Character of light intensity distribution over the width of a slit illuminated by a plane monochromatic wave at image formation by a bounded light beam. Part 2

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I obtain expressions that enable one to determine the position of fringes in the diffraction pattern within the image of a slit illuminated a bounded parallel beam of a monochromatic light. The expressions well agree with the experiments and thus confirm explanations of the fringes' origin.

The first part of this paper[1] presents experimental facts on the appearance of a maxima and minima of intensity J in the image of a slit Sl_1 illuminated by a plane light wave ($\lambda = 0.53$ μm) in the case when the slit width S is increased and the light beam which forms the image is bounded by a slit of variable width (Sl_0).

It was noted that experimentally observed variation of J across the S' segment of the Sl_1 slit's image is a consequence of several factors: existence of zones over the screens' surface (deflection zones where light beams are deflected along the directions from the initial direction, both toward the screen and from the screen); increase of the light deflection with a decrease of the distance between their initial trajectories and the screen; appearance of the initial phase difference between the deflected (boundary) and incident light at the beam deflection; interference of beams deflected in the zones of Sl_1 and Sl_0, with those deflected in the weak part of the zones of Sl_1 or propagated without deflection.

Let us show that this is the real case.

In the experimental optical arrangement presented in Fig. 1, *obj.* is a Yupiter–8 lens objective forming the image of the slit Sl_1 without magnification ($S = S'$); H is the half-width of the bounding slit Sl_0 placed at a distance l from Sl_1; t is the half-width of Sl_1; $H \gg t$.

At each point a' of the image of Sl_1, at the distance h_1 from the image's right-hand edge, the rays *1–6* converge. The beam *1* is the imaginary one; it is used to identify the conjugate point a in the plane of Sl_1; *2* and *3* are the rays of light incident onto Sl_1 and deflected by angles α' from the initial direction in the deflection zones of its left-hand and right-hand screens at a point that is at the distance h_1 from the left-hand screen; *5* is the ray deflected by an angle δ' mainly in the zone of the left-hand screen of Sl_1 from the distance $h_{z.1}$ and by an angle γ_1 mainly in the zone of the right-hand screen of Sl_0 from the distance $h_{z.01}$; *6* is the imaginary ray propagated from the point a toward the conjugate point a' without a deflection in the plane of Sl_0; *4* is the ray of incident light beam passing through the point a without a deflection in the planes of Sl_1 and Sl_0.

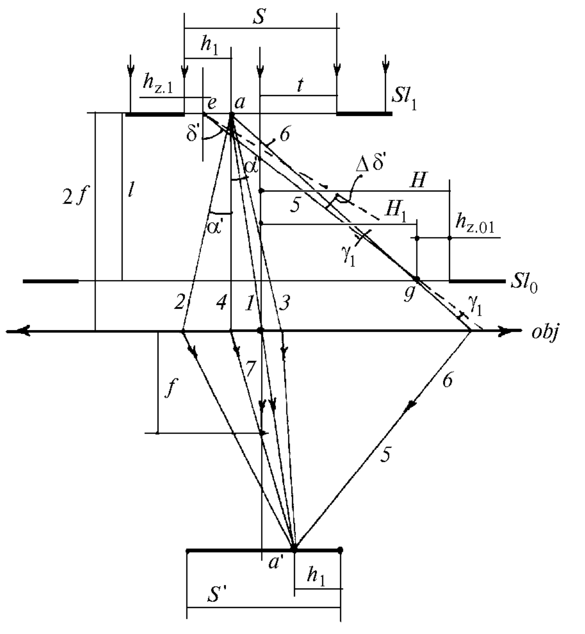

Fig. 1. Formation of the first diffraction pattern within the limits of the slit image formed by a bounded light beam.

Existence of the ray *4* was first supposed in the hypothesis[2] proposed to explain the experimental results. According to the hypothesis, light quanta propagated along the ray trajectories are in three states with respect to the direction of their deflection in the deflection zone. In the first state, they deflect onto the screen, in the second state from the screen; in the third state, they are propagated through the zone without deflection.

