Fiber Source for Pumping a Fiber-Optical Parametric Generator at $\sim$800 nm

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Abstract. The coherent anti-Stokes Raman spectroscopy (CARS) has attracted a great attention as non-invasive method of real-time monitoring of processes occurring in biological tissues and cells. It needs a special kind of optical source that would be compact, stable and low cost. We investigate a possibility of using highly-chirped dissipative soliton oscillator together with a narrowband fiber Bragg grating and all-fiber amplifier. Optical pulses with the duration of 85 ps and the peak power of 400 W were generated at the output of the fiber system with the repetition rate about 13 MHz. Developed source is suitable to pump a fiber optical parametric oscillator for CARS.

1. Introduction

Recently, methods of optical diagnostics that allow non-invasive, real-time monitoring of processes occurring in biological tissues and cells (bio-imaging) have been actively developed: optical coherence tomography, multiphoton microscopy, Raman spectroscopy, including the coherent anti-Stokes Raman spectroscopy (CARS). Thanks to these methods, physicians and biologists have obtained a new tool for non-invasive research of biological objects with high resolution. Especially noteworthy CARS microscopy, which uses the molecular vibrational properties of organic compounds included in the composition of biological objects, thereby opens new perspectives in the study of inter- and intracellular interactions, selective processes at the level of the membrane, cytoplasm, lipids, nuclei and their inherent RNA- and DNA interactions.

One of the unique possibilities of CARS microscopy is real-time visualization and tracking of lipids in living systems, which are one of the main components of biological membranes, affect the permeability of cells and the activity of many enzymes, participate in the transmission of a nerve impulse, in muscular contraction, in immunochemical processes, etc.

CARS microscopy requires coherent, time-synchronized optical pump and signal radiation with a difference of optical frequencies of 1000–3300 cm$^{-1}$, depending on the composition of the test substance. Usually the pump wavelength is taken around 800 nm and the thermal heating of the sample limits the pulse duration to $<100$ ps. Bulk laser systems are usually used for optical CARS microscopy. Initially, these were two time synchronized independent tunable sources (often picosecond Ti:sapphire lasers) [1], then bulk optical parametric oscillators were used [2]. Providing a large tuning range and high peak and average powers, they are nevertheless expensive and complicated to maintain.
Fiber lasers which are characterized by compactness, stability, high beam quality, and relatively low cost, can find application in medicine where reliability and low cost of equipment are required. The currently existing fiber sources cannot replace solid-state lasers for CARS primarily because of a limited range of generation wavelengths (near-IR). Thereby, nonlinear frequency conversion in fibers of different kind are applied to obtain a wide tuning range. One of the first fiber sources for CARS used photonic crystal fibers (PCF) and was developed on the method of soliton self-frequency shift into the long-wavelength region [3] and the generation of a supercontinuum. Despite the large tuning range, these sources had a fairly wide spectrum of generation and small spectral power density resulted in contrast reduction of the recorded image. Another method used to develop CARS sources is parametric four wave mixing (FWM) in the PCF that is the most perspective nonlinear conversion technique. In hybrid fiber-optic systems, the parametric radiation for CARS at wavelength of 0.7–1 μm generated at pumping by solid-state laser [4] or a fiber laser [5, 6] is combined with signal radiation on a bulk dichroic mirror. The drawback of this scheme was the complexity of the system and the presence of bulk elements that require periodic adjustment. Using 50-100 ps pulses, the group of A. Tünnermann demonstrated fiber systems for CARS where the pump and signal pulses were automatically overlapped at the output of the PCF [7, 8]. In order to reduce the noise of the generated pulses, continuous wave (CW) seed radiation was used [6, 9]. The group of F. Wise in [10] showed that the scheme of a fiber optic parametric oscillator allows reducing the relative intensity noise and to abandon an additional seed laser. Though the subsequently developed fiber OPO (FOPO) schemes include elements of bulk optics [10, 11, 12, 13], the researchers work on the all-fiber configuration of FOPO [14], whose implementation and optimization is one of the main tasks at the moment.

In this work we investigate a new type of all-fiber source for pumping a FOPO at 800 nm. It involves our latest achievements in a femtosecond fiber Bragg grating (FBG) inscription [15] and highly-chirped dissipative soliton generation [16].

Figure 1. Schematics of the experimental setup: LD – laser diode, PBS – polarization beam splitter, ISO – isolator, PM – polarization maintaining component, WDM – wavelength division multiplexer, BPF – bandpass filter, PC – polarization controller.
2. Experimental setup

The scheme of the experiment is presented in Figure 1. It consists of a master oscillator — Yb-doped fiber source of dissipative solitons that is similar to developed in [16]. A standard fiber with core diameter of 6 micron was used to build the laser cavity in both polarization maintaining (PM) and standard single mode parts. The total length of the cavity was chosen to operate below the Stimulated Raman Scattering threshold, so resulted repetition rate was about 13 MHz. To set the central wavelength near 1030 nm, we used two different kind of spectral filters: Lyot-filter to form an appropriate profile of spectral losses and 8-nm-width bandpass filter to avoid generation at sidebands. As a next step, a special fiber Bragg grating cuts out a narrowband (40 pm) pulses through the 3-port circulator. To increase a peak power to the required level we used three-stage optical Yb-doped fiber amplifier consisting of PM single-mode fibers and pumped into the core by single-mode laser diodes at 976 nm through wavelength division multiplexers.

3. Results

The master oscillator operates in highly-chirped dissipative soliton regime that could be seen by its broad optical spectra with sharp edges (see Figure 2). The spectrum reflected from the FBG is shown by the red line at the same figure. A quality of used FBG is extremely important as it defines the background level and pulse shape. One of the best result is presented in Figure 3 in the logarithmic scale. It could be seen that almost 15-dB contrast exists after amplification. To obtain such result a several FBGs were checked. The spectral bandwidth is very close to the instrumental resolution of used optical spectrum analyzer (Yokogawa AQ6370) and estimated duration exceeds the range of a typical autocorrelator. Therefore we used FROG analyzer (Mesa Photonics, LLC) with the extended range up to 2 ns to measure the auto-correlation function (ACF) of the pulse after amplification. The traces are depicted in Figure 4. We chose the grating that corresponded to the 85-ps pulse duration and the lowest sideband amplitude. After optimization of each amplification cascade we were able to increase the peak power at the output up to 400 W (Figure 5). It was enough to observe a weak single-pass parametric generation at 793 nm in a 5-m-long LMA5-PM PCF.

Figure 2. The optical spectra of the femtosecond master oscillator before and after the FBG filter.

Figure 3. Comparison of the optical spectra before and after amplification for the best FBG.
4. Conclusion
The all-fiber source of narrowband pulses with a high peak power was investigated. Optimization of used FBG gives 85-ps pulses that were amplified in the three cascades of all-fiber amplifier up to 400 W of peak power with repetition rate 13 MHz. The weak parametric generation at 793 nm in single-pass configuration with 5-m-long PCF was observed. So, this source could be used for pumping of a FOPO based on an external fiber cavity to enhance the parametric signal.

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