Ultraviolet-visible non-supercontinuum ultrafast source enabled by switching single silicon strand-like photonic crystal fibers

Haohua Tu[*] and Stephen A. Boppart[†]

Biophotonics Imaging Laboratory, Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA
[*]htu@illinois.edu
[†]boppart@illinois.edu

Abstract: Cherenkov radiation from short photonic crystal fiber with a high air-fill fraction can selectively convert the 1020 nm fs pump pulses from a laser oscillator to the fundamental-mode signal pulses at a significantly shorter wavelength. Across the ultraviolet-visible spectral region, the typical fiber output is characterized by a single isolated Cherenkov band having a multimilliwatt-level average power, a Gaussian-shaped spectrum, and a 3-dB bandwidth of 15 nm. By selecting photonic crystal fibers with smaller cores, the central wavelength of the Cherenkov band can be easily extended to 347 nm in the ultraviolet, in sharp contrast to various supercontinuum or non-supercontinuum fiber sources that have difficulty extending their emission spectra below 400 nm. The supercontinuum generation often associated with fs pulse-pumped fibers is efficiently suppressed by detuning the zero-dispersion wavelength of the photonic crystal fiber far shorter than the pump wavelength, a condition termed as the short nonlinear-interaction condition.

OCIS codes: (190.4370) Nonlinear optics, fibers; (060.5295) Photonic crystal fibers; (190.5530) Pulse propagation and solitons

References and links

1. P. N. Prasad, *Introduction to Biophotonics* (John Wiley & Sons Inc., 2003).
2. N. I. Nikolov, T. Sørensen, O. Bang, and A. Bjarklev, "Improving efficiency of supercontinuum generation in photonic crystal fibers by direct degenerate four-wave mixing," J. Opt. Soc. Am. B **20**(11), 2329–2337 (2003).
3. P. A. Champert, V. Couderc, P. Leproux, S. Février, V. Tombelaine, L. Labonté, P. Roy, C. Froehly, and P. Nérin, "White-light supercontinuum generation in normally dispersive optical fiber using original multi-wavelength pumping system," Opt. Express **12**(19), 4366–4371 (2004).
4. G. Genty, M. Lehtonen, H. Ludvigsen, and M. Kaivola, "Enhanced bandwidth of supercontinuum generated in microstructured fibers," Opt. Express **12**(15), 3471–3480 (2004).
5. P. Westbrook, J. Nicholson, K. Feder, and A. Yablon, "Improved supercontinuum generation through UV processing of highly nonlinear fibers," J. Lightwave Technol. **23**(1), 13–18 (2005).
6. J. C. Travers, S. V. Popov, and J. R. Taylor, "Extended blue supercontinuum generation in cascaded holey fibers," Opt. Lett. **30**(23), 3132–3134 (2005).
7. A. Kudlinski, A. K. George, J. C. Knight, J. C. Travers, A. B. Rulkov, S. V. Popov, and J. R. Taylor, "Zero-dispersion wavelength decreasing photonic crystal fibers for ultraviolet-extended supercontinuum generation," Opt. Express **14**(12), 5715–5722 (2006).
8. J. M. Stone, and J. C. Knight, "Visibly "white" light generation in uniform photonic crystal fiber using a microchip laser," Opt. Express **16**(4), 2670–2675 (2008).
9. M. H. Frosz, P. M. Moselund, P. D. Rasmussen, C. L. Thomsen, and O. Bang, "Increasing the blue-shift of a supercontinuum by modifying the fiber glass composition," Opt. Express **16**(25), 21076–21086 (2008).
10. G. Qin, and X. Yan, C. Kito, M. Liao, C. Chaudhari, T. Suzuki, and Y. Ohishi, "Supercontinuum generation spanning over three octaves from UV to 3.85 μm in a fluoride fiber," Opt. Lett. **34**, 2015–2017 (2009).
11. G. McConnell, "Confocal laser scanning fluorescence microscopy with a visible continuum source," Opt. Express **12**(13), 2844–2850 (2004).
12. J. H. Frank, A. D. Elder, J. Swartling, A. R. Venkitaraman, A. D. Jeyasekharan, and C. F. Kaminski, "A white light confocal microscope for spectrally resolved multidimensional imaging," J. Microsc. **227**(3), 203–215 (2007).

