography system projects the photo mask **143** and produces the resist pattern on the resist layer of the wafer **108**. The mask projector **130** is described in more details with respect to FIGS. **7**A and **7**B.

FIG. **5** illustrates a schematic diagram of an exemplary source sampler system **500** for optimizing a TCC operator. FIG. **5** shows an input source **402**, e.g., an illumination source, and a TCC generator module **421**. In some embodiments, the input source **402**, e.g., the illumination source, is a parametric illumination source of an optical system, e.g., optical systems **800** and **850** of FIGS. **8**A and **8**B, of a lithographic system. In some embodiments, the input source **402** is a laser source. In some embodiments, the input source **402** has a Gaussian profile with a standard deviation between about 1 cm to about 20 cm. In some embodiments, the input source **402** has a circular profile having a radius between 1 cm and 20 cm and having a uniform amplitude. In some embodiments, the input source **402** is one of a coherent or partially coherent source. In some embodiments, the input source **402** is a non-coherent source. In some embodiments, the input source **402** is a deep ultraviolet (DUV) with a wavelength of about 250 nm to about 100 nm, or an extreme ultraviolet (EUV) source with a wavelength of about 100 nm to about 10 nm. In some embodiments, the input source **402** has dimensions of about 1 cm by 1 cm (a diameter of about 2 cm) to about 20 cm by 20 cm (a diameter of about 40 cm). FIG. **5** also shows a discretize source operator **406** and a TCC generator module **423**. The discretize source operator **406** performs sampling of the input source **402** and provides a discrete source **420**. As shown in FIG. **5**, the TCC generator module **421** uses the input source **402** and the optical parameters **411**, which includes an exit pupil, consistent with the exit pupil **830** or **831** of FIGS. **8**A and **8**B, and generates, e.g., calculates, a TCC operator **404**. The TCC generator module **423** uses the discrete source **420** and the optical parameters **411** and generates, e.g., calculates, a TCC operator **408**. In some embodiments, the TCC generator modules **421** and **423** use equation (2) below to generate the TCC operators **404** and **408**. Also, as shown in FIG. **5**, the source sampler system **500** provides the TCC operators **404** and **408** and the discrete source **420** as outputs.

Thus, in some embodiments, the TCC operator **404** depends on the input source **402**, e.g., a shape and size of the input source **402**, and the TCC operator **408** depends on the discrete source **420**, e.g., a distribution of the sampled points of the input source **402**. As shown below in equation (2), the TCC operator depends on the spatial Fourier transform of the input source. Additionally, the TCC operators **404** and **408** depend on the optical parameters **411** of the lithographic system, e.g., the optical parameters **411** of the optical system of the lithographic system. Thus, the TCC operators **404** and **408** may depend on a wavelength of the illumination source of the optical system, an amount of coherency of the illumination source, a numerical aperture of the optical system, a shape and size of an exit pupil of the optical system, and an aberrations of the optical system. In some embodiments, an error calculator **410** determines an error between the TCC operator **404** and the TCC operator **408**. In some embodiments, the error calculator **410** generates an error **422**, which is a sum of squared differences between the TCC operator **404** and the TCC operator **408**, e.g., an L2 norm, a Frobenius-norm, which is a sum of squared differences between corresponding points of the TCC operator **404** and the TCC operator **408**.

In some embodiments, the intensity I of a projected image, e.g., the projected resist pattern **101** of FIG. **2**A or the projected resist pattern **458** of FIG. **4** is defined with the following equations (1) and (2):

$$I(x)=\iint M(\alpha)T(\alpha,\alpha')M^*(\alpha')e^{2\pi i(\alpha-\alpha')\cdot x}d\alpha d\alpha' \quad \text{Equation (1)}$$

$$T(\alpha,\alpha')=\int S(\alpha_s)P(\alpha+\alpha_s)P^*(\alpha'+\alpha_s)d\alpha_s \quad \text{Equation (2)}$$

Where α is the spatial frequency coordinates, M is the spatial Fourier transform of the layout pattern of the mask, P is the exit pupil function of the optical system, S is the spatial Fourier transform of the intensity distribution of the illumination source, and Tis the TCC operator. In some embodiments, the TCC operator includes the exit pupil function P and the spatial Fourier transform of the illumination source S as shown in equation (2). Additionally, the TCC operator incorporates the operation of the integral of equation (1). In some embodiments, an exit pupil of an optical system is a virtual aperture such that only the rays that pass through the exit pupil can exit the optical system.

In some embodiments, an exit pupil function P(α) is a representation of the exit pupil as a function of the variable α, where α is a two-dimensional (2D) variable in a 2D coordinate system, e.g., a 2D point ($\alpha=(F_x$ and $F_y))$ in a frequency plane. In some embodiments, the TCC generator modules **421** and **423** generate the TCC operator **404** and the TCC operator **408** according to equation (2) as functions of the two variables α and α' and the respective intensity I of equation (1) using the TCC operator **404** and the TCC operator **408** are numerically evaluated. The two variables α and α' are sampled and the TCC operator **404**, the TCC operator **408**, and the intensity I of equation (1) are calculated at the sampled points of the variables. In some embodiments, the sampling resolution of the of two variables α and α' in the spatial frequency coordinates is higher than the corresponding sampling resolution of the input source **402** and, thus, the sampling of the variables α and α' to evaluate the TCC operators **404** and **408** and the intensity I of equation (1) causes negligible error, e.g., less than one percent, in the calculation of equation (1). In some embodiments, the exit pupil function is a real function represented by an amplitude that has a value of one inside a circle and a value of zero outside the circle. As shown above, the TCC operator depends on the exit pupil function and the illumination source distribution. In some embodiments, the exit pupil function is a complex function that is represented with an amplitude and a phase at each point of the exit pupil function, where the phase of the pupil function includes the aberrations of the optical system. The exit pupil is described with respect to FIGS. **8**A and **8**B. In some embodiments, the TCC operator is symmetric and positive definite and, thus, can be expanded, with non-negative expansion coefficients λ_n, into separable kernels φ_n and φ^*_n as shown in equation (3) below:

$$T(\alpha,\alpha')=\Sigma_n\lambda_n\varphi_n(\alpha)\varphi^*_n(\alpha'),\lambda_n=1,\ 2,\ 3, \qquad \text{Equation (3)}$$