Propagation of a part of light rays through the zone without changes in direction seems to be confirmed in Ref. 3. In this paper, it was established that each flux of light rays coming from an arbitrary

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part of the deflection zone and deflected toward the screen and out from it is equal to 0.143 of the light flux incident onto that part of the zone. Therefore, even in case of coincidence of the flows' phases before splitting into individual components, their sum $(\sqrt{0.143} + \sqrt{0.143})^2 = 0.57$ appears to be less than the incident flux.

Based on findings from Ref. 4, the deflection angles δ' and α' of the rays *5*, *2*, and *3* are determined by the expression

$$\delta'(\alpha') = 259.5/[h_{z.1}(h_1) + 0.786], \quad (1)$$

where the values of the angles and $h_{z.1}(h_1)$ are represented in minutes of arc and μm, respectively.

As is shown below, the rays *2–4* that take part in forming max and min of intensity within S' come from the points a, situated at $h_1 \gg h_{z.1}$, so $\alpha' \ll \delta'$. As a consequence, the rays *2* and *3* propagate at a long distance from the edges of Sl_0, in weak parts of its deflection zones which in fact do not make any obstacles for the rays' arrival at the conjugate points a'.

Because of the tautochronism, no phase difference occurs between the beams *2*, *3*, *4*, and *6*, but it appears between them and the ray *5*, which propagates from the point e and comes toward the point a' due to its deflection in the right-hand screen's zone of the slit Sl_0.

The ray *5* and the imaginary ray *6* propagated along the same path from the plane of Sl_0 toward the point a'. Therefore, the geometrical phase between the rays *5* and *6* (and between the rays *2–4*) is

$$\Delta_{5,6} = (eg - ag); \quad eg = (l + \Delta_1); \; ag = (l + \Delta_2),$$

so

$$\Delta_{5,6} = (\Delta_1 - \Delta_2).$$

The value

$$H_1 = (H - h_{z.01});$$

$$\Delta_1 = (H_1 + t - h_{z.1})^2/2l,$$

$$\Delta_2 = (H_1 + t - h_1)^2/2l,$$

$$\Delta_{5,6} = 2(H_1 + t - h_{z.1})\cdot(h_1 - h_{z.1}) - (h_1 - h_{z.1})^2 = k'\lambda/2;$$

$$h_1 = (H_1 + t) - \sqrt{(H_1 + t - h_{z.1})^2 - k'\lambda l}.$$

According to Refs. 3 and 5, light rays get equal advance and delay with respect to the incident light at their deflection out from the screen and towards it, respectively. In the experiments, the advance and delay are mainly within the limits of $\lambda/2$.

It is still unclear whether this salient feature manifests itself only at the first deflection or takes place also at other deflections.

The ray *5* is deflected out from the screen in the deflection zones of the left-hand (Sl_1) and right-hand (Sl_0) screens. Therefore, during the deflection process, it undergoes an advance by $k_{01}\lambda/2$ which is equal at least to the advance received in the zone of the left-hand screen Sl_1.

It is evident that the first max of intensity J is formed at the point a' where the initial advance of the ray *5* (i.e., advance acquired in the zone) appears to be equal to its geometrically explained phase lag from the beams *2–4* and *6*.

Taking this into account, the formula for h_1 takes the form

$$h_1 = (H_1 + t) - \sqrt{(H_1 + t - h_{z.1})^2 - (k_{01} + k)\lambda l}, \quad (2)$$

where $k = 0, 2, 4, \ldots$ and $k = 1, 3, 5, \ldots$ are the numbers of J maxima and minima, respectively.

This formula is valid for calculated points $a(a')$ in both of the $S(S')$ halves.

