Optica Applicata, Vol. XXXVIII, No. 2, 2008

Interference coloring of regularly scattered white light

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Interference coloring of the regular component of a polychromatic light scattered by a colorless dielectric slab with a rough surface is considered. To explain the observed alternation of colors as the depth of roughness grows, we apply the model of a transient layer associated with surface roughness, which extends the well-known analogy between the layer and a light-scattering particle. It is shown that coloring of the forward-scattered component of a white light can be interpreted as the action of a peculiar quarter-wavelength (anti-reflecting) layer for some spectral component of a polychromatic probing beam. By applying the modern chromascopic technique, we compare the coloring of the forward-scattered and the specularly reflected radiation. As the demonstration, the effect of "a blue Moon" and "a red Moon" caused by the spectral changes induced by white-light scattering at the rough surface of a colorless glass is represented. — *Natura simplex et fecunda*, A. Fresnel.

Keywords: interference, light scattering, rough surfaces, chromascope.

1. Introduction

Interference coloring is intrinsic to numerous objects of the Universe, being caused by the object's fine structure rather than by the presence of a dye in the object. That is why such colors are often referred to as the structural colors [1], and the phenomenon of the interference coloring is called *pseudochromatism* [2]. Structural coloring of the image of a white-light source is among the most beautiful and changeable optical phenomena, being at the same time one of the most difficult to interpret, especially in the case when the probabilistic character of the phenomena obscures its real sense [3].

There are generally known manifestations of interference coloring:
– Newton's rings in regular and diffuse white light [4],
– colors of thin films,
– delightful coloring of butterfly wings,

– coloring of the image reconstructed by the Denisyuk’s (reflection) hologram reconstructed in a white light due to spectral selectivity of volume diffraction gratings [5].

In most mentioned cases pseudochromatism rises from two-beam or multi-beam interference involving regular periodic structures with spacing comparable with a wavelength associated with any component of the polychromatic probing radiation.

Another class of the phenomena resulting in interference colors belongs to light scattering at irregular structures. Such phenomena are much more rare than those mentioned above, though not unprecedented. To all appearances, blue coloring of the Moon followed the eruption of Krakatoa volcano in 1883 is one of the most known and reliably documented (firstly by Lord Rayleigh, to our knowledge) examples of this kind. Moreover, the extremely rare phenomenon of blue-coloring of the Moon or of the Sun became proverbial (saying, *in a once blue moon* [6, 7]). This effect is prescribed, but rather tentatively, to light scattering by small particles, namely to scattering by the layer of (accidentally) highly monodisperse particles of volcano dust [7]. The observation of a similar effect of coloring of the forward-scattered component of a white light transmitted by hoarfrost is reported in [8]. It is worthy to note that up to now such effects were observed under uncontrolled natural circumstances alone.

Here we consider the effect of interference coloring of the image of a white-light source that is realized when radiation passes thorough a colorless dielectric slab’s rough surface whose heights of inhomegeneities are comparable with (being slightly less than) a wavelength associated with some spectral component of a polychromatic probing beam. This effect has been recently discussed as a peculiar effect of singular optics in [9], where the reader can find out the relevant early references. The main purpose of this paper is to explain the alternation of colors into the image formed through a colorless dielectric slab with a rough surface with respect to the roughness depth, which is observed in practice. The organization of the paper is as follows. In Section 2 we concisely formulate the standard interpretation of the scattering-induced spectral changes following [9] and show the main difficulty of such interpretation. Further, in Section 3, we apply the model of a transient layer associated with surface roughness [10] to the problem of interest. Both physical argumentations based on the results of polarization optics and the numerical simulation using Berry’s chromascopic technique [11] confirm the fact that the true alternation of colors at the image formed through a rough surface is determined by the properties of a transient layer as an anti-reflecting coating for some spectral components of the probing radiation. Note also that, within the context of our study, the remarkable analogy between a light-scattering particle and a layer [7] is for the first time extended fruitfully to the case of light scattering by a rough surface, what evidences the fundamental unity of the Nature. In Section 4 we present demonstrations (for the first time, to our knowledge) showing that the arresting phenomenon of “a blue Moon” or “a red Moon” can be easily realized and handled by any interested observer with the aid of improvised means. Section 5 summaries the results of our study.

