Spectral Model of Halftone on a Fluorescent Substrate

Li Yang
Campus Norrköping (ITN), Linköping University
Norrköping, Sweden

Abstract

A unified spectral model with consideration of the effects of physical and optical dot gains and fluorescence of substrates is presented. In the model the effects of either physical or optical dot gain are characterized by a single parameter, while those of fluorescence by two sets of spectral parameters, one for fluorescence of bare paper and one for fluorescence of a print solid. This model is tested and further illustrated with applications to images generated by a laser color printer on ordinary office papers.

Introduction

All natural materials, like fibers, pigments etc., have a yellowish tint. The bleaching of pulp removes lignin and other non-fibrous materials, but residual lignin and other colored substances cause the yellowish tint of the chemical pulp. For a paper-maker, the use of fluorescent whitening agents (FWAs) and shading colorants are the main tools to eliminate this yellowish hue and to improve paper whiteness. The FWAs convert invisible ultraviolet radiation at 300 − 400 nm to visible light at 400 − 500 nm. Using FWAs is a convenient way to increase reflectance of paper and simultaneously to move the shade from yellow to blue. This subtle tint change makes the paper look even whiter.

For a printed image, the paper substrate contributes either directly or indirectly to the color rendition, either as a part of the image or by providing a reflective support to the ink dots. Studies on fluorescence related issues have therefore attracted great interests of researchers from both paper-making and Graphic Arts industries. Among others, Emmel and Hersch[1,2] proposed a spectral model of a transparent fluorescent ink on a transparent support or on a non-fluorescent paper. Rogers[3] extended this model to including boundary reflections at air/paper and air/ink interfaces. Nevertheless, there is no spectral model available, concerning the use of a fluorescent substrate.

This paper aims at providing a spectral model of halftone on a fluorescent substrate, with consideration of the effects of physical and optical dot gain.

Measurements

The test patches were created by a laser color jet with 600 dpi and scalable screening. The substrate was the MultiCopy paper (80g/m^2) produced by Stora Enso, containing FWAs. The nominal dot percentage of the patches are, σ_0 = 0, 5, 10, 20, 35, 50, 75, and 100%, for each primary color. Spectral reflectance values of these patches were measured by employing a spectrophotometer (*LW Relpho*). The spectra cover a spectral range of λ = 400 to 700 nm and an interval of 10 nm, when no UV filter is applied. With a UV (cutoff) filter, the effective spectral range becomes λ = 420 and 700 nm instead. Therefore, the effective spectral range of this study lies between λ = 420 and 700 nm.

Methods

In the present model, we consider effects of fluorescence, physical dot gain as well as optical dot gain. In the case of optical dot gain, light diffusion due to light scattering in the substrate is considered. Another process relating to optical dot gain, i.e, multiple internal reflections at air/paper and air/ink interfaces, is omitted. An extended model including this effect is under development. Readers that are interested in this topic may continue to read Ref. [4].

Spectral Reflectance of Paper and Print Solid

Let the intensity of illumination be $I_0 = I_u + I_v$, consisting of visible (I_v) and UV (I_u) radiations. The reflected light from a piece of bare paper may be computed by,

$$\begin{aligned} I(\lambda) &= [I_v(\lambda) + \int I_u(\lambda')f(\lambda - \lambda')d\lambda']R_g(\lambda) \\ &= I_v(\lambda)R_g(\lambda) + [I_u * f(\lambda)]R_g(\lambda) \end{aligned} \tag{1}$$

with * indicting a convolution. In Eq. (1), $R_g(\lambda)$ are the ordinary spectral reflectance values of a paper (excluding fluorescence) and $f(\lambda - \lambda')$ a spectral response function (quantum efficiency) of FWAs to the UV stimulation. For the fluorescent part, a two-step approximation is applied, i.e., the UV light, $I_u(\lambda')$, is first converted into visible light, $I_u * f(\lambda)$, by activating FWAs in the paper, which is then reflected as does the ordinary visible light. Such an assumption can be proper when FWAs lie closely to the surface of the paper.