If one restricts himself to studying variation of J at the center of S', i.e., when $h_1 = t$, the formula (2) reduces to the following form:

$$t = \sqrt{H_1^2 + (k_{01} + k)\lambda l} - (H_1 - h_{z.1}), \quad (3)$$

where $k = 0, 2, 4,\ldots$ correspond to max at the center of S'; $k = 1, 3, 5,\ldots$ correspond to min; t is the value of the half-width of Sl_1 at the moments of max and min at the center of S'.

For $l = 72$ mm, $\lambda = 0.53$ μm, $H > 1$ mm, the fringes of different orders k on S' and in the center of it, on the scale of dimensions of S, have in fact similar width.

According to Eqs. (2) and (3), fringe width depends mainly on H, l, and λ because $H \gg t$. With the increase of H and decrease of l, the fringes become narrower. Their number increases with the increasing t and H.

The diffraction pattern formed by the rays *5* jointly with the rays *2–4* (the first diffraction pattern) begins from the right-hand side edge of S', i.e., the order of fringes in it increases as they approach the left-hand side edge of S'. Since the rays *5* in the plane of the slit Sl_0 are deflected near its right-hand screen, the pattern still takes place when the left-hand side screen of Sl_0 is removed.

From Eq. (2) it follows that

$$k_{01} = \{[2(H_1 + t - h_{z.1}) \cdot (h_1 - h_{z.1}) - (h_1 - h_{z.1})^2]/\lambda l - k\}. \quad (4)$$

In this formula, H_1 and $h_{z.1}$.are unknown values.

As it was established in Ref. 4, if light rays are deflected in the deflection zone of a screen by an angle $\varepsilon(\delta' + \Delta\delta')$,

$$h_z = (259.5 - 0.786\varepsilon)/\varepsilon, \quad (5)$$

where h_z and ε are expressed in μm and minutes of arc, respectively.

Under conditions considered, the ray *5* propagate simultaneously through the overlapping deflection zones of the left-hand and right-hand screens of Sl_1, and is deflected out from those.

If we suppose that both of these zones effect the ray independently, we have, in accordance with Eq. (1), that

$$(\delta' + \Delta\delta') = 259.5/(h_{z.1} + 0.786);$$

$$\Delta\delta' = 259.5/(S - h_{z.1} + 0.786).$$

In this case, the deflection angle of the ray *5* is

$$\delta' = \frac{259.5}{h_{z.1} + 0.786} - \frac{259.5}{S - h_{z.1} + 0.786}\,. \qquad (6)$$

At the same time,

$$\delta' = 3438(H_1 + 0.5\cdot 10^{-3}\,S - 10^{-3}\,h_{z.1})/l, \qquad (7)$$

where H_1 and l are in mm; S and $h_{z.1}$ in μm. As a result of joint transformation of these expressions, we obtain

$$h_{z.1} = A_1 - \sqrt{A_1^2 - B_1}\,, \qquad (8)$$

where

$$A_1 = \frac{S(H_1 + 0.5\cdot 10^{-3}\,S) + 0.1508\,l}{2(H_1 + 1.5\cdot 10^{-3}\,S)}\,;$$

$$B_1 = \frac{S(0.0754\,l - 0.786\,H_1 - 0.393\cdot 10^{-3}S) - 0.618\,H_1}{H_1 + 1.5\cdot 10^{-3}S}\,;$$

S and $h_{z.1}$ are in μm; l and H_1 in mm.

Passing through the Sl_0, in the zones of the right-hand and left-hand side screens of the slit the ray *5* is deflected from them by the angles $\gamma_1 + \Delta\gamma_1$ and $\Delta\gamma_1$:

$$(\gamma_1 + \Delta\gamma_1) = 259.5/(h_{z.01} + 0.786);$$

$$\Delta\gamma_1 = 259.5/(2H - h_{z.01} + 0.786).$$

Therefore, the angle of the resulting deflection of a ray within the limits of Sl_0 is

$$\gamma_1 = \frac{259.5}{h_{z.01} + 0.786} - \frac{259.5}{2H - h_{z.01} + 0.786} = \frac{3.438(h_1 - h_{z.1})}{l}\,,$$

where H, $h_{z.01}$, h_1, and $h_{z.1}$ are in μm; l in mm.

