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研 究 経 過 報 告 書

東京大学学生委員会委員長　殿

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下記のとおり研究経過を報告します。

研究テーマ	ナノ機能構造の光学的検査を実現する コヒーレント型構造照明超解像顕微法の開発
研究経過報告	（注：適宜参考資料を添付してください。） 本研究は，構造照明を用いてコヒーレント光学系における超解像の実現を目指す研究である．とくに半導体パターン検査現場への応用を見据えた実験装置の発展的開発に重点をおいている． 本年度は 1. 超解像アルゴリズムの改善 2. 位相情報を利用した超解像手法導入に向けた予備的検討 3. 点像分布関数制御機構を備えた実験装置の構築 4. 国内外学会における研究成果の発信 に取り組んだ． 1. コヒーレント系において扱いが重要な点像分布関数に関連する超解像処理時の計算手法の改善に取り組んだ．また，これまで用いてきた逐次再構成アルゴリズムとは異なる再構成法として非線形最適化手法の開発に取り組んだ． 2. 位相情報を取得して利用する超解像手法開発に先駆けて，試料から発せられる散乱光が位相の不整合を有する場合の結像面における電場の様子を，フーリエ光学に基づくシミュレーションにより調査した． 3. 本研究では点像分布関数の負値を除去するために，物体面に対応するフーリエ変換面にガウシアンフィルタを設置する．対物レンズ鏡筒内にあって直接フィルタを設置することができないフーリエ変換面を，共役な位置に拡大しつつ取り出す構成を有する実験装置を構築し，フーリエ変換面における光の強度のプロファイルを確認した． 4. 国内会議精密工学会秋季大会（仙台）と国際会議ISMTII2015（台北，台湾）に参加した．前者では特に点像分布関数制御による超解像について，後者では本研究の超解像手法を包括的に口頭発表した（資料1，2）． 今後は上記内容を修士論文にまとめる．

上記の通り相違ありません。

指導教員：高橋 哲　㊞

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資料 1

定在波シフトによる半導体ウエハ表面の超解像光学式欠陥検査（第**20**報）
– ガウシアンフィルタを用いた点像分布関数制御の基礎的検討 –

東京大学　○久米 大将，金 成碩，道畑 正岐，高増 潔，高橋 哲

Super-Resolution Optical Inspection for Semiconductor Defects Using Standing Wave Shift:
Method for Elimination of Negative Values in Point Spread Function with Gaussian Filter

The University of Tokyo　Hiromasa KUME, Chengshuo JIN, Masaki MICHIHATA, Kiyoshi TAKAMASU, and Satoru TAKAHASHI

Optical measurement techniques with high resolution beyond the diffraction limit are required for defect detection and inspection of microstructures including line patterns on silicon wafers. Conventional methods using standing wave illuminations cannot be applied to coherent imaging systems because the destructive superposition occurs. The dominant cause is the differences of adjacent peaks of the standing wave. Another cause is negative values of the point spread function. We have developed a super-resolution method using a standing wave illumination with three-beam interference to solve the problem due to the former. In this paper, in order to solve the latter, we introduce a Gaussian filter for modifying the point spread function. We confirmed the feasibility of the proposed method by simulations.

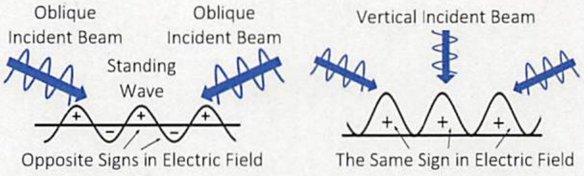
1. 序論

半導体デバイスの製造現場において，デバイスの欠陥検出のために高速で高分解能を有する計測手法の確立が求められている．SEM や SPM を用いた計測は高い解像力を有する反面，真空環境を要すること，観察対象を損なう恐れがあること，計測に長時間を要することなどの欠点がある．対して光学的計測は真空環境不要・非侵襲・一括計測性という利点を有するが分解能が回折により制限される．そこで回折限界を超える解像（超解像）を目指した研究が行われてきた．これまで構造照明顕微法[1]に着目した超解像顕微技術が盛んに開発されている．しかし，現在確立されている技術は蛍光試料などを対象としたインコヒーレント結像系への適用に限定されており，コヒーレント結像系への適用は困難である．その主な原因は，構造照明の電場の異符号領域にある散乱体から発せられる散乱光同士が破壊的干渉を起こすことである．我々は，この問題を解決しコヒーレント結像系への適用を可能とする超解像顕微法として，電場の符号が全領域で等しい 3 光束干渉定在波照明を微小シフトさせて計測する手法を開発してきた[2]．

