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Some features of photolithography image formation in partially coherent light

M.A. Kitsak, A.I. Kitsak

Abstract. **The coherent-noise level in projection images of an opaque-screen sharp edge, formed in the model scheme of photolithography system at different degrees of spatial coherence of screen-illuminating light is studied experimentally. The spatial coherence of laser radiation was reduced by applying a specially developed device, used as a separate functional unit in the system model. The smoothing of the spatial fluctuations of radiation intensity caused by the random spatial inhomogeneity of the initial beam intensity in the obtained images is shown to be highly efficient.**

Keywords: *coherent noise, spatial coherence, photolithography system.*

1. Introduction

It is well known that, in order to reach the resolution limit in projection schemes of image formation, for example, in projection lithography, one must optimise (at a specified wavelength of object-illuminating light and objective numerical aperture) many optical parameters of the imaging system components, including the characteristics of illuminating light [1–5]. In particular, the spatial distribution of light intensity in the object plane is homogenised and the degree of light spatial coherence is optimised. The purpose of these operations is to obtain uniform illumination of image elements and their high contrast in the detection plane. The necessity for equalising the illuminance is as follows. Modern projection lithography systems (steppers and scanners) use and, obviously, will use in the nearest future (in immersion lithography) [6–8] laser sources generating beams that are characterised by a narrow time-frequency spectrum and generally have spatially nonuniform (Gaussian) intensity distribution. In addition, a typical feature of these beams is spatial intensity fluctuations, which are caused by the spatially nonuniform reflectance of the laser cavity mirrors [9]. Nonuniform illuminance in the image plane can also be caused by the so-called speckle-noise [10], which is the result of light scattering from random amplitude and phase inhomogeneities of the optical elements of the lithography system and air (or immersion-liquid filled) gaps between the components of the system. The level of this noise is determined by the degree of spatial coherence of the light used to record an image. Nonuniform illumination of image elements leads to nonuniform illumination of the recording medium and defects in the image developed. The allowable deviation of the illuminance distribution in the plane of submicron- and nanometer-resolution images from the uniform distribution is $\sim$2% [11].

Transformation of the spatial structure of laser beams and variation of their spatial coherence in lithography systems are performed using special devices, which are placed between the radiation source and condenser [11]. The main requirements for these devices are high operating speed and minimal variations in the temporal coherence of light. Currently, there are many different designs of converters of coherent and spatial characteristics of light, and most of them are applied in modern lithography systems [12, 13].

The degree of spatial light coherence can be efficiently transformed for short times using devices based on delay lines [14–16]. They reduce the spatial coherence as a result of forming a set of independent light sources (spatially coherent modes) by splitting the initial laser beam into partial components, time-shifted with respect to each other by intervals equal to or exceeding the coherence interval. An advantage of this technique for transforming light coherence is the absence of time frequency shift, which is characteristic of the conversion schemes based on time modulation of the spatial radiation phase. Among the coherence-conversion schemes that are promising for EUV projection lithography, we would select the delay line proposed in [17, 18]. Its advantages are the minimum absorption loss (because spatially coherent modes are formed by a system of mirrors) and the possibility of synthesising secondary sources of different shape (for example, in the form of arc, quadrupole, etc.) to improve the spatial resolution.

In this paper, we report the results of the experimental study of the coherent (speckle) noise smoothing efficiency in the projection images formed in the model scheme of photolithography system, with light spatial coherence varied by a device incorporated into the system as an individual element.

2. Optical scheme of the photolithography model

We investigated the efficiency of noise suppression in test-object images recorded with application of a decoherence device in the recording scheme. To this end, we developed an experimental setup, whose optical scheme is shown in Fig. 1.

The light optical characteristics and the main structural components of the scheme are described below. The light pulse energy at the wavelength λ = 266 nm was $\sim$25 mJ. The modulus of the degree of temporal coherence of the light is shown in Fig. 2.