It follows that

$$h_{z.01} = \left(\frac{75.48\,l}{h_1 - h_{z.1}} + H\right) - \sqrt{\left(\frac{75.48\,l}{h_1 - h_{z.1}} + H\right)^2 - \left(\frac{75.48\,l}{h_1 - h_{z.1}} - 0.786\right)2H - 0.62}\,. \qquad (9)$$

To determine k_{01} for different H and t from the experimental values of $h_1 - h_e$, one can apply the following technique:

1. Find the underestimated value of $h_{z.01}$ by Eq. (9) ignoring $h_{z.1}$.
2. Determine $H_1 = (H - h_{z.01})$.
3. Determine $h_{z.1}$ by Eq. (8).
4. Repeat the calculations 1–3 with the account of obtained $h_{z.1}$ until H_1 is almost constant.
5. Find k_{01} by Eq. (4).

The results of calculations of k_{01} for the bands of different orders are presented in Table 1, where α' is determined by substitution of h_e for $h_{z.1}$ in Eq. (6).

As one can see from these results, the values $(k_{01} - 0.5)$ are small as compared with $(0.5 + k)$. Therefore, Eq. (2) describes the position of the diffraction bands in S' quite reliably.

The presented values of k_{01} are within the limits of the values of k_0 observed in the experiments[3,5] on light diffraction on a screen with a rectangular edge.

Table 1. Light intensity variation across the slit's image (l = 72; 71.25 mm)

S, μm	H, mm	h_e, μm	Fringe	k	$h_{z.1}$, μm	γ_1, min	δ', min	α', min	$h_{z.01}$, mm	k_{01}	k_{02}	$h_{z.2}$, μm
141	0.55	35.5	max_1	0	12.04	1.12	18	4.7	0.231	0.451	0.524	15.6
		70.5	min_1	1	8.64	2.95	24.8	0	0.087	0.604	0.355	11.3
81	0.975	20.5	max_1	0	7.15	0.637	28.75	7.96	0.406	0.417	–	–
		40.5	min_1	1	4.93	1.72	41.1	0	0.15	0.596	–	–
		20.25	max_1	0	7.36	0.616	29	9.8	0.421	0.406	0.372	7.84
121	0.975	39	min_1	1	5.12	1.618	41.5	3.4	0.16	0.517	0.31	5.85
		60.5	max_2	2	4.75	2.66	44.6	0	0.097	0.652	0.465	5.43
		19.25	max_1	0	8.21	0.527	26.55	11.1	0.49	0.317	–	–
161	0.975	38	min_1	1	5.1	1.57	42.3	4.6	0.164	0.5	–	–
		59.9	max_2	2	4.71	2.63	45.5	1.73	0.098	0.678	–	–
		80.5	min_2	3	4.54	3.63	46.8	0	0.071	0.753	–	–
		10.5	max_1	0	2.99	0.36	66	20.5	0.723	0.542	0.55	2.96
		19.9	min_1	1	2.15	0.85	86	9.9	0.305	0.67	0.583	2.3
116	2.05	29.25	max_2	2	1.99	1.3	91.1	5.7	0.2	0.71	0.58	2.15
		39.25	min_2	3	1.92	1.78	93.7	3.14	0.145	0.8	0.648	2.07
		48.25	max_3	4	1.87	2.22	95	1.51	0.116	0.78	0.607	2
		58	min_3	5	1.85	2.68	96	0	0.096	0.84	0.66	2
		Sl_0 without the left-hand side screen; l = 71.25 mm										
		10	max_1	0	3	0.34	65.2	20.8	0.766	0.5	–	–
		20	min_1	1	2.07	0.87	87.8	8.8	0.3	0.713	–	–
90	2.05	27.6	max_2	2	1.94	1.24	92.1	5	0.209	0.582	–	–
		37	min_2	3	1.86	1.7	94.9	2	0.152	0.623	–	–
		45	max_3	4	1.82	2.08	96.2	0	0.124	0.515	–	–

