Quantum Electronics **51** (10) 947–952 (2021)

https://doi.org/10.1070/QEL17630

Simulation of interaction of polarised laser light with plant leaves

Yu.N. Kulchin, A.A. Sergeev, Yu.A. Zinin,
D.O. Gol'tsova, S.O. Kozhanov, E.P. Subbotin

Abstract. **An optical model is proposed to describe the features of interaction of polarised laser light with plant leaves. It is shown that the epidermal layer of plant leaves has optical anisotropy that arises during their development. This anisotropy can serve as an important factor determining the peculiarities of interaction of polarised laser light with biomolecules, proteins and enzymes contained in plant leaf cells, which are characterised by isomerism of physical and chemical properties. The proposed model is verified experimentally.**

Keywords: *polarised laser light, epidermis anisotropy, plant leaves, interaction model.*

1. Introduction

Light is one of the most important factors in plant development: it regulates the processes of photosynthesis, morphogenesis, metabolism, gene expression, and other physiological and biochemical reactions. As a rule, when describing the processes affecting plant growth, such characteristics of light as intensity, spectral composition, and photoperiod are considered. In practice, however, the situation turns out to be more complicated. Today, when special attention is paid all over the world to the development of controlled agriculture based on the widespread use of LED lighting, it is necessary to take into account other quantitative and qualitative characteristics of radiation. These include the achieved the powers of photosynthetically active radiation, the dynamics of changes in the intensity and spectrum of the illuminating light, its coherence and polarisation, and the direction of illumination. It is these unique characteristics, absent in ordinary sunlight, which have proven to be available using laser and LED light.

In a number of papers, attention was drawn to the effect of radiation polarisation on the development of plants [1, 2], but no detailed study of the process of interaction of polarised light with plants has been carried out. The aim of this work is to simulate the interaction of polarised laser light with the epidermal cell system of plants.

Yu.N. Kulchin Institute of Automation and Control Processes, Far Eastern Branch, Russian Academy of Sciences, ul. Radio 5, 690041 Vladivostok, Russia; Far Eastern Federal University, Ayaks village 10, Russky Island, 690922 Vladivostok, Russia;
A.A.Sergeev, Yu.A. Zinin, D.O. Gol'tsova, E.P. Subbotin Institute of Automation and Control Processes, Far Eastern Branch, Russian Academy of Sciences, ul. Radio 5, 690041 Vladivostok, Russia;
e-mail: s.e.p@list.ru;
S.O. Kozhanov Far Eastern Federal University, Ayaks village 10, Russky Island, 690922 Vladivostok, Russia

Received 12 July 2021
Kvantovaya Elektronika **51** (10) 947–952 (2021)
Translated by V.L. Derbov

2. Model and optical properties of the epidermis of plant leaves

The modern cell theory is based on the unity of the division of multicellular organisms into cells and the integrity of the organism, based on the interaction of cells [3–5]. The shape and size of plant cells varies greatly and depends on the position of the cells in the plant body and the functions they perform. In higher plants, the size of the parenchymal cells that make up the tissues of leaves and flowers is usually within the range of 10–100 μm [6].

In the cells of adult plants, three main parts can be distinguished: the cell membrane, the protoplast, and the vacuole. The cell membrane is usually colourless and transparent, easily transmits light, and water and dissolved low-molecular substances can move over it [7]. The cell membrane consists mainly of polysaccharides, proteins, mineral salts, lignin, pigments, cellulose microfibrils and other substances. The thickness of the plant cell membranes varies widely depending on the function of the cells and their age and can be more than 10 μm, filling a significant part of the cell volume. The refractive index of the cell membrane of plant leaves varies within the range 1.40–1.50 [8–11].

The main component of the cell, which determines its functioning as an elementary biological system, is the protoplast, which consists of the cell nucleus and cytoplasm [12]. The chemical composition of the protoplast is very diverse and constantly changes in the process of life. Its main components are constitutional substances (proteins, nucleic acids, lipids, carbohydrates, mineral salts, and water) and ergastic substances (storage substances and waste). The content of vacuoles – the cell sap – is an aqueous solution of carbohydrates, proteins, amino acids, organic acids and their salts, mineral ions, alkaloids, glycosides, pigments, tannins, etc. In this regard, the refractive index of the internal contents of the cell can vary within a wide range from 1.34 to 1.42 [13–15].