M.A. Kitsak Cooperative Association for Internet Data Analysis, University of California, San Diego, 9500 Gilman dr, La Jolla, CA, 92093, USA; e-mail: maxkitsak@yahoo.com
A.I. Kitsak Department of Laser Physics and Spectroscopy, Belarusian State University, prosp. Nezavisimosti 4, 220030 Minsk, Belarus; e-mail: kitsak48@mail.ru

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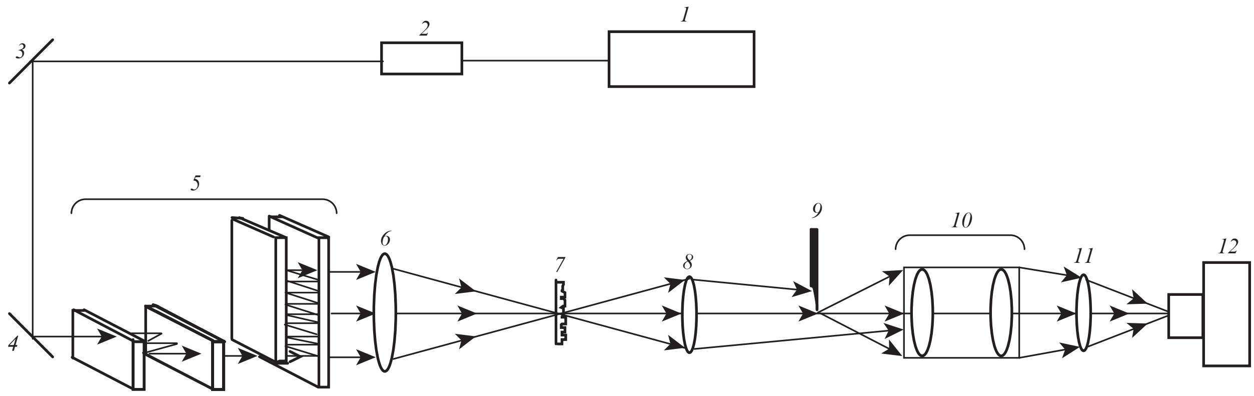

Figure 1. Optical scheme of the setup for recording images with partially coherent light:
(*1*) coherent-light source (pulsed solid-state Nd:YAG laser), (*2*) light frequency converter into the fourth harmonic (λ = 266 nm), (*3*, *4*) system of rotating mirrors, (*5*) delay line, (*6*) lens for forming secondary-radiation source, (*7*) randomly inhomogeneous phase plate, (*8*) condenser lens, (*9*) test object, (*10*) projection objective, (*11*) lens, and (*12*) linear CCD camera.

The delay line (*5*) consists of two groups of mirrors for splitting the initial laser beam into a set of partial beams with approximately equal intensities. The distance between the mirrors is chosen so as to provide a temporal shift of light beam pulses with respect to each other by a value either equal to or exceeding the coherence time of the initial light. The beam intensities were equalised using mirrors with a variable reflectance at a specified wavelength. The number of effective spatially coherent modes formed at the delay line output, which determine the degree of light spatial coherence, can be written as [17]

$$P_{\text{eff}} = P_{\text{eff}}^{(0)}\left(\sum_{n=0}^{p-1} I_n\right)^2 \Bigg/ \sum_{n=0}^{p-1} I_n^2$$

$$+2\sum_{n=0}^{p-1}\sum_{n'=n+1}^{p-1} I_n I_{n'}\left|\gamma(\tau_n-\tau_{n'})\right|^2, \qquad (1)$$

where $P_{\text{eff}}^{(0)}$ is the effective number of spatially coherent light modes at the input of the delay line; I_n is the individual beam intensity; and $|\gamma(\tau_n-\tau_{n'})|$ is the modulus of the degree of temporal coherence between the beams with numbers n and n', in which light pulses are shifted with respect to each other by the time interval $\tau_n - \tau_{n'}$. In the limit $|\gamma(\tau_n-\tau_{n'})| \to 0$ and $I_n = I_{n'}$, we have $P_{\text{eff}} = P_{\text{eff}}^{(0)} p$, where p is the number of beams at the delay line output. The delay line (*5*), in combination with the lens (*6*) and random phase modulator (*7*), form a device aimed at suppressing coherence and homogenysing the initial laser beam for a time on the order of the pulse width. Spatial beam-phase mismatch was implemented using a quartz plate, one of the surfaces of which had a small-scale random corrugation.

