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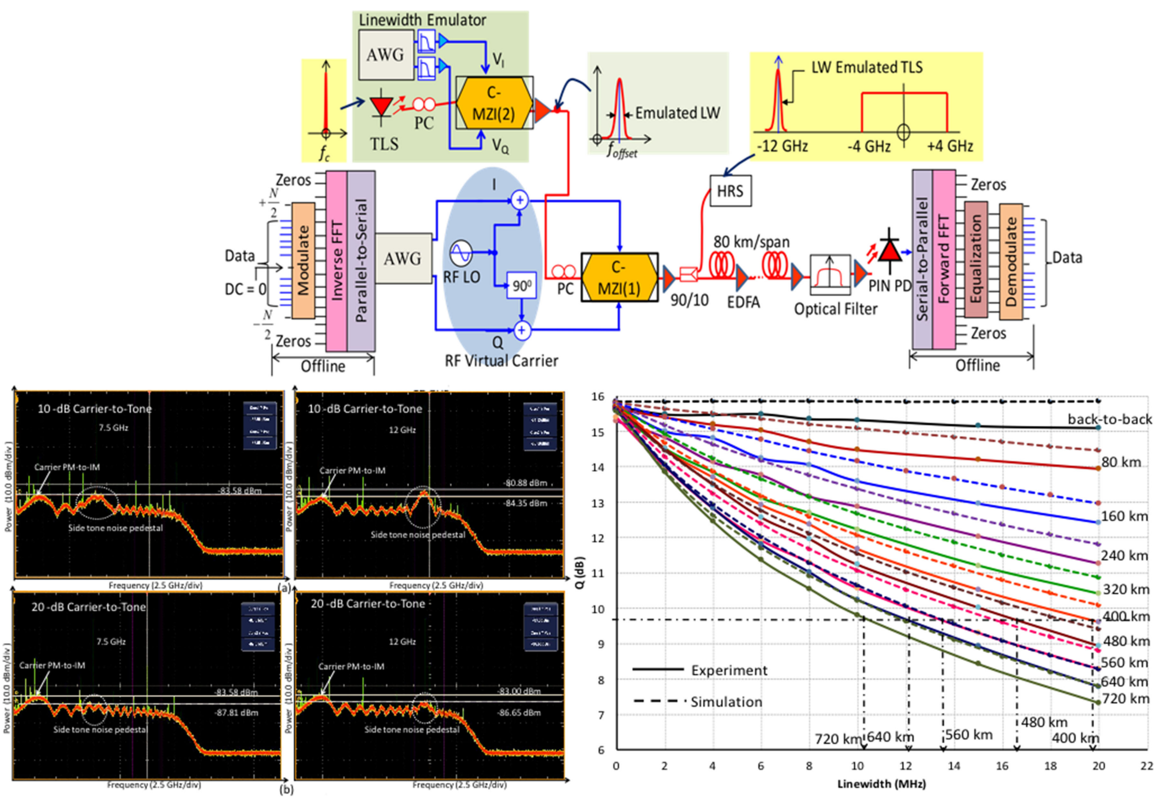

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Laser Phase Noise Tolerance in Direct Detection Optical OFDM Transmission Using Laser Linewidth Emulator

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Abstract: Laser phase noise tolerance in direct detection optical orthogonal frequency division multiplexing (OFDM) transmission system is experimentally demonstrated using laser linewidth emulator. With this linewidth emulator, the linewidth of the laser can be broadened independently without inducing other laser's noise characteristics such as relative intensity noise and chirping. The results show the effect of phase-to-intensity noise conversion due to the laser's phase noise and chromatic dispersion. This induces noise pedestals not only onto the optical carrier, but also to each of the subcarriers, and thus produces intersubcarriers interference. Measurements show 6 dB Q-degradation is suffered by the system when 10 MHz linewidth is used as compared to using narrowest emulator linewidth of 256 kHz. Transmission with the linewidth emulator set to 20 MHz is also shown where it can still be tolerated by 400 km of fiber at the Q of 9.606 dB with respect to 1.6×10^{-3} bit error rate. Simulation of 16 quadratic-amplitude modulation (QAM) (∼128 Gb/s) and 4 QAM (∼100 Gb/s) using VPItransmissionMaker are also presented to demonstrate the effect of carrier's phase-to-intensity noise conversion when a high data rate and wide OFDM signal bandwidth are used with the linewidth emulator as the system's laser source. The results show that a phase rotation term is insignificant for lower *M*-size QAM with fiber length less than 500 km. This presents the high effectiveness and reliability of the laser linewidth emulator to discretely determine an independent phase noise tolerance from the other laser's noise characteristics in the optical OFDM transmission system.

Index Terms: Laser linewidth, phase noise tolerance, optical OFDM, direct detection, linewidth emulator.

1. Introduction

The performance of many optical communication systems depends critically on the laser's noise characteristics [1]–[5]. The noise characteristics include the relative intensity noise (RIN), phase noise or linewidth and chirping which are inter-dependent with each other [6]. A typical way to vary the linewidth is by using the dependence of linewidth Δv, on the inverse of the laser's output power, $\Delta v = F(1/P)$ [7]. However, creating a wide linewidth requires operation at very low power and this causes a decrease in spectral purity such as the appearance of additional modes and a very high RIN resonance. Previously, we demonstrated a prototype of a flexible and stable laser linewidth emulator [8]. With this linewidth emulator, the linewidth can be dialed-up and varied independently of the other laser's noise characteristics. More specifically, the linewidth can be broadened without inducing the RIN and can be operated at high laser's output power, experimentally. With this linewidth emulator, an independent dialed-up linewidth laser can be achieved. The emulator enabled the linewidth to be adjusted over a range of 256 kHz to 150 MHz full-width half-maximum (FWHM). This allows the investigation of independent linewidth effects of the other noise characteristics in any optical system. The signals driven for the linewidth emulator can also be used to characterize the linearity of in-phase and quadrature (IQ) optical modulator. The linewidth emulator is also stable over many hours since the linewidth is generated digitally. This setup can be developed in a laboratory environment to test for an independent phase noise effect to the system by using the available external cavity laser source. The narrowest linewidth of the emulator will be determined by the linewidth of the external cavity laser used in the setup.

In this paper, laser linewidth emulator is used as a laser source to transmit an orthogonal frequency division multiplexing (OFDM) signal. The optical OFDM transmission system is a well-known potential candidate to accommodate the ever-increasing bandwidth demand. The OFDM modulation technique was first adapted into an optical transmission system for its provision of electronic dispersion compensation (EDC) technique [9]. Two major types of optical OFDM are proposed based on its receiver design, namely direct and coherent detections [9]–[11]. Since then, the optical OFDM system continues to capture high interests among researchers where many have reported on the transmission of high speed superchannels, real-time transmission, implementation in access networks and radio-over-fiber (RoF) [5], [12]–[15]. The optical OFDM system is known to be able to compensate for the effect of chromatic dispersion electronically using the assignment of cyclic prefix (CP) in the OFDM symbols. However, the effects of the chromatic dispersion cannot be entirely compensated with the CP when the signal is transmitted using a wide laser linewidth over a high total dispersion ($<$180 km). This is because of the laser's phase noise will be converted to an intensity noise due to the dispersion known as the phase-modulation to intensity-modulation (PM-to-IM) conversion noise [16]. The PM-to-IM conversion noise will impose a noise pedestal underneath each of the OFDM subcarrier. The OFDM symbols will also experience some phase rotation at the receiver which can be observed for the transmission of the OFDM signals using a wide linewidth and higher M-size than 4 QAM over a very long-haul transmission ($<$500 km) [17]. In coherent-detection, it is known that the system requires stringent linewidth requirement of the laser source. The system requires much narrower linewidth (in kilo-hertz) than the direct-detection system [18]. This is because a new free-running laser source that acts as a local oscillator is required at the receiver to tract the phase variation of the received signal [1], [10], [18], [19]. On the other hand, the direct-detection system is also limited by the linewidth of the laser source due to the conversion noise. A wide linewidth (in mega-hertz) laser is usually used to generate the carrier of the system [20]–[22], [24]. With the dispersion, the conversion noise originated from the carrier will be imposed onto each of the subcarriers since the carrier is transmitted together with the subcarriers in direct-detection system.