#116623 - $15.00 USD Received 2 Sep 2009; revised 16 Sep 2009; accepted 17 Sep 2009; published 22 Sep 2009

13. C. Dunsby, P. M. P. Lanigan, J. McGinty, D. S. Elson, J. Requejo-Isidro, I. Munro, N. Galletly, F. McCann, B. Treanor, B. Önfelt, D. M. Davis, M. A. A. Neil, and P. M. W. French, “An electronically tunable ultrafast laser source applied to fluorescence imaging and fluorescence lifetime imaging microscopy,” J. Phys. D **37**(23), 3296–3303 (2004).
14. Y. Q. Xu, S. G. Murdoch, R. Leonhardt, and J. D. Harvey, “Widely tunable photonic crystal fiber Fabry-Perot optical parametric oscillator,” Opt. Lett. **33**(12), 1351–1353 (2008).
15. H. Tu, Z. Jiang, D. L. Marks, and S. A. Boppart, “Intermodal four-wave mixing from femtosecond pulse-pumped photonic crystal fiber,” Appl. Phys. Lett. **94**(10), 101109 (2009).
16. F. Lu, and W. H. Knox, “Generation, characterization, and application of broadband coherent femtosecond visible pulses in dispersion micromanaged holey fibers,” J. Opt. Soc. Am. B **23**(6), 1221–1227 (2006).
17. K. Moutzouris, E. Adler, F. Sotier, D. Träutlein, and A. Leitenstorfer, “Multimilliwatt ultrashort pulses continuously tunable in the visible from a compact fiber source,” Opt. Lett. **31**(8), 1148–1150 (2006).
18. M. Hu, C. Y. Wang, L. Chai, and A. Zheltikov, “Frequency-tunable anti-Stokes line emission by eigenmodes of a birefringent microstructure fiber,” Opt. Express **12**(9), 1932–1937 (2004).
19. H. Tu, and S. A. Boppart, “Optical frequency up-conversion by supercontinuum-free widely-tunable fiber-optic Cherenkov radiation,” Opt. Express **17**(12), 9858–9872 (2009).
20. J. Herrmann, U. Griebner, N. Zhavoronkov, A. Husakou, D. Nickel, J. C. Knight, W. J. Wadsworth, P. S. Russell, and G. Korn, “Experimental evidence for supercontinuum generation by fission of higher-order solitons in photonic fibers,” Phys. Rev. Lett. **88**(17), 173901 (2002).
21. I. Cristiani, R. Tediosi, L. Tartara, and V. Degiorgio, “Dispersive wave generation by solitons in microstructured optical fibers,” Opt. Express **12**(1), 124–135 (2004).
22. D. R. Austin, C. M. de Sterke, B. J. Eggleton, and T. G. Brown, “Dispersive wave blue-shift in supercontinuum generation,” Opt. Express **14**(25), 11997–12007 (2006).
23. G. Genty, M. Lehtonen, H. Ludvigsen, J. Broeng, and M. Kaivola, “Spectral broadening of femtosecond pulses into continuum radiation in microstructured fibers,” Opt. Express **10**(20), 1083–1098 (2002).

1. Introduction

Compact ultrafast (ps or fs) pulsed sources, particular in the visible and the ultraviolet (UV) portion of the electromagnetic spectrum, allow both static and time-resolved studies in photobiology and photochemistry, and are therefore in high demand for applications such as fluorescence spectroscopy, short-wavelength multiphoton microscopy, and fluorescence lifetime imaging microscopy (FLIM). As an example, many fluorescent molecules of biomedical importance allow one-photon excitation within the 350-600 nm spectral range and two-photon excitation within the 500-700 nm spectral range [1]. Presently, the unamplified tunable UV-visible ps-fs pulses are mainly generated from Ti:sapphire laser-pumped optical parametric oscillators or argon laser-pumped dye lasers, neither of which is compact, cost-effective, or easy to maintain. Since the desirable pulse properties, such as those of pulse duration, energy per pulse, and repetition rate, are more readily available in infrared sources, it is useful to frequency up-convert infrared pulses into the visible (or UV) while retaining, if not enhancing, requisite spectral and temporal characteristics. Following this guidance, researchers have actively pursued either the supercontinuum or the non-supercontinuum UV-visible sources based on nonlinear fiber optics.

