PHOTON MIGRATION IN PULP AND PAPER

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OULU 2004

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Academic Dissertation to be presented with the assent of the Faculty of Technology, University of Oulu, for public discussion in Raahensali (Auditorium L10), Linnanmaa, on December 17th, 2004, at 12 noon

OULUN YLIOPISTO, OULU 2004

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ISBN 951-42-7583-7 (nid.)
ISBN 951-42-7584-5 (PDF) http://herkules.oulu.fi/isbn9514275845/

ISSN 0355-3213 http://herkules.oulu.fi/issn03553213/

OULU UNIVERSITY PRESS
OULU 2004

Saarela, Juha, Photon migration in pulp and paper
Faculty of Technology, Department of Electrical and Information Engineering, University of Oulu, P.O.Box 4500, FIN-90014 University of Oulu, Finland
2004
Oulu, Finland

Abstract

The thesis clearly demonstrates that photon migration measurements allow characterization of pulp and paper properties, especially the fines and filler content of pulp, and the basis weight, thickness and porosity of paper.

Pulp and paper are materials with a worldwide significance. Their properties strongly depend on the manufacturing process used. For efficient process control, the employed monitoring and measuring has to be fast. Therefore it is worthwhile to try to develop new approaches and techniques for such measurements. Recent advancements in optics offer new possibilities for such development.

If two samples have different optical properties their photon migration distributions are different. The measurement of a photon migration distribution allows some features between two optically slightly dissimilar samples to be distinguished. Some simple measurements, which only yielded the photons' average time of flight, were made with an oscilloscope and a time-of-flight lidar. More precise measurements yielding photon pathway distribution or some selected characteristics like light pulse rise time, broadening, or fall time were measured with a streak camera. Two methods to assess photon path length distribution were introduced: particle determination with simulation, and streak camera with deconvolution.

The basic properties for pulp are consistency and fines content and for paper the basic properties are thickness, basis weight and porosity. The influence on photon migration caused by changes in these basic properties was determined.

As pulp and paper are rarely very basic, an additional property was demonstrated for both materials. For pulp it was the content of filler talc, and for paper it was the use of beaten pulp as a raw material. These additional properties were also distinguishable.

Keywords: consistency, filler content, fines content, lidar, measurements, paper, photon migration, porosity, pulp, streak camera, time of flight

Acknowledgements

This thesis is based on research carried out in the Optoelectronics and Measurement Technology Laboratory, Measurement and Sensor Laboratory and Infotech Oulu, which are all parts of University of Oulu. The work was carried out during the years of 1999-2004. I wish to express my sincere gratitude to my supervisor Professor Risto Myllylä.

I owe special thanks to my closest colleague and co-author Matti Törmänen for introducing me to pulp measurements and to my colleague Raimo Männistö for introducing me to paper measurements.

My warm thanks goes to the contributors of ideas, devices and measurements from the Measurement and Sensor laboratory: Kyösti Karttunen, Juha Kalliokoski, Pertti Karjalainen and Asta Leinonen; from the Optoelectronics and Measurement Technology Laboratory: Jukka Hast and Matti Kinnunen; from the Laboratory of Mechanical Process Engineering: Tapio Tirri, Jarno Karvonen and Sami Heikkinen and from the Electronics laboratory: Sergey Vainshtein, Ari Kilpelä, Kari Määttä and Matti Polojärvi and finally from workshop of the Department of Electrical Engineering the whole staff, especially Anssi Rimpiläinen and Vesa Kaltio.

Thanks goes to Michael Collins and Zach Shelby for improving the English of this thesis.

I express deep gratitude to my parents, Mikko and Anja Saarela, for the support they have given me all my life.

I owe my warmest thanks to my wife Johanna and sons Ilkka and Mikko for their love and patience during these years.

This research was mostly done as an Infotech Oulu graduate school student, supported by the Academy of Finland. The following foundations also financially supported the work: The Walter Ahlströmin säätiö, the Tauno Tönningin säätiö, The Finnish Foundation for Technical Advancement (Tekniikan edistämissäätiö) and The Finnish Foundation for Economic and Technology Sciences – KAUTE Jukka Härmälän erikoisrahasto.

Abbreviations and symbols

FWHM	Full width at half maximum
MCP	Micro Channel Plate
TMP	Thermomechanical pulp
TOF	Time of Flight

A	area
m	mass (weight)
t	thickness
V	volume, volume of paper
V_f	volume of fibres
w	basis weight
ρ	density, density of paper
ρ_f	density of fibres
ϕ	porosity

List of original papers

This thesis is a summary of the work published in the following seven papers:

I Saarela J, Törmänen M & Myllylä R (2003) Measuring pulp consistency and fines content with a streak camera, Measurement Science and Technology, 14: 180-6. (www.iop.org/journals/mst)

II Saarela J & Myllylä R (2003) Changes in the time-of-flight of a laser pulse during paper compression, Journal of Pulp and Paper Science, 29: 224-7.

III Saarela J, Törmänen M & Myllylä R (2004) Three methods for photon migration measurements in pulp, Opto-Electronics Review, 12: 193-7.

IV Saarela J, Törmänen M & Myllylä R (2001) Changes in time-of-flight in thermomechanical pulp (TMP) measured with a streak-camera, Proceedings of SPIE, Saratov Fall Meeting 2000 Coherent Optics of Ordered and Random Media, 4242: 156-63.