An experimental investigation on the effect of the laser linewidth will involve the purchase of sets of lasers with different linewidth characteristics or by driving a distributed-feedback laser (DFB) with different biasing currents. The second method however will also induce other noise characteristics. For example, a low-biasing current supplied to the DFB laser will also induce high RIN. Thus, an independent effect of linewidth from the other noise characteristics cannot be investigated with the normal off-the-shelf laser source.

In this paper, we demonstrate the use of laser linewidth emulator to investigate the tolerance of phase noise in a direct detection optical OFDM system. With the laser linewidth emulator, the effects of the linewidth or phase noise to the optical OFDM system's performance can be investigated experimentally thus, the requirement of multiple laser sources with different linewidth characteristics can be eliminated. With a single narrow-linewidth laser source, the effects of phase noise to a system can be studied by using this linewidth emulator. In this experiment, the effect from an amplified spontaneous emission (ASE) noise was also limited with the use of a programmable optical filter at the receiver input. This paper presents the phase noise tolerance of the

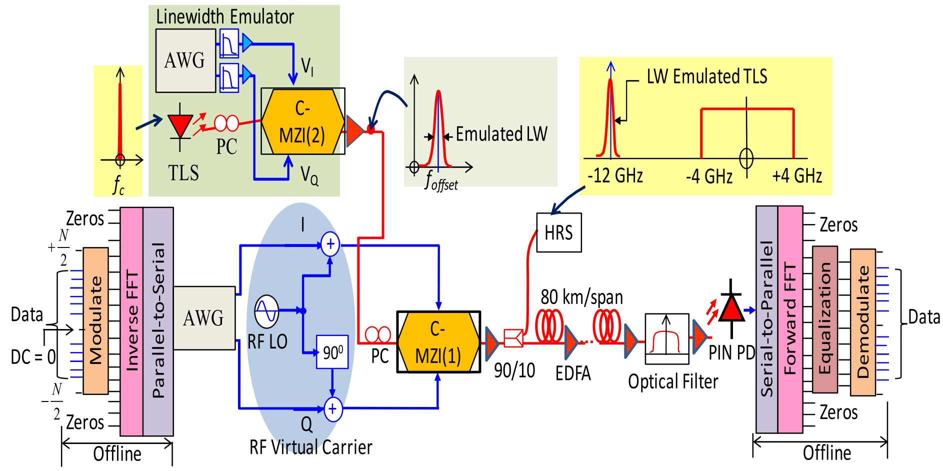


Fig. 1. Experimental setup of laser linewidth emulator to transmit optical OFDM signal.

direct-detection optical OFDM system for up to 20 MHz linewidth without inducing RIN. This enables an independent investigation on the laser linewidth effects from the other laser's noise characteristic in a dispersive optical OFDM transmission system. The details of the linewidth emulator setup are also presented which can be performed on any system-under-study in a laboratory.

2. Experimental Setup

As presented in [8], a laser linewidth emulator phase modulates the output of a narrow linewidth laser to broaden its linewidth, Δv. The modulating signal is a digitally-generated phase modulation with phase, θ_n, at sample time, $n.\Delta T$. The phase will be updated at every time step, ΔT. The change of the phase per time step, $\theta_n - \theta_{n-1}$ is a Gaussian random variable with a variance $\sigma^2 = 2\pi \Delta v \Delta T$.

Fig. 1 illustrates the experimental setup of a direct-detection optical OFDM (DDO-OFDM) transmission system using a laser linewidth emulator shown in the green-inset. In this setup, an RF virtual-carrier technique is used to represent the optical carrier [20], [21]. The virtual carrier is generated using a Hewlett Packard 83620A synthesized sweeper tuned to 12 GHz to provide an 8-GHz guard-band between the carrier and the subcarriers.

A similar guard-band width with the subcarriers signal band is required to allocate the subcarrier $\times$ subcarrier beating when the signal is detected at a photodiode [22]. This lower sideband optical carrier is generated by adding the RF tone to the inphase (I) and quadrature (Q) drives [19], [20]. The upper sideband of the virtual carrier is completely cancelled out using a 90° phase shift. This technique provides a flexible way to sweep the carrier across the transmitted bandwidth to provide more signal bandwidth and to increase or decrease the guard-band. Also, this technique provides the flexibility of varying a carrier-to-signal power ratio by tuning the RF tone's power with the sweeper. Apart from using the virtual carrier technique at the transmitter, a shifted optical carrier can also be generated by using a subcarrier assigned at the negative fast-Fourier transform (FFT)-side [22]. However, this technique will provide a lower signal bandwidth compared to the virtual carrier technique since only the positive FFT-side can be used as the data carrying subcarriers.

The OFDM signal is generated offline using MATLAB. For this setup, the OFDM subcarriers at both positive and negative sides of the inverse-FFT points are used to carry the data. 410 subcarriers are used for the data transmission out from the total of 512 FFT points, giving an 8-GHz OFDM signal bandwidth ($\pm$4 GHz). A cyclic prefix (CP) composed of 128 subcarriers is taken at the end of the OFDM symbol and copied to the front of the symbol which gives 25% overhead. This is sufficient to compensate for the power leak into the adjacent subcarriers causing the inter-carrier interference (ICI) and into the adjacent OFDM symbols causing the inter-symbol interference due to the chromatic dispersion [9]. No data is assigned at the DC point as this will be for the optical carrier generated from the laser linewidth emulator. The data is then multiplied with a pre-emphasis data set to compensate for optical modulator's frequency response. After the iFFT, the I and Q signals are converted into serial configuration and loaded into a Tektronix 7102 Arbitrary Waveform Generator (AWG) operated at $2 \times 10\,\text{GS/s}$ as the digital to analogue converter (DAC). This gives an approximate transmission data rate of 16.02 Gb/s. The outputs of the AWG are amplified using Marki Microwave AP-0020 5-MHz to 20-GHz amplifiers before driving a 40 Gb/s Sumitomo T-SBXI.5-20P modulator as a complex-Mach Zehnder Interferometer marked as C-MZI(1). The C-MZI(1) is biased at null to completely suppressed the DC. The transmission of a low-data rate in this work is due to the limited number of the available AWG and its sampling rate. A high data rate of a hundred giga-bit per second can be achieved if there are two AWGs with considerably higher sampling rate than the 10 GS/s. For example, ~100 Gb/s transmission can be achieved using 4 QAM with two AWGs in which each AWG is operated at 50 GS/s using the interleave output. The two AWGs need to be synchronized so that each AWG will output the electrical I and Q signals as presented in [19]. Nevertheless, the transmission at this low-rate can still present the application of the linewidth emulator into the DDO-OFDM system to investigate the impact of an independent phase noise from the other laser's noise characteristics, experimentally.

The optical input to drive C-MZI(1) is from the output of the linewidth emulator shown in the green-inset. Similar to a typical transmission setup, the output from the linewidth emulator is connected to a polarization controller (PC) before driving the C-MZI(1). For the linewidth emulator setup, a C-MZI (marked as C-MZI(2)) is also required because a $LiNbO_3$ phase modulator has a limitation in its modulation which sets by the limits of its drive voltage [8]. A tunable laser source (TLS) by Photonetics Tunics External Cavity Laser (ECL) is used to drive the C-MZI(2). The TLS is tuned to 193.0 THz with a 256-kHz linewidth. Signals to emulate the TLS; V_I and V_Q are generated using VPItransmissionMaker and uploaded into an AWG. The signals are 52.4288 μs long and the AWG repeated them continuously every T_{AWG}. The outputs of the AWG are connected to a 5 GHz low-pass filter to filter out an image spectrum before driving the inputs of the C-MZI(2). The output of the TLS is frequency shifted by 3 GHz to a new center frequency, f_{shift}. This frequency shifted is compulsory for this setup due to the usage of DC-blocked RF amplifiers. With the C-MZI, the frequency shift of 3 GHz can be imposed on the emulated laser's output by applying a continuously increasing phase shift defined as follows;

$$V_{I,n} = k\cos(\theta_n + 2\pi\Delta fn\Delta T) \quad \text{and} \quad V_{Q,n} = k\sin\,(\theta_n + 2\pi\Delta fn\Delta T) \tag{1}$$

where k is the drive amplitude of the V_I and V_Q. The DC voltage biases are supplied to the upper- and lower-MZIs in the nested-configuration of the C-MZI to ensure that each is biased at null and the output of the upper- and lower-MZIs are in quadrature [8]. The drive amplitude, k of the RF signals need to be much lower than V_π of the C-MZI to avoid driving the modulator into its nonlinear region ($k = V_\pi$) [8]. In this experiment, k is 1.35 V and V_π is 5.6 V.