2. Singular-optical interpretation of the scattering-induced spectral changes

Observing a white-light source through a colorless slightly rough surface obtained, to say, by one-sided grinding of a common window glass with corundum with a mean size of grains ~7 to 10 μm, one can notice surprisingly intense coloring of the source, which varies from turquoise to magenta. This effect cannot be explained as a result of selective absorption. Such coloring certainly has the interference origin, being closely connected with the phenomena of singular optics [12] which studies the so-called phase singularities of optical fields, viz. amplitude zeroes where the phase of the complex amplitude or the phase of any other complex parameter of the field is undetermined. In polychromatic fields, the phase singularities are associated with some spectral component. Referring to [9] for the details of preliminary interpretation of the interference (singular-optical) mechanism of the spectral changes in the forward-scattered component of a white light, one can reduce the essence of this effect as follows.

The presence of the regular component in scattered radiation implies that the heights of surface inhomogeneities *h* do not exceed the wavelength of a probing beam – here, wavelengths of all spectral components of a polychromatic beam. This key statement of our consideration means that the assumption concerning mutual incoherence of partial waves scattered by various surface inhomogeneities is violated, and the phase relations between such waves must be taken into account both for the forward-scattered and for the specularly reflected radiation, even for the case of a white-light probing beam from an extended source, when both spatial and temporal coherence is extremely low.

Note that under developed light scattering, when the regular component is absent, one can observe another coloring effect whose singular optical character is reliably proved. Namely, if a rough surface with large surface inhomogeneities is illuminated by a white-light beam and the illuminated area is small enough to provide high spatial coherence, the scattered field shows polychromatic (colored) speckles, and the phase singularities in the spectral component of such pattern can be diagnosed using edge diffraction [13, 14], interferentionally [15] or by applying a chromascope [11] and an inverted chromascope [16].

A simple uniform distribution of the heights of surface inhomogeneities $p(h) = H^{-1}$ is a proper approximation for representing a slight roughness [10], whose irregularities are almost monodisperse, due to the limiting character of a delta-function. Note that the principal result of our consideration, viz. interference coloring of the image of a white-light source caused by light scattering at the rough surface, is not changed, when one takes another height distribution function [17]. But the uniform height distribution function, being of course an idealized one, provides at this stage of our considerations the intuitive interpretation of the phenomena of interest as the singular optical effect. The corresponding spectral modifier [9] governing the spectral changes in the forward-scattered component is of the form $\mathrm{sinc}\,x = \sin x/x$, where

$x = [\pi(n - n_0)H]/\lambda = [\pi(n - n_0)\sqrt{12}\,\sigma]/\lambda$, n and n_0, being refraction indices of a glass and the environment, respectively, and σ being a root-mean-square deviation of the surface profile from a mean surface line associated with the uniform distribution. (Note that from now on we neglect dispersion, namely the dependence of the refraction index n in the dielectric slab on the wavelength over the visible range; taking into account the dispersion results in negligibly small correction of the magnitudes of the governing parameters.) When a sinc-function approaches zero (viz., undergoes a phase singularity and changes its sign crossing the corresponding amplitude zero) for any λ_z, its magnitude becomes small over more or less large spectral domain also adjacent to this wavelength. In this way, the entire normalized spectrum of the forward--scattered radiation is considerably modified, and complementary (with respect to λ_z) color, λ_p, with the adjacent spectral domain prevails in the observed image. Thus, one can observe more or less intense (though always mixed, not pure) colours of the forward-scattered radiation.

Let us note that the considered here amplitude zeroes are associated with the strength of scattering [9] for some spectral component of a polychromatic radiation, rather than with a common complex amplitude of a free-propagating monochromatic stationary scattered field, such as speckle-fields produced by stationary scattering of a laser beam at a rough surface with large surface inhomogeneities. In the last case, one observes isolated optical vortices [12] penetrating a speckle field and manifesting themselves in the three-dimensional space as the so-called snake-like distortions of a wave front [18]. In contrast, the amplitude zero of the strength of scattering of the specified spectral component of a polychromatic radiation manifests itself as a non-localized (at the plane of observation), infinitely extended colored interference fringe. The closest (but not literal) analogue of this phenomenon is the so-called interference structure of the extinguished curve of the ensemble of light-scattering particles [7, 19].

