# A Multiwavelength CW Source Based on Longitudinal Mode-Carving of Supercontinuum Generated in Fibers and Noise Performance

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***Abstract*—We experimentally demonstrate novel multiple wavelength continuous wave (CW) sources based on longitudinal mode-carving of supercontinuum (SC) generated in optical fibers. We show that by longitudinal mode-carving of the SC we can generate > 600 wavelength channels with 10-GHz precise channel spacing and −6-dBm/ch power level at the > 48-nm flat region (±0.5-dB spectral uniformity) of the SC. By full utilization of the generated SC, the channel count exceeding 1600 can be accomplished. Moreover, we study the noise performance of the carved CW signals experimentally and theoretically. Experimentally, we measure the relative intensity noise (RIN) to characterize the noise performance of the generated CW signals. An average RIN value of −107 dB/Hz is obtained. Compared with the CW sources carved directly from the pump laser, a 4-dB/Hz RIN degradation is measured. The two main reasons behind the high RIN values are determined to be the frequency instability and the low side-mode suppression ratio of the pump laser. Experimentally, we confirm that the combined effect of the frequency instability and the low side-mode suppression ratio of the pump laser can degrade the RIN as much as ∼30 dB/Hz. Theoretically, we estimate the lowest achievable RIN values as −160-dB/Hz and −144-dB/Hz RIN after the erbium-doped fiber amplifier (EDFA) and the SC fiber, respectively. These results indicate that, starting with a stable pump laser, CW lasers with < −140-dB/Hz RIN can be achieved.**

***Index Terms*—Broadband communication, laser stability, lasers, optical communication, optical distortion, optical fiber communications, optical fiber lasers, optical Kerr effect, optical noise, optical propagation, optical propagation on nonlinear media, optical signal processing.**

## I. INTRODUCTION

WAVELENGTH division multiplexing (WDM) systems with very dense channel spacing is an attractive option for providing increased capacity in both short-distance and long-distance lightwave transmission systems. As the current demand moves toward building dense wavelength division multiplexing (DWDM) systems with 25-GHz-or-less channel spacing, the key challenge is to provide a low-noise multiple wavelength continuous wave (CW) source with very high wavelength accuracy, high amplitude stability, and high brightness. Since passive filters set its wavelength stability, WDM sources carved from a broadband light source can satisfy current demand in wavelength stability.

In our experiments, we show that novel CW WDM sources based on longitudinal mode-carving of supercontinuum (SC) generated in optical fibers will be a strong candidate for future optical networks because of its low amplitude noise degradation (< 4 dB/Hz), broad bandwidth (> 140 nm), high brightness (> −6 dBm/ch), high amplitude uniformity (±0.5 dB), high wavelength stability, and periodicity.

The spectrum-slicing scheme for generating a CW source, which is compatible to operate in nonreturn-to-zero (NRZ) formats, has been researched by several groups. By spectral slicing of 40-nm amplified spontaneous emission (ASE) spectra 1.7-Gb/s data transmission over 165-km dispersion-shifted fiber has been demonstrated [1].

In a similar approach, Holloway *et al.* have demonstrated CW generation by spectral slicing of ASE from a Fabry–Pérot laser, which is biased below threshold [2]. However, the performance of CW sources generated by these two techniques is limited by the intrinsic spontaneous-spontaneous beat noise due to incoherent nature of the ASE. This beat noise increases with decreasing channel bandwidth and limits the channel density of the communication system. In a different approach, Sanjoh *et al.* have demonstrated CW generation by spectral slicing of longitudinal modes of mode-locked semiconductor laser [3]. However, the bandwidth and the spectral shape of the mode-locked laser limit the maximum achievable channel count and spectral uniformity, respectively.

In a similar approach, 13-channel CW carving with 10-dB spectral uniformity and 64-GHz channel spacing has been demonstrated by using an externally modulated distributed feedback (DFB) laser followed by a 31-km dispersion-shifted fiber to generate spectral broadening [4]. Similar to the previous method, the channel count and spectral uniformity is limited by the amount of self-phase modulation (SPM) in the dispersion-shifted fiber.

In this paper, we present the novel CW generation scheme for DWDM applications by utilizing the longitudinal modes of the SC generated in optical fibers and its noise performance. Previously, we have demonstrated the pulsed WDM source and its coherence properties by using the similar SC setup [5].

