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# OPTICAL SPECKLE-FIELD VISIBILITY DIMINISHING BY REDUCTION OF A TEMPORAL COHERENCE

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***Abstract.*** *The paper is a report of an experimental study to suppress the speckle structure of a coherent optical field. The technique proposed is based on the reduction of the temporal coherence utilizing enriching the output spectrum of Nd:YVO$_4$ laser with intra-cavity second harmonic generation by additional emission lines. Temperature-controlled simultaneous emission of two components at 1.063 μm and 1.066 μm with nearly equal intensities in IR is achieved. In the second-harmonic output the emission lines 531.7 nm, 532.3 nm and 532.8 nm were recorded. The influence of the spectrum variation on the formation of a speckle field was checked. Successfully removed intensity zeros and reduced contrast (visibility) from 0.92 to 0.65 in a light scattered by a ground glass diffuser at the angle 35°. A simple consideration of the speckle field dumping mechanism is presented.*

**Keywords:** speckle field, coherence, visibility

# OPTYCZNE ZMNIEJSZANIE WIDOCZNOŚCI POLA PLAMKOWEGO POPRZEZ REDUKCJĘ SPÓJNOŚCI CZASOWEJ

***Streszczenie.*** *Praca jest raportem z badań eksperymentalnych mających na celu stłumienie struktury plamkowej spójnego pola optycznego. Proponowana technika polega na redukcji spójności czasowej poprzez wzbogacenie widma wyjściowego lasera Nd:YVO$_4$ o wewnątrzwnękową generację drugiej harmonicznej przez dodatkowe linie emisyjne. Osiągnięto kontrolowaną temperaturowo jednoczesną emisję dwóch składników przy 1,063 μm i 1,066 μm przy prawie równych intensywnościach w podczerwieni. Na wyjściu drugiej harmonicznej zarejestrowano linie emisyjne 531,7 nm, 532,3 nm i 532,8 nm. Sprawdzono wpływ zmiany widma na powstawanie pola plamkowego. Udało się usunąć zera intensywności i zmniejszyć kontrast (widoczność) z 0,92 do 0,65 w świetle rozproszonym przez dyfuzor ze szkła szlifowanego pod kątem 35°. Przedstawiono proste rozważenie mechanizmu zmniejszenia pola plamkowego.*

**Słowa kluczowe:** pole plamkowe, spójność, widzialność

## Introduction

The interference in wave optics manifests itself as observable intensity variation over space and/or time, usually represented in the form of periodic distribution (fringes pattern) [3]. However, the interference in a general sense is a summation of participating field vectors which cannot be resolved in time when the oscillating frequencies differ substantially, or the mutual coherence is low. In the opposite case, under the circumstances of nearly plane monochromatic waves with a little frequency shift, the interferometric fringes can be observed with the naked eye. The measure of the visibility is a contrast of the pattern, i.e. the ratio of the residual of the intensity maximum and minimum, to their sum. In the case of several interfering waves (or fields with a wide spatial spectrum), the sum of their intensities equals the average intensity over a given time or space domain, but the spatial pattern is a matter of their temporal coherence. It could be expected that the field distribution will exhibit a smooth profile, but this is not true in general. For an optical vector field with irregularly varying polarization, the intensity distribution does not possess special peculiarities but the polarization state obeys some topological rules [9, 13]. Below we restrict ourselves by the situation of a scalar field, i.e. with the same polarization state across the observation region.

An example of an irregular optical field is a speckle structure usually observed in a scattered laser (monochromatic) radiation [5]. This unavoidable feature accompanies laser beam reflection by rough surface or propagation through inhomogeneous media like turbulent atmosphere, liquid flow or another diffuser. In any case, interference of monochromatic wavelets results in a modulated intensity distribution. More correct is to explain the result as a random phase-amplitude field formation, where the constructive summation generates bright speckles surrounded by dark borders of destructive interference containing zero amplitude points [2]. The presence of exact intensity zeroes makes the visibility of a speckle field equal to unity. We note that the number of zero-intensity minima coincides with the number of the bright maxima, i.e. there is one amplitude zero (phase vortex) between neighbor speckles.

