Experimental Demonstration of Optical Nyquist Generation of 32-Gbaud QPSK using a Comb-based Tunable Optical Tapped-Delay-Line FIR Filter

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Abstract: We experimentally demonstrate tunable optical Nyquist generation of 32Gbaud QPSK signals using optical tapped-delay line. Optical Nyquist spectra for different number of taps are shown, and 20% EVM and 2.8 dB OSNR penalty at BER of 1e-3 are measured.

OCIS codes: (060.2360) Fiber optics links and subsystems; (190.4223) Nonlinear Wave Mixing.

1. Introduction

Optical communication systems are ever-more interested in being efficient with the available spectrum, such that spectrally efficient data channels are of key interest.[1-3] In addition to higher-order modulation formats, the ability to form a data signal such that it occupies the minimum bandwidth possible, i.e., the Nyquist bandwidth, brings performance advantages.[4,5]

There have been several impressive reports of Nyquist channels in optical fiber communication systems.[3-9] Such demonstrations have typically used electronic signal processing to shape the data stream such that the data channel spectrum has a flat top and steeply sloping sides.[4,10,11] The electronic methods tend to operate in the time domain using tapped-delay-lines that produce a finite-impulse-response (FIR) filter.[4,10] However, the electronic approaches typically require a digital-to-analog converter (DAC) that operates at twice the baud rate, making it difficult.[4,11] Therefore, there might be motivation to perform the channel shaping optically in order to potentially enable a higher baud rate. There have been reports of optically generating a Nyquist channel using optical wavelength filtering techniques.[5,8,11,12] These optical filters tend to shape the Nyquist data channel by removing power at different frequencies. This is in contrast to tapped-delay-line FIR filters that shape the Nyquist data channel by redistributing the channel power into different frequency locations.[12] A laudable goal might be to tunably and optically generate a Nyquist data channel by operating in the time domain as does an FIR filter.

We experimentally demonstrate optical Nyquist channel generation of a 32-Gbaud QPSK signal using a comb-based tunable optical tapped-delay-line (OTDL) FIR filter. We use the frequency fingers of the optical frequency comb source as the OTDL taps. By using a wavelength dependent delay element, the signals are delayed and in one stage of nonlinearity, they are coherently multiplexed with taps. We experimentally generated an optical Nyquist QPSK signal at 32-Gbaud with error vector magnitude (EVM) of 20% by setting the Nyquist filter tap coefficients (11-taps). This result is also achieved for a 26-Gbaud QPSK signal, demonstrating the tunablity of this approach. We also achieved an optical signal to noise ratio (OSNR) penalty of ~2.8 dB at bit error rate (BER) of 1e-3.

2. Concept

Fig. 1(a) shows the concept of the Nyquist generation using an FIR filter. The input signal has Sinc (Sinc(x)=sin(x)/x) shape in frequency domain and rectangular pulse in time domain. When passed through a TDL-FIR Nyquist filter, this signal is converted to a Nyquist pulse which has rectangular shape in the frequency domain (Fig. 1(a)). Fig. 1(b) depicts optical Nyquist signal generation using a frequency comb based OTDL, in which the frequency comb fingers are modulated with a QPSK signal such that the number of taps is the number of fingers. These modulated fingers are sent through a chromatic dispersive element, *e.g.*, dispersion compensating fiber (DCF), to induce wavelength-dependent delays on the signal copies. The relative delay between two adjacent replicas can be obtained by $\Delta T = D\times\Delta\lambda$, where D is the dispersion parameter and $\Delta\lambda$ is the wavelength separation between two frequency fingers. To realize a Nyquist filter, the delay needs to be set to the half of symbol duration, *i.e.*, T/2. In this way, tap-delays can be continuously tuned by varying the frequency comb finger spacing or changing the length of the DCF. These delayed signals are equivalent to OTDL taps that need to be coherently combined. Tap weights are tuned using a spatial light modulator (SLM) to introduce arbitrary phase and amplitude on the fingers. The taps are multiplexedin a periodically poled lithium niobate (PPLN) waveguide with quasi-phase matching (QPM) frequency of f_{QPM}, in which each delayed signal at $f_{s,i}$ mixes with another finger of frequency comb source at $f_{D,i} = 2\times f_{QPM} - f_{s,i}$ through the sum-frequency-generation (SFG) process to create a signal at $2\times f_{QPM}$. Because all the signals and pumps are mutually coherent, all the generated signals at $2\times f_{QPM}$ are combined coherently. Another pump laser at f_{Pump} is injected into the PPLN waveguide for the difference-frequency generation (DFG) process to convert these signals onto f_{out} as the output of the FIR filter, which is analyzed by the optical spectrum analyzer and coherent receiver. To achieve the Nyquist shape signal at the output, we set the phase and amplitude of coherent pumps to the tap weights of a Nyquist filter.