In the current experiment, we demonstrate that by longitudinal mode-carving of the SC spectra, up to 1600 CW channels can be achieved with 10-GHz precise channel spacing over

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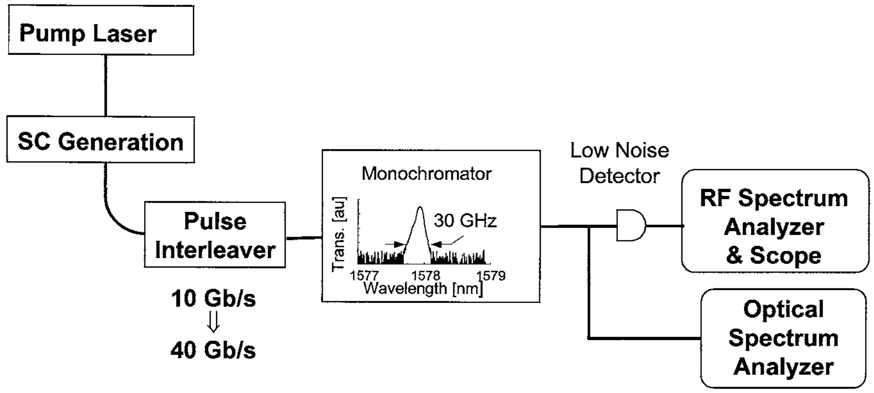



Fig. 1. The experimental setup used for CW generation by longitudinal mode-carving. The longitudinal modes of the 10-GHz SC are carved by a monochromator to obtain a multiple wavelength CW source. RIN is measured to characterize the noise performance of the CW signals.

140-nm spectral bandwidth, where the wavelength stability and the channel spacing of the carved signals are set by the wavelength stability and the repetition rate of the pump laser, respectively [6]. By using the flat region of the SC, $>600$ CW channels with $\pm 0.5$-dB spectral uniformity and $-6$-dBm/ch power level are achievable.

As a figure of merit, we measure the relative intensity noise (RIN) of the generated CW. We start with the RIN measurement of the CW signals before and after the SC fiber by using the conventional RIN and measurement technique. Experimentally, we measure the average RIN value of $-107$ dB/Hz for the CW signals carved from the SC spectra. Compared with the CW signal carved from the pump laser, RIN degradation of $<4$ dB/Hz is measured. Sources of high RIN values are also investigated.

The frequency stability and side-mode suppression ratio of the pump laser, ASE generation in the erbium-doped fiber amplifier (EDFA), and the amplification of the ASE in the SC fiber are found to be the four reasons for the high RIN values. Based on the experimental research on the actively mode-locked fiber lasers, we show that the RIN is mainly limited by frequency instability and the low side-mode suppression ratio of the mode-locked laser used for SC generation. After frequency stabilization of the mode-locked laser, the worst-case RIN values of the CW laser carved directly from the pump laser are reduced to $-120$ dB/Hz from $-111$ dB/Hz. These worst-case RIN values occur at frequency values that coincide with integer multiples of the fundamental repetition rate of the sigma laser. However, RIN values as low as $\sim -148$ dB/Hz are measured at frequencies between the fundamental cavity modes of the laser.

These results show that the side-mode suppression ratio of the mode-locked laser significantly contributes to high RIN values. Since the coherence of the SC is preserved, we expect that signal-spontaneous and spontaneous-spontaneous beat noise will have a tolerable effect on RIN values [5]. In a theoretical study, we show that the lowest RIN value of $-160$ dB/Hz is achievable after the amplifier. We also show that amplification of ASE by modulational instability during SC generation degrades RIN values. The results indicate that coherence degradation raises the minimum RIN value to $-144$ dB/Hz. The results also show that starting with a stable pulse source with RIN $<-150$ dB/Hz, a stable multiple wavelength CW source with a $<-140$-dB/Hz RIN value, which is an acceptable level for commercial applications, is achievable.

The outline of the paper is as follows. In Section II, we will describe the experimental setup used for SC generation and CW carving. The experimental results, including the generated SC and RIN measurements, will be presented. In Section III, the effect of laser stabilization on RIN will be discussed. Limitations of harmonically mode-locked lasers will also be presented in the same section. Theoretical results of RIN degradation in EDFA and in SC fiber will be presented in Section IV. Section V contains a discussion of possible system applications of the short fiber SC generation as a DWDM source as well as its advantages. Finally, Section VI summarizes our findings.

## II. Experimental Results of CW Generation

The experimental setup used in multiwavelength CW generation by longitudinal mode-carving is shown in Fig. 1. As a pump laser, we use an actively mode-locked fiber laser, which generates a 10-GHz train of squared hyperbolic secant pulses with a 1.2-ps pulsewidth and $\Delta\tau\Delta\nu = 0.32$ at 1552 nm. By using a high-power EDFA, the pulse train is amplified to an average power of 800 mW.