Numerous efforts have been devoted to extend the blue edge of the supercontinuum toward the UV-visible region. The reported techniques include controlling four-wave mixing (FWM) [2], pumping at multiple wavelengths [3], using photonic crystal fiber (PCF) with two zero-dispersion wavelengths (ZDW) [4], irradiating germanosilicate fiber by UV light [5], cascading multiple fibers [6], tapering the fiber [7], selecting PCF with a high air-fill fraction [8], and modifying the fiber glass composition [9, 10]. Supercontinuum sources with high power spectral density across 420-2400 nm have become commercially available. Selective spectral filtering of the supercontinuum sources in the visible region have allowed continuous tuning of the excitation wavelength in laser-scanning confocal microscopy [11, 12] and FLIM [13]. Despite all these successes, it is challenging for the supercontinuum sources to cover the UV region (< 400 nm) with practically useful power spectral density. Also, the spectral filtering often results in elongated pulse duration and decreased pulse energy to forbid the applications of the supercontinuum sources to ultrafast fluorescence spectroscopy and short-wavelength multiphoton microscopy.

The non-supercontinuum sources involve specific routing of the pulse energy from the infrared pump to a narrow (< 30 nm 3-dB bandwidth) signal band in the UV-visible region. This approach is attractive because it minimizes the pulse energy loss to the nonspecific

#116623 - $15.00 USD Received 2 Sep 2009; revised 16 Sep 2009; accepted 17 Sep 2009; published 22 Sep 2009

wavelength conversion of supercontinuum generation. Such specific wavelength conversion has been enabled by the phase-matching condition of either FWM or Cherenkov radiation (CR) (also known as dispersive wave generation or non-solitonic radiation). The FWM has generated tunable fundamental-mode signal across the visible spectrum, but with a small average power (< 1 mW) [14], or multimilliwatt visible signal, but in an undesired higher-order fiber mode [15]. To date, the pulse walk-off effect and/or the supercontinuum onset have largely limited the pump-to-signal conversion efficiency of the FWM, preventing the generation of a multimilliwatt-level fundamental-mode signal. Such signal can be produced through the CR, but at the cost of additional complexities introduced to the simple fiber-pumping procedure of the supercontinuum generation and FWM. These include accurately controlled fiber tapering [16] and complicated combinations of fiber dispersion engineering and bulk optics frequency doubling [17]. Another study has directly produced multimilliwatt visible CR signal through the simple fiber-pumping procedure [18]. However, the tuning of the signal wavelength over 20 nm has not been demonstrated.

Our recent study has generated multimilliwatt fundamental-mode CR signal tunable across 485-690 nm from two dispersion-engineered PCFs, which are intrinsically poor candidates for supercontinuum generation due to their unique group-index profiles [19]. The signal wavelength is tuned by varying the pump wavelength of a relatively expensive Ti:sapphire laser which affords a wide tuning range of 690-1020 nm. In this work, we show that neither the special dispersion engineering nor the tuning of the pump wavelength is necessary for generating such CR signal. By fixing the pump wavelength at 1020 nm, we obtain similar CR signal across 347-680 nm from one series of PCFs whose dispersion properties approximate those of single circular silica strands in air.

2. Experiment

We select one series of short (15-18 cm) PCFs consisting of 13 fibers (Table 1) with similar structural cross sections (Fig. 1, insets), except for the varying core size and ZDW (Table 1). Each of these fibers is pumped by 1020 nm, 80 MHz, near transform-limited ~170 fs, ~10 nm bandwidth (FWHM) pulses from an unamplified Ti:sapphire laser (Mai Tai HP, Spectra-Physics, Mountain View, CA). By using a small aspheric lens (C330TME-B, Thorlabs, Newton, NJ) and a pump power below 250 mW, the launching efficiency of the fiber is attained at ~70% (Table 1). The spectrum of the exiting light is measured by a spectrometer (USB2000, Ocean Optics, Dunedin, FL) in the spectral range of 300-1100 nm.

Table 1. Properties of commercial photonic crystal fibers (Crystal Fibre A/S, Denmark).

