Propagation of Fluorescence Radiation through μ-capillary Holes of Glass Micro-channel Plate

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Abstract— The features of soft X-ray fluorescence spectra of radiation propagating inside micro-channel plates have been studied in the framework of wave approximation. X-ray and fluorescence yield due to the grazing incidence reflection phenomenon have been investigated with respect to the geometry of channel walls. We researched experimental spectra collected at the exit of micro-capillaries under total X-ray reflection condition and supported them with theoretical calculations taking into account a surface transition layer at waveguide surface. It was shown that the wave penetrating through cladding material substantially modifies the wave field near the waveguide surface. It results in a significant increase of total energy flux inside guiding layer and leads to additional spatial modulation of the electromagnetic field. Diffraction phenomena at the exit of a hollow X-ray waveguide (with real and imaginary parts of permittivity) were investigated using the model of Fraunhofer diffraction of waves at far zone.

1. INTRODUCTION

Capillary optics is one of the fastest growing X-ray optical technologies [1] because of its superior capacity of generating high flux density beam in the μm- and sub μm range. Properties and peculiarities of X-ray beams formed by polycapillary optics have been intensively studied in the past 25 years [2–6]. Investigations of X-ray waveguides and micro-capillary optics based on the phenomenon of multiple total external reflections are devoted to ultra focusing properties and partially coherent beams. Application of the wave optics methods allows the process of guided transmission of X-ray radiation to be described in details. In microchannels the propagation features are defined by the radiation interaction with a curved surface and characterized by the waves that propagate close to the capillary walls. Basic point of the X-ray beam transportation in capillary channel (as an X-ray waveguide) is the mode regime [2] associated in particular with a surface channeling of X-ray radiation.

Propagation of X-rays through micro-capillaries is of great interest due to the high efficiency of radiation transportation by holes of micro-capillaries, and, as a consequence, due to the possibility for creation of new optical elements conditioning the X-ray beams. In addition to the high practical importance, capillary optical systems represent a fine tool for studying fundamental features of radiation dispersion by a surface. The continuing investment in, and development of, new sources of intense and even coherent x-ray radiation as well as the refinement and extension of methods to probe matter with these sources attests to the continuing importance of this field.

The micro-channel plate (MCP) systems can be applied to focus and collimate X-rays. The optics can provide a highly effective low weight device and may be ideally suited for use in a lot of applications. Grazing-incidence X-ray methods based on the analysis of the secondary radiation (fluorescence) from a solid surface as a result of interaction with primary radiation have a great scientific and applied interest. If the grazing angle is less than the Fresnel one, and incident photons are capable to excite the atomic levels then both X-ray fluorescence and elastic scattering are observed. In the previous manuscripts were published [7–11] experimental results on the spectroscopy of X-ray fluorescence transportation through the MCP.

One of the goals of this work is to present the theoretical model on transmission of X-ray fluorescence radiation emitted by walls of the silicon glass micro-channels through microcapillary structures. Inelastic scattering and propagation of fluorescence radiation have been studied in anomalous dispersion region of the energy range near the SiL — absorption edge. Also, we have presented results on X-ray transmission through microcapillary structures, aimed at the Research&Development of dedicated optics working in "water window" spectral region (energy 100–600 eV).

2. METHOD

2.1. Basic Steps of Our Theoretical Model

► Calculation of propagation constants and constants of attenuation (excitation) too for wave modes of a single capillary;
► It was considered that wave parameters of the single capillary are correspond to the parameters of micro-channel plate (MCP) polycapillary structures;
► Mode amplitudes at the input of the polycapillary structures have been calculated with the help of Kirchhoff - Huygens method;
► Using attenuation (excitation) constants mode amplitudes was calculated at the output of the capillaries;
► Angular distribution of X-ray radiation at the exit of MCP was calculated on the base of Kirchhoff-Huygens method;
► Investigation of the X-ray diffraction (diffraction pattern) at a long distance from the MCP have been performed using the model of Fraunhofer diffraction of waves.

2.2. Calculation of Parameters of Waveguide Modes in a Single Capillary

X-ray radiation propagates through silicon glass plates in a vacuum inside the holey cylindrical waveguides (pores). According to our model transition layer was taken into account at the surface of inner shell microchannels. In this approximation the permittivity ($\varepsilon \approx 1-\delta-i\beta$) varies smoothly between value of 1 to the value for substrate - dielectric constant of silicon glass (see Figure 1).

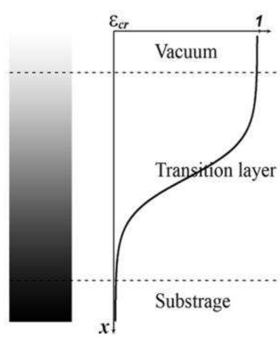

Figure 1: The model of transition layer for the waveguide channel surface.

