Scattering-induced spectral changes

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ABSTRACT

The model of intermediately rough surface as the specific anti-reflection layer is presented for explaining the coloring of the regular component of a white-light beam forward scattered by a colorless glass with such surface. It is shown that this model predicts the sequence of colors of the forward scattered component of a white-light beam that is observed in practice. New experimental arguments supported this approach are provided.

Keywords: induced spectral changes, rough surfaces, anti-reflection coatings

1. INTRODUCTION

This paper is devoted to the phenomenon of coloring of the forward scattered component of a white-light probing beam passing a colorless dielectric slab with a rough surface whose inhomogeneities are comparable with some wavelength portion of the probing radiation. To our best knowledge, this phenomenon was firstly observed and interpreted at the early seventies of the XX century by V.K. Polyanskii[1,2].

Observing a white-light source through a colorless intermediately rough surface obtained by one-sided grinding of a glass plate with corundum with a mean size of grains ~7 μm 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. The observed modifications of the normalized spectrum of the forward-scattered component of a polychromatic beam and the resulting coloring of the source image have certainly interference origin. The presence of the regular component in the scattered radiation implies that the heights of surface inhomogeneities, h, or, more precisely, *rms* deviation of the relief from a mean surface line, σ_h, are comparable with the wavelength of the probing beam, here the wavelengths of all spectral components of the polychromatic beam. Depending on the heights of roughness inhomogeneities, one observes coloring in blue (for smaller inhomogeneities) and in red (for large ones). Illustration of this phenomenon is given in Fig. 1†. The photos of a natural Moon presented in this figure were obtained by Peter Polyanskii Spring 2007. Fragment Fig. 1 **a** has been obtained without scatterer in front of the camera, and fragments Fig. 1 **b** and **c** have been obtained with the use of two samples of grinded glass with different roughness in front of the camera. Note, that there is none software correction of colors in Fig. 1 has made. Image brightness has been increased alone in fragments **b** and **c**. The distrustful observer can suspect of the use of spectral filters for obtaining the images shown in Fig. 1 **b** and **c**. This opinion is correct (!), taking into account the exceptional origin of spectral properties of colorless glass with slightly rough surface.

Explaining this effect we have two main problems of interest in our study. The first problem consists in explanation of the fact of scattering-induced coloring of the forward-scattered component *per se*. Giving an intuitive explanation of the Wolf's spectral effect (the effect of correlation-induced spectral shifts[3,4]), Tatarskii[5] compares angular distribution of a polychromatic radiation from a temporary source and from partially coherently illuminated one, see Fig. 2. In the first case directivity for red and blue is the same, and the initial spectrum of the source is reproduced in any direction of observation. But when a polychromatic radiation (to say, from a quasar) illuminates the removed cloud of cosmic dust, then due to the Van-Cittert – Zernike theorem such cloud occurs to be partially coherent re-transmitter with different directivity for red and blue. So, in various directions one observes red or blue shifts within the initial spectrum, *excluding the forward direction*, where the initial spectrum is conserved. It is clear that spectral modifications are the most pronounc-

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† Color illustrations for this paper are available from the SPIE Digital Library.

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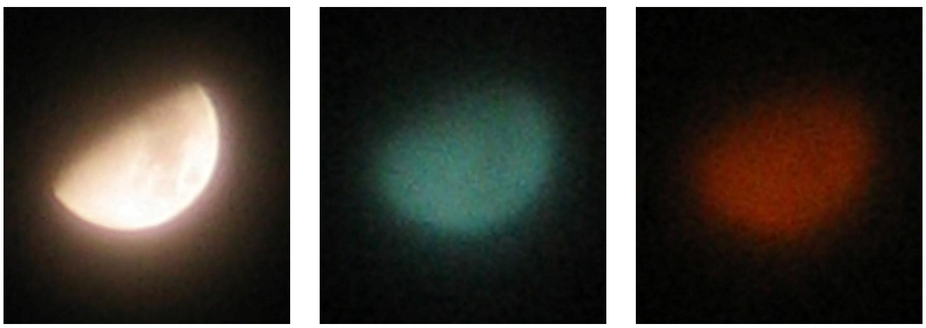
ing when some spectral component vanishes for the specified direction of observation, and the complementary spectral component predominates. The main peculiarity of the case of the spectral changes induced by scattering at rough surface, as we see, consists just in the coloring of the forward-scattered component of a white-light probing beam.