The structure of a plant leaf is closely related to the functional characteristics of its constituents. As a rule, it consists of three layers (Fig. 1a) [16]. Above and below, the leaf is coated with a transparent layer of the epidermis, which protects it from damage and drying out. Usually, the epidermis consists of a single layer of cells that secrete a wax-like cuticle that covers the leaf surface and protects it from water evaporation. Below is a layer of columnar parenchyma formed by cells of a prismatic shape – the main photosynthetic cells of the leaf, which contain many chloroplasts. Even below is the

spongy parenchyma, consisting of cells of irregular shape that are loosely adjacent to each other with a small amount of chloroplasts and the vascular system in the form of conducting bundles (veins).

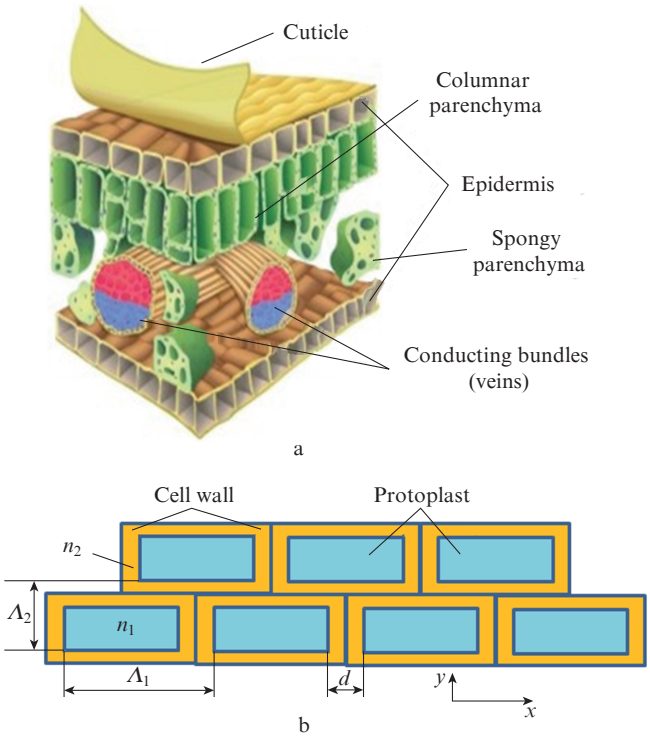

Figure 1. (Colour online) (a) Plant leaf structure and (b) optical model of the multicellular epidermis of plant leaves (top view).

The interactions between incident radiation and plants are extremely complex due to the variety in the size, shape, composition and arrangement of cells, leaves, stems, and the plants themselves in ecosystems. However, almost all of these interactions can be grouped into three types: absorption, reflection and transmission of light.

Currently, a number of models have been proposed to describe the optical properties of plant leaves (optical models) [17, 18]. However, none of them is perfect, especially for describing the interaction of plants with polarised light.

The absorption of light by plants is associated with its interaction with pigments, water and other biological components contained in plant cells. The efficiency and features of light absorption are due to changes in electronic energy states or changes in the vibrational or rotational characteristics of molecules, determined by the composition and topological features of their structure [19, 20].

Light incident on a plant leaf primarily interacts with the air-cuticle-epidermis interfaces. The light reflected from the surface of the leaf usually changes insignificantly in spectral composition. In addition, the reflected light is polarised, which is used in remote sensing to obtain information about the fine features of the leaf surface and the species composition of communities in plant crops [21]. In the absence of noticeable amounts of wax on the surface of the leaf, the epidermis layer plays a decisive role in the reflection of light, which, due to the peculiarities of the structure of its cells, is able to influence the radiation passing into the leaf.

The authors of Ref. [22] investigated the polarisation of solar radiation reflected from the surfaces of flowers and leaves of the plant *Campsis radicans* at angles exceeding 45° with respect to the normal. It was shown that the reflectivity of leaves is highest in the blue and green ranges of the spectrum. Depending on the orientation, the leaves of *Campsis radicans* reflected partially polarised light with a degree of polarisation Δ from 10% to 80%, with s-polarised radiation predominating.