The transmitted optical OFDM signal is shown in the yellow-inset where the laser linewidth emulated carrier is spaced by 8 GHz away from the signal band from −4- to +4-GHz. This is easily done by tuning the sweeper to 12 GHz in the virtual carrier setup. The signal is amplified using a LightWave 2020 erbium doped fiber amplifier (EDFA) and connected to a 90/10 3-dB coupler. The 90% coupler's output is connected through the first 80-km standard SMF while the 10% output is connected into an Agilent high-resolution spectrophotometer (HRS) to monitor the DC biasing of the C-MZI(2) for the linewidth emulator and the C-MZI(1) for the OFDM signal modulation. This is convenient since both of the C-MZIs' biasing can be monitored at the same port. The output of the laser linewidth emulator can be measured by turning off the AWG's outputs into the C-MZI(1) with biasing supplied to it. To transmit the OFDM signals, the AWG's outputs into the C-MZI(1) are turned on with the RF virtual carrier added to the I and Q signals. For the virtual carrier technique, the suppression of the upper sideband relative to the lower sideband is also monitored. At least 20-dB suppression is required for this technique to work effectively [20].

In this experiment, the optical OFDM signal is transmitted over 720 km, with an amplification at every 80 km of the fiber span using the LightWave 2020 EDFAs and received with a direct-detection receiver. The optical signal-to-noise ratio (OSNR) is maintained at around 20 dB in which 7.5 dB

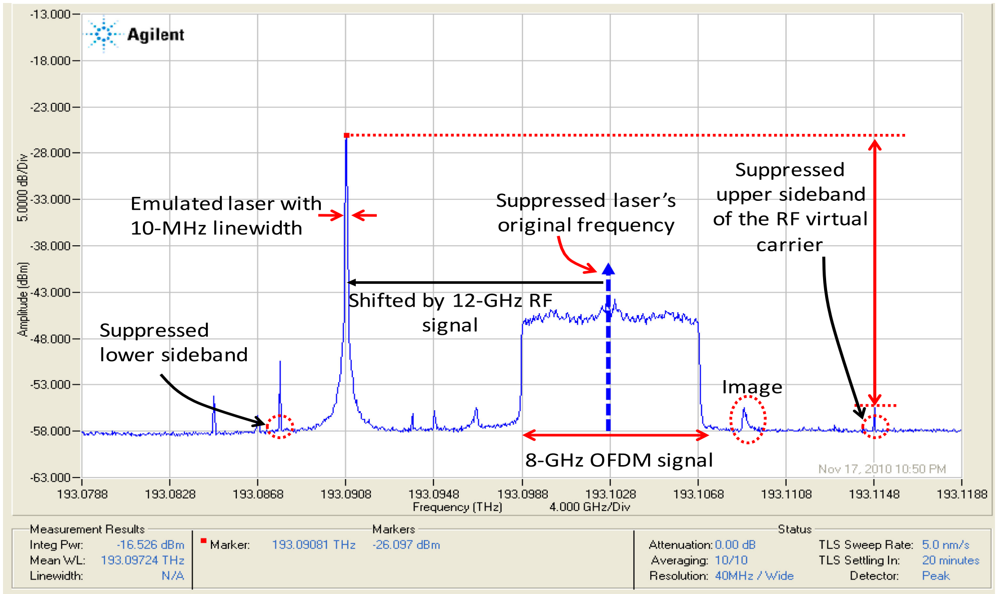


Fig. 2. Measured transmit optical OFDM signal using 10-MHz dialed laser linewidth emulator.

more than the minimum requirement for 4 QAM with respect to BER of 1×10^{-3} presented in [21]. The OSNR measurement is done using an Agilent 86142b optical spectrum analyzer at 0.1 nm resolution. A Finisar Waveshaper optical filter is programmed to operate as an optical bandpass filter with a 30-GHz bandwidth and applied before the receiver to limit the effect of an amplified spontaneous emission (ASE) noise. The received electrical signal is captured using a Tektronix 72004 20-GHz 50-GSa/s digital sampling oscilloscope (DSO). The captured signal is then down-converted and equalized offline using MATLAB.

3. Results and Discussion

Signal at a 10% output of a 90/10 3-dB coupler is measured using HRS where DC-biases for both C-MZIs are monitored. The measured spectrum is the signal with virtual carrier and OFDM signal using linewidth emulator as the original laser source.

Fig. 2 shows a spectrum of the suppressed original frequency of the laser linewidth emulator that drives the C-MZM(1). A virtual carrier is added and shifted away from the original frequency to have a guard-band equal to the OFDM signal band. The shifted carrier linewidth is broadened from its original linewidth of 256-kHz TLS into a 10-MHz emulated laser linewidth. This shows the linewidth emulator also works for the shifted virtual carrier. A 28-dB suppression of the upper sideband of the RF virtual carrier is also achieved with 90° phase shift of the RF tone added to the Q signal.

Fig. 3 shows the effects when improper DC-biasing voltage is applied to the C-MZI(2) of the laser linewidth emulator, which is commonly known as a DC-leakage. This is due to the instability of the C-MZI's transfer function over its operating time. As a result, it is required to monitor the biasing voltage drift of the C-MZI to ensure that it is operated at null and completely suppress the laser's original center frequency. When the C-MZI is not properly biased, a tone can appear in the transmit optical spectrum as shown in Fig. 3. This high-power tone can be seen to also carrying its signal bandwidth where 3-GHz of it can be seen in the guard band, while the other 5 GHz falls within the desired signal band. This will cause interference between the unwanted leaking signal band and the desired signal hence reducing the performance of the first 5 GHz subcarriers.

Fig. 4 shows the received signal captured using DSO. It shows the received OFDM RF waveform signal and its FFT spectrum after 720 km transmission with the laser linewidth emulator set to 20 MHz. The waveform shows two received signal blocks, where the second block represents the

