# High efficiency supercontinuum generation using ultra-long Raman fiber cavities

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**Abstract:** Supercontinuum generation in a multi-fiber ultra-long Raman fiber laser cavity is experimentally investigated for the first time. We demonstrate significantly enhanced spectral flatness and supercontinuum generation efficiency using only conventional single mode silica fiber. With a pump power of only 1.63W a ~15dB bandwidth >260 nm wide (from 1440 to >1700nm) supercontinuum source is reported with a flatness of <1dB over 180nm using an optimised hybrid TW/HNLF cavity. We address the dependence of the supercontinuum spectrum on the input pump power and ultra-long Raman cavity.



**OCIS codes:** (000.0000) General; (000.2700) General science.

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## 1. Introduction

Supercontinuum (SC) generation in optical fibers finds numerous applications in several fields such as time-resolved spectroscopy, sensing, optical coherence tomography, optical frequency metrology and wavelength division multiplexing (WDM) sources for optical communications. The general mechanism of CW pumped SC sources is well understood; in this regime the

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spectral broadening is attributed to the breakup of the pump into short pulses through the process known as soliton fission, which requires pumping at a wavelength in which the fiber exhibits low anomalous dispersion, in order to efficiently induce modulation instability (MI), after which a combination of stimulated Raman scattering (SRS) and parametric processes in the fiber trigger nonlinear broadening over a broad bandwidth, leading to SC generation [1]. A number of supercontinuum light sources relying on CW pumping schemes have been reported [2–7]; up to now, most CW pumped SC sources demonstrated have used highly nonlinear, dispersion–shifted fibers (HN-DSFs) as originally demonstrated in [2]. Other approaches include the use of dispersion decreasing fibers which can enhance the width of the generated continuum [3]. However, one of the problems of generating a SC is the degradation of the output spectral flatness, especially when high pump powers are used. Another problem is that most of the energy is initially in a sharp peak at the pump wavelength, and therefore the spectrally flat region of the SC usually displays low power compared with that peak. Using Photonic Crystal fibers (PCF), a SC output over 600nm with 8dB variation has been demonstrated using a 44W CW pump source in [4]. Using more conventional fibers, a CW-SC source with a 20dB width in excess of 232nm in the 1.2-1.5µm region has also been recently achieved [5] using a pump power of the order of 8.7W. Recently the idea of ultra-long Raman lasers was proposed and implemented, finding immediate application in quasi-lossless signal transmission through fiber communication links [8,9]. The existence of such ultra-long Raman laser cavities opens the possibility for a new kind of CW-pumped SC generation architecture, which offers improved spectral flatness and SC bandwidth whilst also allowing an increase in SC generation efficiency.

In this paper, we explore the potential benefits of this new approach, demonstrating SC generation over most of the spectral range of interest for optical communication systems, inside a TrueWave fiber based ultra-long cavity. We have confirmed that for this design, using only conventional telecom fibers, the energy transfer from the pump to longer wavelengths is improved, leading to a more efficient distribution of pump power across the spectral region of interest. In this way, a careful choice of dispersion profile, input pump power and fiber length can be used to optimise the spectral flatness of the SC in the desired band. In particular, a flat SC with <1dB power variation over more than 180nm in the range 1.44-1.7µm using a CW pump power of only 1.63W has been attained using this scheme.

## 2. Experimental setup

The experimental setup of the CW pumped SC source is schematically illustrated in Fig. 1. A Raman laser source operating at 1365nm was used to forward pump a cavity delimited by two highly reflective (~98% reflectivity) fiber Bragg gratings (FBG). These gratings have a 3dB bandwidth of 1nm, centred at 1455 nm. Pumping above the cavity threshold, we observe lasing of a stable Stokes component at the 1455 nm feedback wavelength. [REMOVED SHAPE FIELD]Different configurations were tested for our cavity fiber: (a) a TrueWave (TW) fiber span; (b) a hybrid configuration combining TW fiber and 1km of highly nonlinear fiber (HNLF) with a zero dispersion wavelength of ~1464.5 nm; (c) a hybrid configuration combining a section of standard single-mode fiber (SMF) displaying a zero-dispersion wavelength ($\lambda_0$) around 1310 nm and a TW fiber. A 1/99 optical coupler was placed before the output FBG to monitor the intracavity SC power and spectrum. The output optical spectrum of the generated SC was monitored using an optical spectrum analyzer (OSA) with a resolution of ~0.07 nm.

