Optical DP-High Order-QAM Transmission System for High-speed Short Links Utilizing Copropagating Twin Local Lights

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Abstract— **A novel optical high order quadrature amplitude modulation (QAM) transmission system for high-speed short links is described. Dual-polarization (DP) QAM and twin local lights are generated from one light source in the system, and these lightwaves are simultaneously transmitted via standard single mode fiber. The receiver can be constructed simply because it does not require a coherent light source under wavelength control. The system enables a 3.1 Gbaud DP-16-QAM signal to be successfully demodulated after 80-km transmission without using an optical dispersion compensator. It also achieves high tolerance against phase noise in the signal light source.**

Keywords— QAM; digital coherent detection; phase noise

I. INTRODUCTION

The explosive growth of the data traffic has created a strong demand for the development of high-speed optical short links, such as next-generation Ethernet. Several approaches to developing them have been proposed that are based on intensity modulated and direct detection (IMDD) systems, with various signal formats [1-3]. In classical IMDD systems, transmission length and bitrate are strongly restricted by the chromatic dispersion (CD) and frequency characteristic of the photodetector(s) inside a receiver. It is expected that the dispersion tolerance and capacity of links can be improved by utilizing a digital signal processor (DSP) and/or an advanced signal format, e.g., dual polarization quadrature amplitude modulation (DP-QAM) with digital coherent detection. Utilizing a DSP and a maximum likelihood sequence estimation approach, Chen et al. demonstrated 56 Gbps C-band transmissions over 26 km single mode fiber (SMF) using PAM-4 [3]. Iiyama et al. showed the feasibility of an access network with digital coherent detection, and demonstrated star 8-QAM (30 Gbps) transmission over 20-km SMF [4]. In classical digital coherent detection systems, continuous wave (CW) light sources must be located on both the transmitter and receiver side to provide signal light and local light. In such systems, the local light wavelength must be controllable, because it must be adjusted to the signal light wavelength. Moreover, to achieve stable carrier phase recovery, these light sources are required to have a high coherency, which can offer low phase noise [5]. In recent years, several digital coherent detection techniques have been proposed that utilize the local light launched from the transmitter side [6-7]. In [6], single polarization (SP) 64-QAM (30 Gbps) signal and local light are polarization division multiplexed and simultaneously transmitted over 60-km fiber. Though these techniques were mainly intended to relax the demand for high coherency over CW light sources, they also make it possible to simplify receiver construction because the receiver does not require a coherent light source with a wavelength control circuit.

We show a novel digital coherent transmission system dedicated to dual polarization (DP)-high order-QAM signals. In this system, signal and twin local lights are generated from the same CW light source, and wavelength division multiplexed on the transmitter side. Its concept and experimental confirmation using quadrature phase shift keying (QPSK) signals were described in [8]. In this paper, we show how we expanded the system and with it successfully demodulated 3.125 Gbaud DP-16-QAM signals (25 Gbps) after 80-km transmission. Polarization demultiplexing and compensation for CD were achieved in the receiver DSP. We also show that the techniques the system uses can mitigate the penalty induced by the phase noise in the CW light source. These techniques enable the development of optical high-speed short links with high tolerance against dispersion and phase noise, utilizing a simple receiver circuit.

II. SYSTEM CONFIGURATION

Fig. 1 shows the configuration of the system's transmitter (TX) and receiver (RX) [8]. In the TX, the CW light is divided by a coupler, and launched into a DP-IQ modulator and pulse carver. The DP-IQ modulator generates a DP-QAM signal polarized in X and Y. The pulse carver, which is driven by an oscillator with angular frequency ω_{RZ}, generates a carrier-suppressed return-to-zero (CS-RZ) optical pulse train [9] polarized in X. Here, $\omega_{RZ}/(2\pi)$ must be larger than the baud rate of the DP-QAM. The DP-QAM signal and CS-RZ optical pulse train are combined using a wavelength multiplexer. Fig. 1 also shows measured optical spectra at the TX output. The two dashed lines and black line respectively show the spectra of CS-RZ, DP-QAM and multiplexed light. Two frequency components generated by CS-RZ (denoted as Lo #1 and Lo #2

