Laser radiation producing no interference speckle patterns

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Abstract

Approaches to development of an incoherent laser are analysed. Implementation of such a laser on the basis of noise-like pulse generation is discussed. Fairly high stability of the average out-put power in such a regime leads to contemplation of practical avenues to development of an incoherent laser relying on noise-like pulses. Implementation of such a laser on the basis of the fibre-optical platform further poses such requirements as all-fibre design using polarisation-maintaining fibre and adoption of alternatives to material-based saturable absorbers. Applica-tions are demonstrated in which an incoherent laser—a radically new source of optical radiation—is a requirement. Laser layouts are shown, which are close to the desired layout of the incoherent laser

Keywords: incoherent laser, noise-like pulses, fibre-optical platform

Introduction

Normally, laser radiation is highly coherent, thus leading to random interference of incident upon and reflected from a surface laser beams, which forms a typical speckled pattern [1]. This speckle structure is an unwanted effect in many cases, including applications that involve observation of an image illuminated by laser light (laser projection systems and so on [2]). A good deal of research is dedicated to reduction of speckle structure contrast [3–10]. Methods of contrast reduction may be provisionally classified into two categories: 'internal' and 'external'. The 'internal' methods directly aim to achieve low coherence of the laser radiation itself, whereas the 'external' methods are used to reduce the existing coherence of radiation, which are usually applied outside the laser source. Among the 'internal' methods are classed the ways of spectral line broadening (up to super-continuum [11, 12]), application of random feed-back [5, 13], weakening of speckle pattern contrast due to polarisation and angular effects [14]. In the present work, we would like to draw the reader's attention to still another method, which may be efficient in as the basis of a laser capable of producing speckle-free images. We refer to special generation regimes usually observed in fibre lasers, in which the laser emits a regular train of so-called noise-like pulses [15–17]. The appellation originated from the random envelope observed as a result of many sub-pulses with varying magnitude and duration. Essentially, each of these envelopes or pulses represents a unique combination of sub-pulses with random parameters. Despite random distribution of sub-pulses in each pulse of the train, the laser running in the regime of noise-like pulse generation exhibits rather stable average parameters, the instability of the output radiation power, in particular, not exceeding few per cent [18–21].

Incoherent laser

1.1 Structure of noise-like pulses

Random distribution of the amplitude, duration, and relative delay of the sub-pulses in the train of the resulting pulses exhibits a distribution of electro-magnetic field within each compact wave packed resembling a chaotic or noise-like one (a typical profile of noise-like pulses is given in Fig. 1).

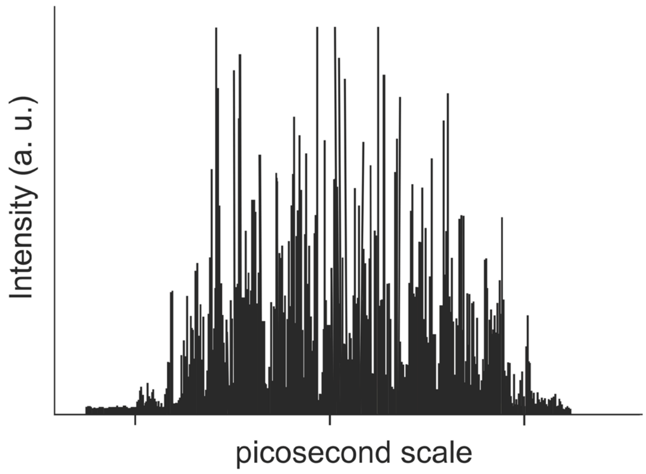

Figure 1. A typical profile of noise-like pulses.

