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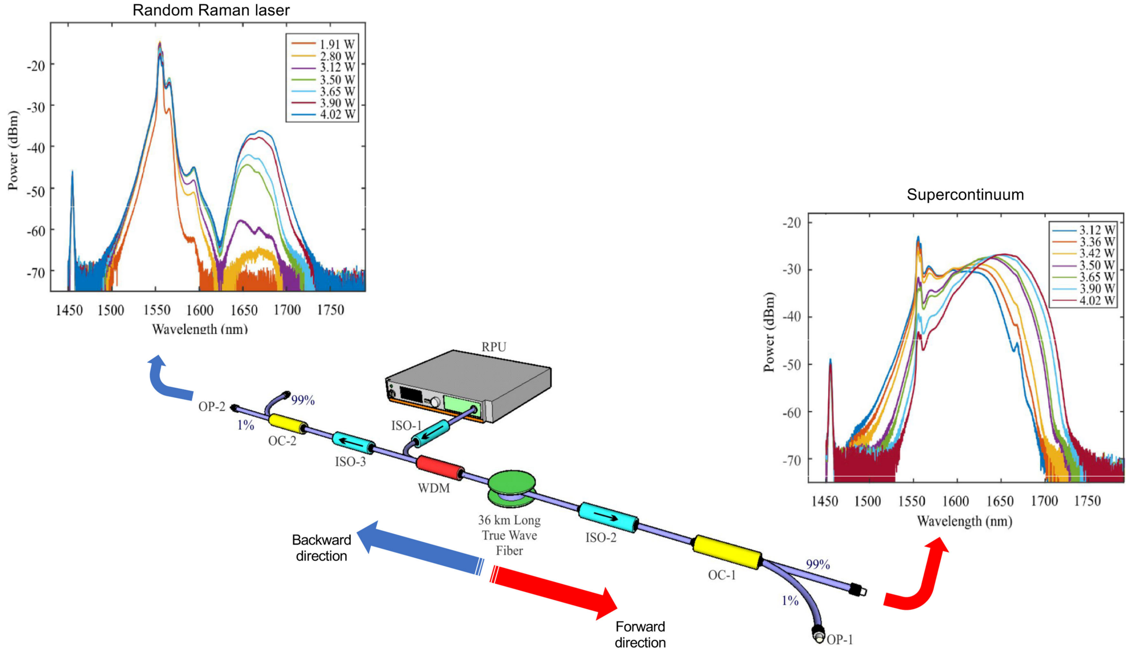

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Abstract: In this paper, we demonstrated a continuous-wave pumping supercontinuum generation in a random distributed feedback fiber laser with a completely open laser cavity. A broadband wavelength conversion was obtained by pumping a 36-km long TrueWaveREACH fiber in anomalous dispersion regime with a high power continuous-wave Raman laser. The spectral broadening was assisted via nonlinear mechanism such as modulation instability and stimulated Raman scattering. An extended 10-dB flat supercontinuum with 129-nm bandwidth spanning over C-, L-, and U-band wavelengths was generated in the forward direction of lasing cavity under 3.65-W pump power. The super-continuum exhibited excellent bandwidth stability in 60 minutes of lasing operation. A simultaneous generation of random Raman laser operating in the backward direction of cavity was also demonstrated within the same gain fiber. The simple laser cavity presented significant versatility in its generation of novel light sources for both telecommunication and applied science applications.

Index Terms: Supercontinuum generation, random fiber lasers.

1. Introduction

Supercontinuum (SC) generation in optical fibers is highly attractive due to its smooth and broad spectral bandwidth that often spans over multiple bands. The SC has been widely used in numerous applications such as in time-domain absorption spectroscopy [1], dense wavelength division multiplexing [2], optical sensing [3], and ultra-high resolution optical coherence tomography [4]. The most common approach to generate SC is to pump high peak power femtosecond pulses into optical fiber where the interplay between dispersion and complex nonlinear processes such as Raman scattering, self- and cross-phase modulations, four-wave mixing and multisoliton will facilitate efficient power transfer to generate new frequencies within the pulse spectrum [5], [6]. More than an octave-spanning SC generation was demonstrated from speciality optical fibers such as highly nonlinear fiber [7], photonics crystal fiber [8], dispersion shifted fiber [9], and small core tapered fiber [10]. The intrinsic parameters of these fibers such as dispersion, nonlinearity and confinement were tailored to efficiently control the pulse evolution to generate SC even at a fairly short optical fiber length [11]. While pumping at anomalous dispersion regime of the fiber promises the broadest spectra [12], numerical and experimental works have also revealed the feasibility of obtaining high coherence, stable and flat SC when pumping at normal dispersion regime. As the inherently noisy process of soliton fission that usually affects the pulse width does not occur in normal dispersion regime [13], the coherence of ultrashort input pulses is preserved during the propagation to result in a uniform spectral and temporal SC profile [14].

