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Demonstration and Evaluation of an Optimized RFS Comb for Terabit Flexible Optical Networks

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Abstract—We experimentally demonstrate and evaluate an optimization strategy of recirculating frequency shifting (RFS) optical comb for terabit flexible optical networks. We achieve increased optical signal to noise ratio (OSNR) with good stability (no system outage) by reducing erbium doped fiber amplifier gain in the shifting loop, and deploying an in-loop noise suppression filter. We demonstrate that this source can support 20 × 200 Gb/s dual polarization Nyquist-16QAM transmission. With optimization, the RFS comb has greater and more uniform OSNR per channel. Flexible optical networks with software defined networking are particularly suited to this enhanced RFS due to 1) programmable frequency spacing, 2) dense, stable spacing enabling very high spectral efficiency, 3) uniform performance across channels, and 4) sufficient OSNR for high order modulation. The RFS can be used in short links when using low overhead forward error correction (FEC). Distances as great as 1150 km are achieved when using a 20% FEC overhead. Long distance tests at 4 Tb/s result in a post-FEC net rate of 3.3 Tb/s and 6.3 bit/s/Hz of spectral efficiency.

Index Terms—Flexible optical network; Optical frequency comb; Nyquist-WDM; Coherent detection

I. INTRODUCTION

Flexible grids are a promising solution for next generation optical communications exploiting software defined networking (SDN). The flexible grid with SDN adapts the granularity, symbol rate, and modulation format to maximize the throughput and spectral efficiency of the entire network [1-2]. Future high performance flexible optical network incorporate an IQ transmitter, a frequency selective coherent receiver, adaptive coding and digital signal processing (DSP) [3]. Another important component is the multi-carrier comb source. This source allows the network to achieve terabit/s with high spectral efficiency (SE), while decreasing hardware complexity.

Compared with a laser array, an optical frequency comb source provides carrier lines with more stable spacing. This stability enables more tightly spaced wavelength division multiplexing (WDM) as intra-channel crosstalk due to laser frequency drifting can be avoided. Tighter spacing achieves near optimal SE with Nyquist-WDM [4-7] and OFDM [8].

Desirable properties of an optical frequency comb source include a reasonable number of carriers, tunable carrier spacing to accommodate a flexible grid, excellent optical signal to noise ratio (OSNR), and a flat spectrum. The tunable carrier spacing would enable a tunable baud rate for flexible networks, and the excellent OSRN would provide enough power margin to support higher order QAM and/or longer distances. The comb lines would be uniform to assure good performance across all channels.

The comb based flexible optical network has been demonstrated by many structures in short and long reach optical systems, such as parametric methods [4], gain-switched comb [5-6], external modulation with cascaded modulators [9-10] and recirculating frequency shifting (RFS) [11-17]. Parametric methods offer a tremendous number of carrier lines over the C and L bands, but they have a relatively complex configuration (requiring highly nonlinear fiber and high pump power) compared to the other methods mentioned. Gain switched combs have a simple configuration, but a limited number of carriers. Cascaded modulators could provide several tens of comb lines, but the complexity scales with the number of carriers, and they require high RF power.

RFS comb sources generate carrier lines by shifting and circulating seed tones. This comb has a relatively complex configuration (an additional EDFA and optical tunable bandpass filter), but can generate hundreds of carrier lines [17]. RFS sources provide good uniformity among tones, and easy tunability. Grid spacing can be adjusted by tuning the in-loop filter and the frequency of the RF signal. We focus on this solution, overcoming shortcomings identified in the literature.

RFS sources have been proposed for super-channel long haul systems with QPSK modulation [11]. One of the few data transmission demonstrations with higher order QAM [15] saw inadequate OSNR due to accumulated amplified spontaneous emission (ASE) noise during circulation. While
50 carriers were modulated with OFDM-16QAM, it required high-overhead error correction. In [16] 16QAM was investigated, but at low bit rate due to insufficient OSNR.