In addition to the first diffraction pattern in the slit's Sl_1 image, one more diffraction pattern is formed due to the interference of the rays *2–4* and the rays *8* (Fig. 2) deflected toward the screen mostly in the zones of the left-hand side screens of Sl_1 and Sl_0.

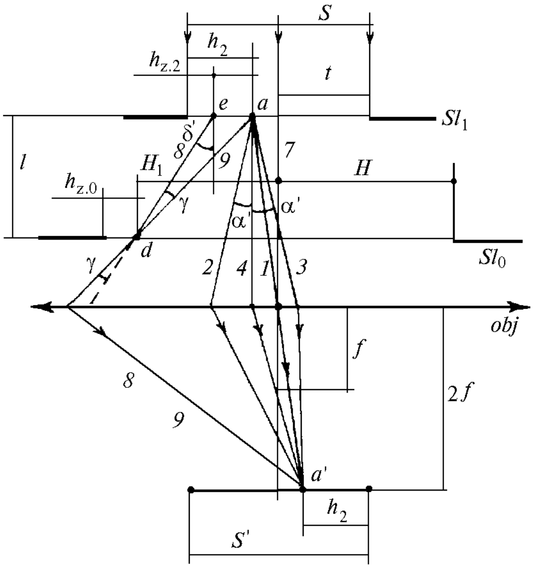

Fig. 2. Formation of the second diffraction pattern within the limits of the slit image.

Having passed the slit Sl_0, the ray *8* propagates along the path of the imaginary ray *9*. So the phase difference between the rays *8* and *9* (and, therefore, between the beams *8* and *2–4*) is

$$\Delta_{9,8} = (ad - ed).$$

The value

$$ad = (l + \Delta_9);$$
$$ed = (l + \Delta_8);\ \Delta_{9,8} = (\Delta_9 - \Delta_8).$$

Since

$$\Delta_9 = (H_1 - t + h_2)^2/2l,$$
$$\Delta_8 = (H_1 - t + h_{z.2})^2/2l,$$

we have

$$h_2 = -(H_1 - t) + \sqrt{(H_1 - t + h_{z.2})^2 + k'\lambda l}.$$

Because of the deflection toward the screen in the deflection zones, the ray *8* is delayed by $k_{02}\lambda/2$. So the first maximum of J is formed at the point a' where the initial delay of the ray *8* is compensated for by the geometrical phase difference between the rays *2–4* Eq. (9) and the given ray. In this connection we have,

$$h_2 = -(H_1 - t) + \sqrt{(H_1 - t + h_{z.2})^2 + (k_{02} + k)\lambda l}, \quad (10)$$

$k = 0, 2, 4, \ldots$ denote the maxima; $k = 1, 3, 5, \ldots$ denote the minima.

From Eq. (10) it follows that,

$$k_{02} = \left[\frac{2(H_1 - t + h_{z.2})(h_2 - h_{z.2}) + (h_2 - h_{z.2})^2}{\lambda l} - k\right]. \quad (11)$$

Under the conditions of formation of the second pattern,

$$h_{z.2} = A_2 - \sqrt{A_2^2 - B_2}, \quad (12)$$

where

$$A_2 = \frac{S(H_1 - 0.5\cdot 10^{-3}\,S) + 0.1508\,l}{2(H_1 - 1.5\cdot 10^{-3}\,S)};$$

$$B_2 = \frac{S(0.0754\,l - 0.786\,H_1 + 0.393\cdot 10^{-3} S) - 0.62\,H_1}{H_1 - 1.5\cdot 10^{-3} S};$$

S and $h_{z.2}$ are in μm; H_1 and l are in mm.

