Optica Applicata, Vol. XXXI, No. 1, 2001

Model examination of the crossover effect in two-layer light-sensitive system

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The results of computer simulation of the effect of light scattering in a system composed of two heterogenic light-sensitive layers coated on two sides of a transparent base are presented. It has been assumed that the modelled system is irradiated with a directed X-ray beam, while the photographic effect is caused only by the light emitted by the fluorescent screens adjacent to the light-sensitive layers and containing phosphors fluorescing due to X-ray irradiation. The scattered light transpassing the base reaches the opposite light sensitive layer, thus damaging the sharpness of the details. This effect called crossover is disadvantageous in roentgenography. Qualitative dependence of the modulation transfer function of the system on both its geometric and optical parameters was examined. It has been shown that worsening of the image is the stronger the thinner the light-sensitive layers and the weaker the light scattering by single silver halide crystals. This result is surprising since in the case of single-layer light-sensitive systems not suffering from the crossover effect opposite effects are observed.

1. Introduction

In radiography of living organisms the minimisation of the harmful ionising radiation is of great importance. Therefore, producers of silver halide materials for medical diagnostics put forth an effort to increase their sensitivity. A very successful method of increasing the effectiveness of radiation detection is to apply a photographic film composed of two silver halide light-sensitive layers deposited on the two sides of a transparent base, together with application during exposure of the so-called fluorescent or intensifying screens adjacent to the light-sensitive layers. The intensifying screens contain compounds of rare-earth elements, which fluoresce under the influence of the X-ray in the region of near ultraviolet and visible light, *i.e.*, in the sensitivity range of silver halides [1]. Conversion of the radiation is so effective that the image is created mainly by the effect of light (rather than X-rays). A disadvantage of the method described lies in the worsening of image sharpness caused by the crossover effect. This effect consists in mutual irradiation of the light-sensitive layers with the scattered light leaving the layer located on the opposite side of the base. The principle of crossover effect creation is illustrated in Fig. 1. As mentioned above, this effect results in a diminishing of sharpness of the recorded image. In the case of point exposure of the system with a beam perpendicular to its

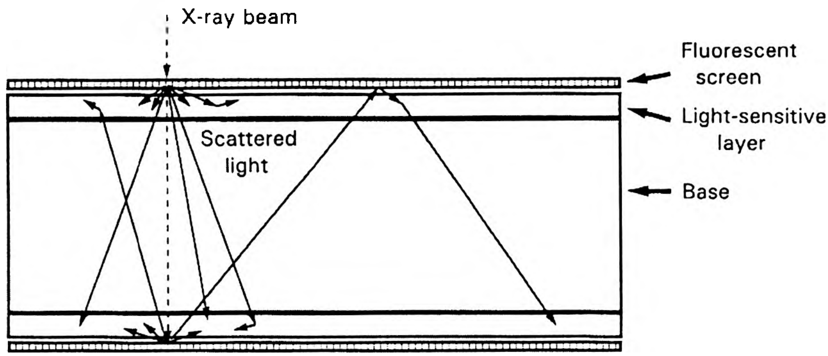

Fig. 1. Principle of crossover effect in a system composed of two-layer light-sensitive film and fluorescent screens. The scale is not preserved in the illustrated cross-section of the system in order to make the interpretation of the effect easier.

surface, a kind of "double" image will be recorded being composed of one relatively sharp part and the other one being diffused in the form of a disk. This effect is illustrated in Fig. 2, being obtained from one of the computer simulations. This illustration shows two-dimensional spatial distribution of the photon absorption acts around the irradiated point.