The problem of how plant organs reach their final shape is central and still unresolved in biology [23]. At present, the concept of a mechanical feedback between the polarity of deformation of epidermal cells and the maximum tensile mechanical stress in the epidermis during leaf growth, when cells divide and reorganise, is being developed. In this case, the development of a complex shape of epidermal cells provides an effective strategy for reducing mechanical stress in its cell wall, which is caused by the action of turgor pressure [24–26]. As shown in Ref. [26], as a result of mechanical stretching, the tissue environment of the plant leaf changes, giving rise to response changes in the polarity of cell deformation, which determines the orientation of cell and tissue growth. In this case, the central part of the leaf epidermis cells has a predominantly co-directional directory of cell deformation polarity, which rotates when approaching the leaf edges [26]. Thus, a consequence of the directed deformation of epidermal cells caused by their mechanical stretching during growth is the difference in the optical characteristics of the plant leaf in the longitudinal and transverse directions.

All of the above allowed us to propose an optical model for the epidermis layer of plant leaves (Fig. 1b). This model takes into account the codirectional orientation of epidermal cells and the anisotropy of cell elongation, as a result of which their size in the longitudinal direction (along the x axis) Λ_1 exceeds the size in the transverse direction (along the y axis) Λ_2. The thickness of the cell shell is $d/2$. As noted above, the refractive index of the inner cell content (cytosol) n_1 depends on the composition of its protoplast and can vary from 1.34 to 1.42, and the refractive index of the cell membrane n_2, which depends on the type and age of the cell, can vary within 1.40–1.50. The stretching anisotropy of epidermal cells determines the anisotropy of its refractive index and the entire layer of the epidermis of the plant leaf. According to the proposed model and works [27, 28], the values of the refractive indices of epidermal cells for the light polarised along the x and y axes can be defined as

$$n_x = \left[n_1^2 + (n_2^2 - n_1^2)\frac{d}{\Lambda_1}\right]^{1/2}, \quad (1)$$

$$n_y = \left[n_1^2 + (n_2^2 - n_1^2)\frac{d}{\Lambda_2}\right]^{1/2}. \quad (2)$$

The cell size of the epidermis of plant leaves can vary within 10–300 μm, the anisotropy of cell deformation can reach 10%–30%, and the thickness of the cell membrane (depending on the type of plant and its age) can be from 5% to 30% of the longitudinal cell size. As a result, taking into account the range of changes in the refractive indices n_1 and n_2, using expressions (1) and (2), it can be shown that the anisotropy of the refractive index of the epidermal layer of the cell leaf $\delta n = n_y - n_x$ is in the range 0.002–0.07. Thus, the epidermal layer of a plant leaf has a natural optical anisotropy, which can change

during plant development due to changes in the optical and geometric parameters of its cells. Apparently, this determines the features of the interaction of polarised laser light with plants, in which optical isomerism is characteristic for such important groups of biomolecules as proteins, DNA, RNA, enzymes, antibodies, hormones, etc. In the basic metabolism of all living beings, only one of the two possible optical isomers is always involved [29]. As a result, the conformation of organic biomolecules plays an extremely important role in many biochemical processes, and therefore the ability of the epidermis layer to rotate the plane of polarisation of laser radiation passing through it makes the process of interaction of laser light with plant cells more efficient.

Using Ref. [30] and Eqns (1), (2), we can obtain expressions for the reflection coefficients of light waves polarised in the plane of incidence and perpendicular to it:

$$R_{\parallel} = \left| \frac{n_0 \sqrt{n_x^2 - (n_0 \sin\theta_i)^2} - n_x^2 \cos\theta_i}{n_0 \sqrt{n_x^2 - (n_0 \sin\theta_i)^2} + n_x^2 \cos\theta_i} \right|^2, \quad (3)$$

$$R_{\perp} = \left| \frac{n_0 \cos\theta_i - \sqrt{n_y^2 - (n_0 \sin\theta_i)^2}}{n_0 \cos\theta_i + \sqrt{n_y^2 - (n_0 \sin\theta_i)^2}} \right|^2, \quad (4)$$

where n_0 is the refractive index of the environment surrounding the leaves, and θ_i is the angle of light incidence on the leaf surface with respect to the normal (Fig. 2).

