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*Communication*

# Noise-like Pulses as a Source of Pump Energy

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**Abstract:** This work analyses application particulars of noise-like pulses used as pulsed pump radiation for lasers (including Raman lasers) and amplifiers. The absence of a phase relationship between the electromagnetic field of the pump and that of the output laser radiation allows for a new application as a pump energy source of noise-like pulses, which may feature relatively high energy parameters. Questions related to this application are considered: configurations for noise-like pulse generation that hold a significant potential, specific aspects of amplification and compression, and characterisation of parameters of these pulses. Possibilities of the efficient application of noise-like pulses as pico- and nano-second pumping radiation are also discussed.

**Keywords:** noise-like pulses; fiber laser; pico- and nano-second pumping

## 1. Introduction

Noise-like pulses [1–5] are pico- or nano-second light pulse sequences containing significant numbers of randomly spaced sub-pulses with chaotic duration and amplitude. Such sequences may be generated in mode-locked fibre lasers. In recent years, studies have shown that these sequences may carry comparatively high radiation energy [6–10] and that their average radiation power is stable [11–13] (instability of the average output power may as low as 1% and even smaller) and relatively high [14–17]. Application of these pulses for the generation of super-continuum [18–21], higher harmonics [22–24], Raman radiation [25–27], and bio-medical uses [28] have demonstrated a significant practical potential for such types of pulsed radiation. However, this potential may actually be even higher if noise-like pulses are considered not only as relatively low-power radiation for the mentioned applications, but also as powerful pulsed pumping radiation with a more universal scope, which may be used for synchronous (or quasi-synchronous) pumping of lasers and/or amplifiers. These expectations are substantiated not only by the comparatively high energy parameters of noise-like pulses produced directly in master oscillators, but also by their straightforward amplification up to the average power levels exceeding 10 W [15] and relatively high slope efficiency of their generation [29] reaching 23%. The efficiency of noise-like pulse generation cannot be regarded as significant. Nevertheless, in combination with the relative simplicity of amplification of these pulses, such pumping may be practically viable. Using noise-like pulses as pumping pulses is interesting as these pulses can also combine relatively short duration with relatively high energy. Q-switched laser pulses or the active modulated pulsed lasers generated by optical chopping have a significantly longer pulse duration. The present work studies the feasibility of noise-like pulses as powerful pulsed pumping radiation for lasers and/or amplifiers.

## 2. Production of Noise-like Pulses

Although noise-like pulses are traditionally generated directly within lasers [30–32], there exist other ways of to produce them, in particular using an extra-cavity waveguide where solitons are transformed into noise-like pulses [33]. It is necessary to mention the great variety of laser cavity configurations in which noise-like pulses may be generated [34–37]. Their generation is predominantly possible in mode-locked operation,



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but such pulses may also be produced in Q-switched lasers [38]. Live control over the parameters of these pulses (degree of coherence, fluctuations of the average and/or peak power, and duration, as discussed later) is a complicated problem which cannot be solved without the introduction of new ideas and approaches.

The structure of noise-like pulses is non-trivial and includes many randomly spaced sub-pulses with random amplitude [3,4]. It was not a goal of the present work to study the properties of this structure. For our treatment, it is important that noise-like pulses may sustain relatively high average radiation power [14,15] and carry relatively high energy [10].

## 3. Characterisation of Noise-like Pulses

A salient trait of noise-like pulses is their auto-correlation function, exhibiting two distinct scales of features. This is why such pulses are sometimes termed "double-scale pulses" [2,39]. Essentially, this is the only certain measurable distinguishing feature of these pulses. There are no characteristic quantitative relations between the widths of the narrow and wide parts of their auto-correlation function (ACF), but they should differ broadly (the wide ACF part should be an order of magnitude wider or even more [40–42]).

Another specific feature of noise-like pulses is their broad radiation spectrum [43–46]. Again, here we do not have any quantitative measures. For this purpose, a wide spectrum may be defined as being much broader that the width arising from the reciprocal value of the ACF pedestal duration (i.e., one defined by the reciprocal of the duration of the noise-like pulse envelope).