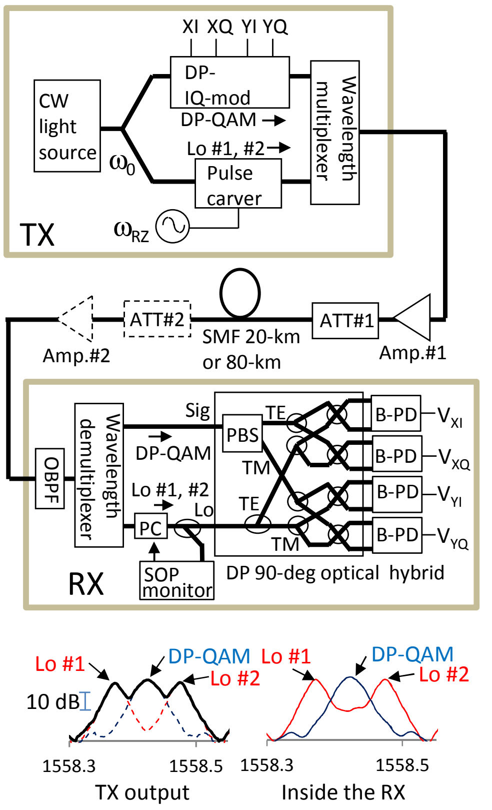

Fig. 1. Transmission system and measured optical spectra of the DP-QAM signal and twin local lights. Resolution was 0.01 nm.

in Fig. 1) are used as twin local lights. These lights and the DP-QAM signal are launched into the transmission line simultaneously. Because ω_{RZ} is very small compared with the carrier angular frequency ω_0, the twin local lights ($\omega_0 + \omega_{RZ}$, $\omega_0 - \omega_{RZ}$) and QAM signal (ω_0) can be grouped and then added or dropped at network nodes as necessary. In the RX, amplified spontaneous emission noise induced by an optical amplifier is removed by an optical band pass filter (OBPF). The received DP-QAM signal and twin local lights are optically divided using a wavelength demultiplexer. The measured optical spectra of the divided DP-QAM and twin local lights are also shown in Fig. 1. In an experiment we conducted, we used a conventional Mach-Zehnder interferometer (MZI) as the wavelength demultiplexer. The divided lights are launched into a signal port and local port of a DP 90-degree optical hybrid. Though the system utilizes twin local lights, a commercially available DP 90-degree optical hybrid can also be utilized. Because the local port of the conventional 90-degree optical hybrid requires linearly polarized local light, the polarization controller (PC) is placed before the local port. Since the twin local lights have almost the same wavelength, their states of polarization (SOP) are almost identical. The SOP of the tapped local lights was monitored by a SOP monitor, and the results were fed back to a PC [10]. In the TX and RX, the skew of the optical paths dedicated to the DP-QAM signal and local light, T_{skew}, is less than a few ns. The four pairs of optical lights generated by the DP 90-degree optical hybrid are converted into four RF signals (V_{XI}, V_{XQ}, V_{YI}, V_{YQ}) by four balanced photo detectors (B-PDs). These are input to the DSP via an analog-digital converter (not shown) and demodulated with the technique described in the next section.

III. Demodulation Procedure in the RX

The basic concept of the demodulation process was previously described in [8] for DP-QPSK. In this section, we describe the expansion of this technique, dedicated to the DP-high order QAM signal. The optical electric fields of the twin local lights (E_{Lo}) and each polarization of the DP-QAM signal (E_{sigX} and E_{sigY}) are described as

$$E_{LO} = \exp\{j(\omega_0 - \omega_{RZ})\cdot t + j\varphi_{noise} + j\theta_{1X}\} + \exp\{j(\omega_0 + \omega_{RZ})\cdot t + j\varphi_{noise} + j\theta_{2X}\} \tag{1}$$