Fiber type	ZDW (nm)	Geometric core diameter (μm)	ZDW equivalent silica strand diameter (μm)	Launching efficiency (%)	CR (predicted) (nm)	CR (measured) (nm)
NL-1.5-670	670	1.5	1.34	60	359	348
NL-1.7-670	670	1.7	1.34	62	359	369
NL-1.8-710	710	1.8	1.55	66	389	394
NL-2.0-735	735	2.0	1.71	70	414	420
NL-2.0-745	745	2.0	1.78	72	425	433
NL-2.3-790	790	2.3	2.14	75	486	490
NL-2.4-800	800	2.4	2.24	75	502	509
NL-2.5-810	810	2.5	2.34	76	520	523
NL-2.6-825	825	2.6	2.51	76	549	548
NL-2.8-840	840	2.8	2.70	78	583	585
NL-3.0-850	850	3.0	2.83	80	610	632
NL-3.0-870	870	3.0	3.12	82	659	639
NL-3.0-890	890	3.0	3.48	85	726	695

#116623 - $15.00 USD Received 2 Sep 2009; revised 16 Sep 2009; accepted 17 Sep 2009; published 22 Sep 2009

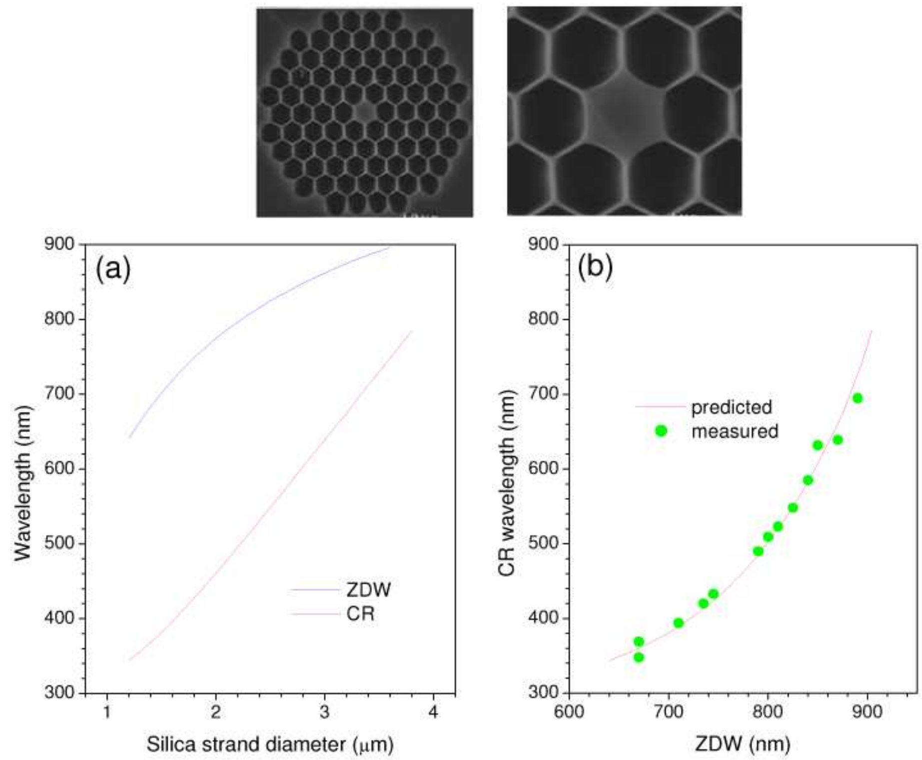

Fig. 1. CR wavelengths associated with 1020 nm pumping. (a) Dependence of the ZDW and the CR wavelength of single silica strand for varying silica strand diameter. (b) Predicted CR wavelength of single silica strand as a function of the ZDW of the silica strand (line), and measured CR wavelengths of 13 high-Δ PCFs with varying ZDWs (points). Insets: representative scanning electron microscopy images of the cross section (left) and the core (right) of the PCFs.

3. Phase-matching condition

Because of the high air-fill fraction (> 90%) in the cladding of these PCFs (termed as high-Δ PCFs), it is reasonable to assume that the dispersion properties of the fibers approximate those of single circular silica strands in air. For a given silica strand diameter, the fundamental-mode propagation constant β as a function of optical frequency ω can be readily calculated according to the reported refractive index data of silica. The calculated β-ω relation can in turn be used to derive the dispersion profile of the silica strand that specifies its ZDW, and to predict the CR wavelength through a phase-matching condition [20]. If the nonlinear phase of the soliton is ignored (which is a good assumption at low peak pump powers), this condition can be written as [19, 21],

$$\sum_{n\geq 2}\frac{\beta_n(\omega_S)}{n!}(\omega_{CR}-\omega_S)=0 \tag{1}$$

where ω_{CR} is the CR frequency, $\beta_n(\omega_S)$ is the n-th order derivative of β at the soliton frequency ω_S, which is taken as the pump frequency corresponding to the 1020 nm wavelength.