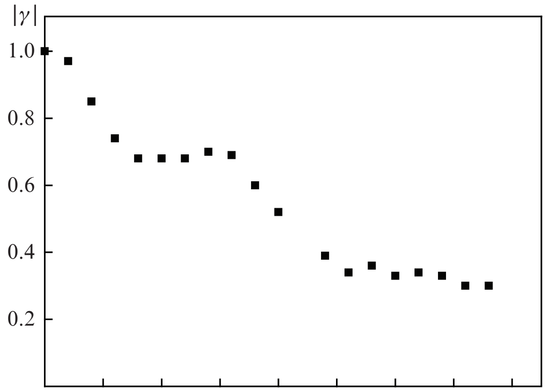

Figure 2. Dependence of the modulus of the degree of temporal coherence of light $|\gamma|$ on the light-beam path difference Δl.

The test object (*9*) was projected onto the image plane using the objective (*10*) (Binar-266, NPO Planar, Belarus), which is designed for the radiation wavelength λ = 266 nm with a minimum resolution of 0.8 μm. The objective numerical aperture was 0.4, and its rear focal length was 8 mm. Since there are no radiation detectors with a spatial resolution below 0.8 μm, the test-object image was constructed on an enlarged scale. To this end, the test object was located practically in the focal plane of the objective, behind which the lens (*11*) was placed to form its image at a finite distance. A thin opaque screen with a sharp edge played the role of the test object (*9*). The screen image was recorded by the linear CCD camera (*12*) with a minimum spatial resolution of ~14 μm.

3. Results of analysing the coherent noise level in the test-object images formed in partially coherent light

The screen image was recorded under illumination by light with different degrees of spatial coherence, which was varied by placing diaphragms of different diameter in the laser cavity and changing the number of delay-line beams forming the secondary source. The degree of light spatial coherence was estimated from the number of effective spatially coherent modes P_{eff} in the expansion of the spatial cross-correlation function of light intensity in eigenvalues and eigenfunctions [19,20]. For a Gaussian cross-correlation function the P_{eff} value is related to the light coherence coefficient $C = r/a$ (r is the light coherence length and a is the light beam radius in the illumination plane) as follows: $P_{\rm eff} = 1 + 2/C^2$ [21]. The number of spatially coherent light-beam modes can be determined by estimating the ratio of the standard deviation of intensity fluctuations, g, to the mean light intensity $\langle I\rangle$ in the intensity distribution, which can be detected behind a random phase modulator with a Gaussian statistics of phase inhomogeneities, placed in the beam [22]. In this case,

$$P_{\rm eff} = 1/K^2, \quad (2)$$

where $K = g/\langle I\rangle$ is the so-called speckle contrast.

The optical-image quality is characterised by the two main parameters: frequency-contrast characteristic of the image-forming system and the signal-to-noise ratio in the image [23].