コヒーレント結像系における破壊的干渉のもう一つの原因は，点像分布関数（Point Spread Function, PSF）が負値を持つことである．一般に PSF はベッセル関数形であり負値を持つため，照明の電場の符号が等しい場合でも発せられる散乱光は破壊的干渉を起こす．このため，散乱体の散乱効率分布が離散的でない場合に解像性能を低下させる原因となる．本稿では，3 光束干渉定在波の利用に加えガウシアンフィルタにより周波数領域で PSF を制御することで PSF の負値を除去する手法を提案する．連続的な散乱効率分布を持つ試料を想定した散乱体分布再構成シミュレーションにより提案手法の有効性を検証する．

2. 3 光束干渉定在波照明シフトによる超解像法

本研究では，試料面に対向レーザ光（斜方照明）を照射することで形成される 2 光束干渉定在波に落射照明を加えた 3 光束干渉定在波を構造照明として用いる．2 光束干渉定在波は領域により電場の符号が異なり（Fig. 1 (a)），コヒーレント結像系では異符号の電場領域から発せられた散乱光同士が破壊的干渉を起こす．これは，散乱体の分布に応じた散乱強度が観察されるという超解像処理の前提に反するため解像結果に悪影響を及ぼす．そこで，試料面に垂直方向からレーザ光（落射照明）を照射し，斜方照明に同期させることで 2 光束干渉定在波を嵩上げし，全領域で電場の符号が等しい定在波を生成する（Fig. 1 (b)）．定在波が全領域で同符号であるため，照明に起因する破壊的干渉が起こらずコヒーレント結像条件の逐次再構成処理を適用することができる．3 光束干渉定在波シフトによる超解像法のフローチャートを Fig. **2** に示す．



(a)　(b)

Fig. 1 Standing wave formed by two beams (a) and that by three beams (b).

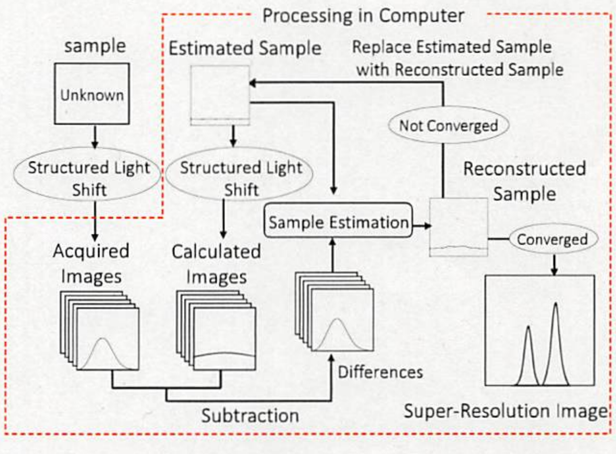


Fig. 2 Diagram of super-resolution image reconstruction algorithm.

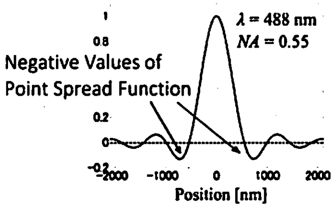


Fig. 3 The point spread function expressed by Bessel function.

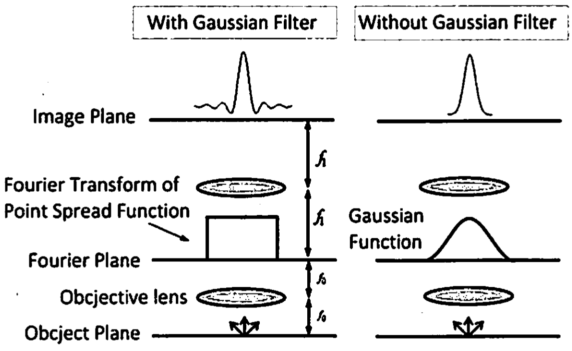


Fig. 4 Schematic of the method with a Gaussian filter.