Following the EDFA, three sections of fibers are used for SC generation [7], [5]. The first two sections are mainly used for pulse compression by a soliton-effect pulse compression scheme. The combined effect of third-order dispersion and SPM is utilized in the last section to generate the SC. The fibers used for SC generation are 6.8 m of SMF-28 fiber followed by 15.7 m of dispersion-shifted fiber with $\lambda_0 = 1492$ nm. The last section is 6.6 m of another dispersion-shifted fiber with $\lambda_0 = 1546$ nm. Due to difficulty in finding narrow-band optical filters with $<10$-GHz bandwidth, longitudinal mode spacing of the SC was increased to 40 GHz by using a pulse interleaver. The pulse interleaver is made of two $1 \times 4$ couplers spliced to each other with 25-ps relative delay in each arm.

As a bandpass filter, we use a monochromator to carve out the longitudinal modes of the generated SC. The resolution of the monochromator is $\sim$6. The bandwidth of the filter is 30 GHz at a 20-dB level. An optical spectrum analyzer is used to characterize the spectral features of the generated SC and the carved CW signal. We use a 10-MHz low-noise optical detector to detect the carved CW. The noise performance of the carved CW

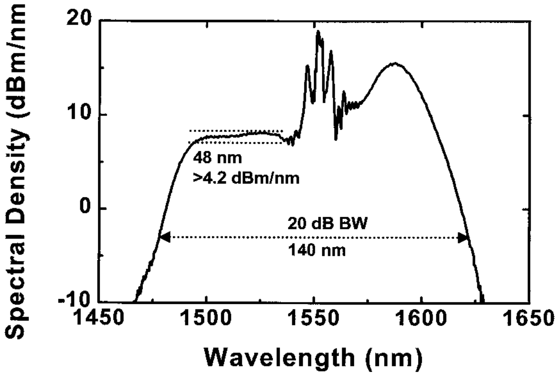



Fig. 2. The normalized SC spectra generated in conventional dispersion-shifted fibers. A 140-nm bandwidth is measured with ±0.5-dB uniformity over 48 nm. Power spectral density is measured to be 4.2 dBm/nm over the flat region.

signals is characterized by using a radio frequency (RF) spectrum analyzer and a scope after the detection.

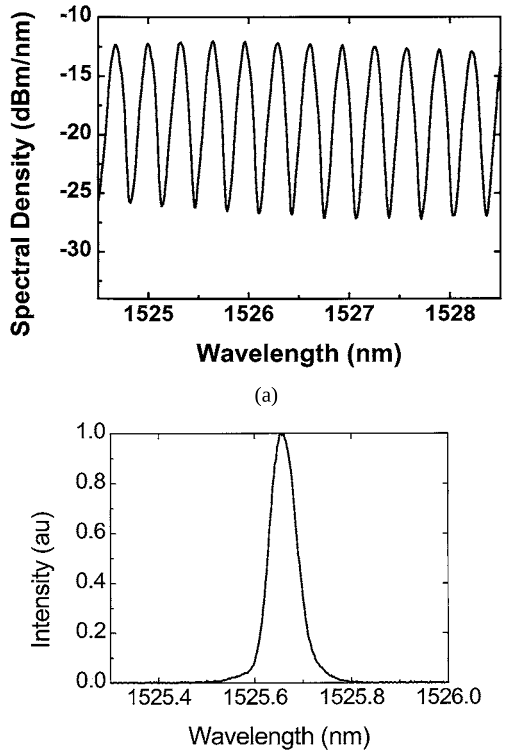
Fig. 2 shows the normalized 10-Gb/s SC spectra generated in three sections of conventional dispersion-shifted fibers. The 20-dB bandwidth measured from the peak is 140 nm. On the anti-Stokes' side, we obtain ±0.5-dB flatness over 48 nm (6.34 THz). The average power spectral density over the flat region is measured to be 4.2 dBm/nm. On Stokes' side, a spectral peak with a 30-nm bandwidth (3.59 THz) at a 3-dB point is obtained. The power spectral density of 7.48 dBm/nm or higher is measured on the Stokes' side. By using a different configuration of SC fibers, the power spectral density of the SC can be increased to $>7$ dBm/nm over the flat region. Similarly, a 20-dB bandwidth of the SC can be increased to $>250$ nm with a ±0.5-dB spectral uniformity exceeding 80 nm by using high nonlinearity fibers [5].