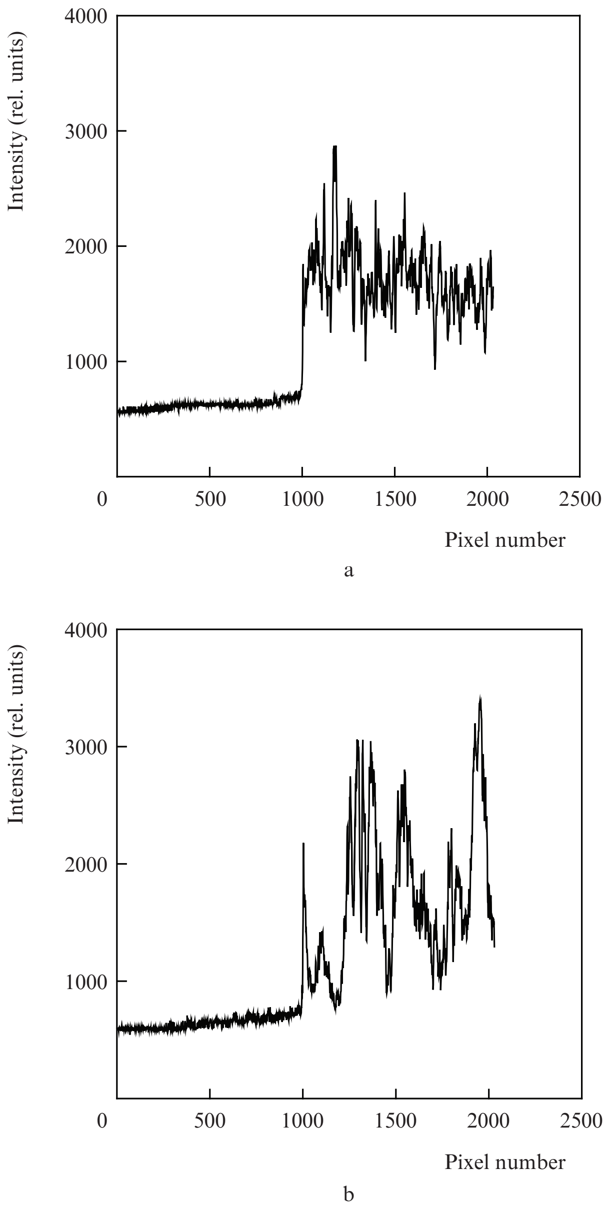

Figure 3. Intensity distributions in the images of the sharp edge of a screen, obtained under illumination by light with $P_{\rm eff}^{(0)} = 3$, emerging from a frequency doubler (a) and transmitted through a randomly inhomogeneous phase plate (b).

In coherent optics the degree of image noisiness is characterised by the inverse signal-to-noise ratio, which is referred to as the contrast (speckle) noise. The noise is assumed to be equal to the rms value of intensity fluctuations in the image of the illuminated parts of the object, and the signal is considered as the mean intensity. It follows from relation (2) that in the case of Gaussian statistics of spatial fluctuations of light phases in the noise field the noise contrast is determined by the number of spatially coherent modes forming this noise.

Figure 3a shows the intensity distribution in the image of an opaque screen with a sharp edge, formed under illumination with $\lambda = 266$ nm, in the absence of the delay line (*5*), lens (*6*), and phase modulator (*7*) (Figure 1), but with a 1.5-mm diaphragm placed in the laser cavity. One can see a sharp increase in intensity directly after the unilluminated area in the screen image. This increase is due to the light diffraction from the screen edge. The illuminated area in the screen image plane exhibits large-amplitude spatial fluctuations of light intensity, which are due to the spatial inhomogeneity of light illuminating the screen. The noise contrast was measured to be 0.26. To estimate the number of spatially coherent modes involved in image formation, we recorded a screen image under illumination by the same light, transmitted through the random phase modulator (*7*) (see Fig. 1). This image is shown in Fig. 3b. The speckle-noise contrast in the illuminated part was measured to be 0.6. Accordingly, the number of spatially coherent modes in the initial light is $\sim$3.

In the next experiment the light beam from the frequency doubler was directed to the delay line. Eighty one partial beams were formed at the output of the delay line, and the optical path of each beam exceeded that of the previous beam by Δl. The length Δl was chosen so as to minimise the modulus of the degree of temporal coherence between neighboring beams. As can be seen in Fig. 2, this distance is $\sim$2.5 cm. The beams were focused by the lens (*6*) onto the plane of the phase modulator (*7*) (Fig. 1) to form a secondary source, the light from which was transferred by the lens (*8*) to the plane of screen (*9*). The phase modulator converted the wavefronts of partial beams into the wavefronts with different spatial phase distributions. The screen-edge image obtained under secondary-source illumination is presented in Fig. 4a.

It can be seen that the general view of the image spatial structure is the same as in Fig. 3a, i.e., it exhibits a diffraction-induced sharp increase in intensity and intensity fluctuations in the illuminated screen area. However, the magnitude of these fluctuations is smaller than in Fig. 3. The noise contrast is ~ 0.13. The level of intensity fluctuations is reduced because the number of spatially coherent modes in the light illuminating the screen increases with a decrease in the degree of spatial coherence. Noise smoothing involves two mechanisms: time orthogonalisation of the partial light beams (formation of independent spatially coherent light sources), which is performed by the delay line, and spatial orthogonalisation of their wavefronts at the beam passage through the phase modulator at different angles. In this case, the result of wavefront addition in the screen plane is similar to the well-known averaging effect during detection of spatial fluctuations of laser beam intensity, induced by a rotating phase modulator placed in the beam [19].

