Generation of femtosecond pulses at 1350 nm by Čerenkov radiation in higher-order-mode fiber

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We demonstrate a method of generating short pulses at 1350 nm by exciting Čerenkov radiation in a higher-order-mode fiber with a 1064 nm femtosecond fiber laser. We measure a 106 fs, 0.66 nJ output pulse. Čerenkov radiation in fibers allows for energy transfer between a soliton and a dispersive wave, providing an effective and engineerable platform to shift the wavelength of a femtosecond source. With appropriate design of the higher-order-mode fiber, this method of generating short pulses at 1350 nm can be extended to other wavelengths and to higher pulse energies. © 2007 Optical Society of America

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The higher-order-mode (HOM) fiber has attracted significant interest recently due to the freedom it provides to design unique dispersion characteristics in all-solid silica (nonholey) fibers.[1] This new fiber platform allows for anomalous dispersion below 1300 nm by propagating light solely in one of the higher-order modes.[1] Such dispersion characteristics were previously attainable only by photonic crystal fibers (PCFs). The unique characteristics of the HOM fiber, such as large anomalous dispersion and a large effective area (approximately ten times that of PCF), provide a number of new opportunities for applications in nonlinear fiber optics. For example, we recently demonstrated soliton self-frequency shift (SSFS) below 1300 nm in a HOM fiber. The advantage of using a HOM fiber lies in the ability to generate higher energy self-frequency-shifted solitons than attainable in microstructured PCF.[2] Output pulse energy obtainable for cleanly frequency-shifted solitons in index-guided PCF is limited to fractions of a nanojoule[3,4] due to light confinement to a smaller effective area, rendering pulses more susceptible to nonlinearity. In contrast, the HOM fiber platform allows advantages of interesting dispersion curves similar to PCF, yet with a higher tolerance to nonlinearity. The ability to obtain complex dispersive profiles in fiber is interesting because of its prospect for realizing sources in hard-to-access spectral regions by exploiting the generation of Čerenkov radiation[5]: that is, the dispersive waves shed by solitons near the zero-dispersion wavelength. HOM fibers, with their higher tolerance to nonlinearities, will allow for energetic sources at wavelengths where sources are not currently available.

Čerenkov radiation in fibers has been demonstrated in microstructured fibers pumped near the zero-dispersion wavelength as well as experiments generating self-frequency-shifted solitons.[5–9] An ideal soliton requires a perfect balance between dispersion and nonlinearity so that energy becomes confined to a discrete packet both spectrally and temporally. With the introduction of perturbations such as higher-order dispersion, this stable solution breaks down, allowing the transfer of energy between the soliton in the anomalous dispersion regime and newly shed dispersive radiation in the normal dispersion regime. Such energy transfer occurs most efficiently in fibers for solitons near the zero-dispersion wavelength. The spectral regime to which energy couples most efficiently has been dubbed "Čerenkov radiation" due to an analogous phase-matching condition in particle physics. The phenomenon of Čerenkov radiation in fibers is often associated with SSFS as it allows a convenient mechanism for more efficient energy transfer between the soliton and the Čerenkov band. When the third-order dispersion is negative, SSFS will shift the center frequency of the soliton toward the zero-dispersion wavelength, resulting in efficient energy transfer into the Čerenkov radiation in the normal dispersion regime. A more rigorous description and analytical derivation of Čerenkov radiation in fibers can be found in various theoretical works.[10–12]

In this Letter, we generate Čerenkov radiation at 1350 nm in a HOM fiber with 20% power conversion efficiency (~25% photon efficiency). We successfully filter and compress the Čerenkov output pulses to 106 fs. Čerenkov radiation generated in the normal dispersion regime of this HOM fiber can be used to extend frequency shifting even further, or to create a three-color femtosecond source (centered at the pump, frequency-shifted soliton, and Čerenkov radiation wavelengths). This new class of fiber shows great promise for generating femtosecond pulses at various wavelengths in the energy regime of several nanojoules.

The experimental setup is shown in Fig. 1(a). The pump source consists of a pulsed fiber laser (Fianium FP1060-1S) centered at 1064 nm, with an 80 MHz repetition rate and a 200 fs pulse width. We couple the source into the HOM fiber module, which consists of a 12.5 cm standard single-mode fiber (flexcore) pigtail, 2.5 cm of long period grating (LPG), and 1 m of HOM fiber. The LPG converts the fundamental mode to the higher-order LP_{02} mode with good (>90%) efficiency over a large (50 nm) bandwidth; for the input wavelength of 1064 nm, 99% of the fundamental mode is converted to the LP_{02} mode, which exhibits anomalous dispersion in the HOM fiber between 908 and 1247 nm (Ref. 1) [see Fig. 1(b)]. At the input wavelength, the LP_{02} mode, shown in Fig. 1(c), has an effective area $A_{eff}=44\ \mu m^2$. The output of the HOM fiber module is collimated and measured with an optical spectrum analyzer and a second-order interferometric autocorrelator. A 1300 nm long-pass filter is used to select out the Čerenkov radiation, and a pair of silicon prisms are used for dispersion compensation and to simultaneously filter out any residual pump wavelength. A polarizer and a half-wave-plate serve as a variable optical attenuator at the input of the HOM fiber module.

