# Wood – Base material for Optical Elements for Terahertz Waves?

Peter Zolliker[1], Elena Mavrona[1], Erwin Hack[1], Markus Rüggeberg[2,3,4], Zhihui Zeng[3], Gilberto Siqueira[3], Gustav Nyström[3]
[1]Laboratory for Transport at Nanoscale Interfaces, Empa, 8600 Dübendorf, Switzerland
[2]Institute for Building Materials, Swiss Federal Institute of Technology, ETH Zürich, 8092 Zürich, Switzerland
[3]Laboratory for Cellulose & Wood Materials, Empa, 8600 Dübendorf, Switzerland
[4]Institut für Holztechnologie Dresden, 01217 Dresden, Germany

***Abstract*—Polarized THz time domain spectroscopy is used to study anisotropic optical properties of wood and artificial cellulose materials in view of a potential use of such materials as optical elements in the THz range, such as for Half Wave Plates and Quarter Wave Plates. Wood samples of different species, sample thickness as well as water content are studied experimentally. In addition artificially produced cellulose samples are characterized in terms of birefringent properties and compared to the properties of the wood samples.**

## I. INTRODUCTION

Wood is a highly anisotropic and inhomogeneous biological material. It shows anisotropic optical properties in the THz frequency range in particular birefringence, which is mainly caused by preferential orientation of cellulose microfibrils in the wood cell walls [1, 2]. In recent years, artificial materials made out of wood components, in particular cellulose, gain more and more attention. They are produced by different methods such as 3D printing, or freeze casting Additional functional materials (e.g. carbon particles or metallic fibers) can furthermore be added in order to design compounds with new properties. Anisotropic optical properties of such materials can be designed in particular using cellulose fibers with preferred orientation.

The potential of wood for use as low price optical elements was reported in the literature [3] but has not been systematically investigated up to now. Here we present a study on the optical properties of wooden and artificial cellulose samples potentially suited for use as half-wave plates (HWP) and quarter-wave plates (QWP). The anisotropic absorption properties of the studied materials cannot be neglected and need an appropriate modelling. The most interesting property is the efficiency of an optical element, defined as the relative transmitted intensity for a targeted frequency to produce a 90°-rotated linear (HWP) or a pure circular polarized wave (QWP) from a linear polarized wave.

## II. METHODS

Birefringent materials can be modelled using the complex refractive index $\tilde{n}$ in two orthogonal principal directions $\tilde{n}_1 = n_1+\kappa_1$ and $\tilde{n}_2 = n_2+i\kappa_2$ with refraction index $n$ and extinction coefficient $\kappa$. We use the Jones Matrix formalism [4] to determine the operating frequency $\nu_{\mathrm{WP}}$ and rotation angle $\alpha_{\mathrm{WP}}$ for a wave plate as well as its efficiency $\varepsilon_{\mathrm{WP}}$. The Jones matrix $B_0$ of a birefringent, absorbing material, with principal axes oriented along the x- and y-axis is

$$B_0 = \begin{bmatrix} e^{if\tilde{n}_1} & 0 \\ 0 & e^{if\tilde{n}_2} \end{bmatrix}$$

where $f = 2\pi\nu\, d/c_0$ with frequency $\nu$, $c_0$ the speed of light, $d$ the wave plate thickness. If the sample is rotated by an angle $\alpha$ the Jones Matrix $B(\alpha)$ can be expressed as

$$B(\alpha) = R(-\alpha)B_0R(\alpha)$$

Using the rotation matrix for angle $\alpha$

$$R(\alpha) = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix}$$

With this formalism conditions for working frequency $\nu_{\mathrm{WP}}$ and operating angle $\alpha_{\mathrm{WP}}(\nu)$ of a wave plate can be derived. For an operating wave plate both, the angular and the frequency condition have to be met. As frequency condition we get

$$\nu_{\mathrm{WP}} = \frac{mc_0}{4d\Delta n}$$

where $m = 1,3,5\ldots$ for a quarter-wave plate and $m = 2,4,6\ldots$ for a half wave plate, and $\Delta n = n_2\text{-}n_1$ is the frequency dependent birefringence of the wave plate. The frequency conditions for m = 1 and 2, respectively, are illustrated in Fig. 1 as black vertical lines.