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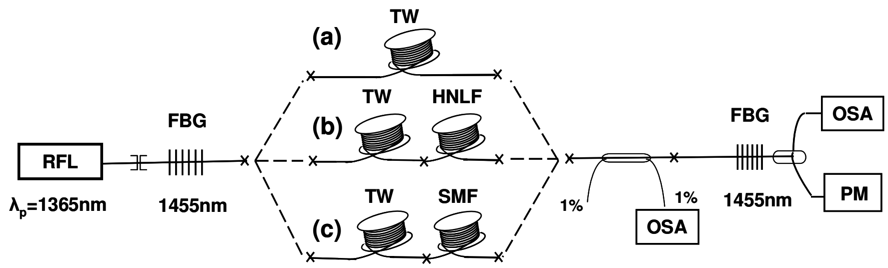


Fig. 1. Schematic diagram of the supercontinuum Ultra-long Raman fiber cavities under study: a) with TrueWave (TW) fiber only; b) TrueWave (TW) fiber combined with high nonlinear fiber (HNLF); c) TrueWave (TW) fiber combined with single mode fiber (SMF). RFL: Raman fiber laser, FBG: fiber Bragg grating, OSA: optical spectrum analyzer, and PM: power meter.

## 3. Results

### *3.1 Single-fiber configuration*

Figure 2 illustrates the evolution of the generated radiation inside the cavity as pump power increases (the values of pump power are measured at the input of the fiber) for a cavity comprised of only a 11.3 km length of TrueWave fiber. The vertical dotted line indicates the zero-dispersion wavelength of the fiber (~1443.5 nm, with a dispersion slope of 0.046 ps/nm$^2$/km). The non-linear coefficient of the TrueWave (TW) fiber was ~1.84W$^{-1}$km$^{-1}$ at 1550nm. In our configuration, the fiber used gives a similar $\gamma L$ product to 1km of HNLF with non-linear coefficient of ~20 W$^{-1}$km$^{-1}$. The center wavelength of our pump laser is 1365 nm, and hence lies well within the normal dispersion regime of the fiber. However, if the cavity is pumped above its threshold, lasing of a stable Stokes component centered at 1455 nm (the central wavelength of the grating reflectors) is observed. This Stokes component acts effectively as a secondary pump in the spectral region of low anomalous dispersion. Note that although the intensity inside the cavity is higher than outside the cavity, spectrally they are similar except that the profile of the fiber Bragg grating is visible if the spectrum is measured outside the cavity.

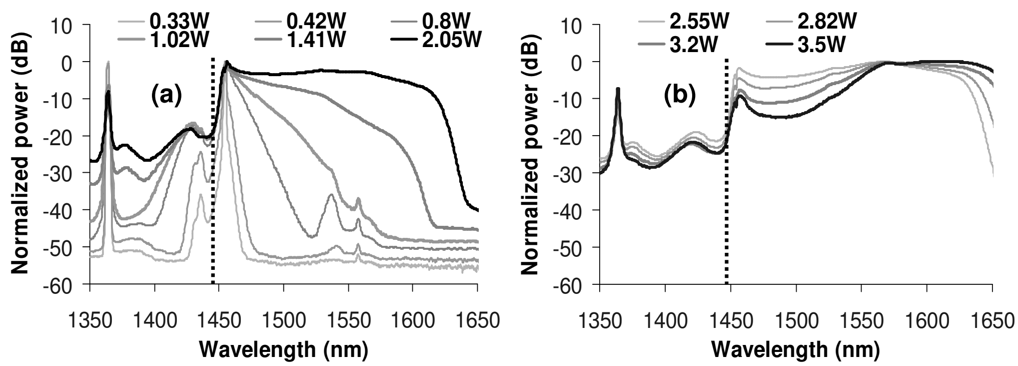


Fig. 2. Supercontinuum spectra for Ultra-long Raman fiber cavity with TW fiber only (Fig. 1a) as a function of pump power a) up to power 2.05W b) from 2.27 to 3.5W