Although a part of FWAs may penetrate into the bulk of paper in a practical paper making processes, it can hardly be activated because of strong absorption to the UV light by other paper materials. This makes the two-step approximation a generally proper approach. With this approximation, light scattering of fluorescence can be treated exactly the same way as ordinary visible light. To evaluate the contribution of fluorescence to a reflectance spectrum of the visible light, the intensity of fluorescence is normalized with respect to the incident light of the same wavelength, i.e.,

$$F_p(\lambda) = \frac{I_u * f(\lambda)}{I_v(\lambda)}. \tag{2}$$

The total reflectance of the paper, $R_p(\lambda)$, including fluorescence can then be computed by

$$\begin{aligned} R_p(\lambda) &= \frac{I(\lambda)}{I_v(\lambda)} \\ &= R_g(\lambda) + F_p R_g(\lambda). \end{aligned} \tag{3}$$

Quantities, $R_g(\lambda)$ and $R_p(\lambda)$, correspond to spectral reflectance values of paper, experimentally measured with and without employing a UV filter to the illumination. Consequently, quantity, F_p, can be determined from these spectral values, i.e.,

$$F_p(\lambda) = \frac{R_p(\lambda) - R_g(\lambda)}{R_g(\lambda)}. \tag{4}$$

Equation (3) reveals such a fact that the measured reflection spectra of paper, R_p, consist of two parts, reflection of ordinary visible light, R_g, as well as (reflected) fluorescence, F_pR_g. These are clearly demonstrated by the measured spectra of ordinary office copy paper, shown in Fig. 1.

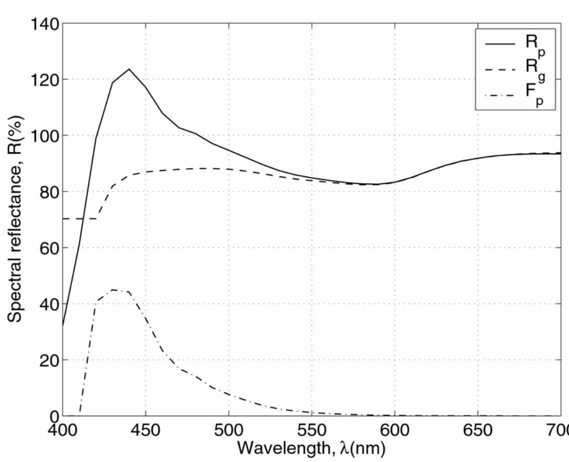

Figure 1. The spectral reflectance values of paper, measured with (Rg) and without (R_p) employing a UV filter, respectively, and the fluorescence, F_p, computed according to Eq. (4).

A similar reasoning applies even to a print solid. In the case of no ink penetration, the intensity of reflected light equals to

$$I_i(\lambda) = \; I_v(\lambda)T^2 + T \; I_u(\lambda')T(\lambda')f(\lambda - \lambda')d\lambda \; R_g(\lambda), \tag{5}$$

where T is the spectral transmittance of ink. Correspondingly, the spectral reflectance of a print solid, including fluorescence, equals,

$$R_i(\lambda) = R_g T^2(\lambda) + T(\lambda) R_g F_i(\lambda) \tag{6}$$

where quantity, F_i, resulted from fluorescence, is defined as

$$F_i(\lambda) = \frac{(I_0 T) * f(\lambda)}{I_v(\lambda)}. \tag{7}$$

Measuring spectral reflectance of a solid print with employing a UV filter, $R_i'(\lambda)$, one can estimate the spectral transmittance of an ink layer,

$$T(\lambda) = \sqrt{\frac{R_i'(\lambda)}{R_g(\lambda)}}. \tag{8}$$

Consequently, F_i, can be estimated from experimental spectra, i.e.,

$$F_i(\lambda) = \frac{R_i(\lambda) - R_i'(\lambda)}{T(\lambda) R_g(\lambda)}. \tag{9}$$

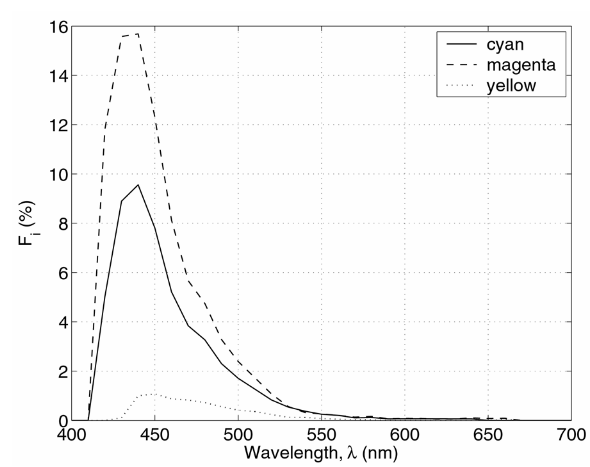

Figure 2. The spectral fluorescence values of print solids on fluorescent paper, Fi, computed according to Eq. (9).