CW generation by longitudinal mode-carving is done after quadrupling the repetition rate to 40 Gb/s by a 4-bit interleaver. Magnified SC spectra after the bit interleaver is shown in Fig. 3(a). A ~13 dB of modulation depth is obtained, and this modulation depth of the longitudinal modes is mainly set by the resolution of the optical spectrum analyzer (~6.3 GHz) and the polarization sensitivity of the bit interleaver. By using the monochromator as a bandpass filter, we carve out each individual mode to generate a CW signal. Fig. 3(b) shows the typical CW spectrum obtained by spectral slicing of the SC. The linewidth of the CW signal is also set by the resolution of the optical spectrum analyzer used in the experiment.

RIN is one of the measurements used for characterizing the noise performance of the CW signals. RIN defines the ratio of noise power at every frequency to the average dc power level, and it is formulated as

$$\mathrm{RIN} = 10^{*}\mathrm{Log}(\Delta P/P_{\mathrm{ave}}) \quad [\mathrm{dB/Hz}]$$

where $\Delta P$ [W/Hz] describes the power spectral density of the amplitude noise and $P_{\mathrm{ave}}$ describes the average dc power obtained from the CW signal [8]. RIN values across the SC spectra are calculated after measuring $\Delta P$ and $P_{\mathrm{ave}}$ values experimentally. Average dc power level is measured by using a scope with a 50-Ω input impedance after detecting the generated CW signal




(a)

(b)

Fig. 3. (a) The magnified SC spectra after the interleaver. The repetition rate of the generated SC is increased to 40 Gb/s to eliminate difficulty in filtering the modes 10 GHz apart. (b) Typical spectrum of the generated CW signals after the longitudinal mode-carving.

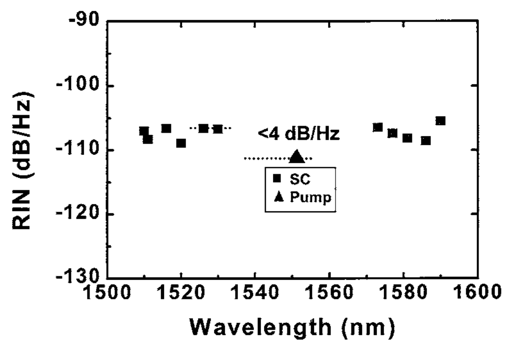



Fig. 4. RIN values of the carved CW signals. The noise performance of the generated CW signals is characterized by RIN measurement. An average RIN value of $-107$ dB/Hz is obtained. A $<4$-dB/Hz RIN degradation is measured compared with the CW carved directly from the pump laser.

by a 10-MHz low-noise detector. The power spectral density of the noise distribution $(\Delta P)$ is measured by using an RF spectrum analyzer with a bandwidth of 6 GHz.

Fig. 4 shows the calculated RIN values at different wavelengths across the SC spectra. The results show that the carved CW signals have an average RIN of $-107$ dB/Hz with variation of ~4 dB/Hz. Due to the temporal instability of the mode-locked laser, the measurements are done at a single scan on a narrow frequency range to avoid sudden jumps in the RF spectrum. The effect of the mode stability will be discussed in the following section in detail. The measurements are done mainly on the high spectral density and uniform regions of the SC spectra. CW lasers carved from the SC spectra between 1535 nm and 1565

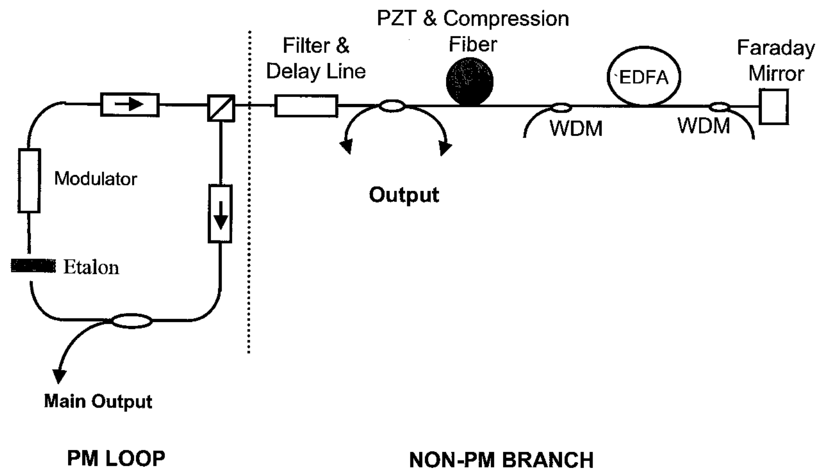



Fig. 5. The pump laser is modified to increase frequency stability. By inserting a solid etalon with a 10-GHz free spectral range and a finesse of 67, mode-shifting of the laser is eliminated.

nm generally gives noisier results. However, since CW lasers within this wavelength range can be carved directly from the pump laser before SC generation, CW lasers with better RIN values can be generated within this wavelength range directly from the pump laser.