The values of k_{02} calculated by Eq. (11) for $h_2 = h_e$ are close (see Table 1) to those of k_{01}. For this reason, the fringes of the first pattern are shifted a little bit relative to the analogous fringes in the second pattern. Somewhat lower values of k_{02}, as compared with k_{01} demonstrate that $h_2 > h_1$ for similar values of k_0. Therefore, for $k_{01} = k_{02}$, $(h_1 + h_2)/2 = h_e$.

Together with the patterns in S' considered, similar but mirror-image patterns *3* and *4* are formed as a result of interference of the rays *2–4* with the rays *5′* deflected near the right-hand (Sl_1) and left-hand (Sl_0) screens along the direction from the screens (the third pattern) and with the rays *8′* deflected near the right-hand (Sl_1 and Sl_0) screens toward the screen (the fourth pattern).

The order of fringes in the patterns grows from left to right, i.e., the zero value of h is at the left-hand edge of the image of Sl_1.

It is easy to understand that formation of max or min of intensity J at the center of S' is a condition for matching of the patterns *1* and *2* with the patterns *3* and *4*. For values of S, H, λ, and l that do not satisfy this condition, the patterns *1* and *2* are shifted with respect to the patterns *3* and *4* by half-width of the fringe or by a fraction of it. Owing to this fact, the resulting pattern either disappears or has weakly manifested irregular fringes.

In the case when the left-hand side screen of Sl_0 is removed, the diffraction pattern on S' is a sum of the patterns *1* and *4*; with removing of the right-hand side screen it is a sum of the patterns *2* and *3*.

According to data from Table 1, a small increase of k_0 occurs simultaneously with the growth of the diffraction angles γ_1 and δ' of the edge (coming from the domain near the screen edge) rays.

This seems to be a convincing fact that k_0 is a function of $(\delta' + \gamma_1)$. However, if the left-hand side screen of Sl_0 is removed, k_0 does not grow with the increase of $(\delta' + \gamma_1)$. Perhaps there is a phase difference between the parallel rays entering the deflection zones of the left-hand and right-hand side screens of Sl_1; otherwise, there is either a phase difference increasing with decreasing h_z, or the initial phase differences

$k_{03,4}\lambda/2$ acquired by the rays *5'* and *8'* in the zone of the right-hand side screen of Sl_1 somewhat differ from $k_{01,2}\lambda/2$ and the stronger the smaller is h_z.

This supposition is quite well explained by the facts considered in Ref. 6 (influence of the absorptivity, thickness, shape of the screen upon an edge wave), as well as by an incomplete identity of the screens of Sl_1 and because of ignoring the edge light component arising as a result of reflection of incident beams off the screen edge.

As it was mentioned in the first part of the paper, the rays *2–4* form the mean illumination in the image of Sl_1. As follows from Table 1, their deflection angles $\alpha' \ll \delta'$, so the light power in the optical arrangement considered, while Sl_1 is illuminated by a parallel beam, does not depend on the width of Sl_0.

Table 2. Light intensity variation at the center of the slit image as a function of *t* and *H*