V Saarela J, Törmänen M & Myllylä R (2003) Light scattering in thermomechanical pulp (TMP) and talc measured with a time-of-flight (TOF) lidar, Proceedings of SPIE, 12th International Workshop on Lidar Multiple Scattering Experiments, 5059: 58-65.

VI Saarela J & Myllylä R (2003) Light scattering in paper measured with a time-of - flight lidar, Proceedings of SPIE, Advanced Optical Devices and Materials, 5123: 42-8.

VII Saarela J, Törmänen M, Karttunen K & Myllylä R (2005) Two approaches for assessing photon path length distribution in pulp, Proceedings of SPIE, 4th International Conference on Advanced Optical Materials and Devices. (accepted)

The core of photon migration in pulp is presented in Paper I. In the same style the fundamental parameters of photon migration in paper is presented in Paper II. Papers V and VI are example studies on how the basic idea has to be broaden to cover more practical applications. Paper V broadens the idea for pulp and Paper VI for paper. Paper III is a review of the technologies which have been used to measure photon migration. Paper IV is a prestudy for paper I. Paper VII compares two approaches on photon migration in pulp. All the papers were written by the author, except for the chapter on the oscilloscope in Paper III, which was written by Matti Törmänen. The sample preparation, measurements and analysis described in Papers I, III, IV, V and VII were done together with Matti Törmänen and in Papers II and VI by the author alone. Simulations in Paper VII were done by Kyösti Karttunen.

Contents

1 Introduction

The modern Finland was built on two corner stones: the wood industry and the metal industry. The first has long traditions starting in the 18^{th} century with the export of tar. The latter bloomed from factories built to fulfil the requirements of the Paris peace treaty after World War II. A third corner stone has emerged from the metal industry: the electronics and telecommunication industry. As the newer Finnish corner stones are sold abroad at an increasing rate, the Finnish wood industry is expanding abroad. Therefore Finland will remain an important player in the wood industry and in its major sub industry: the pulp and paper industry.

Modern paper mills continually increase their production speed to be as fast as possible. At the same time the demand for using recycled pulp increases. This means increasing the speed and accuracy demands on inspection and controll processes. Optical inspection combined with fast data processing is a possibility for meeting the demands.

One approach to optical pulp and paper inspection is time resolved spectroscopy. To be able to use it the basic knowledge of photon migration in pulp and paper has to be known. Can pulp consistency, fines content and the amount of fillers be determined? Can paper thickness, basis weight and structure be measured? Can they be done by studying photon migration?

1.1 Light and a random media

1.1.1 The basics

As light travels through a medium it can be absorbed. Absorption is a process by which radiant flux is converted to another form of energy; usually heat. Two things can happen when light encounters the surface between two optically different media. Either the light is reflected away from the surface or it penetrates the surface and refracts depending on the angle of incidence and the refractive indexes of the media. Energy is divided between these two phenomena. If one medium is formed of particles the consequence of light interacting with material can be called scattering. [1,2]

Ultrashort light pulses passing through a random inhomogeneous medium are temporally spread into ballistic, snake and diffuse components [3]. The intensity and the speed of the ballistic pulse are found to depend on the scattering characteristics of the medium. The diffuse component can be approximated by the diffusion theory when light propagates through a distance of more than ten mean free paths. The early arriving portion of the diffuse pulse, known as the snake component, consists of photons that propagate along zigzag paths slightly off the straight path [3]. In each case light travels a different distance through the medium, and its time-of-flight depends on the distance travelled and the refractive index of the medium. These three components are demonstrated in Figure 1.

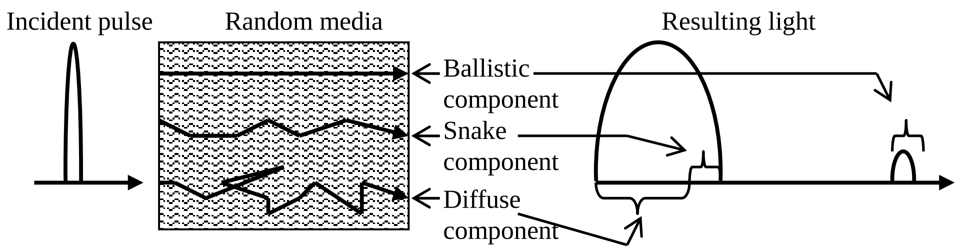

Fig. 1. A light pulse propagating through a random medium spreads into ballistic, snake and diffuse components.

The properties of a number of highly scattering materials can be determined by measuring their optical parameters. These include the refractive index, attenuation coefficient, scattering coefficient and anisotropy factor, all of which are wavelength dependent. In anisotropic materials these parameters also depend on the direction of light propagation. Measuring these parameters is a complicated process, which is often impossible to perform in a non-invasive way in real time. Most applications require such measurements to be performed with a sample preparation and place a restriction on measurement time.

Some methods have been developed to calculate light propagation in a random medium. The most common are the diffusion and Monte Carlo techniques. To reduce computational difficulties simplifying flux models have been designed most famous being the Kubelka-Munk theory. [4,5,6,7]

1.1.2 Light and a random media containing wood fibres

In an optical sense pulp and paper can be regarded as a media of water or air containing wood particles. For light propagation in pulp the diffusion and the Monte Carlo techniques can be used. For modelling light propagation in paper the Kubelka-Munk theory is widely used [8]. Four types of interaction for light and paper are shown in Figure 2 [9].