The high noise contrast in the screen image obtained in this experiment is explained by high residual temporal coherence of the light beams emerging from the delay line. Figure 2 shows that the temporal coherence between the beams is $|\gamma(\tau_n - \tau_{n'})| \sim 0.3$ at $\Delta l = 2.5$ cm. In this case, the number of

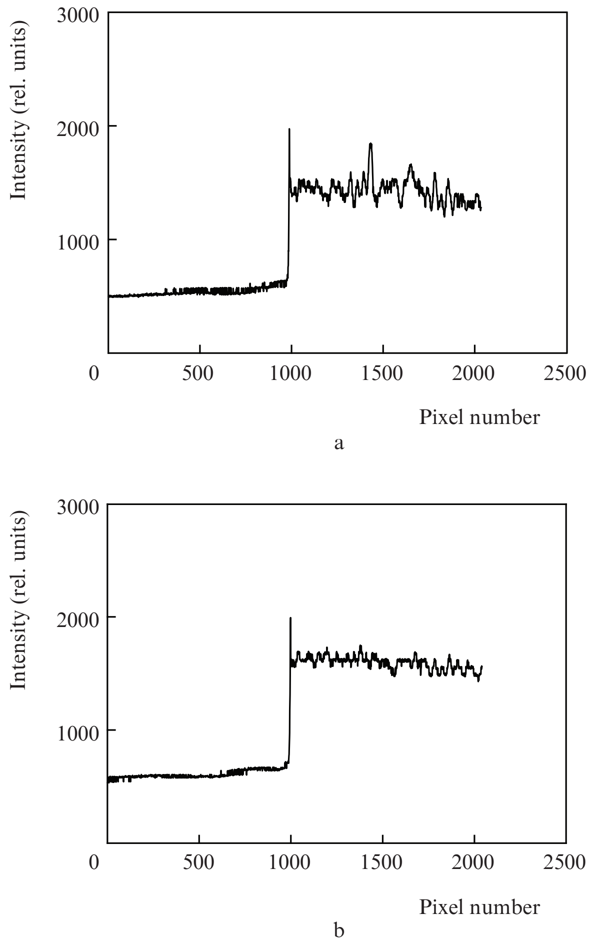

Figure 4. Intensity distributions in the images of the sharp edge of a screen, obtained under illumination by light transmitted through the delay line (*5*) at $P_{\mathrm{eff}}^{(0)}$ = (a) 59 and (b) 400.

effective spatially coherent light modes illuminating the screen is $P_{\mathrm{eff}} \cong 59$.

To reduce even more the secondary-source spatial coherence in the scheme under consideration, we removed the diaphragm from the laser cavity. Figure 4b shows the intensity distribution in the screen image for this situation.

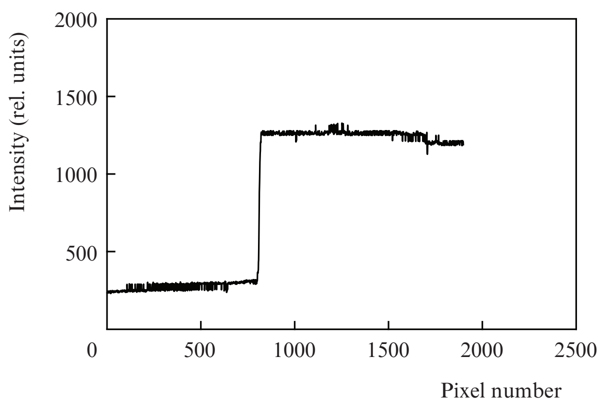

Figure 5. Intensity distribution in the image of the screen sharp edge, obtained under illumination with incoherent light.

It can be seen that an increase in the number of spatially coherent modes in the light illuminating the screen leads to effective smoothing of intensity fluctuations in the screen image. The residual-noise contrast is $\sim$0.05 and $P_{\mathrm{eff}} \cong 400$. For comparative estimation of the degree of uniformity of the spatial intensity distribution in the screen image obtained in this case, Fig. 5 shows the intensity distribution in the image recorded in incoherent light at $P_{\mathrm{eff}} \to \infty$. The source of incoherent (white) light was a 4603LXHLME1C LED (LUXEON). The observed nonuniformity of intensity distribution in the illuminated area of the screen image is caused by the spatial inhomogeneity of the energy sensitivity of individual CCD pixels. The contrast of this 'noise' was measured to be 0.03. This value can be considered as the relative error in measuring (by linear CCD camera) the noise contrast in the images formed in partially coherent light in the photolithography scheme under consideration.