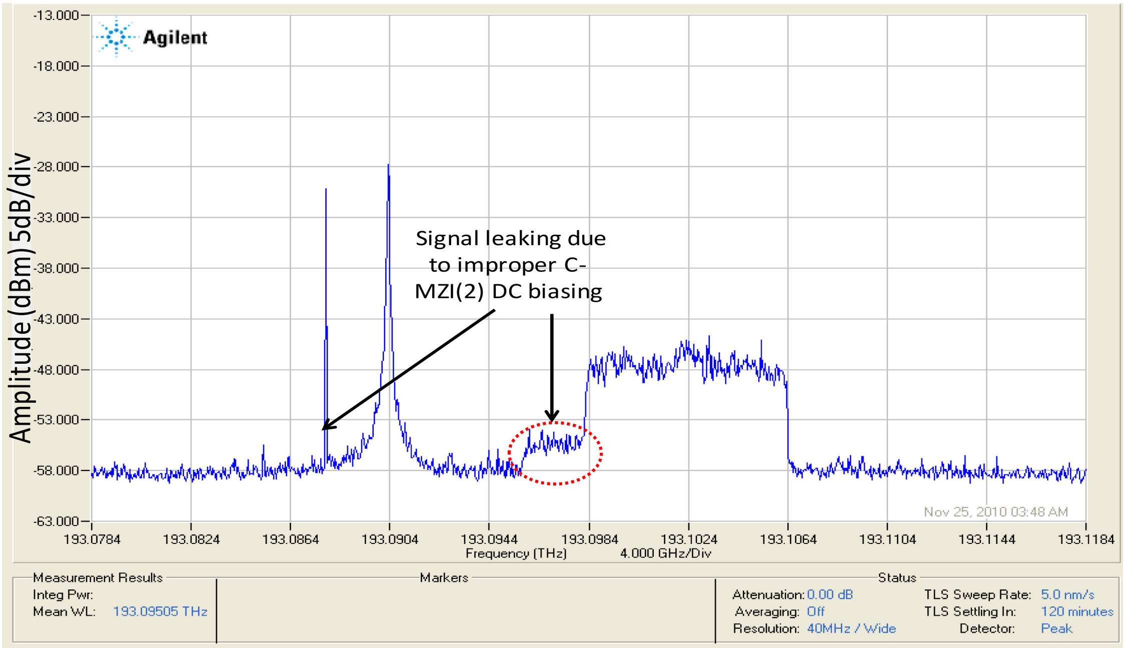


Fig. 3. Measured spectrum at 10% output of 90/10 coupler with signal leakage due to improper DC biasing to the CMZI(2).

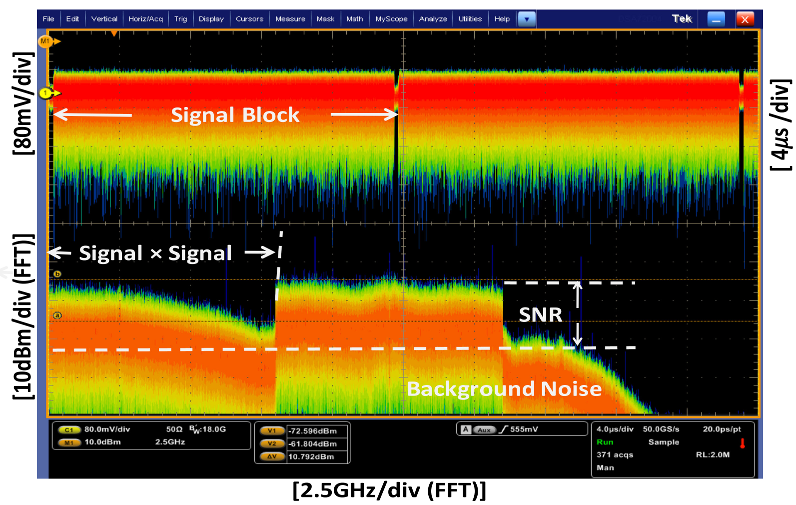


Fig. 4. Measured electrical spectrum showing the signal waveform and its FFT spectrum when the signal detected at the photodiode after 720 km transmission using 20 MHz linewidth emulator.

repetition of the signal block. The FFT-spectrum shows the subcarrier × subcarrier beating noise falls on the guard-band and gives a considerably flat response across the subcarriers. The SNR of the received signal can be estimated from the FFT spectrum in which for this signal, the measured SNR is 10.8 dB.

Fig. 5 shows the constellations after the received signals are equalized and QAM demodulated using the offline signal processing. These constellations are plotted for the transmission over back-to-back, 240 km, 400 km and 720 km fiber length with 20 MHz linewidth set to the laser linewidth emulator. The symbols mapped on the constellation show a circular distribution shape in each quadrant. This even circular Gaussian distribution constellation suggests the effect of the PM-to-IM conversion noise due to the fiber dispersion [16], [17]. No phase rotation can be seen from the

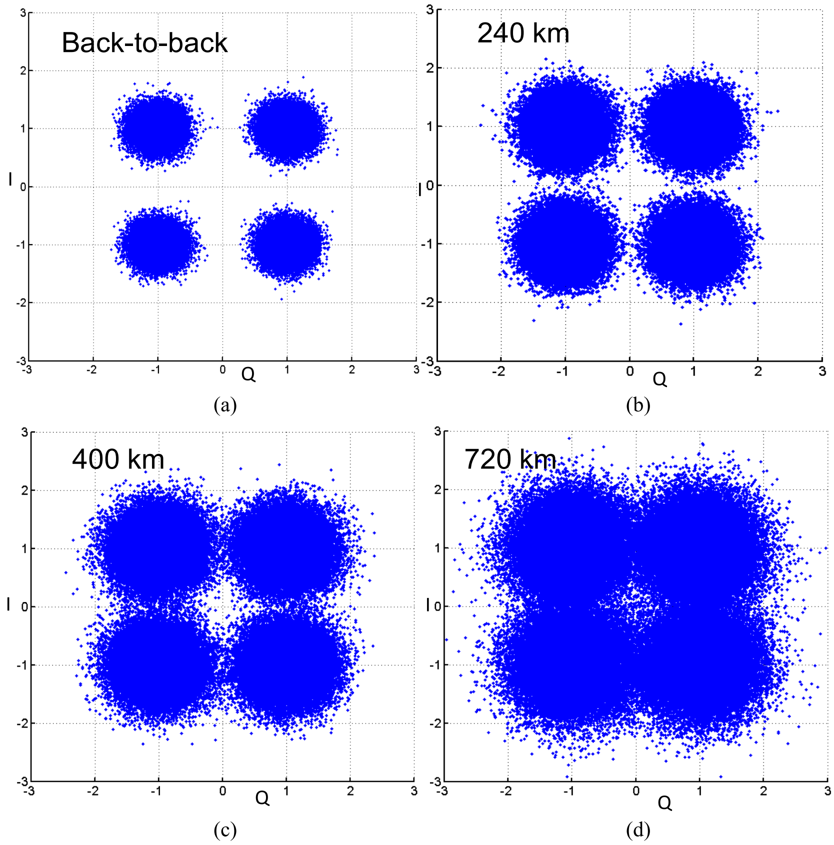


Fig. 5. Received constellation plots for DDO-OFDM transmission over (a) Back-to-back (b) 240 km (c) 400 km and (d) 720 km with linewidth emulator set to 20 MHz.

constellation as low *M*-size QAM is used and the phase rotation is severe for higher *M* is and a very long fiber transmission as reported in [17].

Fig. 6 shows the Q-factor versus linewidth when the signal is received with a DDO receiver for a back-to-back to 720 km, where it is amplified at every 80 km of fiber span. The full- and dotted-lines represent the experimental and simulation results, respectively. Results for back-to-back show stable Q performance between 15.4 to 15.9 dB which resembles no effect of linewidth, even for the transmission using a wide linewidth of 20 MHz. Note that, the 0 MHz linewidth for the experiment is subjected to the original TLS linewidth used in the emulator setup of 256 kHz. The simulation is developed to mimic the real experiment in which a continuous wave laser module (CW Laser) with 256 kHz is used. The constant Q for the back-to-back transmission shows that the linewidth emulator produced an independent phase noise. The back-to-back Q measurement also shows that the system performance will not be affected by the independent-phase noise without any dispersion.

