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Noise-like pulses: stabilization, production, and application

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Various aspects are analyzed, which are related to the generation of unusual laser pulses with stochastic internal structure known as noise-like pulses. A new mechanism of their stabilization is proposed on the basis of an analogy between a noise-like pulse and a drop of soliton liquid. The properties of noise-like pulses are considered. It is further noted that these pulses are more and more used in a number of applications (supercontinuum generation, industrial processing, medical treatment, etc.). The causes of low coherence of noise-like pulses are identified. A method of coherence degree measurement relying on the autocorrelation function of these pulses is discussed. The most promising configurations for generation of noise-like pulses are provided. © 2024 Optica Publishing Group

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1. INTRODUCTION

Today, the demonstration of advanced laser pulse parameters is no longer at the forefront of research. Light pulses have been generated with duration, energy, and wavelength covering enormous ranges. Great efforts have been invested into profiling these pulses and structuring them for application in solving many problems. However, among all this diversity, there is one unconventional category that is usually termed noise-like pulses [1–3]. The noise-like pulse regime is one of the characteristic regimes of passively mode-locked fiber lasers. These pulses were discovered more than 20 years ago, and they were studied in many publications. Several reviews [4–9] and book chapters [2,3] were dedicated to their analysis, but, in spite of all that, certain important questions on the generation and applications of these pulses remain hitherto unclear. First of all, to this day, we do not have a comprehensible qualitative explanation of the process of their formation. The implementation of noise-like pulse regimes in various dispersion and nonlinear conditions suggests certain common features of this process. Sometimes, the generation of noise-like pulses is considered as incomplete mode locking [10,11], even though the noise-like pulse envelope is very consistently repeated at the inter-mode frequency of the cavity. Possibly, the reason for such a view is found in chaotic variation of the internal structure of such a noise-like pulse. Second, the coherent properties of these pulses have only been studied partially—the inter-pulse coherence of radiation was experimentally explored [12], whereas the coherence of radiation within a single pulse was not really studied. It is not clear on which cavity or pulse parameters it depends. Third, the application area of noise-like pulses largely remains undefined even though it is possible to develop on their base an incoherent laser [13] with a broad application area ranging from multi-media to material processing.

It is well worth mentioning separately the conditions for noise-like pulse generation. In most cases, noise-like pulse generation was observed in fiber lasers, although sometimes such pulses were reported in volumetric solid-state lasers as well [14]. After the demonstration of a technology for efficient transformation of conventional soliton pulses into noise-like ones outside the laser cavity [15], their specific sources became of secondary importance; however, the fact that such pulses are generated predominantly in fiber lasers—which are in the process of active development—is undoubtedly an advantage of noise-like pulses.

Here we will provide a general introduction to noise-like pulses. Such pulses appear entirely conventional when registered with most oscilloscopes because even fast measurement equipment may not resolve the internal structure of noise-like pulses. In reality, however, they are pico- or nanosecond pulse trains or wave packets with temporally stable envelope chaotically filled with subpulses (having random amplitude and duration). One of the indirect indications of noise-like pulses may be noticeable instability of the train amplitude [16] (it may be as high as tens percent), with the caveat that not every instance of noise-like pulse generation exhibits this, because it may also be relatively stable [17] (within 1%). This means that the radiation intensity instability alone cannot be used to identify noise-like pulse generation. Neither is it possible by the radiation spectrum shape: it is broad and smooth, but these are qualitative parameters. The autocorrelation function (ACF) of noise-like pulses may serve as a more reliable indicator: it exhibits a typical double-scale shape (a narrow peak sitting on a broad pedestal). This is why noise-like pulses are sometimes referred to as double-scale pulses [14,18,19]. The height and width of the central ACF peak may vary in certain ranges. As a rule, the amplitude of the central peak amounts up to 50%–60% of the overall ACF amplitude, whereas the central peak width is within femto- or pico-second ranges. The narrowest observed peak (14.5 fs) was reported in [20] and the broadest (4.9 ps) in [21]. The pedestal width may vary from subpicoseconds [22] to as broad as nanoseconds [17,23,24]. The ratio of the pedestal width to that of the central peak usually lies within the range of 135–175, even though rarely it may deviate into both smaller (∼73 [10]) and larger (∼1000 [25]) values.

Exploration of the properties of noise-like pulses is complicated by the inability of conventional measurements (optical spectrum, train comb, autocorrelation function, and so forth) to comprehensively characterize the internal structure of these pulses (essentially, due to limited speed of the available equipment). Consequently, new theoretical and experimental methods are being developed that provide better insight into the mechanisms of formation, transformation, and propagation of these unusual pulses.

In this work, we would like to pay more attention to the questions outlined above and to analyze the recent publications focused on noise-like pulses.

2. MECHANISM OF NOISE-LIKE PULSE FORMATION

The great variety of generation regimes constitutes an important advantage of fiber lasers as used in various applications. In addition to conventional single-pulse passive mode locking, these lasers can operate in multi-pulse regimes and exhibit hysteresis phenomena, bistability, and multi-stability [26–44]. The authors of [45] point out an analogy between soliton structures emerging in fiber lasers and various aggregate states of matter (the existence of soliton gas, soliton liquid, soliton glass, and soliton crystal). One of the efficient approaches to identification of the mechanisms participating in the formation of various soliton structures is numerical modeling of the physical processes occurring in such formation. This approach allows identification of the major causes leading to formation of noise-like pulses in passively mode-locked fiber lasers. Mechanisms of noise-like pulse formation were analyzed in [7,46–51].

The dynamics of noise-like pulse generation appears paradoxical. Although the solitons forming it are so unstable that their envelope is continuously and significantly fluctuating, while solitons themselves are emerge and disappear stochastically, nevertheless such a chaotic noise-like pulse maintains stability and consistency as a well-localized object continuously moving along the cavity. Such dynamics of noise-like pulses turned out to be pretty common in fiber lasers.