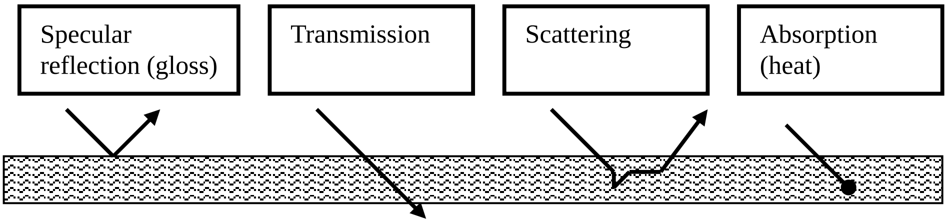

Fig. 2. Interactions of light with paper.

1.2 Pulp

The purpose of all the pulping processes is to break down the wood into fibres and make them suitable for papermaking. Wood can be made into pulp several ways. Chemical treatments dissolve lignin, leaving woodfibres whole, while mechanical pulping processes keep all wood portions like lignin in the process. For paper in the future to have the desired properties, both pulp types have to be treated mechanically. For chemical pulp the treatment is called beating and it happens in a paper mill while mechanical pulp refining happens during the mechanical pulping process itself. [10]

1.3 Paper

Papermaking is a long and complex process. It contains a great number of different unit processes, which through different mechanisms, produce the desired effects on the fibre suspension, and subsequently, on the fibrious web. It starts with the slushing of fibres and other raw materials in water, continues through the paper machine and ends with the packaging of the paper or board. [11]

1.4 Pulp and paper testing

This thesis studies pulps consistency, fines content and filler content, and the thickness, basis weight, density and porosity of paper. Therefore only methods to test these properties are introduced. Pulp also has properties like drainage, and fibre coarseness whereas paper has properties like stiffness and opacity, which have their own tests, but as they are not closely related to this thesis they will not be described.

As pulp and paper are complex materials most properties are measured with a standardised test, which is related to, but is not necessarily an accurate measure of the desired property. For example airflow measurements for measuring paper surface roughness.

1.4.1 Pulp consistency

The standard method (EN 4119:1996) includes drying two samples in a 105°C oven. The result is the ratio of the dried weight to the moist weight. For practical purposes drying with an instant dryer is sufficiently accurate [12]. The industry uses meters that are based on shear force, light polarisation, light scattering, microwaves and gamma radiation. [13, 14, 15, 16, 17]

1.4.2 Pulp fines content

Fibre length distribution meters are used to measure fines content. The fibre length distribution can be estimated by selecting screens with a suitable slot size and by measuring the portion of fibre that does not pass through the screen. The fines content is the material that passes the smallest slot, usually with a size of 200 mesh. A typical piece of equipment is the Bauer-McNett apparatus (SCAN-M6:69). [12]

There are fibre length measurement devices that utilize computers. The pulp sample is diluted to a suitable level and then it goes through a chamber where the woodfibres are photographed. From these pictures the fibre size distribution is calculated. These devices don't measure particles passing through a 200 mesh screen so another definition on fines has to be used if using them. [18, 19]

1.4.3 Pulp filler content

To determine pulps filler content, i.e., ash, the pulp suspension should be dewatered with an ash-free filter paper, dried and subsequently combusted (SCAN-C6:62) [20]. On-line measurements can be done optically [21].

1.4.4 Paper thickness

Paper thickness would seem an easy property to measure. Surface roughness however makes it impossible to determine where the paper exactly starts and ends. Also the papermaking process causes fluctuations in paper thickness. The standardised method (EN 20534:1994) uses a defined measurement tip and force to determine the paper surface. Several measurements have to be made to get the overall thickness of a paper sheet [22]. There are no inline thickness measurement devices.

1.4.5 Paper basis weight

Basis weight is determined by weighing a piece of paper with a known area (EN536:1996). If high precision is needed, test piece punching equipment is available. [23] The formula for calculating basis weight is:

$$w = \frac{m}{A} \tag{1}$$

where w = basis weight
m = mass (weight)
A = area

For inline basis weight measurements a radiation source is placed on one side of the paper web and the radiation on the other side is measured. The changes in radiation correspond to the basis weight. [24]

1.4.6 Paper density

Paper density can be calculated from papers thickness and basis weight with the formula:

$$\rho = \frac{w}{t} \tag{2}$$

where ρ = density
w = basis weight
t = thickness

As basis weight is a clear measure the uncertainty of paper thickness gives the density a bit of uncertainty [22]. Paper density is therefore defined in the same standard as thickness.

1.4.7 Paper porosity

The character of paper porosity is complex. If porosity is considered to be the volume of pores or of air the following formula may be used:

$$\phi = \frac{V - V_f}{V} = 1 - \frac{\rho}{\rho_f} \quad (3)$$

where ϕ = porosity
V = volume of paper
V_f = volume of fibres
ρ = density of paper
ρ_f = density of fibres = 1500 kg/m^3 for perfect cellulosic fibrils.

Again as the paper surface is not clear these definitions are somewhat inaccurate [22]. People interested in printability have their own definition and measure of porosity. If air is blown through paper and the flow is measured it corresponds to the amount and size of the pores through paper and thus gives an estimate of how ink penetrates to the pores.

1.5 Previous studies on photon migration in pulp and paper

Karppinen *et al.* performed a related study on papermaking pulp properties using time-of-flight (TOF) measurements. The pulp samples they tested were of low consistency, the maximum value being 0.8%. They concluded that the TOF measurement technique is best suited for measuring fines content. [25]

Carlsson *et al.* described a method for the time-resolved recording of light scattering with a streak camera in thin highly scattering media. The method was applied to paper. Then they studied the dependence of light scattering on basis weight and density. [8]

1.6 Organization of the thesis

Chapter 2 gives technical information about the equipment used to measure photon migration.