In some embodiments, the kernels are numerically evaluated at sampled points of the variables α and α'. In addition, in some embodiments, the TCC operator **404** and the TCC operator **408** are approximated as a weighted sum of a finite number of the kernels. In some embodiments, the TCC operator **404** or TCC operator **408** are discretized and represented as matrices, e.g., 2D positive definite TCC matrices. In some embodiments, the TCC operator **404** and the TCC operator **408** expand in the same range of variables α and α' and, thus, the TCC matrices corresponding the TCC operator **404** and the TCC operator **408** have the same dimensions. In addition, the integral of equation (1) is represented as a matrix multiplication of a TCC matrix and the discretized spatial Fourier transform of the layout pattern of the mask M. In some embodiments, the TCC generator modules **421** and **423** of the source sampler system **500** further perform a discretization and the TCC operators **404** and **408** are provided as TCC matrices at the output. In addition, the error calculator **410** generates the error **422** as a sum of squared differences between the corresponding elements of the TCC matrices.

In addition, the kernels φ_n and φ^*_n are respectively discretized and represented as horizontal or vertical vectors, e.g., one-dimensional (1D) horizontal or 1D vertical matrices. In some embodiments, the error calculator **410** generates the error **422** as a sum of squared differences between the corresponding elements of the TCC matrices. In some embodiments, when the TCC matrix is positive definite, the TCC matrix is expanded into a weighted sum, using the coefficients λ_n as the weights, of a plurality of matrices, where each matrix is generated as the multiplication of each vertical vector and a corresponding horizontal vector associated with one of the kernels φ_n and φ^*_n. The weighted sum is a matrix form of equation (3). In some embodiments, as shown in equation (3), the TCC operator **404** or TCC operator **408** is expanded into the weighted sum of the kernels. In some embodiments, the TCC operator **404** and/or the TCC operator **408** is approximated by selecting a subset of the kernels φ_n and φ^*_n. In addition, the projected image of the lithographic mask is approximated by the approximated TCC operators **404** and **408**. In some embodiments, the finite number of the kernels are selected by ordering the non-negative coefficients λ_n and then selecting the coefficients λ_n larger than a threshold and the kernels associated with the coefficients larger than the threshold. The coefficients λ_n smaller than the threshold and the kernels associated with the coefficients λ_n smaller than the threshold are discarded.

After calculating the error **422** by the error calculator **410**, the error is compared by lower (first) and upper (second) thresholds in operation **412**. If the error **422** is within the upper threshold and the lower threshold, the discrete source **420** is acceptable and the discrete source **420** is provided as an output. In some embodiments, the discrete source **420** and the corresponding TCC operator **408** are used for calculating a projection of the mask in the mask projector **130** of FIGS. **2**A and **4**. In some embodiments, a singular value decomposition is used for defining the kernels and selecting the kernels having the highest energy. In some embodiments, determining the TCC operator **404** or TCC operator **408** includes determining a cross section between two exit pupils P having different offsets α and α' as shown in equation (2). In some embodiments, when the illumination source is partially coherent, determining the TCC operator **404** or TCC operator **408** includes determining a cross section between the two exit pupils and a circle having a radius equal to the coherent length of the illumination source limiting the spatial Fourier transform S of the illumination source.

In some embodiments, if the error **422** is more than the second threshold, the number of sampling points are increased, e.g., based on the error **422**, and the discrete source **420** is resampled. The resampling is performed by a re-discretize source **414** operator and the TCC operator **408** is re-determined based on the re-sampled discrete source. In some embodiments, by increasing the number of sampling points, the error **422** is decreased. In some embodiments, if the error **422** is less than the first threshold, the number of sampling points is reduced, e.g., based on the error **422**, and the discrete source **420** is resampled by the re-discretize source **414** operator and the TCC operator **408** is re-determined based on the re-sampled discrete source. In some embodiments, by decreasing the number of sampling points, an amount of calculation time of the mask projector **130** is reduced and calculating the projected image becomes faster. Either after reducing or increasing the number of sampling points, the error **422** is recalculated by the error calculator **410** to determine whether the error **422** is maintained between the first threshold and the second threshold. In some embodiments, the error **422** is defined by other norms such as the L-infinity norm (maximum value) or linear algebraic norms, e.g., the Frobenius norm or the nuclear norm, where the linear algebraic norms are used for TCC matrices.

