Change in the coherence of light scattering from the surface of apples and their transpiration during storage

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Abstract. The potential possibility of using coherent optics for non-destructive testing to modify the microstructure of the surface of apples under the influence of chemical factors was studied. The model objects included solar and shade sides of fruits of Antonovka Common variety, untreated (control) and treated with diphenylamine (DPA). The amplitude-phase parameters of laser radiation reflected from the fruit surface were evaluated using a polarization shearing interferometer. It was experimentally shown that by the intensity and degree of coherence of the reflected laser radiation of the surface of apples, it is possible to register the anatomical and morphological characteristics of their tissues. It was revealed that after two months of storage, the spatial coherence of light scattering of the shadow side of an apple is higher than that of the solar, and the surface of apples treated with diphenylamine has a higher coherence of light scattering of the surface of both the solar and shadow sides. It was shown that the transpiration of apples treated with diphenylamine exceeds the transpiration of control apples.

1. Introduction
The most important task in the production and storage of apples is to ensure their quality, which is determined, among other things, by appearance. One of the physiological disturbances of apples is the browning (tanning) of skin during storage. The nature of this phenomenon has not yet been determined, so research should be carried out to clarify the causes of this. It was previously established \cite{1} that the most important methodological technique when studying the ripening of apples is their separation into solar and shadow sides. This technique revealed a new phenomenon in which tanning never develops on the solar side of green apples \cite{2}.

Browning appears only on the shadow side of apples. These studies are aimed at obtaining a non-destructive method to monitor the state of the surface structure of the skin of apples, which will contribute to the study of the browning nature.

Few publications in this field confirm the possibility of using deterministic and non-deterministic interferometry methods to solve this problem \cite{3,4,5}. This paper is devoted to the analysis of the potential of polarization interferometry for non-destructive testing to modify the microstructure of the surface of apples under the influence of physical or chemical factors.
2. Materials and methods
Fruits of Antonovka variety were taken from trees in the garden on August 31, 2020. One batch of apples in the amount of 15 pieces was determined as control, another batch in the amount of 15 pieces was treated with 0.5% diphenylamine (DPA) solution by spraying. Diphenylamine is used as an agent to protect apples from browning. The amplitude-phase parameters of light scattering of laser radiation were measured one hour after treatment and drying on solar and shadow sides of apples. Measurements of apple transpiration by weight were also carried out.

Control apples and apples treated with diphenylamine were stored in a refrigeration chamber at T=3-4°C and HR=85-90%. During storage, the apples were removed from the chamber three times: September 18, October 16 and December 24, and were kept at T=18-2 °C for two hours to dry from condensate prior to optical measurements. After measurements, the apples were put back for storage. At the same time, the apple transpiration by weight was measured.

The amplitude-phase parameters of laser light scattering were estimated using a polarization interferometer with the following laser beam parameters: wavelength – 650 nm, power – 2.6 mW, beam diameter – 1.5 mm. The real-time image was processed by a specialized computer program and the following parameters were determined: G, % – degree of spatial coherence of light scattering reflecting the microstructural features of surface tissues; I, AU – average intensity of light scattering defined as the average intensity of the entire interference pattern [6].

3. Results of optical measurements of light scattering of apple surfaces
During ripening while storage the microstructure of the skin and pulp of apples changes (the volume of cells increases and the content of cell juice and starch in them changes; the middle plates are loosened, the volume of intercellular space increases), which causes a connection between the ripeness of fruits and the degree of spatial coherence of the optical flow reflected from their surface. This is most clearly seen in the analysis of optical measurements of solar and shadow sides of the fruit immediately after it was taken from a tree (Table 1), from which it follows that the shadow side of apples has a lower intensity of light scattering and a higher degree of coherence of light scattering. The solar side has higher hardness, on average, the hardness of the solar side of an apple during ripening in the garden exceeds the shadow one by 0.5 kg/cm^2. At the same time, the solar side may be considered as the more mature side of an apple compared to the shadow side: it undergoes more intensive hydrolysis of starch, less chlorophyll is contained and the tissues have denser cell arrangement. Since the laser beam “captures” several millimeters of a layer of pulp adjacent to the skin, they make a specific contribution to the specifics of light scattering. As it is known, the concentration of chlorophyll absorbing light in the red region is higher on the shadow side of fruits [2, 7] and this is associated with lower light scattering intensity. The explanation of lower light scattering coherence of the solar side requires more detailed study. More than twice the variance of the coherence values of the solar side of apples may characterize these sides as more uniform.