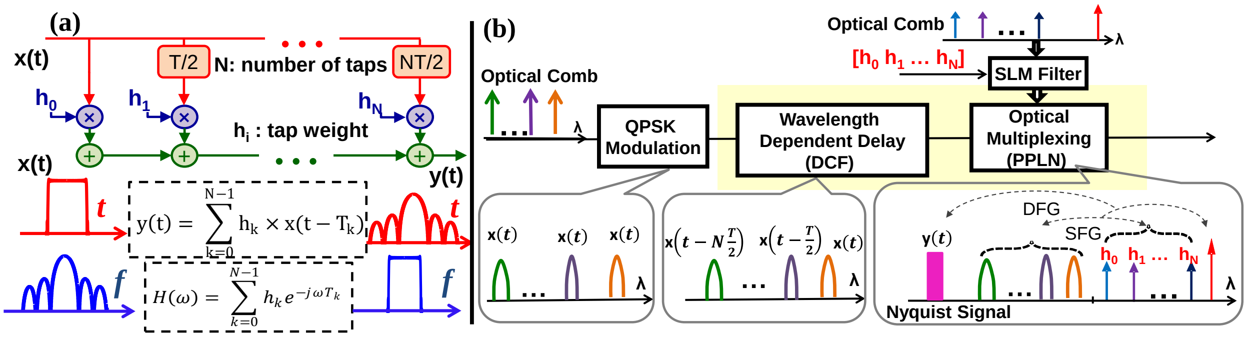

Fig. 1. (a) Concept of Nyquist FIR filter. (b) Concept of optical Nyquist generation using comb based OTDL (using optical comb as the taps of the FIR filter and utilizing DCF to delay the tapped signals and multiplexing the tapped delayed signals in a PPLN waveguide).

3. Experimental Setup

Fig. 2 shows the experimental setup for the optical Nyquist generation using a comb based tunable OTDL-FIR filter. A mode-locked laser with a 10GHz repetition rate and a 2ps pulse width generates a coherent frequency comb with a 10-GHz frequency spacing. The optical frequency comb is passed through a DLI with a free spectral range (FSR) of 20-GHz to increase the frequency spacing between the fingers. The resulting 20-GHz frequency comb is sent through a highly nonlinear fiber (HNLF) to generate a flat and broad spectrum (as shown). The SLM filter selects and writes complex weights on the comb fingers, and separates the path of the signals and coherent pumps. For each path, we select up to 11 comb fingers with a spacing of 0.965 nm. After pre-amplification, a nested Mach-Zehnder modulator generates the 64- Gb/s (and 52-Gb/s) QPSK data (PRBS 2^{31}-1) on the comb fingers. After being amplified in an erbium doped fiber amplifier (EDFA), the signals travel through a ~200 m (and 250 m) DCF to introduce one symbol time relative delay between adjacent signals. To increase stability, the amplified pumps from another path with another amplified continuous wave (CW) laser pump at ~1564 nm are also passed through the same DCF. All the signals and pumps are sent to a 4-cm-long PPLN waveguide to create the Nyquist signal with the spectrum shown. Fig 2 also shows the Nyquist shape signal, created by writing the tap coefficients on the coherent pumps. The QPM wavelength of the PPLN waveguide is temperature tuned to the wavelength of ~1550.5 nm. The output signal is filtered and sent to the optical spectrum analyzer and coherent receiver.

