Generation of Cerenkov radiation at 850 nm in higher-order-mode fiber

Ji Cheng,1,* Jennifer H. Lee,1 Ke Wang,1 Chris Xu,1 Kim G. Jespersen,2 Martin Garmund,2 Lars Grünner-Nielsen,2 and Dan Jakobsen2

1School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853, USA
2OFS Fitel Denmark, Prisørparken 680, 2605 Brondby, Denmark
*jc875@cornell.edu

Abstract: We demonstrate generation of Cerenkov radiation at 850 nm in a higher-order-mode (HOM) fiber. The LP02 mode in this solid, silica-based fiber has anomalous dispersion from 690 nm to 810 nm. Cerenkov radiation with 3 nJ pulse energy is generated in this module, exhibiting 60% energy conversion efficiency from the input. The HOM fiber provides a valuable fiber platform for nonlinear wavelength conversion with pulse energies in-between index-directed silica-core photonic crystal fibers and air-core photonic bandgap fibers.

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1. Introduction

Soliton self-frequency shift (SSFS) and Cerenkov radiation in optical fibers have been theoretically studied [1,2], and experimentally demonstrated in a variety of fibers in the past [3–10]. It has been shown that a soliton formed in the anomalous dispersion regime can continuously red-shift its central wavelength through the stimulated Raman scattering process. In the case of fibers transitioning to normal dispersion at longer wavelength, SSFS is limited by the second (i.e., at the long wavelength side) zero dispersion wavelength (ZDW). As the frequency-shifted soliton approaches the second ZDW, a phase-matched, red-shifted dispersive wave in the normal dispersion regime, known as Cerenkov radiation, will be emitted by the soliton. The phase-matching condition required for Cerenkov radiation can also be met by the input pulse in the anomalous dispersion regime and a blue-shifted dispersive wave at a wavelength shorter than the first ZDW [9,11,12]. As photonic crystal fibers (PCFs) can provide anomalous dispersion in different wavelength regimes, both SSFS and Cerenkov radiation have been previously explored in PCFs at various wavelengths [5,7–9,12]. A number of applications have also been demonstrated using these PCF-based wavelength conversion effects [4,8,9].

By propagating light in the LP02 mode, all solid silica-based higher-order-mode (HOM) fibers can be designed to have dispersion characteristics dramatically different from conventional step-index single-mode fibers (SMFs) [13,14]. HOM fibers have been engineered to have anomalous dispersion below 1300 nm which was previously possible only with PCFs [15]. This allows HOM fibers to generate SSFS between 1064 nm and 1300 nm [15,16] and red-shifted Cerenkov radiation generation at 1350 nm [17]. Compared to PCFs, including both index-guided silica-core PCFs and air-core photonic bandgap fibers (PBGFs), HOM fibers are able to generate frequency-shifted solitons and red-shifted Cerenkov radiation at different energy levels [15]. For index-guided silica-core PCFs, the achievable pulse energy of soliton and Cerenkov radiation is restricted by its high nonlinearity, as silica-core PCFs require a small core size to achieve sufficient anomalous dispersion. Approximating these PCF structures by a silica rod surrounded by air, it has been calculated that the maximum core diameter of PCFs is limited to 2.3 μm to obtain anomalous dispersion below 800 nm [18,19]. This translates to a core size of 4.15 μm² and an effective mode area (Aeff) of approximately 2 μm². To have the second ZDW at 800 nm for the generation of red-shifted Cerenkov radiation at 850 nm, the maximum core diameter is further limited to less than 800 nm, corresponding to an Aeff of 0.5 μm² [20]. The core size of an actual silica-core PCF exhibiting the same...
dispersion characteristics would be even smaller. As a result, the pulse energy obtainable in cleanly frequency-shifted solitons in silica-core PCFs is limited to small fractions of a nanojoule [3–8], and the red-shifted Cerenkov radiation in silica-core PCFs demonstrated in previous experiments is below 100 pJ [7,21]. On the other hand, the pulse energy for solitons in an air-core photonic bandgap fiber (PBGF) is on the order of 100 nJ due to the low nonlinearity of air in the PBGF [22]. The nonlinearity values of HOM fibers lie in-between silica-core PCF and air-core PBGF as they propagate light in a solid silica core but with a significantly larger A_{eff} than that of silica-core PCFs. Thus, the HOM fiber is able to generate soliton and red-shifted Cerenkov radiation with pulse energy on the order of 1 nJ [16,17]. Therefore, the HOM fiber is a valuable platform of nonlinear wavelength conversion with pulse energies in-between index-guided silica-core PCFs and air-core PBGFs.