In Chapter 3 the measurements made from pulp are presented. The main aspect is to link photon migration with pulps consistency and fines content. Also a case study on talcs effect on photons is presented.

In Chapter 4 the measurements made from paper are presented. The main aspect is linking photon migration to paper thickness and basis weight. A case study on modified paper, i.e., paper made from beaten pulp, is presented.

Chapter 5 contains some discussion and a summary of the thesis is presented in Chapter 6.

2 Devices for measuring photon migration

In order to be able to measure photon migration a light source and a detector is needed.

2.1 Lasers

In this thesis the photon source was a laser. Some lasers can produce short pulses or at least sharp edges. For photon migration measurement, this is the most important property a light source can have. Another advantage of using a laser is monochromaticity. The behaviour of different wavelengths doesn't have to be considered. A suitable wavelength can be selected to utilize an optical window, and the laser's power is distributed as planned. In principle laser beams are easily guided and focused with lenses and mirrors, but as in this work the wavelength was in the infrared region troubles installing the optics were inevitable.

2.2 Oscilloscope

An oscilloscope can be used to measure photon migration if it is equipped with a detecting probe. This device was used only in the beginning of the research and none of the presented results are measured with an oscilloscope. More details on the oscilloscope measurement of photon migration can be read in Paper III.

2.3 Time of flight lidar

A Time of flight (TOF) lidar was originally designed for rapid distance measurements. A laser pulse is aimed at a target and the returning pulse is recorded. Rapid time measurement electronics allow the detection of the laser pulse's echo time. In addition, a discriminator is used to reduce errors caused by timing jitter, walk, nonlinearity and drift. Finally, several TOFs are averaged to eliminate statistical errors in calculating the target distance. The technique is currently being used in new applications. More details on the TOF lidar can be read in Paper III. [26]

2.4 Streak camera

A streak camera is a device for measuring ultra-fast light phenomena. It produces information about intensity versus time versus position. The heart of a streak camera is the streak tube. First, the light being measured passes through a slit and forms an image on the photocathode of the streak tube. Secondly, the light striking the photocathode is converted into electrons, the number of which is proportional to the intensity of the light. This photocathode is the starting point of the streak tube. Thirdly, as the electrons produced by the incident light pass a pair of sweep electrodes, a high voltage is applied to the sweep electrodes at a timing synchronised to the incident light. During the high-speed sweep, the electrons, which arrive at slightly different times, are deflected at slightly different angles in the vertical direction and enter a micro-channel plate (MCP). Fourthly, as the electrons pass the MCP they are multiplied several thousands of times. Finally, the electrons collide against the phosphor screen, where they are converted back into light. The phosphor screen is positioned at the end of the streak tube. [27]

Details on the streak camera and some example measurements can be found in Paper III.

3 Photon migration measurements in pulp

3.1 Two approaches for assessing photon path length in pulp

In theory photon migration should be easy to mathematically model. To test this a theoretical method and a metrological method were compared.

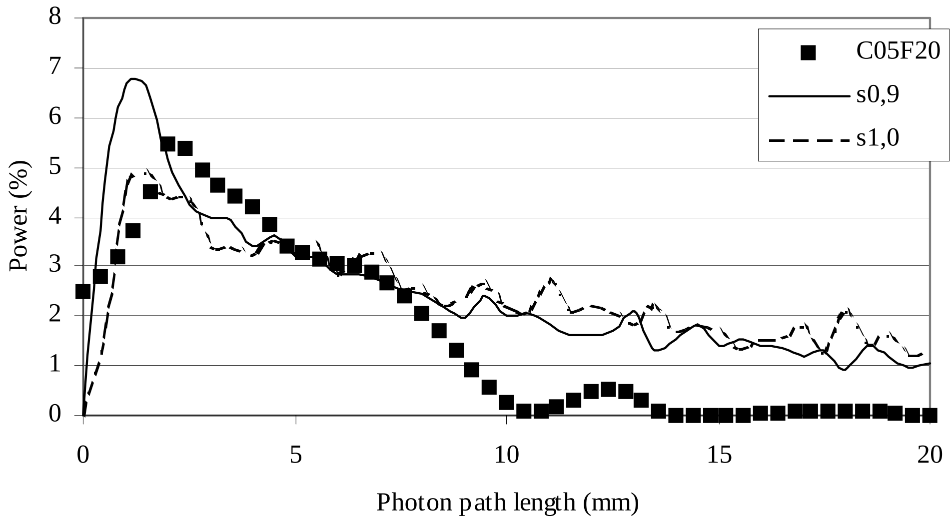

Fig. 3. Photon path length distribution of a pulp sample with 0,5% consistency and 20% fines content measured with the streak camera with deconvolution method lies between simulation curves of scattering coefficients 0,9 and 1,0. The laser wave length was 905nm.

3.1.1 Particle determination and simulation

In order to determine the mean free path for simulation, the size of the scattering particle must be known. This can be found in several ways. In this experiment the equipment took pictures and used picture analysis software to determine the particles' physical dimensions. These are used to calculate the scattering coefficients.