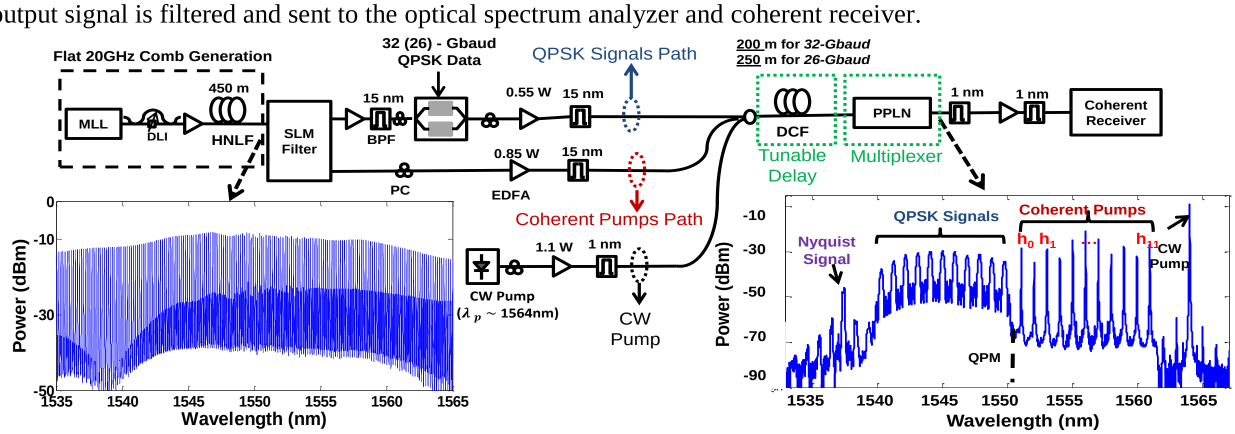

Fig. 2. Experimental setup. MLL: Mode Lock Laser, DLI: Delay Lin Interferometer, BPF: Band Pass Filter, PC: Polarization Controller,

4. Results and Discussion

Fig. 3 depicts the simulation and experimental results of optical Nyquist generation of QPSK signals using a comb based optical tapped-delay line FIR filter at 32 (and 26) Gbaud. Fig. 3(a) shows the simulation and experimental results for 32-Gbaud QPSK signals. The FIR Nyquist filter and the corresponding Nyquist signal for different number of taps are simulated. Moreover, the experimental results of the optical spectra of Nyquist filter and signal for the tap numbers are shown. The experimental results are in match with the simulation. We also implement a 26-Gbaud Nyquist QPSK signal generation in order to show the tunablity of the presented approach. We adjust the setup to 26-Gbaud signals by tuning the delay between the adjacent signals. The delay is tuned by substituting a 200-m DCF (for the 32-Gbaud experiment) with a 250-m DCF to achieve the particular half-symbol time delay between two adjacent signals with 0.965 nm spacing. Fig. 3(b) shows the simulation and experimental results of 26-Gbaud Nyquist filter and signal generation. As shown in Fig. 3, increasing the number of taps can shrink the generated signal bandwidth to the Nyquist bandwidth and flatten the top of the input signal. We also measured an EVM of 13% and 20% at 32-Gbaud, which correspond to the input QPSK signal and 11-taps Nyquist QPSK signal, respectively (Fig. 4(a)). Fig. 4(a) shows the BER curves for different number taps at different optical signal to noise ratios (OSNRs) for the 32-Gbaud QPSK signal. An OSNR penalty of 2.8 dB at BER of 1e-3 is achieved for 11-tap filter, compared to the back to back operation of the input signal. EVMs of 11.9% and 19% at 26-Gbaud are achieved for the input signal and the Nyquist output of 11-tap OTDL, respectively (Fig. 4(b)). The OSNR penalty of 2.6 dB at BER of 1e-3 is achieved for 11-taps Nyquist filtering at 26-Gbaud. Finally, Fig. 4(c) shows the OSNR penalty vs. number of taps, as well as spectral efficiency. We define the bandwidth (BW) efficiency as the bandwidth between the main ripples on the Nyquist signal spectrum divided by ideal Nyquist bandwidth. This figure shows the trade-off between the OSNR penalty and spectral efficiency of the presented Nyquist generation method.