It is not surprising that the solitons forming a noise-like pulse exhibit stochastic behavior. Indeed, various mechanisms of soliton stochastization exist. Among them, there is periodic impact action on solitons propagating in a fiber laser with localized nonlinear losses [52] or in fiber-optical cavities composed of spliced fiber patches with different frequency dispersion values of the refractive index [53]. This is why stochastization in a noise-like pulse of solitons composing it is not a remarkable fact. Something else is surprising. Why, in spite of busy stochastic movement of solitons that form a noise-like pulse, does this pulse itself not decompose into isolated solitons randomly distributed along the cavity? What kind of forces prevent a noise-like pulse from decay and fragmentation into separate independent solitons? These questions are of prime importance in analysis of noise-like pulse formation.

In the above-mentioned analogy between soliton structures inside a fiber laser and different aggregate states of matter, a noise-like pulse plays the role of a drop of soliton liquid. Chaotic movement and evolution of solitons forming such a drop is related to the mechanism of intra-pulse destabilization of stationary radiation distribution. Publication [7] studied the mechanism of such destabilization related to higher-order nonlinearities of the refractive index of the intra-cavity element. Ref. [50] analyzed another type of destabilization stemming from periodic compression and expansion of solitons as the pulse propagates through a fiber-optical cavity containing stretches of fiber with normal and anomalous dispersion. In both cases, the emerging properties of noise-like pulses are in qualitative agreement.

Figure 1 shows the transient process and stabilization of the temporal distribution of the radiation intensity $I(\tau)$ that stochastically evolves from one pass of the field along the cavity to the next, as a result of numerical modeling of generation in an Er-doped fiber laser [7]. The dimensional time t and intensity I' are determined from the corresponding dimensional quantities by the following relations: $t = 0.2\tau$ ps and $I' = 23I$ W. The initial field distribution was a Gaussian pulse. In Fig. 1(b), the temporal intensity distribution is given in log scale for $\zeta = 600$ when the transition process is completed. As may be seen from this figure, a noise-like pulse has a pedestal with an intensity much lower than that of the solitons making up the noise-like pulse. This pedestal is an important structural element of the noise-like pulse. From this pedestal, solitons are spawned with relatively weak frequency chirp, which leads to their more efficient amplification compared to already present powerful solitons carrying significant frequency chirp. Due to saturation of nonlinear losses, the intensity of newly created solitons grows, their frequency chirp also increasing due to nonlinearity of the refractive index. As a result, due to a finite spectral gain width, the amplification efficiency for these solitons begins to drop. Eventually, they disappear in the radiation of the pulse pedestal, leaving space for the emergence of new solitons. Owing to a bell-shaped temporal profile of the pedestal, new solitons replacing the extinguished ones in fulfilment of conservation of the full radiation energy in the laser cavity are more likely to spring up in the center of the noise-like pulse where the pedestal radiation intensity is the highest. This mechanism continuously renewing solitons that constitute a noise-like pulse is one of the elements working to conserve the spatio-temoral localization of noise-like pulses.

Similar to the case of molecules evaporating from a drop of liquid matter, some solitons leave the soliton droplet as a result of intensive stochastic motion and emerge outside the noise-like pulse. Because of the growing chirp of such solitons, which is connected to the nonlinearity of the fiber refractive index, their strength of interaction with the gain medium decreases and eventually they disappear from generation. An example of

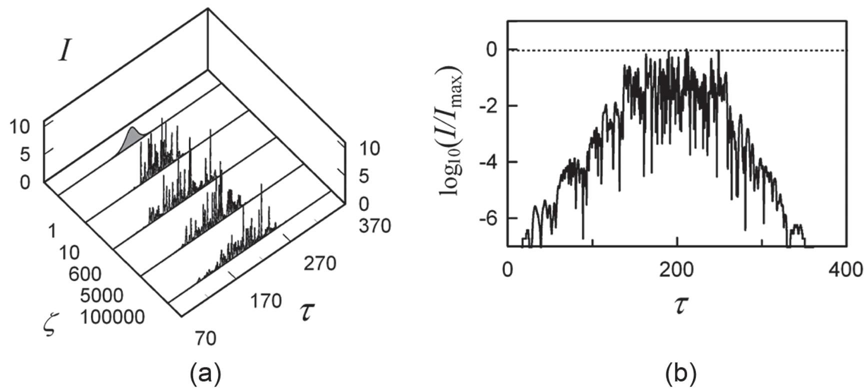

Fig. 1. (a) Temporal intensity distribution $I(\tau)$ as a function of the number of passes of radiation through the cavity ζ in the noise-like pulse generation regime. (b) Intensity distribution $I(\tau)$ in log scale $\log_{10}(I/I_{\max})$ for $\zeta = 1000$. $I_{\max}$, highest intensity value.

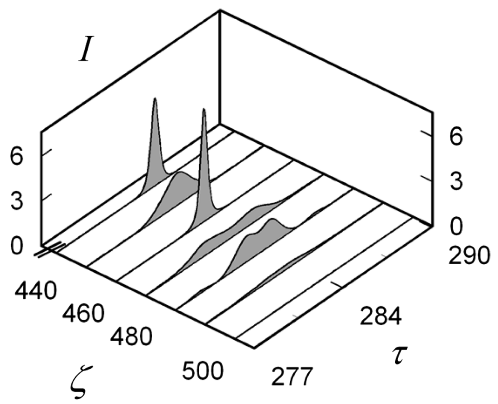

Fig. 2. Evolution of a single soliton localized outside a noise-like pulse that leads to its disappearance.

the evolution of such solitons departed from the soliton droplet is given in Fig. 2. The existing mechanism that suppresses solitons exiting the noise-like pulse is among the major ones that maintain the spatio-temporal localization of the noise-like pulse.

In other words, we can say that the key element that bounds all the stochastic solitons is a significant pedestal of the noise-like pulse. It determines the stability and competitive advantage of the noise-like pulse. As a result, the competition between a noise-like pulse and a soliton outside the noise-like pulse follows the same law as the competition between two pulses with different energies.

It must be noted, however, that the mechanism conserving the average energy and average soliton number in a noise-like pulse is quite interesting. Indeed, when a single soliton leaves the noise-like pulse, the pulse's energy is reduced by that of the dropped soliton. Nevertheless, when this single soliton disappears as a result of competition the energy of the noise-like pulse is restored due to conservation of the total radiation energy in the laser cavity. Consequently, the average energy and the average number of solitons in a noise-like pulse are conserved. As the results of numerical simulation show (see Fig. 1), the structure of the noise-like pulse and its spatiotemporal localization are also preserved.

