Monitoring the Water Content of Plant Leaves with THz Time Domain Spectroscopy

R. Gente, N. Born, A. Velauthapillai, J. C. Balzer, and M. Koch
Faculty of Physics and Material Sciences Center, Philipps-University Marburg, Renthof 5, D-35032 Marburg

***Abstract*—We present an automated measurement setup which employs a fiber-coupled THz time domain spectrometer for simultaneous monitoring of the change in leaf water content of several plants at once. Moreover, it combines the collected THz spectra with data from other sensors. While the strong absorption of THz radiation by polar liquids like water tends to a problem in most biological and medical applications, it is a reliable indicator for leaf water content. We take this well-known basic principle to a level where biological experiments which explore the physiological behavior of plants under different drought stress condition become possible.**

I. Introduction

THE field of plant phenotyping uses many different sensors and techniques for the characterization of the physical appearance of plants. Many of the established methods are based on image analysis and can already detect many properties of plants, which are interesting for plant scientists and plant breeders [1]. But measuring leaf water content in vivo is still difficult. A technique which can fill this gap is THz time domain spectroscopy. In the frequency range between a few hundred GHz and a few THz there is a very high contrast between the absorption coefficients of liquid water and other components which can be found inside a plant's leaf. The proof of principle for this kind of measurement was provided by the early works of Mittleman [2] and Hu [3]. While these first measurements were based on free space laboratory setups, in the past two decades the technology has made vast progress towards real applications in plant science and crop breeding [4,5].

II. Methods

Two objectives need to be addressed to enable meaningful biological experiments: Several plants need to be monitored simultaneously and the experiments may last several days or even weeks. This renders manual operation of the measurements in a traditional laboratory THz setup impossible. Both objectives can be achieved by employing a fiber-coupled THz time domain spectrometer and automating the mechanical handling of the measurements. We realize this approach by integrating the fiber-coupled THz antennas and the THz optics into a compact sensor head, which is mounted on the arm of a goniometer. Sample holders are erected in a circular arrangement around the goniometer. Hence each holder can be reached by the sensor head. These holders are used to hold the inspected leaves in place for the measurements. This setup allows for experiments on 15 to 20 plants simultaneously. In addition to the THz time domain spectra the weight of each pot and the air temperature and humidity are recorded. This combination of sensors enables systematic studies on the drought stress behavior of plants like rye and other crops.

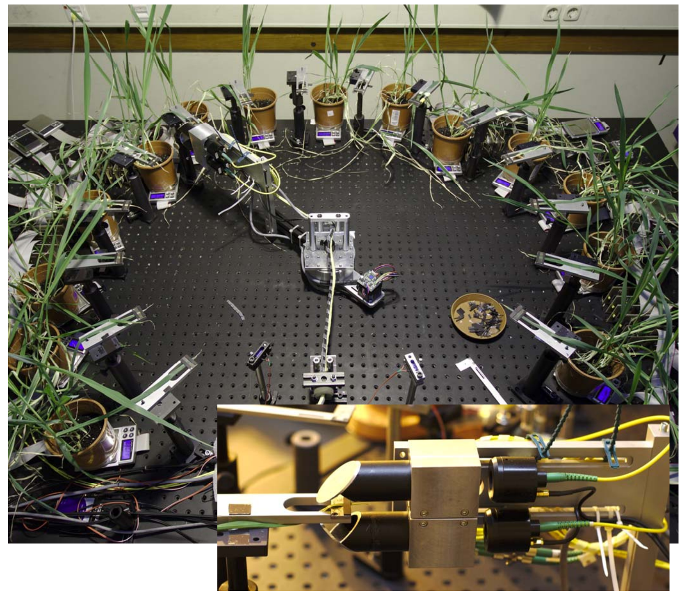

Fig. 1. Pots with rye plants are placed in a circular arrangement on an optical table. One leaf from each plant is fixed in a sample holder. The sample holders can be reached by the motorized arm of the goniometer. On this arm the fiber coupled THz emitter and detector and the THz optics are mounted as shown in the inset.

Each of the sample holders incorporates an aperture with a diameter of 3 mm. These apertures are adjusted to be in the focus of the THz beam path. During the experiment a reference measurement through air is performed next to each sample holder before the measurement of the leaf through the aperture. Before the start of the actual experiment, measurements are performed without samples to characterize the empty sample holders and to account for variations in their adjustment. After this step one leaf of each plant is placed on a sample holder and covers the aperture. Magnets are used to hold the leaves tightly in place. This kind of mechanical fixation has proven to be sufficiently robust while not squeezing the leaves too much.

In a typical drought stress experiment, plants are initially kept under good watering conditions. After some days the plants are deprived from water. As the residual amount of water in the soil decreases, drought stress emerges for the plant. Eventually, the plant is rewatered. After rewatering, it becomes apparent if the plant can recover from the drought stress or if it already was beyond its permanent wilting point which can also be described as the "point of no return" after which the plant is irrecoverably damaged by the drought stress [4]. During these three phases of different watering conditions the plants' leaf water content is monitored using the fiber-coupled THz time domain setup as described above. The results of such an experiment are plotted in fig. 2 and fig. 3 and will be discussed in the following.