l, mm	H, mm	t, μm	Fringe	k	$h_{z.1}$, μm	γ_1, min	δ', min	$h_{z.01}$, mm	k_{01}
72	0.55	35.5	$\max_1$	0	11.2	1.16	16.8	0.223	0.432
		70.5	$\min_1$	1	8.64	2.95	24.75	0.087	0.604
		108	$\max_2$	2	7.87	4.78	28.5	0.054	0.867
		22	$\max_1$	0	5.96	0.766	31.8	0.338	0.541
		41	$\min_1$	1	4.93	1.72	41.1	0.15	0.596
72	0.975	59.5	$\max_2$	2	4.72	2.62	44.5	0.099	0.597
		79.5	$\min_2$	3	4.55	3.58	46.7	0.072	0.698
		101	$\max_3$	4	4.4	4.61	48.5	0.056	0.9
		10.5	$\max_1$	0	2.44	0.39	66.1	0.673	0.63
		20.5	$\min_1$	1	2.05	0.88	84.7	0.294	0.712
72	2.05	30	$\max_2$	2	1.94	1.34	90	0.193	0.754
		40	$\min_2$	3	1.9	1.82	92.8	0.142	0.847
		49.25	$\max_3$	4	1.87	2.26	94.7	0.114	0.87
		58	$\min_3$	5	1.85	2.68	96	0.096	0.838
		67.4	$\max_4$	6	1.83	3.13	97.1	0.082	0.88
		8	$\max_1$	0	1.31	0.32	106.3	0.803	0.804
		15	$\min_1$	1	1.11	0.67	127.8	0.386	0.93
		21.1	$\max_2$	2	1.07	0.97	132.8	0.268	0.92
		28.6	$\min_2$	3	1.05	1.33	136.7	0.194	1.12
71.25	3	35	$\max_3$	4	1.03	1.64	139	0.158	1.15
		41.25	$\min_3$	5	1.02	1.94	140.3	0.133	1.15
		49.25	$\max_4$	6	1.01	2.33	141.8	0.111	1.44
		54.25	$\min_4$	7	1	2.57	142.6	0.1	1.24
		60.5	$\max_5$	8	1	2.87	143.3	0.09	1.26

Table 3. Light intensity variation at the center of the slit image as a function of *t*, *H* in removing the left-hand screen of Sl_0

H, mm	t, μm	Fringe	k	$h_{z.1}$, μm	γ_1, min	δ', min	$h_{z.01}$, mm	k_{01}
	19.25	$\max_1$	0	5.45	0.67	33.8	0.39	0.506
	35.5	$\min_1$	1	4.5	1.5	45	0.173	0.507
1.075	53	$\max_2$	2	4.2	2.35	48.9	0.11	0.558
	71.75	$\min_2$	3	4.07	3.27	51.3	0.079	0.694
	87	$\max_3$	4	4	4	52.8	0.64	0.627
	10	$\max_1$	0	2.43	0.37	66.2	0.71	0.551
	17.4	$\min_1$	1	2.05	0.74	84	0.35	0.414
	27.4	$\max_2$	2	1.91	1.23	91.2	0.21	0.536
2.075	35.5	$\min_2$	3	1.87	1.62	94.1	0.16	0.44
	45	$\max_3$	4	1.82	2.08	96.2	0.124	0.514
	53	$\min_3$	5	1.8	2.47	97.6	0.104	0.413
	61.1	$\max_4$	6	1.78	2.86	98.7	0.09	0.33
	7	$\max_1$	0	1.364	0.27	100.24	0.95	0.615
	12.4	$\min_1$	1	1.12	0.544	123.5	0.476	0.53
	19.5	$\max_2$	2	1.08	0.89	133	0.291	0.673
3.025	27	$\min_2$	3	1.03	1.25	137.3	0.206	0.9
	32.5	$\max_3$	4	1.02	1.52	139.3	0.17	0.79
	38.6	$\min_3$	5	1.01	1.81	141	0.142	0.78
	44.25	$\max_4$	6	1	2.09	142.1	0.124	0.7

Tables 2 and 3 present the values of k_0 at the moments of max and min of intensity J at the axis of the image of the slit Sl_1. These were calculated by Eq. (4) for $h_1 = t$ and different values of H, t, and l in the experiments with Sl_0 and Sl_0 without its left-hand side screen.

When $H \le 2.1$ mm, they are approximately equal to those given in Table 1. With the increase of the Sl_0 width up to 6 mm, additional increase of k_0 took place. In the case of Sl_0 without its left-hand side screen ($l = 71.25$ mm), k_0 is almost independent of k and in principle insignificantly differs from 0.5.

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