# Application of time-of-flight near infrared spectroscopy to wood

**Satoru Tsuchikawa[a] and Shigeaki Tsutsumi[b]**

[a]*Graduate School of Bioagricultural Sciences, Nagoya University, Nagoya 464-8601, Japan*

[b]*Department of Mechanical Engineering, School of Engineering, Fukui University of Technology, Fukui 910-8505, Japan*

## Introduction

The behaviour of light propagation in wood is directly affected by the cellular structure. Recently, we constructed the optical characteristic models to provide a background and framework for developing a non-destructive measurement system applicable to such biological materials.[1,2] Furthermore, we examined the non-destructive quantitative assessment of moisture and physical conditions in bulky wood by using a near infrared (NIR) spectrophotometer with low output power. The calibration equations for moisture content, orientation of fibre, etc. with sufficient precision were found from a multi-term linear regression analysis.[3,4] However, the information from such an optical method measuring the diffuse reflectance spectra was confined to part of the subsurface layer of a sample.

To find the wide application of NIR to a wooden article (i.e. timber, lumber or furniture), it is important to establish a high power measurement system in which the measurable sample thickness is larger than that in the traditional apparatus. In this study, an advanced step forward in this investigation, an optical measurement system which was mainly composed of a parametric tuneable laser and a near infrared photoelectric multiplier, was introduced at the viewpoint of the time-of-flight near infrared (ToF-NIR) instrument.[5,6] This system combines the best features of the spectrophotometer and the laser beam, and more advantageously, the time-resolved profile of transmitted output power could be measured sensitively in nanoseconds. The combined effects of the cellular structure of wood samples, the wavelength of the laser beam and the detection position of transmitted light on the time-resolved profiles were investigated in detail.

## Materials and method

The wood samples used were Sitka spruce (soft wood) that had an oven-dried density of 0.47 g cm$^{-3}$ and Beech (hard wood) that had an oven-dried density of 0.68 g cm$^{-3}$.

The wavelength of the pulsed laser $\lambda$ was tuned from 700 nm to 1300 nm by the optical parametric oscillation of a BBO ($\beta$-$BaB_2O_4$) crystal.[7,8] The transmitted output power was measured by an NIR photoelectric multiplier having a spectral response ranging between 300 nm and 1700 nm through an optical fibre cable having a diameter of 7 mm. The sampling time and the average number of the transmitted output power were 100 ns and 300 times, respectively.

The normalised time-resolved profiles of Sitka spruce (90 mm in width, 34 mm in length) are shown in Figure 1. A time-resolved profile as the reference was selected by complying with the measuring conditions. In this figure, the time-resolved profile at $d$ = 1 mm is taken as a reference. As shown Figure 1, the variations of the peak maxima, the time delay of peak maxima and the variation of



Near Infrared Spectroscopy: Proceedings of the 10th International Conference

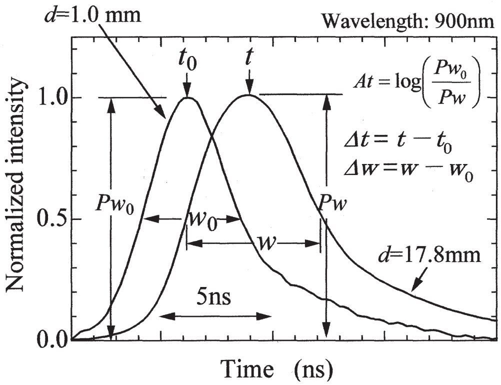


**Figure 1. Normalised time-resolved profiles.**

full width at half maximum of the profile were examined at the required measuring conditions, respectively.

## Results

First, we examined the variation of time-resolved profile with sample thickness *d*. Figure 2 indicates the spectral variation of each optical parameter at the opposite face. It is commonly known that *At* increases monotonically as *d* increases. On the other hand, $\Delta t$ also increases gradually as *d* increases. However, its wavelength dependency is inversely related to *At*. At the absorption band of water around at 1000 nm