The second problem consists in explanation of the order of colors observed for growing depth of the surface roughness. So, the Newton's rings in *transmitted* polychromatic radiation are the close deterministic analog of the effect of interest. One could expect the same color sequence accompanying growing the relief depth as for the Newton's rings for increasing radii, *viz.* white – brown-white – brown – dark violet – blue – gray-blue – blue-green – yellow-green (for the first order). In practice, however, the color sequence differs in two cases, namely, for scattering at rough surface it resembles the Newton's rings observed in *reflection* (from blue to red). The reason is that the pure effect of interference is realized in Newton's rings, without any "intermediary", such as material medium. In contrast, in the case of interest in this paper interference is only one of the components of much more complex phenomenon, such as light-scattering at inhomogeneities of a rough surface, which results both in forward transmission and reflection of radiation, and in scattering in other directions.

This paper continues recent studies[6,7] elaborating the phenomenon of the spectral changes induced by scattering of polychromatic light at rough surface.



(a) (b) (c)

Fig. 1. Photos of a natural Moon (a), a blue Moon (b), and a red Moon (c).

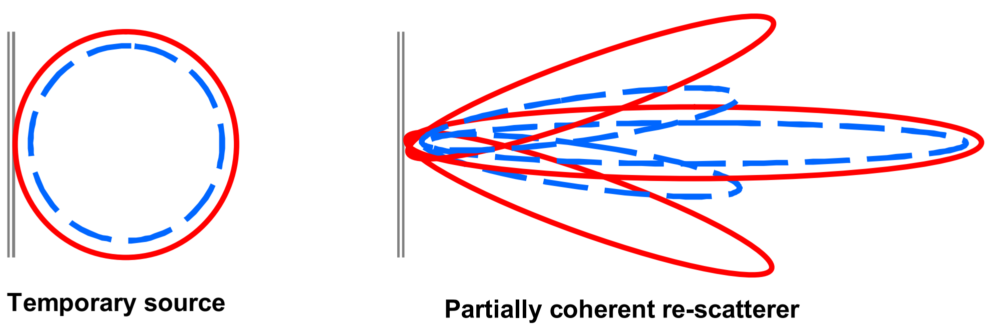


Fig. 2. Tatarskii's intuitive explanation of the Wolf's spectral effect.

Solid and dashed lines schematically show directivity of red and blue, respectively.

2. SURFACE ROUGHNESS AS THE TRANSITION LAYER

For interpretation of the observed sequence of colors induced by scattering of a white-light beam with respect to increasing roughness, we apply the model of a rough surface as a transition layer with the "diluted" index of refraction, which extends the well-known analogy between light-scattering particle and layer[8,9].

The real height distribution function of the inhomogeneities characterizing the given rough surface is generally unknown. However, irrespective of the specific functional form of such distribution function, one can consider a surface roughness as an irregular transition layer with a "diluted" index of refraction, whose magnitude is the geometrical mean of the indices of refraction of glass and air, $n_2 = \sqrt{n_1 n_3}$, see Fig. 3. If the optical thickness of the transition layer, $n_2 H$, effectively equals $\lambda/4$ for some spectral component of the probing beam, this layer acts similarly to an anti-reflection coating for this component, while under the assumed relation between the indices of refraction of the three media, the waves reflected from two boundaries of the transition layer are in opposite phases, being of almost the same amplitude, and interfere destructively. This certainly happens for some wavelength due to the condition $\lambda < H$ for all spectral components. As a result, this spectral component and its spectral vicinity will prevail in the forward-scattered light. This approach is easily formalized using generally known formulas for anti-reflection coatings.