In addition, we can taken into account an insignificant polarization of X-ray waves in the X-ray waveguide ($|\varepsilon| \cong 1$) and field was described with the help of scalar potential $\Psi(r,\varphi,z) = U(r)\cos m\varphi \exp(-i\gamma z)$, where γ — is a complex propagation constant. Function $\Psi(r,\varphi,z)$ satisfies to the Helmholtz equation

$$\Delta\Psi\left(r,\varphi,z\right) + k^2\varepsilon\left(r\right)\Psi\left(r,\varphi,z\right) = 0$$

Δ — is the Laplace operator, $k = 2\pi/\lambda$, λ — is a radiation wavelength in vacuum.

In the frame of our approximation of transition layer the cylindrical transition layer (inner shell of the micro-channel) was deviated into N sub-layers (rings in the cross section). The permittivity of the each ring is a constant and it was determined by the dielectric constant corresponding to the radius of the middle of this ring. The dispersion equation for the complex value of the propagation constant γ can be solved numerically using the math method proposed in [12].

2.3. The Calculation of the Mode Amplitude at the Input of the Capillaries

We considered a propagation of plane waves and coordinates $z = 0$, $z = -h$ corresponded to the entrance and exit of waveguide ends respectively. The math expression below is present by a plane waves at the input of the capillaries

$$\Psi^{ext}\left(x,z\right) = \exp\left[i\ \left(k_x x + k_z z\right)\right], \tag{1}$$

where $k_x = k\sin\varphi$, $k_z = k\cos\varphi$, φ — grazing angle between the X-ray beam and wall of the microchannel wall. In the plane of $z = 0$ we have

$$\Psi^{ext}(x,0) = \exp(ik_x x) = \exp(ik_x r\cos\varphi) = 2\sum_{m=0}^{\infty}\nu_m i^m J_m(k_x r)\cos m\varphi$$
$$\nu_n = \begin{cases}\frac{1}{2}, & n=0,\\ 1, & n\neq 0.\end{cases} \tag{2}$$

At the entrance of the capillary the wave amplitude $A_{mn}(0)$ can be calculated with the help of integral:

$$A_{mn}(0) = \int_0^R rdr\int_0^{2\pi}\Psi^{ext}(r\cos\varphi,0)\,\Psi_{mn}(r,\varphi,0)\,d\varphi \tag{3}$$

After substituting the Equations (1), (2) in the (3) was obtained the relations:

$$A_{mn} = 2\pi\, i^m I(m,\kappa_{mn},k_x,R)$$
$$I(m,\kappa_{mn},k_x,R) = \int_0^R rJ_m(k_x r)\,J_m(\kappa_{mn}r)\,dr$$
$$= R\frac{\kappa_{mn}J_{m-1}(\kappa_{mn}R)\,J_m(k_xR) - k_xJ_m(\kappa_{mn}R)\,J_{m-1}(k_xR)}{(\kappa_{mn})^2 - k_x^2}$$

κ_{mn} — transverse wave mode number which has index mn.

The amplitude at the exit of the capillary is equal:

$$A_{mn}(h) = A_{mn}(0)\exp\left(-\gamma''_{mn}h\right),$$

where $\gamma''_{mn} = \mathrm{Im}\gamma_{mn}$ is the attenuation coefficient in the case of $\gamma''_{mn} > 0$, and excitation coefficient for $\gamma''_{mn} < 0$.

Summary field in the capillary was calculated in our model as:

$$U_\Sigma(r,\varphi,z) = \sum_{m=0}^{\infty}\sum_{n=1}^{\infty}A_{mn}U_{mn}(r,\varphi,z) = \sum_{m=0}^{\infty}\sum_{n=1}^{\infty}A_{mn}J_m(\kappa_{mn}r)\cos m\varphi\exp(i\gamma_{mn}z) \tag{4}$$

2.4. Angular Distribution of the X-ray Radiation Intensity Calculation Collected at the Output of the MCP

The radiation field at the output of the MCP was consider as a double row on spatial harmonics

$$V(x,y,z) = \sum_{p=-\infty}^{\infty}\sum_{q=-\infty}^{\infty}B_{pq}\exp\left[i\chi_{pq}(x,y,z)\right] \tag{5}$$

where B_{pq} — is the amplitudes of spatial harmonic and $\chi_{pq}(x,y,z)$ is the phases.

We have taken into account for X-ray condition of $z \gg \lambda$ to perform calculations only for waves $k > \rho_{pq}$.

