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All-fiber femtosecond Cherenkov radiation source

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An all-fiber femtosecond source of spectrally isolated Cherenkov radiation is reported, to the best of our knowledge, for the first time. Using a monolithic, self-starting femtosecond Yb-doped fiber laser as the pump source and the combination of photonic crystal fibers as the wave-conversion medium, we demonstrate milliwatt-level, stable, and tunable Cherenkov radiation at visible wavelengths 580–630 nm, with pulse duration of sub-160-fs, and the 3 dB spectral bandwidth not exceeding 36 nm. Such an all-fiber Cherenkov radiation source is promising for practical applications in biophotonics such as bioimaging and microscopy. © 2012 Optical Society of America

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Traditionally, Cherenkov radiation (CR) is known as light produced by charged particles passing through a given dielectric medium at speeds greater than the phase velocity of light in that medium [1]. In nonlinear fiber optics, the concept of CR, also called dispersive wave generation or nonsolitonic radiation, originates from the perturbation of a stable temporal soliton by the higher-order fiber dispersion [2,3], which has a formal mathematical analogy to the traditional CR. This process is a key characteristic in the fiber-based supercontinuum (SC) sources that have been developed over the past decade [4].

While picosecond-pumped fiber SC sources are of interest for the generation of high-brightness near-IR (NIR), visible (VIS), and UV light, they have limitations in terms of noise characteristics [5] and pulse duration [4]. For a femtosecond-pumped SC, low average power in the short-wavelength spectrum is an issue [4,5]. Also, an all-fiber solution for a femtosecond SC source has not been demonstrated so far.

An attractive alternative to SC for ultrafast NIR, VIS, or UV generation in fiber-based systems is the generation of narrowband CR output in short pieces of photonic crystal fiber (PCF) using femtosecond pump pulses [6]. A milliwatt-level CR can be generated in this way, which is wavelength-tunable across the NIR–VIS–UV spectral range by choosing the PCFs with suitable zero-dispersion wavelength (ZDW). This fiber-optic-generated CR is attractive for multimodality biophotonics imaging, such as discussed in [7]. To the best of our knowledge, all previously demonstrated femtosecond CR fiber sources were based on systems with free-space optical coupling, using solid-state lasers as pumps. Solid-state lasers usually have a rather high pulse quality as compared to fiber lasers. On the other hand, the free-space optical coupling to thin-core PCFs used for CR naturally leads to environmental instability of such CR-generation systems and makes them not suitable for practical biophotonics imaging applications outside of the laboratory. Importantly for this work, CR generation in fibers is not critically dependent on the pump pulse duration since the input pulse is easily compressed in fibers. As will be shown below, the pulses from all-fiber laser systems, with spectro-temporal properties more complicated than of their solid-state counterparts, can generate sub-160-fs, relatively clean CR pulses. At the same time, such a monolithic, all-fiber CR-generation system provides a very high environmental and operational stability, defined by that of a self-stabilized all-fiber laser used as a pump.

In this Letter, we present an all-fiber, fully monolithic system based on an Yb-fiber femtosecond laser, producing electrically tunable femtosecond CR output in the spectral range of 580–630 nm with average power in the milliwatt range. Its layout is shown in Fig. 1. The system consists of two parts: an all-fiber nanojoule-level self-stabilized [8] femtosecond laser operating at 1035 nm wavelength and 26.7 MHz repetition rate used as the pump source, and a spliced-on multisegment PCF link used for Cherenkov wave conversion. More details of the pump laser can be found in [9,10] and references therein. The small-core nonlinear PCF NL-3.0-850 (NKT Photonics A/S), which has a ZDW around 850 nm, is used for CR generation. The mode-field diameters (MFDs) of the NL-3.0-850 fiber and the hollow-core anomalous dispersion PCF (HC-PCF) delivering the pulse-compressed pump laser signal are 1.8 and 7.5 μm, respectively. Therefore, the direct splicing of these two fibers would result in