We also measure the RIN of a CW signal carved directly from the pump without an SC fiber. The results indicate that a −111-dB/Hz RIN is achievable by CW carving from a mode–locked laser and that a $<$4-dB/Hz RIN degradation occurs during the SC generation. Since the experiment has started with a noisy laser, the effect of the EDFA noise figure on RIN is calculated to be a ∼2.5-dB degradation. The 1.5-dB degradation can be attributed to ASE amplification due to a four-wave mixing process during the SC generation. Due to the temporal instability of the mode-locked laser, the measurements are done at a single scan on a narrow frequency range to avoid sudden jumps in the RF spectrum. The RIN degradation in the case of a stable laser and the effect of mode stability on RIN will be calculated and discussed in following sections. In any case, the results confirm that the pump laser used for SC generation ultimately sets the lowest limit of the achievable RIN value.

## III. Effect of Laser Stabilization

In the second phase of the experiment, we study the effect of the laser stability on RIN. In our experiment, we are using an actively mode-locked fiber laser with $\sigma$ cavity configuration [9]. Recently, the amplitude stability and the pulse dropout characteristics of the $\sigma$ lasers have been studied theoretically and experimentally [10], [11]. Since we are using longitudinal mode-carving technique to generate a CW signal, frequency (mode) stability of the fiber laser is the main concern. Since the filter position is fixed to a certain frequency to carve out a CW signal in the experiment, any changes in the laser frequency translate into amplitude noise by the fixed CW carving filter.

Experimentally, we measure the highest RIN value as −107-dB/Hz RIN at frequencies between 20 kHz and 400 kHz. This peak RIN value moves to different frequencies randomly. The same RIN pattern repeats itself for the CW signals carved from the pump laser as well. This result shows that random changes in laser frequency translate into RIN during the CW carving. Theoretically, the frequency instability of the laser arises from the fact that the laser cavity has the fundamental repetition rate of ∼2.3 MHz. A 10-GHz repetition rate is obtained after selective amplification of every 4300th harmonics of the cavity modes during the active mode-locking process [12]. Since there is no active component in the cavity to determine which supermodes will be selected during the mode-locking, lasing modes change randomly with any perturbation in the cavity. This frequency instability can also cause amplitude noise through the beating of different frequencies [12].

Frequency stabilization of the pump laser is realized by inserting a Fabry–Pérot filter with fixed free spectral range into the laser cavity. Fig. 5 shows the modified laser cavity. A solid etalon with free spectral range of 10 GHz and a finesse of ∼67 is placed in the unidirectional ring portion of the laser cavity in order to eliminate the back reflection from the etalon going back into the laser cavity. By placing the etalon, we observe a stable pulse train with 100-ps separation.

Fig. 6 shows the RF spectrum of this detected pulse train. The side-mode suppression ratio of the pulse train is measured to be ∼65 dB for the best case. However, due to a 4-dB insertion loss of the etalon used in the experiment, output pulsewidth is increased to 8 ps from 1.2 ps. By choosing low-loss components, stable short pulses can be generated. Although the pulse broadening due to high loss makes it difficult to generate SC in short fibers without additional pulse compression before the SC generation, it makes easy to understand RIN degradation due to the frequency instability of the laser.

The amplitude noise distribution of the CW signal carved from the pump laser is shown in Fig. 7. To calculate the RIN values, the average signal power at the detector output is measured by an oscilloscope and the noise power distribution is measured by an RF spectrum analyzer.

Mainly, we obtain two different RIN values—RIN at the same frequencies as the harmonics of the fundamental laser cavity frequency and at the frequencies in between. When the side-mode

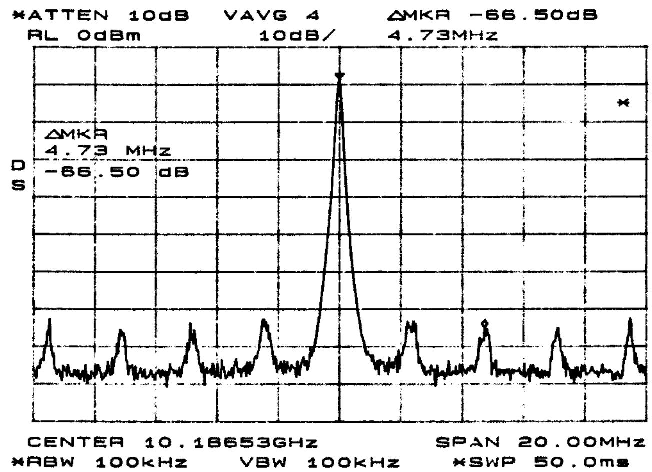



Fig. 6. RF spectrum of the mode-locked laser after stabilization is measured. A side-mode suppression ratio of ~65 dB is obtained.

