ARTICLE IN PRESS

Optical Fiber Technology xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Invited Paper

All-normal dispersion fiber lasers mode-locked with a nonlinear amplifying loop mirror

Antoine F.J. Runge [a], Claude Aguergaray [b], Richard Provo [c], Miro Erkintalo [a], Neil G.R. Broderick [a,*]

[a] Department of Physics, University of Auckland, Auckland, New Zealand
[b] ALPhANOV, Institut d'optique d'Aquitaine, Rue Françcois Mitterrand, Talence, France
[c] Southern Photonics, 49 Symonds Street, Auckland, New Zealand

ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Fiber Lasers
Passive mode-locking
All-normal dispersion

ABSTRACT

We review our recent progress on the design, modeling and construction of all-normal dispersion Yb-doped fiber lasers mode-locked using a nonlinear amplifying loop mirror. The all-fiber nature of the devices we consider permits accurate numerical simulations with minimal approximations or free-running parameters, and we describe in detail a refined numerical modeling scheme that combines generalized nonlinear envelope equations with analytically simulated gain dynamics. Guided by insights obtained from numerical modeling, we have experimentally realized robust, environmentally stable laser designs that offer flexible operation performance for a wide variety of applications. In particular, the unique all-PM-fiber design makes our devices ideally suitable for industrial laser micromachining applications.

1. Introduction

Mode-locked fiber lasers are associated with a number of advantages compared to their solid-state counterparts [1]. These include compactness, lack of sensitivity to alignment and low manufacturing costs. Owing to these benefits ultrashort fiber lasers are attractive for a wide variety of commercial applications in spectroscopy, nonlinear imaging and micromachining, which has led to a rapidly growing interest in the development of these devices [1,2]. Although there are many different ways to mode-lock a fiber laser, among the most common are nonlinear polarization rotation [3] and the use of semiconductor based saturable absorbers [4,5]. However, both these methods have drawbacks when trying to create a robust laser that will start reliably in an industrial setting. In contrast we have adopted the use of a nonlinear amplifying loop mirror for mode-locking [6], which brings with it additional benefits compared to other means, and in this paper we review our recent work towards developing such lasers into commercial instruments [7–9].

Our lasers are constructed of commercially available 100% polarization maintaining components, including the Yb-doped fibers used as the gain medium. Moreover, all the cavity components posses normal group-velocity dispersion, and thus soliton effects are eliminated leading to the potential for higher pulse energies [10–17]. However this brings with it the problem of finding a propagating pulse that satisfies the periodic boundary conditions created by the laser cavity. The solution we have adopted is to use a global attractor (i.e. the parabolic pulse [18]), combined with a narrowband filter to ensure that, despite the large pulse evolution over a single roundtrip, the propagation is truly periodic giving excellent stability and low timing jitters [12].

A schematic of our laser design is shown in Fig. 1 and the basic principle of operation is that in the main cavity the long length of Yb-doped fiber allows the pulse to evolve towards a parabolic pulse shape, while the nonlinear amplifying loop mirror (NALM) acts as a mode-locker and typically provides very little gain. The band-pass filter acts to reduce the temporal width of the pulse so that it can rapidly evolve back towards the parabolic pulse solution over the next roundtrip [20]. By adjusting the precise cavity parameters, such as fiber lengths, output coupling, pump powers, etc., it is possible to produce a wide range of outputs with tailored performance characteristics. To optimize the cavity to deliver desired pulse characteristics we have developed new numerical methods that enable pulse formation to be modeled under experimental configurations with minimal approximations.

Although the cavity geometry is the same as in figure eight lasers (such as those used for example in [21] or [22]) the behavior and operation of this laser is quite different due to the presence of two independent lengths of doped fiber. Indeed, a drawback of

* Corresponding author.
E-mail address: n.broderick@auckland.ac.nz (N.G.R. Broderick).

http://dx.doi.org/10.1016/j.yofte.2014.07.010
1068-5200/© 2014 Elsevier Inc. All rights reserved.

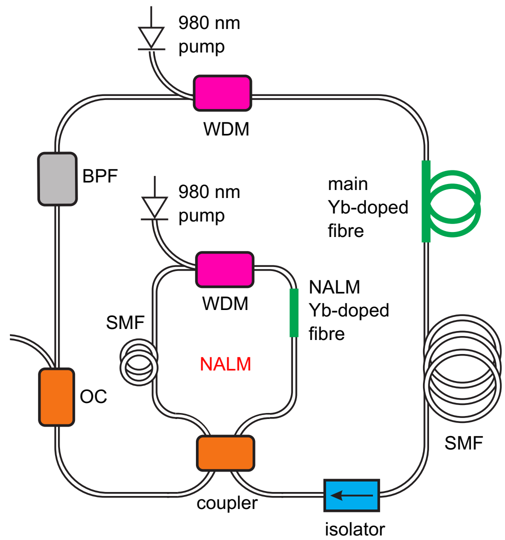

Fig. 1. A schematic illustration of the basic laser design. The lengths of the single-mode fibre (SMF) and the doped fibers vary according to the desired output characteristics, as do the precise values of all the couplers. Adapted from [19].

most figure eight fiber lasers is that the gain medium serves two roles; firstly it counteracts the losses in the cavity and secondly it provides an asymmetry in the loop mirror to allow for nonlinear transmission. It is thus hard to optimize the NALM for both functions and instead in our design the gain function is provided by the Yb-doped fiber in the main cavity while the second length of doped fiber acts principally as a mode-locker. In fact this is to the best of our knowledge the only fiber laser design that has two independent lengths of doped fiber, and we will show that this additional degree of freedom allows for great flexibility in designing the laser to meet different output pulse requirements.