The SC generation process can be explained as a combination of modulation instability (MI), stimulated Raman scattering (SRS) and four-wave mixing (FWM). As a CW pump is used here, the effect of self-phase modulation is negligible and the SC generation is initiated by modulation instability (MI) induced break up of the CW Stokes shifted radiation generated in the anomalous dispersion regime of the cavity fiber. The location of the MI sidebands depends on the first Stokes power, $P_{fs}$, (i.e. the intracavity power at 1455nm in our case), such

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that they are shifted further from the 1455nm component as the power increases. The position of the peak can be estimated from the relation:

$$\Omega_s = \left(2\gamma\, P_{fs} \exp\left(-\alpha L\right) / |\beta_2|\right)^{1/2} \quad (1)$$

where $\Omega_s$ is the frequency shift from the first Stokes frequency, α is the loss, L is the fiber length and $\beta_2$ is the second-order dispersion coefficient at the laser frequency [10]; the frequency shift is inversely proportional to the square root of the dispersion therefore the frequency shift for the instability peak is larger with lower dispersion. The dispersion coefficient $\beta_2$ is in our case of $-0.52 ps^2/km$. Considering that the loss is 0.35 dB/km, the calculated peak should appear in the range of approximately 1451nm to 1441nm for intracavity powers of the Stokes shifted radiation in the range of 0.2-1.5W. However, the confinement of the 1455nm component in the fiber cavity leads to a large amount of broadening, such that the MI peak is not prominent in the SC spectrum. On the other hand, at a low pump power of only 0.33W, another component at 1437nm is observed which can be attributed to a combination of Raman gain from the 1365 nm pump and dispersive-wave radiation (particularly at pump powers above 0.8 W, for which the soliton red-shift is clearly visible). For input powers above 0.43W, two peaks at 1542nm and 1555nm become visible. It is likely that these are caused by SRS of the 1437 and 1455nm components respectively, since the frequency separation is consistent with the Raman shift of silica fibers. There is also a strong power transfer to the region between 1455 and 1550 nm. As pump power is increased beyond 1W, spectral components in the 1550 - 1650nm region are generated. In this regime MI converts the CW beam into a periodic pulse train with a period defined by:

$$T_{MI} = 2\pi \left(\left|\beta_2\right| / 2\gamma P_{fs}\right)^{1/2} \quad (2)$$

which is equal to ~2.4ps when $P_{fs}$ increases to 1W [9]. This short-pulse propagation leads to the formation of higher-order solitons which are perturbed by higher order nonlinear effects and experience fission into fundamental solitons, which, along with SRS, can be related to the appearance of red-shift components [11,12]. In our case, at a pump power of 2.05W, the generated supercontinuum spectrum extended to 1640nm and the generated SC displays optimal spectral flatness; in the 1460 to 1560nm region where the power variation is ~1dB and the difference between the 1455nm peak and the flattest part of the SC is only ~2dB. The coherence of the SC has not been investigated here but as it is generated from a CW source it is likely that the SC has relatively low coherence. By increasing the pump power beyond 2W (Fig. 2b), we were able to observe modulation on the wings of our primary pump and depletion of the Stokes shifted radiation as the power is transferred to wavelengths higher than 1560nm. Our results show that the region of optimal spectral flatness can be tuned to higher wavelengths by increasing the pump power, with a pump power of ~3W giving a flat SC in the 1570 and 1640nm telecommunications L–band.