Other optical parameters were chosen. The absorption coefficient was selected to be small (0,001/mm) so it wouldn't limit diffuse photons. The anisotropy parameter 0,5 was selected. Boundaries had no reflectivity. These parameters were entered in the simulation program, which then calculated the distribution of photon paths. A detailed description of the experiment can be found in Paper VII.

3.1.2 Streak camera measurement and deconvolution

Streak camera measurements give the shape of the pulse as a result. If a pulse without a sample or a null sample is regarded as the input pulse and a pulse that has gone through a sample as an output pulse, the transfer function is the photon path length distribution. A detailed description of the experiment can be found in Paper VII.

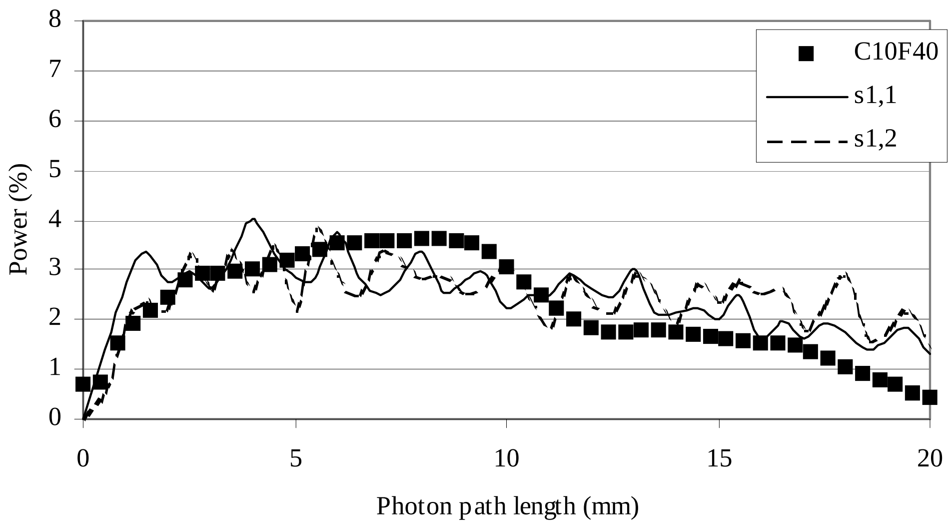

Fig. 4. Photon path length distribution of a pulp sample with 1.0% consistency and 40% fines content measured with the streak camera (laser wave length 905 nm) and deconvolution method lies between simulation curves of scattering coefficients 1,1 and 1,2.

3.1.3 Results

The two methods produce quite different results as can be seen in Paper VII. Problems associated with the first method are the requirement for the correct measurement of the original parameters, the acceptability of the generalisations introduced, and the functioning of the program according to expectations. The nature of the second method involves the problems of noise, laser drift and calculation. At this point it would appear that the second method produces more accurate results. If the photon path length distributions obtained from the second method are compared with the simulations, the correct scattering coefficient for 0,5% consistency pulp should be between 0,9/mm and 1,0/mm as seen in Figure 3 and for 1,0% consistency pulp between 1,1/mm and 1,2/mm as seen in Figure 4. The largest single source of error lies in the determination of scattering particles.

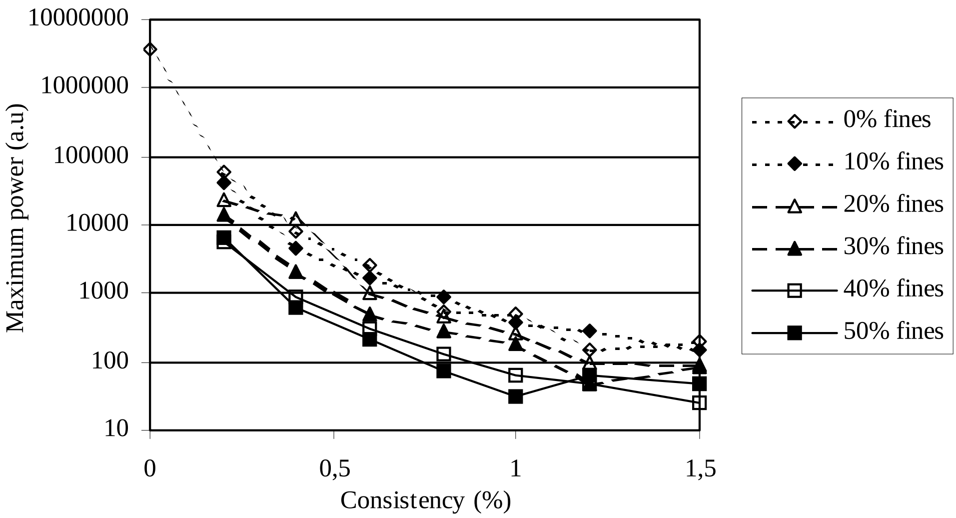

Fig. 5. The maximum power passed through a pulp sample as a function of consistency. A streak camera was used to record laser pulses that before entering the sample had a wavelength of 905 nm and full width at half maximum (fwhm) 40 ps.

3.2 The effect of changes in the consistency and fines content of thermomechanical pulp on photon migration

The problem of determining the fines content of pulp in cases where consistency is not known remains to be solved. The hypothesis that this problem may be solved by studying shape changes in a laser pulse after it has travelled through the pulp was explored. The basic idea is that pulp, as it is a strongly scattering material, delays and broadens the light pulse.

First some measurements were conducted with a streak camera to find the best measurement setting. At this point only the laser pulses delay was recorded. These measurements are described in Paper IV.