When chromatic dispersion is applied using a standard SMF, the Q performance started to deteriorate for every additional 80-km span of fiber. This is due to the PM-to-IM noise [16]. For a 4 QAM DDO-OFDM system, the Q of 9.8 dB is required to achieve a BER of 1×10^{-3}. A dotted-line of Q equals to 9.8 dB to achieve the BER of 1×10^{-3} for the 4-QAM is drawn to cross the curves. The tolerance of the phase noise to the DDO-OFDM transmission is shown for the transmission of 80- to- 320-km of fiber where the system can tolerate the laser linewidth of wider than 20 MHz. From the experimental results, it can be observed that the system can still tolerate the linewidth of a little more than 10 MHz for 720 km. Significant degradation of 6-dB can be seen when 10-MHz of linewidth is used throughout 720 km as compared to using 256 kHz of the emulator's narrowest linewidth. Overall, the simulation results show a relatively good agreement with the experimental

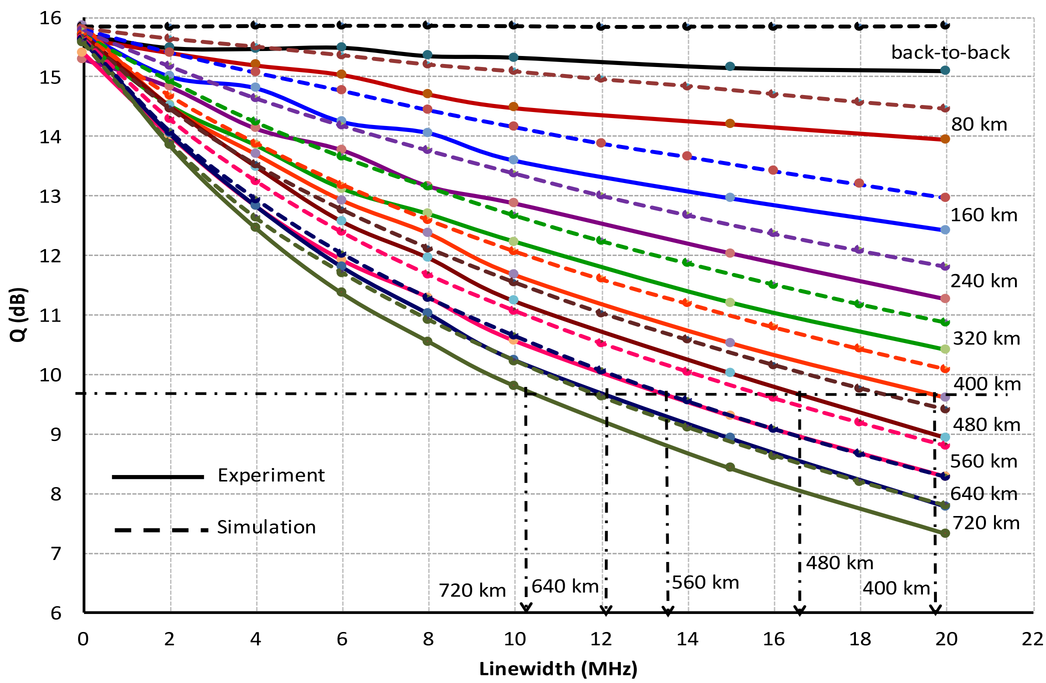


Fig. 6. Q-factor versus emulated laser linewidth for 4-QAM transmission from back-to-back to 720 km fiber.

results, in which 0.6 dB difference is shown between the two. The discrepancies between the simulation and experimental results are due to the additional noise in the real experimental setup due to the dc leakages of the two C-MZIs. This on the other hand is not appear in the simulation results. Furthermore, high extinction ratio of the MZIs to construct the C-MZIs are used in the simulation which prevent dc leakages in the simulation setup.

When transmitting the signal using a wide linewidth, a typical laser source will also produce high RIN and low laser output power. This is because of the RIN is inversely proportional to the power-cubed (RIN $\propto \frac{1}{P^3}$) and linewidth is inversely proportional to the power (LW $\propto \frac{1}{P}$). This high RIN and low laser power will reduce the performance of the transmission system even for the back-to-back and in a simulation for a zero-linewidth due to the addition of intensity noise to the system. This was presented in [24] where the Q was imposed with 5-dB degradation when using a zero-linewidth laser but with the increased of RIN from -150 dB/Hz to -105 dB/Hz. The curves plotted in [24] showed the changes of the Q versus linewidth for the transmission of 320-km with respect to the lowest RIN which gradually fit the curve for the 320-km in Fig. 6.

Fig. 7 shows the effects of the laser linewidth emulator phase noise with chromatic dispersion across the OFDM signal bandwidth from the frequency of 8- to 16-GHz. The linewidth emulator's center frequency is at 0 Hz where it is spaced at 8-GHz away from the lowest subcarrier frequency. The linewidth emulator in this measurement is set to 20 MHz. The measurements are taken at every 80 km of the fiber span. For a back-to-back and short fiber length of 80 km, the overall Q performance is degraded due to the frequency separation of the bandgap that is equal to the OFDM signal bandwidth between the carrier to the subcarriers. This means that, if the subcarriers can be placed down to the 0-Hz of the carrier, no dispersion effect is expected at the subcarriers. A lower Q of 1.5 dB at the first 3-GHz bandwidth of the signal bandwidth for the back-to-back is due to some leakage of DC of the C-MZM(2) as well as the background noise of the oscilloscope. The graph shows that the higher frequency subcarriers started to deteriorate for the transmission of 180 km and longer with the linewidth of 20 MHz. A significant reduction in the Q across the subcarriers from the low to the highest subcarriers frequency can be seen for the fiber length of 320 to 720 km. This is

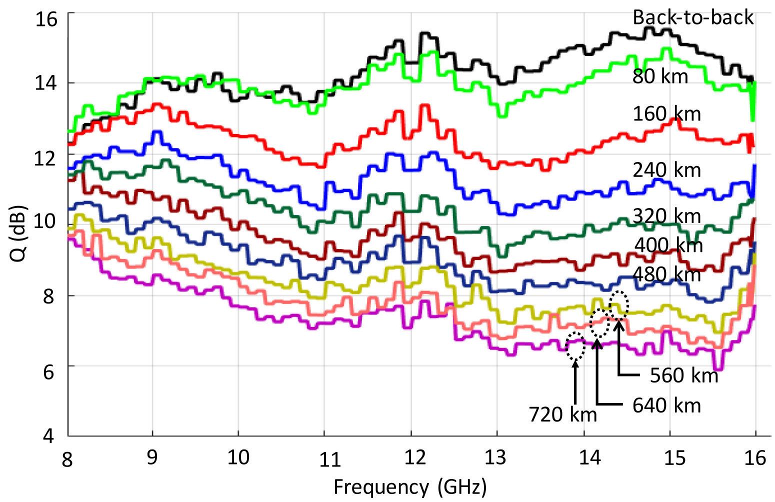
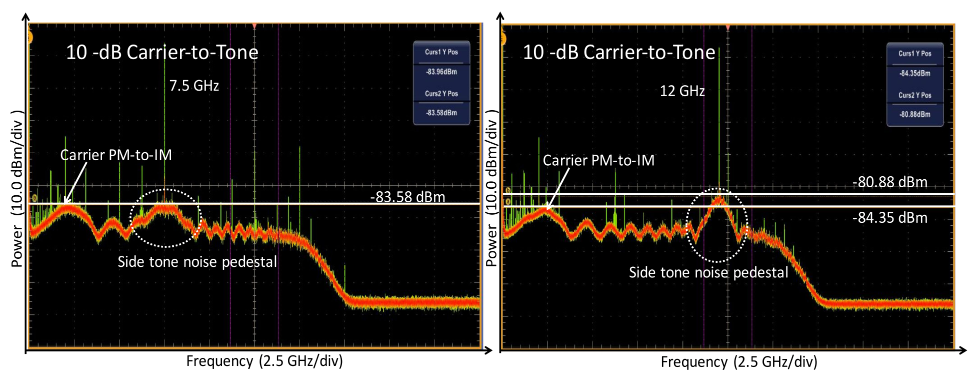
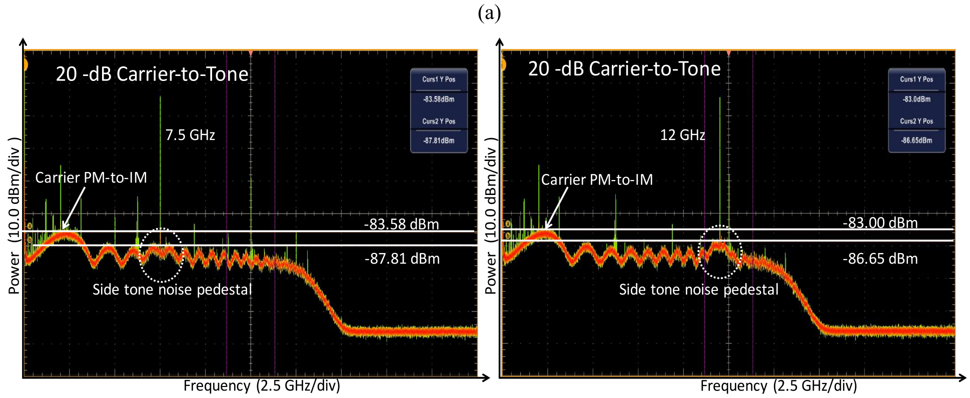


Fig. 7. Effect of chromatic dispersion to OFDM subcarriers using 20 MHz laser linewidth emulator.



