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# A New Phase Shifting Method for High Resolution Microlithography

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## ABSTRACT

This paper reports simulation and experimental details of a novel phase shifting technique based on interferometry. Phase shifting [1] is one of the most promising techniques for future high density DRAM fabrication. Conventional phase shifting-masks [2], however, are difficult to fabricate as they require regions of different optical thickness. This new phase shifting technique does not require any phase shifting materials on the mask. A special interferometer and a mask that has both transmitting areas and reflective areas accomplish the required phase-shift at the image plane. Phase shifting effects are confirmed using both CCD camera analysis as well as photoresist response. The results of computer simulations of critical resolution and error tolerance for this new method as compared with the conventional phase shifting technique are also presented.

## 1. INTRODUCTION

Advanced microlithography will be required in order to achieve the smaller size features demanded by future high density integrated circuit designs [3]. Phase shifting methods [4] are considered one of the most promising techniques to achieve this and, in recent years, many phase shifting methods have been proposed to extend the resolution limit and the contrast of image patterns. These techniques, however, have several limitations. The phase shifting elements on the mask need precise placement and exact thickness in order to achieve the desired amount of phase shifting. Further adjustment becomes impossible once the masks are fabricated. As a result, the manufacturing cost of phase shifting masks is high, and yields are at present quite low. This has slowed the introduction of the phase shift technique into the production line.

## 2. NEW PHASE SHIFTING METHOD

We describe here a new technique that does not require any phase shifting elements to be incorporated into the mask, but rather is based upon a special interferometric scheme shown in figure 1. A conventional one-layered reticle is used as both a reflective mask and a transmission mask.

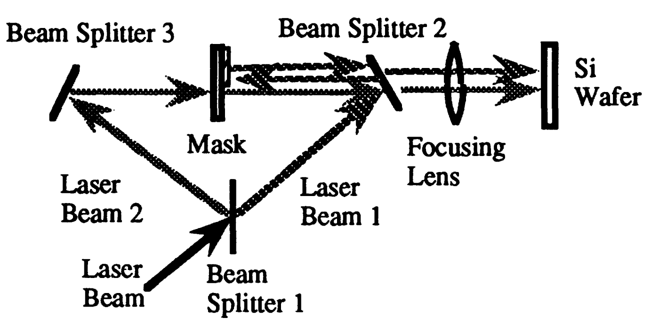


Figure 1. Scheme of the new phase shifting method.

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An incoming laser beam is divided into two by a beam splitter. These beams irradiate the mask from both the front and back side via two additional beam splitters. The reflected and transmitted beams are then combined and projected onto the target wafer through a focusing lens. The optical paths of the beams are chosen so that the phase of the two beams is different by an odd multiple of $\pi$ radians at the surface of the wafer. This is accomplished by adjusting the position of the mask to achieve the desired phase shifting effect as illustrated in figure 2. This method is particularly useful for shorter wavelengths, where it becomes increasingly difficult to find appropriate materials with which to fabricate a conventional phase shifting mask.

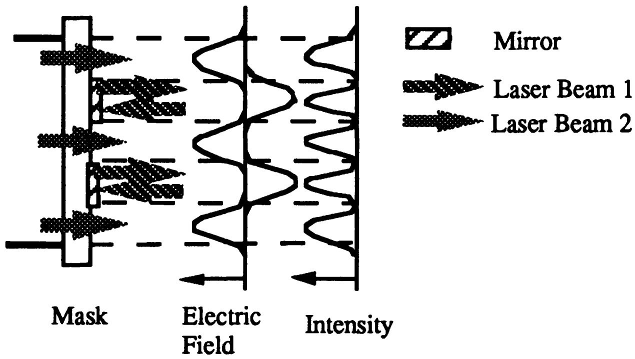



Figure 2. Phase shifting effects obtained by interferometry.

## 3. SIMULATIONS

To confirm and evaluate the performance of this new phase shift method, a comparison of the resolution achievable using a transmission mask, a conventional Levenson-type phase shifting mask [1,5,6,7] and the new method was simulated using the DEPICT photolithography simulator. DEPICT [8] is a lithography simulator produced by Technology Modeling Associates.