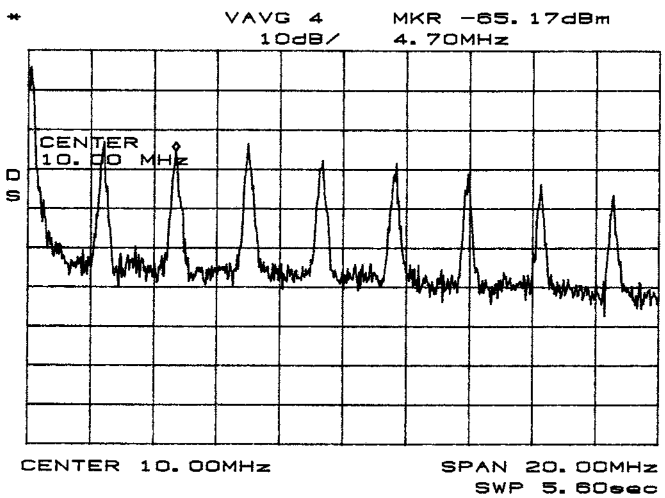



Fig. 7. RIN distribution of the CW signals carved directly from the pump laser. A maximum RIN value of −120 dB/Hz is measured. The RIN value is set by the side-mode suppression ratio of the mode-locked laser. In between the cavity modes, RIN values as low as −148 dB/Hz are obtained.

suppression ratio is about 63 dB, RIN values at the same frequencies as the supermodes of the laser cavity are calculated to be −120 dB/Hz. This result shows only a 9-dB/Hz improvement compared with the previous results.

At the frequencies in between, however, the supermodes' RIN value goes down to as low as −148 dB/Hz. Moreover, by adjusting the quality of the mode-locking, we observe that the side-mode suppression ratio of the laser changes the RIN values. Higher RIN values are obtained with a mode-locking position with lower side-mode suppression ratio. These results indicate that the low side-mode suppression ratio of the active mode-locking is the second limitation of obtaining a stable CW signal by longitudinal mode-carving. However, obtaining as low as a −148-dB/Hz RIN value at frequencies between the cavity modes indicates that stable CW sources can be obtained by using a stable-pulsed laser by longitudinal mode-carving. Since it will not have a problem of side-mode suppression ratio like in mode-locked lasers, an externally modulated short-pulse source will be the best approach for a pump source.

## IV. RIN Degradation in EDFA and SC Fiber

RIN degradation due to amplification and SC generation is also studied theoretically. To calculate the RIN degradation, we estimate the amount of ASE accumulation after the EDFA and the SC fiber. From the estimated ASE power, we can calculate the amount of the photocurrent generated due to noise and the signal. Mainly, we focus on the two effects—noise current due to spontaneous-spontaneous beating and noise current due to signal-spontaneous beating [13]. For calculation purposes, we assume an ideal detection system with negligible circuit noise. We also ignore the effect of the side-mode suppression ratio and assume that we start with an externally modulated laser source. The photocurrents generated by the noise and the signal are formulated as

$$\begin{aligned} I_{\mathrm{ASE}} &= e \cdot \eta \cdot m \cdot n_{\mathrm{sp}} \cdot (G-1) \cdot B_o \\ I_i &= e \cdot \eta \cdot G \cdot P_i / h\nu_s \\ I_{\mathrm{s-sp}}^2 &= 4 I_{\mathrm{ASE}} I_i B_e / (m \cdot B_o) \\ I_{\mathrm{sp-sp}}^2 &= 2 I_{\mathrm{ASE}}^2 B_e / \left(m \cdot B_o\right) \end{aligned}$$