FIGS. **6**A, **6**B, and **6**C illustrate schematic diagrams of exemplary systems for sampling and re-sampling an illumination source and generating a TCC operator. FIG. **6**A shows a diagram for sampling the input source **402**. In some embodiments, the input source **402** is a parametric illumination source as described above. The input source **402** is sampled by a sampler **630** that determines the number of sampling points and a distribution of the sampled points. In some embodiments, the sampler **630** uses the optical parameters **411**, described above, to determine a number of sampling points, e.g., sampling resolution, of the input source **402** to produce the discrete source **420**. In some embodiments, the sampler **630** uses the Nyquist rate based on a spatial frequency content of the input source **402** to determine the number of sampling points. In addition, a discrete source generator **632** receives the number of sampling points and determines how the sampling points are distributed, e.g., uniformly or non-uniformly, in the input source **402**. In some embodiments, a combination of the sampler **630** and the discrete source generator **632** is consistent with the discretize source operator **406** of FIG. **5**.

FIG. **6**B shows a diagram for re-sampling the discrete source **420**. The discrete source **420** is re-sampled by a re-sampler **624** that determines a modified number of sampling points **634** and a distribution of the modified sampled points. In some embodiments, the re-sampler **624** uses the optical parameters **411**, described above, and the error **422** to determine the modified number of sampling points **634**, e.g., a modified sampling resolution, of the discrete source **420** to produce a modified discrete source. In some embodiments, a discrete source generator **626** receives the modified number of sampling points **634** and determines how the modified sampling points are distributed. In some embodiments, a combination of the re-sampler **624** and the discrete source generator **626** is consistent with the re-discretize source **414** of FIG. **5**. In some embodiments, a local or a global operator is used for resampling. In some embodiments, the discrete Fourier transform operator is used for resampling such that the original sampled points of the discrete source **420** are Fourier transformed to the frequency domain. Then, the inverse Fourier transform is applied to the frequency domain to generate a continuous inverse Fourier transform function in the spatial domain. The inverse Fourier transform function is sampled by the modified number of sampling points at the locations defined by the discrete source generator **626**.

FIG. **6**C shows a diagram for distributing the modified number of sampling points and defining the locations of the modified number of sampling points. The intensity location initializer **642** receives the modified number of sampling points and uniformly distributes the modified number of sampling points. The discretize source operator **406** finds an intensity of the modified number of sampling points, e.g., by performing Fourier transform/inverse Fourier transform described above. The discretize source operator **406** generates a new discrete source **420**. The error **422** when using the new discrete source **420** to generate a new TCC operator **408** is calculated between TCC operator **408** and the TCC operator **404** at operation **621**. The location of the modified number of sampling points are recursively modified by an intensity location adjuster **625** until the error **422** is minimized. A new discrete source **420** is generated when the error **422** is minimized. In some embodiments, the error **422** is minimized when the error **422** is between the second threshold that is defined with respect to FIG. **5**.

FIGS. **7**A and **7**B illustrate schematic diagrams of exemplary systems for calculating projection images using a TCC operator. FIGS. **7**A and **7**B show different implementations of the mask projector **130** of FIGS. **2**A and **4** that is consistent with the mask projector **130** of FIG. **5**. FIG. **7**A shows a projected image calculator **702** that generates, consistent with equation (1), the result of performing the TCC operator **404** on the layout pattern of the photo mask **143** to produce a projected image **706** consistent with the projected resist pattern **101** of FIG. **2**A or the projected resist pattern **458** of FIG. **4**. FIG. **7**B shows the projected image calculator **702** that generates, consistent with equation (1), the result of performing the TCC operator **408** on the layout pattern of the photo mask **143** to produce a projected image **708** consistent with the projected resist pattern **101** of FIG. **2**A or the projected resist pattern **458** of FIG. **4**. As shown in FIG. **7**B, the TCC operator can be factored into kernels by a kernel generator **704** and kernels **710** are used by a projected image calculator **703** for producing the projected image **708** in some embodiments.

FIGS. **8**A and **8**B illustrate schematic diagrams of exemplary optical systems of an optical system of a lithographic system. FIG. **8**A shows an optical system **800** that is used in a lithographic system in some embodiments. The optical system **800** shows an illumination source **802** at a distance **808** from a lens **804**. The lens **804** transmits a radiation beam of the light source through the photo mask **143**. The transmitted radiation beam **810** converges using an objective lens system **806** to generate the convergent beam **812** and to create a projected image of the photo mask **143** on the wafer **108**. As shown, blades **814** block any radiation that is outside an exit pupil **830** of the optical system **800**. FIG. **8**B shows an optical system **850** that is used in a lithographic system in some embodiments. The optical system **850** shows the illumination source **802**. The lens **804** transmits a radiation beam of the illumination source **802**. The radiation beam is reflected by a mirror **820** and is directed towards a mask **843**, e.g., a reflective mask, and produces the reflected radiation beam **811** that is reflected off the mask **843**. The reflected radiation beam **811** converges using the objective lens system **806** to generate a convergent beam **812** and to create a projected image of the reflected mask **843** on the wafer **108**. FIG. **8**B also shows the exit pupil **831** of the optical system **850**.

FIG. **9** illustrates a flow diagram of an exemplary process for enhancing a photo mask in accordance with some embodiments of the disclosure. The process **900** may be performed by the system of FIGS. **2**A and **11**. In some embodiments, the process **900** or a portion of the process **900** is performed and/or is controlled by the computer system **1000** described below with respect to FIGS. **10**A and **10**B. In some embodiments, the process **900** is performed by the system **1100** of FIG. **11**. The method includes an operation S**902** of determining a first TCC operator of an optical system of a lithographic system based on an illumination source of the optical system. In some embodiments, the TCC operator **404** of FIG. **7**A is produced based on an input source **402**, e.g., the illumination source. In operation S**904**, the illumination source, e.g., the input source **402**, of the optical system is sampled by a first number of sampling points to produce a discrete source **420**. In operation S**906**, a second TCC operator of the optical system of the lithographic system is determined based on the discrete source. In some embodiments, the TCC operator **408** of FIG. **7**B is determined based on the discrete source **420**.