Several approaches have been proposed to improve RFS comb OSNR. In [18-21], multi-seed, multi-loop circulating and complementary shifting based RFS structures have been proposed to reduce the number of recirculations, hence reducing ASE. In [22], a linear frequency shifter based structure was proposed to improve the power efficiency of frequency shifting, reducing ASE. In [23], an in-loop, optical FIR comb filter improved comb OSNR. Stimulated-Brillouin-based narrowband amplification in an RFS comb [24] was proposed to avoid EDFA-induced excessive ASE noise, but at a cost of duplicated electro-optic components to generate a pump comb.

In these enhanced RFS combs, most experimental demonstrations are confined to measuring OSNR improvement, without the data transmission required to validate the performance improvement and stability of the comb for high order QAM communications. We start with the in-loop optical FIR comb filter approach to improving OSNR [23] – for which to date only optical spectrum analyzer measurements of OSNR are available. We find operating regimes that permit translating OSNR improvements into improved BER performance for QAM, i.e., with a sidelobe suppression ratio sufficient for achieving stable QAM transmission. We further demonstrate how the operating point affects the uniformity of QAM performance across the comb lines.

The enhanced RFS comb is experimentally demonstrated to carry 20 × 200 Gb/s Nyquist-16QAM. We establish that with comprehensive optimization, the RFS comb can provide adequate margin to boost capacity with higher order QAM and tighter spacing in a flexible optical network, thus attaining higher SE and higher data rate. This RFS comb for terabit flexible optical network can be optimized to achieve both BER performance and stability (i.e., fading free operation with no outage).

II. CONFIGURATION AND OPTIMIZATION OF RFS COMB

A. Configuration and theoretical analysis

The structure of the RFS comb is shown in Fig. 1, and we quickly review the working principle [25]. The seed laser is fed to the circulating loop and the optical carrier is shifted by a frequency shifter (usually implemented by an I/Q modulator based single-side-band modulation). An optical amplifier is in the loop to compensate loss. The shifted tone, together with a newly injected seed tone, enters the next recirculation, generating a third frequency tone. After N round trip inside the loop, N carrier lines are produced at the output. Due to the in-loop amplification, ASE noise accumulates during circulation, corrupting OSNR. The last several (or tens) carriers suffer the worst OSNR degradation.

![Fig. 1. Principle of operation of an RFS comb](image)

To optimize RFS combs for terabit systems (requiring high order QAM), a theoretical analysis on its OSNR performance is needed. The OSNR of the RFS comb is defined as the worst case OSNR across tones. For simplicity we assume identical power $P_c$ for every tone. Since the last tone sees the greatest accumulated ASE, the OSNR is dominated by the noise power in $N^{th}$ carrier, $P_s,N$. Let $B_c$ denote the carrier frequency spacing, the $P_s,N$ can be approximated by [23]

$$P_s,N = \sum_{k=1}^{N} S_i(f)df \approx \frac{1}{2} \sum_{k=1}^{N} F_s(G-1) \cdot h \cdot f_0 \int |H(f)|^2 df$$

where $f$ is the optical frequency, $f_0$ is the center frequency, $S_i(f)$ is the ASE power spectrum density (PSD) in the $k^{th}$ round trip, $H(f)$ is the transfer function of the optical filter, $F_s$ is the erbium doped fiber amplifier (EDFA) noise figure, $G$ is the required gain, and $h$ is Planck’s constant [26]. Then OSNR is approximated by

$$OSNR = 10 \log \frac{P_c}{P_s,N} + 10 \log \frac{B_c}{B_{ref}}$$

where $B_{ref}$ is the reference noise bandwidth of 12.5GHz.

Given $B_c$ and $F_s$, two approaches to reduce noise power are: 1) reduce required gain $G$, and 2) enhance optical filtering to eliminate more ASE.

