High Power, High Efficiency, Continuous-Wave Supercontinuum Generation using Standard Telecom Fibers

S. Arun, Vishal Choudhury, V. Balaswamy and V.R. Supradeepa*
Center for Nano Science and Engineering, Indian Institute of Science, Bengaluru 560012, India
*Corresponding author: supradeepa@cense.iisc.ernet.in

Abstract: We propose a novel technique to convert any high-power, continuous-wave, Ytterbium fiber laser into a supercontinuum source using standard telecom fiber. We demonstrate an octave-spanning supercontinuum (880nm to >1900nm) with power >34W and ~44% conversion efficiency.

OCIS codes: 320.6629 Supercontinuum generation, 140.3550 Lasers, Raman, 140.3510 Lasers, fiber, 140.3615 Lasers, ytterbium, 140.3460 Lasers, 060.4370 Nonlinear optics, fibers

1. Introduction
Supercontinuum lasers find a wide range of applications in spectroscopy, test and measurement, LIDAR and communications [1-3]. Among them, continuous-wave (CW) supercontinuum sources are particularly interesting because of their higher average power which results in greater power per unit spectrum. The CW supercontinuum process primarily relies on pumping a non-linear medium, such as optical fiber, in the anomalous dispersion region near its zero-dispersion wavelength. The combined effects of modulational instability, four wave mixing and SRS then leads to supercontinuum generation. A lot of work has been done on generating supercontinuum using photonic crystal fiber, because its zero-dispersion wavelength can be tailored and brought down to the emission window of Yb where high power fiber lasers are now standard products [4]. However, to achieve power scaling and build an all fiber architecture, supercontinuum sources based on conventional Silica fibers are more effective since they can be spliced together without significant loss and can be pumped simultaneously. Several supercontinuum sources using Silica fibers operating at different power levels have been reported [5-8]. In these cases, specialty fibers such as highly non-linear fibers were used whose zero-dispersion wavelength is around 1500 nm and they were pumped using Raman lasers or Erbium-Ytterbium co-doped lasers operating in the 1.5um band. But as the zero-dispersion wavelength of these fibers is at longer wavelengths, the shorter wavelength cutoff of the supercontinuum is also shifted towards the longer wavelength side. This occurs because, fiber losses limits the longer wavelength cutoff to ~2000nm and the short wavelength cut-off arises from a four wave mixing process involving the long wavelength cutoff. This limits the bandwidth of the supercontinuum laser [6]. So the preferred alternative is to use an all silica fiber with a zero dispersion wavelength substantially below 1550 nm. Such an alternative is provided by standard telecom fibers (SMF) which have a zero-dispersion wavelength around 1310nm. However, supercontinuum generation using such fibers has been limited due to lack of high power sources at these wavelengths. In addition, in contrast to high power Ytterbium doped fiber lasers which are standard, robust products, supercontinuum sources are still considered niche technology which are both complex and substantially more expensive.

In this work, we propose and demonstrate a simple scheme to convert any high power, Ytterbium doped fiber laser into a broadband supercontinuum source using standard telecom fiber. We leverage the recent developments in high efficiency, cascaded Raman amplifiers to develop high power sources at a wide variety of wavelengths. In this work, we convert two different Ytterbium doped fiber lasers to >34W continuous wave supercontinuum sources with over 1 octave bandwidth (spanning from 880nm to > 1900 nm, 20-dB bandwidth). The conversion efficiency is ~44%.

2. Experiment
Figure 1 shows the architecture. High power Yb doped fiber lasers operating at 1117 nm and 1085nm generating over 80W of single mode output power were used as the primary laser sources. The output light from the laser is then fed into 2 km long, standard telecom fiber (SMF 28e), where efficient stimulated Raman scattering is enabled and the laser light reaches beyond 1310 nm through a series of Raman stokes shift and undergoes further stimulated Raman scattering into the anomalous dispersion region of the fiber. In [6], a similar idea was used to convert an Yb doped laser to the 1550 band to utilize the zero-dispersion wavelength of highly nonlinear fiber. Here, in addition to using standard SMF, which substantially enhances the bandwidth, another key novelty is to utilize the recently proposed cascaded Raman amplifier architecture with distributed feedback [9-12] which converts the Yb doped fiber laser to the zero-dispersion wavelength region with high efficiency. The implementation of this is indicated in fig 1. A fused fiber wavelength division multiplexer (WDM) working between the 1micron and 1.5micron bands with a
simple flat-cleave in the input side is used to provide the necessary recoupling of the backward distributed feedback. The entire supercontinuum generator is a simple passive module constituting a fused fiber WDM spliced to standard telecom fiber. This simple module can convert any high power, Yb doped fiber laser into a broadband supercontinuum source.

![Fig 1: Architecture for the supercontinuum laser generation](image)

The stimulated Raman scattering process is well seeded using the distributed feedback architecture ensuring efficient forward Raman conversion [9-12]. The feedback provided by the flat cleave at the input ports of WDM (as shown in fig 1.) is sufficient for high efficiency conversion. We could couple around 76 W of power into the 2 km telecom fiber and as soon as the Stokes conversion reaches the zero dispersion wavelength, the continuous wave light through modulation instability, four wave mixing and other nonlinear effects, broadens into a supercontinuum source. We believe that through the distributed pumping scheme of the Raman laser, we seed the dispersive wave generation better and this leads to a relatively smoother spectrum in the normal dispersion regime [6]. The evolution of supercontinuum is shown in fig 2.