Measurement of coherent properties of these pulses [22–24] have shown either absence or only marginal presence of phase relationship between the field in successive pulses. Qualitatively, the absence of phase correlations was established, though quantitative estimations of the radiation coherence degree have not been made to date. It is obvious that this coherence degree is close to zero, but works [22, 23] did not present estimates of its numerical value. Furthermore, the scope of studies did not comprehend the question of influence of generation parameters (especially, such as the type of mode locker or excess over the generation threshold) upon the degree of coherence. Perhaps, this influence (if it be found at all) will be mostly observable in the domain of low coherence degree, but certain conditions may lead to much greater degrees of coherence around ~0.5 [24]. If we choose to consider the conditions leading to absence of phase correlations between optical field oscillations in adjacent wave packets, they make it possible to create an incoherent laser. This would be a laser, in which conventional properties of laser radiation (high directivity and brightness) are combined with a quite non-laser feature of output radiation, virtual lack of coherence. In other words, the regime of noise-like pulse generation enables a new type of lasers, whose radiation does not produce such an undesirable effect as speckle interference. Development of a source of incoherent (or low-coherence) radiation on the basis of noise-like pulse generation is promising because the average output power of such generation is rather stable despite chaotic distribution of the optical field within each wave packet.

1.2. Laser radiation without specles

Laser sources of incoherent radiation are radically new sources of optical radiation combining the radiation properties conventionally associated with lasers (high directivity, high intensity, ultra-short light pulses) with those generally inherent in light sources lacking any correlation within the light field (such as incandescent sources, LED, spontaneous radiation). Laser sources of incoherent or low-coherence radiation are needed in a host of applications where unwanted interference caused by radiation coherence may adversely impact the result of using laser radiation. Among these applications one finds laser projection systems (‘laser television’, elimination of speckle noise from diffusively scattered coherent radiation), many modes of material processing (removal of light field modulation arising from mutual interference among many components of coherent radiation), many bio-medical applications (reduction of interference in coherent radiation scattered from rough surface of skin or within a solid volume), and so forth. Development of new radiation sources demanded by the user community (laser sources of incoherent radiation) opens up the way to perfection of many heretofore existing technologies and to introduction of new ones.

1.3. Configurations for noise-like pulse generation

Among the simplest ways of producing noise-like pulses, one may use relatively long resonant cavities (hundreds of metres or even exceeding a kilometre) [18, 25–28] and the effect of non-linear polarisation evolution [29] for laser mode locking. Elongation of laser cavities may have stemmed from the desire to intensify non-linear effects [30] and, most certainly, to raise the pulse energy [31, 32]. Impracticality of this method for generation of noise-like pulses arises from the need to use radiation polarisation controllers, which latter, implemented as fibre-optical components, require monitoring of the output radiation and lack stability (due to plastic deformation of quartz, etc.), whereas implemented with discrete elements also require monitoring of the output radiation and additionally break the all-fibre concept. It must be noted here that the first noise-like pulses were also generated in comparatively long cavities, but in those days the term ‘long cavity’ was used to designate lengths of the order of 10 m [15]. Nevertheless, numerous later implementations of such a generation regime have shown that the correspondingly greater values of dispersion or birefringence do not play a major role in generation of noise-like pulses, and they began to be produced in rather short cavities mode-locked due to other mechanisms of artificial saturation of absorption [33-39]. Some time ago, research was undertaken in order to find out whether noise-like pulses might have giant chirp [26] and their compression might be possible [40]. It was established that sub-pulses of noise-like pulses do not have giant chirp and, therefore, noise-like pulses are not amenable to significant compression [41].

1.4. Control of the noise-like pulse content

Even though in general the filling of noise-like pulses is quite chaotic [42], the degree of this chaos may, nevertheless, be amenable to adjustment [19, 22, 43–46]. Of course, the degree of radiation coherence arising from phase relationships among the optical field oscillations in adjacent pulses lies within the ~0–0.5 range, i.e. comparatively low, but minimisation of this correlation leads to the goal of lasers producing incoherent radiation. It should be pointed out that in the above-mentioned publications there is no universal element for 'adjustment' of the coherence degree of noise-like pulses. Different configurations implement this adjustment in different ways. Controllers of radiation polarisation used in some of these configurations cannot perform such a function because their settings practically cannot be reproduced, their other drawbacks listed earlier on. Furthermore, because the stated (or analysed) goal is to minimise the total radiation coherence, solutions are used that minimise not only the temporal, but also spatial coherence of generated radiation [47]. Also, for user convenience, such sources are preferably implemented as all-fibre systems [48], which, in its turn, complicates the task of adjustment and minimisation of the output degree of coherence. It is important to mention that the problem of precise control over exceptionally complex dynamics of the fine internal structure of noise-like pulses is far from trivial and still remains be solved in the general case.