(a)



(b)

Fig. 8. Measured RF spectra with RF tones at 7.5- and 12-GHz for (a) 10-dB and (b) 20-dB carrier-to-tone power ratio after 500 km transmission using laser linewidth of 10 MHz.

due to the PM-to-IM conversion noise of the laser's phase noise with the chromatic dispersion. The conversion noise produces noise pedestal not just to the optical carrier but also underneath each of the subcarriers. This can be shown with the transmission of single tone at 7.5- and 12.5-GHz with laser linewidth of 10 MHz.

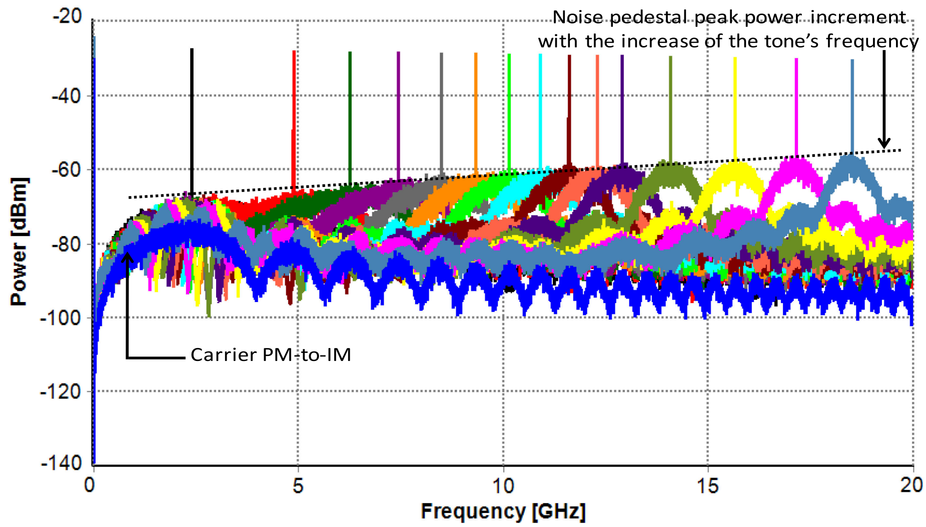
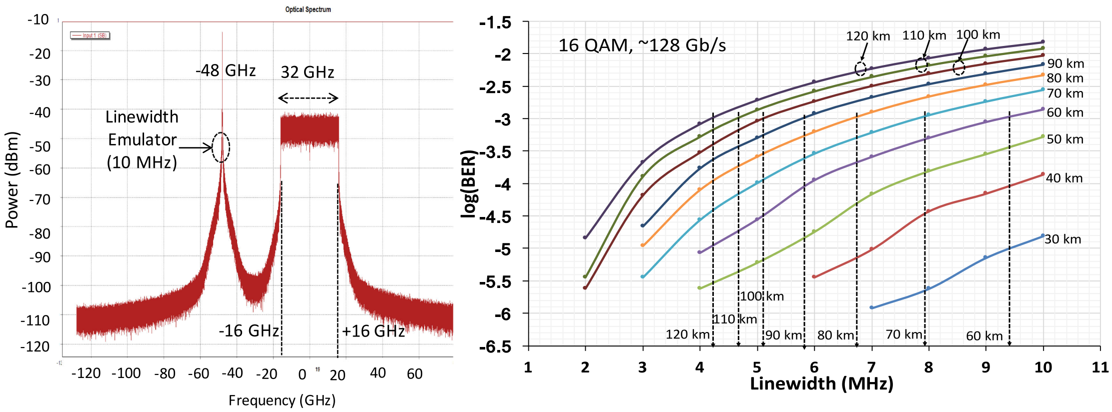


Fig. 9. Simulated spectra of a single RF tone originated from a carrier with 100 MHz laser linewidth across 20 GHz bandwidth over 500 km dispersive fiber.

Fig. 8 shows the received RF spectra when an RF tone is originated from a laser source with a linewidth of 10 MHz and transmitted over a 500 km of fiber. The tone is generated using an RF signal generator where a 90° phase shifter is used for the Q signal and modulated with a laser source using a complex modulator. This allows flexible sweeping of the frequency across the bandwidth and controlling the power difference between the carrier and the RF tone. The measured spectra show the carrier's PM-to-IM conversion noise pedestal with the first null frequency of 3.75 GHz and the noise pedestal imposed to the tone. Fig. 8(a) shows that the higher noise pedestal is imposed to the higher frequency tone of 12.5 GHz compared to the tone at 7.5 GHz. Fig. 8 also shows that the carrier power also contributed to the noise pedestal where higher carrier power will impose lower noise pedestal power of 4.23 dB for the 7.5 GHz and 5.77 dB for the 12 GHz tones. Note that the carrier-to-tone power is controlled by the tone's power by simply tuning the power of the RF signal generator. The power of the laser cannot be increased as it will also cause the narrowing of its linewidth. The noise pedestals show that in a transmission system where the RF tones or the subcarriers are originated from the same laser and transmitted over a dispersive fiber, there is a strong phase correlation between the carrier and the RF tones. This permits the use of a direct-detection receiver design with single photo-detection. However, the signal propagation over the dispersive fiber can induce some time-delay upon photo-detection which causes relative delay of the subcarriers to the carrier due to group velocity dispersion (GVD). This will de-correlate the phase of the RF tones relative to the carrier and each of the subcarriers will experience a different time delay, τ_d relative to the carrier. The effect of this phase de-correlation has been demonstrated in [25] through their linewidth measurement technique.

Fig. 9 shows the simulated spectra of a single RF tone modulated using a wide linewidth laser of 100 MHz and the frequency, f_{shift} is swept across a 20 GHz bandwidth and transmitted over 500 km of dispersive fiber. This simulation is done using VPItransmissionMaker version 9.1. PM-to-IM conversion noise sidelobes of an unmodulated carrier is also shown. For the same tone power, more than 10 dB increment of a noise pedestal power can be seen from the lowest frequency tone up to the highest. This explains the low response of Q at the high-frequencies subcarriers showed in Fig. 7 which suggests that the effects of PM-to-IM conversion noise can be greatly reduced if the subcarriers are made closer to the carrier and is realigned to compensate for the τ_d of each of the subcarriers. A simple technique for this has been shown in [26], [27]. However, for a true direct-detection transmission system, this will involve complex computation in DSP.



(a) (b)

Fig. 10. ∼128 Gb/s transmission using 16 QAM over 32 GHz signal bandwidth (a) Optical signal spectrum (b) log(BER) versus emulated laser linewidth.