Thus, if we consider a noise-like pulse as a soliton droplet, the evaporation process in this analogy for the soliton droplet and a drop of liquid leads to quite different results. In the first case, the average number of solitons in a soliton droplet is approximately conserved, whereas the number of molecules in a liquid drop is monotonically reduced.

The conducted research demonstrates that as the laser parameters change so as to result in greater soliton mobility in a soliton droplet, the evaporation is intensified. In this process, the pulse pedestal is destroyed and the noise-like pulse disappears into a soliton gas that fills the entire laser cavity. In the model studied in [7], greater soliton mobility was achieved by lowering the frequency dispersion of gain D_r. Reference [50] analyzed the formation of noise-like pulses in a fiber ring laser model, in which anomalous dispersion of the cavity fiber was partially compensated by normal-dispersion fiber. When the normal-dispersion fiber was replaced with an anomalous-dispersion one, soliton mobility was greatly increased and the noise-like pulse regime was transformed into the generation of a soliton gas. Radiation distributions for both generation regimes are shown in Fig. 3. In the case of soliton gas, single solitons visible in Fig. 3(b) are in constant motion relative to each other, which is a result of their unequal carrier frequencies. When colliding with each other, they either elastically bounce back or travel through each other. Solitons have high mobility, which prevents the formation of bound states (soliton molecules, crystals, glasses, and noise-like pulses). This is one of the typical generation regimes in passively mode-locked fiber lasers [50,51].

In the case of intra-pulse destabilization due to higher-order nonlinearities of the refraction index (Kerr effect), noise-like pulse generation was also observed in the model of the laser cavity with normal dispersion [7].

Figure 4(a) exhibits the instantaneous spectrum of the noise-like pulse of Fig. 1(a) [7]. It evolves stochastically with successive field passes through the cavity. However, the instantaneous spectrum, averaged over a large number of radiation passes through the resonator, has a high degree of orderliness. It may be very precisely approximated by a squared hyperbolic secant [see Fig. 4(b)]. In Fig. 4, the dimensional frequency ω' is determined from the corresponding dimensionless frequency ω by the following relations: $\omega' = 5\omega\ \mathrm{ps}^{-1}$.

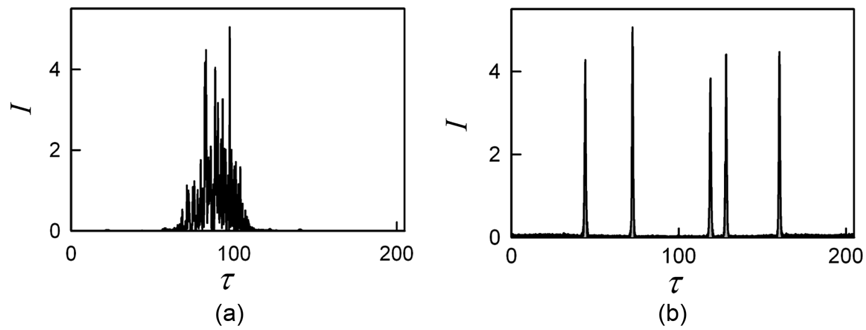

Fig. 3. (a) Noise-like pulse observed with partial compensation of anomalous dispersion of the cavity fiber by normal-dispersion fiber. (b) Generation of soliton gas emerging after the second fiber with normal dispersion was replaced with an anomalous-dispersion one.

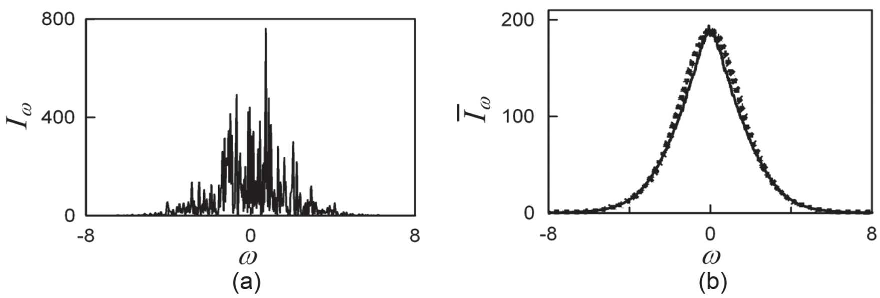

Fig. 4. (a) Instantaneous spectral distribution of a noise-like pulse I_ω, and (b) averaged spectral distribution I_ω (solid line). The averaging span is $\delta\zeta = 10^4$. Dotted line corresponds to the dependence $I_\omega = 190/\cosh^2(0.5\omega)$.

Therefore, formation of stable noise-like pulses is related, first of all, to the presence of a mechanism that destabilizes the stationary intra-pulse distribution of radiation. And stable spatio-temporal localization of the noise-like pulse stems from continuous renewal of intra-pulse radiation: from the pulse pedestal, narrow-spectrum solitons are born, which win initially against powerful solitons with significant frequency chirp and therefore grow with time. Gradually, they acquire more frequency chirp and start losing the competition with newly born solitons spawned from the pulse pedestal. Due to this spectral renewal, the noise-like pulse wins against isolated solitons emerging outside the pulse and lacking such a renewal mechanism. Nevertheless, as the laser parameters are changed leading to greater soliton mobility, the resultant increasing diffusion of radiation out of the pulse may lead to destruction of the pulse pedestal and, hence, the dissipation of the noise-like pulse. As a result of this, the generation regime passes from noise-like pulses to soliton gas.

The noise-like pulse can have a rectangular time profile [54]. In [51], it was shown that a rectangular pulse (dissipative soliton resonance with anomalous dispersion and zero nonlinearity of the refractive index) becomes rectangular noise-like pulse if the nonlinearity of the refractive index is changed to a sufficiently large one. As the pump decreases, the length of such a rectangular noise-like pulse decreases and it becomes a bell-shaped noise-like pulse, the same as shown in Figs. 3(a) and 4(a). The transition from a stationary rectangular pulse to a noise-like rectangular pulse is associated with the phase modulation instability of the stationary radiation distribution.