The calculations of the dispersion and Eq. (1) allow the ZDW and CR wavelength as a function of the silica strand diameter to be numerically derived using β_n up to the 9-th order [Fig. 1(a)]. Thus, the dependence of the CR wavelength on the ZDW of the silica strand can be established [Fig. 1(b)]. According to the function of ZDW vs. silica strand diameter [Fig. 1(a)], the manufacturer-specified geometric core diameter of each PCF can be approximated

#116623 - $15.00 USD Received 2 Sep 2009; revised 16 Sep 2009; accepted 17 Sep 2009; published 22 Sep 2009

by the diameter of the silica strand that has the same ZDW as the PCF (termed as ZDW equivalent silica strand diameter) (Table 1). This evidence confirms that the dispersion properties of the PCFs indeed approximate those of the single silica strands. Similarly, the CR wavelength as a function of the ZDW derived from the silica strands [Fig. 1(b)] should also be applicable to the PCFs, implying that the ZDW of each PCF is sufficient to predict the wavelength of its CR signal at low-power 1020 nm pumping (Table 1).

4. Results and discussions

Typical output spectra from the series of PCFs pumped at an average power of 54-250 mW are shown in Fig. 2. In the UV-visible region, the spectrum from each fiber exhibits a single Gaussian-shaped band having a 3-dB bandwidth of ~15 nm and an average power of a few milliwatts, measured after removing the infrared power by two visible-infrared cutoff filters. The far-field images of the output light indicate that this band propagates in the fundamental-mode of the fiber (Fig. 2, insets). The pump power can be lowered by 30-50% toward a threshold where this band is minimally observable at a slightly red-shifted central wavelength (Fig. 2). The dependence of this central wavelength on the ZDW of the PCF is shown in Table 1 and Fig. 1(b), and is found to approximate the CR wavelength as a function of the ZDW of single silica strand in air. Such unusual agreement confirms the CR nature of the observed band and validates the simplified phase-matching condition described above.

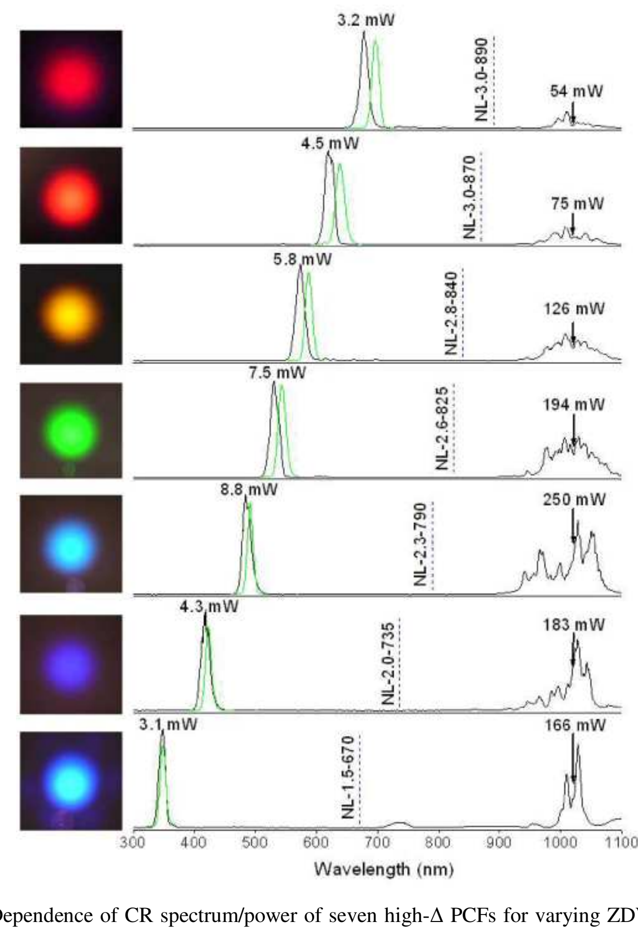

Fig. 2. Dependence of CR spectrum/power of seven high-Δ PCFs for varying ZDWs (broken vertical lines) and 1020 nm pump powers (arrows). The red-shifted CR spectra (green) are obtained at lower pump powers where the CR signals are minimally observable. The insets show the far-field images of the output light on a paper screen. Autofluorescence from the paper gives the bottom image a false blue color.