For a more comprehensive investigation a matrix of pulp samples was constructed, with consistencies varying from 0 to 1,5% by increments of 0,2% and fines contents varying from 0% to 50% by 10% increments. A streak camera was used to record three pulses simultaneously. The first was a reference pulse, which was used to calibrate the measurement pulses. The second was a pulse measured at an angle of 90 degrees to the straight light path. These pulses were clear only for some samples so they were not exploited. The third was the straight path pulse.

If trying to distinguish two parameters, in this case consistency and fines content, at least two independent parameters have to be measured. To have well-defined measurement points and maximum changes the optical parameters were selected to be maximum power and the time of 50% power drop. The latter contains both the delay and the broadening of the pulse. Different fines contents form their own lines on consistency-maximum power graphs as Figure 5 shows and on consistency-time of 50% power fall graphs. When transmitted power is plotted against the 50% power fall time, the lines representing different fines contents cross each other. This can be seen in Figure 6. These results indicate that the fines content and consistency can be measured in some cases with a single measurement. Also, if water is added in a controlled manner, measurement of the new sample allows the original consistency and fines content to be determined. The results indicate that fines content and pulp consistency can be determined in certain cases using a single laser pulse. This is the case when the sample has an unique pair of measured values. Furthermore, if the consistency is lowered by adding water and the laser pulse measurement is repeated the original pulp consistency and fines content may be determined. A detailed description of the experiment and more illustrative guidance of the conclusions can be found in Paper I.

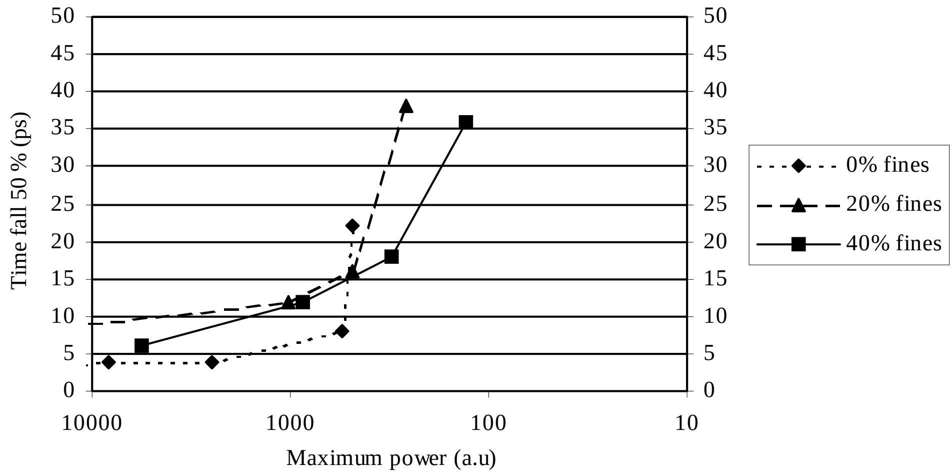

Fig. 6. A selected fine content forms a curve as the consistency of the sample is changed in a selected optical parameter axis. A streak camera was used to record laser pulses that before entering the sample had a wavelength of 905 nm and fwhm 40 ps.

3.3 The effect of changes in thermomechanical pulp filler content on photon migration

In the previous section (3.2) a very simple type of pulp was used. In its simplest form, pulp is only long wood fibres and water. To make better paper the wood fibres have to be broken. This produces fines. The next step is to add fillers. As an example of how fillers effect photon migration in pulp, a case study using talc as a filler was conducted. In Figure 7 results for constant talc content samples are presented.

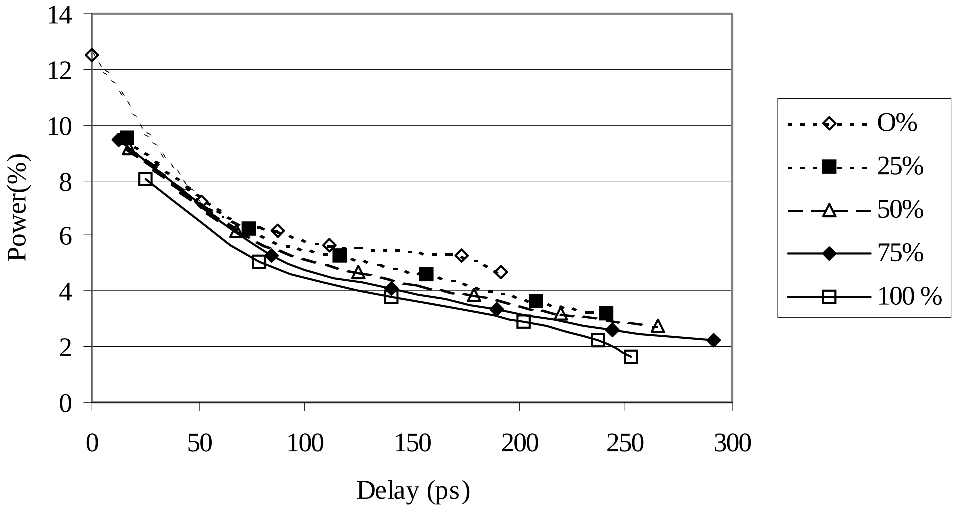

Fig. 7. Different portions of talc presented in delay and power axes. The delay was measured with a lidar and the power was measured with an optical power meter. Laser had a wavelength of 850 nm.

