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CONTROL OF LASER RADIATION PARAMETERS

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Cross modulation method of transformation of the spatial coherence of pulsed laser radiation in a nonlinear medium

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***Abstract*. The cross modulation method of transformation of the spatial coherence of low-power pulsed laser radiation in a nonlinear medium is proposed. The method is realised experimentally in a multimode optical fibre. The estimates of the degree of spatial coherence of radiation subjected to the phase cross modulation demonstrated the high efficiency of this radiation decorrelation mechanism.**

Keywords: *phase cross modulation, spatial coherence, multimode optical fibre.*

1. Introduction

Currently lasers find increasing applications in new highly informative technologies such as photolithography [1], optical tomography [2], laser projection television [3], and systems for optical data imaging and processing. The efficiency of using lasers for these applications is determined by the possibilities of controlling the spectrum of spatial and time frequencies of generated radiation or its coherence. Thus, to obtain a high spatial resolution in laser projection photolithography and laser projection television, light beams should have simultaneously the low spatial and high time coherence [4]. In optical tomography, a high resolution is achieved, on the contrary, in the case of the low time and high spatial coherence of radiation [5].

One of the fast mechanisms of the extracavity transformation (reduction) of the spatial coherence of pulsed laser radiation is based on the effect of self-phase modulation (SPM) in a nonlinear medium [6, 7]. The efficiency of radiation decorrelation in this method depends on the radiation intensity. The higher is the radiation intensity, the greater is the decrease in coherence. In the case of low radiation powers, it is necessary to use long interaction lengths. The absorption in a nonlinear mediam leads to a strong attenuation of the signal at long lengths, which prevents the transformation of coherence of low-power light beams by this method in the UV region.

In this connection it was proposed to use the effect of cross phase modulation (CPM) for transformation of the spatial coherence of low-power radiation. This effect [8, 9] is based on the phase modulation of a light wave (signal wave) by the permittivity of a nonlinear medium induced by the intensity of another wave propagating simultaneously with the signal wave. The second wave can differ from the signal wave by the wavelength and can be much more powerful. The interaction of the waves in the nonlinear medium due to CPM leads to many interesting nonlinear effects [10]. In particular, the nonlinear CPM of signal radiation in time leads to the change in the frequency spectrum. These processes were studied theoretically and experimentally in nonlinear fibres in papers [11, 12]. Along with the CPM of radiation in time, the radiation phase is also modulated over spatial coordinates, which can lead to the broadening of the angular emission spectrum. However, the observation of this effect was not reported and its properties were not analysed in the literature so far.

The aim of our paper is to perform the CPM transformation of the spatial coherence of low-power laser radiation in a long waveguide nonlinear medium (multimode optical fibre) and to estimate the degree of coherence obtained.

2. Cross-modulation principle of transformation of the angular radiation frequency spectrum

Consider two quasi-plane, quasi-monochromatic light waves E_1 and E_2 of the same polarisation with different frequencies ω_1 and ω_2 propagating in a nonlinear waveguide medium:

$$E_1 = A_1(\boldsymbol{r}, t)\exp[\mathrm{i}(\omega_1 t - \boldsymbol{kr})],$$
$$E_2 = A_2(\boldsymbol{r}, t)\exp[\mathrm{i}(\omega_2 t - \boldsymbol{kr})]. \quad (1)$$

Here, A_1 and A_2 are the complex wave amplitudes slowly varying in time and $\boldsymbol{k}$ and $\boldsymbol{r}$ are the wave vector and radius vector of the observation point, respectively.

Let us write the expression for the nonlinear polarisation P_{NL} of a medium with the cubic susceptibility $\chi^{(3)}$ induced by the total field of the waves, which is responsible for self-

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interaction processes. By neglecting four-wave mixing processes, we obtain the instant response of the medium in the form [10]

$$P_{\mathrm{NL}} = \chi^{(3)}|E_1 + E_2|^2(E_1 + E_2) \sim \chi^{(3)}\{(|E_1|^2 + 2|E_2|^2)E_1 + (|E_2|^2 + 2|E_1|^2)E_2\}. \quad (2)$$

The total polarisation of the medium $P = \varepsilon E$ (ε is the permittivity of the medium) is determined by the sum of linear and nonlinear polarisations at frequencies ω_1 and ω_2:

$$P(\omega_j) = \varepsilon_j E_j, \quad (3)$$

where $j = 1, 2$; $\varepsilon_j = \varepsilon_j^{\mathrm{L}} + \varepsilon_j^{\mathrm{NL}} = (n_j + \Delta n_j)^2$; n_j is the linear part of the refractive index of the medium; Δn_j is the nonlinear addition to the refractive index. For $\Delta n_j \ll n_j$

$$\varepsilon_j \simeq n_j^2 + 2n_j\Delta n_j, \quad (4)$$

where the nonlinear part of the refractive index is determined by the relation

$$\Delta n_j \simeq \frac{\varepsilon_j^{\mathrm{NL}}}{2n_j} \simeq n_2(|E_j|^2 + 2|E_{3-j}|^2), \quad (5)$$

where $n_2 = (3/8\pi)\chi^{(3)}$ is the nonlinear refractive index of the medium.