The presence of speckle structure seriously degrades the quality of the image, even where the scattering is relatively small. For instance, in optical tomography coherent speckle noise reduces the contrast and makes difficult to resolve boundaries between highly scattering structures in tissue [11]. In this view, the problem of speckle noise suppression is of importance in many optical applications [10, 14].

The basic principle of speckle suppression is an averaging of different speckle patterns that is their overlapping in space or time resulting in the reduced speckle contrast. These speckle patterns could be obtained using a moving diffuser, polarization diversity, wavelength diversity, and/or angle diversity [6]. The averaging of the speckle structure is usually achieved using a rapidly moving (for example, rapidly rotating) light-scattering diffuser [4]. A current review of methods for speckle-noise suppression can be found in [7, 8].

## 1. Reduction of laser emission coherence

The approach accepted to the problem solution in this study consists in the diminishing of the temporal coherence of the optical field in order to damp the speckle structure. For this research, we used a commercial cw Nd:YVO$_4$ laser with intra-cavity second harmonic generation using BiB$_3$O$_6$ crystal (BIBO). The laser output consists normally of IR emission (1064 nm) and double-frequency radiation (532 nm) which makes it a convenient tool for our goal. Light emission power (in green light) was measured 7 mWt.

The peculiarity of this laser is sporadically appearing additional oscillating wavelengths. These oscillating spectral components were detected in a first diffraction order of a grating 1400 mm$^{-1}$ as schematically shown in Fig. 1. An explanation of the origin of additional components lies in the possibility of an emission line at 1083 nm to appear, apart main emission at 1064 nm (we refer to the details in the report [15]). As a result, three wavelengths of laser emission (532 nm, 537 nm, 542 nm) were observed. The output at these lines oscillating simultaneously originates owing to the second-harmonic generation of 1064 nm and 1083 nm, and sum-frequency generation. All these spectral components satisfy the longitudinal synchronism conditions for frequency doubling and are not separated within the output laser beam. In this view, the emission spectrum can be controlled without variation a beam direction and divergence. As it is seen, the emission at 532 nm is noticeably stronger, due to the relative power difference in the oscillations at 1064 nm and 1083 nm. The measured fundamental emission spectrum is shown in the inset of Fig. 1.

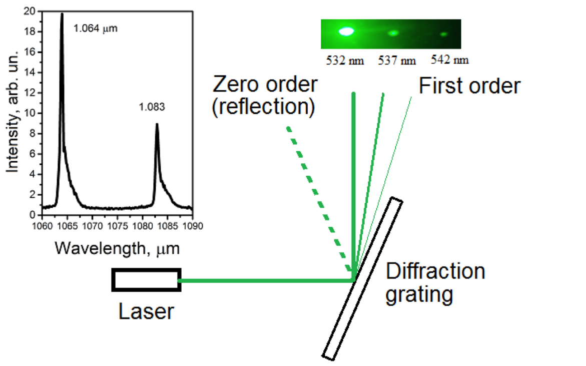


*Fig. 1. Elementary scheme for observation of spectral components in the emission of Nd:YVO$_4$/BIBO laser (second harmonic generation). The laser output beam is directed to a grating 1400 mm$^{-1}$. In the first order of diffraction, apart of the strongest diffracted beam with the wavelength 532 nm two satellites are seen with the wavelengths 537 and 542 nm. Insert shows the measured fundamental frequency spectrum with an additional emission line at 1.083 μm*

The outcoming problem that had to be solved was stabilization and switching the laser output regimes (single line operation at 532 nm or three-line operation at 532 nm, 537 nm and 542 nm). However, this regime was found less convenient for the experiment. The reason was a necessity to cool the laser to a temperature lower than 15° C for a steady operation. Instead, we detected a fine splitting of the main oscillation line under temperature variation of the environment by heating the laser. (For the details we refer to the spectroscopic measurements of temperature-dependent stimulated emission in $Nd^{3+}$:YVO$_4$ [12]). Therefore, this tool can be better used for our goal.