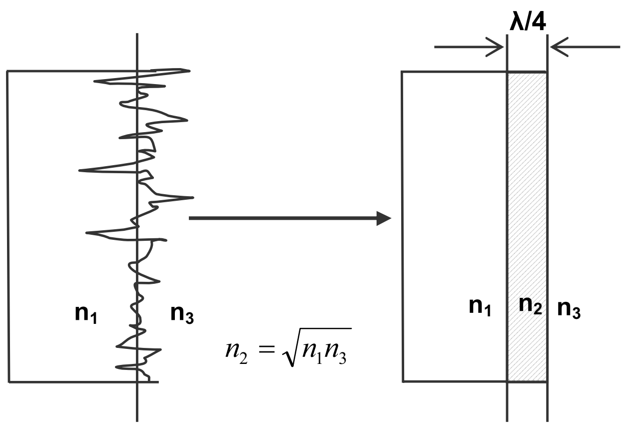


Fig. 3. Analogy between a surface roughness and a transition layer with "diluted" index of refraction.

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 light, as a function of the wavelength[11]:

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

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 for the reflected radiation. Then the relative intensity of the forward-scattered component at the same wavelength λ_i is determined by the difference:

$$\frac{I_f}{I_i} = 1 - \frac{I_r}{I_i}. \tag{2}$$

In writing Eq. (2), we neglected light scattering in all other directions. However, such approximation is reliably justified for intermediate heights of the roughness; cf. the estimations of the effective thickness of the transient layer below.

To illustrate the sequence of colors following from the model of transition layer, we apply the novel technique of chromascopic processing of colored optical fields introduced by Berry[10] for observing the chromatic effects near an isolated white-light vortex in speckle-fields. Peculiarity of the case of interest is that we apply it to the regular component of the scattered field, which is analogous to the zero (infinitely extended) interference fringe.

To reveal the colors, the RGB values of the tested field are scaled to iso-luminance by the transformation:

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix}_{CR} \Rightarrow \begin{pmatrix} R \\ G \\ B \end{pmatrix} \Big/ \max\{R, G, B\}. \tag{3}$$

This procedure preserves the ratios between the three RGB values while making the strongest one equal to unity. We implement the chromascopic simulation of a uniform color image of a white-light source formed by the forward-scattered component of radiation.

Figure 4 illustrates the colors of the forward-scattered component for the cases of vanishing in reflection blue λ_b = 435,8 nm (**a**), or green λ_g = 546,1 nm (**b**), or red λ_r = 700 nm (**c**). The effective depths of the transition layer of 88.36 nm, 110.73 nm, and 141.93 nm, respectively, which are close to 0.1 of the mean diameter of the corundum assumed to be used for obtaining the color effects (~ 10 μm). The result of simulation is in a quite agreement with the sequence of colors observed in practice. It is seen from Fig. 4 that newer intense green is observed in the forward-scattered component of polychromatic radiation, even in the case when the condition of anti-reflection layer is satisfied for green and green predominates in the forward direction. Colors change from blue to red omitting green but rather through gray. This remarkable fact will be demonstrated experimentally in Section 3. Really, to obtain intense green one must provide zero reflections for blue and red simultaneously and select narrow spectral interval in the vicinity of green (555 nm, approximately). This condition is not fulfilled in practice. Spectral band transmitted by the transition layer when green vanishes in reflection and predominates in the forward-scattered component leaves two broad, so that one observes almost the same as in absence of the roughness, see Fig. 4 **b**. The situation is similar to that for the case, when conventional anti-reflecting coating for green is used for lenses to provide a true color rendering.