where $I_{\mathrm{ASE}}$ defines the generated dc current due to ASE, $I_i$ defines dc photocurrent due to signal, $I_{\mathrm{s-sp}}$ defines the noise current generated due to signal-spontaneous beating, and $I_{\mathrm{sp-sp}}$ defines the generated noise current due to spontaneous-spontaneous beating [13]. The parameter $\eta$ is the quantum efficiency of the detector, $e$ is electron charge, $G$ is gain, $n_{\mathrm{sp}}$ is the spontaneous emission factor of the amplifier, $m$ is the number of amplifier modes, and $P_i$ is the optical input power to the amplifier. $B_e$ and $B_o$ defines the electrical bandwidth of the detector and the optical bandwidth of the filter, respectively. The noise and signal power levels are calculated by using the formula

$$\begin{aligned} \Delta P &= \left(I_{\mathrm{sp-sp}}^2 + I_{\mathrm{s-sp}}^2\right) \cdot R \\ P &= \left(I_{\mathrm{ASE}}^2 + I_i^2\right) \cdot R \end{aligned}$$

where $R$ is the input impedance of the diagnostics.

Fig. 8 shows the changes in RIN values due to ASE accumulation in the EDFA. For calculations, we use $m = 2, n_{\mathrm{sp}} = 1.7, G = 80, P_i = 10$ mW, $B_e = 10$ MHz, and $B_o = 30$ GHz. The analytical calculations indicate that for low initial RIN values, the ASE power limits the lowest achievable RIN value. RIN values as low as −160 dB/Hz can be achieved by spectral slicing of longitudinal modes when we start with a very stable source. Since the generated ASE will dominate the source noise after the EDFA, the saturation near −160 dB/Hz occurs. As the RIN of the pump laser increases, the RIN of the EDFA output is set by the initial RIN value of the source and the ASE generation inside the EDFA has a minimal effect on RIN values. According to Fig. 8, the experimental RIN value of −148 dB/Hz at the frequencies in between the fundamental cavity modes indicates that our source laser has the initial RIN of ~−150 dB/Hz.

We also calculate the RIN degradation due to SC generation. In our previous work, we have demonstrated that the signal-to-noise ratio (SNR) of the generated SC in a similar setup formed by the same fiber types is degraded at frequencies away from the pump wavelength due to amplification of ASE noise by modulational instability [5], [15]. SC generation of different types will

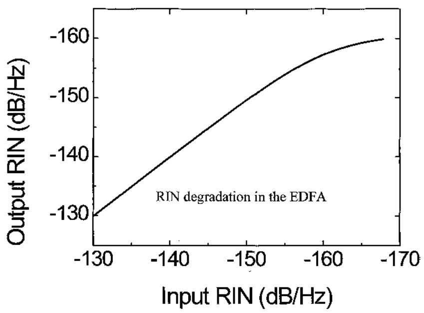



Fig. 8. RIN degradation due to EDFA is calculated. For RIN values $< -160$ dB/Hz, ASE sets the RIN value to $\sim -160$ dB/Hz. For initial values $> -160$ dB/Hz, the EDFA has minimal effect.

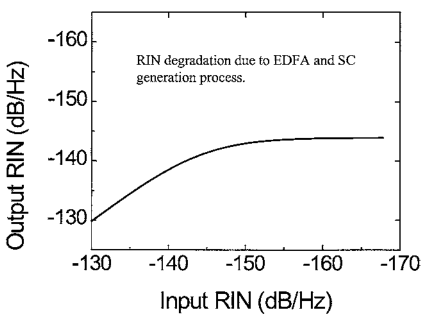



Fig. 9. RIN degradation due to SC generation is calculated. Coherence degradation during the SC generation sets the lower limit of the RIN value as $-144$ dB/Hz. For initial RIN values $> -145$ dB/Hz, the coherence degradation has minimal contribution and the final RIN value is set by the initial condition.

result in different SNR degradation. However, the worst SNR degradation for the given three sections of fibers with a staircase overall dispersion profile are estimated to be 20 dB, which occurs at the edge of the SC spectra near 1490 nm [5].

For RIN degradation modeling, we consider a noise-free SC source followed by an EDFA with unity gain and 20-dB noise figures to add the noise into the system. This 20-dB noise figure is the extreme case for RIN degradation, and it increases the spontaneous emission factor $n_{\rm sp}$ by nearly 25 times [14]. Therefore, an $n_{\rm sp}$ value of 50 is a conservative estimation in this case.

Fig. 9 shows the variation of RIN values due to amplification and the SC generation. The results indicate that the ultimate value of the RIN is set by the coherence degradation during the SC generation. Even though we start with a very stable laser, the ASE generation in the EDFA and the ASE amplification during the SC generation will saturate the RIN value. According to the results, RIN values as low as $-144$ dB/Hz are still achievable when we start with a laser with the initial RIN $< -150$ dB/Hz to generate the SC. For the initial RIN values of $> -145$ dB/Hz, the quality of the CW source generated by the longitudinal mode-carving is limited by the pump laser.