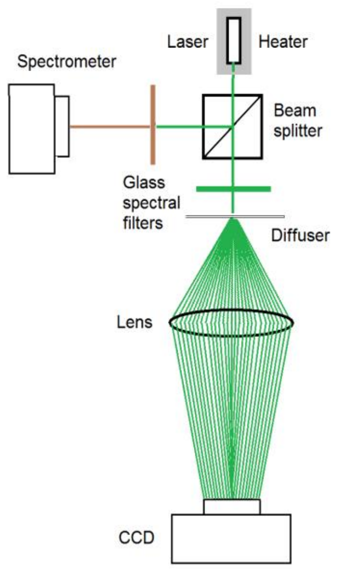


*Fig. 2. General scheme for the observation of the laser output spectrum variation and the speckle-field transformations with temperature. Laser output contains both fundamental frequency emission in IR region and second-harmonic green emission. The heater system is used to control the laser temperature. Glass spectral filters are used to cut off the IR radiation in the field scattered by the ground glass diffuser and separate IR or double-frequency components detected by the spectrometer. The CCD camera is placed at the focal plane of 80cm focal distance converging lens*

Below we report on the results obtained with laser emission controlled by the temperature. The experimental scheme is presented in Fig. 2. A laser head temperature can vary from 15°C to 50°C. The output beam containing the fundamental-frequency IR component and the doubled-frequency radiation was split by a beamsplitter to measure simultaneously the spectral content of the fundamental frequency emission by the spectrometer Ocean Optics USB 4000 and record the speckle-field pattern. A ground glass diffuser scattered green light isolated from IR component and CCD camera (Lumenera LM 135 M) was placed in the focal plane of the lens.

We observed a gradual spectral transformation in a temperature region from 15°C to room temperature and then from room temperature to 45°C. First, the emission at 1083 nm line was detected at 15°C and disappeared at about below 25°C. This regime was not stable enough for precise temperature control. Another extra emission line at 1066 nm was detected in the temperature interval after 40°C. With better stability and reproducibility we performed the experiments in this interval. The corresponding spectra of single-line emission at 27.5°C and double-line emission at 45°C are shown in Fig. 3.

Again, the emission in this bichromatic regime (IR) results in the three-chromatic output in the second harmonic radiation, as seen in Fig. 4. The measured spectrum contains the components at 531.7 nm, 532.3 nm and 532.8 nm. Fine tuning of the relative intensities of the emission lines was achieved by the pump LED current control.

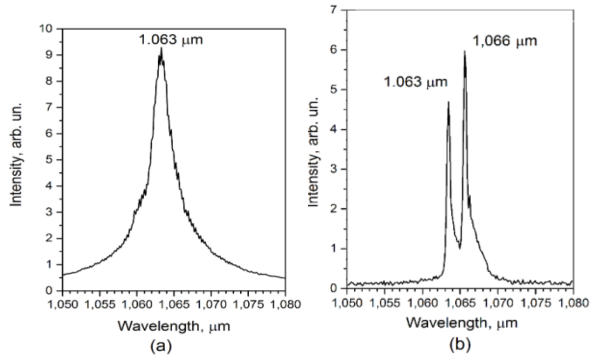


*Fig. 3. Laser output spectrum transformation with temperature: (a) at the room temperature 27.5°C, (b) 45°C*

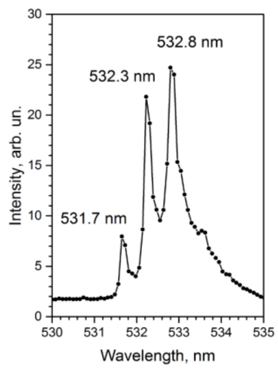


*Fig. 4. Measured spectrum of second-harmonic output with three maxima at the temperature 45°C*

## 2. Visibility measurements

To start the visibility measurements, we elaborated a laboratory set up with a test object (light diffuser) as a ground glass plate (Fig. 2). Under the temperature control we monitored the scattered field with a CCD camera, and a processing of the digital image (intensity cross-section) gives the visibility quantitative measure.