Here, we have considered two mechanisms destabilizing intra-pulse radiation related to higher-order nonlinearity of the cavity fiber and to splicing of fibers with opposite sign of frequency dispersion. In both cases, these mechanisms result in periodical oscillations of the intensity and other parameters of an isolated soliton. These oscillations, in turn, give rise to stochastization of solitons in an ensemble of interacting solitons. Undoubtedly, other destabilization mechanisms of intra-pulse stationary intensity distribution of radiation are also possible.

Earlier, we discussed noise-like pulses in fiber lasers with anomalous cavity dispersion where solitons are formed due to nonlinearity and refractive index dispersion of the cavity medium. A thorough experimental study of noise-like pulses in such a laser was conducted in [55]. The authors worked with an erbium-doped fiber laser where nonlinear losses arose from nonlinear polarization rotation. On the basis of their experimental data and numerical modeling, the authors came to the conclusion that noise-like pulse generation is a natural generation regime in fiber lasers, resulting from combined action of soliton collapse and the reduction of cavity losses at higher radiation intensities. The authors of this work did not discuss the mechanism of noise-like pulse stabilization.

In work [56], Zhao *et al.* reported the generation of specific noise-like pulses in an erbium-doped fiber laser with polarization rotation and purely positive cavity dispersion. Their experimental data and numerical modeling showed that in the case of positive dispersion, a different mechanism of noise-like pulse formation emerges. In this case, when the peak power reaches a certain critical level, any further increase of pump power does not result in higher output peak power. It does, however, amplify dispersion waves and background noise, leading to noise-like pulse formation. It is worth noting that in the case of negative cavity dispersion, the mechanism of peak power limitation related to the technique of nonlinear polarization rotation leads to quantization of intra-cavity radiation into separate identical pulses and to multi-pulse passive mode locking [36,37]. As opposed to the generation of noise-like pulses in conventional soliton lasers where the state of noise-like pulse always emerges abruptly as the control parameter is continuously adjusted, a laser with positive cavity dispersion starts emitting noise-like pulses gradually.

The effect of additional devices on the formation of noise-like pulses in fiber lasers was studied by many researchers. The authors of works [57,58] observed transition from multi-pulse generation into noise-like pulses with additional filtration of radiation in an ytterbium-doped laser with positive cavity dispersion. Nonlinear losses were created by a saturable absorber. In [59], a numerical and experimental study is reported of the generation and evolution of noise-like pulses in an ytterbium-doped mode-locked fiber laser with nonlinear polarization rotation (NPR) and total normal dispersion. The results clearly demonstrate that amplitude modulation provided by inverse saturation of absorption and the effect of peak power limitation by NPR may lead to oscillation of the fine structure of noise-like pulses. The authors of [60] observe for the first time bound states of noise-like pulses in ytterbium-doped fiber lasers with normal dispersion. The mechanism of emergence of these bound states stems from the Raman effect. At present, physics and technology of noise-like pulses continue to attract significant attention of the research community.

3. PROPERTIES OF NOISE-LIKE PULSES

The general features of noise-like pulses have already been mentioned in Section 1, but now we will take a closer look at their properties. One of the important traits of noise-like pulses is their ability to carry high energy. Moreover, this may be achieved directly in a laser cavity (∼12 μJ [61]). Sometimes the noise-like generation regime may develop from the generation of conventional solitons at higher pumping radiation powers [62]. The energy level in the vicinity of 10 μJ [63] may be considered the highest attainable with noise-like pulses today. The ability of noise-like pulses to contain relatively high energy translates into high average radiation power [15,16,23,64–69]. High energy parameters of noise-like pulses make them efficient as pumping radiation [70], and their temporal energy distribution allows modification of conventional pulse amplification techniques [71]. These techniques are nowadays becoming more important in relation to ways of soliton conversion into noise-like pulses and *vice versa* [15,72].

Noise-like pulses are gradually becoming more and more in demand. At the moment, there is little doubt in the efficiency of noise-like pulses as used for supercontinuum (SC) generation. One of the important properties of noise-like pulses in relation to the generation of SC with the highest uniformity of spectral radiation distribution is the smooth spectral distribution of noise-like pulse radiation that does not exhibit sharp features, such as Kelly sidebands [73], and so forth. It is also important that the radiation spectrum of noise-like pulses is inherently broad. In particular, it may span the area of zero dispersion of the medium (usually, optical fiber) where spectral broadening of the initial pulses occurs especially rapidly [74]. Even though noise-like pulses with a spectrum lying far from the medium zero dispersion also generate SC, the resulting SC spectrum is comparatively narrow [75]. Naturally, the peak radiation power of subpulses within the noise-like pulse plays a likewise important role, producing the entire range of nonlinear effects that participate in SC formation [76] and ensure relatively high spectral power density of SC. It is because of these strong nonlinear effects that SC generation resulting from noise-like pulses was possible in optical fibers with conventional core and in fibers with the zero-dispersion wavelength far from the spectrum of noise-like pulses. To the present day, SC pumped by noise-like pulses has been demonstrated in various optical fibers, including microfiber [77], photonic crystal fiber [78], dispersion-shifted fiber [79], highly nonlinear fiber [80–85], standard fiber [74,86–89], P_2O_5-doped silica fiber [90], Tellurite fiber [91], and a combination of fibers [92,93]. Besides, SC was observed directly in a laser capable of noise-like pulse generation [94,95] and in the process of noise-like pulse amplification [96]. These types of SC cannot be properly compared since their spectra differ not only in the width, but also in the degree of nonuniformity of radiation spectral distribution, and in dephasing of the field oscillations at different wavelengths, which was not often measured. One may list as preferable approaches SC generation in the standard fiber, in a laser, and in an amplifier.

It should be noted that the spectral width of noise-like pulses may exceed 100 nm [97] (and reach several hundred nanometers [46]). This is why in such cases noise-like pulses could be called "mini supercontinuum." These pulses may exhibit spectral width in excess of 300 nm [98], in other words exceeding the gain bandwidth of the active medium. Modeling demonstrates that such excess may be as high as by an order of magnitude [48].

