Optical Fiber Technology xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Invited Paper

On the formation of noise-like pulses in fiber ring cavity configurations

Yoonchan Jeong *, Luis Alonso Vazquez-Zuniga, Seungjong Lee, Youngchul Kwon

Laser Engineering and Applications Laboratory, Department of Electrical and Computer Engineering, Seoul National University, 599 Gwanak-Ro, Gwanak-Gu, Seoul 151-744, Republic of Korea

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Noise-like pulses
Fiber lasers
Mode-locked lasers

ABSTRACT

We give an overview of the current status of fiber-based noise-like pulse (NLP) research conducted over the past decade, together with presenting the newly conducted, systematic study on their temporal, spectral, and coherence characteristics in nonlinear polarization rotation (NPR)-based erbium-doped fiber ring cavity configurations. Firstly, our study includes experimental investigations on the characteristic features of NLPs both in the net anomalous dispersion regime and in the net normal dispersion regime, in comparison with coherent optical pulses that can alternatively be obtained from the same cavity configurations, i.e., with the conventional and dissipative solitons. Secondly, our study includes numerical simulations on the formation of NLPs, utilizing a simplified, scalar-field model based on the characteristic transfer function of the NPR mechanism in conjunction with the split-step Fourier algorithm, which offer a great help in exploring the interrelationship between the NLP formation and various cavity parameters, and eventually present good agreement with the experimental results. We stress that if the cavity operates with excessively high gain, i.e., higher than the levels just required for generating coherent mode-locked pulses, i.e., conventional solitons and dissipative solitons, it may trigger NLPs, depending on the characteristic transfer function of the NPR mechanism induced in the cavity. In particular, the NPR transfer function is characterized by the critical saturation power and the linear loss ratio. Finally, we also report on the applications of the fiber-based NLP sources, including supercontinuum generation in a master-oscillator power amplifier configuration seeded by a fiber-based NLP source, as one typical example. We expect that the NLP-related research area will continue to expand, and that NLP-based sources will also find more applications in the future.

1. Introduction

Over the past decade, the passively mode-locked fiber laser (PMLFL) technology has made remarkable advances, thereby being capable of offering attractive and reliable solutions to a wide range of scientific and industrial applications, which include micromachining [1], optical metrology [2], and various biomedical applications such as multi-photon microscopy [3], optical-coherence tomography [4], and ophthalmology [5]. In fact, their numerous advantageous features inherited from fiber laser technology allow them to compete in terms of performance and practicality with other ultrafast laser technologies, including various bulk-type counterparts [6]. In particular, the waveguide architecture in a form of fiber allows for scalable high gain in single pass configurations, easy thermal management, and excellent spatial mode quality [7], notwithstanding its thin and long geometry in turn may give rise to undesirable nonlinear effects, such as self-phase modulation (SPM), stimulated Raman scattering (SRS), etc. The broad emission spectra readily achievable from rare-earth-doped fibers (~20 THz) are another merit to note for generating ultrashort pulses [8]. Furthermore, the alignment-free, all-fiberized compact configurations implemented to most PMLFLs eventually bring in unheard of practicality and reliability on top of their outstanding performance.

Up to date, a variety of operating regimes of PMLFLs have been demonstrated and investigated to generate stable, coherent ultrashort pulses, including the net anomalous dispersion regime that generates conventional soliton pulses [9], the dispersion-managed soliton regime [10], the self-similar pulse regime [11], the all-normal dispersion (ANDi) regime [12], and most recently the dissipative soliton resonance regime [13,14]. In general, the pulse energy routinely achievable from such sources ranges from sub-nJ to tens of nJ, depending on the operating regime [9–12].

It is noteworthy that while the above-mentioned operating regimes are supposed to generate stable, coherent ultrashort pulses in ordinary mode-locking conditions, it has also been reported that they can switch into extraordinary, the so-called

* Corresponding author.
E-mail address: yoonchan@snu.ac.kr (Y. Jeong).

http://dx.doi.org/10.1016/j.yofte.2014.07.004
1068-5200/

"noise-like pulse" (NLP) regime even in the very similar cavity configurations, generating a trail of "quasi-stable" packets of ultrashort pulses. This happens when some of the cavity parameters are tweaked from the ordinary operating conditions, e.g., when the cavity is highly pumped or the cavity loss or transmission is significantly altered [15,16]. Over the past decade, a number of research groups have reported and investigated such extraordinary features accompanied by a variety of types of PMLFLs [15–21]. It is also worth noting that the NLP formation appears regardless of cavity configurations or cavity dispersion regimes [15,18,19]. In general, although the NLPs are randomly generated and distributed, they can eventually form quasi-stable, bunched-pulses traveling at the fundamental repetition rate of the laser cavity [15]. The autocorrelation trace of such NLPs typically shows a coherence spike (or peak) in the femtosecond time scale located on top of a broad pedestal usually in the picosecond time range. In fact, the latter indicates the actual duration of a whole NLP packet. In addition, NLPs can form very broad output spectra, which are sometimes even broader than the gain bandwidth of the active fiber [20–22] if the intracavity nonlinear effects are significantly involved. These typical features of NLPs are indeed too extraordinary to simply overlook from a scientific point of view.