Figure 2 shows simulated OSNR performance for different gain factors and optical filters. With an ordinary RFS setup, the filter is all pass, i.e., $H(f)$ equals to 1, and the gain is set to $G_0$ sufficient to achieve 40 dB OSNR for the first carrier tone. As indicated by the blue curve in Fig. 2, we can see that the OSNR dramatically decreases with carrier number, with OSNRs of only ~27dB and ~18dB for 20th and 50th carriers, which is inadequate for 16QAM.

With approach 1), we set the required gain $G$ to 0.5$G_0$ (3 dB smaller), and $H(f)$ is all-pass. We expect 1 dB gain savings to translate into 1 dB OSNR improvement. A lower required gain can be obtained indirectly by a higher power frequency shifter, which can be realized either by increasing RF drive signal to the I/Q modulator, or by using an IQ modulator with a very linear transfer function to increase shifting efficiency [22]. The higher the frequency shifter power, the lower the required EDFA gain, and hence the lower the ASE noise.

With approach 2), a comb filter could take the form of a
2-tap optical FIR filter, with \( |H(f)|^2 = \cos(2\pi f / B_n) / 2 \). Such a filter leads to 3 dB less ASE. Even with a simple 2-tap filter, about 8 dB improvement can be observed at the 50th carrier tone. Asymmetric Mach Zehnder interferometers, commonly available commercially as differential phase shift keying (DPSK) demodulators, can be used as a cost-effective implementation of this 2-tap comb-like filter. For convenience, a programmable Waveshaper could be used. Even better noise suppression can be achieved with multi-tap components, such as an 8-tap filter, but these components are uncommon.

The pink curve in Fig. 2 shows the total improvement when using the combination of the two approaches. There is potentially 12 dB improvement for the 50th carrier tone.

The two approaches described in the previous section are experimentally investigated in a 20-carrier generation. We 1) optimize the OSNR of the last tone (worst one) by setting RF power to run the EDFA at lower gain, and 2) reduce ASE with an in-loop filter programmed to a 2-tap comb response.

The experimental setup of the RFS comb is shown in Fig. 3. An external cavity laser (ECL) at 193.288 THz with 100 kHz linewidth (Cobrite DX1) provides the seed tone. The frequency shifter is implemented with an SHF46213D I/Q modulator. Polarization controllers (PCs) align polarization for the modulator. The output of an Anritsu MG3695C radio frequency (RF) synthesizer at 26.43 GHz was sent to a 2×2 90°hybrid that split the signal and introduced a 90° phase difference in one arm; these outputs were fed to the I/Q modulator inputs. After frequency shifting, a KEOPSYS EDFA with 28 dBm output power compensates modulation loss and total insertion loss. A programmable optical band pass filter (OBPF, Waveshaper 1000S) with ~528.6 GHz bandwidth is placed after the EDFA to reject ASE and limit the output to 20 carrier lines.

1) Reducing required gain

To reduce required gain, our optimization focuses on the RF driver power that determines the power of the shifted signal tone. The shifted tone power is monitored on the spectrum in an open loop test, and a typical measurement is shown as the inset plot in Fig. 4. The IQ bias voltages are carefully optimized to maximize the sidelobe suppression ratio (SSR), defined as the power ratio between shifted signal and highest side tone. The open loop test is crucial because the quality of frequency shifting (including both the absolute power of the shifted tone and SSR) determines the OSNR and flatness when the loop is closed.

The absolute power of the shifted tone can be increased by detuning the applied RF power, but this is accompanied by increased sidelobes introduced by the nonlinearity of Mach-Zehnder modulators (MZM) [25]. Fig. 4 shows the measured optical powers vs. RF power for the shifted tones (blue curve with square markers) and the sidelobes or side tones (red curve with dot markers). Both the shifted tone and side tone increase with the RF power, but the side tone goes up faster, resulting in decreased SSR.

After the open loop test, a series of closed-loop tests are run to determine how OSNR varies with RF power. Observing the output spectrum allows us to measure the tone-to-noise ratio (TNR): the ratio of tone power and noise floor. The OSNR is the sum of TNR and 10log10(100 MHz/12.5 GHz), where 100 MHz is the resolution of our optical spectrum analyzer and 12.5 GHz (0.1 nm) is the reference bandwidth. We optimize the IQ bias condition for each test to keep the 20 carriers as flat as possible.