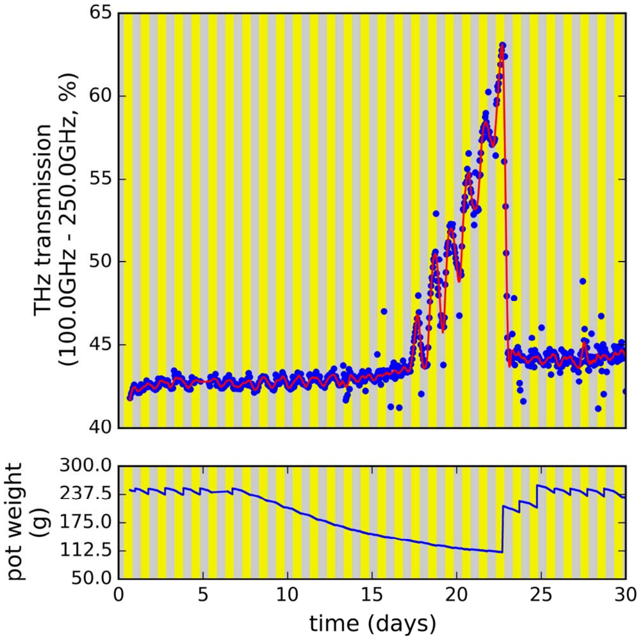

Fig. 2. Example for the dynamics of drought stress and rewatering of a rye plant. With shrinking water supply drought stress builds up and the THz transmission increases as expected. The plot reveals that the leaf dries out during daytime (yellow), while during the night (grey) it can recover a little bit. After rewatering, which is marked by the steep increase of the pot's weight, the plant recovers immediately and the leaf comes back to its initial transmission value within a few hours.

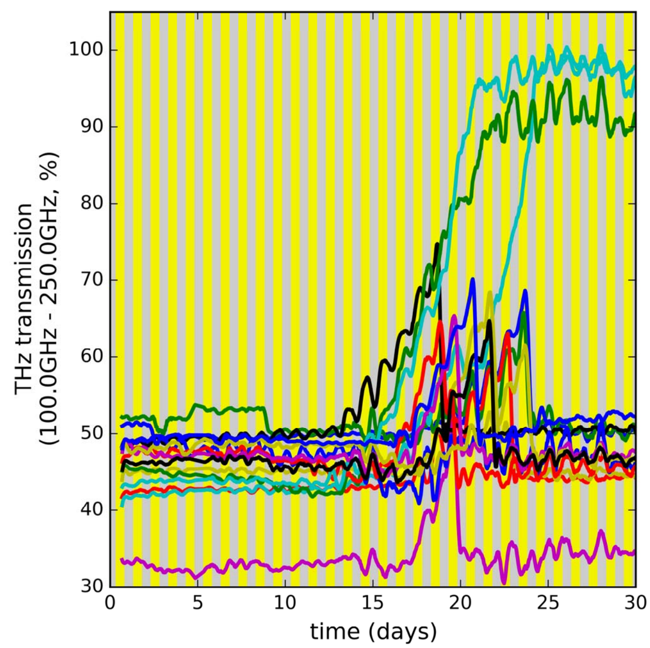

Fig. 3. Overall 15 Plants were used in the experiment. All plants are watered regularly in the first days of the experiment. After they are deprived from water, their leaf water content decreases which becomes apparent in the increased transmission of THz radiation. After rewatering most plants recover within a few hours while some leaves continue to dry, which means that they already were beyond their permanent wilting point.

III. Results

The measurements show a clear connection between drought stress and THz transmission. This is revealed by the comparison of the pot's weight and the THz transmission trough the leaf. Fig. 2 shows an example for a dataset, which was obtained using the automated setup. As explained above the plant is watered regularly during the first days of the experiment. After the 7th day the plant is deprived from water. This results in an increase of the THz transmission which is measured through one of the plant's leaves. The increase mainly takes place during daytime, while during nighttime a slight recovery of the plant's leaf water content is observed. On the 23rd day the plant is rewatered. Within a few hours the plant recovers from drought stress and the THz transmission returns to about the same level as before the drought stress started. In Fig. 3 the measurement results from 15 plants are plotted together. Most of the plants behave in a similar way like the one in fig. 2. All plants were rewatered after some days of drought stress, but for some plants the rewatering came too late and the leaf under inspection could not recover anymore. Though, the plants as a whole were able to recover in all cases.

IV. Summary

Based on a fiber-coupled THz time domain spectrometer, we established a measurement setup, which can monitor the leaf water content of several plants in parallel. The combination with other sensors allows for a comprehensive view on the drought stress dynamics of the plants. For this purpose long term measurements over several weeks have been performed with the setup.

References

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