Different from the case of bare paper, the UV light passes through the ink layer before reaching the fluorescent substrate and activating FWAs in the substrate. Therefore, spectral properties (absorption power) of the ink layer in the UV band can significantly reduce the yield of fluorescence. Spectral dependence of F_i values of primary inks printed on the ordinary office copy paper, is shown in Fig. 2, estimated from experimental spectra with Eq. (9). As ink cyan is more transparent than magenta in the blue region (see Fig. 3), the smaller F_i value of cyan suggests that cyan absorbs more UV light than magenta does.

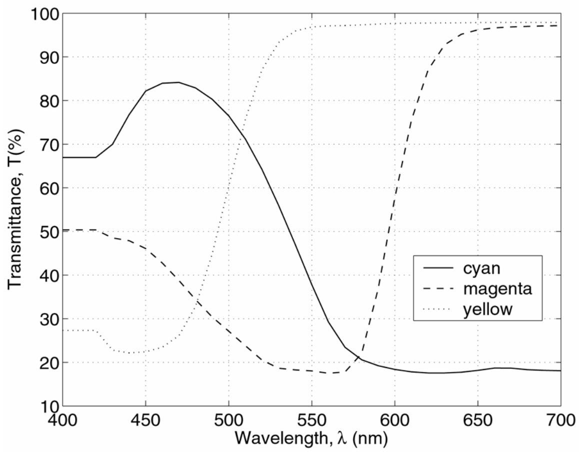

Figure 3. Spectral transmittance values of primary ink layers estimated by using Eq. (8).

Spectral Reflectance of Halftone Patches

For a halftone image, light exchanges between different regions of the paper substrate (paper under dots and paper between dots), causing optical dot gain or the Yule-Nielsen effect, have to be considered. In probability approach,[5,6] light exchanges can be described by a set of conditional probabilities. For a mono-chromatic image, there are two distinct chromatic regions, paper between dots (noted as Σ_0) and paper under dots (noted as Σ_1). The conditional probabilities, P_{00}, P_{01}, P_{10}, and P_{11}, describe the probabilities of light entering paper from one region (denoted with the first subscribe index) and then exiting from another (denoted with the second subscribe index). For example, P_{01}, represents the probability that light strikes the paper in the region Σ_0 and then left the paper from the region Σ_1. These probabilities fulfil the following constraints,[6]

$$P_{01} + P_{00} = R_g, \qquad P_{11} + P_{10} = R_g \tag{10}$$

Assume that the percentage of ink coverage is σ (Σ_1) and paper between dots (Σ_0) is then $(1 - \sigma)$. If the intensity of an irradiance onto the whole area, $\Sigma = \Sigma_0 + \Sigma_1$, is I_0, the flux of photons striking the dots (Σ_1) and the paper (Σ_0) areas are $I_0\sigma$ and $I_0(1 - \sigma)$, respectively. The probabilities describing photon exchanges between different regions, P_{01} and P_{10}, correlate with each other by,

$$P_{10}\,\sigma = P_{01}(1 - \sigma) \tag{11}$$

These probabilities can be further expressed in terms of point spread function (PSF), i.e.,

$$P_{01} = \bar{p}\sigma, \quad P_{10} = \bar{p}(1-\sigma) \tag{12}$$

with

$$\bar{p} = \frac{1}{\sigma(1-\sigma)} \int_{\Sigma_1}\int_{\Sigma_0} p(\mathbf{r}_1,\mathbf{r}_0)\,d\sigma_1 d\sigma_0. \tag{13}$$