2) Trading-off stability and OSNR

High OSNR means low noise, which benefits the bit error

![Image](356x114 to 510x237)

**Fig. 3** Schematic of recirculating frequency shifter loop

**Fig. 4** The power of shifted tone and side tones measured in the open loop test, and the spectrum.

![Image](356x114 to 510x237)

**Fig. 5** Measured SSR (open loop test) vs. OSNR (closed loop test) when sweeping RF powers; colored arrows show worsening behavior in the red zone and improved behavior in green.
rate (BER) performance. High SSR contributes to flat and stable output; instability leads to system outage and must be avoided. However, high OSNR and high SSR cannot be achieved simultaneously, and a trade-off must be sought. OSNR and SSR are both functions of RF power, and their relationship is found experimentally and presented in Fig. 5.

Extremely low noise and OSNR of 27 dB (TNR 48 dB) can be achieved with 27 dB SSR, but such low SSR will cause outage due to signal fading from fluctuations in carrier power. Hence this region is shaded in red. Similarly, the region of very stable, flat comb at SSR of 38 dB leads to low OSNR, 15 dB, hence this region is also shaded red. The blue shaded area in the middle of Fig. 5 offers the best trade-off where fading does not cause outage, and OSNR is high enough to support 16QAM. We choose two cases in the blue shaded region for experiments.

We focus on two points, cases A and B shown in Fig. 5, that represent extreme ends of the trade-off region. In the next section we run data transmission experiments for these points, but here we focus on the characteristics of the comb source. First we use coherent detection and capture the time domain signal using an RTO covering a number of μs. We check for fluctuations in the detected signal amplitude. If no fading is visible in the amplitude, we conclude the transmission is stable for these operating points. Figs. 6a and 6b shows the spectrums of case A with OSNR = 19 dB and case B with OSNR = 24 dB (TNR equals to 40 dB and 45 dB, respectively). The comb with 19 dB OSNR has fairly flat power spectrum across all carriers, while the comb with 24 dB OSNR has stable data recovery, but some variation in power across channels.

3) Filtering ASE in-loop

To suppress ASE with in-loop filtering, the OBPF in the RFS loop was programmed to have 13 GHz passband within each 26.4 GHz-spaced channel. This is an approximation of the response of a comb filter (CF) with a 2-tap optical FIR structure. The true 2-tap structure would offer better ASE suppression than our experimental OBPF, approaching the ~7 dB OSNR improvement on the 20th (worst) carrier according to calculations in the previous section. Fig. 6c shows an improved (vis-à-vis noise) spectrum when using a comb filter for the case B of closed-loop 24 dB OSNR. The OSNR per carrier for the three cases examined are given in Fig. 6d. For the best-case carrier we can see a 5 dB improvement without comb filtering and attributable to reduced required gain. When adding comb filtering another 7 dB gain is achieved. The trends observed correspond well with simulations in Fig. 2. We observe the ASE spectrum changes from flat to hillocks around occupied frequencies, reducing total noise.

An RFS for flexible SDN can tune carrier spacing by tuning the RF frequency in the recirculating roof. To maintain this flexibility when using a comb filter to enhance OSNR, the comb filter spacing should also be tunable. As a tunable comb filter also has application in reception of differential phase shift keying, solutions have emerged for tuning the delay in the interferometer structure of a 2-tap optical FIR [27,28].

In the next section, these two combs of OSNR 19 dB and 24 dB with and without applying CF for noise suppression are used in data transmission. The effectiveness of the optimization strategy is evaluated. We show the RFS comb is suitable for flexible optical networks due to its tunable channel spacing and compatibility with high order 16QAM.