Another paradigm to SC generation is to use high power continuous-wave (CW) laser to pump several kilometer long standard optical fibers [15], [16]. These works have been motivated by the availability of pump source and standard optical fiber assembling simpler and robust pumping schemes; as the CW fiber laser can be spliced directly to the gain fiber. The key to CW pumping SC is the phenomenon of modulation instability (MI) seeding the spontaneous growth of supercontinua in low anomalous dispersion regime, i.e., close to zero-dispersion wavelength (ZDW) of the fiber [13], [15]. The longer-wavelength MI sidebands will experience Raman amplification leading to formation of Raman Stokes wave. The combination of this effect with parametric processes achieves the desirable spectrum broadening sought after in supercontinuum generation [17]. To date, much of the attention was given on the observation of SC in highly nonlinear fiber when pumped with a CW Raman laser within ring and linear fiber laser cavities [15], [18]–[21]. The bandwidth and spectral flatness can be tuned with a hybrid gain medium simply by splicing multiple fibers of different dispersion and nonlinear parameters together [17].

Further observation was also extended to the generation of CW pumping SC in the vicinity of one-dimensional random cavity fiber laser (RFL) also known as random distributed feedback (DFB) fiber laser [22], [23]. Multiple Rayleigh scattering and stimulated Raman scattering (SRS) provide random distributed feedback in the cavity to result in lasing when the build-up power increases beyond the threshold value [24], [25]. By utilizing the simplest lasing structure of RFL to be a pump source, a SC near 100 nm bandwidth with 20 dB variation has been demonstrated from a hybrid gain medium of TrueWaveREACH (TW) fiber and dispersion-compensated fiber at $\sim$3.2 W pump power [23]. A fiber Bragg grating (FBG) with central wavelength near to the pump wavelength has been used as a point reflector, thus forming a half-open cavity for SC generation. Another report highlighted a simultaneous generation of SC and random Raman lasing within the same gain fiber in a completely-open cavity RFL [22]. A 1365 nm laser pumped the TW fiber at normal dispersion regime to produce a SC over 170 nm with 10 dB variation at 4.2 W pump power.

In this paper, we explored the potential of extending the work in Ref. [22] via pumping TW fiber beyond ZDW in a completely-open cavity RFL. We utilized a longer length of gain fiber; 36 km in comparison to that of 16 km in Ref. [22]. From the spectral evolution, pumping at anomalous dispersion wavelength promoted rapid broadening of SC in the RFL cavity. A cascaded random Raman laser was also demonstrated in the backward output that led us to postulate that separate cavities within the same gain fiber host the SC and random Raman laser. We believe that our findings will pave a way for simpler generation of SC light source by using a standard telecommunication fiber and the most readily available components in laboratory.

2. Experimental Setup

Fig. 1 illustrates the experimental setup of completely-open cavity RFL for SC and random Raman laser generations. A Raman pump unit (RPU) centered at 1455 nm wavelength was utilized as the pump source for the cavity. A 1455 nm isolator (ISO-1) was employed to prevent any backward reflections to RPU. A 1480/1550 wavelength division multiplexer (WDM) was used to couple the input pump power into a 36 km long TW gain fiber. The TW fiber possesses a typical optical attenuation of 0.2 dB/km with a ZDW at 1405 nm (dispersion slope of 0.045 ps/nm^2.km at 1550

