STUDY ON LIGHT RESPONSE OF PACHIRA AQUATICA'S LEAF VIA SURFACE PLASMON RESONANCE TECHNIQUE

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Abstract- Light response of a pachira aquatica's leaf at room temperature was investigated with a strong p-wave electromagnetic field by utilizing a surface plasmon resonance (SPR) based sensor technique of angular interrogation method for biological and chemical sensing. The essential principle of SPR biosensing is based on measurement of the change regarding leaf's microstructure against the sensor's metallic surface owing to the interaction with the strong p-wave electromagnetic field. The test result shows that the pachira aquatica's leaf responds to each light lamp within 1 minute.

Index terms*: surface plasmon resonance, pachira aquatica, angular interrogation, p-wave, light response.*

I. INTRODUCTION

In this article, we investigated light response of a pachira aquatica's leaf at room temperature with a strong TM mode (p-wave) electromagnetic field as described in Fig. 1, utilizing a surface plasmon resonance (SPR) based sensor technique by angular interrogation method. SPR is a novel technique for biological and chemical sensing, which employs not only the amplitude of a resonantly reflected light wave, but also its phase as well. The essential principle of SPR biosensing is based on any changes regarding the microstructure of leaf's surface against the sensor's metallic surface owing to the strong p-wave electromagnetic field. SPR is very sensitive to slight changes of sensing layer thickness and refractive index affected by a tested sample. Conventionally, three methods have been employed to monitor the excitation of SPR by measuring the reflection signal from the SPR sensor surface, including wavelength interrogation, angular interrogation and intensity measurement.[1-3] In this paper, we will use the angular interrogation method to study light response of a pachira aquatica's leaf to different light sources.
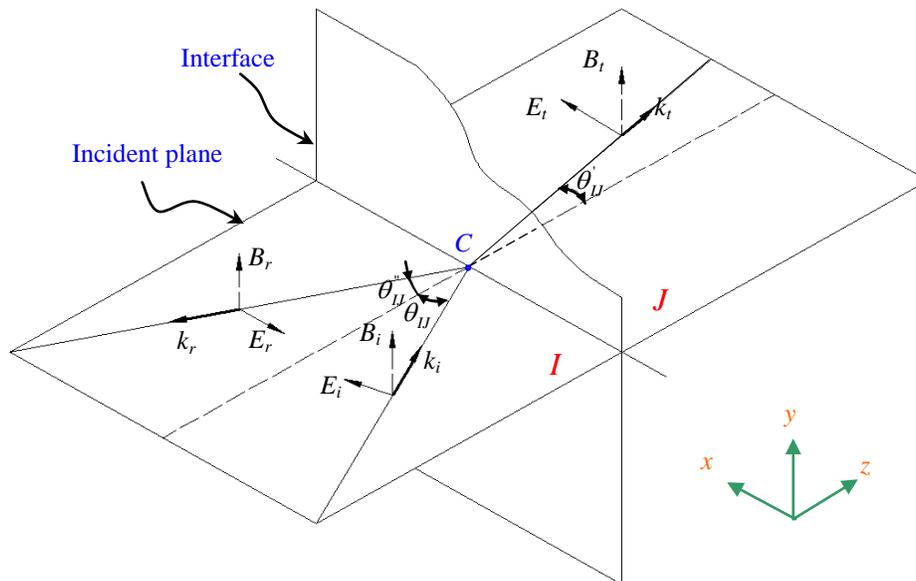

Fig. 1   Propagation of TM mode (p-wave) electromagnetic wave crossing the interface between connected *I* and *J* media.

Many plant-organs contain various photosensitive compounds, each reacting specifically to certain wavelengths of light. These light-sensors tell the plant whether the ambient is bright or dark, how much light is available, how long the day is and from where the light comes.[4] In this paper, we chose a pachira aquatica tree for demonstration of our SPR method. Pachira aquatica is a tropical wetland tree of the genus pachira, native to central and south America where it grows in swamps. It is also known by the common names Malabar chestnut, Guiana chestnut, provision tree, saba nut, Monguba (Brazil), Pumpo (Guatemala). We may see it in market commercially sold under the name as money tree and money plant. It can be classified in the subfamily Bombacoideae of the family Malvaceae.[5-6]