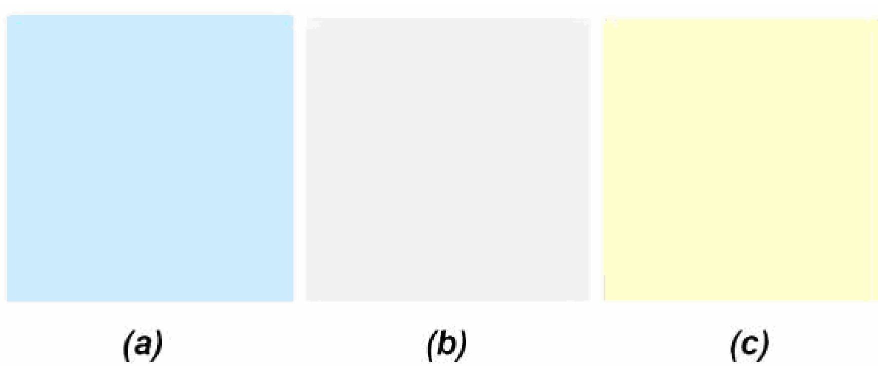


Fig. 4. Chromascopic simulation of spectral changes in the forward-scattered component of a white-light probing beam following the model of surface roughness as the transition layer.

3. EXPERIMENTAL

Let us present some experimental arguments in favor of the correspondence of the color sequence to the degree of surface roughness followed from the model of transition layer.

It is generally known that conventional microscopic observation of a rough surface does not provide reliable notion on the surface topography. Nevertheless, in the problem of interest microscopy of a surface roughness with various degree of processing by mechanical grinding enables to argue the pointed out subsequence of colors of the forward-scattered component of a white-light beam. The idea of the experiment is illustrated by Fig. 5. One chooses a sample of glass with considerably wavy surface. Using such a sample of glass with large deviations of a wavy macro-surface from a mean surface line, we are in a position to trace in dynamics color modifications induced by scattering at rough surfaces even with the single sample of a surface. Namely, we observe a white-light source through different areas of such roughness and fixed the areas providing blue or red shifts. Then we obtain a microscopic images of the corresponding areas to examine topography of them.

At the beginning stage of mechanical grinding of such surface, a roughness at first appears at hills, where at once many scattering centers occur. At slopes one obtains less and less such centers, which are like islands in the sea of non-processed areas. At last, hollows are practically non-processed, the scattering centers are absent. In Fig. 5one can see the photos (with magnification x40) of the corresponding areas of a sample of grinded glass prepared by grinding using electrocorundum with a mean grain diameter 10 μm. A mean cross-section of isolated inhomogeneities is about 15-20 μm.

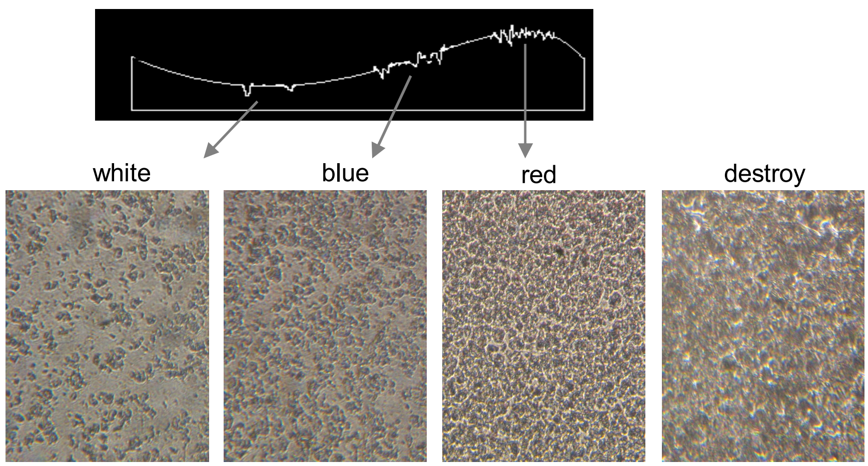


Fig. 5. Topography of intermediately rough surface surfaces inducing coloring the forward-scattered component of a white-light probing beam; the right fragment shows deeply rough surface when the forward-scattered component is completely destroyed.