The amplitudes of space harmonics can be estimated with the help of integral:

$$B_{pq} = \int_0^R rdr\int_0^{2\pi}V(x,y,h)\,U_\Sigma(r,\varphi,h)\,d\varphi \tag{6}$$

After substituting the Equations (4), (5) in the (6) was obtained the relations below:

$$B_{pq} = 2\pi\sum_{m=0}^{\infty}i^m\sum_{n=1}^{\infty}A_{mn}I(m,\kappa_{mn},\rho_{pq},R) \tag{7}$$

In the calculations in (7) in the sum over n considered only propagating waveguide modes, the upper limit of summation in the sum over m was selected numerical experiment, it usually does not exceed three. Each space harmonic — is a plane wave which projections of wave vector on the axis "x, y" are equal to α_p, β_{qp}, respectively. The angles of the diffraction peaks (in the spherical coordinates) are defined by

$$k_{x,pq} = k\cos\varphi_{pq}\sin\theta_{pq} = \alpha_p,\ k_{y,pq} = k\sin\varphi_{pq}\sin\theta_{pq} = \beta_{qp},$$
$$k_{z,pq} = k\cos\theta_{pq} = \gamma_{pq}.$$

3. RESULT

In this work, we have studied the angular distribution of the X-ray field passed through microchannels whose energy corresponds to the anomalous dispersion region of the $\mathrm{SiL}_{2,3}$ absorption edges. The transition layer was considered as a waveguide, where the total reflection effect occurs only at the interface with the material. Radiation leaves the transition layer at the interface with vacuum; as a result, the wave rapidly damps. The damping of the wave in the waveguide can be compensated in the presence of amplification owing to the excitation of X-ray SiL fluorescence inside this layer.

The experimental layout shown in Figure 2, describes the optical configuration available at the Polarimeter end-station of the UE52_SGM at the BESSY II synchrotron radiation facility. We used for the experiments ~0.3 mm thick MCPs with a hexagonal shape in the transverse cross-section, made with a lead silicate ($\mathrm{PbSiO_3}$) composition, manufactured by the BASPIK [13]. Such compact optical devices contain regular holey channels with a diameter of 3.4 μm and with a pitch size of 4.2 μm. As shown in Figure 2, the entrance surface of the MCP was illuminated by a primary monochromatic radiation. The radiation propagating inside the micro-channels was collected by a single photodiode placed on the other side of the polycapillary structure. In the transmission geometry, the grazing angle θ between the incident primary beam and MCP microchannel walls was set while rotating the device around the "θ" axis (see Figure 2).

The angular distribution of the radiation, i.e., the intensity vs. angle at the exit of a MCP, in the total external reflection condition for different grazing angles of the incident beam has been investigated. Performing the angular scan of the photodiode position sets at the exit of the MCP (angles "ϕ" of the photodiode), we may identify the positions where the maximum intensity of emitted radiation occurs. For any fixed value of the θ-angle between the incident monochromatic radiation and MCP microchannel walls, the intensity distribution between two maxima $\phi = \pm\theta$ in the angular range $-\phi \leq \phi \leq \theta$ has been measured. Finally, the spectra for different θ angles and for different positions of the photodiode: ϕ_1, ϕ_2, ϕ_3, …, ϕ_n, have been collected.

Figure 3 shows the angular distribution of the radiation intensity at the output of the microchannel plate experimentally obtained at the Polarimeter experimental station at the BESSY II synchrotron center (1) and calculated distributions (2, 3) on the base of the theoretical model presented here. The performed calculation shows that radiation intensity maxima at $E = 120\,\mathrm{eV}$ at the output of the micro-channel plate should be observed at the angles $\theta = \pm 5\,\mathrm{deg.}$ and

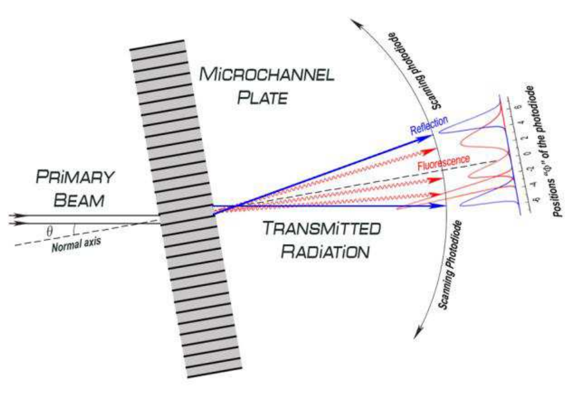

Figure 2: Experimental layout for transmission mode radiation though MCP.