A convincing argument in favor of the proposed interpretation of coloring of the component of a white light, which is forward-scattered at a rough surface, springs from the consideration of diffraction of a polychromatic radiation at bleached (phase-only) relief holographic gratings. It is known [5] that diffraction efficiency η_l for the l-th diffraction order of a phase hologram with a harmonic relief (including the zero order, $l = 0$) characterized by the amplitude transmittance,

$$T_g = \exp\left[iq\cos\left(\frac{2\pi}{p}x\right)\right] \equiv \sum_{l=-\infty}^{\infty} i^l J_l(q)\exp\left(il\,\frac{2\pi}{p}\,x\right) \tag{1}$$

where $q = (2\pi/\lambda)(n - n_0)H$ being the phase modulation percentage, n and n_0 being the indices of refraction of the emulsion and the air, respectively, and π being the grating's period along x-axis, equals the squared l-th order Bessel function of the first kind: $\eta_l = [J_l(q)]^2$. It is not surprising that the governing parameter for the spectral changes at the forward-diffracted component of a polychromatic radiation contains the ratio H/λ for the phase-only holographic gratings. Moreover, due to deterministic character of diffraction at such gratings, the observed coloring of the source's image occurs much more intensive than in the case of a random rough surface. What is more important, any limited area of a rough surface can be represented as the set of harmonic gratings with the amplitude transmittance

$$T_r = \exp\left[i\sum_m q_m \cos\left(\frac{2\pi}{p_m}x\right)\right] \equiv \prod_m \left[\sum_{l=-\infty}^{\infty} i^l J_l(q_m) \exp\left(il\frac{2\pi}{p_m}x\right)\right] \tag{2}$$

where $q_m = (2\pi/\lambda)(n - n_0)H_m$, so that one obtains for the forward-diffracted component in the first approximation:

$$\eta_0 = \prod_m J_0^2(q_m) \tag{3}$$

Obviously, vanishing of any factor in Eq. (3) for any lz leads to vanishing of the product as a whole for the specified wavelength. It means that for arbitrary (not uniform without fail) height distribution function, a phase singularity associated with the crossing of zero magnitude of the zero-order Bessel function of the first kind certainly takes place for some wavelength of the polychromatic probing radiation and for the corresponding term of the expansion (2). This statement implies independent confirmation of the interpretation of coloring of the forward-scattered component of a polychromatic radiation as a peculiar effect of singular optics.

Providing a conceptual background for understanding of the coloring of the forward--scattered polychromatic radiation, such model leaves nevertheless some sense of discontent. The main difficulty consists in a seeming contradiction between the observed sequence of the colours and the predictions of the general theory of light scattering [7, 19]. Namely, one observes a blue-coloured forward-scattered component for very small roughness, and a red-coloured one for increasing roughness. In contrast, as it follows from the generally-known explanation of reddening of the Sun at sunset, as well as of blue colour of a sky [2, 3, 7, 19], the strength of scattering is in inverse proportion (in some power) to the wavelength. It just means that, as the roughness increases, the scattering-induced spectral changes must manifest themselves only as a red-shift of the initial spectrum, and such reddening is accompanied by gradual attenuation of the forward-scattered component up to its disappearance. In other words, blue is “washed away” from the forward-scattered component of a polychromatic probing beam in favor of general scattering (in all other directions) earlier than red. An instructive example of this kind is given by Bohren and Huffman [7], where the well-known red shift in radiation of quasars is explained just as the result of light scattering at the particles of cosmic dust rather than as the manifestation of the Doppler effect. The same (“non-cosmological”) interpretation of the reddening of radiation of quasars is shared and is re-formulated in terms of the concept of correlation-induced spectral shifts by Wolf [20].