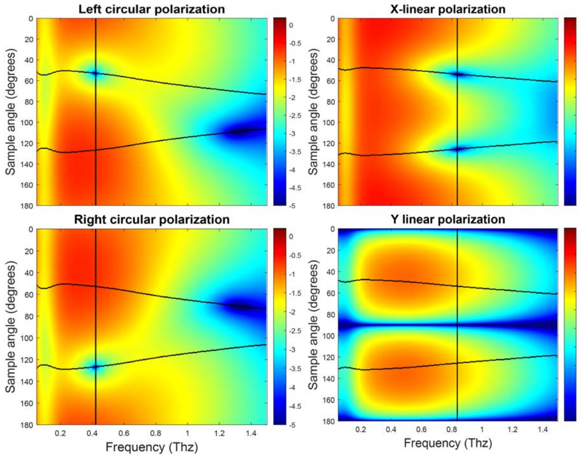

**Fig. 1.** Transmission intensity of a 2mm spruce sample as a function of frequency and sample rotation angle for a linear polarized incoming THz pulse (log scale). Left and right circular polarized component (left) and x- and y-polarized component (right) of the outcoming pulse. Vertical black line show angular condition of a quarter wave plate (m=1, left images) and half-wave plates (m=2, right images). Horizontal black curves show angular condition.

The angular condition $\alpha_{\mathrm{WP}}(\nu)$ (angle of the waveplate with respect to the incoming polarization) for quarter- and half-wave plates are

$$\cos\alpha_{\mathrm{QWP}} = \frac{1}{\sqrt{1+e^{-2f\Delta\kappa}}} \qquad \cos\alpha_{\mathrm{HWP}} = \frac{1}{\sqrt{1+e^{-f\Delta\kappa}}}$$

where $\Delta\kappa = \kappa_2\text{-}\kappa_1$. The angular condition is illustrated in Fig. 1 as a frequency dependent curve. Note, that if $\Delta\kappa$ is non-zero the angle deviates from 45°/135° as it would be for an ideal wave plate with isotropic absorption.

The efficiency $\varepsilon_{WP}$ is the intensity of the orthogonal polarization at the angular and frequency position for which the intensity of a specific polarization is zero.

$$\epsilon_{\text{QWP}} = \frac{2}{e^{2f\kappa_1} + e^{2f\kappa_2}} \qquad \epsilon_{\text{HWP}} = \frac{1}{e^{f(\kappa_1+\kappa_2)}}$$

## III. EXPERIMENTS

A THz time domain spectroscopy setup (Teraflash from Toptica) was used to measure the angle dependent optical properties of the samples. The transmission of the samples was measured using a focused beam with a spot size of approximatively 2 mm. We used a linear polarizer $P_1(\varphi_1)$ in front of a sample $S(\alpha)$ and a second polarizer $P_2(\varphi_2)$ after the sample to resolve polarization-dependent THz measurements, where $\varphi_1$, $\varphi_2$ and $\alpha$ represent rotation angles of the two polarizers and the sample.

Jones matrix elements can be determined from measurements in four polarizer angle combinations at $\varphi_1/\varphi_2 = [45^o/45^o, 45^o/135^o, 135^o/45^o, 135^o/135^o]$ and two reference measurements without sample at $\varphi_1/\varphi_2 = [45^o/45^o, 135^o/135^o]$. The use of the Fourier transform of the measured THz pulse allows acquiring frequency dependent Jones Matrixes. If the principal axes of the birefringence is known the number of measurements can be reduced to two sample orientations at $0^o$ and $90^o$ with polarizer orientation at $\varphi_1/\varphi_2 = [0^o/0^o]$ and one reference measurement without sample, as the off-diagonal elements can be assumed to be zero. By multiplying the Jones Matrix of the sample with that of a specific polarizer (linear X, Y or circular left, right) intensity maps as a function of frequency and sample angle can be visualized as illustrated in Fig. 1.