III. EXPERIMENTAL EVALUATION

A. RFS comb based source

The experimental setup of the RFS comb based transmission system with 20×25 Gbaud DP-Nyquist 16QAM is shown in Fig. 7. It consists of four sections: the RFS comb source, the Nyquist-16QAM generator, the transmission circulating loop and the coherent detector.

The configuration of the RFS comb is shown in Fig. 3, with the same RF and optical setup parameters used in section II. The RFS comb generates 20 carrier lines, with 26.4 GHz spacing. Two benchmarks with OSNR 19 dB and 24 dB are tested.

The comb is sent to a QAM transmitter (SHF46213D); each carrier is imprinted with the same Nyquist 16QAM signal. Nyquist pulse shaping is realized in the digital domain: the transmitter (Tx) digital signal processing (DSP)
flowchart is shown in Fig. 7. The pseudo-random bit sequence (PRBS) of length 2^19-1 is mapped to a Gray-coded 16QAM constellation. We use a 128-tap raised-cosine FIR filter with a roll-off factor of 0.01 for pulse shaping. The signal is down sampled to 2.56 samples per symbol. A digital pre-distorter compensates the QAM modulator nonlinear transmission curve. The complex 52.5 Gbaud Nyquist-16QAM signal is sent to two 64 GSa/s Fujitsu digital to analog converters (DACs). Dual-polarization transmission is emulated by separating the 20-channel output into two equal power paths with a polarization beam splitter (PBS), and recombining with a polarization beam combiner (PBC) after one path is delayed. The final signal is a 4 Tbit/s ultra-dense WDM with 26.45 GHz spacing and 200 Gbs per channel, occupying ~528.6 GHz bandwidth. The optical spectrum of the 4 Tbit/s signal is shown as the inset in Fig. 7 for case B with comb filtering. The spectrum shows a fairly flat comb without spectrum shaping.

The signal is boosted by an EDFA and launched into the transmission loop controlled by two acoustic optical modulators (AOMs). The recirculating loop consists of a span of 80 km standard single mode fiber (SSMF) with attenuation of 0.19 dB/km, an EDFA with 23 dBm output power, and a Waveshaper 4000S OBPF. The OBPF is programmed with a tilted passband window of 560 GHz width to equalize the EDFA gain spectrum and reject out-of-band ASE noise.

At the receiver end (Rx), the channel of interest is selected by a tunable OBPF (Alnair Labs BFV-200-SM-FA) with ~50 GHz bandwidth, and amplified with an EDFA. Another 0.8 nm OBPF reduces ASE noise before detection. The signal with power of -4 dBm is coherently mixed with a 13 dBm 0.8 nm OBPF reduces ASE noise before detection. The signal is filtered by a 10th order super Gaussian low pass filter (LPF) with 26.25 GHz bandwidth. Chromatic dispersion is compensated in the frequency domain [29]. After that, a 33-tap T/4-spaced (T, symbol period) constant-modulus-algorithm (CMA) is used to coarsely compensate the polarization dependent impairments and intersymbol interference (ISI). A second stage of multi-modulus-algorithm (MMA) is cascaded to improve performance [30]. The carrier frequency offset compensation (FOC) is estimated in two steps [31]: FFT based coarse estimation following by mean square error method for fine tuning. The carrier phase recovery (CPR) is a blind phase search (BPS) with 32 test angles and the maximum likelihood (ML) method [32]. To further reduce residual ISI and IQ imbalance, a T-spaced decision-directed least mean squares (DD-LMS) filter is applied on the in-phase and quadrature components separately. Finally, the recovered symbols are demodulated into binary streams for bit error rate (BER) measurement over 120,000 symbols per test.

**B. Back-to-back BER results**

For the back-to-back (B2B) tests, we bypass the booster EDFA and transmission link. Fig. 8a shows the BER curves measured using the case A comb source with 19 dB OSNR and its combination with CF, and Fig. 8b shows the corresponding results for case B with 24 dB OSNR group. Results
both with and without in-loop filtering are presented.