It follows from (5) that the nonlinear part of the refractive index for each of the waves propagating in the nonlinear medium is determined not only by the wave intensity but also by the intensities of other waves propagating simultaneously in the medium. Variations in the refractive index of the medium induced by the waves lead to the change in their phases by the value

$$\Delta f_j = \frac{\omega_j}{c}\Delta n_j L \simeq \frac{\omega_j n_2 L}{c}(|E_j|^2 + 2|E_{3-j}|^2), \quad (6)$$

where c is the speed of light in vacuum and L is the interaction length.

The first term in (6) is caused by the SPM and the second one – by the CPM appearing due to the modulation of the phase of one wave by the other. If the intensity of one of the waves is small, its phase modulation is completely determined by the intensity of the other wave. When the intensity of the high-power wave is a random function of spatial coordinates or the nonstationary interaction takes place in the nonlinear medium, the spatial phase distribution of the low-power wave becomes random, which results in the transformation of its spatial coherence and broadening of the angular frequency spectrum. The inhomogeneous stochastic distribution of the wave intensity can be formed, for example, during the wave propagation in a multimode optical fibre due to the interference of modes. Therefore, the nonlinear interaction of waves in a multimode waveguide medium can be used for the transformation of correlation characteristics of laser beams.

The efficient CPM of radiation is obtained when the length of a nonlinear medium does not exceed the dispersion separation length L_{w} of radiation pulses – the distance at which pulses cease to overlap in time. The value of L_{w} can be estimated from the expression [10]

$$L_{\mathrm{w}} = T/|d_{\mathrm{cm}}|, \quad (7)$$

where T is the duration of the longest of the interacting pulses; $d_{\mathrm{cm}} = v_{\mathrm{g}}^{-1}(\lambda_{\mathrm{s}}) - v_{\mathrm{g}}^{-1}(\lambda_{\mathrm{m}})$ is the mismatch of the group velocities of the waves; λ_{s} and λ_{m} are the wavelengths of the signal and modulating pulses. In this case, the peak power of modulating radiation should not exceed the damage threshold for the fibre end-face.

3. Experiment

Figure 1 shows the optical scheme of the experimental setup. Pulsed signal (*1*) and high-power modulating (*2*) radiations at wavelengths 532 and 1060 nm, respectively, are coupled with the help of mirror (*3*) and microobjective (*4*) into multimode optical fibre (*5*) with the numerical aperture smaller than that of the microobjective. The modulating radiation propagated through the fibre is suppressed with 530-nm interference filter (*6*). The signal radiation propagates through filter (*6*), scatters in mat plate (*7*), and is detected with linear CCD (*8*) with the spectral sensitivity region between 230 and 1020 nm and pixels of size ~ 14 μm.

The transformation of the coherence of signal radiation is described by the following mechanism. Spatial radiation modes excited in the fibre interfere with each other due to nonstationary interaction [13] and/or the presence of defects in the fibre (bendings and variations in the fibre diameter) by forming spatially random nonstationary intensity distributions (speckles). The nonlinear interaction of high-power modulating radiation with the fibre core induces the random modulation of the permittivity of the core material. The scattering of signal radiation by phase inhomogeneities induced by the modulating wave causes the spatial and time modulation of phases of the signal-wave modes. The averaging of the signal-field intensity during the detection time is similar to the formation of a radiation source with a lowered spatial coherence.

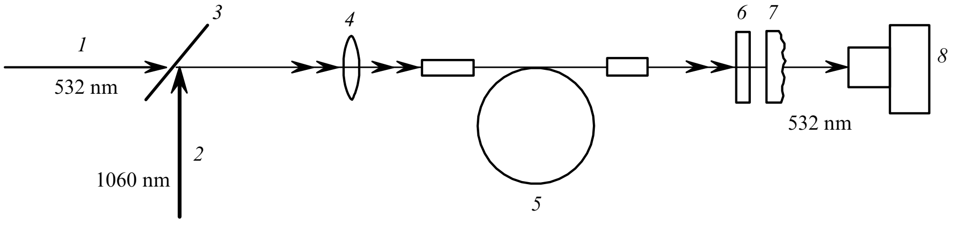

Figure 1. Optical scheme of the experimental setup.

The length of a silica fibre used in experiments was ~ 100 m and was almost half as much as the dispersion separation length of the interacting pulses of duration 15 ns. The diameter of the fibre core was ~ 60 μm. The modulating radiation power $P_{\rm m} = 1.4$ kW was approximately two orders of magnitude lower than the damage threshold of the input end-face of the fibre. The signal radiation power at the fibre input was ~ 13 W.