3. ガウシアンフィルタを用いた点像分布関数制御

試料から発せられる散乱光分布と点像分布関数（PSF）の畳み込みにより像が形成される．PSFはベッセル関数で表され負値を持つため（Fig. 3），コヒーレント結像系において散乱体から発せられた散乱光は，PSFの負値領域に相当する位置から発せられた散乱光との間に破壊的干渉を起こす．散乱体が離散的に分布し，散乱効率が1または0とみなせる場合，PSFの負値に起因する破壊的干渉が超解像再構成処理に与える影響は無視できる．しかし，試料の散乱効率が空間的に連続して変化する場合は，PSFの負値に起因する破壊的干渉は解像結果に著しい悪影響を与えると考えられる．

そこで，負値を持たずかつフーリエ変換前後で関数形が保存されるガウス関数に着目し，ガウス関数状に透過率が変化するフィルタ（ガウシアンフィルタ）を光学系のフーリエ面（レンズの焦点面）に設置することでPSFの負値を除去する手法を提案する．ガウシアンフィルタによるPSF制御の概念図をFig. 4に示す．物体面から発せられた散乱光の情報は光学系のフーリエ面で周波数情報へと変換される．フーリエ面にガウシアンフィルタを設置することで，PSFのフーリエ変換は，ベッセル関数のフーリエ変換である矩形関数にガウス関数を乗じた形へと変換される．したがって，結像面においてPSFは負値を持たないガウス関数形となり，PSFに由来する破壊的干渉は起こらない．ここでは，ガウス関数の1%半径（ガウス関数の最大値の1%の値をとる周波数）が遮断周波数（$\frac{NA}{\lambda}$）と一致するようにフィルタを設計している．

4. 連続的散乱効率分布再構成シミュレーション

3光束干渉定在波照明に加えてガウシアンフィルタを用い，試料の表面組成・性状の変化に起因して散乱効率分布が連続的に変化する試料を想定した基礎的なシミュレーションを，フーリエ光学に基づいて行った．想定した試料の散乱効率分布をFig. 5に示す．まず，3光束干渉定在波照明を9回シフトさせコヒーレント結像条件で10枚の散乱光結像分布を算出する．光源波長，対物レンズのNA，定在波ピーク間隔，1回の照明シフト距離はそれぞれ488 nm，0.55，519 nm，51.9 nmである．ガウシアンフィルタを用いない場合と用いた場合に得られる結像分布を重畳表示したものをそれぞれFig. 6，Fig. 7に示し，取得像にもとづき逐次再構成処理により散乱効率分布を再構成した結果をそれぞれFig. 8，Fig. 9に示す．ガウシアンフィルタを用いない場合には全く復元されない散乱効率分布が，ガウシアンフィルタによりある一定の周波数成分まで復元されており，フィルタを用いることによる再構成結果の改善が確認された．

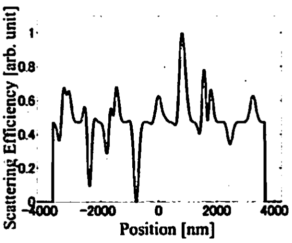


Fig. 5 Sample in which scattering efficiency varies continuously.

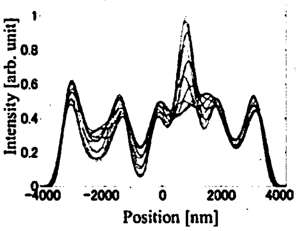


Fig. 6 Acquired images without a Gaussian filter.

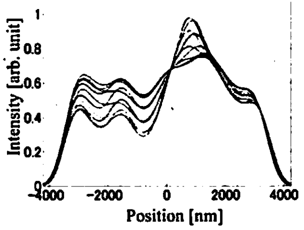


Fig. 7 Acquired images with a Gaussian filter.