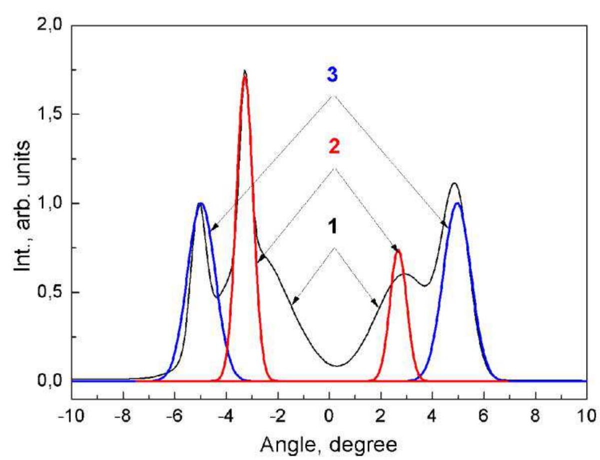

Figure 3: Angular distribution of the radiation intensity at the output of the micro-channel plate.

$\theta \approx \pm 3$ deg.. Two peaks marked by (2) in the figure are lines which have been calculated in the case of excitation radiation inside the microchannels. We have found that angle of output X-ray fluorescent radiation does not dependent on the angle of incidence radiation on the MCP.

Thus, the theoretical values are in good agreement with the experimentally observed values. We attribute the revealed maxima at $\theta = \pm 5$ deg. with reflection of primary radiation at the exit and $\theta \approx \pm 3$ deg. in the distribution of the intensity of X-rays at the output of micro-capillaries to the surface fluorescence waves propagating in the transition layer of microchannels. Experimental spectrum shows the additional maximum at the angle about $\theta \approx -2$ deg. which nature may be connected with X-ray fluorescence radiation according to the theoretical possibility yield fluorescence at small angles too.

4. CONCLUSIONS

The x-ray fine structures and the angular distribution of X-ray radiation propagating inside microchannels of MCPs have been interpreted in the energy range of the anomalous dispersion of the $SiL_{2,3}$ absorption edges thanks to calculations performed within a model that takes into account a surface transition layer at the sample surface. In this work was revealed that transition layer where the total reflection of X-rays takes place acts as an effective waveguide. As a consequence, for a device whose channels are much longer than the radiation wavelength, the radiation at the exit of MCPs shows maxima at angles corresponding to theoretical calculations.

In the future it may be allowed to identify optimal transport conditions for the fluorescence radiation excited inside of microcapillary structures. The fluorescence transport conditions optimization is very important for improvement of X-ray focusing properties and, in principle, for delivery of high flux density on a sub-micrometer area of sample.

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REFERENCES

1. Tsuji, K., J. Injuk, and R. Van Grieken, Eds., *X-ray Spectrometry: Recent Technological Advances*, Wiley, 2004.
2. Dabagov, S. B., *Phys. Usp.*, Vol. 46, 1053–1075, 2003.
3. Kumakhov, M. A. and F. F. Komarov, *Phys. Rep.*, Vol. 191, 289–350, 1990.
4. Bilderback, D. H., S. A. Hoffman, and D. J. Thiel, *Science*, Vol. 263, 201–203, 1994.
5. Pfeiffer, F., C. David, M. Burghammer, C. Riekel, and T. Salditt, *Science*, Vol. 297, 230–234, 2002.
6. Dabagov, S. B., M. A. Kumakhov, S. V. Nikitina, et al., *J. Synchrotron Rad.*, Vol. 2, 132–135, 1995.
7. Mazuritskiy, M. I., *JETP Letters*, Vol. 84, No. 7, 381–383, 2006.
8. Mazuritskiy, M. I. and J. Synchrotr, *Rad.*, Vol. 19, 129–131, 2012.
9. Mazuritskiy, M. I., S. B. Dabagov, K. Dziedzic-kocurek, and A. Marcelli, *NIM B*, Vol. 309, 240–243, 2013.
10. Mazuritskiy, M. I., A. M. Lerer, A. A. Novakovich, and R. V. Vedrinskii, *Jetp Lett.*, Vol. 98, 130–133, 2013.
11. Mazuritskiy, M. I., S. B. Dabagov, A. Marcelli, A. Lerer, et al., *J. Opt. Soc. Am. B*, Vol. 31, No. 9, 2182–2187, 2014.
12. Lerer, A. M., I. V. Donets, G. A. Kalinchenko, and P. V. Makhno, *Photon. Res.*, Vol. 2, 31–37, 2014.
13. Vladikavkaz Technological Center "BASPIK", Microchannel Plates, http://www.baspik.com/eng/products/nauka/.