We included the following samples into our study:

- Beech wood (2 mm, 6 mm) and with different humidity conditions (ambient and dry),
- Spruce wood (2 mm, 6 mm) and different humidity conditions (ambient and dry),
- Spruce sample containing only the early wood (EW), i.e. the low-density part at different humidity conditions (ambient and dry).
- 3D printed cellulose composites of different thickness produced by direct writing of concentrated, viscoelastic aqueous and monomer-based cellulose nanocrystal inks [5].
- Ultralight and highly flexible biopolymer aerogels, composed of biomimetic cellular microstructures formed from cellulose nanofibers and silver nanowires [6] of different thickness (1.5-2.5 mm) containing oriented silver nanowires of different concentrations (2-5 wt%).

## IV. RESULTS

Fig. 2 shows efficiencies and operating frequencies for the studies samples used as a quarter-wave plate. For wood samples and the best performing artificial cellulose materials, the efficiencies are in the order of 20% which is rather low for the targeted application. An exception are the samples cut from early wood of spruce and the dry wood samples with efficiencies of 40 - 55%. Note that a half wave plate can be looked at as a combination of two quarter-wave plates, i.e. its efficiency is roughly the square of that of a quarter wave plate. Two factors determine the efficiency of wave plates, (i) the extent of the birefringence and (ii) the absorption properties. For wood samples, the water content and the absorption of cellulose are the main contributors to the absorption. The water contribution can be eliminated using dry samples, but not that of the cellulose. For artificial cellulose samples one can maximize birefringence with an optimized 3D printed structure or one can minimize the cellulose density maintaining the birefringence by adding oriented conducting elements, such as silver nanowires, which themselves also contribute to the absorption. We have shown that both methods turn out to work to some extent and can reach the performance of wood at ambient conditions.

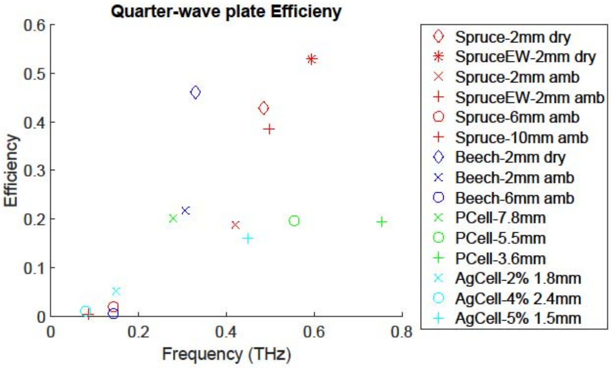

**Fig. 2.** Efficiencies and operating frequencies for a quarter-wave plate: spruce (red), beech (blue), printed cellulose (green) and freeze-dried cellulose containing silver nanowires (cyan).

## V. SUMMARY

Wood is a prototype material for optical elements in THz (QWP, HWP). Its absorption properties limits the efficiency, and the strong dependency on humidity calls for optimization. Artificially produced cellulose materials have the potential for designing and further optimizing such optical elements. However, the rather high absorption of cellulose makes this approach challenging. An alternative could be the replacement of cellulose by a different low absorbing material, but maintaining the geometry of the wood structure.

## REFERENCES

[1] T. M. Todoruk, I. D. Hartley and M. E. Reid, “Origin of birefringence in wood at terahertz frequencies”, IEEE Trans. Terahertz Sci. Technol. 2, 123 – 130 (2012).
[2] P. Zolliker, M. Rüggeberg, L. Valzania and E. Hack, "Extracting Wood Properties from structured THz spectra: birefringence and water content," in IEEE Transactions on Terahertz Science and Technology, vol. 7, no. 6, pp. 722-731, Nov. 2017.
[3] M. Reid and R. Fedosejevs, "Terahertz birefringence and attenuation properties of wood and paper," Appl. Opt. **45**, 2766-2772 (2006).
[4] R. Clark Jones, J. Opt. Soc. Am. **31**, 488-493 (1941).
[5] G. Siqueira *et al.*, “Cellulose nanocrystal inks for 3D printing of textured cellular architectures”, *Adv. Funct. Mater.*, vol. 27, no. 12, p. 1604619 (2017).
[6] Z Zeng, T Wu, D Han, Q Ren, G Siqueira, G Nyström, "Ultralight, flexible, and biomimetic nanocellulose/silver nanowire aerogels for electromagnetic interference shielding," ACS nano 14 (3), 2927-2938 (2020).

We acknowledge partial financing by the Swiss National Science Foundation Project Nr. 200021_179061 / 1.