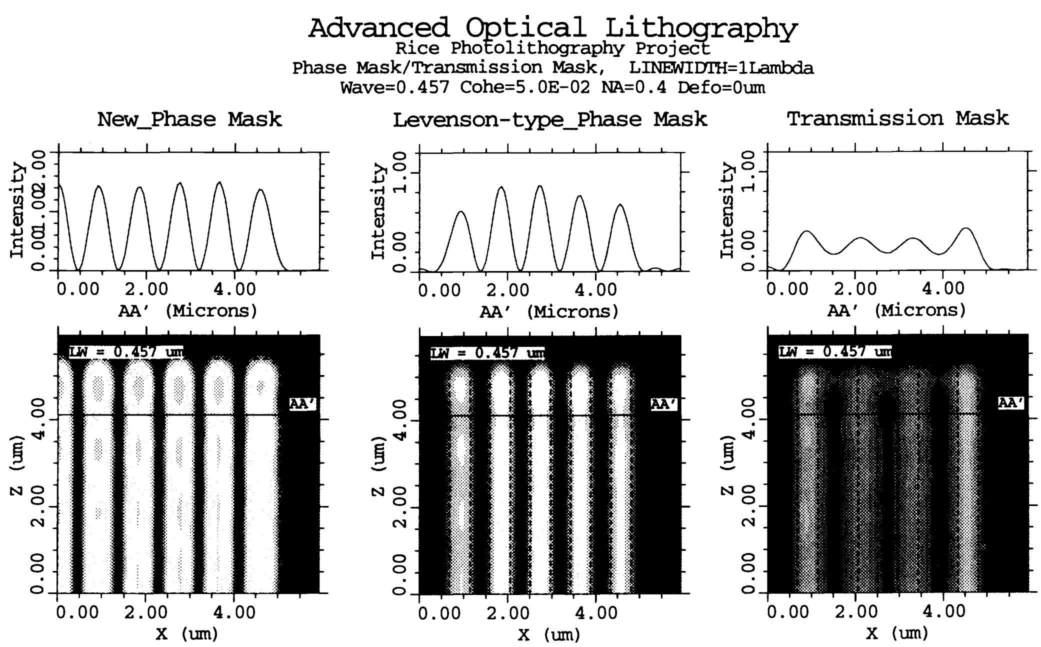



Figure 3. DEPICT results.

A line and space pattern was used to evaluate the resolution of each method. A standard line and space design was used for the Levenson-type phase mask and the transmission mask, and an alternating mirror and space pattern [8] for the new method. The system parameters were as follows: a numerical aperture (NA) of 0.4, spatial coherence of 0.05, and three laser wavelengths of 632.8 nm (He-Ne laser), 457 nm ($Ar^+$ laser) and 248 nm (KrF laser). Figure 3 shows the results of both one and two dimensional beam intensity distributions for each method.

Using a modified Rayleigh criteria many authors [9, 10] express the minimum resolution image period (P) as

$$\frac{P}{2} = \frac{K_1 \lambda}{NA} \qquad (1)$$

where $\lambda$ is the irradiated laser wavelength, NA is the numerical aperture [11] of the focusing lens, and $K_1$ is an empirical parameter ~ 0.5 for most imaging systems. P/2 is nearly equal to the line size (d in figure 4) in the critical regions, so that it is a good measure of the image size. Furthermore, the minimum resolution line width (~P/2) should scale with wavelength $\lambda$. This proved to be the case in the DEPICT simulations. Thus we can normalize the minimum linewidth by using

$$K_1 = \frac{P\ NA}{2\lambda} \qquad (2)$$

which then includes the effects of systems with different illumination wavelengths $\lambda$ or numerical aperture.

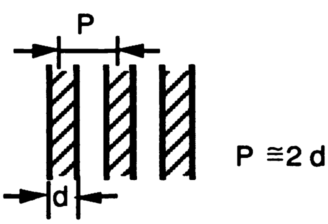
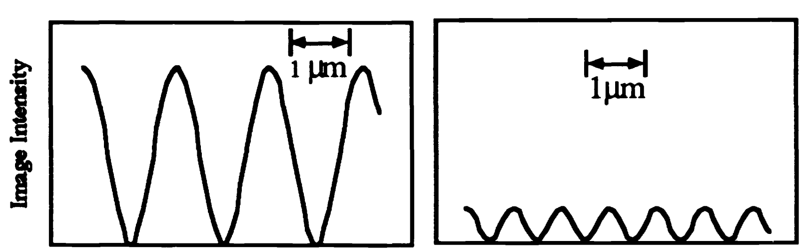



Figure 4. Definition of image period and line size.