1.5. Configurations producing noise-like pulses that may become the foundation of the incoherent laser

Quite a number of various configurations for generation of noise-like pulses have been to date explored, but not every one of them could expand beyond the laboratory and become the base of a new commercial product. First of all, those of them are preferred, of course, which may be implemented as all-fibre layouts. In developing a source of noise-like pulses, it is a natural desire to retain all the advantages brought by all-fibre lasers. Secondly, in cases where the laser optical train is made of polarisation-maintaining fibre, it is possible to avoid fibre-optical polarisation controllers (their problems were discussed in the foregoing sections) and thereby significantly reduce the effect of the ambient conditions on the laser output properties. Third, ruling out material-based saturable absorbers in favour of their artificial counterparts prolongs quite substantially the system's lifetime. Additionally, the properties of artificial absorbers may be electrically controlled. Selection of possible configurations according to these three considerations produces, as a first approximation, the configurations presented in [20, 21, 37], but they do not allow any interactive control over the radiation coherence.

Conclusion

The presented analysis of ways to development of an incoherent laser has shown that such a laser may be implemented on the basis of generation regimes producing noise-like pulses. Noise-like distribution of amplitude, duration, and relative delay of sub-pulses in the output pulse train breaks phase relationships among the optical field oscillations in neighbouring wave packets. All-fibre configuration solutions for noise-like pulse generation have already been demonstrated that use polarisation-maintaining fibre and artificial saturable absorbers for passive mode locking. However, the problem of live control over the relatively low coherence degree of noise-like pulses remains still to be solved. Perhaps, this problem may be solved with the help of absorbers featuring electrically adjustable properties [49].

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References

[1] Francon M 1979 Laser speckle and applications in optics (Academic Press) ISBN 978-0-12-265760-3.
[2] Busker M 2008 Laser projection: coupling optics, light management, and speckle reduction. (VDM Verlag Dr. Müller) ISBN 978-3-63-909556-2.
[3] Rogowska J 2006 Chapter 11 - Digital image processing techniques for speckle reduction, enhancement, and segmentation of optical coherence tomography (OCT) images - in book "Optical Coherence Tomography. Principles and Applications", p. 305-329, 329a (Academic Press) ISBN 978-0-12-133570-0.
[4] Ouyang G, Tong Z, Akram M, Wang K, Kartashov V, Yan X and Chen X 2010 Speckle reduction using a motionless diffractive optical element *Opt. Lett.* **35** 2852-54.
[5] Fotiadi A 2010 An incoherent fibre laser *Nature Photonics* **4** 204–5.
[6] Bianco V, Memmolo P, Leo M, Montresor S, Distante C, Paturzo M, Picart P, Javidi B and Ferraro P. 2018 Strategies for reducing speckle noise in digital holography *Light Sci. Appl.* **7** 48.
[7] Prygun A, Morozov Y, Kliuieva T, Borodin Y and Le Z 2019 Completely passive method of speckle reduction utilizing static multimode optical fibre and two-dimensional diffractive optical element *J. Mod. Opt.* **66** (16) 1688-94.