In Eq. 13, $p(\mathbf{r}_1, \mathbf{r}_0)$ is the PSF of the substrate, $\mathbf{r}_0$ and $\mathbf{r}_1$ denote positions where a photon enters and then exits the surface of the substrate, respectively. When the average distance a photon diffuse before exiting the paper is much greater that the distance between the dots (a complete light scattering), the photon has an identical probability to be scattered wherever in the substrate. $\bar{p}$ is then a constant, $\bar{p} = R_g$, and is independent of the incident and exiting positions.[6,7] Consequently, the curve of optical dot gain, has a single maximum at $\sigma = 50\%$ and a symmetric form around the maximum. Nevertheless, when there exists a physical dot gain, the real dot percentage, σ, differs from its nominal value, σ_0, i.e., $\sigma \neq \sigma_0$. Then, the ΔR_{opt} curve becomes asymmetric around $\sigma_0 = 50\%$, as discussed in the previous study.[8]

It is worth to notice that the optical reciprocity for light exchanges between the inked area (Σ_1) and the area void of ink (Σ_0) may no longer hold, because of absorption of an ink layer to UV light. Striking directly on the surface of the paper, for example, the UV light is converted into fluorescence which is then passing through the ink layer, while the UV light may be absorbed by the ink layer before its reaching the fluorescent substrate and activating FWAs in paper when it first hits the ink dots and then is filtered by the dots.

It has been proven that the spectral reflectance of a halftone image (dot percentage σ) can be expressed as,[9]

$$\begin{aligned} R(\lambda,\sigma) &= R_0(\lambda,\sigma)(1-\sigma) + R_1(\lambda,\sigma)\sigma \\ &= R_{MD}(\lambda,\sigma) - \Delta R_{opt}(\lambda,\sigma) \end{aligned} \tag{14}$$

where

$$R_{MD}(\sigma) = R_g(1+F_P)(1-\sigma) + R_g T(T+F_i)\sigma, \tag{15}$$

$$\Delta R_{opt}(\sigma) = (1-T)\left[1+F_p-T-F_i\right]\bar{p}\sigma(1-\sigma). \tag{16}$$

R_{MD} in Eq. (15) corresponds to the computation with the Murray-Davies approximation including fluorescence, consisting of reflection of both paper between dots and printed dots. ΔR_{opt} in Eq. (16), on the other hand, corresponds to the optical dot gain resulting from light exchanging between Σ_0 and Σ_1 due to light scattering. Clearly, all the equations given in Eqs. (14)-(16), degenerate into the corresponding equations derived previously,[6] when fluorescence was omitted ($F_p = F_i = 0$).

A Spectral Model with Consideration of Fluorescence and Dot Gain

In practical printing processes, there exists almost always the so-called physical dot gain, by which a nominal dot percentage, σ_0, is enlarged into $\sigma = \sigma_0 + \Delta\sigma$. Generally speaking, the physical dot gain, $\Delta\sigma$, is a systematic behavior of a printing system, and can probably be characterized by a single parameter,[8] g, i.e.,

$$\begin{aligned}\Delta\sigma &= \sigma = \sigma_0 \\ &= (g-1)\sigma_0(1-\sigma_0)\end{aligned} \tag{17}$$

The printed dot size is therefore,

$$\sigma = g\sigma_0 + (1-g)\sigma_0^2 \tag{18}$$

where the quantity, g, depends on printing technologies (offset, ink jet, etc.), printing materials (inks and substrates) used, and even printing environments, etc. Evidently, constraints of $\Delta\sigma = 0$ at $\sigma_0 = 0$ and 1, are automatically fulfilled in Eq. (17). Besides, the quantity, g, provides a measure to the physical dot gain. For example, when there exists no physical dot gain, $g = 1$, while $g > 1$ or $g < 1$ corresponds a physical dot extension ($\sigma > \sigma_0$) or contraction ($\sigma < \sigma_0$).

