# Speckle suppression in laser-scanning dark-field imaging systems with Laguerre-Gaussian beams and matched filtering.

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Abstract – We present a novel speckle-suppression technique for a darkfield laser scanning imaging system, which uses Laguerre-Gaussian beams together with matched filtering to suppress speckle noise and boost signal to noise ratio (SNR). Using a numerical electromagnetic simulation for a line and space layer, we show a 1.8X improvement in SNR. This technique could have applications in large array regions of patterned wafers, deposition layers and film inspection.

## I. Introduction

A key problem that all coherent or partially coherent wafer inspection systems face today is that of speckle noise from surface roughness or line edge roughness. Historically, various methods have been used to suppress speckle *viz.*, channel fusion, which uses de-correlation between the collection channels to improve signal to noise ratio, cross-polarization in collection with respect to the illumination polarization and creating of partially coherent systems with angular or wavelength diversity. Also, matched filtering has been used previously to suppress uncorrelated noise sources like shot-noise. However, it is well known that when a rough area is scanned with a Gaussian beam, the speckle generated retains the point spread function of the incident beam and therefore using a matched filter does not result in any improvement in the defect signal to noise ratio. In this paper, we present a new method to obtain speckle suppression by inspecting wafers with Laguerre-Gaussian (LG) beams and algorithmic filters matched to the PSF of the higher order LG beams. Below we begin with an introduction to LG beams, followed by the concept of the detection scheme, followed by simulation results, and conclusion

### A. Laguerre-Gaussian Beams

LG beams are essentially higher order Gaussian beams. Fig. 1 shows the equation of Laguerre-Gaussian beams [1]. Here $p$ corresponds to the radial component of the beam and $l$ is related to the azimuthal axis. LG beams with $l > 0$ carry an orbital angular momentum [1]. The traditional Gaussian beam corresponds to $l = 0, p = 0$ and results in a phase that is azimuthally symmetric. However, for $l > 0$, the phase gets an additional contribution from $\exp(-il\phi)$. LG beams can be generated using spiral phase plates or diffractive optical elements. There are companies that can manufacture such phase plates for DUV and UV wavelengths (e.g. HOLO OR, www.holoor.com). Fig. 2 shows the points spread function of $u_{01}$ beams. The point spread function of $u_{01}$ beams is that of a doughnut. Introduction of a spiral phase plate in the path of a traditional Gaussian beam $u_{00}$ imparts an orbital angular momentum to the beam and creates a doughnut shaped point-spread function. A spiral phase plate also breaks the phase symmetry for a Gaussian beam.

$$u_{pl}(r,\phi,z) = \frac{C}{(1+z^2/z_R^2)^{1/2}} \left[\frac{r\sqrt{2}}{w(z)}\right]^l L_p^l \left[\frac{2r^2}{w^2(z)}\right] \times \exp\left[\frac{-r^2}{w^2(z)}\right] \exp\frac{-ikr^2 z}{2(z^2+z_R^2)} \exp(-il\phi) \times \exp\left[i(2p+l+1)\tan^{-1}\frac{z}{z_R}\right],$$

**Fig. 1**. Equation for a Laguerre-Gaussian beam. Here p,l are the radial and azimuthal index of the beam, $z_R$ is the Rayleigh-range, $w(z)$ is the radius of the beam, $L_p^l$ is the associated Laguerre polynomial and C is a constant [1].

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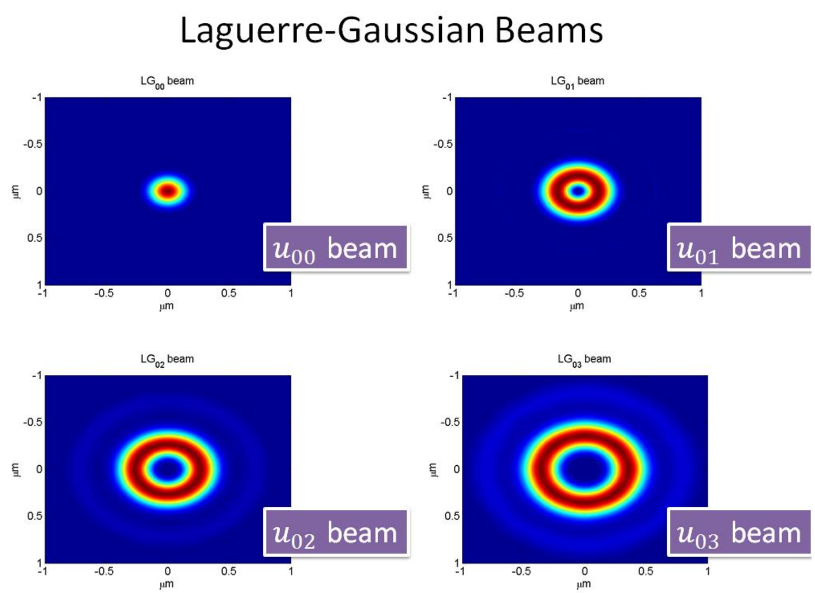