Supercontinuum or mini supercontinuum generated from noise-like pulses will definitely lack a stable phase relationship between oscillations in different spectral positions, but this is not so important for a number of applications, including WDM telecommunication [99]. If a question is posed about the type of SC easiest to produce, the answer will be the SC generated from noise-like pulses. The spectrum of noise-like pulses may be from the beginning much broader than that of any other pulses, which means that it is easier to expand it even further. Additionally, noise-like pulses may carry higher energy and trigger more nonlinear processes (more efficiently) that result in a broader SC spectrum. If one were to compare the complexity in producing unstructured ultra-short pulses and noise-like pulses, the advantage, again, will be in favor of the latter.

The ability of noise-like pulses to carry high radiation energy may be used both in technological applications, for instance, in remote industrial laser processing techniques [100–102], medical treatment [103–105], for laser initiation of explosive substances [106–108], for active medium pumping [70], and in many nonlinear processes. Second harmonic generation and Raman conversion of radiation may be efficiently implemented on the basis of noise-like pulses, as well [109–112].

Summarizing the foregoing discussion, it may be stated that the best applications of noise-like pulses are related to processes where the phase relationships between the electromagnetic oscillations at the input and output are not important, while the short pulse duration and energy are, on the contrary, crucial (the pulse train energy or peak power in the subpulses).

4. LOW COHERENCE DEGREE OF NOISE-LIKE PULSES

The coherence degree of noise-like pulses is assumed low due to their chaotic internal structure. However, direct measurements of this parameter have up until now been only conducted for inter-pulse coherence [12]. The absence of phase correlation between field oscillations in adjacent noise-like pulses was indicated by the zero visibility of interference fringes at the exit of a Michaelson interferometer, into which noise-like pulses were guided (the path difference of the interferometer was set equal to the cavity length). On the grounds of this measurement, the subsequent publications drew numerous conclusions about low coherence of noise-like pulses. It must be nevertheless emphasized that this original measurement was an indicator of inter-pulse (not intra-pulse) coherence of radiation in noise-like pulses. Moreover, this conclusion was drawn for very specific parameters of noise-like pulses; namely, the ratio of the narrow coherence peak amplitude to that of the broad pedestal of the auto-correlation function of those pulses was equal to 1 (coherence peak amplitude is measured from the pedestal). This parameter may vary from 1 to 0 (conventional solitons), and therefore a natural question arises as to whether or not this ratio may serve as a measure of noise-like pulse coherence. The corresponding experimental studies have not yet been conducted. For this, it will be necessary to generate noise-like pulses with an auto-correlation function that has different values of the ratio between the amplitude of the coherence peak in the center and that of the pedestal. Then, it will be necessary to measure the visibility of interference fringes with a Michaelson interferometer where the path difference may be varied within a range of the pulse duration. The ratio of the height of the coherence peak to that of the auto-correlation function pedestal would be quite convenient for estimation of the coherence degree of noise-like pulses because this function is almost always measured anyway in order to find the temporal parameters of the pulses within an ultra-short range of durations, which is inaccessible for oscilloscopes and other similar equipment. Simultaneous measurement of temporal and coherence properties of noise-like pulses from their auto-correlation function would be an efficient characterization method.

It must me noted that chaotization of the internal structure of a noise-like pulses is not the only decoherence mechanism in these pulses. Another important mechanism is phase modulation (chirp) that is present in any fiber laser cavity where the net dispersion is not intentionally compensated. Pulse chirp leads to the weakening (or absence) of interference between radiation from different parts of the pulse, and hence to a lower degree of coherence in such a pulse. Significant chirp may be the dominant cause of radiation decoherence in a pulse. Besides, in this case, the specific type of pulse may be of relatively secondary importance (whether it be a soliton or a noise-like pulse). In the case of noise-like pulses, the degree of coherence may be even lower if both mechanisms—chaotic internal structure and phase modulation—are active at the same time.

A. Autocorrelation Functions

These functions are widely used for the characterization of radiation properties. The autocorrelation function of the first order A_1 is defined as a convolution of the slow field amplitude $E(t)$:

$$A_1(\tau) = \int E(t)E^*(t-\tau)\mathrm{d}t = \int |E(\omega)|^2 \exp(-i\tau\omega)\mathrm{d}\omega, \tag{1}$$

where the fast-oscillating field amplitude $\mathcal{E}$ is related to the slow amplitude $E(t)$ as $\mathcal{E} = E\exp(i\omega_0 t) + E^*\exp(-i\omega_0 t)$, and ω_0 is the central frequency of the generated radiation. The complex degree of coherence $\gamma(\tau)$ is a normalized function of A_1 and may be written in the following way [113]:

$$\gamma(\tau) = \frac{\int |E(\omega)|^2 \exp(-i\tau\omega)\mathrm{d}\omega}{\int |E(\omega)|^2\mathrm{d}\omega}. \tag{2}$$

The absolute value of the complex degree of coherence $|\gamma(\tau)|$ represents the coherence degree of radiation and determines visibility of interference fringes V in various interference measurement methods, such as the Michaelson interferometer:

$$V \equiv \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = |\gamma(\tau)|, \tag{3}$$

where $I_{\max}$ and $I_{\min}$ are the maximum and minimum intensity values ($I = |E|^2$), respectively.

The autocorrelation function of the second order A_2 is introduced in a similar way:

$$A_2(\tau) = \int I(t)I^*(t-\tau)\mathrm{d}t. \tag{4}$$

Let us introduce an additional kind of correlation function that we will use further on:

$$A_{|1|}(\tau) = \int |E(t)|\,|E(t-\tau)|\,\mathrm{d}t. \tag{5}$$

Function (5), just as function (4), does not depend on phase modulation of the field. For a field with no phase modulation, functions (5) and (1) become identical. Therefore, correlation function (5) describes the degree of radiation decoherence, which is only related to its amplitude modulation. In this case, the decoherence due to phase modulation of radiation is not taken into account.