Assume that a nominal dot percentage, σ_0, becomes $\sigma = \sigma_0 + \Delta\sigma$ after printing due to physical dot gain. According to the Eqs. (14-16) the overall spectral reflectance values can be computed by

$$\begin{aligned}R(\sigma) &= R_{MD}(\sigma) - \Delta R_{opt}(\sigma) \\ &= R_{MD}(\sigma_0) - \Delta R_{phy}(\sigma_0) - \Delta R_{opt}(\sigma).\end{aligned} \tag{19}$$

In the equation, $R_{MD}(\sigma_0)$ defined in Eq. (15), is the spectral reflectance of an image computed with Murray-Davis equation and nominal dot percentage, σ_0. $\Delta R_{opt}(\sigma)$ given in Eq. (16) is the optical dot gain and depends on the over-all dot percentage, $\sigma = \sigma_0 + \Delta\sigma$. Finally, $\Delta R_{phy}(\sigma_0)$, corresponds to contributions from the physical dot gain of the nominal dot percentage, σ_0, and is computed by,

$$\begin{aligned}\Delta R_{phy} &= R_g(1+F_P) - R_g T(T+F_i)\Delta\sigma \\ &= R_g\left[1+F_P - T(T+F_i)\right](g-1)\sigma_0(1-\sigma_0).\end{aligned} \tag{20}$$

Thus, the physical dot gain has its maximum at $\sigma_0 = 50\%$ and is symmetric about the maximum.

Dependence of the optical dot gain, ΔR_{opt}, on the overall physical dot size including the physical dot gain, i.e., $\sigma = \sigma_0 + \Delta\sigma$, is clearly seen from Eq. (16). Because the physical and optical dot gains (including fluorescence) contribute simultaneously to reflectance measurements, an overall effect of dot gain, ΔR, defined as,

$$\Delta R(\sigma) = \Delta R_{phy}(\sigma_0) + \Delta R_{opt}(\sigma), \tag{21}$$

is actually measured.

According to Eqs. (16) and (19)-(21), in addition to the optical properties of the paper and ink, R_p, F_p, F_i, T, known from spectral measurements, the spectral reflectance, R (or the overall dot gain, ΔR), is determined by the parameters, $\bar{p}$ and g, characterizing the optical and physical dot gain, respectively. If a complete light scattering is further assumed, there is $\bar{p} = R_g$. Then, there will be only a single unknown parameter, g, remaining. Therefore, by fitting to a set of experimental data, such as reflectance vales or CIEXYZ tristimulus values of the test patches, one can determine the quantity, g, then the physical dot extension, $\Delta\sigma$, and finally, the overall spectral reflectance values, $R(\sigma)$.

Simulations

The simulations were carried out by fitting the computed spectral reflectance values, R_{simu}, according to Eqs. (16), (19), and (20), to the measurements, R_{exp}, in a sense of least squared error (LSQ), ie.,

$$Q = \sum_{\lambda}\sum_{\sigma}\left[R_{simu}(\sigma,\lambda) \quad R_{exp}(\sigma,\lambda)\right]^2. \tag{22}$$

Optical dot gain resulting from light scattering in substrate was approximated by the complete light scattering, and $\bar{p} = R_g$ was assumed in the simulation. Therefore, for each color, there is only one parameter, g, describing physical dot gain of printed dots, involved in the data-fitting processes.

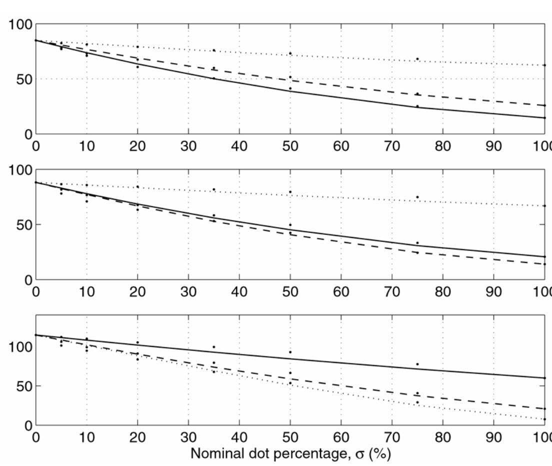

Figure 4. Simulated (lines) and measured (dots) CIEXYZ tristimulus values of cyan (solid lines), magenta (dashed lines), and yellow (dotted lines).