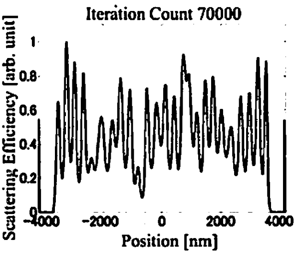


Fig. 8 Result of the method without a Gaussian filter.

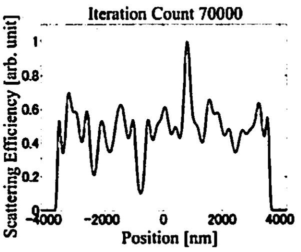


Fig. 9 Result of the method with a Gaussian filter.

5. 結論と今後の展望

3光束干渉定在波照明に加えガウシアンフィルタを用いて，破壊的干渉の原因の一つである点像分布関数の負値を除去する手法を提案し，シミュレーションにより連続的散乱効率分布を持つ試料に対する解像結果の向上を確認した．今後は実サンプルを用いて提案手法の検証実験を行う．フィルタの中心と光軸の不一致が解像結果に与える影響の調査などが今後の課題である．

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資料2

Super-Resolution Optical Measurement Method Using Standing Wave Illumination with Three-Beam Interference

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Keywords: Standing Wave Illumination, Image Reconstruction, Super-Resolution

Abstract. Optical measurement techniques with high resolution beyond the diffraction limit are required for defect detection and inspection of microstructures including line patterns on silicon wafers. Conventional methods using standing wave illuminations with two-beam interference cannot be applied to patterned wafer inspections which deal with coherent imaging systems because the destructive superposition occurs. There are two causes of the destructive superposition. The dominant cause is the differences of phases of adjacent peaks of the standing wave. The other is the point spread function. We propose a method with a standing wave illumination generated by three-beam interference and with a Gaussian filter. We confirmed the feasibility of the proposed method by simulations.

Introduction

As semiconductor devices have been become smaller, measurement techniques with high resolution are required for defect detection and inspection of microstructures including line patterns on silicon wafers. Compared to measurement methods with SEM or SPM [1], optical measurement methods are effective because of being nondestructive and their wide measurement ranges. In optical measurements, however, resolution is limited by numerical apertures because of influence of diffraction. Therefore optical measurement methods with resolution beyond the diffraction limit have been proposed. Methods using structured light can be expected to have higher resolution than those using normal light with a flat distribution of intensity [2, 3].

Methods using standing wave illuminations as structured light illuminations have been developed and applied to fields of biotechnology [4]. However, the range of applications of the methods is limited to incoherent imaging systems such as fluorescent samples because destructive superposition occurs.

There are two causes of the destructive superposition. The dominant one is the structured light illumination used in the methods. In the conventional methods, a standing wave is generated by two oblique incident beams. The electric fields of adjacent peaks of the standing wave illumination have different signs. Therefore, scattered lights from scattering objects in the electric fields that have different signs interfere destructively. This is contrary to a premise that observed intensity distributions of scattered light depend on distributions of scattering objects. Therefore the range of applications of the methods is limited to incoherent imaging systems in which destructive interference does not occur. The other cause of destructive superposition is negative values in the point spread function expressed by a Bessel function.

In order to solve the problem due to the former, we propose a method with a standing wave illumination generated by three-beam interference. In the standing wave in the proposed method, the signs of the electric fields are the same. Therefore, destructive superposition is not caused by the illumination and consequently reconstruction computations can be applied to this method in coherent imaging systems. In addition, a Gaussian filter is used to solve the latter. A Gaussian filter is a filter whose transmittance varies as a Gaussian function. By placing a Gaussian filter at the Fourier plane, the point spread function can be expressed by a Gaussian function which has no negative values, and thus the destructive superposition does not occur.

Our simulation results demonstrate the validity of this method. The results show that the proposed method has a resolution beyond the diffraction limit, and is capable of reconstructing structures of scattering objects that cannot be reconstructed with the conventional methods in coherent imaging systems.