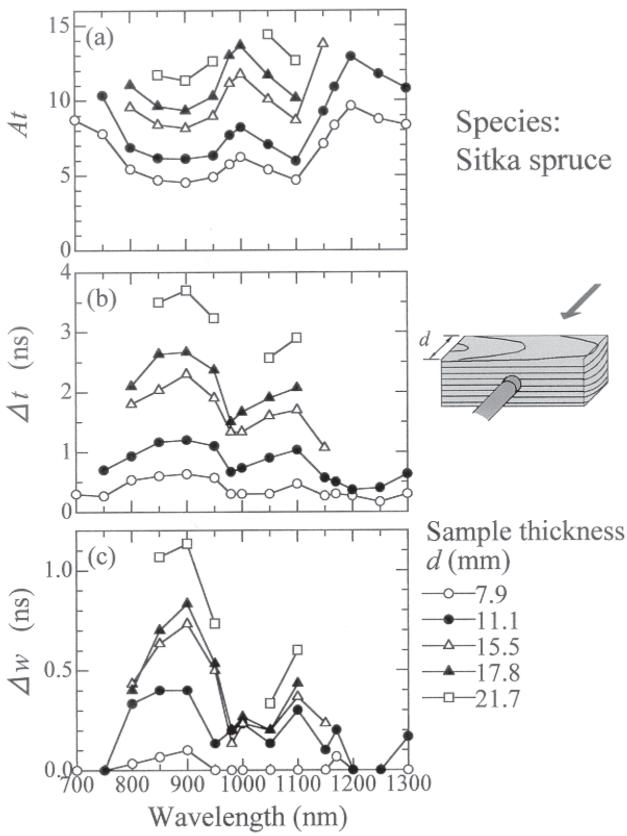


**Figure 2. Spectral variation of the attenuance *At*, the time delay of peak maxima $\Delta t$ and the variation of full width at half maximum $\Delta w$. Wood species: Sitka spruce. Detection position: Centre of opposite face of the sample.**

and 1200 nm, the transmitted light is attenuated greatly and the light path time through a sample is becoming faster. As is known from Figure 2(c), $\Delta w$ also shows the same trend as $\Delta t$. These results directly mean that the diffusely-scattered light having relatively longer optical path length is attenuated or absorbed by water and, therefore, the time delay of peak maxima shortens substantially.

The light scattering condition in wood sample was estimated from the product of $\Delta t$ and $\Delta w$. Figure 3 shows the variation of $\Delta t \times \Delta w$ with sample thickness $d$ or irradiation point $l$ at representative wavelengths. In every case, $\Delta t \times \Delta w$ increases exponentially with $d$ or $l$. However, their absolute value varied greatly with wood species or wavelength. When the transmitted light was detected at the opposite face [see Figure 3(a)], $\Delta t \times \Delta w$ for Beech shows larger value than those for Sitka spruce at every wavelength band. On the other hand, in the case of the measurement at the side face [see Figure 3(b)], $\Delta t \times \Delta w$ for Sitka spruce show larger value. The soft wood (Sitka spruce) is mainly composed of the tracheid with hollow fibre, where the scattered light from wood substance and that from the lumen coexist. In particular, there may be considerable light scattering in the lumen of tracheid, which performs as multiple specular reflection and be easy to propagate along the length of the wood fibre. In the case of Beech with little space between wood fibres, variations in the light propagation along the length of wood fibre may be small, whereas the time delay related to the high density of wood substance is remarkable. When we apply ToF-NIR to the cellular structural materials like wood, it is very important to give attention to the difference in the light scattering within the cell wall and the multiple specular-like reflections between cell walls.