Nonlinear wavelength conversion at or below 850 nm has also been achieved through blue-shifted Cerenkov radiation at a wavelength shorter than the first ZDW [9,12,23]. In this case, the required anomalous dispersion regime is shifted to longer wavelengths, reducing the core-size constraints described in the previous paragraph. However, the demonstrated pulse energies in PCFs are still below 100 pJ [9,12]. Similar blue-shifted Cerenkov radiation with approximately 0.4 nJ pulse energy and 5% conversion efficiency has been generated using highly nonlinear germanosilicate bulk fiber [23]. However, both the pulse energy and the conversion efficiency are significantly lower than red-shifted Cerenkov radiation in HOM fibers. In this paper, we characterize a novel HOM fiber module with a large anomalous dispersion of 120 ps/km/nm and a large A_{eff} of 15 μm^2 at 772 nm (approximately 5 times larger than the A_{eff} of silica-core PCFs designed to have anomalous dispersion below 800 nm). We demonstrate red-shifted Cerenkov radiation generation at 850 nm with 3 nJ pulse energy and up to 60% power conversion efficiency from the input light source (66% photon conversion efficiency) in this module.

2. Setup

The experimental setup is shown in Fig. 1(a). An 80 MHz mode-locked Ti:Sapphire laser is used as the input source. The initial pulse launched into the HOM fiber module is centered at 772 nm and has a spectral bandwidth (full width at half maximum, FWHM) of 8 nm. The HOM fiber module consists of a 1.3 m SMF (ClearLite 780-11, OFS), a long period grating (LPG) to convert light from the fundamental mode (LP_{01}) to the LP_{02} mode with more than 99% efficiency between 762 nm and 778 nm, and 5.3 m HOM fiber (FemtoComp 800, OFS). The LP_{02} mode of the HOM fiber has anomalous dispersion between 690 nm and 810 nm [Fig. 1(b)]. The A_{eff} of the LP_{02} mode is between 10 and 15 μm^2 [Fig. 1(c)] in the vicinity of the input wavelength. The input power to the HOM fiber module can be tuned without changing the input polarization by a variable optical attenuator (VOA), which consists of a half-wave-plate and a polarizer. The input pulse is broadened to 300 fs by dispersion in the optical isolator. It is then further broadened to 2 ps by a glass rod to reduce the effects of spectral broadening from self-phase modulation in the SMF pigtail and to protect the LPG from nonlinear photodamage. The output pulse is characterized with an optical spectrum analyzer after collimation. A long pass filter with a cutoff wavelength at 810 nm is used to separate the Cerenkov radiation from the residue input. The pulse energy of the Cerenkov radiation is measured, taking into account the transmission of the long pass filter. The filtered Cerenkov radiation is temporally characterized by a second-order autocorrelator.
3. Simulated and experimental results

The fiber propagation process is numerically modeled using the generalized nonlinear Schrödinger equation [24,25]. The laser source is modeled as a hyperbolic secant pulse with 90 fs FWHM. The pulse is broadened to 2 ps by normal dispersion before entering the HOM fiber module. For propagation in the HOM fiber, our simulation incorporates the contribution of dispersion, self-phase modulation, stimulated Raman scattering, self-steepening, wavelength dependent $A_{\text{eff}}$, and other high order nonlinear effects. The nonlinear refractive index used in the simulation is $n_2 = 2.0 \times 10^{-20} \text{m}^2/\text{W}$. The dispersion coefficients (up to 14th order) and $A_{\text{eff}}$ values are obtained by directly fitting the dispersion and $A_{\text{eff}}$ curves shown in Figs. 1(b) and 1(c). The Raman response function is written as