Measurement Methods with Standing Wave Illumination in Coherent Imaging Systems

Problems of Application to Coherent Imaging Systems. The outline of methods with structured light illumination is as follows: First, multiple images are acquired while the position of the structured light illumination changes. The acquired images vary depending on the position of the illumination, and each image contains high frequency information of each intensity distribution of the illumination. Second, an image reconstruction processing is performed in order to obtain the super-resolution image. In order to make use of the high frequency information contained in the images acquired by using the structured light illumination, a reconstruction algorithm based on the Richardson-Lucy method [5] is used after the image acquisition. The diagram of the algorithm is shown in Fig. 1. Measurement objects are expressed as scattering efficiency distributions, and it is assumed that the response of each scattering object on the sample is proportional to the product of the electric field produced by the illumination and the scattering efficiency. In this process, first, estimated image distributions at each position of the illumination are calculated based on the estimated sample distribution. The initial solution of the sample distribution is a uniform value. Then, the differences between the acquired image distributions and the estimated image distributions are fed back to the estimated sample distribution, which becomes the next estimated solution. The above process is repeated until convergence and the sample distribution is obtained.

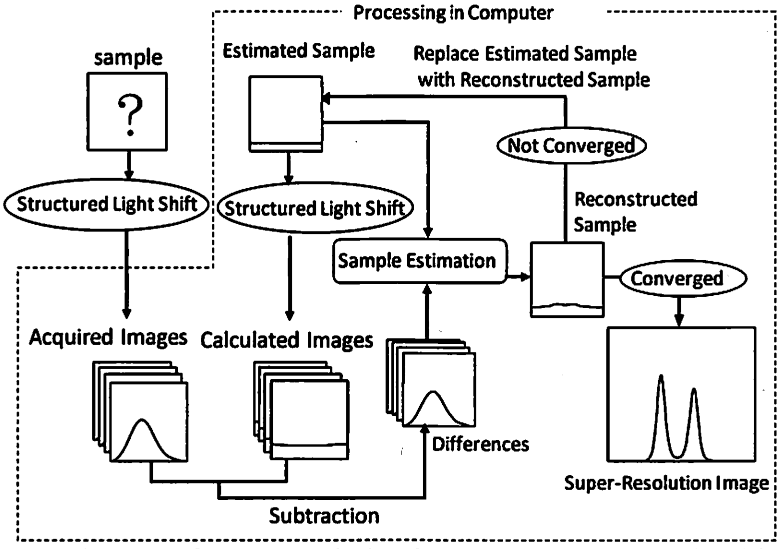

Fig. 1. Diagram of super-resolution image reconstruction algorithm.

In the conventional methods, a standing wave illumination is used as a structured light illumination. The standing wave illumination with two-beam interference is generated by two oblique incident laser beams. The schematic of the standing wave with two-beam interference is shown in Fig. 2. The reconstruction processing described above is based on a premise that observed intensity distributions of scattered light depend on scattering object distributions. However, this premise is not satisfied in coherent systems. This is because destructive interference in which scattered lights from scattering objects cancel with each other can occur. In the conventional methods, the signs of the electric fields of adjacent peaks in the standing wave are different from each other. In incoherent imaging systems, this difference of signs does not cause the destructive interference because images are formed by superposition of squares of the electric fields. In contrast, in coherent imaging systems, images are formed by squares of superposition of the electric fields. Therefore, scattered lights from scattering objects in electric fields that have different signs interfere destructively. Consequently, the conventional methods with standing wave illumination cannot be applied to coherent imaging systems.

There is another problem that causes the destructive interference in coherent imaging systems: the negative values in the point spread function. Images are formed by convolution of scattering light distributions and the point spread function. A schematic of the point spread function is shown in Fig. 3. The point spread function is expressed by a Bessel function which has negative values. In coherent imaging systems, scattered lights from scattering objects in negative parts of the point spread function of other scattering objects interfere destructively. In cases where scattering objects are distributed discretely and their scattering efficiencies can be treated as binary digits, it can be assumed that the performance of the reconstruction processing is hardly affected by negative values of the point spread function. However, in cases where the scattering distribution varies continuously, the reconstruction performance can be seriously affected by the negative values.

