Towards environmentally stable laser for nonlinear imaging: ultrafast all-fiber Nd-doped oscillator at 928 nm

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Abstract
Replacing commonly used bulky Ti:Sapphire lasers with compact fiber-based systems can reduce maintenance costs and improve the quality of nonlinear imaging. This work presents an environmentally stable all-polarization-maintaining Nd-doped fiber laser oscillator, which delivers nJ-level ultrashort pulses at 928 nm. The system is a turn-key solution with an extended lifetime thanks to an artificial saturable absorber based on a 3x3 fiber coupler.

Keywords
Two-photon imaging, fiber lasers, nonlinear imaging, stimulated Raman scattering.

1. Introduction

All-fiber laser systems are known for being robust and environmentally stable thanks to the lack of bulky free-space optical components. They are immune to misalignment, high dustiness or humidity changes. The best performance can be obtained when the whole cavity consists of birefringent polarization-maintaining (PM) optical fibers, which can sufficiently decouple the system from mechanical vibrations and temperature variations [1]. Yet another essential practical feature refers to the lifetime of the system. The ultrashort pulsed operation is typically induced by material saturable absorbers (SAs). However, one has to consider their deterioration over time, which results in breakdowns of lasers after years of operation [2]. This problem is not apparent when using artificial SAs, like nonlinear loop mirrors, which are based on nonlinear effects present inside the core of the optical fibers. On the other hand, nonlinear loop mirrors sometimes suffer from problematic initiation of the mode-locking regime. This means that after turning on the system, other activities are necessary to switch from continuous wave operation to the generation of stable pulses. The aforementioned problem has been solved by replacing 2x2 fiber couplers with 3x3 versions, which, by introducing a phase shift, enable self-starting pulsed operation [3].

Nevertheless, the wavelength ranges offered by fiber lasers are limited by the available rare-earth-doped media. Most commonly used are Yb-doped and Er-doped fibers, which allow generating ultrashort pulses in 1 µm and 1.5 µm spectral regions, respectively [4]. Still, many applications require wavelengths shorter than 1 µm. Particularly, the demand for such systems is driven by nonlinear imaging techniques. For two-photon excitation, plenty of fluorophores request wavelengths shorter than 1000 nm [5]. Furthermore, shorter wavelengths might also be desired for stimulated Raman scattering microscopy [6].

Until recently, the standard source of ultrashort pulses below 1 µm has consisted of Ti:Sapphire oscillator, which covers the wavelengths from 700 nm to 1100 nm. Novel fiber-based systems typically use Yb-doped or Er-doped oscillators followed by the generation of various nonlinear effects, among others, second harmonic generation [7], supercontinuum generation [8], soliton self-frequency shift [9], four-wave mixing or fiber optical parametric oscillators [6]. This work proposes a more straightforward solution to accessing wavelengths around 920 nm by exploiting Nd-doped fibers. We propose using a hybrid approach consisting of two different types of Nd-doped fiber, which allows for efficient suppression of the four-level transition at 1064 nm and assists the operation using the three-level transition around 920 nm. In contrast to state-of-the-art Nd-doped fiber oscillators, we present a setup operating in a dissipative soliton regime.

2. Experimental results

The scheme of the experimental setup is presented in Figure 1(a). We used two pieces of the active fibers: a specially designed double-clad W-shaped fiber (DC-NDF), and a standard single-clad Nd-doped fiber (SC-NDF), which are pumped through the pump combiner (PC) and the wavelength division multiplexer (WDM) by 808 nm laser diodes (LD1 and LD2). The residual pump beam is eliminated by the cladding pump stripper (CPS). An optical isolator (ISO) ensures unidirectional beam propagation.

The ultrashort pulse operation is obtained via passive mode-locking by a 3x3 nonlinear amplifying loop mirror, which, to the best of our knowledge, is utilized for the first time in this spectral region. The oscillator operates in a dissipative soliton regime, acquired by combining all-normal-dispersion components and spectral filtering. We used a Lyot filter consisting of two 45°splices followed by a polarization beam splitter (PBS). The system has three output ports (P1, P2, P3), created by a 3x3 fiber coupler and an additional 2x2 fiber coupler with a power splitting ratio of 10/90.

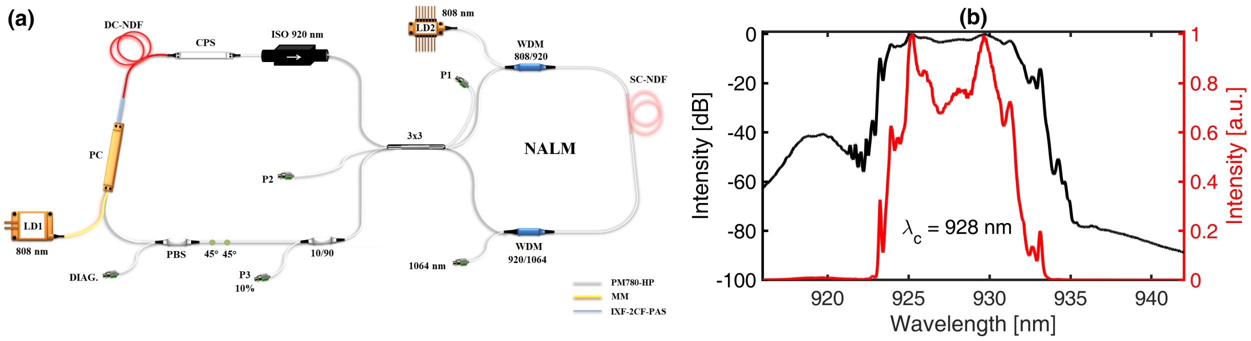

Fig. 1. All-fiber ultrafast Nd-doped fiber oscillator. (a) Scheme of the experimental setup. LD1, L2 - laser diodes, PC - pump combiner, WDM - wavelength division multiplexer, DC-NDF - double-clad W-shaped Nd-doped fiber, SC-NDF - single-clad Nd-doped fiber, CPS - cladding pump stripper, ISO - optical isolator, 3x3 - fiber coupler with 33/33/33 splitting ratio, 10/90 - fiber coupler with a power splitting ratio of 10/90, PBS - polarizing beam splitter realizing the Lyot filter, DIAG. - diagnostic port, P1, P2, P3 - outputs. (b) Spectral characteristics of the oscillator from port P1 in logarithmic (black) and linear (red) scales.

The oscillator delivers picosecond pulses with an energy exceeding 1 nJ at the central wavelength of 928 nm. An external compressor can reduce the pulse duration to hundreds of femtoseconds. We reckon incorporating other amplification stages will pave the way for a reliable fiber laser, which can be applied in nonlinear imaging.

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4. References

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