Fig. 10 shows the results of a ∼128 Gb/s DDO-OFDM transmission using 16 QAM over 32 GHz signal bandwidth. The same setup as in Fig. 1 is used to present a high data rate transmission using laser linewidth emulator and to show the effect of phase noise to the system. The DDO-OFDM transmission is used over coherent-detection to present the effect of the subcarriers' phase walk-off relative to the carrier due to the GVD. This effect cannot be demonstrated using the coherent detection because the carrier is filtered out after the complex optical modulation, where the subcarriers are transmitted throughout the optical fiber without the carrier. Hence, there are no phase correlation between the carrier and the subcarriers at the receiver where it requires a free-running laser source as a local oscillator and a phase-locked loop to track the received signal [10], [11]. Furthermore, it is known that the coherent system requires a narrow linewidth laser, hence, developing such a system to demonstrate the use of the laser linewidth emulator may not be suitable. Fig. 10(a) shows the spectrum with the linewidth emulator set to 10 MHz. The 32 GHz RF signal bandwidth can be achieved using two DACs to drive C-MZI's RF inputs where each is operated at 32 GS/s. The output channels of these DACs can be taken at the interleave outputs considering a real experimental setup for a virtual carrier. In this simulation, the virtual carrier is used to obtain the 32 GHz bandwidth with a 48 GHz RF frequency synthesizer [19], [20]. The setup producing the 32 GHz RF signal bandwidth with the 48 GHz frequency synthesizer is developed to suit the equipment availability in the market. Fig. 10(b) shows $\log_{10}$(BER) versus linewidth when the signal is transmitted over 30- to 120-km standard-SMF. Apart from the higher data rate than 4 QAM, the 16 QAM is also used to investigate the effects of the phase noise using the linewidth emulator when a higher-*M*-size QAM is used. An OSNR of 45 dB is used to support the transmission of 16 QAM (∼128 Gb/s) which produced 1×10^{-3} at 120 km. This OSNR is used to evaluate the 16 QAM's system performance over a high total dispersion for such high data rate and variable linewidth. In [28], 30 dB OSNR was used to transmit 16 QAM, 40 Gb/s using 0.1 MHz linewidth for 20 km. The plot in Fig. 10(b) shows that 4.2 MHz of linewidth can be used to transmit the 16 QAM signal at 120 km and 60 km transmission of this high data rate is possible using 9.6 MHz linewidth where BER of 1×10^{-3} is obtained.

Fig. 11 shows the constellation plots and the SNR/bit versus subcarrier frequency for the transmission of (a) 16 QAM with 32 GHz signal bandwidth (∼128 Gb/s) over 120 km and (b) 4 QAM with 50 GHz signal bandwidth (∼100 Gb/s) both at the BER of 1×10^{-3}. Both constellations show Gaussian distribution of symbols. A slight tilt on the phase can be seen in the 4 QAM constellation plot with wide linewidth emulator of 10 MHz. 5 dB SNR/bit degradation can be seen from the lowest to highest frequency subcarriers for the 16 QAM transmission and 4 dB for the 4 QAM. This significant degradation clearly shows the effect of phase walk-off due to the PM-to-IM conversion noise in which the highest frequency subcarriers (the subcarriers that are far away relative to the

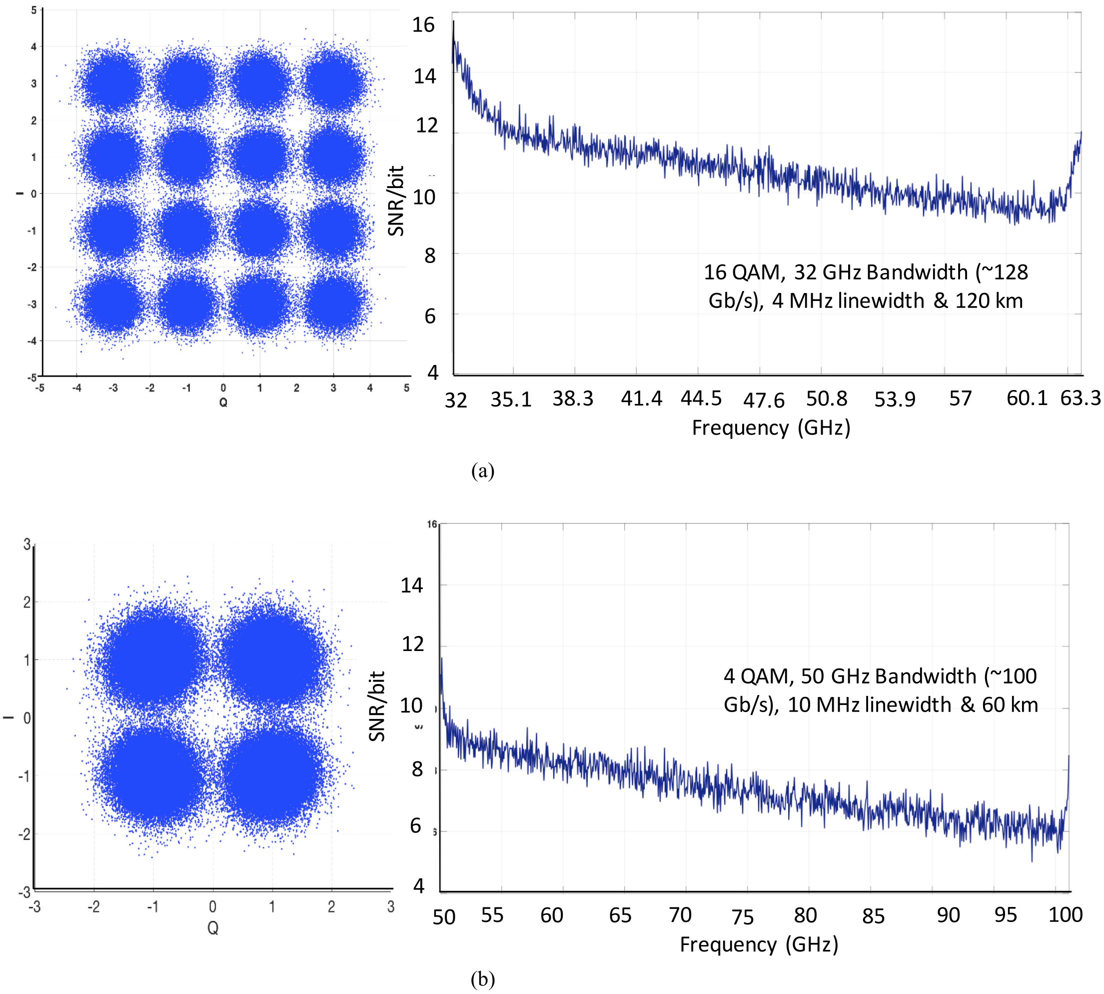


Fig. 11. Constellation plots and SNR/bit versus subcarriers frequency for (a) 16 QAM with 32 GHz signal bandwidth (∼128 Gb/s) over 120 km using 4 MHz linewidth and (b) 4 QAM with 50 GHz signal bandwidth (∼100 Gb/s) over 60 km using 10 MHz linewidth emulator.

carrier) suffer more from the conversion noise. This is due to the high intensity of the noise pedestal imposed onto the high frequency subcarriers as shown in Fig. 9. This also demonstrates that the linewidth emulator can be reliably used to investigate the effect of the phase noise to this system. The Gaussian distribution of the symbols on the constellation plots confirmed that the PRT is not a major issue in direct detection as reported in [17] for short fiber length of less than 500 km.

4. Conclusion

We have experimentally demonstrated the laser phase noise tolerance of a direct detection optical OFDM transmission over a back-to-back to 720 km using a tunable laser linewidth emulator. The linewidth is tuned from 2- to 20-MHz in which a linewidth broadening that is independent of the other noise characteristics can be achieved. With this linewidth, the tolerance of the laser phase noise to the transmission system can be investigated, experimentally. The result showed that Q is degraded when wider linewidth is used for the transmission over a dispersive fiber. 6 dB Q-degradation is shown when the signal is transmitted through 720 km using 10 MHz linewidth compared to transmission at emulator's narrowest linewidth, 256 kHz. The transmission using laser linewidth emulator set to 20 MHz is also shown where it can still be tolerated by 400 km of fiber with BER and Q factor of 1.6 $\times$ 10^{-3} and 9.606 dB, respectively. The effect of PM-to-IM conversion noise is also demonstrated experimentally using a single RF tone modulated to a 10 MHz linewidth laser over 500 km of fiber, where noise pedestals are imposed onto the carrier and tone is clearly shown. The phase decorrelation is confirmed by the simulation result where the RF tone is swept through the bandwidth showing the increase of the noise pedestal from the low- to high-frequency tones. Simulation works using the linewidth emulator to transmit high data rate at 16 and 4 QAM with 32 and 50 GHz OFDM signal bandwidth are also presented. The results confirmed that the highest frequency subcarriers suffered the most from the phase-walk off relative to the carrier. This is due to the high intensity of noise pedestal imposed onto each of the high frequency subcarrier. The PRT effect is shown to be insignificant to the DDO-OFDM transmission system for a short fiber length. In conclusion, the findings of this work have demonstrated the high effectiveness and reliability of the laser linewidth emulator to determine the phase noise tolerance in the optical OFDM transmission system without imposing other noise characteristics of the laser.