It occurs that computation of colors as a function of the ratio H/λ within the framework of the represented model leads to the results which are in agreement

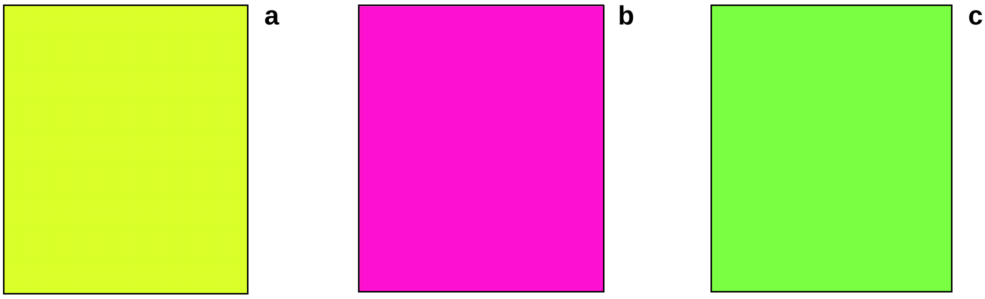

Fig. 1. Chromascopic simulation of the spectral changes of the forward-scattered component of a white light induced by a colorless glass rough surface (n = 1.52, n_0 = 1) with the uniform height distribution function of surface inhomogeneities. Fragments **a**, **b**, **c** correspond to the effective depth of roughness H = 838.1 nm, 1051.2 nm and 1346.1 nm, respectively.

with the standard theory of light scattering, being at the same time in contradiction to the observed in practice alternation of colors. So, in Figure 1 we present the results of computer simulation showing the sequence of colors of the forward-scattered component of the probing, while light-beam corresponds to the uniform height distribution function of surface inhomogeneities with the increased depth H. Our simulation is based on the chromascopic technique [11] (see explanation in Section 3). In this simulation, we use the RGB system with the basic wavelengths λ_b = 435.8 nm, λ_g = 546.1 nm and λ_r = 700 nm. Three fragments of Fig. 1 correspond to vanishing of blue, green and red. As one can see from Fig. 1, reddening of a white-light spectrum is realized firstly (for smaller magnitudes of H, *cf*. Figs. 1**a** and 1**b**), and blue shift is realized secondary (for larger magnitudes of H, *cf*. Fig. 1**c**).

3. Sequence of colors

3.1. Surface roughness as a transient layer

For an interpretation of the observed “anomal” sequence of colors induced by light scattering at a rough surface, we propose some more abstract but more general model, which does not lead out of the interference mechanism of colouring, but specifies it for the heights of inhomogeneities of a surface comparable with (but slightly less than) a wavelength associated with any spectral component of a polychromatic probing beam. There are two key ideas essential for the following consideration: *i*) the regular component of the scattered radiation is always (even in a white light) of a coherent nature, being dependent on the phase relations of partial re-scatterers [19]; *ii*) partial re-scatterers distanced by a portion of a wavelength are inevitably tied up to each other by the common field and constitute the integral oscillating system (optical re-transmitter). Namely, if the phase difference of two partial oscillators (antennas) is $\pi/2$ for some direction, than the system radiates mainly in this direction, on account of extinguishing of radiation in the opposite direction; hence, radiation in all the other directions is much weaker than in the forward direction [21].

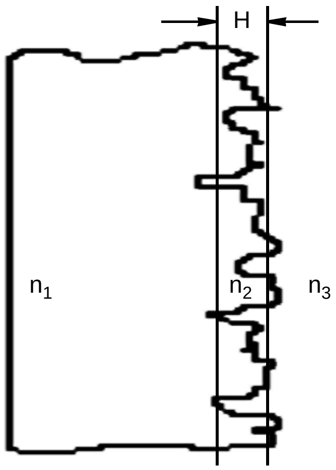

Fig. 2. Illustrating the imaginary boundary planes, $h = 0$ and $h = H$, the phase relations of which determine the scattering--induced spectral modifications in the forward-scattered component of polychromatic radiation.

The real height distribution function of inhomogeneities characterizing the given rough surface is unknown, as a rule. However, irrespective of the specific functional form of such distribution function, one can consider a surface roughness as a peculiar transient layer with the “diluted” index of refraction, *cf.* Fig. 2, whose magnitude is the geometrical mean of the indices of refraction of a glass and the air [1, 4] (of course, the effective thickness of this layer, H, depends on the real height distribution function). Thus, the analysis of the spectral modifications of the forward-scattered component of a polychromatic radiation passed through a rough surface is reduced to the problem of matching of impedances of three media [4], viz., in the context of the optical problem, of the refraction indices of a glass (n_1), a transient layer ($n_2 = (n_1 n_3)^{-1}$), and the environment (n_3). If the optical thickness of the transient layer $n_2 H$ equals $\lambda/4$, λ being a wavelength in the media with a refraction index n_2, for some spectral component of the probing beam (what certainly happens for some wavelength due to the condition $\lambda < H$ for all spectral components), this layer acts similarly to the anti-reflection coating for this component, while under the assumed relation of the indices of refraction of three media, the waves reflected from two boundaries of the transient layer are in opposite phases and interfere perfectly destructively [4]. As a result, this spectral component prevails in the forward-scattered light. Again, as in the above consideration, zero magnitude of the reflected radiation at the given λ implies considerable suppressing of the reflected light over some spectral domain adjacent to this wavelength.