In particular, a series of research reports presented in recent years highlight that the study on the detailed nature of NLPs can provide a better understanding of the fundamental physics for pulse evolution in nonlinear fiber-optic media, including Raman rogue waves or dissipative solitons in fiber laser cavities [23,24]. In addition, fiber-based NLP sources make themselves useful in applications of low spectral coherence interferometry [25–27], micromachining [28], supercontinuum (SC) generation [29,30], etc. Thus, the impact of the decade-long research efforts on the fiber-based NLP sources cannot be underestimated. Here, we believe that it is timely to review the current status of fiber-based NLP research and give an overview of the general features of them, including the experimental and numerical investigations that have been done over the past decade, together with an in-depth systematic study on their temporal, spectral, and coherence characteristics for various key parameters of the laser cavity that has not been conducted thoroughly.

Hence, the structure of our discussion is given as follows: We begin the overview of the fiber-based NLPs in Section 2 with a brief literature review of the experimental and numerical studies carried out so far mostly over the past decade. It is worth noting that saturable absorber (SA) mechanisms based on nonlinear polarization rotation (NPR) or nonlinear optical loop mirror (NOLM) have frequently been used to force laser cavities to operate in NLP regimes [15–22]. Although NLP regimes are not limited to such configurations [31], a simple adjustment of the polarization state of the cavity mode in those configurations can lead to a relatively large amount of change in the effective SA function, thereby providing more degrees of freedom to switch between the normal coherent pulse regime and the NLP regime [31]. Thus, in Section 3 we focus on the NPR technique for the NLP generation, which we hope will help readers understand how various physical processes in the cavity eventually contribute to the NLP formation. In Section 4 we provide our own systematic experimental investigations, demonstrating the typical operating modes obtainable in NPR-based fiber ring cavity configurations. We investigate two mode-locked erbium-doped-fiber (EDF) ring cavity lasers operating in the net anomalous (NAD) regime and in the net normal dispersion (NND) regime. Besides the conventional solitons (CSs) and dissipative solitons (DSs) obtainable from the cavities in the NAD and NND regimes, respectively, we show how the adjustment of pumping power, linear cavity loss, or SA parameters can activate the formation of NLPs in the same cavity configurations. We also discuss the packet-to-packet coherence of the resultant NLPs via an additional experimental arrangement for a delay-line Michelson interferometer [32]. In addition, we briefly discuss another type of fiber-based NLPs which can form an intracavity broadband continuum (BC), including their noise characteristic analysis. In Section 5, we present a simplified numerical technique that can model the formation of NLPs for different conditions of the cavity transmission, and discuss the numerical results based on the technique in comparison with our experimental observations. In Section 6, together with various application examples of fiber-based NLP sources that have been reported in the literature, we present our own experimental results on the NLP-based SC generation in a master-oscillator power amplifier (MOPA) configuration as a typical example of their further applications. In Section 7, we finally give the conclusions of our discussion.

2. Review of fiber-based noise-like pulses

While a description of NLPs in a PMLFL started to appear in the literature in the early 1990s [33], a detailed investigation of their characteristics was first carried out by Horowitz et al. in 1997 [16]. Around that time, fiber-based NLPs started to receive a considerable amount of research attention because of their distinctive, extraordinary features contrasted with ordinarily mode-locked laser pulses [9]. The early results reported mainly on the various typical characteristics of NLPs for different cavity configurations, including anomalous and normal dispersion regimes [17], and also focused on describing the interrelationship between the specific NLP characteristics and the corresponding cavity configurations: Horowitz et al. firstly attributed the formation of the NLPs to the combination of the cavity birefringence (walk-off effect), the cavity gain, and the nonlinear transmission element [16]. Later on, they also investigated the effects of the cavity dispersion and cavity length in Ref. [34], showing that short cavities with low dispersion tended to generate NLPs with a pulsewidth of a few ps, whereas longer cavities tended to generate high-energy pulses whose temporal widths increased with pump power. It is worth noting that this regime should not mistakenly be regarded as the so called DS resonance regime [14], in which the pulses must encompass a linear frequency chirp, thereby having temporal compressibility. In general, such characteristics do not appear to NLPs because of the absence or near absence of the temporal coherence across the NLP packet. Kang et al. investigated in Ref. [17] the behavior of NLPs as a function of the cavity dispersion in more detail, showing that NLPs could be generated in dispersion-mapped cavities with either NAD or NND. However, in their experiments, broader spectral widths were only obtained from cavities with large NND [17]. In addition, Lei et al. discussed in Ref. [35] the effect of birefringence of the cavity fiber on the spectral width of NLPs formed in cavities with anomalous dispersion, showing that spectral width broadening was mainly related to the bend-induced birefringence of the cavity fiber. This was further corroborated with numerical simulations using the beat length of the cavity as a variable parameter.

Following the early experimental research on the characteristic features of fiber-based NLPs, a significant amount of attention has also been paid to analyzing their formation mechanisms. For example, in Ref. [15] Tang et al. suggested that the NLP formation was a consequence of the combined effect of soliton collapse [36] and positive cavity feedback. In Ref. [22], Zhao et al. investigated the dependence of the spectral width of NLPs on the length of the active fiber, reporting that the longer active fibers were used, the broader spectral widths were obtained. For example, they could obtain NLPs with a spectral width of 93 nm in terms of the full width at the half maximum (FWHM) for a 17.6-m length of EDF with anomalous dispersion [22]. In addition, their numerical