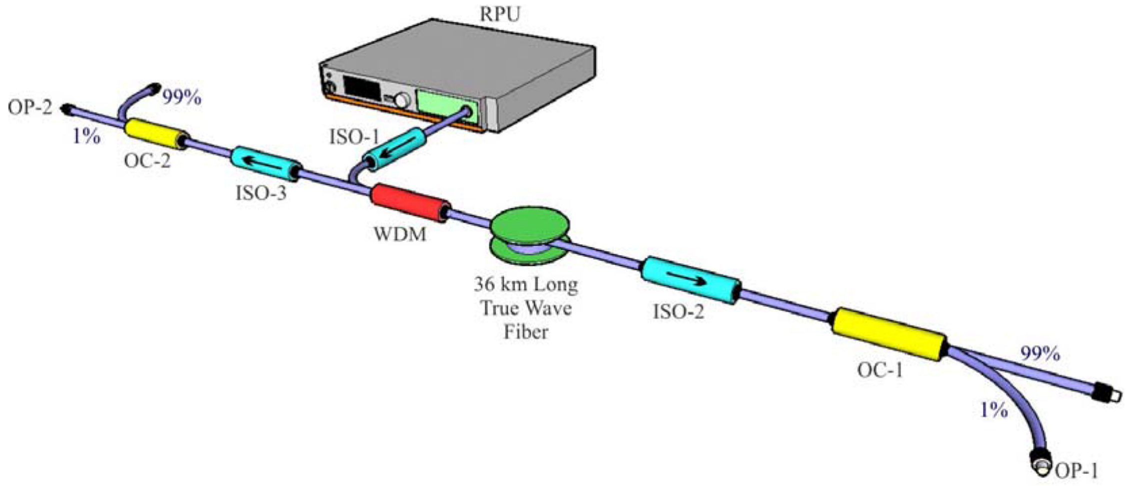

Fig. 1. Schematic diagram of completely-open RFL to generate SC in forward direction and random Raman laser in backward direction of the cavity. RPU: Raman pump unit, ISO: polarization insensitive isolator, WDM: wavelength division multiplexer, OC: optical coupler, OP: output.

nm) was chosen as the gain medium. Furthermore, its Raman gain coefficient is the highest among other telecommunication fibers as reported in Ref. [26]. This allows higher accumulation of random distributed feedback effect through efficient stimulated Raman scattering even at shorter fiber lengths. The gain fiber was pumped at anomalous dispersion regime. A pair of 1550 nm polarization insensitive isolators (ISO-2 and ISO-3) was inserted before the 99:1 optical couplers (OC-1 and OC-2) to prevent the Fresnel reflection from FC/PC pigtail at both ends of fiber cavity. Therefore, effective feedback is contributed by the randomly distributed Rayleigh scattering from the TW gain fiber. The optical spectrum was measured through the 1% port of the OCs to an optical spectrum analyzer (OSA). The low tapped power was used to ensure that the detected power is below the maximum limit of OSA (20 dBm). On the other hand, the output power from the proposed laser cavity was measured via the 99% port of OCs using an optical power meter (OPM). The laser propagation in forward direction (i.e., relative to pump propagation) was measured at the right end of the cavity, OP-1 and the backward laser propagation was evaluated at the left end of cavity, OP-2.

3. Results and Discussions

Fig. 2 shows the spectral evolution of SC as a function of pump power measured from the forward direction of RFL. In Fig. 2(a), the first Raman Stokes emission was centered near 1555 nm. Sidebands due to MI effect starts to appear at 1557.57 and 1556.15 nm at 1.01 W input pump power. In Raman-based fiber laser, MI can be induced by cross phase modulation between high pump power wave and generated Raman Stokes wave in the fiber gain medium [27]. In this case, MI causes phase perturbations on the Stokes waves, forming small amplitudes or random fluctuations that seeds spectral broadening. Frequency detuning due to the MI can be calculated via Equation (1):

$$\Omega_s = \sqrt{\frac{2\gamma P}{|\beta_2|}} \tag{1}$$

where Ω_s is the frequency shift from the first Stokes frequency, P is the pump power, γ is the nonlinear coefficient and β_2 is the 2nd order dispersion coefficient of the fiber [13]. The γ for TW fiber is 1.90 W^{-1} km^{-1} at 1550 nm. The β_2 value was taken from Ref. [17] to be -0.52 ps^2 km^{-1} at 1550 nm. At P in the range of 1.01–2.80 W, the calculated Ω_s is between 2.7–4.5 THz to give 3.5–6.0 nm wavelength shift from the Stokes wave. At pump power beyond 1.77 W, wider sidebands