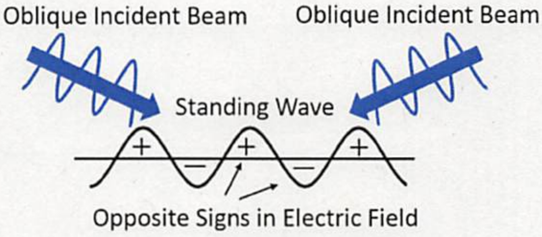

Fig. 2. Standing wave formed by two-beam interference.

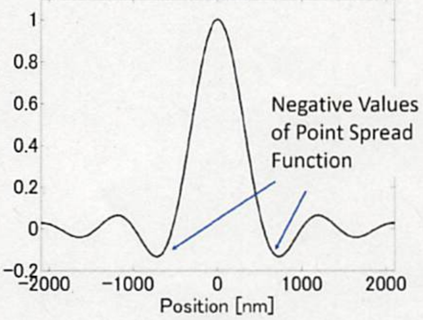

Fig. 3. The point spread function expressed by Bessel function.

Standing Wave Illumination with Three-beam Interference. In order to solve the dominant problem due to the difference of signs of adjacent peaks of the standing wave illumination described in the previous subsection, a standing wave illumination generated by three-beam interference is used in the proposed method. A schematic of the standing wave is shown in Fig. 4. First, a standing wave illumination is generated by two oblique incident beams on the sample plane. Then, a plane wave is entered vertically into it. This vertical incident beam has the same frequency as that of the oblique beams. This plane wave is synchronized to the standing wave so as to raise its standard, and thus it makes all of the signs of the electric field same over the whole area of the observation surface [6]. Therefore, the illumination does not cause destructive superposition and consequently the reconstruction computations can be applied to this method in coherent imaging systems.

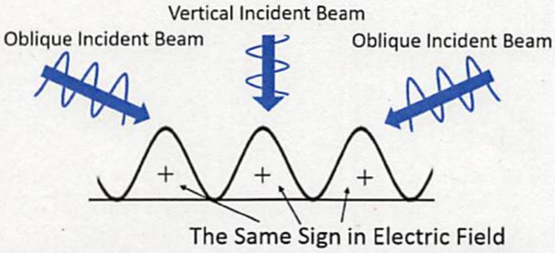

Fig. 4. Standing wave with three-beam interference.

Modified Point Spread Function. In order to solve the second problem described in the previous section, a Gaussian filter is introduced to modify the point spread function. Transmittances of Gaussian filters vary as Gaussian functions. Gaussian functions have no negative values and the Fourier transform of a Gaussian function is also a Gaussian function. A schematic of the method with a Gaussian filter is shown in Fig. 5. By placing a Gaussian filter at the Fourier plane, the Fourier transform of the point spread function becomes the product of a Gaussian function and a rectangular function which is the Fourier transform of a Bessel function. Consequently, the point spread function becomes a Gaussian function at the image plane which has no negative values. Therefore, the destructive interference does not occur. In this method, the Gaussian function is designed with the following condition (Fig. 6): the extent in which values are more than 1 % of the maximum value of the Gaussian function is equal to that from the negative cutoff frequency to the positive one.

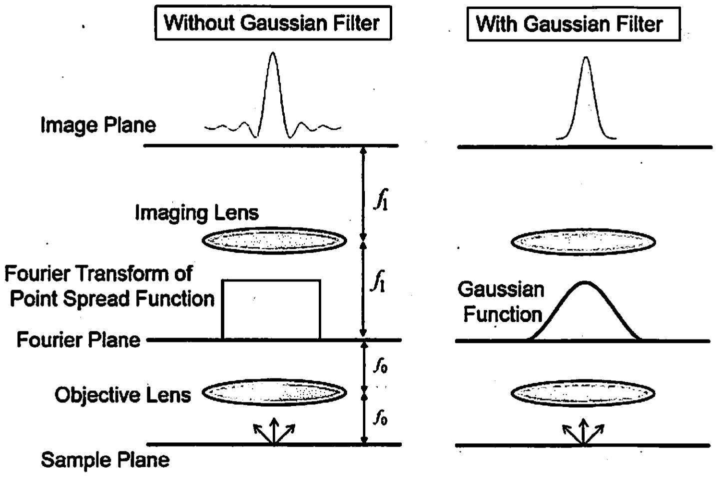

Fig. 5. Schematic of the method with a Gaussian filter.