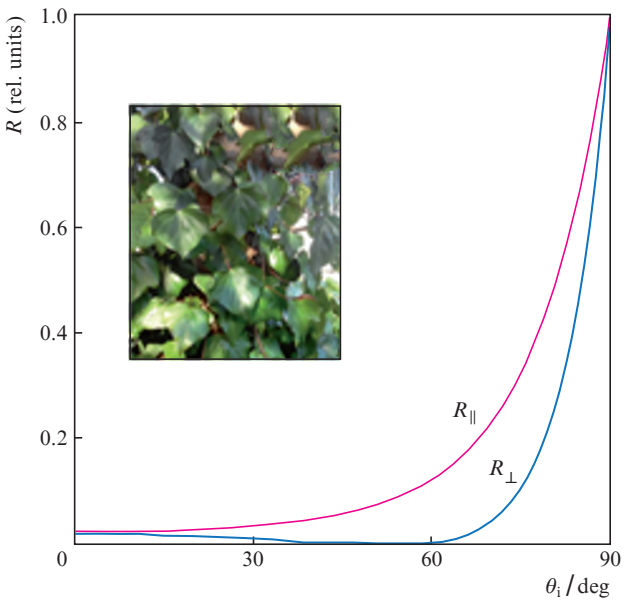

Figure 3. (Colour online) Calculated angular dependences of the reflection coefficients of light waves $R_{\parallel}$ and $R_{\perp}$, polarised in the plane of incidence and perpendicular to it, respectively. Inset: a photograph of the *Hedera maroccana* plant illustrating the dependence of the efficiency of solar radiation reflection by leaves on their orientation with respect to the Earth's surface.