First consider Fig. 8a for OSNR of 19 dB. The pink curve (diamond markers) shows an obvious BER degradation against the channel number, and the BER curve follows the trend of noise floor as shown in Fig. 6a. If we assume 7% FEC overhead with a $3.8 \times 10^{-3}$ BER threshold [33], only half of the 20 tones have adequate OSNR performance to carry DP-16QAM signal. For this case, the OSNR of comb source determines the BER performance. With CF, the accumulated noise is greatly suppressed as shown in Fig. 6c, the system performance is significantly improved. We can see that all the 20 channels have an almost equal BER around $10^{-3}$.

Next consider Fig. 8b, case B with OSNR of 24 dB. We have about 18 channels with BER below the FEC threshold without comb filtering, as indicated by the light blue curve (round markers). However, the curve still follows the trend of the noise floor. The BER curve is not as smooth as with case A in Fig. 8a: the non-flat RFS output leads to non-identical power allocation across channels. Improved BER with in-loop filtering is given by the dark blue curve (square markers). At low channel number the CF does not improve BER as the OSNR is already high. At higher frequencies the ASE noise accumulates, and the BER improvement becomes substantial.

Case B shows less BER improvement than case A. We surmise that case A is OSNR limited, while case B (having higher OSNR) has its BER limited by effects other than additive noise. While A and B suffer the same ICI, this ICI could be the limiting factor in Case B. For the first and last channels, the crosstalk comes from only one side, while interior channels suffer from two-sided crosstalk. Some transmitter nonlinearity also remains (from DACs, amplifiers, etc.), despite the use of a very small roll-off factor and a pre-distorter. In both cases, however, BER is improved and is more flat. Not only does this improve overall capacity, it also enables flexible SDN allocations as the performance is more uniform.

![Fig. 9 BER vs. launch power after 640 km (WDM) and 800 km (single channel).](image)

C. Transmission results

We chose case B for transmission experiments due to higher OSNR: the signal fading was low enough that there was no outage in data recovery during transmission. We sweep launch power to find the optimum operating point.

![Fig. 10 Measured BER for case B with CF for various fiber lengths.](image)

Fig. 9 shows the BER results vs. launch power for both WDM $20 \times 25$ Gbaud DP-Nyquist-16QAM transmission and single channel (SC). For SC, the BERs are measured after 800 km transmission, for WDM after 640 km. We optimized BER on the worst case 17th channel (see Fig. 8b with CF). Results show that -2dBm and -4dBm per channel are the optimum launch powers for SC and WDM respectively, without additional DSP procedures to compensate fiber nonlinearity.

In Fig. 10 we present transmission results when launching 9 dBm total power (-4 dBm per channel) into the SSMF link. The 20 channel BER results are given for several transmission distances. Long distance transmission pushes the BER above the 7% FEC threshold. Achieving both high spectral efficiency and long distance requires a more aggressive error correction.

Assuming 20% FEC overhead a BER below the $2.4 \times 10^{-2}$ FEC threshold is acceptable [34]. This threshold is achieved by all channels in Fig. 10. The 4 Tb/s signal could be transmitted over about 1120 km SSMF (Fig. 10 green curve with inverted triangle markers). Taking into account the FEC overhead, this yields a net 3.3 Tb/s of data rate and spectral efficiency of 6.3 bits/s/Hz ($8*25/26.43/1.2$).

IV. CONCLUSION

We experimentally studied the BER performance using different strategies to optimize a RFS comb to support higher order modulation. The B2B BER results show that jointly optimizing the RF driving voltage and deploying a comb filter in the RFS comb significantly improves performance. This source provides high spectral efficiency and uniform performance across channels. This source is therefore particularly adapted to flexible networks for SDN, where each densely packed channel can be routed independently without balancing uneven performance. DP-Nyquist-16QAM was examined, and BER of all 20 channels are improved below low overhead FEC threshold in a B2B test. Distances as great as 1150 km SSMF can be achieved when using 20% FEC overhead, resulting in a net rate of 3.3 Tb/s and net spectral efficiency of 6.3 bit/s/Hz.

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