In comparing various photolithographic techniques, two quantities are of particular interest; the minimum resolvable feature size, which is represented [12] by $K_1$, and the contrast C, which is usually defined [9] as

$$C = \frac{I_{peak} - I_{min}}{I_{peak} + I_{min}} \qquad (3)$$

where $I_{peak}$ is the intensity at the peak of the pattern and $I_{min}$ is the intensity at its minimum. In simulating the phase shifting methods with DEPICT, it was found that as the feature size was reduced, $I_{min}$ remained ≈ 0, while $I_{peak}$ steadily decreased (See Figure 5).




Larrge Resolution Image    Near-Critical Resolution Image

Figure 5. Image variation with feature size.

With $I_{min} \approx 0$, the contrast remained at nearly 100%, even though the quality of the resultant image was seriously degraded. Thus, a new performance index (PI) was introduced as

$$PI = I_{peak} C = I_{peak} \frac{I_{peak} - I_{min}}{I_{peak} + I_{min}} \quad (4)$$

The PI takes into account the peak intensity of the image, as well as its contrast and is a better measure of image quality than contrast alone.

Figure 6 shows the results of DEPICT simulations of all three photolithographic techniques, where the performance index PI is plotted as a function of $K_1$ or line size. As can be seen, although both the conventional phase shifting method and the new method have comparable minimum features sizes, the PI is significantly greater for the new method. This is because light from both the transparent as well as reflective regions of the mask reach the image plane, which results in a much brighter image. As would be expected, both approaches show significant advantages over the conventional transmission mask performance.

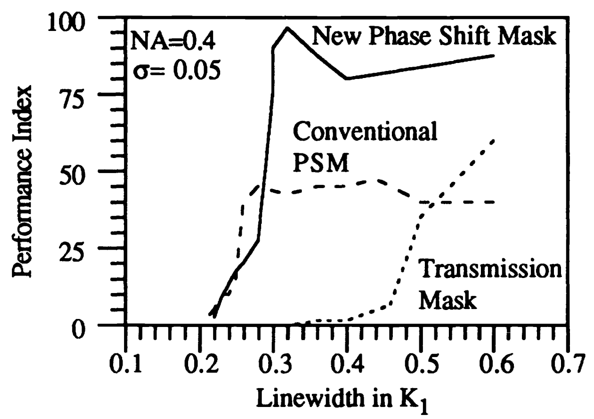



Figure 6. Comparison of the performance index for the new phase shifting method, Levenson-type phase shifting method and transmission mask as a function of normalized linewidth $K_1$.

The possible alignment errors that were simulated are indicated in figure 7. These errors are mainly caused by the alignment error of the external interferometer. The phase error (PE) was defined as the difference between the phase angle of the reflected phase, $\varphi_1$, and the transmitted beam phase, $\varphi_2$, written as

$$PE = 180° - |\varphi_1 - \varphi_2| \quad (5)$$

Zero phase error corresponds to a perfect phase condition. The attenuation error (AE) was defined as the intensity ratio between the transmitted and the reflected beam.

$$AE = \frac{I_{trans}}{I_{ref}} \quad (6)$$

The superposition error (SE) was defined by the offset of the peak position of the reflected image from its ideal position (see Figure 7.)

$$SE = \frac{S}{(L/2)} \quad (7)$$

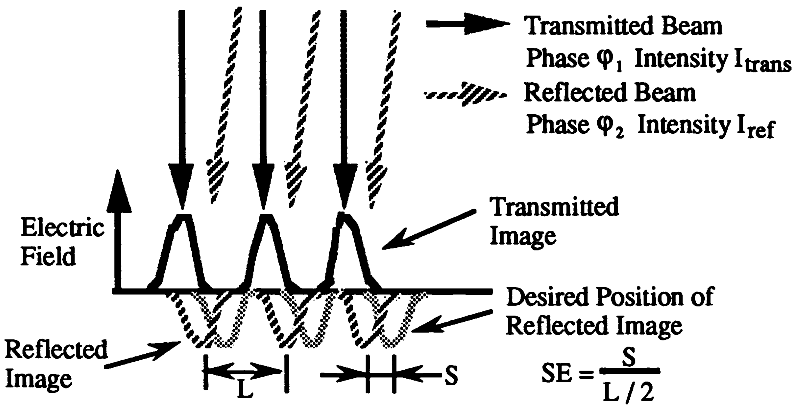



Figure 7. Alignment errors of the new phase shifting method.