## 4. Compression of Noise-like Pulses

Temporal compression of noise-like pulses is attractive from the perspective of raising their specific energy. However, the possibilities of such compression are limited and mostly exist in relation to the pulse envelope. One of the most significant compression results has been reported in [40], where the broad component of the noise-like pulses was compressed from 6.5 ps to 0.92 ps and the narrow component from 98 fs 62 fs. Subsequently [47], these results were slightly improved: the broad component could be shrunk from 6.26 ps to 0.69 ps and the narrow from 227 fs to 59.6 fs. In that study, compression was performed by two diffraction gratings. Experience indicates that reduction of the duration of the noise-like pulse envelope by an order of magnitude is possible, but unfortunately the compression element breaks the all-fibre configuration. Compression of the short sub-pulses inside the noise-like pulse envelope is not as effective (it is possible to reduce their duration by a factor of ~1.5 to 4), but again, such compression is incompatible with the all-fibre concept.

## 5. Amplification of Noise-like Pulses, Powerful Noise-like Pulses

For amplification of noise-like pulses, fibre-optical amplifiers are traditionally used [16,33,48], since these types of pulse are normally generated in fibre-optical master oscillators. This does not pose problems due to a comparatively long duration of the pulse envelope [49]. Such temporal "expansion" may be likened to the first stage of the well-known technology known as "chirped pulse amplification" (CPA) [50], in which amplification of optical pulses occurs after their preliminary temporal "expansion". If it is necessary to spread radiation over longer times, noise-like pulses may be elongated by the same methods used for conventional unstructured pulses. This is not often required because the necessary reduction of radiation exposure of the transmissive elements in the amplifier is achieved due to natural distribution of the radiation of noise-like pulses over time (i.e., relatively long wave packets). It should be noted that noise-like pulses with energies on the order of 10 μJ may be generated directly in master oscillators [7,9]. As such, the number of amplification stages for their subsequent boosting may be rather small. The average output power of radiation in the form of a noise-like pulse train may also be high and reach into the several-watt region in a master oscillator [8,14], while after amplification, it may go up to around 10 W [15,20].

## 6. Promising Configurations for Generation of Noise-like Pulses

As noted before, there exist a significant number of diverse laser configurations in which noise-like pulses may be produced. However, y no means are they all suitable for practical use and providing the end-user level of convenience.

First, this concerns the use of fibre-optical polarisation controllers [51], whose settings are practically irreproducible due to poorly controllable manual operations with the fibre during fabrication of the controller and due to the absence of detailed descriptions of the procedures to be followed in order to arrive at the necessary settings. A good deal of the published research does not provide anything more detailed than the phrase "when the proper adjustments are achieved, this or that result will be obtained". Moreover, even after the "proper adjustments" have been made, the settings of fibre-optical polarisation controllers tend to creep (the so-called "polarisation drift") due to plastic deformation of the quartz fibre undergoing mechanical stress. In view of this, a promising configuration for production of noise-like pulses should not use fibre-optical polarisation controllers, whose poorly reproducible tuning needs to be constantly maintained. Hence, the polarisation state of radiation set by this element is prone to creep, leading to the corresponding drift in the parameters of the generated noise-like pulses or even the collapse of their generation.

Exclusion of polarisation controllers from the laser optical layout does not make the problem of noise-like pulse generation more difficult, nor does it complicate control over the parameters of noise-like pulse radiation. On the contrary, abandoning the polarisation mechanism of mode locking significantly reduces the dependence of the generation parameters upon ambient factors. The flexibility of tuning and laser parameter adjustment may be attained, instead, by variation of other components' properties (for example, material [52] or artificial absorbers [53], etc.).

One may try to automate tuning of the polarisation controller(s). However, such automatic motorised tuning is not convenient because: (1) this tuning may be needed frequently and often takes considerable time and (2) such tuning requires additional measurement equipment in order to monitor the adjustment results. This equipment may require not only arapid photodetector and a fast oscilloscope, but also an auto-correlator and/or a broad-band spectrum analyser. It is possible to speed up the adjustment procedure by implementing a generic algorithm, but the need for this adjustment remains.

The absence of a polarisation controller does not prevent the attainment of significant energy in noise-like pulses. Lasers only using polarization-maintaining components ([54–56]) serve to confirm this.