II. THEORY

Surface plasmon resonance is a charge density oscillation behavior that may exist at the interface of two media with dielectric constants of opposite signs, *e.g.* a metallic material and a dielectric material. The charge density wave is associated with a wave of electromagnetic field. Its field vectors reach their maxima at the interface via multiple reflections and interferences, and decay evanescently into both media. This surface plasmon wave (SPW) is a TM-polarized wave, also called as p-wave. Its magnetic vector is perpendicular to the direction of propagation of the SPW and parallel to the plane of interface, as illustrated in Fig. 1. The propagation constant of the surface plasmon wave propagating at the interface between a semi-infinite dielectric and metal may be given by the following expression [1]:

$$\beta \;=\; k\sqrt{\frac{\varepsilon_m n_s^2}{\varepsilon_m + n_s^2}}\,, \tag{1}$$

where k denotes the free space wave number,

ε_m is the dielectric constant of the metal ($\varepsilon_m = \varepsilon_{mr} + i\,\varepsilon_{mi}$), and

n_s represents the refractive index of the dielectric.

According to the equation (1), the surface plasmon wave may be supported by the structure providing that $\varepsilon_{mr} < -n_s^2$. At optical wavelengths, this condition may be fulfilled by several metals [7] of which gold and silver are the most commonly used. For these metals, a brief comparison of the main characteristics of surface plasmon wave propagating along the interface

between water and the surface plasmon active metal layer is given by Homola *et al*.[1-3] Owing to the large imaginary part of refractive index which results in high loss within the metal, the surface plasmon wave highly attenuates as propagation with the wavelengths in the visible and near-infrared spectral regions. Since both the incident angle and the associated reflection surfaces can cause the incident electromagnetic wave to produce multiple reflections and oscillations in space between reflection surfaces, the electromagnetic field of the surface plasmon wave is distributed in a highly asymmetric fashion and the vast majority of the field is concentrated in the dielectric material. A surface plasmon wave propagating along the surface of silver is less attenuated and able to exhibit higher localization of electromagnetic field in the dielectric than that supported by gold.
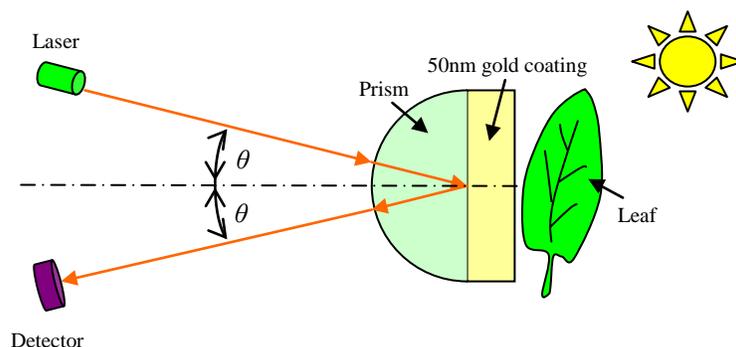

Fig. 2   Schematic plot of the experimental setup for testing the light response of the pachira aquatica's leaf.

In the general, an SPR based sensor comprises an optical system, a transducing medium which is able to interrelate the optical and (bio)chemical domains, a digital electronic system supporting the optoelectronic components of the sensor and allowing data processing, and a mechanical mechanism maintaining the angular positions of light source and detector. This transducing medium transforms changes in the quantity of interest into changes in the refractive index which may be determined by optically interrogating the SPR based sensor. The optical configuration of the SPR based sensor as illustrated in Fig. 2, contains a polarized source of optical radiation and an optical path structure in which SPW is excited and interrogated. In the process of interrogating the SPR, an electronic signal is recorded by a digital acquisition system. Major properties of the SPR based sensor are determined by properties of the sensor's subsystems. The SPR based

sensor's sensitivity, stability, and resolution are mainly dependent upon properties of both the optical system and transducing medium. The selectivity and response time of the SPR based sensor are primarily determined by the properties of the transducing medium and the speed of reaction with the transducing medium near the interface.

The conventional way to study light response of plant leafs relies on Beer's law. By measuring the absorbance during transmission through a tested plant leaf with a monochromatic incident light, an action diagram can be drawn to describe the magnitude of the biological effect.[4] Since the absorbance may be saturated in case the leaf is very thick, this measurement technique is limited by the sample thickness. On the other hand, our method relies on the reflection signal from the SPR interaction with the leaf surface. The reflectance measurement corresponding to the biological signal of a pachira aquatica's leaf to a light source is not limited by the leaf thickness any more.