In operation S**908**, an error is determined between the first TCC operator and the second TCC operator. In some embodiments, the first TCC operator and the second TCC operator are respectively discretized and a first TCC matrix and a second TCC matrix are generated. The error is determined between the first TCC matrix and the second TCC matrix. In operation S**910**, the first number of sampling points is recursively adjusted until the error is below a threshold level and a final discrete source and a final second

TCC operator **408** is determined. In some embodiments, the adjusting the first number of sampling points is described with respect to FIG. **11**. In some embodiments, the iterations continue until the error is less than or equal to a threshold value. In some embodiments, the error is positive and the first number of sampling points is modified such that the error is maintained in an error-range such that the error is less than a positive second threshold level but greater than a positive first threshold level smaller than the second threshold level. In some embodiments, if the error is greater than the second threshold level, the first number of sampling points is increased to increase the accuracy of determining, e.g., calculating, the projected image of the mask projectors **130** of FIGS. **2**A, **4**, **7**A, and **7**B. Conversely, if the error is less than the first threshold level, the first number of sampling points is reduced to increase the speed of determining, e.g., calculating, the projected image of the mask projectors **130** of FIGS. **2**A, **4**, **7**A, and **7**B.

FIGS. **10**A and **10**B illustrate an apparatus for enhancing a photo mask in accordance with some embodiments of the disclosure. In some embodiments, the computer system **1000** is used for enhancing a photo mask. Thus, in some embodiments, the computer system **1000** performs the functions of the OPC enhancer **122**, the mask projector **130**, and the OPC verifier **140** of FIG. **2**A. In some embodiments, as will be described in FIG. **11**, the computer system **1000** performs the functions of the analyzer module **1130**, main controller **1140**, the mask enhancer **1104**, and the mask verifier **1108**. In some embodiments, the computer system **1000** performs a simulation of the mask projector **1106** and the optical system **1105**. FIG. **10**A is a schematic view of a computer system that performs the enhancing of a photo mask. All of or a part of the processes, method and/or operations of the foregoing embodiments can be realized using computer hardware and computer programs executed thereon. In FIG. **10**A, a computer system **1000** is provided with a computer **1001** including an optical disk read only memory (e.g., CD-ROM or DVD-ROM) drive **1005** and a magnetic disk drive **1006**, a keyboard **1002**, a mouse **1003**, and a monitor **1004**.

FIG. **10**B is a diagram showing an internal configuration of the computer system **1000**. In FIG. **10**B, the computer **1001** is provided with, in addition to the optical disk drive **1005** and the magnetic disk drive **1006**, one or more processors, such as a micro processing unit (MPU) **1011**, a ROM **1012** in which a program such as a boot up program is stored, a random access memory (RAM) **1013** that is connected to the MPU **1011** and in which a command of an application program is temporarily stored and a temporary storage area is provided, a hard disk **1014** in which an application program, a system program, and data are stored, and a bus **1015** that connects the MPU **1011**, the ROM **1012**, and the like. Note that the computer **1001** may include a network card (not shown) for providing a connection to a LAN.

The program for causing the computer system **1000** to execute the functions of an apparatus for performing the enhancement of a photo mask in the foregoing embodiments may be stored in an optical disk **1021** or a magnetic disk **1022**, which are inserted into the optical disk drive **1005** or the magnetic disk drive **1006**, and transmitted to the hard disk **1014**. Alternatively, the program may be transmitted via a network (not shown) to the computer **1001** and stored in the hard disk **1014**. At the time of execution, the program is loaded into the RAM **1013**. The program may be loaded from the optical disk **1021** or the magnetic disk **1022**, or directly from a network. The program does not necessarily have to include, for example, an operating system (OS) or a third party program to cause the computer **1001** to execute the functions for enhancing a photo mask in the foregoing embodiments. The program may only include a command portion to call an appropriate function (module) in a controlled mode and obtain desired results.

FIG. **11** illustrates an exemplary system **1100** of enhancing a photo mask in accordance with some embodiments of the disclosure. The system **1100** includes an analyzer module **1130** and a main controller **1140** coupled to each other. The analyzer module **1130** receives the layout pattern **1110**, which is consistent with the target layout pattern M of FIGS. **1** and **2**A. The analyzer module **1130** may send the layout pattern **1110** to a mask enhancer **1104** that is coupled to the main controller **1140**. In some embodiments, the analyzer module **1130**, which is consistent with the discretize source operator **406** and the re-discretize source **414** of FIG. **5**, determines the initial number of sampling points and the initial location of the sampling points. The initial location of the sampling points may be uniformly distributed in an intensity or amplitude profile of the illumination source **1107**, which is consistent with the illumination source **802** of FIGS. **8**A and **8**B. The main controller **1140** is also coupled to a mask projector **1106**, consistent with mask projector **130** of FIGS. **1** and **2**A, an optical system **1105**, and a mask verifier **1108**. The optical system **1105** is consistent with the optical systems **800** and **850** of FIGS. **8**A and **8**B and the mask verifier **1108** is consistent with the OPC verifier **140** of FIG. **2**A and the ILT verifier **456** of FIG. **4**.