Figures 2 and 3 present the far-field intensity distributions of the low-power 532-nm second harmonic radiation from a Nd : YAG laser with the spectral width $\Delta\omega_0 \simeq 0.3$ cm^{-1} recorded with detector (*8*). Figure 2 shows the signal beam intensity distribution recorded behind mat plate (*7*). Figure 3 shows the signal beam intensity distribution recorded behind the same mat plate after propagation through the multimode step-index silica fibre in the absence of modulating radiation [curve (*1*)] and together with modulating radiation of power $P_{\rm m} \sim 1.4$ kW [curve (*2*)]. The mat plate is used here as an indicator of the degree of spatial coherence of radiation.

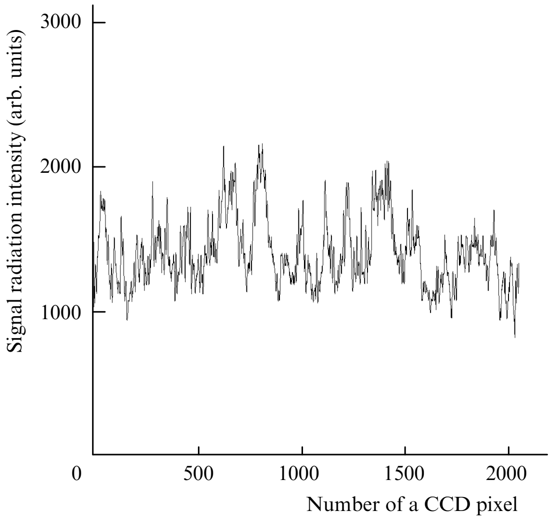

Figure 2. Spatial intensity distribution of the signal laser beam recorded behind a mat plate.

The spatial radiation intensity distribution recorded behind the mat plate (Fig. 2) shows that radiation is strongly inhomogeneous. Radiation intensity fluctuations are the result of the coherent summation of light fields with random phases scattered in the plate and suggest that the initial radiation has a high spatial coherence. The degree of the inhomogeneity of the speckle pattern is estimated by its contrast, which is equal to the ratio of the root-mean-square deviation of the radiation intensity to its average value. The contrast of speckles in Fig. 2 averaged over 20 recorded intensity distributions is 0.19. The contrast of speckles formed at the output of the fibre by low-intensity radiation in the absence of modulating radiation is 0.15 [distribution (*1*) in Fig. 3]. This difference of contrasts is mainly caused by the dispersion of the path of beams in the fibre resulting in the incoherent summation of field modes [14].

The spatial intensity distribution of the beam emerging from the fibre is different if high-power modulating radiation at 1060 nm is simultaneously coupled into the fibre. This radiation induces the nonstationary and spatially nonuniform variation in the refractive index in the fibre, which produces the random spatiotemporal modulation of signal-field phases. The signal-filed intensity fluctuations averaged during the recording time correspond to intensity fluctuations of a virtual radiation source with lowered spatial coherence. The contrast of signal-beam intensity fluctuations in Fig. 3 [distribution (*2*)] is ~ 0.08, i.e. it is approximately half as much as that in the absence of modulating radiation.

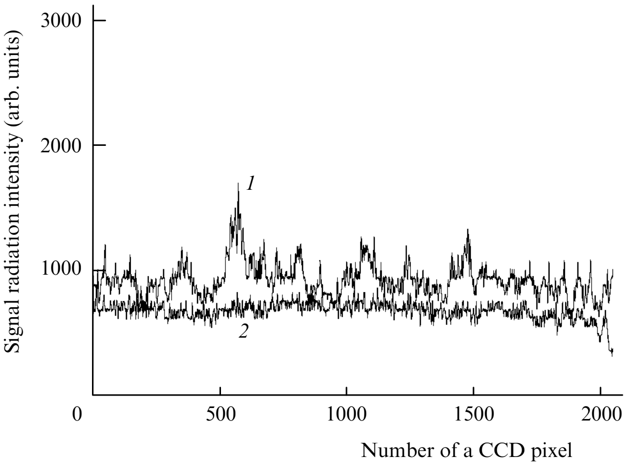

Figure 3. Spatial intensity distributions of the signal laser beam recorded behing a mat plate after propagation of the beam through a fibre in the absence (*1*) and presence (*2*) of modulating radiation.

It was found experimentally that the most efficient transformation of the spatial coherence of a low-power signal field in a silica fibre was achieved when the power of modulation radiation was close to the critical SRS excitation power.

4. Conclusions

We have demonstrated experimentally the efficient CPM transformation of the spatial coherence of low-power pulsed laser radiation in a multimode silica fibre. The advantage of the CPM method is the possibility of a rapid reduction of the spatial coherence of low-power UV beams. The efficiency of coherence transformation by the CPM method is twice that by the SPM method for radiation power equal to the power of modulating radiation.

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