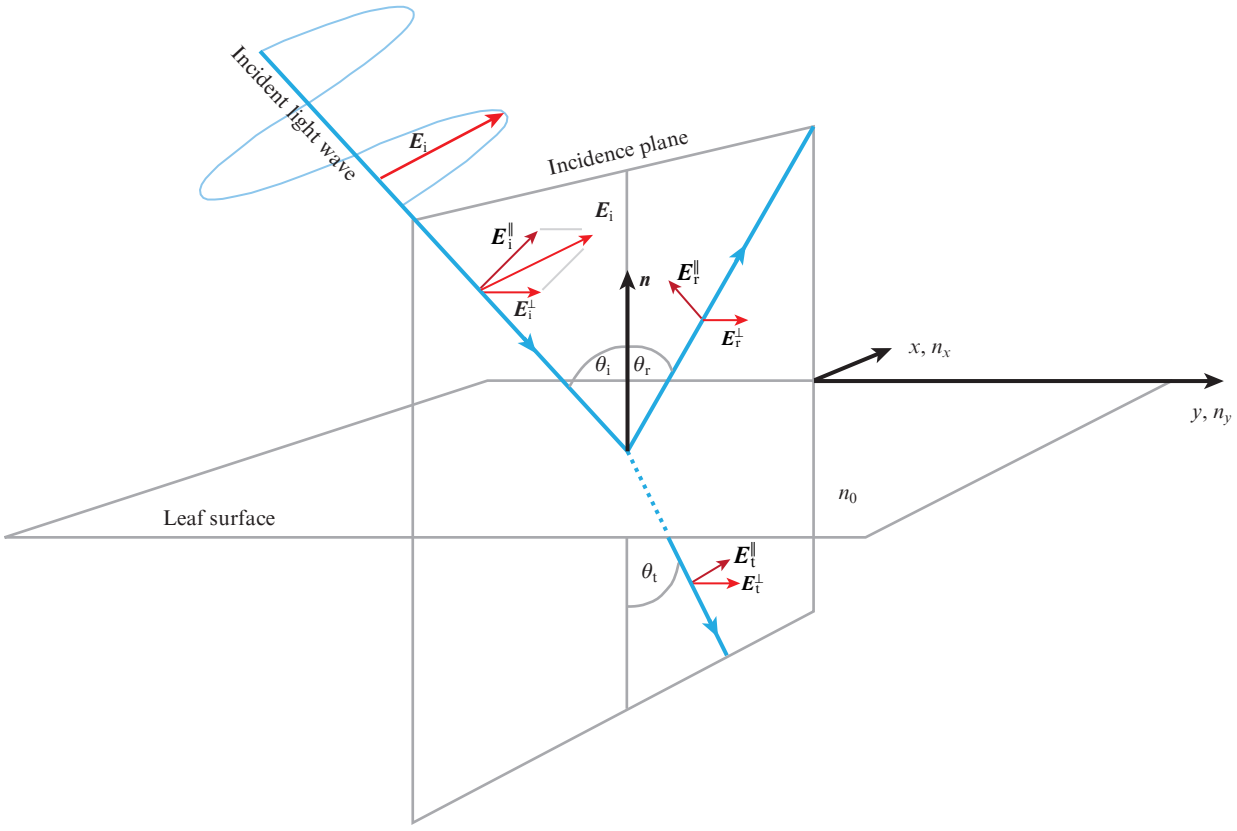

Figure 2. Schematics of the light wave incidence on the leaf surface: ***n*** is the normal vector to the leaf surface; $\boldsymbol{E}_i$, $\boldsymbol{E}_r$, and $\boldsymbol{E}_t$ are the electric field strengths of the incident, reflected and transmitted waves, respectively; θ_i , θ_r , and θ_t are the angles between the directions of propagation of the corresponding waves and the normal; x and y are the coordinate axes coincident with the anisotropy axes of refractive indices n_x, and, n_y; and n_0 is the refractive index of the environment.

Figure 3 shows the dependences of the reflection coefficients of light waves polarised along the x and y axes, calculated using Eqns (3), (4), on the incidence angle for $n_0 = 1.0$ and the averaged parameters of plant leaf cells: $n_1 = 1.34$, $n_2 = 1.46$, $\Lambda_1 = 50$ μm, $\Lambda_2 = 45$ μm and $d/2 = 5$ μm. The inset to Fig. 3 shows a photograph illustrating the dependence of the efficiency of reflection of solar radiation by the leaves of the *Hedera maroccana* plant on their orientation with respect to the Earth's surface and to the observer.

As follows from Fig. 3, taking into account the directory of anisotropy of epidermal cells [24–26], plant leaves should exhibit anisotropy upon reflection of s- and p-polarised light. Using the above physical parameters of epidermal cells and expressions (3), (4), under the assumption that $n_0 \approx 1$, it can be shown that in the solar radiation reflected from the horizontally oriented surface of the epidermis layer in the range of angles 40°–60°, the s-polarised light will dominate, and the maximum degree of polarisation will exceed 70%. The results obtained are in good agreement with the data on the polarisation of solar radiation reflected from the leaf surface of the *Campsis radicans* plant [20], as well as with the data from review [31], which presents the results of measuring the optical characteristics of 30 types of plants.

3. Experimental results and discussion

The study of the interaction of polarised laser light with the epidermis of plant leaves was carried out using a setup, whose optical scheme is shown in Fig. 4. The radiation of a He–Ne laser (*1*) with a wavelength of 632.8 nm was collimated by a lens system (*2*, *3*) to a beam diameter of 5 mm. A Fourier lens (*5*) with a focal length $F = 50$ mm focused the beam on the matrix of a CCD camera (*8*) (Nikon D7100, Japan). The mount with the sample under study (*6*) was placed behind the exit plane of the Fourier objective. A polariser (*4*) was used to control the power of polarised laser radiation, and an analyser (*7*) was used to analyse the optical activity of epidermal samples.

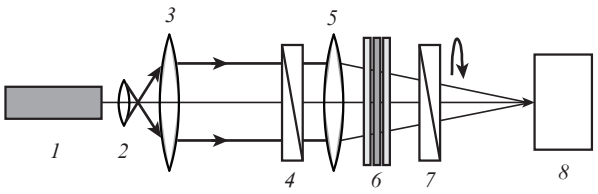

Figure 4. Optical layout of the experimental setup: (*1*) laser; (*2*, *3*) collimating lenses; (*4*) polarising filter; (*5*) Fourier lens; (*6*) test sample; (*7*) analyser; (*8*) CCD camera/polarimeter.

In practice, it is extremely difficult to separate the epidermal layer from the underlying leaf cells without mechanical damage, which made it necessary to find a convenient model to measure the degree of anisotropy of the epidermis optical properties. In this regard, the adaxial epidermis of onion scales was chosen as a model to study the optical properties of the epidermis of plant leaves. Onion epidermis consists of a single layer of thin-walled epidermal cells that are weakly attached to the underlying parenchyma. This makes it easy to isolate the epidermis layer without damaging its cells and without the occurrence of additional mechanical stress. For studies, a segment of the epidermal strip of an onion with a size of 10 × 10 mm was placed between two cover slips 2 mm thick.