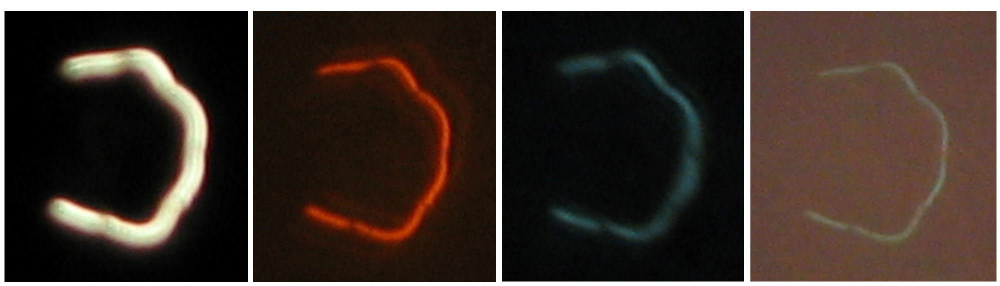
Through the area of a grinded glass corresponding to the left figure one observes non-colored source of a white light. Through the second area, with moderate number of inhomogeneities (and, correspondingly, with larger processed areas) one observes the blue-colored source. Through the third area, where non-processed areas are very small, one observes the red-colored source. The last area corresponds to deep roughness, scattering on which results in complete destroying of the forward-scattered component. Nature of coloring induced by scattering at intermediately rough surfaces is especially evident from the second fragment of Fig. 5. It is clear that coloring results from interference of the light transmitted non-processed areas of a glass with the light forward scattered at separate ingomogeneities. Number of inhomogeneities must be sufficiently large, while pronouncing coloring requires that the processed and unprocessed areas be approximately the same.

This observation, *viz.* transition from the first fragment of Fig. 5 to the third one, provides understanding of the exceptional rarity with which one can observe a blue shift for the forward-scattered component in comparison with a red shift (recall proverbial sentence: “Once in a blue Moon”). *Blue shift is observed only within very narrow interval of the magnitudes of the boundary field’s phase variance*, namely, in the interval between extremely small surface inhomogeneity heights, when coloring still absent, and some larger inhomogeneity heights that it is necessary for blue shift, when blue shift is changed by red shift, which remains such up to complete destroying the regular component. On our estimate, *rms* deviation of the rough surface profile from a mean surface line for the case of observing blue is from λ divided by 20 to λ divided by 10. Corresponding phase variance of the object boundary field is approximately 0.02 to 0.05. As it is known, a blue Moon is observed under similar conditions: blue shift presumes scattering in a cloud of very small mono-disperse particles[12].

Sequent alternating the colors, namely, appearance of a blue after red, would take place only for some special height distribution functions of surface inhomogeneities, for example, for the uniform height distribution function within specified interval of heights. For such distribution the spectral modifier is described as the squared sinc-function with subsequent maxima[1]. Implementation of such distribution in practice is problematic. At the same time, several subsequent spectral changes at the image of a white-light source *can* be observed at the zero diffraction order of pure-phase holographic gratings, for which the spectral modifier is the squared first-kind Bessel function of the zero order. To say, intermediately tough surface can be represented as disordered superposition of pure-phase relief gratings.

Let us now demonstrate the spectral modifications in the forward-scattered component of a white light transmitting a rough surface. For the sake of comparability, we will below provide results with the same source, namely with 150W lamp filament.

An image of a lamp filament as a white-light source, see Fig. 6, is registered using a CCD-camera in front of which one places a sample of grinded glass. You can see the source without a diffuser (fragment **a**) as well as blue-shifted and red-shifted images (fragments **b** to **d**) obtained with the areas of a grinded glass with various degree of roughness. The fragment **d** is of special interest. This photo has been obtained with *two* subsequently positioned diffusers with similar characteristics (both providing individually a blue shift). At first sight it seems that the use of sandwich from two diffusers, what corresponds to the doubling of the effective deepness of a roughness, must result in red shift or in destroying the forward-scattered component. In practice, however, blue remains blue, as it follows from the model of transition layer: being once opened, spectral window remains such, when one uses additional diffusers with similar characteristics. This result leads to the following important conclusion, namely, *the considered effect of spectral modifications induced by light-scattering at a rough surface is not restricted by the single-scattering regime.*



(a) (b) (c) (d)

Fig. 6. Lamp filament without diffuser in front of the CCD-camera (**a**), with red-coloring (**b**) and blue-coloring (c) *colorless* glasses, and with a sandwich of two similar blue-coloring glasses (**d**).