Note that various heights h of surface inhomogeneities are realized at different points of the given surface. So, in reality, the imaginary boundary planes, $h = 0$ and $h = H$, are fragmentary. Nevertheless, in a far field with respect to an isolated inhomogeneity, these “porous” imaginary planes act as being continuous [1]. This statement is quite in agreement with the remarkable analogy among a light-scattering particle and a layer [7, 19], and extends this analogy, for the first time to our knowledge, to the case of a rough surface.

Proceeding from this model, for determining the color of the forward-scattered component of a white-light probing beam, one must firstly compute the relative intensity of the back-scattered (specularly reflected) light, as a function of a wavelength [4]:

$$\frac{I_r}{I_i} = 4\left[\frac{1-\sqrt{n_1}}{1+\sqrt{n_1}}\right]^2 \sin^2\left[\frac{\pi}{2}\left(\frac{\lambda_i}{\lambda_0}-1\right)\right] \tag{4}$$

(where I_r and I_i are the intensities of the reflected and the incident beams, respectively, λ_i is the specified wavelength of the incident beam within the spectral range of the probing radiation, and λ_0 is the wavelength, the amplitude of which vanishes at the reflected radiation), and then find out the relative intensity of the forward-scattered component at the same wavelength λ_i as the difference:

$$\frac{I_f}{I_i} = 1 - \frac{I_r}{I_i} \tag{5}$$

Writing Eq. (5), we neglect light scattering in all other directions. However, such approximation is reliably justified for considerably small heights of a roughness, *cf.* the estimations of the effective thickness of the transient layer below.

Before representing the results of computer simulation based on Eqs. (4) and (5), let us emphasize that adequacy of the used model of the transient layer is justified by the results of the polarization experiment. Namely, it is of interest that Brewster's angle $\varphi_B = \tan^{-1} n$ occurs to be considerably different for the cases when the probing beam incidents upon the opposite surfaces of the same one-sided grinded glass plate, one of which is optically smooth and the other is rough. Taking into account the difference of n_1 and n_2, one expects that the Brewster's angle for the rough side of a plate will be appreciably smaller than the Brewster's angle for the smooth side. So, if $n_1 = 1.52$ and $n_3 = 1$, then $n_2 \cong 1.233$. As a consequence, for a glass-air interface φ_B(smooth) is about 57°, while φ_B(rough) is about 51°. In spite of their surprising character, these estimations are quite in agreement with the experimental results.

3.2. Chromascopic technique-based computer simulation

To illustrate the sequence of colors following from the model of the transient layer, we use the novel technique of chromascopic processing of colored optical fields introduced by BERRY [11] and firstly experimentally implemented by LEACH and PADGETT [22] for observing the chromatic effects near an isolated white-light vortex.

Following [11], to reveal the colors, the RGB values of the tested field are scaled to isoluminance by the transformation:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} \Rightarrow \begin{pmatrix} R \\ G \\ B \end{pmatrix} \Big/ \max(R, G, B) \tag{6}$$