4. Conclusions

The estimation of the speckle-noise contrast in the images of a sharp edge of opaque screen, formed in the model scheme of photolithography system, is indicative of effective smoothing of spatial intensity fluctuations that are caused by the spatial inhomogeneity of the initial light intensity. Light can be homogenised by decreasing its spatial coherence using the specifically developed light-decoherence device. Another advantage of this device is that it can be used to form sources of complex shape for off-axis illumination of photomask in order to increase the spatial resolution of the image-recording scheme.

References

1. Valiev K.A., Zaifart Kh, Il'kaev D.R., Makhviladze T.M. *Mat. Model.*, **2**, 56 (1990).
2. Gurskii V.B., Pyatetskii R.E. *Avtometriya*, **2**, 79 (1984).
3. Nikitin A.V. *Prikl. Fiz.*, 4, 23 (1997).
4. Bernard D., Li J., Rey J., Axelrad V. *Proc. SPIE Int. Soc. Opt. Eng.*, **2726**, 273 (1996).
5. Voznesenskii N.B., Rodionov S A., Domnenko V.M., Ivanova T.V. *Opt. Zh.*, **64** (3), 48 (1997).
6. Seisyan R. *Zh. Tekh. Fiz.*, **75**, 1 (2005).
7. Salashchenko N.N., Chkhalo N.I. *Vestn. Ross. Akad. Nauk*, **78** (5), 450 (2008).
8. Anchutkin V., Bel'skii A., Gushchin O. *Fotonika*, **1**, 11 (2010).
9. Jacob J.J., Litvin T., Merrian A.J. *United States Patent* US 6895149. Int.C1. G 02B 27/48, May 17, 2005.
10. Kleinschimidt J. *United States Patent* US 6898216. Int.C1. G 02B 27/48, May 24, 2005.
11. Kanti J. *Excimer Laser Lithography* (Bellingham, Washington: SPIE Press, 1989) pp 68, 114.
12. Gonting R.A., Vladimirsky J. *United States Patent* US 7411687. Int.C1. G 02B 9/02, Aug.12, 2008.
13. Poultney S.K. *United States Patent* US 7595931. Int.C1. G 02B 5/18, Sep. 29, 2009.
14. Buckles R.G. *United States Patent* US 3633999. Int.C1. G 02B 27/14, Jan. 11, 1972.
15. Michaloski P.F., Stone B.D. *United States Patent* US 6191887. Int.C1. G 02B 5/30. Feb. 20, 2001.
16. Partlo W.N., Oldham W.G. *United States Patent* US 5233460. Int.C1. G 02B 27/28. Aug. 3, 1993.
17. Ivakin E.V., Kitsak A.I., Karelin N.V., Lazaruk A.M., Rubanov A.S. *Kvantovaya Elektron.*, **33**, 255 (2003) [*Quantum Electron.*, **33**, 255 (2003)].
18. Ivakin E.V., Kitsak A.I., Karelin N.V., Lazaruk A.M. *BY Patent* No.7273. MKI. G 02B. G 03H (2005).

19. Mandel L., Wolf E. *Optical Coherence and Quantum Optics* (Cambridge: Cambridge Univ. Press, 1995).
20. Karelin N.V., Lazaruk A.M. *Izv. Vyssh. Uchebn. Zaved., Ser. Radiofiz.*, **40**, 903 (1997).
21. Akhmanov S.A., D'yakov Yu.E., Chirkin F.S. *Vvedenie v statisticheskuyu radiofiziku i optiku* (Introduction to Statistical Radio Physics and Optics) (Moscow: Nauka, 1981).
22. Leshchev A.A. *Opt. Spektrosk.*, **55**, 988 (1983).
23. Zege E.P., Ivanov A.P., Katsev I.L. *Perenos izobrazheniya v rasseivayushchei srede* (Image Transfer in a Scattering Medium) (Minsk: Nauka i Tekhnika, 1985) p. 129.