Figure 5 shows a photograph of the adaxial epidermis of onion scales obtained using an electron microscope (Hitachi TM1000, Japan). The cells of the epidermal layer are clearly visible, the average size of which is 100–350 μm in the longitudinal direction and ~60 μm in the transverse direction, and the average thickness of the cell walls is ~6 μm, which is con-

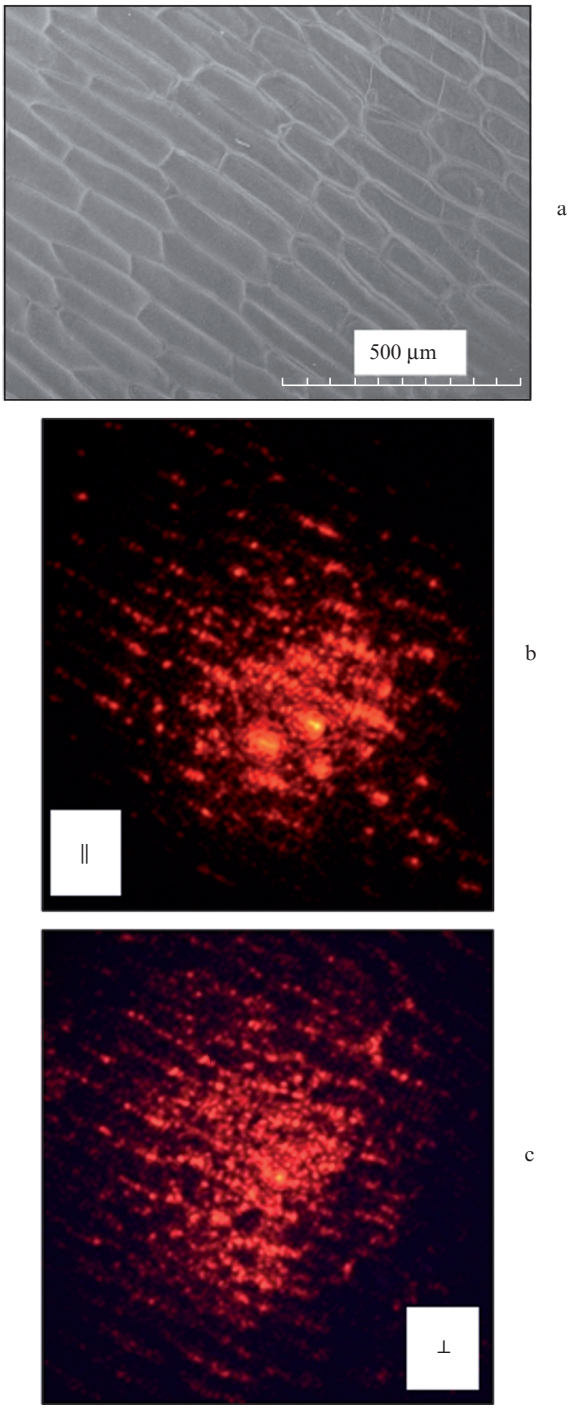

Figure 5. (Colour online) (a) Photograph of the epidermal layer of the onion skin obtained with an electron microscope, as well as (b, c) Fourier spectra of the polarised laser light after passing through the epidermal layer of the onion skin with the analyser orientations (b) co-directed with the laser light polarisation and (c) orthogonal to it.

firmed by the data of Ref. [32]. The average thickness of the epidermis layer, measured using an ellipsometer (Ellipse-1891 SAG, Russia), was 15 μm. The observed regular stacking order of cells in the epidermal layer of onion scales with different refractive indices in mutually perpendicular directions determines the presence of periodic diffraction reflexes in the intensity distribution in the focal plane of the Fourier lens (Figs 5b, 5c), which corresponds to the optical model of the plant leaves epidermal layer adopted by us. In the experiments, no complete weakening of the intensity of the Fourier spectrum of the sample of the epidermal layer was observed when the orientation of the analyser changed from co-directional to orthogonal with respect to the polarisation of laser light (Figs 5b, 5c), which also confirms the presence of optical anisotropy in the epidermal layer.

To determine the optical activity of the onion skin epidermal layer, the value of the ellipticity angle η of the polarisation of the laser light transmitted through the sample was investigated as a function of the angle of rotation ϕ of the x axis. The measurements were carried out using a polarimeter (PAX5710Thorlabs, USA), which was installed instead of the CCD camera (see Fig. 4). The results of measurements performed for the passage of linearly polarised laser light through the cover slip system in the presence and in the absence of an epidermal film between them are shown in Fig. 6.