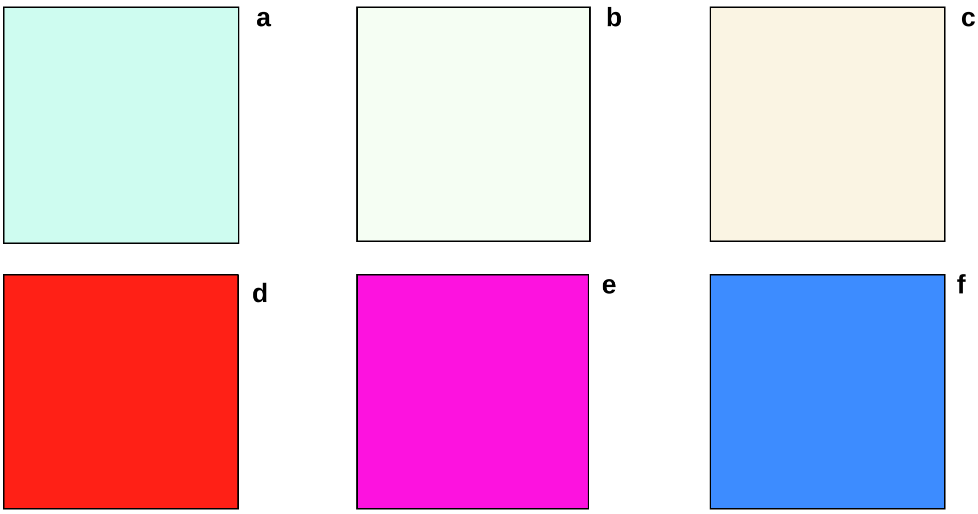

Fig. 3. Chromascopic simulation of the spectral changes of the forward-scattered component of a white light induced by a colorless glass rough surface (n_1 = 1.52, n_2 = 1.233, n_3 = 1) following the model of the transient layer.

This procedure preserves the ratios between the three RGB values while making the biggest one equal to unity. The main difference of our approach from the one realized in [11] and [21] is that we implement the chromascopic processing of an image uniform in color, rather than of the non-uniform "isolated" amplitude zero of the spectral complex amplitude, which varies linearly with the position of the point of observation and with wave number over the visible range [11]. We apply the chromascopic processing following Eq. (6) both to the specularly reflected and to the forward-scattered components of the white-light probing beam.

Figure 3 illustrates the colors of the forward-scattered component (fragments **a**, **b**, **c**) and the colors of the back-scattered (specularly reflected) component (fragments **d**, **e**, **f**) for the cases of vanishing of blue λ_b = 435.8 nm (Figs. 3**a** and 3**d**), or green λ_g = = 546.1 nm (Figs. 3**b** and 3**e**), or red λ_r = 700 nm (Figs. 3**c** and 3**f**). The pairs of fragments **a** and **d**, **b** and **e**, and **c** and **f** correspond to the effective depths of the transient layer 88.36 nm, 110.73 nm, and 141.93 nm, respectively, which are close to 0.1 of the mean diameter of the corundum used for obtaining the color effects (~10 μm). The results of simulation are in agreement with the alternation of the colors observed in the experiment. Namely, blue shift takes place for smaller depth of the transient layer, and reddening of the forward-scattered light is observed for larger depth of this layer. It is quite natural, the inverse sequence of the colors is observed in the specularly reflected light.

Let us formulate some precautions concerning the evaluation of the results represented in Fig. 3:

1. Simulation is performed for a discrete set of spectral components, while in practice one operates with continuous spectrum. That is why the represented data are

only of an instructive nature: real colors are strongly dependent on the real spectral density function of the source, so that one observes different colors induced by the certain sample of a rough surface illuminated by the sources with different color temperatures. Nevertheless, the general tendency (blue shift to the reddening of the forward-scattered component) is truly reflected by the model of transient layer.

2. The colors in the forward-scattered component and in the specularly reflected one are strongly dependent on the value of λ_0 (see Eq. (4)). Our choice of three wavelengths where the reflected beam vanishes is dictated by the considerations of comparability of the results represented in Figs. 1 and 3. Any interested reader can obtain large variety of color pictures following Eqs. (4) to (6), by changing λ_0 within the visible range of spectrum, especially at short-wavelength and long-wavelength domains. Nevertheless, the mentioned general tendency is not changed.

3. Comparing the upper and the lower rows of Fig. 3, an inexperienced observer can conclude that the intensity of colors [2] in specularly reflected radiation is much higher than in the forward-scattered component. However, this is delusion. Seeming higher intensity of colors of the specularly reflected component is the result of the normalization procedure, *cf*. Eq. (6). For that, one must take into account the fact that the colored specularly reflected component is much lower in intensity than the forward-scattered one. It follows from that for the fixed ratio H/λ, the forward--scattered radiation is governed by the multiplier $\pi(n - n_0)$ (see Section 2), while the specularly reflected component of the normally incident beam is governed by the multiplier 4π, so that the effective depth of the transient layer in reflection exceeds its effective depth in transmission (for a glass) by almost one order of magnitude. As a consequence, the relative intensity of the specularly reflected radiation is much lower (by two orders of magnitude, approximately) than the intensity of the forward-scattered component. It is clear, as the same surface, which can be regarded as slightly rough for the transmitted radiation, cannot be slightly rough for the reflected one. This is the reason, for which the observability of the colored beam specularly reflected from a rough surface was called in question earlier [8].