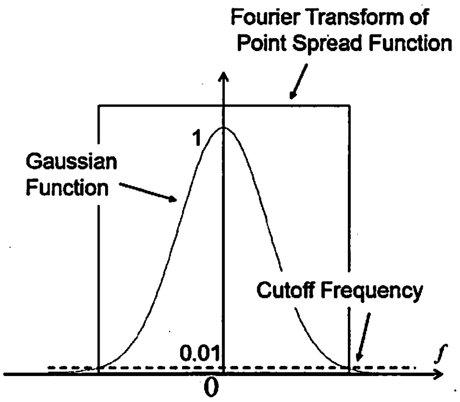

Fig. 6. Design of the Gaussian filter.

Simulation Experiments

Simulation with Basic Sample. We conduct basic simulation experiments based on Fourier optics with a sample that contains two scattering objects. The sample is shown in Fig. 7. The distance of the two scattering objects is 300 nm. The simulation conditions is described below. The wavelength of the laser beams is 488 nm and the numerical aperture (N.A.) of the objective lens is 0.55. The incident angle of the oblique incident beams is 70.0 degree. The standing wave illumination is moved nine times and 10 images are acquired. The amount of each movement is the quotient obtained from division of the interval of the standing wave peaks by the number of the images. From the wavelength and N.A., the Rayleigh diffraction limit is calculated to be 541 nm, which is larger than the distance of the sample.

The results of the conventional method with the two-beam standing wave illumination assuming incoherent imaging system and coherent imaging system are shown in Fig. 8 and Fig. 9, respectively. Although the sample structure can be reconstructed by the method of the two-beam standing wave in the incoherent imaging system, it cannot be reconstructed in the coherent imaging system. It shows that the conventional method cannot be applied to coherent imaging systems. The result of the method with the standing wave illumination generated by three-beam interference assuming coherent imaging system is shown in Fig. 10. The distance of the scattering objects are reconstructed. These results indicates that the proposed method has resolution beyond the diffraction limit and can be applied to coherent imaging systems.

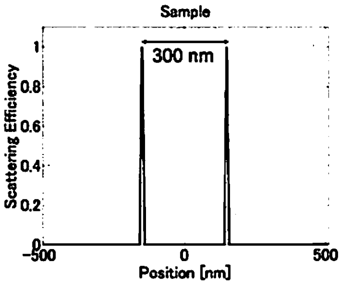

Fig. 7. Sample with two scattering objects.

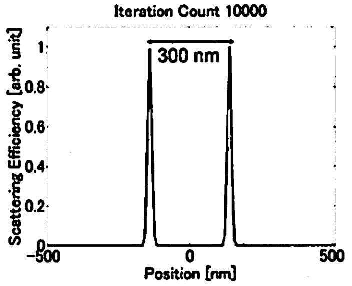

Fig. 8. Result of the method with two-beam standing wave in incoherent imaging system.

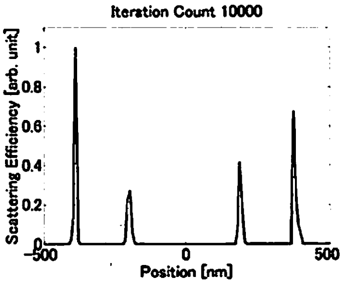

Fig. 9. Result of the method with two-beam standing wave in coherent imaging system.

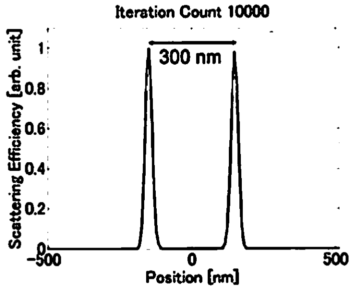

Fig. 10. Result of the method with three-beam standing wave in coherent imaging system.