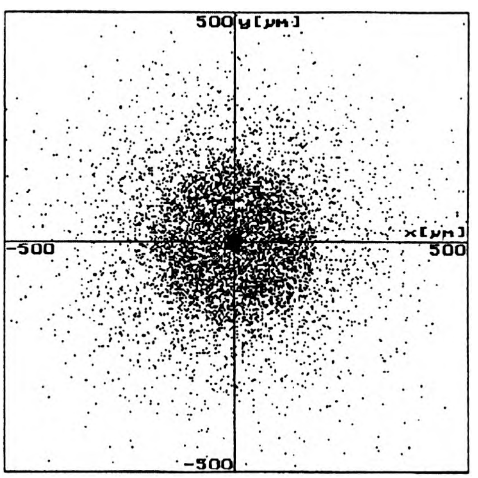

Fig. 2. Diffuse point image obtained from one of the computer simulations and created due to point irradiation of the model light-sensitive system. The black points represent locations in which absorption of the photon by silver halide occurred.

The quality of imaging can be characterised by the optical modulation transfer function (MTF). The domain of MTF is spatial frequency f expressed by the number of cycles (pairs of bright and dark lines) along a unit distance in the recorded image. The MTF is understood as dependence of the ratio of the modulation of the recorded optical signal to that of the original signal on the spatial frequency [2]. The tiny details and edges are represented by high spatial frequencies, hence the course of MTF for a light-sensitive material allows us to evaluate its capability to sharply record the fine details of the image.

The aim of the model investigations was to perform an analysis of the influence of selected physical parameters of a two-layer light-sensitive system on the course of MTF caused by the crossover effect.

2. Characteristics of the model

The models exploiting the Monte Carlo method to examine the light scattering phenomenon inside the photographic layers have been known for many years, and their descriptions and results obtained are given, *e.g.*, in papers [3]–[12]. It should be emphasized that till now no results concerning the model examination of the crossover effect have been published in spite of the fact that the Monte Carlo method was used to investigate optical properties of the fluorescent screens as such [13]. In this paper, a modification of the stochastic model applied earlier [9]–[12] was used based on the following assumptions:

– Photons enter into the layer in random directions but all at the same point of its surface (without taking into account the inner light diffusion of the fluorescence screen).

– Internal reflection of the light from the layer air border is totally scattered (surface of the layer is matt).

– Refractive index of the base and that of the photographic gelatine are the same.

– Probability distribution that a photon has passed a given free distance between the successive collisions with the silver halide crystals is assumed to be an exponential function, the parameter of which is the average free path l of the photon; the standard value for $l = 1.0$ μm has been assumed.

– Assumed standard value of the photon absorption probability during the collision with a silver halide crystal is $p = 0.05$.

– Indicatrix of radiation scattering by particular crystals of silver halide is of ellipsoidal form, the ellipsoid focus takes the position identical with that of crystal middle point and the elongation of indicatrix is defined as the average cosine c of the scattering angle; the standard value of the $c = 0.55$ has been assumed.

– Standard value of the light-sensitive layer thickness $h = 5$ μm.

– Standard value of the base thickness $h_B = 175$ μm.

3. Results

After having worked out a relevant computer program five series of simulation experiments were carried out in which one of the physical parameters was variable while the other four were of standard value. For the sake of comparison four series of simulations for zero base thickness were also carried out. The corresponding MTFs were shown in the figures. A broken line was used to distinguish the system of standardized parameters.

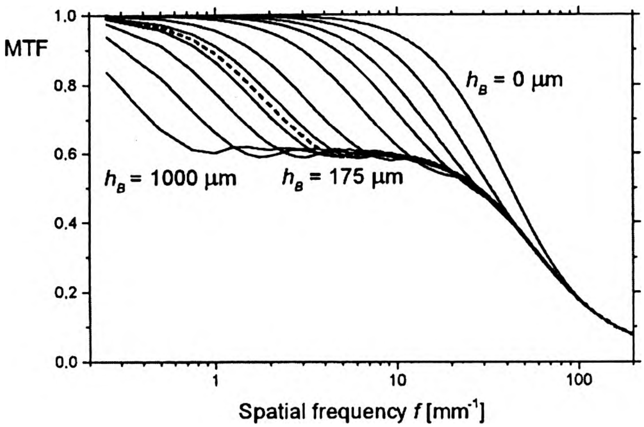

Fig. 3. MTF of the light-sensitive system for the case of variable base thickness h_B = 10, 20, 30, 50, 100, 150, 175, 200, 300, 500 and 1000 μm.