The outline of the paper is as follows. We start by discussing a refined numerical modeling scheme that has enabled us to effortlessly explore a wide variety of cavity configurations. We then discuss experimentally realized configurations, highlighting how a wide variety of output pulse characteristics can be achieved via simple changes to the basic laser design. We then present experimental results that illustrate the stability and long-term reliability of the devices. Finally, we discuss future research directions and draw conclusions.

2. Numerical modeling

Numerical modeling serves two purposes: (i) firstly it provides essential insight into the physics and operational dynamics of experimentally realized architectures while, (ii) secondly, simulations allow for simple and fast exploration of various parameter regimes so as to discover new laser designs with improved performance characteristics. Indeed, due to the number of variable parameters and the complexity of the underlying nonlinear dynamical system, experimental exploration of the full parameter space is rarely possible and instead must be guided by numerics.

In order to successfully perform its functions it is necessary that the model adequately captures the rich dynamics encountered in realistic experiments with minimal approximations. However many numerical models used in the simulation of mode-locked fiber lasers today make unnecessary approximations in either the modeling of the pulse propagation or the gain dynamics. We use the generalized nonlinear envelope equations commonly encountered in the simulation of octave-spanning supercontinua to obtain a minimum approximation description of light propagation through each fiber segment [23]. In addition, a novelty of our model is that instead of making assumptions on the form of the active fiber gain, we model the gain dynamics for given pump diode drive currents. We compare our simulation results with experiments and obtain excellent agreement with minimal adjustable parameters.

2.1. Models

2.1.1. Pulse propagation equation

The propagation of light with an almost arbitrary bandwidth in an optical fiber has been well studied and can be described in terms of an envelope function approach. Thus we can build up a model of our fiber laser by simply concatenating the well known and accurate models for each of the components in Fig. 1, starting with the propagation down a length of doped or un-doped fiber. Moreover, since our devices are constructed of all-polarization maintaining components it is sufficient to consider a linearly polarized electric field, which greatly simplifies the problem.

In a frame of reference moving at the group velocity of an arbitrary reference frequency ω_0, the complex electric field envelope $A(z,T)$ evolves according to [23]:

$$\frac{\partial A}{\partial z} - \frac{g(z,P_{avg},\omega)}{2}A - i\hat{D}\left(i\frac{\partial}{\partial T}\right)A = i\gamma\left(1 + i\tau_{shock}\frac{\partial}{\partial T}\right)\left(A(z,T)\int_{-\infty}^{\infty}R(T')\times|A(z,T-T')|^2dT'\right). \quad (1)$$

The dispersion operator $\hat{D}$ is defined as

$$\hat{D}\left(i\frac{\partial}{\partial T}\right) = \sum_{k\geqslant 2}\frac{\beta_k}{k!}\left(i\frac{\partial}{\partial T}\right)^k, \quad (2)$$

where β_k are the usual dispersion coefficients associated with the Taylor series expansion of the mode propagation constant $\beta(\omega)$ about ω_0 [24]. As usual if $\beta(\omega)$ is explicitly known, all the dispersion terms can be accounted for by simply multiplying the envelope with $\exp(i\hat{D}(\omega-\omega_0))$ in the spectral domain. In general, the gain coefficient $g(z,P_{avg},\omega)$ is a function of frequency ω, the propagation distance z and the average energy of the resonating field P_{avg}. Detailed computation of the gain coefficient dynamics will be presented below, but here we note that of course for un-doped fiber segments $g\rightarrow-\alpha(\omega)$, where $\alpha(\omega)$ denotes the fiber loss coefficient. The fiber nonlinear terms are contained in the right-hand-side of Eq. (1): $\gamma=\omega_0 n_2(\omega_0)/(cA_{eff})$ is the usual nonlinearity coefficient where $n_2(\omega_0)$ is the nonlinear refractive index and A_{eff} the effective area of the fiber mode [24]. The response function $R(T)=(1-f_R)\delta(T)+f_R h_R(T)$ models both the instantaneous electronic (Kerr) nonlinearity as well as the delayed molecular (Raman) nonlinearity, where $f_R = 0.18$ denotes the Raman contribution. The time-domain Raman response function $h_R(T)=\mathscr{F}^{-1}[\tilde{h}_R(\omega)]$ can be readily obtained from the inverse Fourier transform of the experimentally measured Raman spectral response $\tilde{h}_R(\omega)$, yet we note that the use of refined Lorentzian approximations generally yield similar accuracy [24]. Lastly, the time derivative on the right-hand side of Eq. (1) accounts for the dispersion of the nonlinearity and is responsible for self-steepening and associated optical shock-formation effects, with τ_{shock} the shock-formation time-scale.

Eq. (1) has been extensively used in the modeling of complex pulse propagation in optical fibers and agrees with experimental observations with remarkable accuracy [23,25]. We can thus apply it with confidence to the problem of pulse propagation along a fiber cavity. As is usual, we solve Eq. (1) numerically using the split-step Fourier method. The gain and dispersion operators are applied in the frequency domain whilst the nonlinear terms are calculated in the time domain. Due to the temporal derivative on

Please cite this article in press as: A.F.J. Runge et al., All-normal dispersion fiber lasers mode-locked with a nonlinear amplifying loop mirror, Opt. Fiber Technol. (2014), http://dx.doi.org/10.1016/j.yofte.2014.07.010