[8] Ma X, Wang A, Ma F, Wu S and Ming H 2020 Speckle reduction using phase plate array and lens array *Opto-Electron. Adv.* **3** 190036.
[9] Kompanets I and Zalyapin N 2020 Methods and devices of speckle-noise suppression (review) *OPJ*, **10** (10) 219-250.
[10] Kumar V, Kumar A, Mayank D, Veena G, Ankit S, Dalip B and Mehta S 2021 Speckle noise reduction strategies in laser-based projection imaging, fluorescence microscopy, and digital holography with uniform illumination, improved image sharpness, and resolution *Opt. Laser Technol.*, **141** 107079**.**
[11] Ma R, Zhang W, Guo J and Rao Y 2018 Decoherence of fiber supercontinuum light source for speckle-free imaging *Opt. Express* **26** 26758-65**.**
[12] Boobhun J, Otten D, Skinner W and Lancaster D 2020 Supercontinuum laser illumination for NIR reflectance spectroscopy of minerals and speckle reduction *14th Pacific Rim Conference on Lasers and Electro-Optics (CLEO PR)* OSA Technical Digest (Optica Publishing Group), paper C12B_3.
[13] Cao H, Redding B and Choma M 2013 Tailoring the spatial coherence of random lasers. 2013 *Conference on Lasers & Electro-Optics Europe & International Quantum Electronics Conference CLEO EUROPE/IQEC*, pp. 1-1.
[14] Trisnadi J 2002 Speckle contrast reduction in laser projection displays. Proc. SPIE **4657** 131-7.
[15] Horowitz M, Barad Y and Silberberg Y 1997 Noiselike pulses with a broadband spectrum generated from an erbium-doped fiber laser *Opt. Lett.* **22** 799–801.
[16] Jeong Y, Vazquez-Zuniga L, Lee S and Kwon Y 2014 On the formation of noise-like pulses in fiber ring cavity configurations *Opt. Fiber Technol.* **20** (6) 575-92.
[17] Komarov A, Komarov K and Zhao L 2019 Mechanism of formation of noiselike pulses in passively mode-locked fiber lasers *Phys. Rev. A* **100** 033829.
[18] Pan C, Zaytsev A, You Y and Lin C 2016 Chapter 10 - Fiber-laser-generated noise-like pulses and their applications – in book "Fiber laser" (InTechOpen). ISBN 978-9-53-512257-9.
[19] Dong Z, Tian J, Li R, Cui Y, Zhang W and Song Y 2020 Conventional soliton and noise-like pulse generated in an Er-doped fiber laser with carbon nanotube saturable absorbers *Appl. Sci.* **10** 5536.
[20] Wang M, Liu M, Chen Y, Ouyang D, Zhao J, Pei J and Ruan S 2021 Stable noise-like pulse generation in all-PM mode-locked Tm-doped fiber laser based on NOLM *Chin. Opt. Lett.* **19** 091402.
[21] Zhang Y, Zheng Y, Su X, Peng J, Yu H, Sun T and Zhang H 2022 All-polarization maintaining noise-like pulse from mode-locked Thulium-doped fiber laser based on nonlinear loop mirror *IEEE Photon. J.* **14** (1) 1512305.
[22] Runge A, Aguergaray C, Broderick N and Erkintalo M 2013 Coherence and single-shot spectra of noise-like pulse trains 2013 *Conference on Lasers & Electro-Optics Europe & International Quantum Electronics Conference CLEO EUROPE/IQEC*, pp. 1-1.
[23] Runge A, Aguergaray C, Broderick N and Erkintalo M 2013 Coherence and shot-to-shot spectral fluctuations in noise-like ultrafast fiber lasers *Opt. Lett.* **38** 4327-30.
[24] Zhou R, Li Q, Fu H and Nakkeeran K 2021 Quasi-coherent noise-like pulses in a mode-locked fiber laser with a 3D rotatable polarization beam splitter *Opt. Lett.* **46** 1305-08.
[25] Kobtsev S, Kukarin S and Fedotov Y 2008 Ultra-low repetition rate mode-locked fiber laser with high-energy pulses *Opt. Express* **16** (26) 21936-41.
[26] Kelleher E, Travers J, Ippen E, Sun Z, Ferrari A, Popov S and Taylor J 2009 Generation and direct measurement of giant chirp in a passively mode-locked laser *Opt. Lett.* **34** 3526-8.
[27] Boucon A, Barviau B, Fatome J, Finot C, Sylvestre T, Lee M, Grelu P and Millot G 2012 Noise-like pulses generated at high harmonics in a partially-mode-locked km-long Raman fiber laser *Appl. Phys. B* **106** 283–7.
[28] Li K, Tian J, Guoyu H, Xu R and Song Y 2017 Observation of self-mode-locked noise-like pulses from a net normal dispersion erbium-doped fiber laser *Laser Phys. Lett.* **14** 045101.
[29] Matsas V, Newson T, Richardson D and Payne D 1992 Self-starting passively mode-locked fibre ring soliton laser exploiting nonlinear polarisation rotation *Electron. Lett.* **28** 1391.
[30] Donovan G 2015 Dynamics and statistics of noise-like pulses in modelocked lasers *Physica D: Nonlinear Phenomena* **309** 1-8.
[31] Ivanenko A, Kobtsev S, Smirnov S and Kemmer A 2016 Mode-locked long fibre master oscillator with intra-cavity power management and pulse energy > 12 µJ *Opt. Express* **24** (6) 6650-5.
[32] Wang M, Zhao J, Chen Y, Liu M, Ouyang D, Pei J and Ruan S 2021 10 µJ noise-like pulse generated from all fiberized Tm-doped fiber oscillator and amplifier *Opt. Express* **29** 10172-80.
[33] Horowitz M and Silberberg Y 1998 Control of noiselike pulse generation in Erbium-doped fiber lasers *IEEE Photon. Technol. Lett.* **10** (10) 1389-91.
[34] Tang D, Zhao L and Zhao B 2005 Soliton collapse and bunched noise-like pulse generation in a passively modelocked fiber ring laser *Opt. Express* **13** (7) 2289–94.
[35] Gao L, Zhu T, Wabnitz S, Liu M and Huang W 2016 Coherence loss of partially mode-locked fibre laser *Scientific Reports* **6** 24995.
[36] Wang Z, Wang Z, Liu Y, He T, Han S, Wang G, Yang G and Wang X 2018 Noise-like pulses generated from a passively mode-locked fiber laser with a WS_2 saturable absorber on microfiber *Laser Phys. Lett.* **15** 085103.
[37] Michalska M and Swiderski J 2019 Noise-like pulse generation using polarization maintaining mode-locked Thulium-doped fiber laser with nonlinear amplifying loop mirror *IEEE Photonics J.* **11** (5) 1504710.
[38] Ahma H, Ahmed M and Samion M 2020 Generation of mode-locked noise-like pulses in double-clad Tm-doped fibre laser with nonlinear optical loop mirror *J. Mod. Opt.* **67** (2) 146–52.