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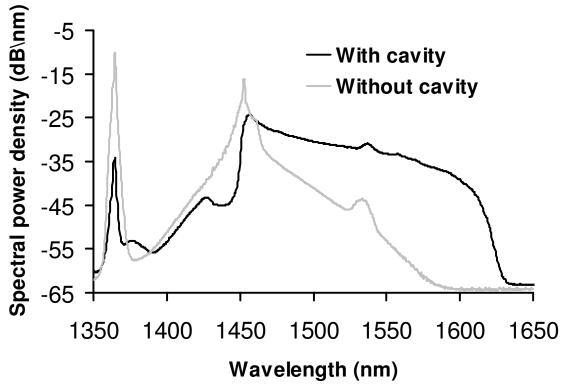


Fig. 3. Optical power spectra of the generated supercontinuum with and without the highly reflecting fiber Bragg gratings at the same pump power, 1.5W.

Increasing cavity length increases the threshold power for the Raman-induced generation of the 1455 nm component, delaying its formation, but simultaneously translates into a higher accumulation of nonlinear effects. On the other side, the SC spectrum is expected to display reduced intensity for longer fiber lengths, due to the additional attenuation. This suggests that cavity length adjustment could allow for future performance optimisation. The effect that the use of the cavity has on the generated supercontinuum can examined by removing the FBG's, Fig. 3 shows two spectra with and without cavity; both spectra correspond to pump powers of 1.5W. These results show that broadening is significantly enhanced inside the ultra-long cavity due to the Stokes wave trapping and more efficient generation of a 1455nm Raman Stokes component, which translates also into an increased SC output power [13].

*3.2 Hybrid fiber configurations*

In order to enhance the range and flatness of the supercontinuum radiation, the TW fiber was combined with 1.1km of HNLF. Figure 4 shows SC spectra as a function of the input pump power when the HNLF included after the TW fiber, see Fig. 1b. The results show that using this configuration improves the spectral width of our SC. In this case (achieved for 1.63W of input pump power) the SC spectrum spans >280 nm; the bandwidth of the SC output was extended beyond 1700nm which was the limit of our OSA. For this configuration the power variation of the output was less than 1dB over a range of 180nm from 1490nm-1670nm for an input pump power of only 1.63W compared to 100nm from 1460nm-1560nm for the equivalent TW only cavity. As the power was increased, the region of optimum spectral flatness was displaced towards longer wavelengths, and at 2.82W pump power we found two flat regions, ranging from 1570 to1610nm and from 1650 to ~1740nm, with respective flatness of ~0.3 and 0.4dB.

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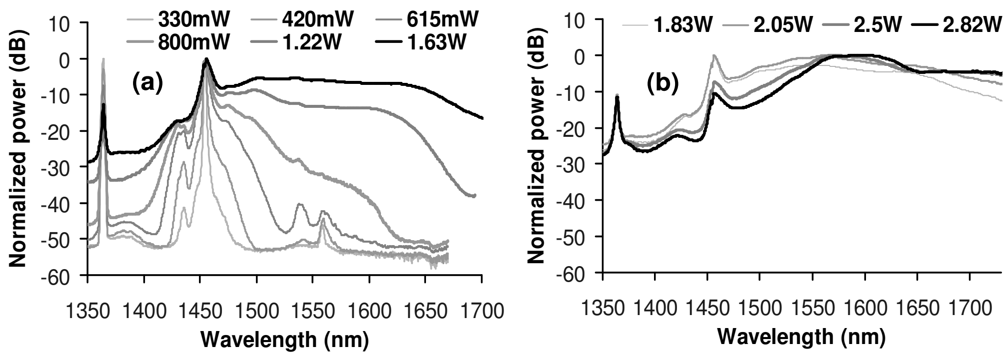


Fig. 4. Supercontinuum spectra for an ultra-long Raman fiber cavity combining TW fiber with HNLF (Fig. 1b) as a function of pump power a) up to power 1.63W b) from 1.83 to 2.82W

In a further demonstration of the possibilities available for increasing the efficiency and spectral flatness of the generated SC by combining different types of standard fiber, we performed an experiment with standard single-mode fiber (SMF) combined with the TW fiber, see Fig. 1c. The fiber cavity tested through this experiment consisted of the 11.3km TW fiber combined with 6.6km of SMF with a zero dispersion wavelength of ~1311 nm. Figures 5 shows comparison spectra for cavities comprising TW fibre only and TW followed by SMF: Fig. 5 (a) and (b) show spectra for pump powers of 1.4W & 1.75W respectively. These results show improved SC generation efficiency when the SMF is included after the TW fibre in the cavity.