#116623 - $15.00 USD Received 2 Sep 2009; revised 16 Sep 2009; accepted 17 Sep 2009; published 22 Sep 2009

In contrast to a previous study [19] which intentionally selects low-Δ PCFs for supercontinuum-free CR generation, all the high-Δ PCFs employed in this study are good candidates for supercontinuum generation [8], and yet very similar supercontinuum-free operation is achieved. It should be noted that the ZDWs of the PCFs are detuned from the pump wavelength by 130-350 nm deep into the anomalous dispersion region (Fig. 2). Such large detuning implies that the pump pulses can only sustain a high peak intensity over a short fiber length, a condition termed as short nonlinear-interaction condition. This unusual condition, along with short fiber length (< 18 cm), efficiently suppresses the supercontinuum generation. The CR pulses, on the other hand, are generated within the first few centimeters of the fiber and simply disperse further down the fiber [21, 22], and are therefore less affected by the short nonlinear-interaction condition. This explains why strong CR signals not obscured by the supercontinuum generation can be generated. Thus, the supercontinuum-free CR may be generated from other PCFs that can be easily manufactured, providing the short nonlinear-interaction condition is attained.

The CR wavelength can be varied across 347-680 nm (Fig. 2), which extends the tuning range of multimilliwatt-level CR by more than 130 nm toward the short-wavelength end [18, 19]. No special fiber treatment or pumping condition is required for such ultraviolet extension, as opposed to the supercontinuum generation. Using a fixed-wavelength 1020 nm pump source allows CR generation from a compact Nd:Glass femtosecond laser or ytterbium-doped fiber laser, which could be useful in biomedical applications. State-of-the-art fiber termination or positioning devices may afford effortless switching of the PCFs to vary the CR wavelength. If the fiber launching is optimized to minimize the possible multi-mode behavior of the high-Δ PCFs, the maximum CR power is limited by the supercontinuum onset occurring above a pump power threshold, as shown in Fig. 2 for the NL-1.5-670 fiber. Higher average powers of supercontinuum-free CR signal may be obtained by optimizing the properties of the pump pulses and/or PCFs. The pulse duration of the CR signal depends on the fiber length, is on the order of a few ps for a ~10 cm length [21–23], and can be near-transform limited in the fs regime for shorter lengths [16, 22].

5. Conclusions

We have developed a non-supercontinuum ultrafast source based on the CR from one series of high-Δ PCFs to generate narrowband multimilliwatt-level pulses within the 347-680 nm spectral region. The CR wavelength can be varied by simply switching the PCFs of different core sizes, without changing any optics in the experimental setup or the wavelength of the pump source. The core size of the PCF to produce the intended CR wavelength can be estimated by a simple calculation of the phase-matching condition, allowing straightforward fabrication of such series of PCFs. The CR process can up-convert the 1020 nm pump with a frequency-shift equivalent to a 673 nm wavelength blue-shift. This allows the CR wavelength to be extended to 347 nm, and may be further UV-extended if PCFs with smaller cores are used. In contrast to the supercontinuum sources, neither fiber post-processing nor special pumping beyond the standard fiber pumping is required for the UV extension of this non-supercontinuum source. The optical setup of the CR generator is simple and cost-effective, while the pump-to-signal conversion efficiency of 2-6% (Fig. 2) compares favorably to other techniques such as fiber-optic FWM. This technique may add to a compact ~1000 nm fs laser the capability of a widely tunable UV-visible ps laser, which would be useful for many applications, but is presently bulky and expensive. Under the short nonlinear-interaction condition, the CR-based frequency up-conversion technique may be generalized to include a wide variety of PCFs, as well as the pump wavelengths other than 1020 nm.

Acknowledgments

This work was supported in part by grants from the NIH (NCI R33 CA115536, Roadmap Initiative R21 EB005321, and NIBIB R01 EB005221, S.A.B.).