First, the spectrum transformation from single oscillation frequency to the three-chromatic regime, as described above, did not produce noticeable changes in the field scattered at small angles, i. e. along the incident beam direction. To detect the scattered pattern variations, we have modified the general scheme with a circular aperture separating the light along a definite direction This choice ensures an isotropic scattering to the angles exceeding 45° without polarization variation.

The modified experimental scheme is shown in Fig. 5 with an example of the speckle field observed in the far-field zone (focal plane of the lens).

With the angle of scattering chosen 35° by the aperture with the diameter 10 mm placed on a distance 10 cm from the illuminated spot on the diffuser we definitely observed radical transformation of the pattern by eye. Instead of highly contrast speckle field, a nearly uniform intensity distribution appears at the observation plane. Figure 6a,b illustrates the pattern variation which occurs with the three-chromatic emission.

In a quantitative measure the visibility reduction was detected from 0.92 to 0.65, as calculated from the measured cross-sections in Fig. 6 (c) and (d), recorded correspondingly for the single IR emission line and the bichromatic regime.

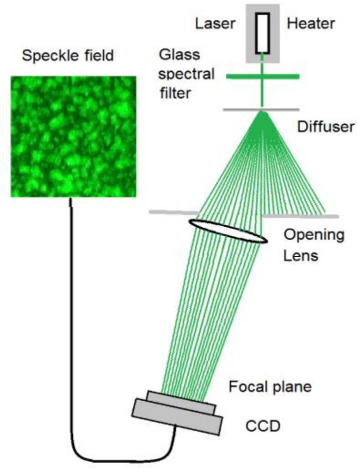


*Fig. 5. A principal scheme of a speckle field generation and processing. Thin ground glass plate serves as a diffuser. The glass filter cuts off the IR radiation. A CCD camera is placed at the focal plane of 80cm focal distance converging lens*

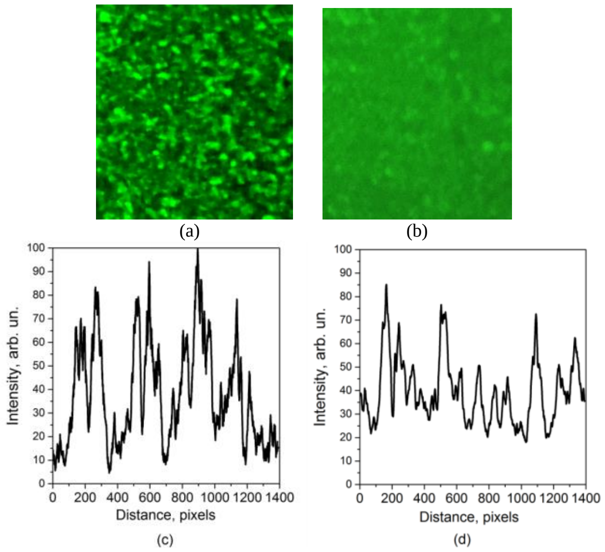


*Fig. 6. A comparison of the obtained speckle patterns in a scattered field with a single radiating line (a) and three lines (b), and the corresponding intensity cross-sections (c), (d). The scale givet in pixels avjunts to 7 mm window of CCD camera*

## 3. Discussion of the results

To give a simple explanation of the speckle-field smoothing by used three-chromatic laser emission and its dependence on the angle of scattering, we can model a diffuser as a thin plate with continuous superposition of periodic phase gratings of spatial frequencies $\Omega = 2\pi/\Lambda$, where $\Lambda$ is a spatial period of a corresponding grating. We assume an optical beam illuminating the diffuser to incident normally to the plate and have a dimension $d$ in the cross section, as depicted schematically in Fig. 7.

