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

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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 fusion spliced with negligible loss and are more robust. 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 wavelength bands. 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.

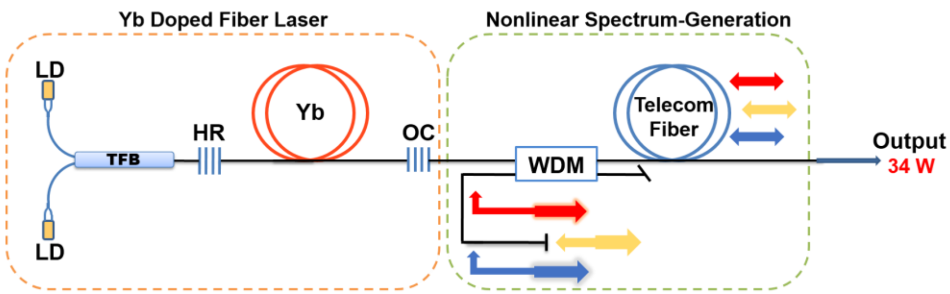

Fig 1: Architecture for the supercontinuum laser generation

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 76W 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.

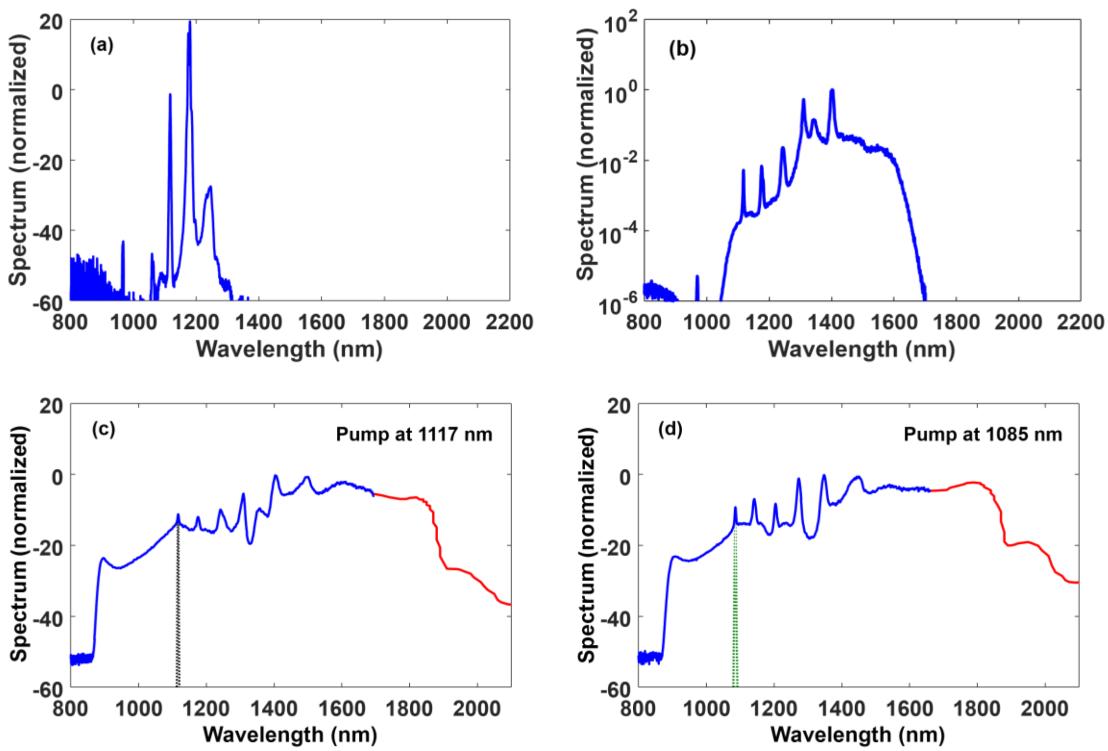

Fig 2 : Supercontinuum evolution at different output power levels (a) 7W (b) 19W (c) 34W. The region of spectrum shown in blue colour is measured using an OSA and the red colour spectrum was measured using an in-house built spectrometer. (c) Complete supercontinuum spectrum for 1117nm pumping (shown in dotted lines) (d) Complete supercontinuum spectrum for 1085nm pumping

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 1117nm laser. The 20-dB bandwidth of the spectrum extends over an octave from 880nm to >1900nm. To the best of our knowledge, this is the widest CW supercontinuum source demonstrated in an 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 880nm. The benefits of use of standard SMF is manifested in the short wavelength cutoff which at 880nm 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.

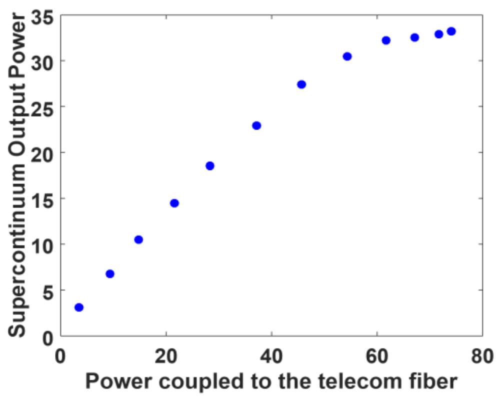

Fig 3: Supercontinuum output power Vs. input power coupled to the telecom fiber

Figure 3 shows the supercontinuum output power vs. the input power for the 1117nm input source. The output power plots are similar for both cases of 1117 and 1085nm pumping. For an input coupled power of ~76W, we obtain over 34W 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 ~34W continuous-wave supercontinuum with a 20-dB bandwidth extending from 880 nm to >1900nm with >44% conversion efficiency.

4.References

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