Simulation with Practical Sample. Additional simulations assuming coherent imaging systems are conducted with a practical sample in which scattering objects are arranged at different intervals. The sample is shown in Fig. 11. Scattering objects are arranged at intervals of 300 nm and 900 nm. This sample is modeled on line patterns on silicon wafers. The simulation conditions are basically the same as those in the two-point sample simulation. In this simulation, the diffraction limit is 541 nm. The result of the simulation with the conventional method using the two-beam standing wave and that with the proposed method using the three-beam standing wave are shown in Fig. 12 and Fig. 13, respectively. The results show that the sample that cannot be reconstructed by the method with two-beam standing wave is reconstructed by the proposed method with three-beam standing wave.

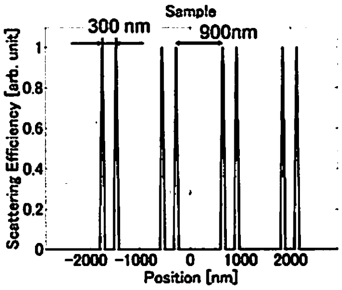

Fig. 11. Sample in which scattering objects arranged at different intervals.

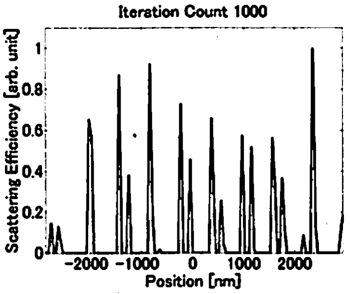

Fig. 12. Result of the method with two-beam standing wave in coherent imaging system.

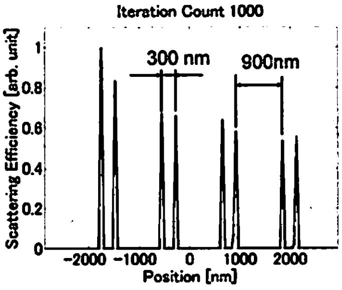

Fig. 13. Result of the method with three-beam standing wave in coherent imaging system.

To confirm the effect of the Gaussian filter, we also conduct simulations with a sample in which scattering efficiencies vary continuously, which is shown in Fig. 14. The result of the simulation with the three-beam standing wave without a Gaussian filter is shown in Fig. 15. The distribution of the scattering efficiency of the sample is not reconstructed. We speculate that the destructive superposition due to negative values of the point spread function affects the performance because the scattering objects are arranged not discretely but continuously. The result of the simulation with the three-beam standing wave with the Gaussian filter is shown in Fig. 16. The result is improved compared to that without a Gaussian filter. The results show the effect of the Gaussian filter.

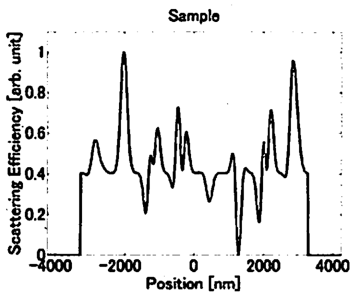

Fig. 14. Sample in which scattering efficiency varies continuously.

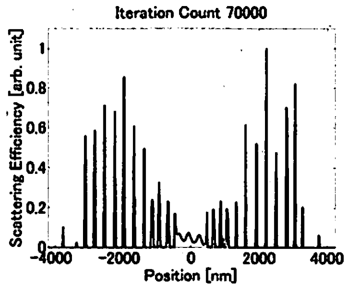

Fig. 15. Result of the method with three-beam standing wave without a Gaussian filter in coherent imagin system.

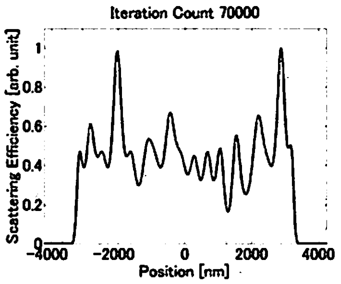

Fig. 16. Result of the method three-beam standing wave with a Gaussian filter in coherent imagin system.

Conclusions

An optical super-resolution measurement method for coherent imaging systems was proposed. We introduced a standing wave illumination generated by three-beam interference to solve the problem caused by the structured light illumination in the conventional method. In addition, we proposed a Gaussian filter to solve the problem caused by the point spread function. Subsequently, simulations assuming coherent imaging systems were conducted, and the basic theoretical validity of our method was demonstrated. Conducting experiments with actual samples forms our future tasks.

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