Although the reflectance measurement is not limited by the leaf thickness, the effective penetration depth from the leaf surface needs to be realized before testing. Besides, the concentration distribution within any test sample can be influenced by the polarized EM wave, and casts a significant role for the variation of refractive index within the interaction zone of surface plasmon resonance. Especially, the depth of penetration (DP) from the half cylindrical prism via the metallic coating into the test sample is an important parameter which can describe the effective thickness of the interaction zone penetrated by the polarized EM wave, and can be written as [8]:

$$ DP \ = \ \frac{1}{2\pi W N_C \sqrt{Sin^2\theta - N_{SC}^2}}, \qquad (2) $$

where W represents wave number of the evanescent wave into the optical activity sample,

N_C is the prism's refractive index,

θ indicates the angle of incidence, and

N_{SC} is the ratio of sample refractive index to prism's refractive index.

The electromagnetic field owing to multi-reflections of the evanescent wave between the metallic coating and the tested sample may decay to zero, in case the depth of penetration in any tested sample from the metallic coating is at least five wavelengths. Both the reflection and transmission coefficients of the multilayer optics system and the reflection optical path via a half

cylindrical prism can be derived systematically using the matrix method, as illustrated in the reference 2.

III. EXPERIMENTAL

The schematic plot of optical path in the experimental SPR system against a Pachira aquatica's leaf is illustrated in Fig. 2. The photograph of the main frame in the experimental setup is shown in Fig. 3. The SPR system consists of:

(1)   He-Ne laser (wavelength: 632.8 nm),

(2)   Glan-Thompson polarizer (wavelength: 320nm-2300nm; Transmission: 90%),

(3)   glass slide of 0.5mm thickness,

(4)   half cylindrical prism (BK7) of 1" radius,

(5)   50nm gold coating,

(6)   PIN photodetector,

(7)   200Ω heater,

(8)   PID thermostat controller,

(9)   temperature-unified plate and

(10)   temperature senor of K-type thermocouple.

Fig. 3 The main frame of the temperature-controlled SPR in the setup of light response experiment.

The detachable half cylindrical prism was coated with a 50nm gold film and a 10nm chromium film served as a buffer layer to release the residual stress. Before testing, the detachable half cylindrical prism must be fully cleansed using an ultrasonic bath filled with distilled water. Furthermore, the leaf sample was tightly sandwiched between a temperature-unified plate and the detachable half cylindrical prism as shown in Fig. 4.
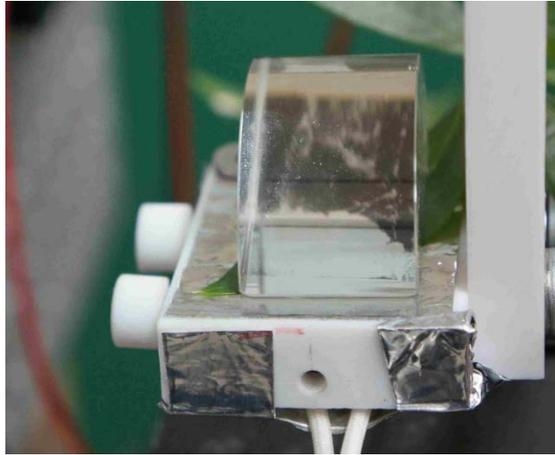

Fig. 4 The sandwiched configuration for testing the leaf between a temperature-unified plate and the detachable half cylindrical prism.

Before measurement, each light lamp was turned on to irradiate the leaf for two hours, and then turned off for 30 minutes, so as to delete any possible memory effect. During measurement, the light lamp was set to be turned off for several minutes in advance, and then turned on to irradiate the leaf. The SPR sequentially recorded the light response each minute.

IV. RESULTS AND DISCUSSION

In Fig. 5, the light response of the pachira aquatica's leaf is presented. At 0 minute, the sun light lamp (MOZOO Aquatic Plant 10W, color temperature: 7500K) was turned off. The light response time chart at the angle of 70° as shown in the right figure of Fig. 6, can be drawn from the sequential SPR diagrams. The reflectances in the SPR diagrams before 13 minutes are greater