In some embodiments, the mask enhancer **1104** performs the OPC or ILT operations on the layout pattern **1110** and the mask enhancer **1104** is consistent with the ILT enhancer **452** of FIG. **4** or the OPC enhancer **122** of FIG. **2**A. In some embodiments, instead of the mask enhancer **1104**, the analyzer module **1130** performs the OPC or ILT operations on the layout pattern **1110** and, thus, the analyzer module **1130** is further consistent with the ILT enhancer **452** of FIG. **4** or the OPC enhancer **122** of FIG. **2**A. In some embodiments, the mask enhancer **1104** or the analyzer module **1130** determines the TCC operator, e.g., the TCC operator **404** or the TCC operator **408**, of an optical system **1105** of a lithographic system and, thus, the mask enhancer **1104** or the analyzer module **1130** and the main controller **1140** together are further consistent with the source sampler system **500**. In some embodiments, the optical system **1105** is consistent with the optical systems **800** and **850** of FIGS. **8**A and **8**B. In some embodiments, the mask enhancer **1104** or the analyzer module **1130** determines the TCC operator, e.g., the TCC operator **404**, of the optical system **1105** of the lithographic system based on an illumination source, e.g., illumination source **802** of FIG. **8**A or **8**B or illumination source **1107** of FIG. **11**. In addition, the mask enhancer **1104** or the analyzer module **1130** determines the TCC operator of the optical system **1105** of the lithographic system based on an exit pupil of an optical system, e.g., the exit pupils **830** and **831** of FIGS. **8**A and **8**B as shown in equation (2). The mask enhancer **1104** or the analyzer module **1130** also determines another TCC operator, e.g., TCC operator **408**, of the optical system **1105** or of the optical systems **800** and **850** of FIGS. **8**A and **8**B based on a discrete source, e.g., the sampled source, and the exit pupils **830** or **831**.

As shown in the system **1100**, the mask enhancer **1104** is coupled to the analyzer module **1130** through the main controller **1140**. In some embodiments, the mask enhancer **1104** is consistent with the OPC enhancer **122** of FIG. **2**A. The system **1100** includes a mask projector **1106** that is coupled to the analyzer module **1130** through the main controller **1140**. In some embodiments, the mask projector **1106** is consistent with the mask projector **130** of FIG. **2**A. The system **1100** further includes a mask verifier **1108** that is coupled to the analyzer module **1130** through the main controller **1140**. In some embodiments, as noted, the mask verifier **1108** is consistent with the OPC verifier **140** of FIG. **2**A. In some embodiments, the mask enhancer **1104**, the mask projector **1106**, and the mask verifier **1108** are included in the main controller **1140**. In some embodiments, adjusting the first number of sampling points is performed by either of the analyzer module **1130** or the mask enhancer **1104**. In some embodiments, the mask projector **1106** is consistent with the combination of the operations performed in FIGS. **7**A and **7**B.

In some embodiments, the illumination source, e.g., input source **402** of FIGS. **5**, and **6**A, is a polarized illumination source. Thus, each one of the electrical or magnetic fields at each point of the input source **402** may be represented by a vector in a plane perpendicular to the direction of travel of the light. In some embodiments, the light at each point of the input source **402** travels in the Z-direction and, thus, the electrical or magnetic fields of the light are in the XY-plane and may be represented by components in the X-direction and Y-direction. In some embodiments, the spatial Fourier transform S of the intensity distribution of the input source **402**, at each spatial frequency α_s, is represented as a 2 by 2 matrix $S_{2\times2}$ in equation (4) below where $S_{xy}=S^*_{yx}$.

$$S_{2\times2}(\alpha_s)=\begin{bmatrix} S_{xx} & S_{xy} \\ S_{yx} & S_{yy} \end{bmatrix} \quad \text{Equation (4)}$$

In some embodiments, the polarization of the input source **402** continuously change with time and, thus, instead of the temporal values of the input source **402**, a time-averaged variance of the electrical or magnetic fields in the two X-direction (s_{xx}) and Y-direction (s_{yy}) and a time-averaged covariance between the electrical or magnetic fields in the two directions (s_{xy} or s_{yx}) are used. In some embodiments, the matrix elements of equation (4) are the spatial Fourier transform of the variance functions and the covariance function at a spatial frequency α_s.

FIG. **12** illustrates a schematic diagram of an exemplary source sampler system for optimizing a TCC operator for vector optics. FIG. **12** shows a vector source, e.g., a polarized illumination source **1202**. As described above the variance and covariance of the polarized illumination source **1202** are determined, e.g., calculated. As shown, a first source component **1204** is the variance s_{xx} of the polarized illumination source **1202**, a second source component **1206** is the variance s_{yy} of the polarized illumination source **1202**, and a third source component **1208** is the covariance s_{xy} of the polarized illumination source **1202**. Because of the covariance symmetry, one of the s_{xy} or s_{yx} is used. The first, second, and third source components **1204**, **1206**, and **1208** are used as independent illumination sources for the three source sampler systems **500** of FIG. **12**. As shown in FIG. **5**, each one of the source sampler systems **500** provide a sampled/re-sampled discrete source **420** at the output. The sampled/re-sampled discrete sources **420** are added component-wise, at operation **430**, and the polarized sampled/re-sampled illumination source **1210** is generated. In some embodiments, the polarized illumination source **1202** is not yet sampled and each source sampler system **500** provides a sampled source. In some embodiments, the polarized illumination source **1202** is already sampled and each source sampler system **500** provides a resampled source. In some embodiments, a single sampling resolution is selected for the first, second, and third source components **1204**, **1206**, and **1208**. In some embodiments, a highest sampling resolution provided by the three source sampler systems **500** is selected for all three of the source sampler systems **500**. The source components having sampling resolutions lower than the highest sampling resolution are resampled such that the first, second, and third source components **1204**, **1206**, and **1208** have the same highest sampling resolution. The first, second, and third source components **1204**, **1206**, and **1208** are combined to produce a single polarized sampled illumination source **1210**. Then a TCC operator or a TCC matrix corresponding to the single polarized sampled illumination source **1210** is computed using a generalization of equation (2) using the components of the single polarized sampled illumination source **1210** to determine a TCC operator or a TCC matrix and the TCC operator or the TCC matrix is used to determine the intensity I of the projected image using a generalization of equation (1).