We also numerically simulate the system using the standard split-step Fourier method. The source is modeled as a Gaussian pulse with added self-phase modulation (SPM) to approximately match the source spectrum from the experiment (Fig. 2 insets). For propagation in the HOM fiber, we include SPM (nonlinear parameter $\gamma=2.2\ W^{-1}\ km^{-1}$), stimulated Raman scattering (Raman response $T_R=5$ fs), self-steepening, wavelength-dependent A_{eff}, and dispersion up to fifth order. Dispersion coefficients are calculated by numerically fitting the dispersion curve shown in Fig. 1(b).[1] We also scale the power accordingly during Raman wavelength shifting to take into account energy lost to phonons.

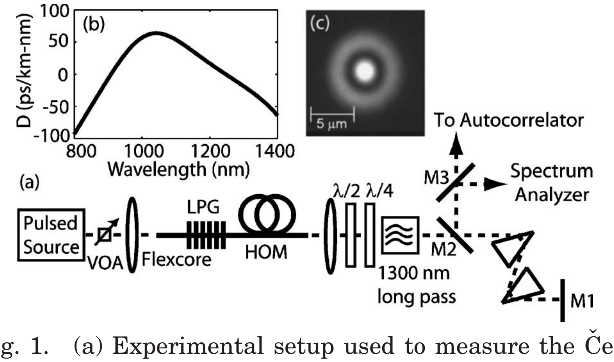

Fig. 1. (a) Experimental setup used to measure the Čerenkov pulse generated in the HOM fiber, (b) measured dispersion for the LP_{02} mode in the HOM fiber, (c) the measured mode profile of the LP_{02} mode. VOA, variable optical attenuator.

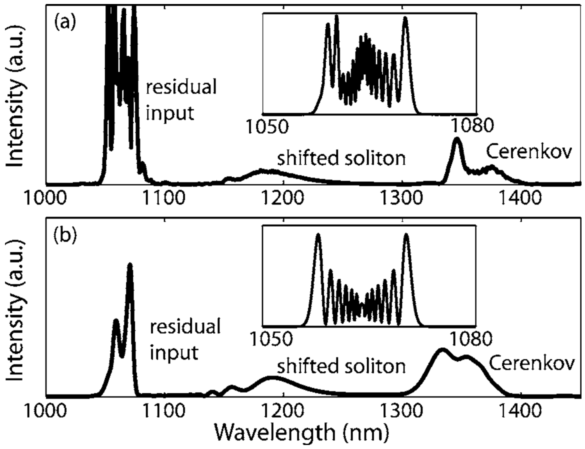

Fig. 2. Optical spectrum at output of the HOM fiber module. (a) From experiment, (b) from simulation. Insets show source spectra in a 30 nm window.

We are able to couple a total power of 265 mW (3.31 nJ pulse energy) into the HOM fiber module. At this power level, the residual input, shifted soliton, and Čerenkov radiation can be clearly seen in the output spectrum shown in Fig. 2(a). The optical power residing in the Čerenkov band is ~53 mW (0.66 nJ pulse energy), a power conversion efficiency of 20% (25% photon conversion efficiency). We qualitatively match the experimental spectrum in simulation, shown in Fig. 2(b). We note the excellent qualitative match between simulation and experiment and the relatively good quantitative match. The observed quantitative discrepancy could arise from our approximation of both the input source characteristics and the dispersion curve, which is not characterized beyond 1400 nm. This simulated spectrum corresponds to an input power of 189 mW (2.36 nJ pulse energy), with 30% conversion to the Čerenkov band, equivalently 0.70 nJ in the Čerenkov pulse. At this power level, the soliton (centered at ~1200 nm) has shifted enough energy past the zero-dispersion wavelength so that resonant coupling occurs efficiently at 1350 nm (Čerenkov radiation). Intuitively, growth of the Čerenkov radiation begins exponentially with increasing input power until the "spectral recoil" exerted by the Čerenkov radiation on the soliton cancels the Raman self-frequency shift.[5] After the soliton is frequency locked, for our experiment at 1200 nm, increasing the pump power will only transfer energy to the Čerenkov spectrum instead of shifting the soliton further. Simulation shows that up to ~5 nJ can be pumped into the Čerenkov band, after which nonlinear effects begin to degrade the system. Experimental pulse energies were limited by the pump source's non-Gaussian beam shape, which results in poor coupling into the HOM fiber module.