**Fig. 2**. Point spread functions of Laguerre-Gaussian beams. Higher order beams have a doughnut shaped PSF.

## II. Concept and Simulation

The point spread function (PSF) of a traditional narrowband systems has been a Gaussian beam (a zero-order LG beam). Because of this, both defects and speckle noise have the same PSF and the only way to differentiate between them is a threshold based on intensity. Current algorithms are designed to harness the idea that a defect will scatter strongly than surface roughness or line edge roughness. However, it is critical to remember that defect scatter is an energy phenomenon, while speckle is an interference phenomenon. **For a higher order Gaussian beam, with high likelihood the defect signal will be highly correlated with incident beam PSF, however for speckle because it originates from interference of scattered waves, the likelihood that it has constructive interference on all points of the PSF is low. Speckle will have similar correlation length (width) as the PSF but not necessarily the same shape.** For a traditional Gaussian beam, the correlation length is related to the width of the PSF. Therefore, a speckle feature and a defect look similar and the only way to differentiate them is the intensity. However, when the PSF is a higher order Gaussian beam, the defect has the shape of the PSF (a doughnut), while the speckle feature need not necessarily have the same shape. **With this a matched filter can be used to extract the defect out of the image, while rejecting the surrounding noise, resulting in higher SNR.**

### *A. Simulation and Results*

A simulation was setup for a 0.67 NA normal incidence illumination system and dark-field collection geometry as shown in Fig. 3. The simulation was carried out with a commercial finite difference time domain (FDTD) solver by Panoramic Technology Inc. . The simulation scenario is shown in Fig. 4, where a 12 nm line (silicon) and 6nm space (air) structure with a line edge roughness equivalent of 0.5 nm RMS and a 6nm x 3nm protrusion defect is simulated.

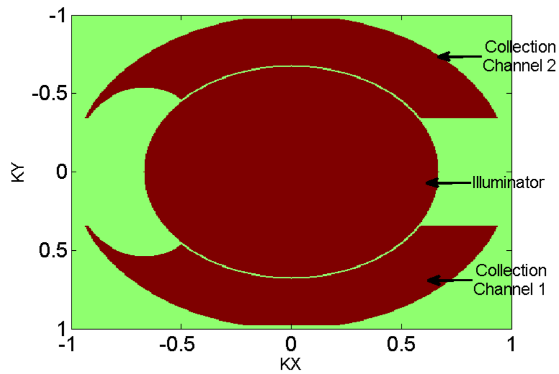


**Fig. 3**. Illumination and collection geometry in the NA space (top down view).

The defect was scanned with a $u_{00}$ beam, $u_{01}$ beam and a $u_{02}$ beam. It is clearly visible that in case of the $u_{00}$ beam the defect and the speckle have very similar shapes. They can only be differentiated on the basis of intensity. On the other hand, when the defect is scanned with a $u_{01}$ or $u_{02}$ beam, the defect retains the shape of the beam, while the speckle point does not. **Now, there are two degrees of freedom on the basis of which the defect and noise can be differentiated**.

We harness this extra degree of freedom with a matched filter. In Fig. 5, we show the matched filtered images at the same scale and also list the corresponding SNR. **The SNR improves by 1.8X.** The images were filtered post additive channel fusion.