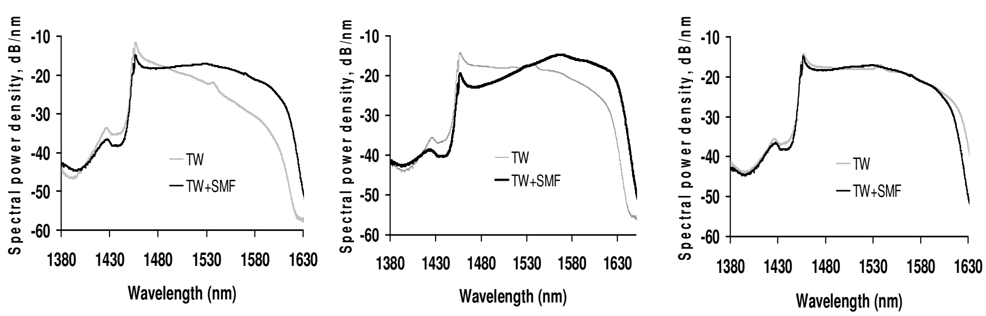


Fig. 5. Supercontinuum spectra for an ultra-long Raman fiber cavity combining TW fiber with SMF (Fig. 1c) for two different pump powers a) 1.4W b) 1.75W and c) a comparison between the SC generated with TW only at 1.75W pump power with SC generated when TW combined with SMF at 1.4W pump power.

In the TW/SMF hybrid cavity the supercontinuum generation is initiated as before by a strong MI at 1455nm in the TW fiber. The supercontinuum generated in the TW then propagates in the SMF fiber with more broadening taking place and more transfer of power from 1455nm component to the longer wavelengths producing a flatter and more extended SC than with TW alone. Further work is required to fully understand the mechanisms involved in supercontinuum generation in this hybrid cavity. To show the increase in generation efficiency, Fig. 5 (c) compares spectra for the TW only cavity with 1.75W pump power and the TW/SMF hybrid cavity with 1.4W pump power. The spectra are very similar showing that by including SMF fibre the pump power required for the same output supercontinuum can be reduced by approximately 20%.

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## 7. Conclusion

In conclusion, supercontinuum generation using an ultra-long cavity Raman amplification scheme has been achieved for the first time. In our experiments using CW pumping, we show that generation efficiency can be improved by using a cavity configuration and that with this configuration a supercontinuum covering over 200nm with ~1dB flatness can be generated using only conventional, low cost silica optical fibre. The dependence of spectral flatness on input power for a cavity containing only TrueWave fibre has been studied. We find that optimum flatness in the 1500-1600nm region is obtained with a 2W pump power and that the wavelength of the supercontinuum can be extended to longer wavelengths with an increase in pump power. Hybrid cavities comprised of TrueWave fibre along with either highly nonlinear fibre or standard single mode fibre were investigated and these were found to provide a further increase in the supercontinuum bandwidth and generation efficiency. With HNLF a pump power of 2.8W gave a flatness of <1dB over more than 180nm and 1.15 W average output power. When standard fibre was used in the cavity we obtained a reduction of 20% in the pump power compared to the TrueWave only cavity, for comparable supercontinuum spectra. The increased flatness, extended bandwidth and improved generation efficiency demonstrated using an ultra-long Raman cavities configuration, combined with the practicality and possibility of using only low cost conventional optical fibres, make this an attractive technique for supercontinuum generation.

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