Nanotube mode-locked, low repetition rate pulse source for fiber-based supercontinuum generation at low average pump power

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Abstract: We demonstrate a nanotube mode-locked fiber laser with low repetition rate (244 kHz), enabling supercontinuum generation in photonic crystal fiber spanning 600 to 2000 nm, at a low average pump power of 87 mW.

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1. Introduction

Passively mode-locked fiber lasers are established sources of near-transform limited picosecond and femtosecond-scale pulses, at MHz repetition rates [1–3]. The all-normal dispersion (ANDi) operation of mode-locked fiber lasers has emerged as a desirable regime for power-scalable chirped pulse generation [4]. Interest exists in extending this laser format, typically through elongation of the laser cavity, to generate pulses possessing a giant chirp at significantly lower repetition rates [4]. This allows the oscillator output to be directly amplified using a simplified configuration [4]. The lower repetition rate means a high pulse energy is achieved for amplification to even modest average power levels and through compression schemes, duty factors over one hundred thousand are potentially achievable [5]. Such a system is thus suitable as a low average power pump source for supercontinuum generation in a photonic crystal fiber (PCF). Carbon nanotubes (CNTs) [6–9] and graphene [2,6], have emerged as promising saturable absorbers (SA) for ultrashort pulse generation [3,10], due to their ultrafast recovery time [3,11], broadband operation [12,13], and ease of fabrication and integration into all-fiber configurations [6,14]. Fiber-based supercontinua have numerous applications, in particular as an illumination source in optical microscopy and a reference tool in optical frequency metrology [15]. Typically, the pump schemes for supercontinuum systems are based on master-oscillator power fiber amplifier (MOPFA) architectures, with the resulting continuum evolution and characteristics determined by both the pump format and fiber properties. Ref. [16] proposed a high-energy supercontinuum pulse generator based on a low repetition rate nonlinear polarization evolution (NPE) mode-locked laser. Here, we adopt a different approach and demonstrate a low-repetition rate seed oscillator utilizing a CNT-based SA, offering improved resistance to environmental perturbations and greater long-term stability. After amplification to modest average power, a broad supercontinuum from 600 to 2000 nm is generated in a PCF.

2. Experimental Setup and Results

Our seed oscillator is an ultra-long ANDi all-fiber ring cavity (Fig.1a) mode-locked by a CNT-based SA composite [6, 7]. The total cavity length is 821 m, with a group delay dispersion of 18.5 ps^2. A 10 nm bandpass filter is included to fix the central lasing wavelength and improve stability, although this is not required to achieve mode-locking.

Self-starting mode-locking is observed, generating a regular pulse train with fundamental repetition rate of 244 kHz. Pulses are fitted by a $sech^2$ shape, with a full-width at half maximum (FWHM) of 0.97 ns (Fig.1b). The corresponding output spectrum (Fig.1c) is centered at 1058.1 nm with 0.55 nm FWHM. A time-bandwidth product of 143 is calculated, over 400 times greater than the transform limit for $sech^2$ pulses, highlighting the giant chirp of the pulses (as we have shown previously [5], through a direct measurement of the pulse spectrogram). The seed oscillator output is randomly polarized and the pulse-to-pulse energy fluctuations are 1.6%, based on RF spectral measurements. The low repetition rate can be further reduced by extending the cavity length, although a fundamental limit of tens of kHz is reached when the cavity round-trip time approaches the upper-state lifetime of the gain medium.

The seed oscillator pulses are amplified to 116 mW average power in a two-stage ytterbium-doped fiber amplifier (YDFA), including a mid-stage bandpass filter to suppress amplified spontaneous emission. The spectral and temporal

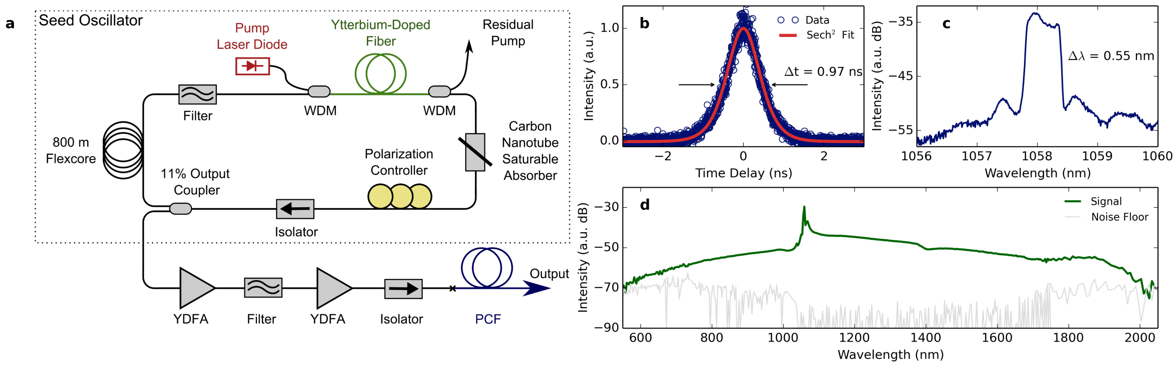

Fig. 1. (a) Laser setup. Seed oscillator pulse (b) temporal profile and (c) spectrum. (d) Supercontinuum after PCF.

pulse properties are preserved during amplification. The pulse train is then launched into ∼30 m solid-core PCF (zero-dispersion wavelength at 1038 nm, 4.9 μm core diameter). After 0.6 dB isolator loss and 0.65 dB splice loss between the delivery fiber and the PCF, the average power of the launched pulses is 87 mW, corresponding to 0.36 μJ pulse energy. A supercontinuum is observed spanning 600 to 2000 nm (Fig.1d). On the long wavelength edge, there is less than 10 dB intensity variation between 1100 and 1850 nm. The feature at ∼1380 nm is related to water loss in the fiber, and ∼1750 nm indicates the transition between data recorded on an optical spectrum analyzer (1 nm resolution) and longer wavelength data measured with a spectrometer (22 nm resolution). Spectral sidebands on the pump were observed during the early evolution of the continuum with increasing pump power, which are a signature of modulation instability (MI); MI-driven continuum dynamics are expected for long-pulse and quasi-CW pump schemes [15].

3. Further seed oscillator development

We then developed a low-noise, linearly polarized seed oscillator using all-polarization-maintaining (PM) fiber, adopting a similar ring cavity design. Comparable mode-locking performance is observed, but the emitted pulses are scalar and the energy variation is only 0.45%, a factor of three lower than the non-PM cavity. The linear polarization state of this pump source will enable further investigation of the polarization dynamics involved in supercontinuum generation in the MI-driven regime.

4. Conclusion and outlook

We have demonstrated the generation of a supercontinuum at low average pump power, using a compact low repetition rate mode-locked fiber laser. Additional improvements will be considered including compression of the giant linear chirp, further lowering the required average power for continuum generation.

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