In Figure 3, changes in the course of MTF of the system of variable thickness of the substrate are illustrated, while in Figs. 4, 6, 8 and 10 the said changes in the course of MTF are shown for the system of the other four variable parameters and for $h_B = 0$. Figures 5, 7, 9 and 10 illustrate the situation for $h_B = 175$ μm.

4. Discussion and conclusions

The results of the computer modelling showed that all the optical and geometrical parameters examined influence essentially the course of MTF. Similarly as was the case of conventional single-layer light-sensitive materials both the increment of the average free path of a photon and the decrement of the photon absorption probability cause disadvantageous changes in the course of the optical MTF [14] consisting in attenuating the higher spatial frequencies. Besides, together with the increase of the base thickness some additional deformations of MTF become stronger (Figs. 4–7). They show that a significant attenuation of not only the high frequencies but also of the middle ones of 1 to 10 mm^{-1} takes place in the images. This effect is essentially disadvantageous since it is just these frequencies that play the most important part in the mechanisms of human vision. It should be remembered that the radiograms are usually observed with naked eye from the distance allowing good vision.

Additionally, it has been shown that the worsening of the image quality is the stronger the thinner the light-sensitive layers and the more elongated indicatrix of the light scattering by a single silver halide crystal (Figs. 8, 9, 11). This is a surprising result since in the case of single-layer light-sensitive systems without crossover effect the corresponding dependences are opposite. These effects can be explained in such a way that both an increase of the thickness of the layer as well as a decrease of the indicatrx elongation diminish the light flux leaving this layer and penetrating the opposite layer across the base. In each of the dependences examined an essential part

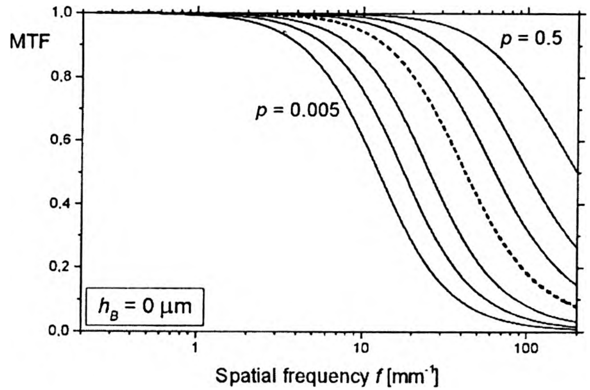

Fig. 4. MTF of the light-sensitive system for the case of variable probability of photon absorption $p = 0.005$, 0.01, 0.02, 0.05, 0.1, 0.2 and 0.5 for the base thickness $h_B = 0$ µm.

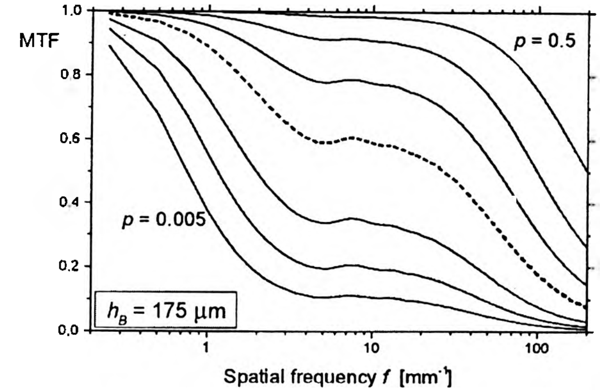

Fig. 5. MTF of the light-sensitive system for the case of variable probability of photon absorption $p = 0.005$, 0.01, 0.02, 0.05, 0.1, 0.2 and 0.5 for the base thickness $h_B = 175$ µm.