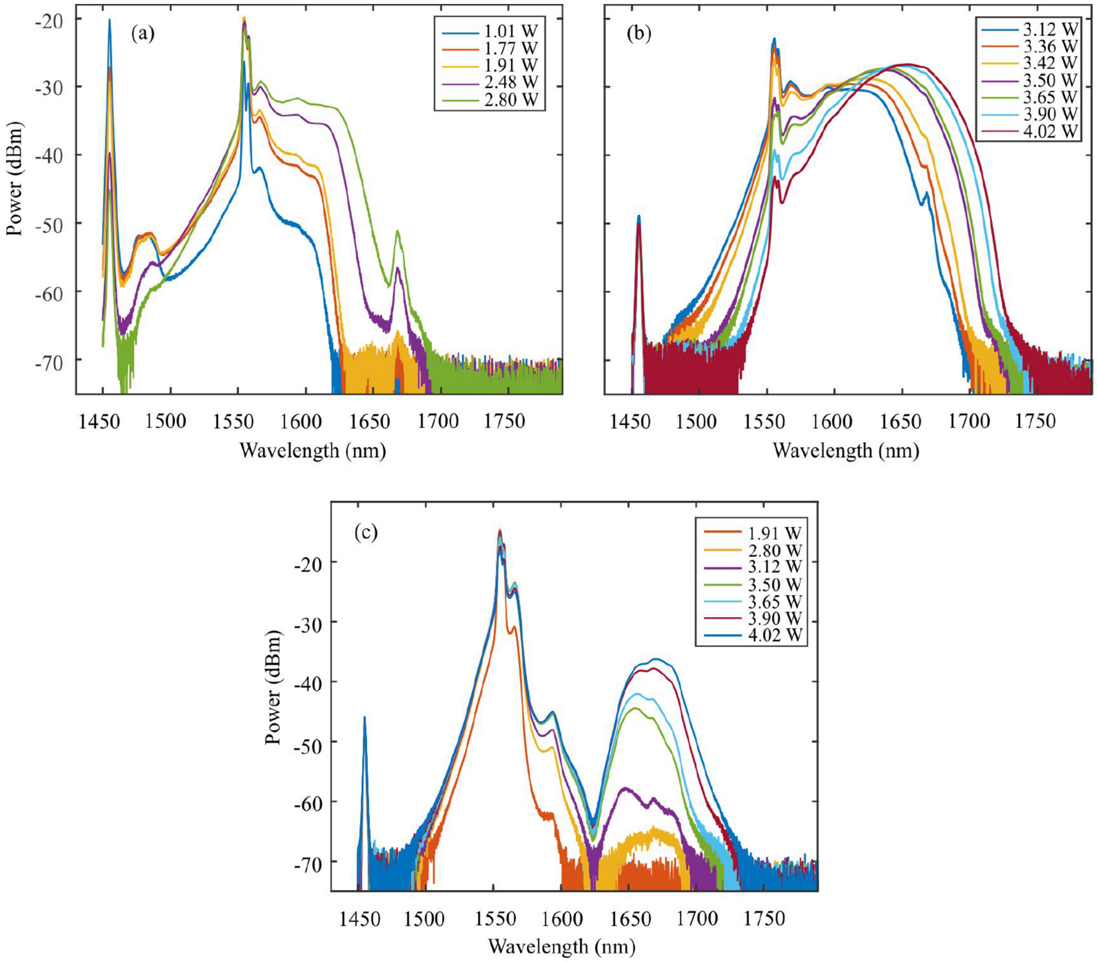

Fig. 2. The SC evolution as a function of pump power of (a) 1.01-2.80 W and (b) 3.12-4.02 W, taken at OP-1 (c) random Raman laser as observed from OP-2 at 1.91-4.02 W pump power.

were created through MI as the pump power was transferred toward the long wavelength side. An asymmetric growth of the MI sidebands can be noted, unlike the symmetrical sidelobes that are typically observed prior to the conventional SC generation. This can be inferred to occur due to minimal contribution of parametric four-wave mixing and selective amplification from SRS effect, i.e., wavelengths that overlap with the Raman Stokes gain profile [13], [15], [17]. The 1st order Raman Stokes wave together with the MI sidebands acts as a broad pump to generate 2nd order Raman Stokes emission at 1669 nm through cascaded SRS effect [15]. Notably, the ∼1480 nm peak corresponds to noise from the residual RPU and can be seen to diminish as the residual RPU decreases with more effective pump-Stokes conversion. Further enhancement of spectral broadening until 4.02 W pump power is shown in Fig. 2(b). With increasing pump power, nonlinear spectral broadening manifested with gradual wavelength shifts, eventually extending the profile to cover C-, L-, and U-band wavelengths (up to ∼1730 nm). The shifting of the SC profile towards longer wavelengths is caused by the stimulation of higher order Raman Stokes wave. This enhances the conversion efficiency of pump to Stokes emission which depletes the waves at the shorter wavelengths [28], making it appear as if the SC profile is shifting.