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References

[1] X. Yi *et al.*, “Phase noise effects on phase-modulated coherent optical OFDM,” *IEEE Photon. J.*, vol. 8, no. 1, Feb. 2016, Art. no. 7800308.
[2] Y. Wang, D. Wang, and J. Ma, “On the performance of coherent OFDM systems in free-space optical communications,” *IEEE Photon. J.*, vol. 7, no. 4, Aug. 2015, Art. no. 7902410.
[3] F. Tan, M. K. Wu, C. Wang, M. Liu, M. Feng, and N. Holonyak, “Effect of microcavity size to the RIN and 40 Gb/s data transmission performance of high speed VCSELs,” in *Proc. Conf. Lasers Electro-Opt.*, 2015, pp. 1–2.
[4] M. Qiu, Q. Zhuge, M. Chagnon, F. Zhang, and D. V. Plant, “Laser phase noise effects and joint carrier phase recovery in coherent optical transmissions with digital subcarrier multiplexing,” *IEEE Photon. J.*, vol. 9, no. 1, Feb. 2017, Art. no. 7901013.
[5] H. H. Elwan, R. Khayatzadeh, J. Poette, and B. Cabon, “Impact of relative intensity noise on 60-GHz radio-over-fiber wireless transmission systems,” *J. Lightw. Technol.*, vol. 34, no. 20, pp. 4751–4757, Oct. 2016.
[6] K. Vahala and A. Yariv, “Semiclassical theory of noise in semiconductor lasers—Part II,” *IEEE J. Quantum Electron.*, vol. QE-19, no. 6, pp. 1102–1109, Jun. 1983.
[7] C. Henry, “Theory of the linewidth of semiconductor lasers,” *IEEE J. Quantum Electron.*, vol. QE-18, no. 2, pp. 259–264, Feb. 1982.
[8] Z. Zan and A. J. Lowery, “Experimental demonstration of a flexible and stable semiconductor laser linewidth emulator,” *Opt. Express*, vol. 18, pp. 13880–13885, Jun. 2010.
[9] B. J. C. Schmidt, A. J. Lowery, and J. Armstrong, “Experimental demonstrations of electronic dispersion compensation for Long-Haul transmission using direct-detection optical OFDM,” *J. Lightw. Technol.*, vol. 26, no. 1, pp. 196–203, Jan. 2008.
[10] W. Shieh and C. Athaudage, “Coherent optical orthogonal frequency division multiplexing,” *Electron. Lett.*, vol. 42, pp. 587–589, 2006.
[11] S. L. Jansen, I. Morita, T. C. W. Schenk, N. Takeda, and H. Tanaka, “Coherent optical 25.8-Gb/s OFDM transmission over 4160-km SSMF,” *J. Lightw. Technol.*, vol. 26, no. 1, pp. 6–15, Jan. 2008.
[12] M. Chen, J. Yu, and X. Xiao, “Real-time Q-band OFDM-RoF systems with optical heterodyning and envelope detection for downlink transmission,” *IEEE Photon. J.*, vol. 9, no. 2, Apr. 2017, Art. no. 7902007.
[13] R. P. Giddings, E. Hugues-Salas, X. Q. Jin, J. L. Wei, and J. M. Tang, “Experimental demonstration of real-time optical OFDM transmission at 7.5 Gb/s over 25-km SSMF using a 1-GHz RSOA,” *IEEE Photon. Technol. Lett.*, vol. 22, no. 11, pp. 745–747, Jun. 2010.
[14] D. Qian, N. Cvijetic, J. Hu, and T. Wang, “108 Gb/s OFDMA-PON with polarization multiplexing and direct detection,” *J. Lightw. Technol.*, vol. 28, no. 4, pp. 484–493, Feb. 2010.
[15] Y. Xie, C. Zhu, B. Song, and A. J. Lowery, “Sidelobe suppression using cancellation sub-carriers for OFDM superchannels,” in *Proc. 42nd Eur. Conf. Opt. Commun.*, 2016, pp. 1–3.
[16] S. Yamamoto, N. Edagawa, H. Taga, Y. Yoshida, and H. Wakabayashi, “Analysis of laser phase noise to intensity noise conversion by chromatic dispersion in intensity modulation and direct detection optical-fiber transmission,” *J. Lightw. Technol.*, vol. 8, no. 11, pp. 1716–1722, Nov. 1990.
[17] W. R. Peng, “Analysis of laser phase noise effect in direct- detection optical OFDM transmission,” *J. Lightw. Technol.*, vol. 28, no. 17, pp. 2526–2536, Sep. 2010.
[18] X. Chen, A. A. Amin, and W. Shieh, “Characterization and monitoring of laser linewidths in coherent systems,” *J. Lightw. Technol.*, vol. 29, no. 17, pp. 2533–2537, Sep. 2011.

[19] J. Zhu, O. Omomukuyo, R. Venkatesan, C. Li, and O. A. Dobre, "Rf-pilot phase noise compensation for long-haul coherent optical OFDM systems," in *Proc. IEEE 14th Can. Workshop Inf. Theory*, 2015, pp. 127–130.

[20] B. J. C. Schmidt, Z. Zan, L. B. Du, and A. J. Lowery, "120 Gbit/s over 500-km using single-band polarization-multiplexed self-coherent optical OFDM," *J. Lightw. Technol.*, vol. 28, no. 4, pp. 328–335, Feb. 2010.

[21] B. J. Schmidt, A. J. Lowery, and L. B. Du, "Low sample rate transmitter for direct-detection optical OFDM," in *Proc. Conf. Opt. Fiber Commun./Nat. Fiber Opt. Eng. Conf.*, San Diego, CA, USA, 2009, pp. 1–3.

[22] A. J. Lowery, "Improving sensitivity and spectral efficiency in direct-detection optical OFDM systems," in *Proc. Conf. Opt. Fiber Commun./Nat. Fiber Opt. Eng. Conf.*, 2008, pp. 1–3.

[23] W. R. Peng, B. Zhang, K. M. Feng, X. Wu, A. E. Willner, and S. Chi, "Spectrally efficient direct-detected OFDM transmission incorporating a tunable frequency gap and an iterative detection techniques," *J. Lightw. Technol.*, vol. 27, no. 24, pp. 5723–5735, Dec. 2009.

[24] Z. Zan, M. Premaratne, and A. J. Lowery, "Laser RIN and linewidth requirements for direct detection optical OFDM," in *Proc. Conf. Lasers Electro-Opt./Conf. Quantum Electron. Laser Sci.*, 2008, pp. 1–2.

[25] L. Richter, H. Mandelberg, M. Kruger, and P. McGrath, "Linewidth determination from self-heterodyne measurements with subcoherence delay times," *IEEE J. Quantum Electron.*, vol. QE-22, no. 11, pp. 2070–2074, Nov. 1986.

[26] Z. Zan, L. B. Y. Du, and A. J. Lowery, "Experimental demonstration on the reduction of linewidth impact in a self-heterodyne optical OFDM system," in *Proc. Conf. Opt. Fiber Commun./Nat. Fiber Opt. Eng. Conf.*, 2010, pp. 1–3.

[27] R. T. Watts, S. G. Murdoch, and L. P. Barry, "Phase noise reduction of an optical frequency comb using a feed-forward heterodyne detection scheme," *IEEE Photon. J.*, vol. 8, no. 1, Feb. 2016, Art. no. 7900707.

[28] J. Ma and W. Zhou, "Joint influence of the optical carrier-to-sideband ratio and guard band on direct-detection SSB-OOFDM system," *IEEE Photon. J.*, vol. 7, no. 5, Oct. 2015, Art. no. 7801713.