Figure 8 shows the change of the performance index as it degrades with increasing phase error for various attenuation errors. One can define the maximum error tolerance as the phase error which reduces the contrast to 60 % (the minimum requirement to produce a desired photoresist feature [13].) The maximum error tolerance is approximately 60 degrees. This corresponds to a position error of 76 nm for the argon ion laser beam and 105 nm for the He-Ne laser beam. An attenuation error degrades the image contrast by about 10 %, but is obviously not a dominant effect.

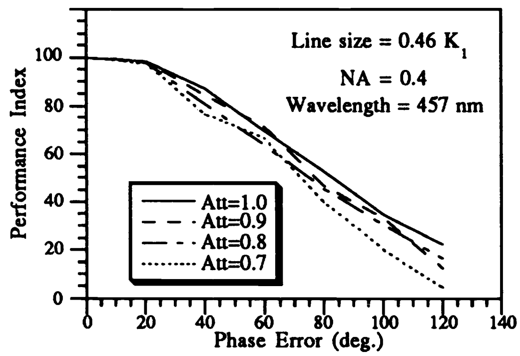



Figure 8. Performance index of new phase shifting method as a function of phase error for various attenuation errors.

Figure 9 shows the results of the misalignment due to non-parallel image beams. Since the reflected and transmitted beams may not be parallel, this can cause a misalignment error in the resulting image. This situation is difficult to analyze using the DEPICT simulator, because there is only one directional light source in the conventional lithographic approach. In order to analyze this somewhat unique alignment error, a one dimensional image contrast simulator was developed which calculates the possible path from the mask to the image plane using phase sensitive ray-tracing.

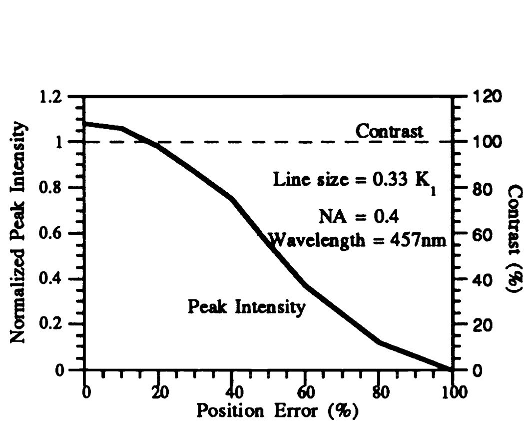



Figure 9. Normalized intensity and contrast of new phase shifting method as a function of superposition error.

The results show that the contrast was not changed by the misalignment but that the peak intensity did change significantly from 100 to 0 %. In actual use the misalignment error can probably be held to less than 10 %. Thus the most important parameter to control is the phase error.

## 4. EXPERIMENTS AND DISCUSSION

A series of experiments were carried out in order to test the feasibility of this new approach. A CCD camera was used to visualize the pattern generated by the new method. Additionally, patterns were exposed and developed in actual photoresist. A 1 mW He-Ne laser (Spectra Physics model 132, 632.8 nm, $TEM_{00}$ mode, 0.8 mm in diameter) and an 100 mW $Ar^+$ laser (Spectra Physics, model 2016, 457 nm (mode selected), $TEM_{00}$ mode, 1.4 mm in diameter) were used. Three 50 % beam splitters were employed in an external interferometric scheme. A 20X microscope objective lens with 0.4 NA was used as a focusing lens. The mask consisted of a single layered chromium line and space pattern, with a line size from 2 to 22 microns. A neutral density filter (density 0.3) was placed on the transmitting branch in order to equalize the beam intensity. A CCD camera (pixel size: 11 microns) was employed to analyze the image. A beam profile software (Big Sky), was used to produce a two dimensional intensity distribution at the image plane.