![Fig 2: Supercontinuum evolution at different output power levels](image)

In our experiment, the optical spectrum analyzer measurement capability was limited to 1700 nm. The longer wavelength cutoff of the supercontinuum spectrum was measured using an in-house built spectrometer. Figure 2(c)
shows the complete supercontinuum spectrum for pumping with a 1117 nm laser. The 20-dB bandwidth of the spectrum extends over an octave from 880 nm to >1900 nm. To the best of our knowledge, this is the widest CW supercontinuum source demonstrated in all fiber architecture. The spectrum in the longer wavelength side exhibits a sharp fall off from 1900 nm to higher wavelengths. This is because of the silica absorption increasing substantially above this wavelength which fundamentally limits the longer wavelength extent of spectrum. The shorter wavelength cutoff, related to the longer wavelength cutoff through four wave mixing is around 880 nm. The benefits of use of standard SMF is manifested in the short wavelength cutoff which at 880 nm is several 100s of nm shorter than demonstrated in [6]. With the architecture proposed here, any Yb doped high power fiber laser can be converted into a supercontinuum source irrespective of its wavelength of operation. To demonstrate this, we have used a Yb doped fiber laser operating at 1085 nm as the pump laser source and obtained similar supercontinuum spectrum at the output (shown in Fig 2d). The distributed feedback enables seeded Raman conversions in the forward direction efficiently independent of pump wavelength and avoid any laser instabilities.

![Fig 3: Supercontinuum output power Vs. input power coupled to the telecom fiber](image)

Figure 3 shows the supercontinuum output power vs. the input power for the 1117 nm input source. The output power plots are similar for both cases of 1117 and 1085 nm pumping. For an input coupled power of ~76 W, we obtain over 34 W at the output corresponding to a conversion efficiency of >44%.

3. Conclusion
We have developed a novel technique to convert any high power Yb doped fiber laser source into a broadband supercontinuum source by using standard telecom fiber. The all fiber architecture, generated ~34 W continuous-wave supercontinuum with a 20-dB bandwidth extending from 880 nm to >1900 nm with >44% conversion efficiency.

4. References
[1] D. M. Owen, E. Auksorius, H. B. Manning, C. B. Talbot, P. A. A. de Beule, C. Dunsby, M. A. A. Neil, and P. M. W. French, "Excitation-resolved hyperspectral fluorescence lifetime imaging using a UV-extended supercontinuum source," Opt. Lett. 32, 3408-3410 (2007).
[2] P. L. Hsiung, Y. Chen, T. H. Ko, J. G. Fujimoto, C. J. S. de Matos, S. V. Popov, J. R. Taylor, and V. P. Gapontsev, "Optical coherence tomography using a continuous-wave, high-power, Raman continuum light source," Opt. Express 12, 5287-5295 (2004).
[3] T. Morioka, H. Takara, S. Kawanishi, O. Kamatani, K. Takiguchi, K. Uchiyama, H. Takahashi, M. Yamada, T. Kanamori, and H. Ono, "1Tbit/s (100 Gbit/sx10 channel) OTDM/WDM transmission using a single supercontinuum WDM source," Electron. Lett. 32, 906-907 (1996).
[4] B. A. Cumberland, J. C. Travers, S. V. Popov, J. R. Taylor, "29 W High power cw supercontinuum source" Optics Express, 16, 8 (2008).
[5] A. K. Abeeluck, C. Headley, C. G. Jorgensen, "High-power supercontinuum generation in highly nonlinear, dispersion-shifted fibers by use of a continuous-wave Raman fiber laser" Optics Letters, 29, 18 (2004).
[6] B. H. Chapman, S. V. Popov, R. Taylor, "Continuous Wave Supercontinuum Generation through Pumping in the Normal Dispersion Region for Spectral Flatness" IEEE Photonics Technology Letters, 24, 15 (2012).
[7] Vishal Choudhury, S Arun, Roopa Prakash and V R Supradeepa, "High Power, Equalized, Continuous-Wave Supercontinuum Generation using Cascaded Raman Fiber Amplifiers" Conference on Lasers and Electro-optics (CLEO) Europe, CD-14, (2017)
[8] Roopa Prakash, Vishal Choudhury, V R Supradeepa, "High power, Continuous Wave, Supercontinuum Generation using Erbium-Ytterbium Co-doped Fiber Lasers," International Conference on Fiber Optics and Photonics, W3.A.78 (2016)
[9] S. A. Babin, E. A. Zlobina, S. I. Kablukov, and E. V. Podivilov, "High-order random Raman lasing in a PM fiber with ultimate efficiency and narrow bandwidth," Sci. Rep. 6, 22625 (2016).
[10] L. Zhang, H. Jiang, X. Yang, W. Fan, and Y. Feng, "Ultra-wide wavelength tuning of a cascaded Raman random fiber laser," Opt. Lett. 41, 215-218 (2016).
[11] S Arun, V Balaswamy, S Aparanji and V R Supradeepa, "High Power, Grating-Free, Cascaded Raman Fiber Lasers" Conference on Lasers and Electro-optics (CLEO) Europe, CJ-2.4, (2017)
[12] V. R. Supradeepa, Y. Feng, J. W. Nicholson, "Raman fiber lasers" Journal of Optics, 19. (2017).