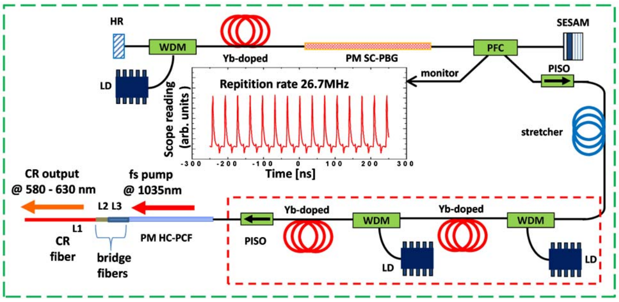

Fig. 1. (Color online) Layout of the all-fiber Cherenkov source. HR, high-reflectivity pigtailed mirror; WDM, 980/1030 wavelength division multiplexer; LD, single-mode pumping diode at 974 nm; PM SC-PBG, polarization-maintaining all-solid photonic bandgap fiber; SESAM, semiconductor saturable absorber mirror; PISO, polarization-maintaining isolator; PFC, 80/20 polarization filter coupler; HC-PCF, laser pulse compressor hollow-core PCF; CR fiber, highly nonlinear fiber for CR generation. (Inset) Oscilloscope reading of the mode-locked pulse train.

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an enormous coupling loss of around 12 dB. In order to minimize this loss, two other types of fibers are spliced in between them as bridge fibers. The MFDs of the two bridge fibers are 3.3 and 6.6 μm respectively, providing a gradual reduction of MFD in the fiber link. As a result, the total splicing loss in such a multisegment CR link is found to be around 4 dB. The NL-3.0-850 fiber and the two bridge fibers are 10 cm (L1), 2 mm (L2), and 8 cm (L3) long, respectively.

The 1035 nm pump pulses used in our experiment had an autocorrelation (AC) FWHM of 460 fs when fully compressed [9]. In this system, to maximize the CR output, the pump pulses were negatively prechirped with group delay dispersion of $-1.46 \cdot 10^4$ fs^2 in order to provide the shortest pulse duration and hence highest peak intensity while *in* the CR-generating NL-3.0-850 fiber. We note here that the dispersion of the bridge fibers used in the link is normal for the pump wavelength.

The pump pulses propagating in the small-core PCF initially undergo nonlinear pulse compression due to the combination of self-phase modulation (SPM) and anomalous dispersion. Around the point of maximal compression, the ultrafast VIS CR pulses are generated. Figure 2(a) shows the emitted CR output spectra measured at different output powers, and the inset shows the typical spectrum of the input pump pulse.

The CR phase-matching condition implies that the generated CR wavelength is dependent on the *peak power* of the pump pulse. In our experiments, when the 1035 nm pump power was increasing from 130 to 330 mW, the central wavelength of the emitted CR was shifting from 630 to 580 nm, yielding the blueshift as expected in this process [11]. This spectral shift is based on the control of the chirp and bandwidth of 1035 nm pump pulse by controlling the inversion in the amplifier section of the Yb-fiber laser (marked by a red dashed box in Fig. 1) [12]. The inversion is simply controlled by the drive current in the pumping laser diode, thus yielding the convenient electrical tunability of CR central wavelength, achieved here without the changing of CR fiber. The 3 dB bandwidth of the emitted CR as a function of the input pump power is shown as the blue stars in Fig. 2(b). When the input 1035 nm pump power increases from 154 to 308 mW, the 3 dB bandwidth of CR increases from 14 to 36 nm. The increase in CR bandwidth with increasing pump power can be ascribed to both SPM/cross-phase modulation effects and Raman-induced redshift of the pump pulses.

The emitted CR power as a function of the average input pump power is shown as the red circles in Fig. 2(b). The CR output shows a generation threshold at the pump power of around 130 mW. The CR conversion efficiency grows significantly until the pump power reaches 180 mW, after which the Cherenkov conversion efficiency saturates. We note here that the generated CR power is also dependent on the polarization state of the NL-3.0-850 [6] and the highest CR output is generated by optimal rotational orientation of the PCF during the fiber splicing process. Figure 2(c) shows the far-field saturated VIS images of the CR emitted from our system, generated as the pump power was increasing in the range 150–300 mW. These images exhibit the typical profile of the PCF mode [12].