Numerical simulations show that the printed test patches have little physical dot gain, or the printer was fairly well calibrated, reducing the impact of physical dot gain. For a conclusive comparison between measurements and simulations, both simulated and experimental spectral reflectance values have been converted into their color coordinates in the *CIEXYZ* color space. In Fig. 4, the simulations are shown by lines (solid, dashed, and dotted lines for cyan, magenta, and yellow, respectively), while the measurements by dots. The figure suggests fairly good agreements between the simulations and the measurements, especially for X and Y color coordinates. Figure 5 further provides a quantitative assessment to color differences between the simulated and experimental spectra. The plots show that the maximal color differences lie between $\Delta E = 4 - 7$, depending on colors. This is comparable to the case of $\Delta E = 11$, when fluorescence was not considered in modeling.[8]

The description for optical dot gain of both ordinary light and fluorescence includes only light scattering in a media. Another process resulting from multiple internal reflections at the air/substrate and air/ink interfaces, has not been taken into account. The multiple internal reflections coupling with light scattering can significantly enhance the effect of optical dot gain, as has been pointed by Rogers.[3] This may, to some extend, explain the discrepancy between the simulated and experimental spectra. A further extension of the present model, including multiple internal reflections, is undergoing.

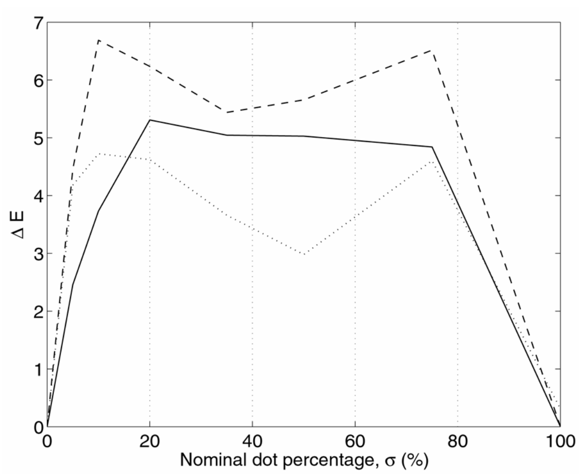

Figure 5. Color differences between simulated and measured spectra of cyan (solid lines), magenta (dashed lines), and yellow (dotted lines).

Acknowledgement

Thanks H. Boija for making the spectral measurements. Thanks Dr. Guyler in Hallmark Cards for providing us with the bi-spectral data and discussions with him have been very valuable. This work has been supported by Swedish Foundation for Strategic Research through Surface Science Printing Program (S2P2).

References

1. P. Emmel and R. D. Hersch, A one channel spectra colour prediction model for transparent fluorescent inks on a transparent support, in Proc. Color Imaging Conference, IS&T, Springfield, VA, pp. 70–77 (1997).
2. P. Emmel and R. D. Hersch, Spectral prediction model for a transparent fluorescent ink on paper, in Proc. Color Imaging Conference, IS&T, Springfield, VA, pp. 116–122 (1998).
3. G. L. Rogers, Spectral model of a fluorescent ink halftone, J. Opt. Soc. Am. A 17, 1975–1981 (2000).
4. G. L. Rogers, A generalized Clapper-Yule model of halftone reflectance, J. Color Res. Appl. 25 402–407 (2000).
5. J. S. Arney, P. G. Engeldrum, and H. Zeng, An expanded Murray-Davies model of tone reproduction in halftone imaging, J. Imaging Sci. Technol. 39 502–508 (1995).
6. L. Yang, R. Lenz, and B. Kruse, Light scattering and ink penetration effects on tone reproduction, J. Opt. Soc. Am. A 18 360–366 (2001).
7. G. L. Rogers, Optical dot gain in a halftone print, J. Imaging Sci. Technol. 41 643–656 (1997).
8. L. Yang, A unified model for optical and physical dot gain in color reproduction of printing, J. Imaging Sci. Technol. (accepted for publication).
9. L. Yang, Spectral model of halftone on a fluorescence substrate, J. Imaging Sci. Technol. (submitted).

Biography

Li Yang is currently a research fellow in the Group of Media Technology, University of Linköping, Sweden. He received his Ph.D, in Linköping University, April 2003. His research interests include Paper Optics, model development for ink-paper interaction with focus on characterization of ink penetration and ink spreading, and (optical and physical) dot gain. He is a member of IS&T and TAGA. More information may be found on his personal web page at http://www.itn.liu.se/～liyan/. Email: liyan@itn.liu.se