To which extent is it possible to extract the properties of autocorrelation function A_1 from those of function A_2? Expression (4) can be written in the following form:

$$A_2(\tau) = \int I(t)I^*(t-\tau)\mathrm{d}t = \iint (|E(t)|\,|E(t-\tau)|) \times \delta\left(t-t'\right)\left(\left|E(t')\right|\left|E\left(t'-\tau\right)\right|\right)\mathrm{d}t'\mathrm{d}t. \tag{6}$$

Representing the function $\delta(t-t')$ as $\delta(t-t') = \int \exp i\omega(t-t')\mathrm{d}\omega/2\pi$, we derive

$$A_2(\tau) = \frac{1}{2\pi}\int |F(\omega,\tau)|^2\mathrm{d}\omega, \tag{7}$$

where

$$F(\omega, \tau) = \int (|E(t)|\,|E(t-\tau)|)\, e^{i\omega t} \mathrm{d}t. \quad \textbf{(8)}$$

The integral of the bell-shaped function $|F(\omega, \tau)|^2$ in (7) may be estimated as

$$A_2(\tau) = \frac{1}{2\pi} |F\,(0, \tau)|^2_{\max} \Delta\omega. \quad \textbf{(9)}$$

The spectrum width $\Delta\omega$ is chosen so that the phase incursion over the duration of the noise-like pulse not exceed π. Taking into consideration that $|F(0, \tau)|^2_{\max} = A^2_{|1|}$, $\Delta\omega \approx 2\pi/\tau_p$ (where τ_p–noise-like pulse duration), we arrive at

$$A_{|1|} \approx \sqrt{\tau_p A_2}. \quad \textbf{(10)}$$

Therefore, autocorrelation function $A_2(\tau)$ allows finding out the autocorrelation function $A_{|1|}(\tau)$ that factors in decoherence arising from amplitude modulation of radiation, but does not include decoherence from phase modulation. It is clear that this function cannot provide a determination of the phase modulation decoherence since this information is simply absent in the autocorrelation function $A_2(\tau)$. A natural question arises: in which proportion does the decoherence described by autocorrelation function A_1 arise respectively from phase and amplitude modulation? Numerical modeling presented below demonstrates that the main contribution to decoherence of noise-like pulses comes from phase modulation of their radiation.

B. Autocorrelation Functions A_1, $A_{|1|}$, A_2 for Noise-like Pulses Obtained from Numerical Model

Shown in Fig. 5 is the temporal intensity distribution of a noise-like pulse. Solitons composing the noise-like pulse are in constant motion and evolution, emerging and dissolving.

Figure 6 shows the full set of used autocorrelation functions A_1, $A_{|1|}$, A_2, and $\sqrt{A_2}$ that depend on the delay time τ. Statistically averaged autocorrelation functions are reliable characteristics of noise-like radiation, including that of noise-like pulses in fiber lasers. The central peaks of the autocorrelation functions correspond to the correlation of each stochastically evolving soliton to itself (see Fig. 5). The wings of these autocorrelation functions reflect the correlation of each soliton to other solitons forming the noise-like pulse. The duration of these pedestals is determined by that of the noise-like pulse.

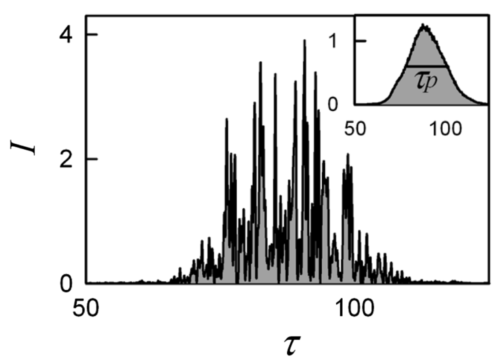

Fig. 5. Instance of the instantaneous temporal intensity distribution within a noise-like pulse $I(\tau)$ in a generation regime established after a transient process. The inset shows the averaged intensity profile of the noise-like pulse. The resulting pulse duration is $\tau_p = 23.3$.

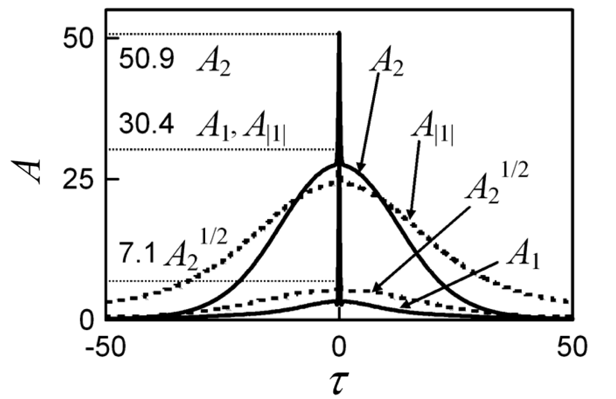

Fig. 6. Autocorrelation functions A_1, A_2 (solid curves) and functions $A_{|1|}$, $\sqrt{A_2}$ (dashed curves) calculated for established generation of noise-like pulses (Fig. 1). The functions values were averaged over 2.5×10^3 cavity round trips. The maxima of the corresponding functions are given to the left of their plots.

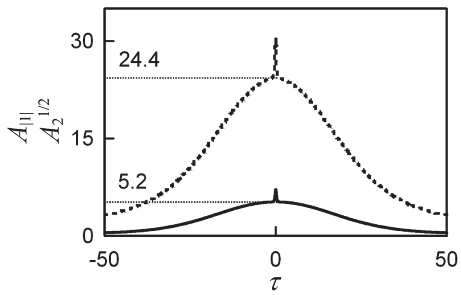

Fig. 7. Autocorrelation functions $A_{|1|}$ (dashed curve) and $\sqrt{A_2}$ (solid curve). The heights of their pedestals are indicated.

The degree of coherence $|\gamma(\tau)|$ as a function of delay time τ, for noise-like pulses, varies between 1 and 0. It is convenient for characterization of the generated noise-like pulses to use—instead of a functional dependence $|\gamma(\tau)|$—a single figure γ, namely the coherence degree in a point of the pedestal immediately next to the central peak: $\gamma = h_p/h_m$, where h_p is the pedestal magnitude and h_m is the highest intensity value in the central peak of the correlation function.

Shown in Fig. 7 are autocorrelation functions $A_{|1|}$ and $\sqrt{A_2}$ with their pedestal height specified. From these values for $A_{|1|}$, we can derive the coherence degree of the noise-like pulse $\gamma_{|1|}$ that takes into account amplitude, but not phase modulation: $\gamma_{|1|} = h_{|1|p}/h_{|1|m} = 24.38/30.35 = 0.80$:

$$\gamma_{|1|} = \frac{h_{|1|p}}{h_{|1|m}}, \quad \textbf{(11)}$$

where $h_{|1|p}$ is the pedestal height for function $A_{|1|}$ and $h_{|1|m}$ is its maximal value.