In order to characterize the temporal profile of the generated CR pulses, an AC was measured. A 1 mm thick, 44.3° cut beta barium borate (BBO) crystal was used in the autocorrelator for CR. The AC of the CR with the output power of 1.7 mW is shown in Fig. 3 along with the AC of the pump pulse, measured at the end of the HC-PCF laser compressor (i.e., before entering the CR-generation fiber link). The FWHM of the AC trace of the 1035 nm pump pulse is 832 fs, whereas the FWHM of the AC trace for the generated CR pulse is 160 fs, i.e., more than five times shorter, which results from the nonlinear pump pulse compression in the CR fiber link. We note that the actual duration of the CR pulse is obviously even shorter than its AC FWHM value. The CR signals emitted in the output power range 1–2.5 mW had the AC FWHM in the range 145–225 fs. From the simulations [13,14] we can estimate the pulse duration of the CR output generated from 10 cm NL-3.0-850 to be of the order of hundreds of femtoseconds, which matches our experimental results. The output power range 1–2.5 mW corresponds to pulse energies of 37–93 pJ. Such energies are rather high and are comparable to those used in previously published two-photon fluorescence microscopy experiments using

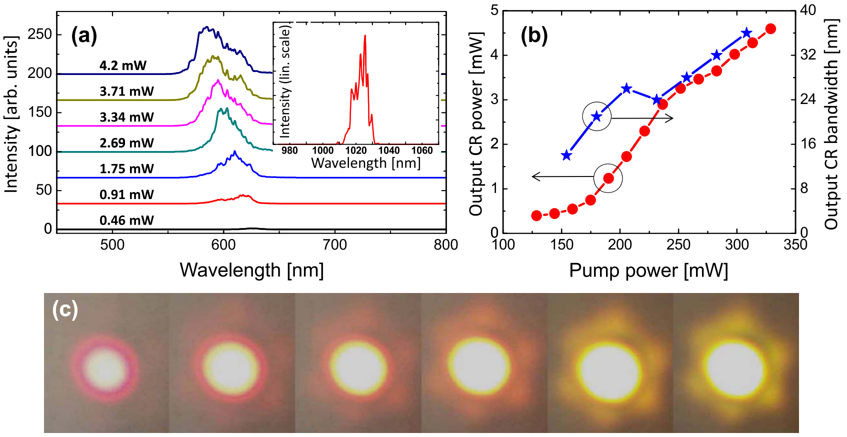

Fig. 2. (Color online) (a) Spectra of CR at variable output power. (Inset) Spectrum of the input femtosecond pump signal. (b) Generated CR output power (red circles) and 3 dB bandwidth (blue stars) as a function of increasing pump power. (c) (From left to right) Far-field saturated VIS images of the generated Cherenkov output as the pump laser power increases from 150 to 300 mW.

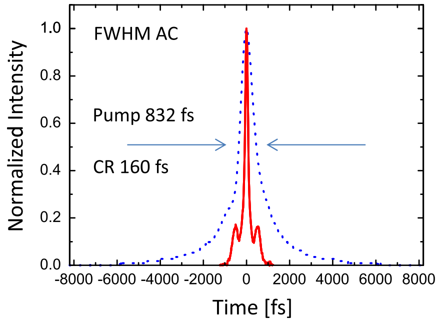

Fig. 3. (Color online) AC of the generated CR pulse (red solid) with the output power of 1.7 mW, and the input pump pulse (blue dotted).

a filtered fiber SC [15,16]. When the CR power increases from around 3 to 4.2 mW, the output CR power is found to temporarily degrade and then recover after about a minute, not leading to any permanent damage in the system. The experiments aimed at understanding this phenomenon are currently in progress.

In this Letter, we have shown a highly stable femtosecond CR source with convenient electrical tunability in the range 580–630 nm and multimilliwatt output powers based on monolithic all-fiber technology. By selecting a PCF with a smaller ZDW, similar tunability in the VIS and even UV spectral ranges can be realized [6,17]. As an example of stable operation, the CR output shown in Fig. 3 remains unchanged during the more than one month long operation of our system, during which over 200 on–off cycles for the whole system occurred. We believe that such stability of our system makes it promising for practical biophotonics applications, e.g., ultrafast spectroscopy, fluorescence lifetime imaging, and multiphoton microscopy, performed in the out-of-the-lab environments.

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