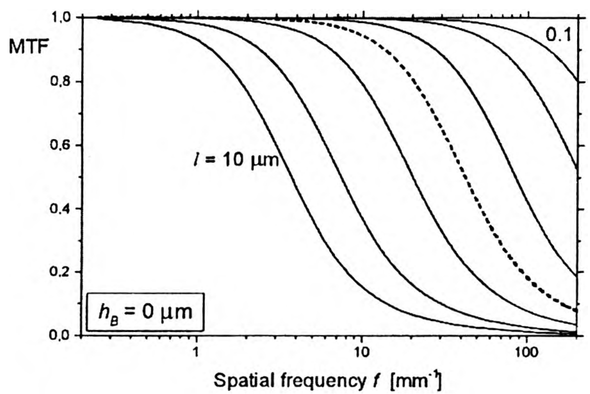

Fig. 6. MTF of the light-sensitive system for the case of variable average free path of the photon $l = 0.1$, 0.2, 0.5, 1, 2, 5 and 10 µm, for the base thickness $h_B = 0$ µm.

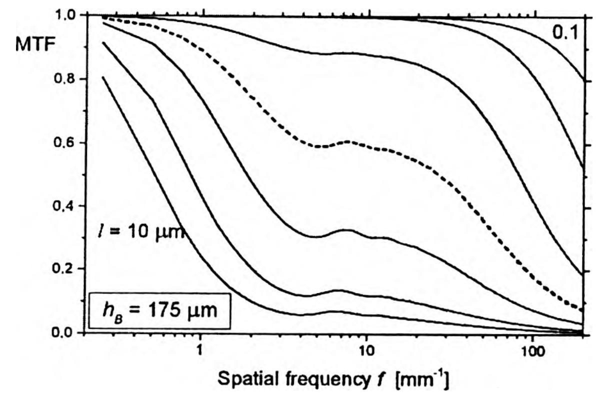

Fig. 7. MTF of the light-sensitive system for the case of variable average free path of the photon $l = 0.1$, 0.2, 0.5, 1, 2, 5 and 10 µm, for the base thickness $h_B = 175$ µm.

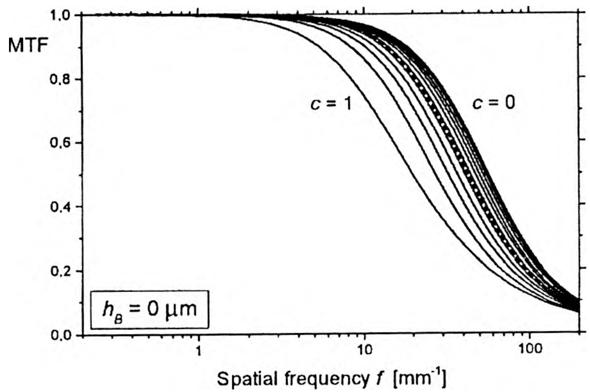

Fig. 8. MTF of the light-sensitive system for the case of variable elongation of the light scattering indicatrix for an average scattering angle $c = 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.55, 0.6, 0.7, 0.8, 0.9$ and 1.0 for the base thickness $h_B = 0$ μm.

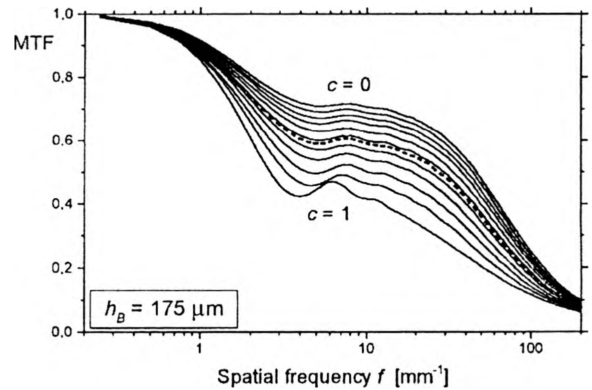

Fig. 9. MTF of the light-sensitive system for the case of variable elongation of the light scattering indicatrix for an average scattering angle $c = 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.55, 0.6, 0.7, 0.8, 0.9$ and 1.0 for the base thickness $h_B = 175$ μm.