Using expression (10), we can calculate an approximated value of $\gamma_{|1|}$ through the parameters of autocorrelation function A_2 (the pedestal height h_{2p} and the function's maximal value h_{2m}):

$$\gamma_{|1|} \approx \sqrt{\frac{h_{2p}}{h_{2m}}}. \quad \textbf{(12)}$$

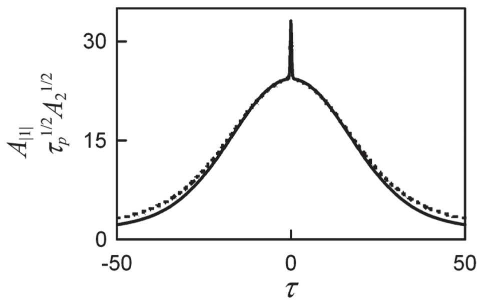

Fig. 8. Autocorrelation function $A_{|1|}(\tau)$ (solid curve) and its approximation $\sqrt{\tau_p A_2(\tau)}$ with $\tau_p = 21.25$ (dashed curve).

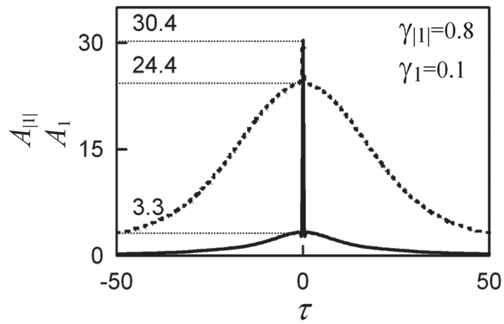

Fig. 9. Autocorrelation function $A_{|1|}$ (dashed curve) and A_1 (solid curve). Their peak amplitude and pedestal values are provided, as are the corresponding degrees of coherence $\gamma_{|1|}$ and γ_1.

From Eq. (12) and values of Fig. 7, we obtain $\gamma_{|1|} \approx 5.24/7.14 = 0.73$. In other words, the approximate value for the degree of coherence described by function $A_{|1|}$ derived from the parameters of correlation function A_2 differs by less than 10% from the accurate value calculated from Eq. (11). Note that for the autocorrelation function A_2, the pedestal-to-peak ratio is equal to $\gamma_2 = h_{2p}/h_{2m} = 0.54$, as follows from Fig. 6.

Figure 8 shows autocorrelation function $A_{|1|}(\tau)$ calculated by Eq. (5) and its approximate value obtained from autocorrelation function $A_2(\tau)$ according to Eq. (10). As can be seen from the figure, these dependencies are closely similar.

In Fig. 9, we presented autocorrelation functions $A_{|1|}(\tau)$ and $A_1(\tau)$. As was pointed out earlier, autocorrelation function $A_{|1|}(\tau)$ describes radiation decoherence only coming from amplitude modulation. Under such decoherence, the coherence degree remains high, $\gamma_{|1|} = 0.8$. Autocorrelation function $A_1(\tau)$ corresponds to radiation decoherence related to both amplitude and phase modulation. Accounting for phase modulation results in dramatic reduction of the coherence degree down to $\gamma_1 = 0.1$. This signifies that for noise-like pulses, phase modulation makes up an overwhelming contribution to decoherence. Phase modulation of noise-like pulses is related to frequency chirp of solitons forming such pulses. Frequency chirp is, in its turn, related to nonlinearity of the refraction index of the fiber that makes the laser cavity. From the presented analysis, it follows that such frequency chirp provides the main contribution to decoherence of radiation in laser that generate noise-like pulses.

Major conclusions

1) Autocorrelation function A_2 allows finding the radiation degree of coherence only related to its stochastic variation of amplitude (not factoring in phase changes).
2) In any case, autocorrelation function A_2 does not allow measurement of radiation's degree of coherence that arises from stochastic evolution of its phase because this function does not incorporate any information about the radiation phase.
3) For noise-like pulses, the radiation degree of coherence γ_1 related to stochastic changes in amplitude and phase is much lower than the analogous parameter $\gamma_{|1|}$, which is only related to stochastic evolution of the amplitude.

5. EXPERIMENTAL IMPLEMENTATION OF NOISE-LIKE PULSE GENERATION

As was mentioned before, the noise-like pulse generation regime has so far been demonstrated predominantly in mode-locked fiber lasers. Let us consider the configurations of such lasers that are most promising in this respect. In our choice of configurations, we will be guided by the following. First, we will not include those layouts that use conventional fiber-optical polarization controllers (whose principle of operation consists in mechanical action on the fiber) because they are impractical in everyday use. Very often, tuning of these controllers cannot be reproduced. Additionally, the settings of such a polarization controller may drift because of plastic deformation in quartz and poorly controlled tension used to fix the controller elements. Users of lasers containing fiber-optical polarization controllers will be doomed to regular chaotic (and therefore taking a long time) tuning of these controllers. Therefore, we will select those configurations that do not rely on fiber-optical polarization controllers. Naturally, we will emphasize all-fiber configurations and, in view of the previous point, those conforming to the "all-PM-fiber" design. Second, we will not consider the configurations using material-based saturable absorbers, which have a limited lifetime and rather narrow spectral range. The available variety of artificial saturable absorbers [114] featuring high damage threshold and ultra-fast recovery time, including some with electrically controllable parameters, allows the development of long-lived systems. Taking into account the above-presented considerations, the choice of possible solutions becomes fairly limited and includes only nine publications [17,115–122]. We will proceed now to analyze them.