4. Experimental

4.1. A *blue Moon* becomes tamed

Proceeding from the conceptual background represented in Section 3, one expects that the effect of coloring of the image of a white-light source formed by the beam scattered at slightly rough surface can be observed under controlled conditions using the samples of rough surfaces prepared by a one-sided mechanical grinding of a dielectric slab.

We have performed the set of observations, the typical example of which is represented in Fig. 4. This figure illustrates the scattering-induced spectral modifications in the forward-scattered component of polychromatic light, viz. in the image of the Moon observed without (fragment **a**) and with (fragments **b** and **c**) the samples of a grinded glass positioned in front of the camera's aperture. These photos have been obtained in Chernivtsi, in March 21, 2006, from 5.00 to 5.10 a.m. The samples were

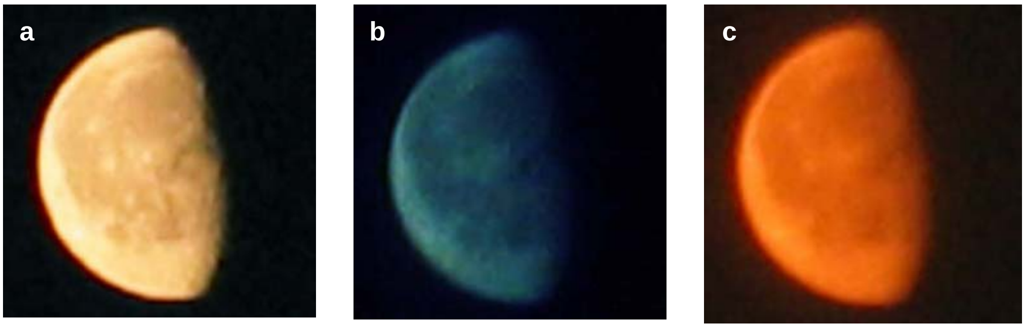

Fig. 4. Photos of a natural Moon (**a**), a blue Moon (**b**), and a red Moon (**c**).

prepared by grinding the glass with corundum with a mean size of grains 10 μm. Depending on the strength of roughness, one observes a blue or a red Moon. Note, any software color correction for the fragments of Fig. 4 was not performed; only brightness of the fragments **b** and **c** was increased. When the strength of roughness changes rapidly over the specified area of a surface, one can observe a blue-to-red Moon, without intense green between these colors. Explanation of this interesting circumstance is the same as given by BERRY [11] for the case of colored phase singularities at the polychromatic speckle fields as well as for the sequence of colors into natural rainbow. Namely, prevailing green presumes that both red and violet domains of the spectrum are suppressed simultaneously. But even in this case an observer has a sense of "unsaturated white", rather than of intense green [11]: although green really predominates in the resulting (modified) spectrum, the main role in estimation of colors belongs to subjective sense, being the subject of psychophysiology of sense of color.

The photos represented in Fig. 4 show that the enigmatic up to now effect of "a blue Moon" (as well as "a blue Sun") becomes handled by any interested observer. The distrustful reader can suspect the use of spectral filters for obtaining the images shown in Figs. 4**b** and 4**c**. This opinion is correct (!), taking into account the exceptional origin of the spectral properties of a colorless glass with slightly rough surface.

4.2. Other relevant observations

One must guardedly relate to the analogy between the surface roughness and the anti--reflecting transient layer introduced in Section 3. Namely, in contrast to the action of any regular (multilayer) interference filter, the influence of a rough surface with respect to the scattering-induced spectral modifications induced by its spectral modifications is dependent on the position of this surface. Namely, the spectral modifications are the most pronouncing, when a rough surface is positioned at the aperture of the imaging device, as it was made for obtaining the photos in Fig. 4. A simple laboratory experiment shows that the same sample of a rough surface does not induce any spectral changes, when it is positioned at the plane of the image of a white-light source, or more generally, at the plane of any of the field-of-view diaphragm of the complex imaging system. This result is quite clear from the point of view of the general theory of imaging through light-scattering media [5]. Namely, a scatterer positioned at the plane of the source changes randomly the (unobservable) phase of the boundary field alone, but it does not affect the imaging process in all other details.