In Fig. 7 the *combined* blue-to-red shift is presented for the case when the image of the same white-light source is formed by the rays transmitted the area of the diffuser with different roughness. It is obvious, that conventional spectral filters (absorption or interference) do not possess such properties. Note, that in correspondence with the Berry's explanation of absence of intense green in effects of singular-optical coloring, here we also observe direct transition from blue shift to red shift omitting green.

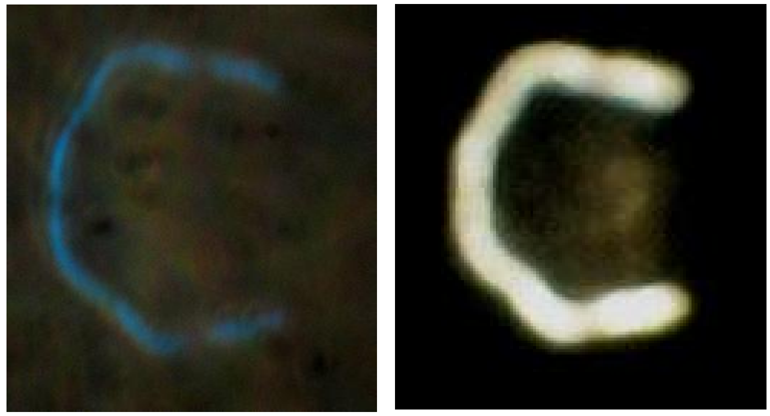


Fig. 7. Combined blue-to-red shift.

Fig. 8. Dependence of the coloring effect on the position of a rough surface in the imaging system: at the aperture diaphragm (left) and at the field-of-view diaphragm (right).

At last, the proposed model of spectral shifts induced by light-scattering at rough surface is argued by the dependence of the spectral properties of colorless grinded glass on its position at the optical system. As one can see from Fig. 8, intense coloring takes place at far field, in part at the image plane, if a diffuser is placed near an aperture diaphragm, but gradually disappear, if a diffuser is moved to the source or to the image plane, or, generally, to any field-of-view diaphragm of the imaging system. For such positions a diffuser causes only changing random phase structure of the radiation field, which is unobservable, but no spectral modifications.

In Fig. 9 the dependence of the effect of the coloring induced by scattering at rough surface on the diffuser orientation at the probing beam is demonstrated. Inclination of a diffuser corresponds to changing the effective depth of the relief that is accompanied by changing the color of the source image. Again, transition from a blue shift to red one takes place omitting green. The decisive experiment in favor to the interference origin of coloring of the forward-scattered component of a white light consists in observation of the *same* source through the *same* colorless sample of a rough surface, for various inclinations of the sample in respect of the probing beam. Simple geometrical considerations show that the effective depth of a microrelief decreases for non-normal incidence of the probing beam. As a consequence, gradual inclination of the sample must lead to blueing of red image and whitening of blue image. This assumption occurs in quite agreement with the observations.