All of these works use saturable absorbers made of loop mirrors containing either only passive fiber [115,118,121,122], a combination of passive and active fibers [17,116,117,119], or a combination of passive and absorbing fibers [120]. Optical layouts of these lasers are presented in Fig. 10. It should be noted that the average output power of these lasers is fairly stable. Where the power fluctuations were specified (in the majority of these articles), they hover around 1% and even less over times on the order of 1 s. This corroborates the possibility of a stable source of noise-like pulses. It is equally important that such a possibility was demonstrated in all three of the spectral ranges corresponding to the most widely used fiber-optical active media (Yb, Er, Tm). Generation efficiency in the majority

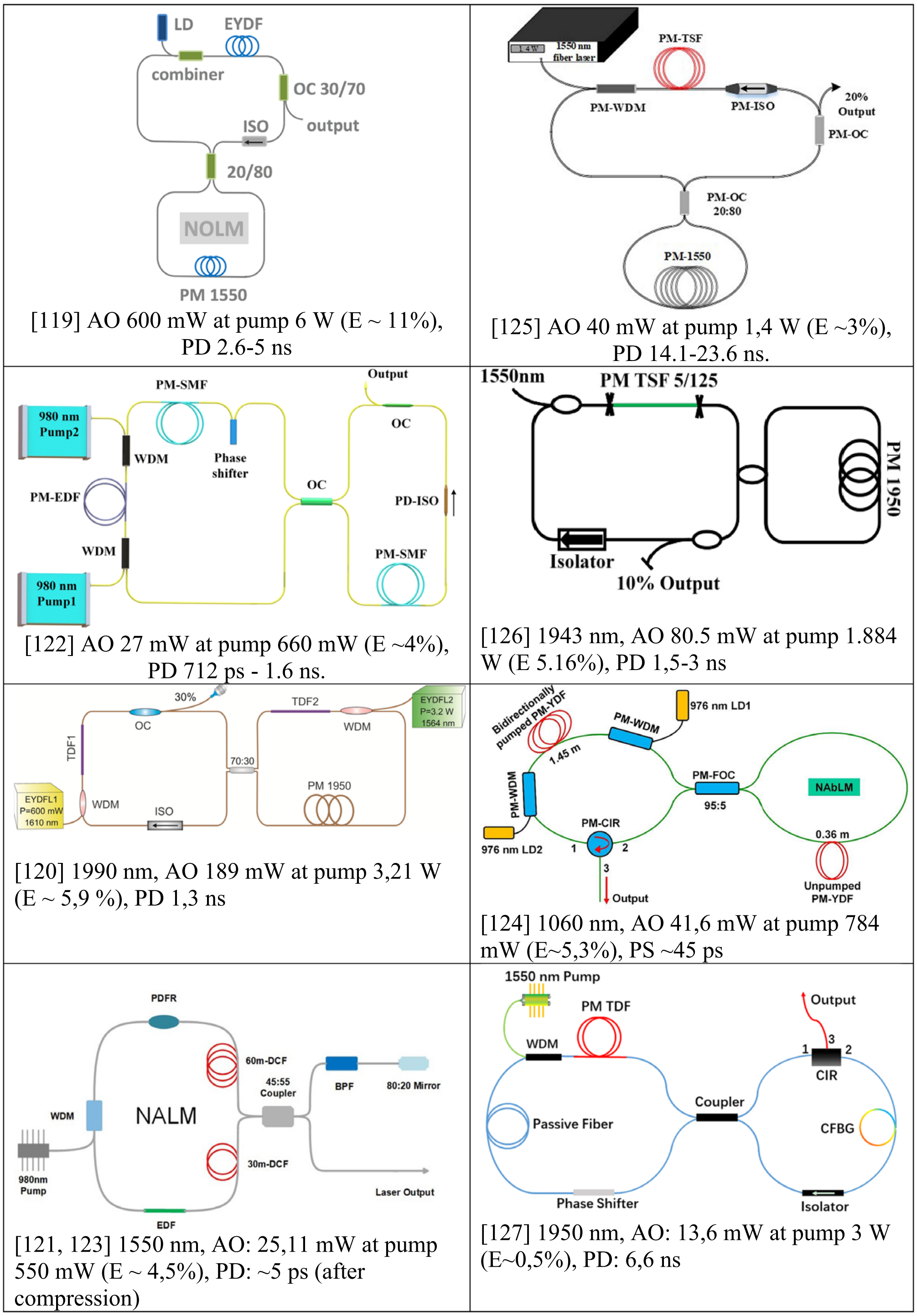

Fig. 10. Laser configurations producing noise-like pulses in "all-PM-fiber" format: AO, average output; E, efficiency; PD, pulse duration.

of the publications is around 5%, even though three of them report considerably higher (11% [116]) or lower (3% [121]) and (0.5% [17]) figures. It is certainly premature to draw any statistical conclusions from the analysis of these nine works, but it is possible to identify certain general approaches. First of all, it is inclusion of multiple pump sources (more than one). Due to the exclusion of polarization controllers, the only remaining continuously controllable element is the pump source, whose power may be adjusted arbitrarily. In order to broaden the possibilities of control, two separate pump sources for a single or two separate active media are used. Inclusion of two independently pumped active media in different [116] or in the same loop [123] of a figure-eight cavity may considerably improve flexibility of control and allows variation of noise-like pulse parameters in broader ranges. Second, it is application of the most widely used optical fiber in the saturable absorber. More complicated solutions using spatial, spectral, or other effects [114] do not appear in the optical configuration of these lasers. It should also be noted that all the discussed configurations are designed on the basis of commercially available components and may be reproduced in other than laboratory conditions.

6. CONCLUSION

A number of publications have been left out of this review, in which noise-like pulses were studied in lasers containing polarization controllers. The demonstration character of these works—often irreproducible because of too scanty descriptions of the tuning procedures for such controllers and high sensitivity of the generation properties to the ambient conditions—prevents considering these results as practically promising.

Noise-like pulse generation is quite frequent in mode-locked lasers, and this type of generation turned out preferable in a number of applications. Noise-like pulse generation is possible in the "all-PM-fiber" format, and the output power fluctuations may be reduced to 1% and even less. In combination with the possibility of high energies, these pulses deserve close attention, and sources of such pulses should be commercially available. Furthermore, certain applications (related to scientific, biological, and industrial processing) may be better optimized if noise-like pumping is used. The recent progress in study of noise-like pulse generation under various conditions makes it possible to controllably generate these pulses and adjust their parameters. The low degree of coherence of noise-like pulses (both inter- and intra-pulse) stands to enable novel applications of these pulses, including development of the incoherent laser. The unique properties of noise-like pulses, broad use of regimes producing such pulses, and wide choice of their applications present the necessary conditions for development of commercial models of noise-like pulse sources.

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Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

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