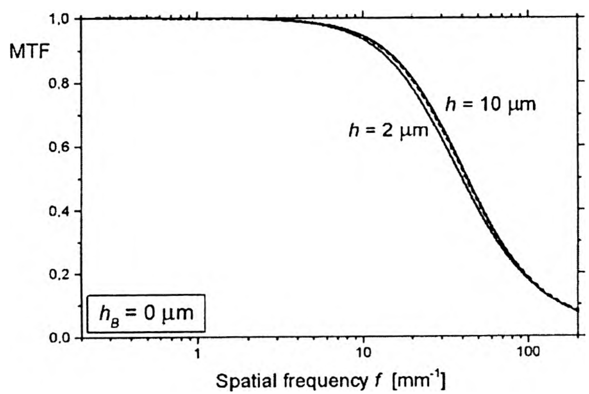

Fig. 10. MTF of the light-sensitive system for the case of variable layers thickness $h = 2$, 5 and 10 μm, for the base thickness $h_B = 0$ μm.

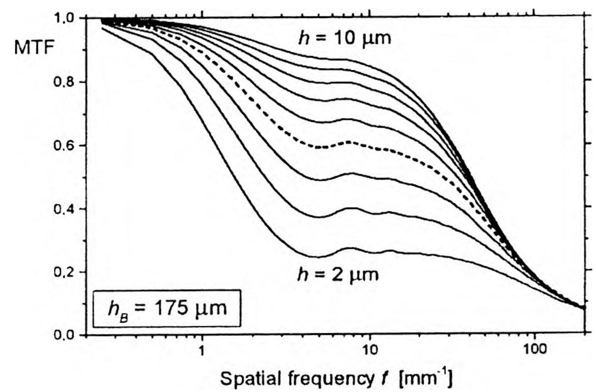

Fig. 11. MTF of the light-sensitive system for the case of variable layers thickness $h = 2, 3, 4, 5, 6, 7, 8, 9$ and 10 μm, for the base thickness $h_B = 175$ μm.

is played by the substrate thickness since the latter influences directly the range of the scattered light in the opposite layers, that is, affects the diameter of the "confusion spot" in the image of the point object.

It is striking that in the case of a system of zero thickness of the base the shape of the MTF is practically independent of the thickness of the light-sensitive silver halogen layers (Fig. 10). In the simulation examinations a zero thickness of the substrate has been assumed as a hypothetical extreme case. The real system fulfilling this condition is a single light-sensitive layer but of doubled thickness with respect to that of the layers located on both sides of the base. The lack of the MTF dependence on the thickness of the light-sensitive silver halide layers can be explained by two factors:

1. All the photons reaching the border of two phases, *i.e.*, that of light-sensitive layer–air, return to the inside of the layer due to either internal reflection from this border or reflection from the fluorescent screen. Thus, independent of the layer thickness the light is completely absorbed by the silver halide crystals.

2. The light-sensitive layer is illuminated by the light already completely scattered while the additional scattering inside the layer has an insignificant range. The consequences of the additional internal scattering are "amplified" first when the two layers are separated by relatively thick unscattering base.

The model worked out can be applied to the design of silver halide radiographic materials appropriate for use with the fluorescent screens. We intend to develope further the model in order to examine more accurate the said phenomena. Also, we plan to modify the model in order to examine the properties of the single-layer systems for use with one fluorescent screen which are also applied in X-ray medical diagnostics.

Acknowledgments — This work was supported by the grant No. 341-831 of the Faculty of Chemistry, Wrocław University of Technology. This paper was presented at VI Local Conference KOWBAN, Wrocław—Polanica Zd., October 28—30, 1999.

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Received February 10, 2000