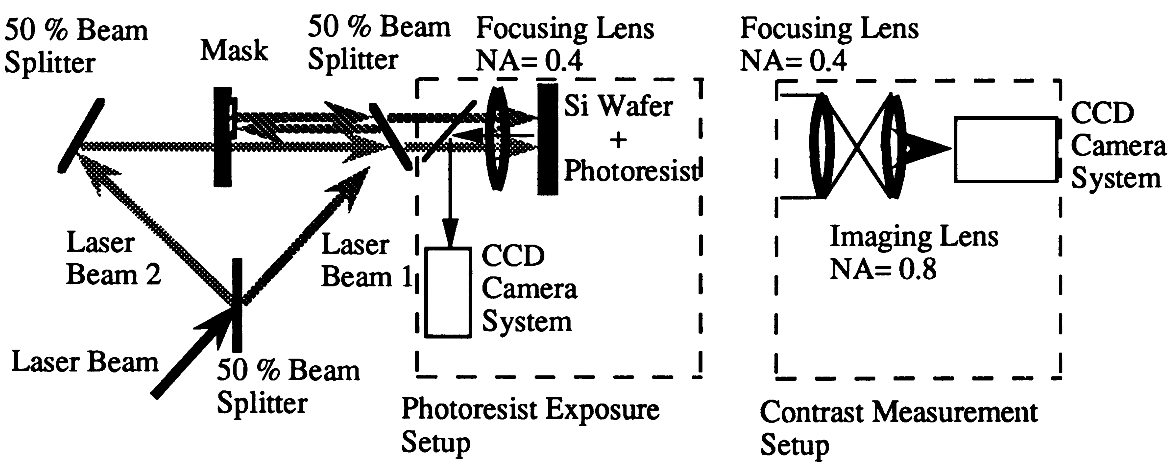



Figure 10. Experimental setup.

The CCD camera system was placed adjacent to the focusing lens in order to measure the image contrast as shown in figure 10. The other form of analysis is based on a UV photoresist AZ1350B-SF and an AZ developer (Hoechst Celanese) applied to a silicon wafer, which is used to record a line pattern. When exposing photoresist, the CCD camera was used to observe the reflected image from the silicon wafer in order to aid in alignment.

Figure 11 and 12 show how the performance index changed for different image line sizes. For 632.8 nm He-Ne laser light, a feature size of 0.47 μm, or 0.75λ, was achieved with an intensity contrast ratio of 50 %, and a feature size of 0.50 μm or 0.79λ, was achieved with 80 % contrast. For 457 nm argon ion laser light, a feature size of 0.375 μm, or 0.82λ, was achieved with 55 % contrast, and a feature size of 0.425 μm or 0.93λ, was achieved with 80 % contrast. The experimental data match well with the simulation data from DEPICT (dashed line) and show that the new scheme is effective in increasing photolithographic capability to generate the reduced feature sizes. The differences between the simulation and the experimental data are due to the phase error from the mask alignment, mechanical vibrations, air disturbances and CCD camera resolution. Although the experiments were performed on an optical table using high quality positioners, extensive efforts at controlling vibration [14] were not attempted for the initial demonstration.

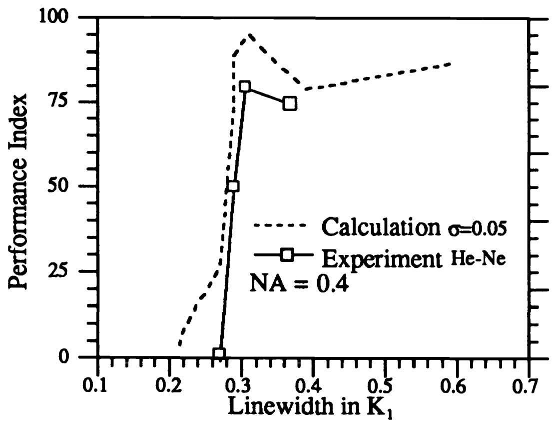



Figure 11. Performance index comparison with experiments and simulation for He-Ne laser as a function of normalized linewidth $K_1$.