A simultaneous generation of Raman laser via random distributed feedback (denoted as random Raman laser in this paper) is observed in the backward direction of the RFL as shown in Fig. 2(c). A higher 1555 nm peak and broader Raman Stokes emission compared to the forward direction is due

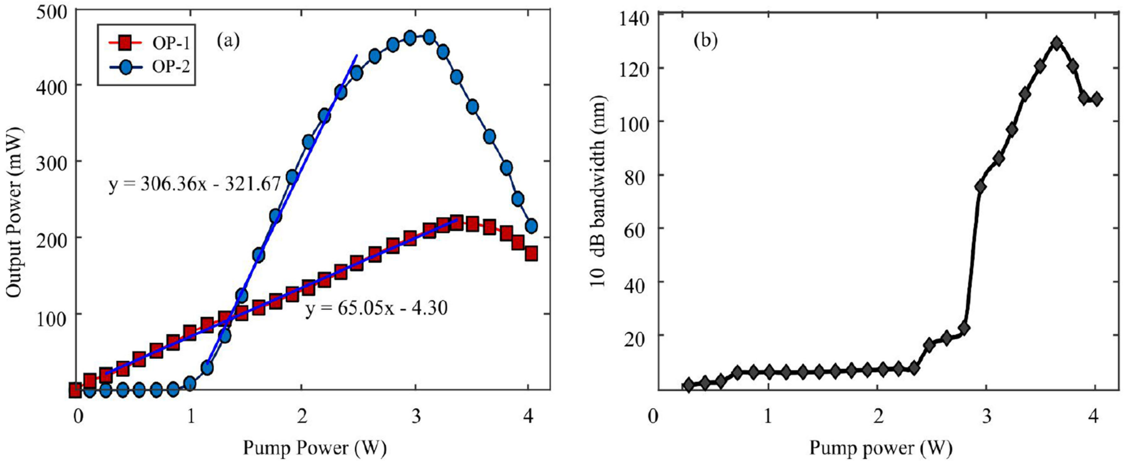

Fig. 3. (a) Power development curve as a function of pump power from RPU as measured from OP-1 (SC) and OP-2 (random Raman laser) outputs. (b) 10 dB bandwidth measurement of SC against pump powers.

to the higher Raman gain distribution near the site of pump injection. This results in higher power of accumulated distributed Rayleigh backscattering effect. High power 1st order Raman Stokes emission led to the formation of 2nd order Raman Stokes wave at 3.12 W. The 2nd order Raman Stokes wave grows with increasing pump power, depleting power from the 1st order Raman Stokes emission. This is a simple straightforward cascaded SRS effect via random distributed feedback, unlike the spectral profile of the RFL in the forward direction.

Random fiber laser constitutes of multiple resonant cavities formed by Rayleigh scattering feedback. These multiple resonant cavities are arbitrary in length and are superimposed upon one another [29]. The observed generation at the output side is the product of these multiple resonances or the resultant resonant curve. Due to the stochastic nature of random laser operation, there exist two ‘main’ cavities in the RFL, each forming a different resultant resonant curve, which are the SC generation and Raman laser generation. This conjecture is based on the distinct differences in pump depletion, formation of the 1st and 2nd order Raman Stokes emissions on each output side. The separation of cavities within the same fiber gain is based on efficient amplification length of Raman and strength of feedback dictated by pump power and Rayleigh scattering [30], [31].

Fig. 3(a) shows output power variation as a function of pump power taken via OPM at OP-1 and OP-2. Based on the result, the SC output power as measured at OP-1 increases immediately and linearly with increasing pump power from RPU. The SC exhibits higher and stable, i.e., follows linear trend-line closely, output growths compared with the results in Ref. [22] at similar pump power ranges due to the higher accumulated random distributed effect in longer cavity length [24]. The SC output power growth falls off from a linear fit at pump power beyond ∼3.50 W due to the formation of higher order Raman Stokes component that depletes the photons at shorter wavelengths (1st order Stokes wave). On the other hand, the output from random Raman laser as measured at OP-2 exhibited higher output power and efficiency than SC due to the large Raman gain distribution near the region of pump injection. However, the lasing threshold was achieved at 1 W of total pump power, a comparable behavior to Raman-based random distributed feedback fiber laser of shorter cavity length [32]. The power of OP-2 output slumps at pump beyond ∼3.12 W which can be attributed to the prominent growth of higher-order Stokes wave.