The second element, which it would be better to avoid, is a material-based saturable absorber. Such absorbers have a limited lifetime (even though it may be relatively long, ranging from 3 to 5 thousand hours) and, as such, their properties progressively degrade [57]. For their replacement, there are many competing solutions based on artificial saturable absorption [53].

The third property expected of a promising configuration for generation of noise-like pulses is that it should only use PM-elements and PM fibre for minimisation of external perturbations and the effects arising from fibre laying. Naturally, one should also avoid, as much as possible, volumetric non-fibre elements in order to keep the configuration within the all-PM-fibre concept.

The foregoing requirements of configurations for production of noise-like pulses are not unfeasible. The possibility of implementing configurations satisfying these requirements has already been demonstrated [54–56]. Demonstration of reliable and convenient configurations for the generation of noise-like pulses opens avenues for a broader application of these types of pulses, including as pumping source.

## 7. Discussion

When noise-like pulses are considered in their application as pumping radiation for a laser's or amplifier's active medium, their duration may be taken to be that of the total pulse envelope containing multiple sub-pulses. Conventionally, this duration lies within the pico- to nano-second range in the absence of separate compression of these pulses [54–56]. Previously, synchronous pumping of a dye-jet laser, for instance, was performed with a train of sub-nanosecond pulses generated by an argon laser [58]. It is important to note that generation of relatively short pulses is not technically difficult in most implementations. On the other hand, synchronous pumping is significantly less widespread when used for mode locking than saturable absorbers are. This arises from the requirement in synchronous pumping that the laser cavity length be matched to the pumping pulse repetition rate. The production of relatively short-pulsed radiation is not a universally solvable problem. When saturable absorbers are used, these problems are not encountered (even though other problems are present [53]). This is why, perhaps, passive mode locking is more often used in lasers for generation of short radiation pulses. However, after a comparison of the mentioned approaches in terms of the key parameters (including minimal number of intra-cavity elements, operation lifetime, and efficiency), synchronous pumping does not appear as definitely inferior. Furthermore, synchronous pumping may be appealing due to the possibility of short output pulses that are substantially shorter than the pumping pulses [59–61]. The emergence of another potential source useable for synchronous pumping—especially a fibre-based one—stands to significantly widen the application area of this mode locking method.

Non-standard sources of pumping radiation (pulse-burst picosecond [62] or ASE sources [63]) are also used practically. Similar to the considered method, the pump source provides the required radiation energy in the above cases, while the specific form in which this energy will be delivered is of secondary importance. First, the considerations related to the user requirements are considered. This is why, for example, diode lasers with high output divergence (affordable and readily available) are used for cladding pumping of fibre devices. Noise-like pulses that can deliver significant radiation energy also feature other parameters suitable for synchronous pumping of fibre lasers and amplifiers.

It is pertinent to note the broad spectral range in which noise-like pulse generation is possible. The fundamental radiation of such pulses was demonstrated to be around 1 µm [2,14,64], 1.5 µm [1,3,15], and 2 µm [9,12,13,16,17]. Efficient non-linear transformation of noise-like pulses is possible towards both the shorter (second-harmonic generation [23]) and longer wavelengths (Raman conversion [27]). It should be further noted that the relatively broad radiation spectrum of noise-like pulses [28] makes it possible to "hit" absorption lines of many active media. The spectral flexibility of noise-like pulses presents another advantage when they are used as pumping radiation.

In our work, we do not study the aspects of applications of noise-like pulses for solving various problems other than from using them as pumping radiation for other lasers.

## 8. Conclusions

Use of noise-like pulses as pumping radiation in processes lacking phase relationships between the pumping and output electromagnetic field opens up a broad field of application for these pulses. Furthermore, noise-like pulses can carry relatively high radiation energy and maintain relatively high average radiation power. This is why these types of pulses are promising as a source of powerful pulsed pumping. Noise-like pulses may be produced in relatively simple configurations, their amplification does not require special methods, and they may be characterised by well-defined methods. The envelope duration of noise-like pulses lies within the pico- to nano-second range, thus suggesting significant potential of much shorter generated output pulses.

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