| Option       | Solar side | Shadow side |
|--------------|------------|-------------|
| Indicator    | I, AU      | G, %        |
| Average      | 50.28      | 5.70        | 43.94 | 9.06 |
| Error        | 0.52       | 0.29        | 0.50  | 0.82 |
| Minimum      | 42.72      | 3.1         | 38.72 | 4.1  |
| Maximum      | 56.04      | 8.7         | 49.89 | 21.2 |

After 2 months of storage the optical measurements of control fruits and fruits treated with diphenylamine were carried out on November 6. The coherence of light scattering from the surface of the treated fruits was higher than in the control, and the solar side, both in the control and DPA treated it was lower than the shadow one (Fig. 1). On the one hand, the starch content of fruits decreases...
during storage, and on the other hand, the middle plates loosen and the intercellular airspace increases, thereby reducing the hardness of apples during storage.

![Figure 1](image.png)

**Figure 1.** Degree of coherence of light scattering of laser radiation from the surface of apples. Shadow control – shadow side of control apples, solar control – solar side of control apples, DPA shadow – shadow side of apples treated with diphenylamine, DPA solar – solar side of apples treated with diphenylamine.

The measurements of the coherence of laser light scattering from the surface of apples during removal and storage show that the coherence after three weeks of apple storage increased, then decreased by mid-October and remained at this level until the end of December. On September 18, there was a difference in the coherence values of the control and DPA treated fruits with the coherence of reflected light in the DPA treated fruits being lower than in the control. After October 16, the coherence of fruits treated with DPA was slightly higher than in control samples, but not significantly.

**Figure 2** shows the transpiration of control and DPA treated fruits. It is apparent that the fruits treated with DPA had higher transpiration than the control samples throughout all periods of the analysis.

It was found that in apples treated with DPA the transpiration during storage was higher than in control samples, and this may indicate that the structure of the apple skin cuticle changed, and this led to increased transpiration, the skin began to pass more moisture and gases. It became more heterogeneous.

**Table 2.** Coherence (G, %) of reflected light from the surface of Antonovka apples of control fruits and apples treated with diphenylamine (DPA) during storage

|          | Control | DPA   | Error |
|----------|---------|-------|-------|
| August 31| 10.28   | 10.05 | 0.44  |
| September| 12.36   | 11.74 | 0.54  |
| October 16| 3.72   | 3.80  | 0.12  |
| December 24| 3.75  | 3.98  | 0.11  |
Figure 2. Transpiration of apples during storage. Control, DPA – apples treated with diphenylamine. Abscissa axis – measurement dates.

A significant variation in apple transpiration and the coherence of reflected light from the surface of apples shows the heterogeneity of apples in the degree of ripeness. At the same time, similar heterogeneity was observed in coherence during the first month of storage of apples in the refrigerator.

4. Conclusion
1. It was experimentally shown that by the intensity and degree of coherence of the reflected laser radiation of the surface of apples, it is possible to register the anatomical and morphological characteristics of their tissues.
2. It was revealed that after two months of storage, the spatial coherence of light scattering of the shadow side of an apple is higher than that of the solar, and the surface of apples treated with diphenylamine has higher coherence of light scattering of the surface of both solar and shadow sides.
3. It was found that in apples treated with DPA the transpiration was higher than in the control for all terms of the analysis, this may indicate that the structure of an apple skin cuticle changed, which led to increased transpiration.

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