$$R(t) = (1 - f_R)\delta(t) + f_R \frac{\tau_1^2 + \tau_2^2}{\tau_1^{\tau_2}} \exp\left(-\frac{t}{\tau_2}\right) \sin\left(\frac{t}{\tau_1}\right) \Theta(t),$$

where $f_R = 0.18$ is the fractional contribution of the delayed Raman response, $\tau_1 = 12.2$ fs, $\tau_2 = 32$ fs, $\Theta(t)$ is the Heaviside step function, and $\delta(t)$ is the Dirac delta function [25].

We systematically characterize the output spectra at different input pulse energies (from 0.15 nJ to 5 nJ) to show the effects of nonlinear pulse propagation. Spectra measured at 0.2 nm resolution with different input pulse energies are shown in Fig. 2(a). At 0.15 nJ input pulse energy (Fig. 2), a 777 nm frequency-shifted soliton is observed with a pulse energy greater than 0.1 nJ. At higher input pulse energies, the soliton can be further red-shifted, and its wavelength is eventually “locked” at 795 nm at 0.3 nJ input pulse energy (Fig. 2), due to the balance of SSFS and the spectral recoil from the generation of the Cerenkov radiation. Multiple solitons with spectral overlap are generated at higher input energies. The spectral beating produced by multiple solitons is clearly observable in the spectrum taken at 0.42 nJ input pulse energy (Fig. 2). The measured Cerenkov pulse energy as a function of input pulse energy is shown in Fig. 3. The onset of Cerenkov radiation occurs at approximately 0.22 nJ input pulse energy (Fig. 2). A threshold behavior (between input energies of 0.22 nJ and 0.25 nJ) and a plateau behavior (between input energies of 0.25 nJ and 0.4 nJ) are observed at the initial stage of the generation of the Cerenkov radiation, which are consistent with previous observations in PCFs and HOM fibers at other wavelengths [7,17]. The Cerenkov energy
rapidly increases again at 0.4 nJ, indicating the onset of the Cerenkov radiation generated by the second frequency-shifted soliton. These behaviors are all identified in Fig. 3.

Fig. 2. (a) Measured spectra at various pulse energies showing soliton generation, soliton self-frequency shift, and Cerenkov radiation. (b) Simulated spectra with the same input conditions. All traces are taken at 0.2 nm spectral resolution. The soliton and Cerenkov radiation are marked by arrows. The input wavelength and the zero-dispersion wavelength (ZDW) are denoted by dashed lines and the input pulse energy (E) is indicated on each trace.

To compare with the experimental data, Fig. 2(b) and the dashed line in Fig. 3 show the simulated traces generated using our numerical modeling program. Simulation results are able to match the spectral features and the pulse energies of Cerenkov radiation at input energies from 0.15 nJ to 1 nJ. The simulated spectra at high input energies show many pronounced fine substructures which are extremely sensitive to small changes of the input energy. These fine spectral features were not observed in our experiments. We believe this discrepancy is due in part to the fact that the measured spectra are averaged over many laser pulses at slightly different pulse energies. Similar phenomenon was also theoretically predicted and experimentally observed in previous works on supercontinuum generation [26]. Other discrepancies between the simulated and experimental results are potentially caused by the inaccuracy of the calculated dispersion and $A_{eff}$ curves. Note that at high input energies, simulation also shows 5-10% higher conversion efficiency of the Cerenkov radiation and lower levels of the residue input than the experimental results. This difference might be attributed to the omission of the vectorial nature of the pulse propagation in the HOM fiber in simulation.
At 5 nJ input pulse energy, Cerenkov radiation with 3 nJ pulse energy and 50 nm spectral bandwidth, which translates to a spectral density of 4.8 mW/nm at 80 MHz repetition rate, can be generated without exhibiting super-continuum-like spectral features. The measured and simulated second-order intensity autocorrelation trace of the Cerenkov radiation at 5 nJ input pulse energy is shown in Fig. 4. The measured and simulated traces show FWHM values of 10 ps and 12 ps, respectively. The long pulse duration of the Cerenkov radiation is due to the long propagation distance (6 m), the broad spectral bandwidth (50 nm), and the high dispersion value of the HOM fiber (100 ps/nm/km). While the Cerenkov energy and its power spectral density can be further increased by using a more energetic input, the potential photodegradation of the LPGs in the HOM fiber modules prevents us from experimenting at higher input powers.