In the far field, scattering to the angle $\theta$ is produced by the spatial components which diffract the incident light into this direction, according to the diffraction law written for the first diffracted order and normal incidence as

$$\Lambda \sin\theta = \lambda \tag{1}$$

where $\lambda$ is the wavelength. Then, variation of the coming light wavelength to a small value $\Delta\lambda$ will not destroy the speckle pattern, but slightly move it along the spatial coordinate $\theta$:

$$\Delta\theta = \Delta\lambda/\Lambda\cos\theta \tag{2}$$

or

$$\Delta\theta = (\Delta\lambda/\lambda)\tan\theta \tag{3}$$

Evidently, the pattern observed at small scattering angles ($\theta \ll 1$) will remain nearly the same with the wavelength variation. That is, in the case of bichromatic incident field, i. e. when both wavelengths $\lambda$ and $\lambda + \Delta\lambda$ are present in the illuminating beam (for simplicity we consider only two spectral components) the generated by them speckles will overlap without spatial shift and add incoherently owing to the frequency difference.

To damp the speckle pattern, namely remove the intensity zeroes and thus diminish the visibility, we must achieve the shift of the constituent patterns at least to the mean spatial angle of an individual speckle. At the far field, the angular speckle dimension is estimated as $\lambda$, thus we have

$$(\Delta\lambda/\lambda)\tan\theta > \lambda/d \tag{4}$$

and therefore

$$\tan\theta > \lambda^2/d\Delta\lambda \tag{5}$$

In our experimental situation, an estimation $\Delta\lambda = 1$ nm $\lambda = 500$ nm and $d = 1$ mm gives $\tan\theta = 0.25$ or the corresponding angle $\theta = 14°$, in a good agreement with the experiment.

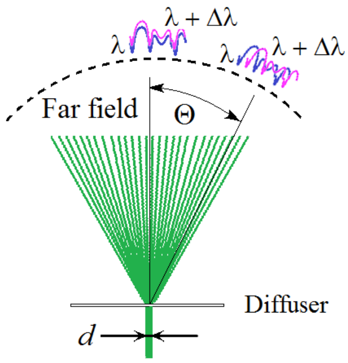


*Fig. 7. Schematic explanation of the summation of speckle fields generated separately by spectral components $\lambda$ and $\lambda + \Delta\lambda$. In the small-angle scattering, the speckle patterns overlap without angular shift. At the angle $\Theta$ the fragments of the speckle pattern are angularly shifted*

## 4. Conclusions

In the summary of the research performed we can report on "proof in principle" result of the influence of a laser emission spectrum on the speckles visibility. In general, the main conclusion of this study is formula (5) which connects the spectral width with the angle of the speckles overlapping. We note this result is in a good consistence with the reported for natural light speckles observation [1].

The theoretical part of the work was accompanied with experimental verification. We elaborated a laboratory set up with temperature-controlled bichromatic emission in IR of Nd:$YVO_4$ laser at the wavelengths 1.063 μm and 1.066 μm. This regime permits to reduce the temporal coherence of the output double-frequency radiation with keeping the quality of a laser beam spatial divergence. Then, we checked the influence of a spectrum transformation on the observed speckle pattern in the far field. In the small-angle scattering we did not detect noticeable variation of the pattern. At higher angles (35°) we fairly observed the damping of the speckle-field pattern.

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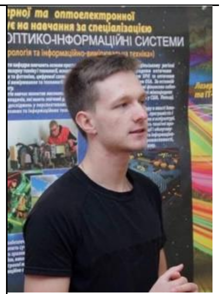


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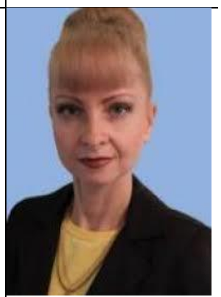


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