We additionally measure Čerenkov output pulse energy as a function of input pulse energy by varying the attenuation at the input of the HOM fiber module. We can see from Fig. 3 that the Čerenkov pulse energy increases rapidly at input energies of approximately 2 nJ (input power 160 mW). This "threshold" behavior, as well as the location of the knee, agrees well with our simulation. The threshold behavior has also been experimentally observed previously in PCF.[5] A discrepancy in Čerenkov pulse energy between numerical results and experiment was found at the highest input pulse energies we investigated, where simulation shows a faster increase in Čerenkov energy than the experimental results. We currently do not have an explanation for this discrepancy.

A second-order autocorrelation trace of the filtered Čerenkov pulse at the output of the HOM fiber module is shown in Fig. 4(a); it is visibly chirped and has an autocorrelation FWHM of 907 fs. We are able to compress this pulse to 207 fs autocorrelation FWHM, shown in Fig. 4(b), with appropriate dispersion compensation by a silicon prism pair. We calculate the dispersion provided by the silicon prism pair (prism separation distance ~7 cm in optical path length) to be $\beta_2 = -0.0065\ \mathrm{ps}^2$ and $\beta_3 = -1.9 \times 10^{-5}\ \mathrm{ps}^3$. Applying such dispersion compensation values to our spectrally matched simulation, we numerically obtain an autocorrelation FWHM of 200 fs and a pulse width of 103 fs. If we assume the same pulse shape, the experimentally measured deconvolved pulse widths with and without dispersion compensation are 106 and 465 fs, respectively.

The location of the Čerenkov radiation can be tuned through engineering of the fiber dispersion.[9] For example, simple dimensional scaling of the index profile of the HOM fiber can be used to shift the dispersion curve of the LP_{02} mode. By shifting the zero-dispersion wavelength 50 nm to the shorter wavelength side, the generated Čerenkov radiation will also shift by approximately the same amount. Such design control could lead to the generation of useful femtosecond pulsed sources in spectral regimes unattainable by current laser systems. Furthermore, the large effective area and flexibility for dispersion engineering in the HOM fiber open up the possibility to achieve pulse energies significantly beyond the level demonstrated here.

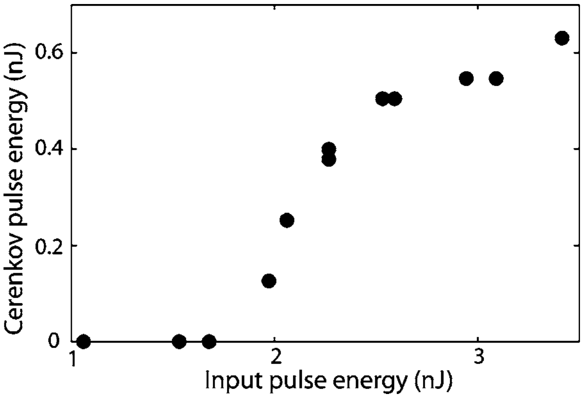

Fig. 3. Čerenkov output pulse energy as a function of input pulse energy.

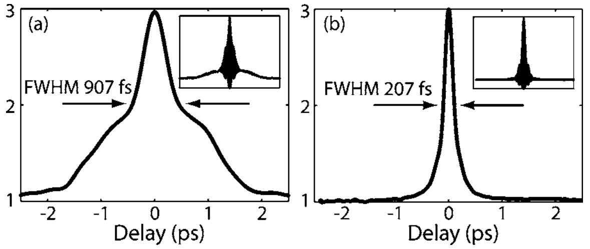

Fig. 4. Intensity autocorrelation traces of Čerenkov pulse, (a) at the output of the HOM fiber module, without dispersion compensation, and (b) dispersion compensated pulse. Vertical axes span from 1 to 3 for collinear autocorrelation. Interferometric autocorrelation traces are shown in the insets. Assuming the pulse shape predicted by simulation, this corresponds to pulse widths of (a) 465 fs and (b) 106 fs.

Although not demonstrated in our experiment, the generated Čerenkov pulse can be converted back to the fundamental mode by another LPG at the output of the HOM fiber module. With proper dispersion matching, efficient and broadband (>100 nm) LPG has already been experimentally demonstrated for mode conversion.[13] On the other hand, depending on the intended usage, the HOM output could also be used directly without mode conversion.

In summary, we demonstrate a method of generating short pulses at 1350 nm by exciting Čerenkov radiation in a HOM fiber with a 1064 nm pulsed fiber source. We have successfully dechirped a 465 fs pulse at the output of the HOM fiber to a 106 fs pulse with a pair of silicon prisms. This method of generating short pulses at 1350 nm can potentially be extended to other wavelengths and to higher pulse energies with appropriate design of the HOM fiber.

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