[39] Kobtsev S 2022 Artificial saturable absorbers for ultrafast fibre lasers *Opt. Fiber Technol.* **68** 102764.
[40] Smirnov S, Kobtsev S and Kukarin S 2015 Linear compression of chirped pulses in optical fibre with large step-index mode area *Opt. Express* **23** 3914-19.
[41] Zhang Z, Tian J, Xu C, Xu R and Song Y 2020 Noise-like pulse with a 690 fs pedestal generated from a nonlinear Yb-doped fiber amplification system *Chin. Opt. Lett.* **18** (12) 121403.
[42] Keren S and Horowitz M 2001 Interrogation of fiber gratings by use of low-coherence spectral interferometry of noiselike pulses *Opt. Lett.* **26** 328-30.
[43] Zaytsev A, Lin C, You Y, Tsai F, Wang C and Pan C 2013 A controllable noise-like operation regime in a Yb-doped dispersion-mapped fiber ring laser *Laser Phys. Lett.* **10** 045104.
[44] Kwon Y, Lee S, Park K, Lee D, Zuniga L and Jeong Y 2015 Numerical study on spectral coherence of noise-like pulses in a fiber ring cavity configuration 2015 *11th Conference on Lasers and Electro-Optics Pacific Rim* (CLEO-PR), pp. 1-2.
[45] Lee S, Vazquez-Zuniga L, Kwon Y, Kim H, Kim H and Jeong Y 2016 Experimental study on the coherence of non-stationary optical pulses generated from a ring laser cavity *Conference on Lasers and Electro-Optics*, OSA Technical Digest (Optica Publishing Group), paper STh4O.7.
[46] Chang S, Wang H, Wang Z and Yang H 2021 Generation of coherent multicolor noise-like pulse complex in Yb-doped fiber laser mode-locked by GIMF-SA *Opt. Express* **29** 14336-44.
[47] Chang W, Lin J, Liao T and Yang C 2018 Characteristics of noise-like pulse with broad bandwidth based on cascaded Raman scattering *Opt. Express* **26** 31808-16.
[48] Wang Q, Chen T, Li M, Zhang B, Lu Y and Chen K 2013 All-fiber ultrafast thulium-doped fiber ring laser with dissipative soliton and noise-like output in normal dispersion by single-wall carbon nanotubes *Appl. Phys. Lett.* **103** 011103.
[49] Kokhanovskiy A, Kobtsev S, Ivanenko A and Smirnov S 2018 Properties of artificial saturable absorbers based on NALM with two pumped active fibres *Laser Phys. Lett.* **15** (12) 125101.