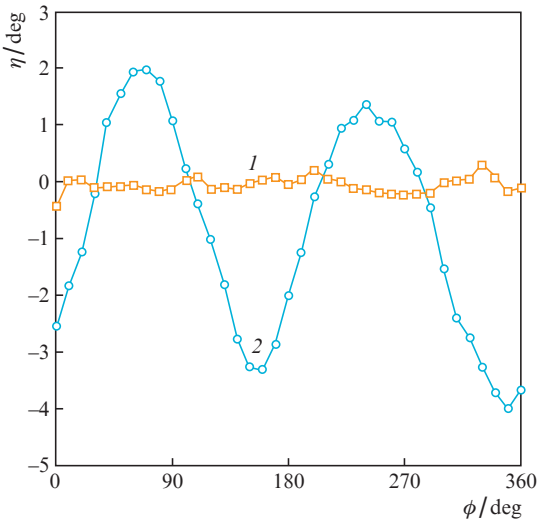

Figure 6. Ellipticity angles η of the polarisation of initially linearly polarised laser light passed through the sample as a function of the x axis rotation angle ϕ (*1*) without and (*2*) with an epidermal film of onion scales between the cover slips.

As follows from Fig. 6, when the laser radiation passes through the cover slip system, the state of its polarisation does not change. When an onion scales sample is placed between the cover slips, a rotation of the light polarisation plane is observed, the magnitude of which depends on the orientation of the sample. The transmitted light remains linearly polarised when upon the sample rotation, the polarisation plane of the laser light coincides with the x or y axis. Otherwise, the transmitted light turns out to be elliptically polarised. The results of polarimetric measurements showed that the average value of the anisotropy of the refractive index δn for the epidermal film of the onion scale is ~ 0.0002, i. e., for the epidermal cells of the onion scale film, the difference in refractive indices between the materials of the cell wall and its protoplast is insignificant. As a rule, the data presented in publications for the values of the refractive indices of the elements included in plant cells have a rather wide scatter [8–15]. Considering that the material of onion epidermis cell walls consists mainly of cellulose microfibrils built into the polysaccharide matrix, and the protoplast of its cells is represented mainly by cytoplasm and organelles, according to Ref. [11], it can be assumed that for epidermal cells of onion scales $n_1 = 1.39$ and $n_2 = 1.4$. Taking into account the practically observed variation in the longitudinal dimensions of the epidermal cells of onion scales and expressions (1) and (2), we find that the calculated values of the anisotropy of the refractive index can be in the range of 0.0008–0.0016, and this is quite close to the experimentally obtained value.

4. Conclusions

The results of our studies confirm our assumption that the multicellular epidermis of plant leaves has optical anisotropy, which is due to the anisotropy of stretching of epidermal cells that occurs during leaf growth. The proposed optical model for the leaf epidermis layer makes it possible to clarify the nature of the interaction of polarised laser light with plants. According to this model, polarised laser light changes the state of polarisation when reflected by the epidermal layer of the leaf or passed through it. As shown by the experiments with model samples of the epidermal layers of onion scales, the change in the light polarisation is significant. This suggests that the optical anisotropy of the epidermal layers of plant leaves is an important factor explaining the practical features of the effect of polarised laser light on plant development, associated with the interaction of laser light with biomolecules, proteins and enzymes contained in plant leaf cells, which are characterised by isomerism of physical and chemical properties.