The first point to notice is that as the delay approaches zero, full power is not attained. Thus, although at low consistencies there are too few particles to cause any delay, they nevertheless, cause attenuation. The second observation is that each type of sample has its own unique delay attenuation value. It is thus possible to determine pulp consistency and the proportion of talc from these two measurements. Only samples consisting solely of talc differ in this respect. There are several explanations for this. Firstly, talc without any wood fibres sediments so quickly that during the averaging period the sample changes. Secondly, with pure talc sample the pulse form is changed to such a degree that the lidar correction no longer functions. The unexpected shortening of the TOF supports this. Finally, talc attached to wood fibres possesses significantly different properties than do free floating talc particles. A detailed description of the experiment can be found in Paper V.

4 Photon migration measurements in paper

4.1 The effect of basis weight, thickness, density and paper porosity changes of paper on photon migration

Every paper has two basic characteristics: basis weight (g/m^2) and thickness (µm). Paper density and porosity can be calculated from these two characteristics.

The paper samples were compressed from $500kg/m^3$ to $1100kg/m^3$, and laser pulses were shot through them during pressing. Changes were observed in the thickness of the samples and in the TOF of the laser pulses. The results show that the TOF decreases during compression. This indicates that the distances between the various scattering sites decreases. This effect is caused by compression. The phenomenon becomes more pronounced as the basis weight increases. At levels lower than $200g/m^2$, however, pressure has little effect on the TOF signal.

Figure 8 shows how density changes cause changes in the TOF. If porosity is defined as the volume of air in paper, Figure 8 shows also that TOF can be used to measure porosity.

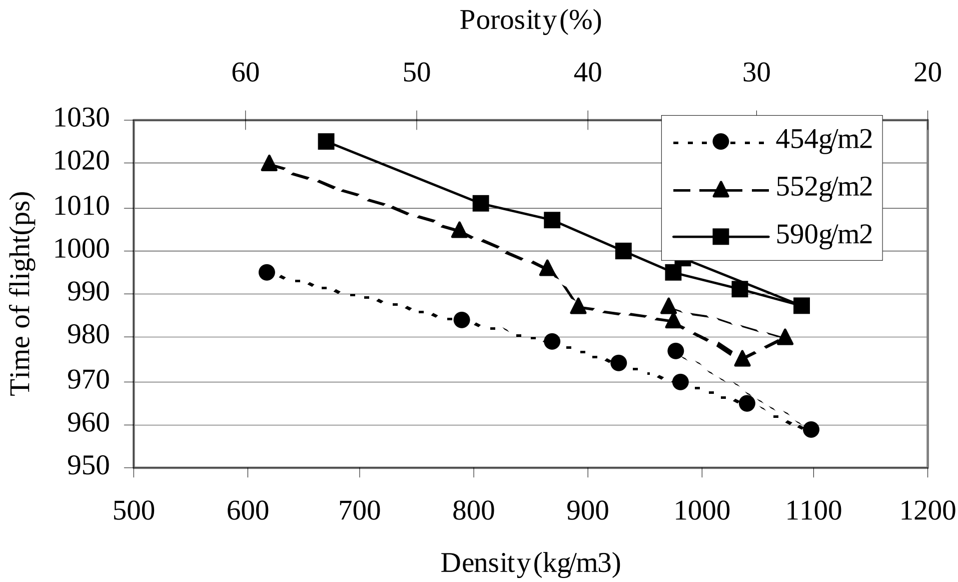

Fig. 8. Time of flight presented as a function of porosity and density. The delay was measured with a lidar. The laser had a wavelength of 850 nm.

Furthermore, the results show that the laser pulses TOF can be used as a measure of paper porosity. A detailed description of the experiment can be found in Paper II.

4.2 The effect of pulp beating on photon migration in paper

In the previous section (4.1) a very simple type of paper was used. Having only basic characters, like thickness and basis weight change the photon migration, the basic knowledge of the phenomenon is revealed. However real life papers have many other characters that have a profound effect on photon migration. The origin of the woodfibre might be different: softwood or hardwood, the pulping process may be different: unbeaten chemical pulp, beaten chemical pulp or mechanical pulp, or the pulp may have fillers or additives. As a case study the effect of pulp beating on photon migration is presented. The pulp beating breaks woodfibres and thus increases the amount of scattering particles. In theory photon migration through a paper from beaten pulp should take longer than through an equivalent paper made from unbeaten pulp.

Figure 9 is a measurement result, comparing the delay per basis weight with the thickness. This suggests that each pulp type has its own unique delay constant. The final delay can be calculated by multiplying the constant with the sample thickness and the basis weight. Therefore the beating of pulp increased the scattering cross-section and thus broadened the laser pulse and thereby increased the delay. Different pulp types have unique delay constants with the unit ps/(g/m^2 * µm). The effect of beating can now be eliminated if paper porosity is measured with the TOF method. A detailed description of the experiment can be found in Paper VI.