According to some embodiments of the present disclosure, a method of enhancing a layout pattern includes determining a first transmission cross coefficient (TCC) operator of an optical system of a lithographic system based on an illumination source of the optical system of the lithographic system. The method includes sampling the illumination source of the optical system by a first number of sampling points to produce a first discrete source and determining a second TCC operator of the optical system of the lithographic system based on the first discrete source. The method also includes determining an error between the first TCC operator and the second TCC operator. The method further includes recursively adjusting the first number of sampling points to re-sample the illumination source and to re-determine the second TCC operator based on the re-sampled illumination source until the error is below a threshold level and a final discrete source and a final second TCC operator is determined. The method includes performing an optical proximity correction (OPC) operation of a first layout pattern of a photo mask, the OPC operation uses the final discrete source and the final second TCC operator to determine a projected image of the first layout pattern of the photo mask on a wafer. In an embodiment, the first layout pattern of the photo mask includes one or more of specific features, and using the final discrete source and the final second TCC operator to determine the projected image of the first layout pattern generates the one or more specific features on a resist layer on the wafer. In an embodiment, the specific features include one or more of a curvature, a vertical line, or a horizontal line. In an embodiment, the method further includes receiving an illumination profile of the illumination source and sampling the illumination profile of the illumination source at a number of locations equal to the first number of sampling points. In an embodiment, the sampling the illumination source is a non-uniform sampling and the re-sampling the illumination source is a uniform sampling. In an embodiment, the illumination profile is one of an amplitude profile or an intensity profile of the illumination source. In an embodiment, the method further includes producing the OPC corrected first layout pattern on a mask-blank to create a photo mask.

According to some embodiments of the present disclosure, a method of enhancing a layout pattern includes determining a first transmission cross coefficient (TCC) operator of an optical system of a lithographic system based on an illumination source of the optical system and an exit pupil of the optical system of the lithographic system. The method includes sampling the illumination source of the optical system by a first number of sampling points at a first number of sampling locations to make a first discrete source and determining a second TCC operator of the optical system of the lithographic system based on the first discrete source and the exit pupil of the optical system. The method also includes determining an error between the first TCC operator and the second TCC operator. The method further includes recursively adjusting the first number of sampling points and the first number of sampling locations to re-sample the illumination source and to re-determine the second TCC operator based on the re-sampled illumination source until the error is within a threshold error range and a final discrete source and a final second TCC operator is determined, the threshold error range has an upper limit and a lower limit. The method includes performing an inverse lithographic transformation (ILT) operation of the first layout pattern of a photo mask, the ILT operation uses the final discrete source and the final second TCC operator to determine a projected image of the first layout pattern of the photo mask on a wafer for determining an ILT enhancement of the first layout pattern and producing the ILT enhanced first layout pattern on a mask-blank to create the photo mask. In an embodiment, the error is above the upper limit of the threshold error range and the re-sampling the illumination source includes increasing the first number of sampling points to a second number of sampling points, uniformly sampling the illumination source with the second number of sampling points, and recursively adjusting sampling locations of the second number of sampling points to re-sample the illumination source and to re-determine the second TCC operator based on the re-sampled illumination source until the error is minimized. In an embodiment, the error is below the lower limit of the threshold error range and the re-sampling the illumination source includes decreasing the first number of sampling points to a second number of sampling points, uniformly sampling the illumination source with the second number of sampling points, and recursively adjusting sampling locations of the second number of sampling points to re-sample the illumination source and to re-determine the second TCC operator based on the re-sampled illumination source until the error is minimized. In an embodiment, the method further includes representing the final second TCC operator by a weighted sum of a plurality of kernels in a kernel space, approximating the final second TCC operator by a weighted sum of two or more kernels of the plurality of kernels, and using the approximated final second TCC operator and the first discrete source to determine the projected image of the first layout pattern of the photo mask on the wafer. In an embodiment, the first TCC operator and the second TCC operator are respectively discretized to generate a first TCC matrix and a second TCC matrix, and the method further includes determining the error by determining a Frobenius-norm error between the first TCC matrix and the second TCC matrix. In an embodiment, the method further includes that prior to the performing the ILT operation of the first layout pattern: performing an optical proximity correction (OPC) operation of the first layout pattern, the ILT operation uses the final discrete source and the final second TCC operator to determine a projected image of the first layout pattern of the photo mask on the wafer, and performing the ILT operation of the OPC corrected first layout pattern using the final discrete source and the final second TCC operator to determine the projected image of the OPC corrected first layout pattern of the photo mask on the wafer. In an embodiment, the method further includes receiving a second layout pattern, different from the first layout pattern, of the photo mask of the lithographic system, and performing the ILT of the second layout pattern using the final discrete source and the final second TCC operator to determine a projected image of the second layout pattern of the photo mask on the wafer.