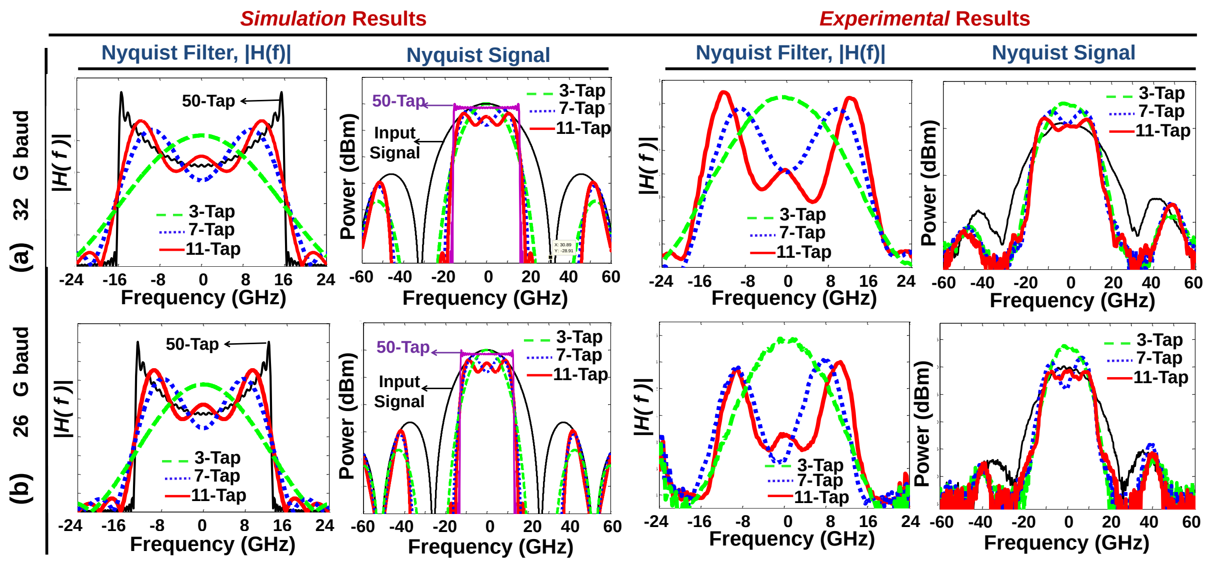

Fig. 3. Results of Nyquist filter shape, i.e., |H(f)|, and Nyquist signal spectrum for different number of taps at. (a) 32-Gbaud. (b) 26-Gbaud.

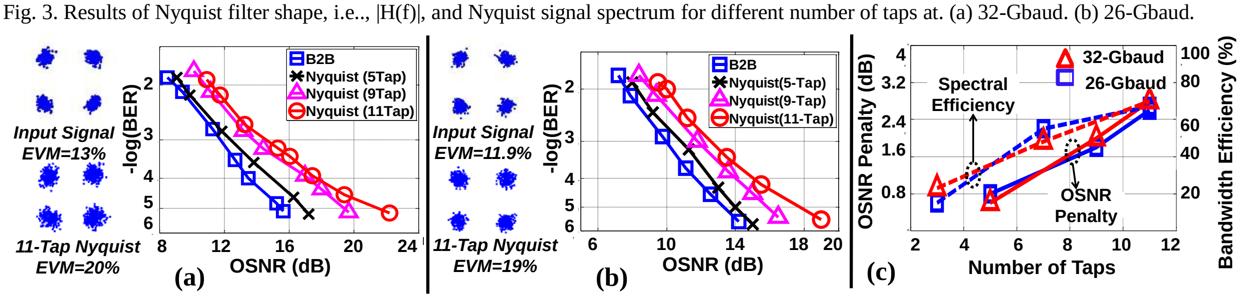

Fig. 4. ***Experimental*** results (a) EVM of input and output signal for 11-taps and BER measurements vs. OSNR of ***32-Gbaud*** QPSK signal. (b) EVM of input and output signal for 11-taps and BER measurements vs. OSNR of ***26-Gbaud*** QPSK signal (c) Measured OSNR penalty and bandwidth efficiency (percentage of bandwidth between two main ripples on obtained Nyquist signal over ideal Nyquist BW) vs. number of taps.

Acknowledgements

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