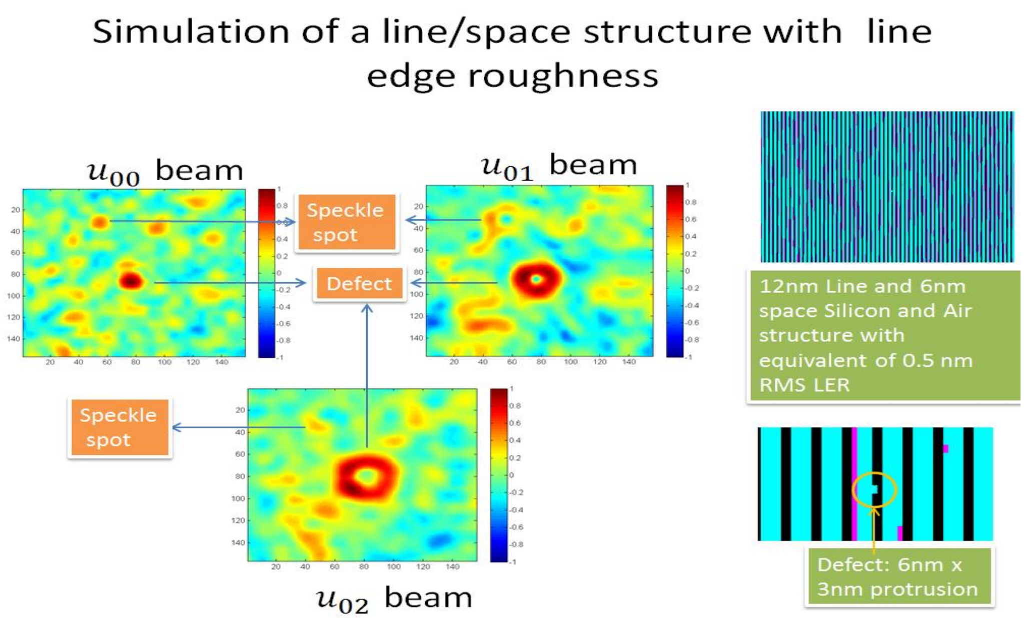


**Fig. 4**. A 6nm x 3nm protrusion scanned with $u_{00}$, $u_{01}$ and $u_{02}$ beams. Notice, how for the $u_{01}$ and $u_{02}$ beams, the defect clearly retains the PSF of the beam it was scanned with, i.e. it is fully “matched” to the PSF, while the speckle spots partially or don’t match at all to the PSF.

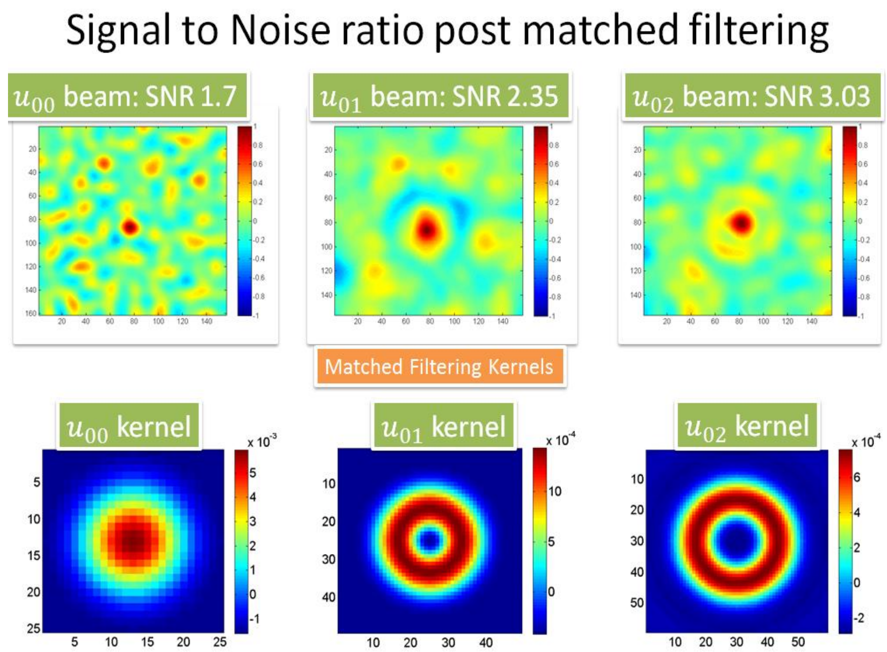


**Fig. 5**. Defect images post matched filtering with kernels corresponding to the $\mathrm{u}_{00}$, $\mathrm{u}_{01}$and $\mathrm{u}_{02}$ beams. A significant boost in SNR of about 1.8X is observed with the $\mathrm{u}_{02}$ beam compared to $\mathrm{u}_{00}$ beam.

## III. Conclusion

We have shown that higher order Gaussian beams can be used for detecting defects in the presence of strong speckle noise. In the simulation we demonstrated a 1.8X improvement in SNR. There are some physics and applications questions that need more study.

The key question with this result is why the speckle point doesn't have the same PSF as a higher order LG beam. There are two possible explanations. One is that a speckle needs to interfere constructively along the whole ring of the higher order Gaussian beam PSF, while it needs to constructively interfere only at the center of the $\mathrm{u}_{00}$ beam. Another possible explanation is the $\exp(il\phi)$ factor that is introduced in the higher order beam. This phase factor destroys the azimuthal symmetry of the $\mathrm{u}_{00}$ beam and the phase along the doughnut ring is no longer constant. The answer to this question requires more study.

The second question relates to the application space. Typical wafers have transition regions between page-break and array, where the tail behavior of a PSF is most important. The higher order beams have longer tails, which can impact defect detection in transition region. This behavior could be improved with appropriate apodization. The higher order beams can become another method that a dark-field imaging system uses especially in large arrays, dep-layers and back-end layers where the large wafer noise limits the use of dark-field systems.

## Bibliography

[1] L. Allen, M. Beijersbergen, R. Spreeuw and J. Woerdman, "Orbital Angular momentum of light and the transformation of Laguerre-Gaussian Modes," *Physical Review A*, vol. 45, no. 11, p. 8185, January 1992.