According to some embodiments of the present disclosure, a lithographic system includes a main controller, a photo mask, a mask enhancer coupled to the main controller, an optical system including an illumination source and coupled to the main controller, and a mask projector coupled to the main controller and the mask enhancer and to produce a projection of the photo mask on a wafer. The system also includes an analyzer module coupled to the main controller, the analyzer module receives a first layout pattern of the photo mask to be produced on the wafer. The mask enhancer is coupled to the analyzer module through the main controller and receives the first layout pattern from the analyzer module and to perform one of an optical proximity correction (OPC) operation or an inverse lithographic transformation (ILT) operation of the first layout pattern. The mask enhancer also determines a final discrete source and a final second TCC operator by receiving a first number of sampling points from the analyzer module, determining a first transmission cross coefficient (TCC) operator of an optical system of the lithographic system based on the illumination source of the optical system and an exit pupil of the optical system, sampling the illumination source of the optical system by the first number of sampling points to make a first discrete source, determining a second TCC operator of the optical system of the lithographic system based on the first discrete source and the exit pupil of the optical system, determining an error between the first TCC operator and the second TCC operator, and recursively adjusting the first number of sampling points to re-sample the illumination source and to re-determining the second TCC operator based on the re-sampled illumination source until the error is below a threshold level and the final discrete source and the final second TCC operator is determined. The mask projector performs the projection of the photo mask on the wafer for the OPC operation or the ILT operation using the final discrete source and the final second TCC operator to determine a projected image of the first layout pattern of the photo mask on the wafer. In an embodiment, the illumination source is a laser source. In an embodiment, the illumination source is one of a coherent source or a partially coherent source. In an embodiment, the profile of the illumination source is either a circular profile having a radius between 1 cm and 20 cm and having a constant amplitude, Or a Gaussian profile with a standard deviation between 1 cm and 20 cm. In an embodiment, the illumination source of the optical system is a polarized illumination source with two time varying electric or magnetic components in a first direction and in a second directions perpendicular to the first direction. The first and second directions are perpendicular to a direction of travel of a beam of the polarized illumination source. The analyzer module further determines a first variance profile of the component in the first direction, a second variance profile of the component is the second direction, and a covariance profile between the components of the first and second directions of the polarized illumination source. The mask enhancer also assigns one of the first variance profile, the second variance profile, or the covariance profile to the profile of the illumination source, determines a final discrete profile of the assigned first variance profile, second variance profile, or the covariance profile, and determines a final second TCC operator of the assigned first variance profile, second variance profile, or the covariance profile. The mask projector also performs a projection of the first layout pattern of the photo mask by the assigned profile of the polarized illumination source on the wafer for the OPC operation or the ILT operation using the determined final discrete profile and the final second TCC operator. In an embodiment, the illumination source is one of a deep ultraviolet or an extreme ultraviolet illumination source.

In some embodiments, implementing the processes and methods mentioned above, adapts the target layout pattern to a modified target layout pattern by using projection simulation. The illumination source of the simulated projection is the illumination source of the optical system of the lithographic system that is sampled. The number of sampling points is adjusted such that the number of sampling points is not too many to create a calculation burden and so that the number of sampling points is not too few to generate a discrepancy between the simulated projection and the physical projection. Therefore, the described methods above provide an efficient number of sampling points to maintain the error between the simulated projection and the physical projection within a desired range without creating unnecessary calculations.

The foregoing outlines features of several embodiments or examples so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments or examples introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

What is claimed is:

1. A method comprising:

determining a first transmission cross coefficient (TCC) operator of an optical system of a lithographic system based on an illumination source of the optical system of the lithographic system;

sampling the illumination source of the optical system by a first number of sampling points to produce a first discrete source;

determining a second TCC operator of the optical system of the lithographic system based on the first discrete source;

determining an error between the first TCC operator and the second TCC operator;

recursively adjusting the first number of sampling points to re-sample the illumination source and to re-determine the second TCC operator based on the re-sampled illumination source until the error is below a threshold level and a final discrete source and a final second TCC operator is determined; and

performing an optical proximity correction (OPC) operation of a first layout pattern of a photo mask, wherein the OPC operation uses the final discrete source and the final second TCC operator to determine a projected image of the first layout pattern of the photo mask on a wafer.

2. The method of claim **1**, wherein the first layout pattern of the photo mask comprises one or more specific features, and wherein using the final discrete source and the final second TCC operator to determine the projected image of the first layout pattern generates the one or more specific features on a resist layer on the wafer.

3. The method of claim **2**, wherein the specific features comprise one or more of a curvature, a vertical line, or a horizontal line.

4. The method of claim **1**, further comprising:

receiving an illumination profile of the illumination source and sampling the illumination profile of the illumination source at a number of locations equal to the first number of sampling points.

5. The method of claim **4**, wherein the sampling the illumination source is a non-uniform sampling and the re-sampling the illumination source is a uniform sampling.

6. The method of claim **4**, wherein the illumination profile is one of an amplitude profile or an intensity profile of the illumination source.

7. The method of claim **1**, further comprising:

producing the OPC corrected first layout pattern on a mask-blank to create a photo mask.

8. A method comprising:

determining a first transmission cross coefficient (TCC) operator of an optical system of a lithographic system based on an illumination source of the optical system and an exit pupil of the optical system of the lithographic system;

sampling the illumination source of the optical system by a first number of sampling points at a first number of sampling locations to make a first discrete source;

determining a second TCC operator of the optical system of the lithographic system based on the first discrete source and the exit pupil of the optical system;

determining an error between the first TCC operator and the second TCC operator;

recursively adjusting the first number of sampling points and the first number of sampling locations to re-sample the illumination source and to re-determine the second TCC operator based on the re-sampled illumination source until the error is within a threshold error range and a final discrete source and a final second TCC operator is determined, wherein the threshold error range has an upper limit and a lower limit;

performing an inverse lithographic transformation (ILT) operation of a first layout pattern of a photo mask, wherein the ILT operation uses the final discrete source and the final second TCC operator to determine a projected image of the first layout pattern of the photo mask on a wafer for determining an ILT enhancement of the first layout pattern; and

producing the ILT enhanced first layout pattern on a mask-blank to create a photo mask.