than those after 14 minutes. The test result shows that the pachira aquatica's leaf responds to the sun light lamp within 1 minute.
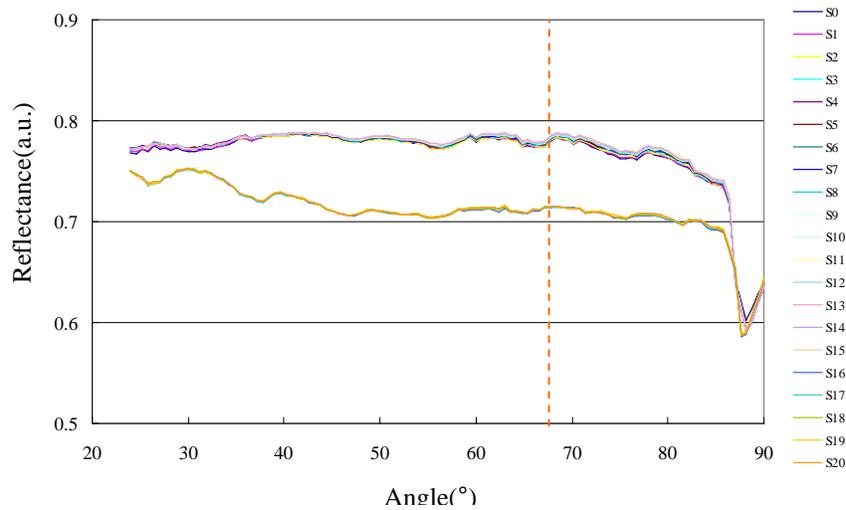

Fig. 5 Light response SPR diagrams of the pachira aquatica's leaf at different times indicated by 21 color lines with respect to the sun light lamp (MOZOO Aquatic Plant 10W, color temperature: 7500K).
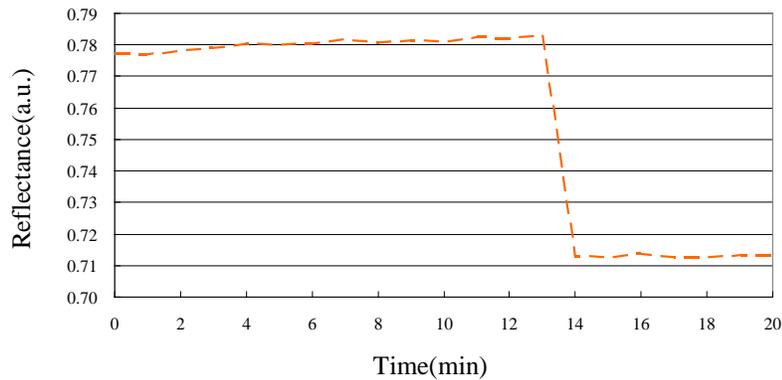

Fig. 6 Light response time chart of the pachira aquatica's leaf with respect to the sun light lamp at the incident angle of 70° indicated in Fig. 5.

Fig. 7 demonstrates the light response of the pachira aquatica's leaf with respect to a UV light lamp (SANKYO DENKI GL10). Before 1 minute, the UV light lamp was turned off. The reflectances in the SPR diagrams before 1 minute are significantly smaller than those after 2

minutes between 24° and 77°. The light response time chart at the angle of 70° as shown in Fig. 8, can be drawn from sequential SPR diagrams. The reflectances in the SPR diagrams jump up after 1 minute. The test result shows that the pachira aquatica's leaf also responds to the UV light lamp within 1 minute. The significant reflectances' difference between Fig. 5 and Fig. 7 may show the potential to measure in detail the enhancement effect of photosynthesis rate and the antagonistic effects of light on cytochrome oxidation.[4]
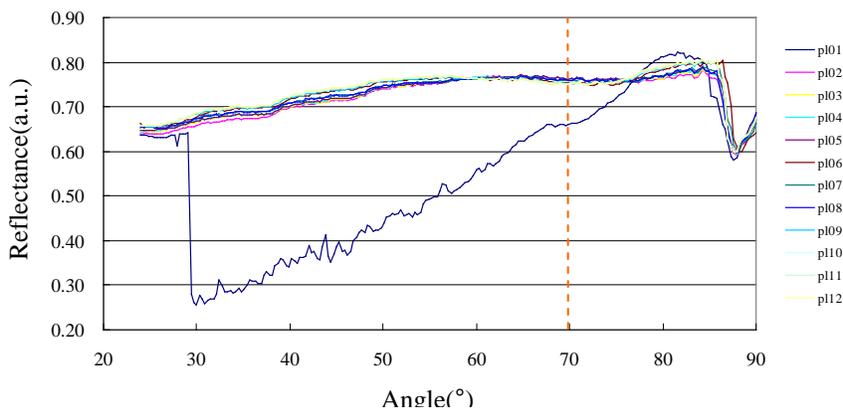