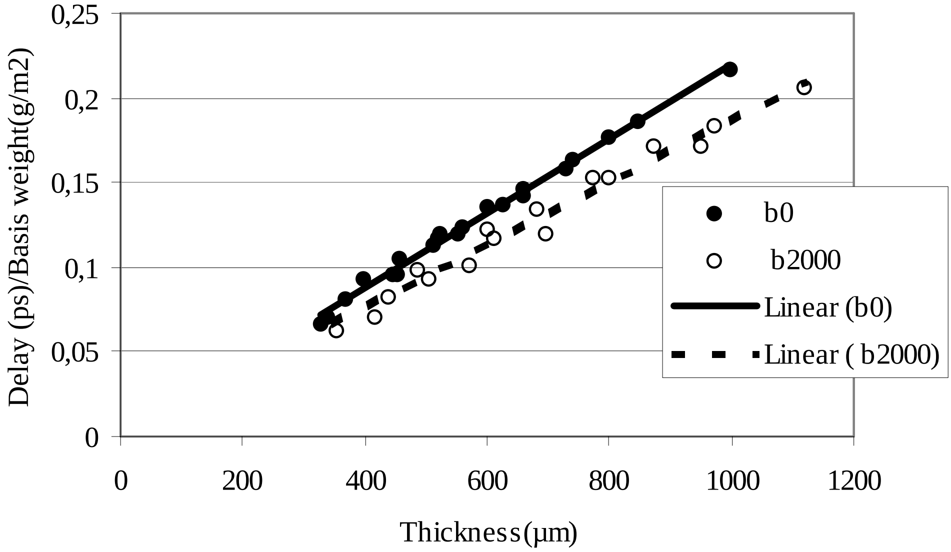

Fig. 9. Different pulp types have their unique photon migration coefficients. The delay was measured with a lidar, and the laser had a wavelength of 850 nm.

5 Discussion

In the beginning of this thesis some questions were raised. Can pulp consistency, fines content and the amount of fillers be determined? Can paper thickness, basis weight and structure be measured? Can they be done by studying photon migration? This thesis demonstrated that at least in the cases measured for the thesis, the answer is yes.

But there is always a but. These measurements have been close to the limits of the measurement equipment. The meters have their own precisions, but their accuracies are somewhat unknown. Are the methods described in this work accurate enough to meet industrial requirements? Are they cost efficient? Are they worth the effort of manufacturing meters? These questions have to be answered by the meter manufacturers.

For pulp measurements the increasing demand to use recycled paper as a raw material can be the driving force for the use of measurement systems based on the ideas presented in this thesis. In the “good old days” a rough estimate of fines content was the time that the pulp had been in a refiner. Now different batches of recycled paper can cause variations in the pulp. At the same time paper machines are faster than ever. The drawback is that they can produce unsatisfactory paper faster than ever. Off-line techniques are too slow to respond to rapid fluctuations in the raw material. On-line and in-line measurements meet this requirement better.

Optical measurements are ideal to meet the demand in speed. In the case of pulp, one can imagine some optical fibres attached to a pipeline and the other ends connected to a lidar system in a disturbance free environment. The information is then transferred to a process controller or lidar system, which then automatically adjusts the process parameters.

In the case of paper measurement, the control loop can be short or long. If problems origin from pulp then even fast optical measurements cannot significantly improve the process. If the paper machine causes the troubles, adjustments can be made faster. There are quite fast basis weight and thickness measurements. They can be used if the accuracy is considered to be satisfactory. Porosity as a property related to printability is somewhat unclear. Even presses don’t know what kind of paper would be ideal for printing.

After the measurements were presented in this book, new measurements have been made with some tricks to improve the precision and hopefully the accuracy. They show the same trends as the presented measurements. The next major improvement in measurements will be a new titanium-sapphire laser producing high power femtosecond laser pulses. Hopefully those measurements will produce new knowledge on photon migration in pulp and paper.

6 Summary

This thesis is based on the idea that materials have different optical parameters. If two samples have different optical properties their photon migration distributions are different. If the refractive index is changed a test pulse of light is forwarded or delayed depending on the change. Changes in the attenuation coefficient and the scattering coefficient are seen in the broadening and decay of the test pulse and anisotropy factor changes in the spatial distribution of the test pulse's photons. Therefore if photon migration is measured, it is possible to characterize some features of the sample.

Simple measurements, which result in only the photon's average time of flight of, were done with an oscilloscope and time of flight lidar. They are quite accurate, inexpensive, fast and useful if clear knowledge of the connection of the parameter under investigation and the photon migration exists. If this connection was not known, more precise measurements of the photon migration distribution or some other selected character like light pulse rise time, broadening or fall time, were measured with a streak camera. They are however expensive and slow.

Two methods to assess photon path length distribution were introduced. They are particle determination and simulation, and a streak camera and deconvolution. The two methods produce quite different results.

The major practical results of this work can be listed as follows:

1. It is established that each pulp specimen, with unique values of consistency and fines content, is characterized by a unique relationship between the delay value and the maximum power of transmitted light measured for a single laser pulse. The delay value includes the lag and the broadening of the pulse. The family of the delay value on maximum power plotted for different pulp specimens exhibits the presence of crossings. Lines only cross and are not even. This allows us to propose the time-domain technique for pulp characterization using controllable changes in consistency, e.g., adding water. Previously it was not known if changes in an optical measurement were due to changes in fines content or consistency. Then consistency had to be determined with some other method. The appearance of air pockets as consistency increases is the limiting factor of this method.

2. Laser pulse time of flight through a paper gives the paper’s porosity. This knowledge was attained with a press enabling the measurement of photon migration through an exact spot of paper at the same time as the paper’s porosity is changed. Previous investigations use different paper sheets and the error caused by the differences between sheets has prevented the other scientist from claiming that photon migration can be used to measure paper porosity. Porosity range from 30% to 60% was investigated.

3. The filler content can be measured if the time and intensity of photon migration is measured. However the fines content of the pulp has to be known.

4. Depending on the properties of the pulp, a paper has a special delay constant with unit ps/(g/m^2*µm).

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