9. The method of claim **8**, wherein the error is above the upper limit of the threshold error range, and wherein the re-sampling the illumination source comprises:

increasing the first number of sampling points to a second number of sampling points;

uniformly sampling the illumination source with the second number of sampling points; and

recursively adjusting sampling locations of the second number of sampling points to re-sample the illumination source and to re-determine the second TCC operator based on the re-sampled illumination source until the error is minimized.

10. The method of claim **8**, wherein the error is below the lower limit of the threshold error range, and wherein the re-sampling the illumination source comprises:

decreasing the first number of sampling points to a second number of sampling points;

uniformly sampling the illumination source with the second number of sampling points; and recursively adjusting sampling locations of the second number of sampling points to re-sample the illumination source and to re-determine the second TCC operator based on the re-sampled illumination source until the error is minimized.

11. The method of claim **8**, further comprising:

representing the final second TCC operator by a weighted sum of a plurality of kernels in a kernel space;

approximating the final second TCC operator by a weighted sum of two or more kernels of the plurality of kernels; and

using the approximated final second TCC operator and the first discrete source to determine the projected image of the first layout pattern of the photo mask on the wafer.

12. The method of claim **8**, wherein the first TCC operator and the second TCC operator are respectively discretized to generate a first TCC matrix and a second TCC matrix, the method further comprising:

determining the error by determining a Frobenius-norm error between the first TCC matrix and the second TCC matrix.

13. The method of claim **8**, further comprising:

prior to the performing the ILT operation of the first layout pattern:

performing an optical proximity correction (OPC) operation of the first layout pattern, wherein the ILT operation uses the final discrete source and the final second TCC operator to determine a projected image of the first layout pattern of the photo mask on the wafer; and

performing the ILT operation of the OPC corrected first layout pattern using the final discrete source and the final second TCC operator to determine the projected image of the OPC corrected first layout pattern of the photo mask on the wafer.

14. The method of claim **8**, further comprising:

receiving a second layout pattern, different from the first layout pattern, of the photo mask of the lithographic system; and

performing the ILT of the second layout pattern using the final discrete source and the final second TCC operator to determine a projected image of the second layout pattern of the photo mask on the wafer.

15. A lithographic system, comprising:

a main controller;

a photo mask;

a mask enhancer coupled to the main controller;

an optical system comprising an illumination source and coupled to the main controller;

a mask projector coupled to the main controller and the mask enhancer and configured to produce a projection of the photo mask on a wafer;

an analyzer module coupled to the main controller, wherein the analyzer module is configured to receive a first layout pattern of the photo mask to be produced on the wafer;

the mask enhancer is coupled to the analyzer module through the main controller and is configured to receive the first layout pattern from the analyzer module and to perform one of an optical proximity correction (OPC) operation or an inverse lithographic transformation (ILT) operation of the first layout pattern;

the mask enhancer is further configured to determine a final discrete source and a final second TCC operator by:

receiving a first number of sampling points from the analyzer module;

determining a first transmission cross coefficient (TCC) operator of the optical system of the lithographic system based on the illumination source of the optical system and an exit pupil of the optical system;

sampling the illumination source of the optical system by the first number of sampling points to make a first discrete source;

determining a second TCC operator of the optical system of the lithographic system based on the first discrete source and the exit pupil of the optical system;

determining an error between the first TCC operator and the second TCC operator;

recursively adjusting the first number of sampling points to re-sample the illumination source and re-determining the second TCC operator based on the re-sampled illumination source until the error is below a threshold level and a final discrete source and a final second TCC operator is determined; and

wherein the mask projector is configured to perform the projection of the photo mask on the wafer for the OPC operation or the ILT operation using the final discrete source and the final second TCC operator to determine a projected image of the first layout pattern of the photo mask on the wafer.

16. The lithographic system of claim **15**, wherein the illumination source is a laser source.

17. The lithographic system of claim **15**, wherein the illumination source is one of a coherent source or a partially coherent source.

18. The lithographic system of claim **15**, wherein a profile of the illumination source is either:

a circular profile having a radius between 1 cm and 20 cm and having a constant amplitude; or

a Gaussian profile with a standard deviation between 1 cm and 20 cm.

19. The lithographic system of claim **18**, wherein:

the illumination source of the optical system is a polarized illumination source with two time varying electric or magnetic components in a first direction and in a second direction perpendicular to the first direction;

the first and second directions are perpendicular to a direction of travel of a beam of the polarized illumination source;

the analyzer module is further configured to determine a first variance profile of the component in the first direction, a second variance profile of the component is the second direction, and a covariance profile between the components of the first and second directions of the polarized illumination source;

the mask enhancer is further configured to:

assign one of the first variance profile, the second variance profile, or the covariance profile to the profile of the illumination source,

determine a final discrete profile of the assigned first variance profile, second variance profile, or the covariance profile, and

determine a final second TCC operator of the assigned first variance profile, second variance profile, or the covariance profile; and

the mask projector is also configured to perform a projection of the first layout pattern of the photo mask by the assigned profile of the polarized illumination source on the wafer for the OPC operation or the ILT operation using the determined final discrete profile and the final second TCC operator.

20. The lithographic system of claim **15**, wherein the illumination source is one of a deep ultraviolet or an extreme ultraviolet illumination source.

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