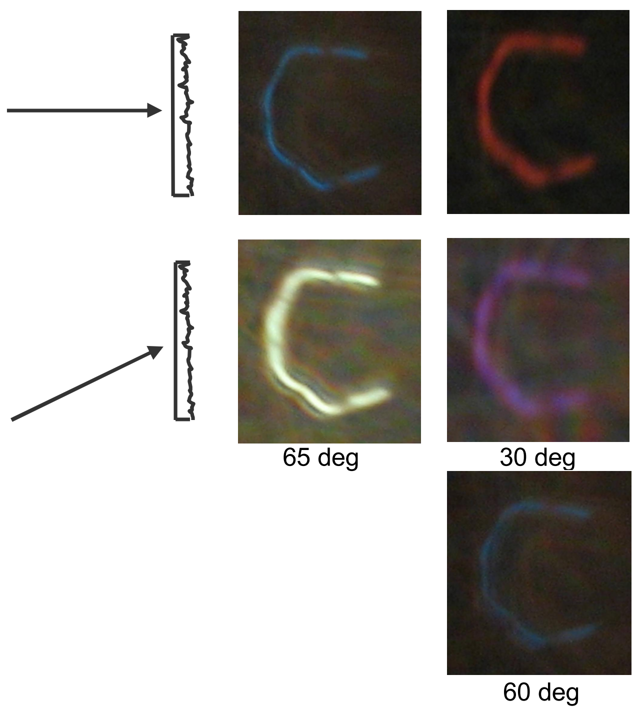


Fig. 9. Dependence of the coloring effect on the inclination of the sample. The upper row show the colors for two specimens for normal incidence of a white-light probing beams, other fragments show changes of colors for the same inclined specimens.

4. CONCLUSIONS

Thus, the presented experimental data confirm the adequacy of the introduced model of spectral modifications induced by light-scattering at intermediately rough surface, namely, the model of the transition layer with “diluted” refraction index, which corresponds to quarter-wavelength anti-reflection coating and provides predominant transition of radiation in forward direction for some spectral interval.

Peculiarity of the elaborated phenomenon consists in unconventional order of colors accompanying growing of the relief depth. This order is opposite to the order of the Newton’s rings observed in transition with white light source. In contrast to the previous models explaining the scattering induced spectral modifications, we propose to determine the spectral component for which the forward scattered component prevails rather than the component for which this component vanishes. This direct consideration predicts the color alternation observed in practice.

For the first time we demonstrate the roughness topography corresponding to blue shift and red shift of the forward scattered component of a white light beam. We also show that the effect of spectral changes induced by scattering at rough surface is not limited by the single-scattering regime, and demonstrate dependence of the coloring effect on the angle of incidence of the probing beam at the same specimen of rough surface. The presented results support the analogy between light-scattering particle, layer and intermediately rough surface.

REFERENCES

1. V.K. Polyanskii, “Spectral characteristics of colorless glass with rough surface,” *Journ. Appl. Spectr.*, **13**, 1039-1042 (1970).
2. V.K. Polyanskii, I.B. Kotlyarova, “Cooperative effects at rough surface in transmitted light,” *Opt. Spectrosc.*, **30**, 1142-1145 (1971).
3. E. Wolf, “Non-cosmological redshifts of spectral lines,” *Nature*, **326**, 363-365 (1987).
4. E. Wolf, D.F.V. James, “Correlation-induced spectral changes,” *Rep. Prog. Phys*,. **59**, 771-818 (1996).
5. V.I. Tatarskii, “An intuitive introduction to the Wolf effect,” *Pure and Applied Optics,* **7**, 953-957 (1998).
6. O.V. Angelsky, P.V. Polyanskii, S.G. Hanson, “Singular-optical coloring of regularly scattered white light,” *Optics Express*, **14** (17) 7579-7586 (2006).
7. P.V. Polyanskii, “Optical correlation diagnostics of phase singularities in polychromatic fields,” Chapter 2 in *Optical Correlation Applications and Techniques* (O. Angelsky, Ed.), SPIE Press **A168**, Bellingham (2007).
8. H.C. van de Hulst, *Light Scattering by Small Particles*. Wiley, New York (1957).
9. C.F. Bohren, D.R. Huffman, *Absorption and Scattering of Light by Small Particles*, Wiley, New York (1983).
10. V. Berry, “Exploring the colours of dark light”, *New Journal of Physics* **4**, 74.1-74.14 (2002).
11. F.S. Grawford, Jr., *Waves. Berkley Physics Course* Vol. 3. McGraw-Hill, New York (1968).
12. S.R. Wilk, “Once in a blue Moon,” *Opt. Phot. News*, **17** (3), 20-21 (2006).