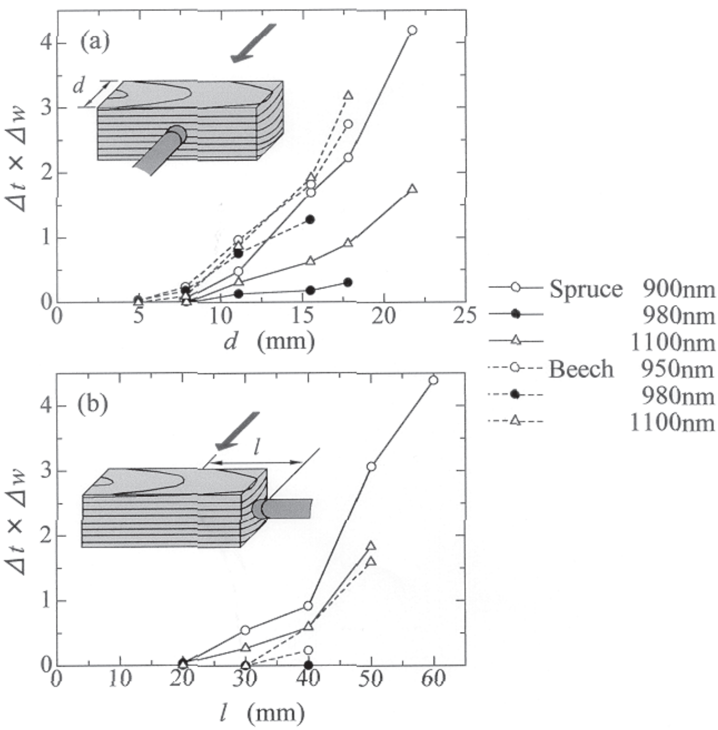


**Figure 3. Variation of $\Delta t \times \Delta w$ with sample thickness or detection position.**

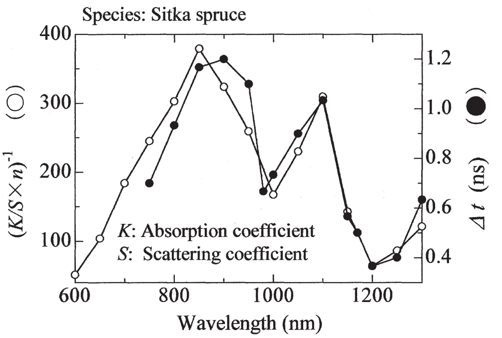


**Figure 4. Spectral curves of ($K/S \times n$)$^{-1}$ and $\Delta t$.**

We tried to express the characteristics of the time-resolved profile on the basis of the optical parameters for light propagation determined by the previous studies, which were absorption coefficient $K$ and scattering coefficient $S$ from the Kubelka–Munk theory[1] and $n$ from $n$th power cosine model of radiant intensity.[2] The anisotropy of light scattering in the sample should be expressed by this parameter of $n$, whereas $S$ and $K$ may be related to the optical characteristics of wood substance, i.e. The cell wall itself. Figure 4 shows the spectral curves of $(K / S \times n)^{-1}$ and $\Delta t$. The species used was Sitka spruce. $(K/S \times n)^{-1}$ and $\Delta t$ showed similar tendency to the variation of wavelength, although the individual variation of $K / S$ or $n$ with the wavelength was not the same as that of $\Delta t$. In this way, the time-of-peak maxima reflect directly the interrelationship between the light-scattering and -absorption characteristics of the wood substance and the anisotropic directional characteristics caused by the cellular structure. Such primary analysis suggests that the light propagation, which is governed by the directional characteristics and the absorption/scattering characteristics, can be easily found by the variation of the time-resolved profile synthetically. Thus, our optical characteristics models, which express the light propagation in the cellular structural material, are also supported by ToF-NIR.

## Conclusion

The newly constructed optical measurement system, which was mainly composed of a parametric tuneable laser and a near infrared photoelectric multiplier, was introduced to clarify the optical characteristics of wood from the viewpoint of time-of-flight near infrared spectroscopy (ToF-NIR). The combined effects of the cellular structure of wood samples, the wavelength of the laser beam and the detection position of transmitted light on the time-resolved profiles were investigated in detail. The arrangement and orientation of cells were directly related to the time delay of light propagation. Applying ToF-NIR to the cellular structural materials, it is very important to give attention to the difference in the light scattering within the cell wall and that caused by the multiple specular-like reflections between the cell walls. It was also known from the optical parameters for light propagation that the variation of the time-resolved profile was governed by the combination of light-absorbing and -scattering condition and the degree of anisotropy. Thus our optical models were experimentally supported by ToF-NIR. These basic data will be essential for this system to put an in-process measurement system in the wood industry to practical use.

## References

1. S. Tsuchikawa, K. Hayashi and S. Tsutsumi, *Appl. Spectrosc.* **50,** 1117 (1996).
2. S. Tsuchikawa and S. Tsutsumi, *Appl. Spectrosc.* **53,** 233 (1999).
3. S. Tsuchikawa, M. Torii and S. Tsutsumi, *Mokuzai Gakkaishi* **42,** 743 (1996).
4. S. Tsuchikawa and S. Tsutsumi, *Mokuzai Gakkaishi* **43,** 149 (1997).
5. L. Leonardi and D.H. Burns, *Appl. Spectrosc.* **53,** 628 (1999).
6. L. Leonardi and D.H. Burns, *Appl. Spectrosc.* **53,** 637 (1999).
7. A. Yariv, *Quantum Electronics,* 2nd Edn. John Wiley & Sons, New York, USA (1975).
8. P.G. Harper and B.S. Wherrett (Eds), *Nonlinear Optics.* Academic Press, New York, USA (1977).