Fig. 7   Light response SPR diagrams of the pachira aquatica's leaf at different times indicated by 12 color lines with respect to the UV light lamp (SANKYO DENKI GL10).
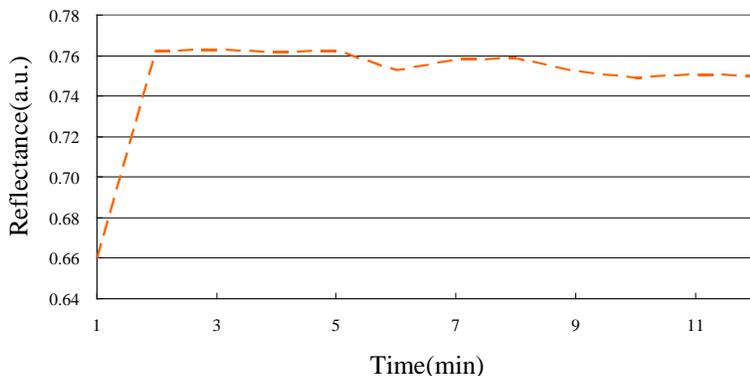

Fig. 8   Light response time chart of the pachira aquatica's leaf with respect to the UV light lamp at the incident angle of 70° indicated in Fig. 7.

Fig. 9 illustrates the light response of the pachira aquatica's leaf with respect to a red light lamp (MOZOO Chili Red 10W). Before 1 minute, the red light lamp was turned off. The reflectances in the SPR diagrams before 1 minute are greater than those after 2 minutes between 55° and 70°. To demonstrate the difference, we choose the angles of 40° and 75° respectively in the sequential SPR diagrams to draw the light response time chart as shown in the right figure of Fig. 10. The test result indicates that the pachira aquatica's leaf responds to the red light lamp within 1 minute, too. Although the reflectances in the SPR diagrams are in a tangle, we can still observe the metabolic activity under the irradiation of red light according to the reflectances' difference.
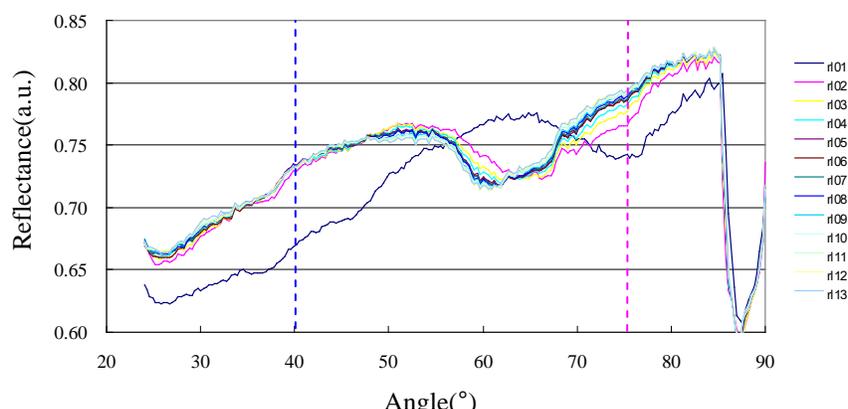
Fig. 9 Light response SPR diagrams of the pachira aquatica's leaf at different times indicated by 13 color lines with respect to the red light lamp (MOZOO Chili Red 10W).
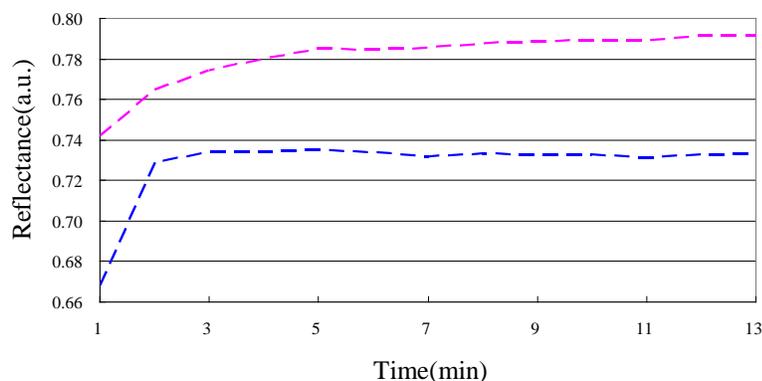
Fig. 10 Light response time chart of the pachira aquatica's leaf with respect to the red light lamp at the incident angles of 40° and 75° indicated in Fig. 9.

CONCLUSIONS

The pachira aquatica's leaf can respond to each light lamp within 1 minute investigated by utilizing a surface plasmon resonance (SPR) based sensor technique by angular interrogation method. The light response of pachira aquatica's leaf drawn from sequential SPR signals demonstrates that the reflection mode can be an alternative way to probe the biological behavior of plant, and SPR may become a powerful tool to detect the light response for study of plant physiology in future.

ACKNOWLEDGMENTS

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