References

1. Macht D.I. *J. Gen. Physiol.*, **10**, 41 (1926).
2. Shibayev P., Pergolizzi R. *Int. J. Botany*, **7**, 113 (2011).
3. Vasiliev A.E., Voronin N.S., et al. *Botanika. Anatomiya i morfologiya rastenii* (Botany. Anatomy and Morphology of Plants) (Moscow: Prosveshchenie, 1988).
4. Chentsov Yu.S. *Vvedenie v kletochnuyu biologiyu* (Introduction to Cell Biology) (Moscow: Akademkniga, 2004).
5. Vorotnikov V.P., Chkalov A.V. *Osobennosti rastitel'noi kletki: Uchebno-metodicheskoe posobie* (Features of the Plant Cell: A Tutorial) (Nizhny Novgorod, Nizhny Novgorod State University, 2010).
6. Moghaddam P.R., Wilman D. *J. Agricultural Science*, **131**, 59 (1998).
7. Alberts B., Johnson A., Lewis J., Raff M., Robert K., Walter P. *Molecular biology of the cell* (New York: Garland Science, 2002).
8. Shackelford J.F. *Introduction to Materials Science for Engineers* (New York: McGraw-Hill, 2000).
9. Landry V., Alemdar A., Blanchet P. *Forest Products J.*, **6** (2), 104 (2011).
10. Lehmuskero A., Chauton M.S., Boström T. *Progress in Oceanography*, **168**, 43 (2018).
11. Tamada Y., Murata T., Hattori M., Oya S., Hayano Y., Kamei Y., Hasebe M. *Int. J. Optomechatronics*, **8**, 89 (2014).
12. Atabekova A.I., Ustinova E.I. *Tsitologiya rastenii* (Plant Cytology) (Moscow: Agropromizdat, 1987).
13. Hassani H., Kreysing E. *Opt. Lett.*, **44** (6), 1359 (2019).
14. Liu P.Y., Chin L.K., Ser W., Chen H.F., Hsieh C.-M., Lee C.-H., Sung K.-B., Ayi T.C., Yap P.H., Liedberg B., Wang K., Bourouinaj T., Leprince-Wang Y.J. *Lab Chip*, **16**, 634 (2016).

15. Choi W., Fang-Yen C., Badizadegan K., Oh S., Lue N., Dasari R.R., Feld M.S. *Nat. Methods*, **4**, 717 (2007).
16. Lotova L.I. *Botanika: Morfologiya i anatomiya vysshikh rastenii* (Botany: Morphology and Anatomy of Higher Plants) (Moscow: Komkniga, 2007).
17. Kumar R., Silva L. *Reflectance Model of a Plant Leaf* (West Lafayette, Purdue University, 1973) LARS Technical Reports, paper 17.
18. Jaquemoud S., Ustin S. *Proc. 8th Int. Symp. Phys. Measurements & Signatures in Remote Sensing* (Aussois (France), 2001, CNES) p. 223.
19. Carter G.A., Knapp A.K. *Amer. J. Botany*, **88** (4), 677 (2001).
20. Sidorova A.E., Malyshko E.V., Kotov A.R., Levashova N.T., Ustinin M.N., Tverdislov V.A. *Bull. RAS: Phys.*, **83**, 91 (2019) [*Izv. Ross. Akad. Nauk. Ser. Fiz.*, **83** (1), 100 (2019)].
21. Vogelmann T.C. *Annu. Rev. Plant Physiol. Plant Mol. Biol.*, **44**, 231 (1993).
22. Horváth G., Gál J., Labhart T., Wehner R. *J. Experimental Biology*, **205**, 3281 (2002).
23. Baluska F., Wojtaszek P., Volkmann D., Barlow P. *Bio Essays*, **25**, 569 (2003).
24. Abley K., Barbier de Reuille P., Strutt D., Bangham A., Prusinkiewicz P., Marée A.F.M., Grieneisen V.A., Coen E. *Development*, **140**, 2061 (2013).
25. Hervieux N., Dumond M., Sapala A., Routier-Kierzkowska A.-L., Kierzkowski D., Roeder A.H.K., Smith R.S., Boudaoud A., Hamant O.A. *Current Biology*, **26**, 1019 (2016).
26. Bringmann M., Bergmann D.C. *Current Biology*, **27**, 877 (2017).
27. Rytov S.M. *Zh. Eksp. Teor. Fiz.*, **29** (5), 605 (1955).
28. Tuchin V.V. *J. Biomed. Opt.*, **21** (7), 071114 (2016).
29. Smirnova I.G., Gildeeva G.N., Kukes V.G. *Moscow University Chem. Bull.*, **53** (3), 147 (2012) [*Vestnik MGU. Ser. Khim.*, **53** (3), 147 (2012)].
30. Born M., Wolf E. *Principles of Optics* (Oxford, London, Edinburgh: Pergamon Press, 1965).
31. Gausman H.W., Allen W.A. *Plant Physiol.*, **52**, 57 (1973).
32. Slikboer E., Ana Sobota A., Garcia Caurel E., Guaitella O. *Sci. Rep.*, **10**, 1358 (2020).