## V. Discussion

The experimental results show that, because of its large bandwidth, $> 140$ nm, and uniformity, $\pm 0.5$ dB over 48 nm, the SC generation is a potential multiple wavelength CW source with precise channel spacing, where the channel spacing is set by the repetition rate of the pump laser and low-noise degradation. However, the noise performance is the main limitation for using the longitudinal mode-carving of SC in communication systems. In general, a RIN value of $-110$ dB/Hz is considered high for a communication system with long-distance propagation. However, this value is not an intrinsic limitation of the method we are using; it is a limitation of the laser used in the current experiment.

Moreover, since the propagation of incoherent CW signals with 1.3–nm bandwidth carved from an ASE spectra through 165 km of dispersion-shifted fiber have already been shown, the coherent CW signal from coherent SC generation can be used in long-distance propagation systems [1]. When we start with a stable pulse source such as an externally modulated CW source to obtain a short-pulse pump source, CW signals with RIN values as low as $-144$ dB/Hz are achievable, and it can accommodate any channel spacing, which is set by the repetition rate of the pump laser. On the other hand, the RIN of the incoherent sources are intrinsically limited by the spontaneous-spontaneous beat noise. The maximum capacity is also estimated as 47 Gb/s for a 40-nm ASE source, as opposed to an 140-nm SC source. Moreover, the RIN value also increases drastically due to the incoherent nature of the ASE source with decreasing filter bandwidth and channel spacing. For example, the lowest theoretical achievable RIN values by using a 0.08-nm and 1.3-nm rectangular filter are estimated as $-100$ dB/Hz and $-112$ dB/Hz, respectively [8].

For lower RIN values, starting with a stable coherent source is a necessity to overcome the high-RIN-value problem. The actively mode-locked lasers have intrinsic limitations of frequency instability and low side-mode suppression ratio when they are used for generating SC. In the first limitation of frequency instability, any random changes in the laser wavelength are translated into the amplitude noise due to the fixed CW carving filter. However, this limitation can be solved by using broadband filters at the expense of high channel count. The side-mode suppression ratio is also an intrinsic property of mode-locked lasers. The beating of the carved CW signal and these totally unsuppressed side modes are the second largest sources of high RIN values ($-120$ dB/Hz).

Using an externally modulated DFB laser with low RIN can be a solution to pump limitations if short pulses are obtained after the external modulation to generate SC. Although coherence degradation during the SC generation is the other limitation due to signal-spontaneous beat, RIN values of $-144$ dB/Hz at 60 nm away from the pump source show that commercial CW sources can be generated despite the coherence degradation. Therefore, starting with a stable pump source, $> 1600$ WDM channels with precise 10-GHz spacing and $< -140$-dB/Hz RIN values can be obtained for commercial applications.

## VI. Summary

In summary, we experimentally demonstrate that longitudinal modes of the SC generated in optical fibers can be used as a CW source. Because of its large bandwidth, $> 140$ nm at 20-dB point, and uniformity, $\pm 0.5$ dB over 48 nm, SC sources can generate a multiple wavelength CW source with high wavelength stability and perfect channel spacing, which is set by the repetition rate of the pump laser.

Based on the 10-GHz repetition rate, $>600$ wavelength CW channels can be carved with a $-6$-dBm/ch power level and 10-GHz exact channel separation. With full utilization of the whole SC spectra, channel count exceeding 1600 can be achieved.

In our experiments, we study the noise performance of the CW signals carved from a mode-locked laser and an SC source. We measure the average RIN value of the CW signals carved from the SC source as 107 dB/Hz with 4 dB/Hz degradation compared to the CW laser directly carved from the pump laser. Experimental results show that the frequency instability and the low side-mode suppression ratio of the pump laser are the main sources of the RIN. Frequency stabilization of the laser reveals that as low as $-148$-dB/Hz RIN values can be achieved after the EDFA. These results show that using a stable pump source for SC generation is essential for low-noise CW source generation. Numerical results indicate that the EDFA and the coherence degradation during the SC generation also increase the RIN values. However, the spontaneous-spontaneous and signal-spontaneous beat noises are not the main limitation of CW sources by longitudinal mode-carving. The lowest achievable RIN values after the EDFA and the SC fiber are calculated to be $-160$ dB/Hz and $-144$ dB/Hz, respectively.

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