In contrast, the following experiment confirms the adequacy of the used model of a transient layer. If one uses the sandwich of two or more samples of rough surfaces with the same characteristics (to say, each of them transmits predominantly "blue"), then the coloring of the image is the same, as in the case when one uses the single sample, though the total depth of roughness is different in two cases. This is just the same result, as one obtains using the sandwich of several identical interference filters. This observation shows that the elaborated effect of the scattering-induced interference coloring of the image is not restricted by the single-scattering regime.

Let us concisely characterize here some other observations performed by us and dealing with the interference coloring of the regular component of a white-light beam scattered at a slightly rough surface. We observed the scattering-induced spectral changes in a white-light beam specularly reflected from a slightly rough surface for very large angles of incidence and reflection. Note that to perform such observation, one must prepare so fine roughness ("hoarfrost" [8]) which does not yet provide the considered above coloring of the forward-scattered component in transmitted radiation. A detailed theory and experimental results will be published elsewhere. (Note that experiments with the reflected light are much more difficult than in the case of the forward-scattered radiation. To say, one does never deal with the image of a polychromatic source in specularly scattered radiation, but only with a weak colored component of the scattered beam.) Here we only specify the sequence of colors of the specular component, which is observed as the angle of incidence of a white-light probing beam decreases gradually from the maximal one (90 deg): white – yellow – orange – red – crimson – blue – yellow – orange – red, and so on. It is remarkable that this sequence of colors is just the same as the one illustrated in Fig. 1. In such a manner, changing synchronically the angles of incidence and observation, we were in a position to observe up to four sequences of the reflected "rainbow". In contrast to the above described experiments using various areas of a grinding glass, these observations are carried out with the single area, and the angle of incidence is the only changing parameter. It is clear that the mentioned sequence of the coloring of the specularly reflected polychromatic beam as a function of the angles of incidence and observation is the criterial argument in favor of the interference mechanism of the scattering-induced spectral modifications of the regularly scattered components of a polychromatic radiation.

Another observation verifying the introduced model of the scattering-induced spectral modifications deals with the use of immersion with the refraction index n_i such that $n_1 < n_2 < n_3$ [23]. If the immersion is rapidly dried, one can observe the alternation of colors in the forward-scattered component of a white-light beam passing the fixed area of the sample, which is predicted in Section 3, in a real time.

5. Conclusions

Thus, in this paper we have considered the effect of interference coloring of the regular component of a polychromatic (white-light) beam scattered at a rough surface with height inhomogeneities comparable with (but slightly less than) any wavelength associated with the spectral components of the probing beam. The main result of our study consists in substantiation of the model of the transient layer with a "diluted" index of refraction that provides prevailing transmission of the radiation with some wavelength, for which the back-scattering (specular reflection) vanishes. This model leads to the sequence of colors of the image of a white-light source, which is observed in practice.

The effect of coloring the forward-scattered component of a polychromatic light explored here differs considerably from the famous Wolf's spectral effect, *i.e.*, the effect of correlation-induced or diffraction-induced spectral changes [20, 24]. Similarly to the Wolf effect (and in contrast to the Doppler effect), modifications of the normalized spectrum of the forward-scattered component are realized only within the initial spectral band of the probing white-light radiation and are accompanied by considerable attenuation of the beam. However, the physical mechanisms of the scattering-induced spectral modifications are quite different in two cases. So, the scattering-induced spectral changes are caused by the coherent character of the forward scattering and are governed by the phase relations among elementary re-scatteres providing constructive or destructive interference for the forward-scattered or the back-scattered component at some wavelength, rather than result from spatial or angular redistribution of spectral components, as in the Wolf effect.

In our opinion, the represented results are of interest not only for opticians, but also for the readers involved in astrophysics, meteorology, quantum mechanics, nanotechnologies, and biomedical diagnostics, due to the universal character of scattering. Looking after the changeable coloring can be applied to practical control of growing of thin films, to modelling of the spectral modification of cosmological radiation [7, 19, 20] *etc*.

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Received May 17, 2007