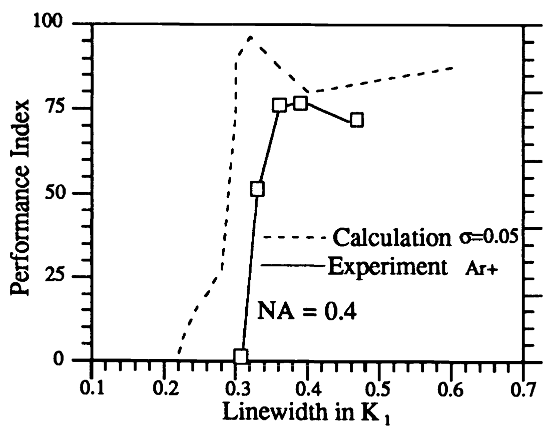



Figure 12. Performance index comparison with experiments and simulation for argon ion laser as a function of normalized linewidth $K_1$.

Images were also written in photoresist using the 457 nm $Ar^+$ laser line. Although not designed for use at 457 nm, the AZ1350B-SF resist has sufficient sensitivity at this wavelength in order to write a pattern. A 0.5 micron thick photoresist layer was deposited on a 1.5 inch silicon wafer by spinning the wafer at 3000 rpm. A Gaussian ($TEM_{00}$) beam, with an energy density of 200 mJ/cm$^2$ was used to expose the wafer. Development time was 60 seconds with an AZ developer (1:1). Figure 13 is a SEM photograph of the features obtained by this scheme. The non-uniform exposure is due to the Gaussian laser beam distribution. The central ring shows adequate exposure and a 0.57 μm line width. The side wall is steep and there is a stair-like feature caused by a standing wave effect. Figure 14 shows an image obtained with an atomic force microscope (Park Scientific Instruments). This instrument cannot follow steep side walls, but it can demonstrate that the thickness of the line features in the photoresist are about 0.44 micron.

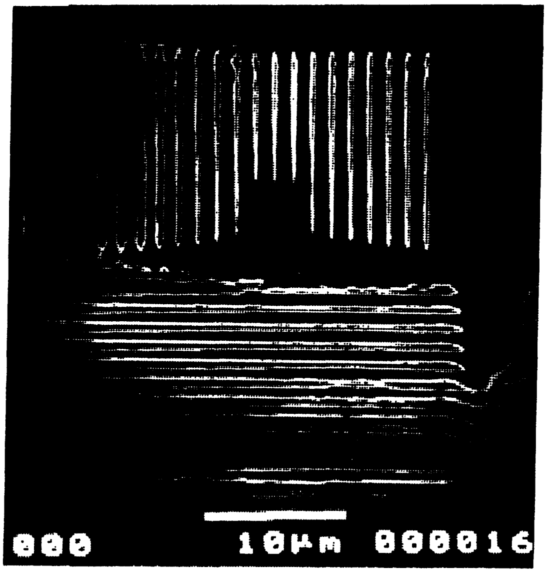



Figure 13. SEM photograph of pattern features produced by new scheme.

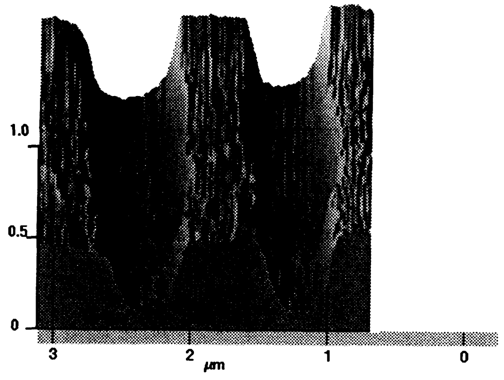



Figure 14. AFM output of pattern feature obtained by new scheme.

## 5. CONCLUSIONS

A new phase shifting method using a novel interferometric scheme and a partially reflective mask was demonstrated. For He-Ne laser light, a feature size of 0.47 μm, or 0.75λ, was achieved with an intensity contrast ratio of 50 % as confirmed by CCD camera analysis. For argon ion laser light, a feature size of 0.375 μm, or 0.82λ, was achieved with 55 % contrast. A line size of 0.57 μm was also achieved with an actual photoresist exposure. The new method provides all of the advantages of phase shifting with increased image intensity and only requires a conventional mask. The error tolerances were examined using DEPICT and our simulator. A spatial resolution of 0.2 μm should be feasible for 248 nm KrF laser illumination applied to our phase shifting method with the same numerical aperture.

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