4. Discussion

Blue-shifted Cerenkov radiation at comparable wavelengths can be generated using the first ZDW of the waveguide. This approach does not require the fiber to achieve anomalous
dispersion below 850 nm, and thus the core diameter of the waveguide can exceed 2.3 μm. However, high energy input pulse must be launched at a wavelength much longer than the first ZDW to avoid super-continuum generation, which significantly limits the energy conversion efficiency [9]. More importantly, red-shifted Cerenkov radiation has much higher energy conversion efficiency than blue-shifted Cerenkov radiation because stimulated Raman scattering shifts the pulse towards the longer wavelength and facilitates the energy conversion to the Cerenkov radiation. For example, the results reported by G. Krauss et al. for the blue-shifted Cerenkov radiation at 860 nm have approximately 0.4 nJ pulse energy with an 8 nJ femtosecond input [23]. The red-shifted Cerenkov radiation reported in our paper has approximately 3 nJ pulse energy with a 5 nJ input. Both the conversion efficiency and the absolute pulse energy represent approximately an order of magnitude improvement over the existing results. These improvements are enabled by the unique propagation characteristics of the HOM fiber, which allows us to generate red-shifted Cerenkov radiation in a fiber with a relatively large $A_{\text{eff}}$.

The demonstrated pulse energy and power spectral density of the red-shifted Cerenkov radiation in the HOM fiber is also significantly higher than red-shifted Cerenkov radiation obtainable in PCFs at comparable wavelengths. Because the much smaller $A_{\text{eff}}$ of the silica-core PCFs (less than 800 nm core diameter for generating the red-shifted Cerenkov radiation at 850 nm) results in much higher optical nonlinearity, supercontinuum could be generated by femtosecond input pulses with 1 nJ pulse energy, which results in much lower power spectral density of the Cerenkov radiation. High power spectral density can potentially be achieved in silica-core PCFs with high power continuous-wave input, but the lack of temporal confinement makes the output unsuitable for various applications that require short pulses, such as pump-probe spectroscopy and Coherent Raman Scattering microscopy.

The picosecond Cerenkov radiation generated in the HOM fiber, together with the residue pump light, provides a convenient, synchronized 2-color picosecond source with high pulse energies, which is desirable for a variety of practical applications including pump-probe spectroscopy, modulation transfer microscopy [27], stimulated emission depletion microscopy (STED) [28], etc. The HOM fiber can also be readily integrated with a frequency-doubled femtosecond fiber laser at 775 nm to achieve a fiber-based, picosecond, two-color light source. Although red-shifted CR in an HOM fiber at 1350 nm has been reported in the past, and it is well-known in theory that the wavelength of the CR can be engineered by shifting the dispersion curve, it is challenging to shift the dispersion curve to much shorter wavelengths due to the large increase of the material dispersion. Our results demonstrate that the concept of CR in an HOM fiber can be applied to achieve nonlinear frequency conversion at much shorter wavelengths while maintaining its significant advantages in higher pulse energy and conversion efficiency.

5. Conclusion

In summary, we demonstrate SSFS below 800 nm and Cerenkov generation at 850 nm in a solid silica-based HOM fiber module. The HOM module generates significantly more energetic Cerenkov radiation than index-guided silica-core PCFs at comparable wavelengths. We are able to achieve a 3 nJ Cerenkov radiation pulse energy, with high power conversion efficiency of 60% and approximately 4.8 mW/nm spectral density. The HOM fiber module provides a valuable fiber platform for nonlinear wavelength conversion around 800 nm with pulse energies in-between index-guided silica-core photonic crystal fibers and air-core photonic bandgap fibers. This fiber platform can also be tailored to other wavelengths of interest with proper dispersion engineering.

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