Fig. 3(b) presents the 10 dB bandwidth of the SC as a function of pump power. The bandwidth begins to increase from 16 nm to 22.6 nm at 2.48 W to 2.80 W pump powers due to strong contribution from 1st order Raman Stokes wave. Rapid and abrupt growths of 10 dB flat spectrum from 75.45 nm to 129.05 nm at pump power of 2.95 W to 3.65 W was attributed to Raman amplified

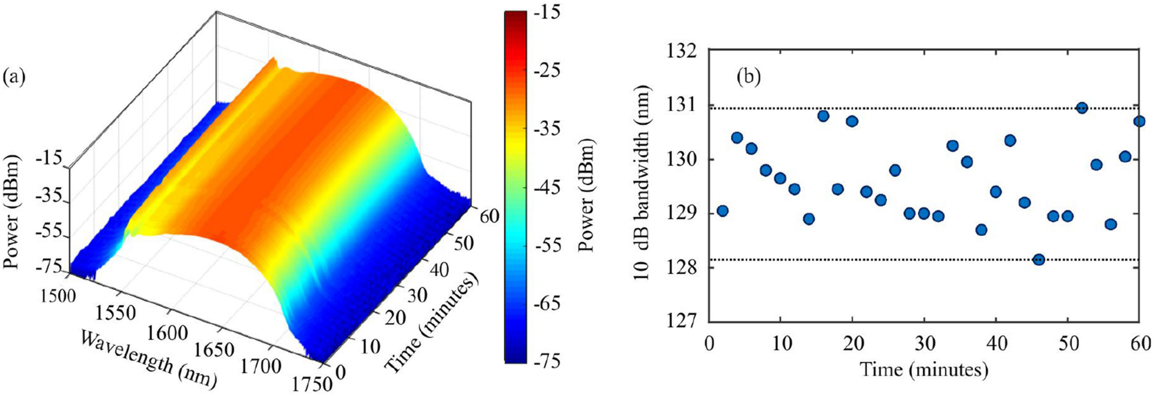

Fig. 4. (a) Stability test and (b) deviation of optimum 10 dB spectral bandwidth under 60 minutes observation time. The horizontal lines indicate the maximum and minimum values of measured 10 dB spectral bandwidth.

MI promoting new wavelengths generation and higher-order Raman Stokes waves. The widest 10 dB flatness of 129.05 nm was recorded between 1552.75 nm to 1681.80 nm wavelengths with 3.65 W pump power. To compare with the SC spectrum at pump power below ~3.5 W in Ref. [22], the obtained spectral broadening showed a rapid 10 dB bandwidth growing trend. We deduced this observation to efficient nonlinear interaction at anomalous dispersion regime and to the long gain fiber length that accumulated high nonlinearity for SC generation [16]. However, the 10 dB bandwidth decreased down to 108.33 nm at 4.02 W pump power due to the nearly depleted 1st order Raman Stokes emission. The formation of strong 1st and 2nd order Raman Stokes waves in the backward direction also limits the amount of power available in the cavity for broader spectral development in the forward direction.

Fig. 4(a) depicts the stability performance test of the SC at the optimum 10 dB bandwidth over 60 minutes of observation period, with its spectral bandwidth plotted against time in Fig. 4(b). The recorded minimum and maximum 10 dB spectral variations were 128.15 nm and 130.95 nm at 46 and 52 minutes of lasing operation, respectively. The mean and the standard deviation of 10 dB bandwidth were 129.61 nm and 0.6948 nm, respectively. The small standard deviation validates the stability SC output even without any physical reflectors in RFL cavity.

4. Conclusions

In conclusion, a SC generation spanning C-, L- and U-band in a completely-open RFL cavity was successfully demonstrated. The gain fiber was pumped with a 1455 nm CW laser source at anomalous dispersion regime. A random Raman laser was also generated within the same gain fiber in the backward direction of the cavity. Based on the low threshold of the random Raman laser, it was deduced that a separation exists between the effective cavity for CW Raman and SC. The SC was generated via nonlinear mechanisms such as MI and SRS with resonance via Raman amplified random Rayleigh distributed feedback. A 10 dB flat SC bandwidth of 129.05 nm (1552.75–1681.80 nm) was achieved at 3.65 W pump power. Stability performance test of the SC at optimal bandwidth presented only a small standard deviation of 0.6948 nm under 60 minutes continuous lasing operation. Pumping at anomalous dispersion regime promoted rapid broadening of SC compared with normal dispersion pumping (see Ref. [22]). It is anticipated that by investigating the optimum gain fiber length, it should be possible to obtain a broader SC using a similar cavity design, and this is likely to be the future direction of this research.

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