$$E_{SigX} = A_{sigX}(t)\cdot \exp(j\omega_0 t + j\varphi_{sigX}(t) + j\varphi_{noise} + j\theta_{3X}) \tag{2}$$

$$E_{SigY} = A_{sigY}(t)\cdot \exp(j\omega_0 t + j\varphi_{sigY}(t) + j\varphi_{noise} + j\theta_{4Y}) \tag{3}$$

where t is time, $A_{sigX}(t)$ and $A_{sigY}(t)$ are QAM signal amplitudes, and $\varphi_{sigX}(t)$ and $\varphi_{sigY}(t)$ are QAM signal phases (insignificant coefficients are ignored). Note that $A_{sigX}(t)$ and $A_{sigY}(t)$ depend on the signal pattern of the n-QAM ($n > 4$), unlike the QPSK. The term φ_{noise} is the random phase noise of the CW light source. It can be induced by outer noise, e.g., bias voltage instability for a diode laser, dither signals dedicated to wavelength control, etc. We assume that the change in φ_{noise} is slow and that φ_{noise} (t) is almost the same as φ_{noise} ($t + T_{skew}$). The factor θ is an additional optical phase shift, induced by the CS-RZ modulation, T_{skew}, etc. Inside the DP 90-degree optical hybrid, the combined E_{sigX} and E_{sigY} are divided into E_{sigTE} and E_{sigTM} by a polarization beam splitter (PBS). They are described as

$$E_{SigTE} = \sqrt{\alpha}\cdot E_{sigX} + \sqrt{1-\alpha}\cdot E_{sigY} \tag{4}$$

$$E_{SigTM} = \sqrt{1-\alpha}\cdot E_{sigX} + \sqrt{\alpha}\cdot E_{sigY} \tag{5}$$

where α is a constant determined by the SOP of the DP-QAM after transmission. The terms V_{XI} and V_{XQ} are obtainable as

$$\begin{aligned} V_{XI} &= |E_{sigTE} + jE_{LO}|^2 - |E_{sigTE} - jE_{LO}|^2 \\ &= \{\sqrt{\alpha}\cdot A_{sigX}(t)\cdot \sin(\varphi_{sigX}(t) + \theta_{312}) \\ &+ \sqrt{1-\alpha}\cdot A_{sigY}(t)\cdot \sin(\varphi_{sigY}(t) + \theta_{412})\}\times(BeatTerm) \end{aligned} \tag{6}$$

$$\begin{aligned} V_{XQ} &= |E_{sigTE} + E_{LO}|^2 - |E_{sigTE} - E_{LO}|^2 \\ &= \{\sqrt{\alpha}\cdot A_{sigX}(t)\cos(\varphi_{sigX}(t) + \theta_{312}) \\ &+ \sqrt{1-\alpha}\cdot A_{sigY}(t)\cos(\varphi_{sigY}(t) + \theta_{412})\}\times(BeatTerm) \end{aligned} \tag{7}$$

$$(BeatTerm) = \cos\{\omega_{RZ}t + (-\theta_1 + \theta_2)/2\} \tag{8}$$

where $\theta_{312} = \theta_{3X} - (\theta_{1X} + \theta_{2X})/2$ and $\theta_{412} = \theta_{4Y} - (\theta_{1X} + \theta_{2X})/2$. The terms V_{YI} and V_{YQ} are obtained by exchanging E_{sigTE} and E_{sigTM} in (6) and (7). Note that the φ_{noise} is cancelled in these equations. What this means is this technique can achieve high tolerance against the phase noise in a CW light source. The beat terms in (6)-(8) are removed by the DSP. Fig. 2 shows the flow chart of this process. It also shows in-processing digitized data as a function of time. These digitized data were plotted by an offline computer that emulates the function of the DSP. The sample data V_{XI} and V_{XQ}, were experimentally obtained using the DP-16-QAM signal and a storage oscilloscope. The symbol duration time T is $4\pi/\omega_{RZ}$ and the sampling rate is $6.4\omega_{RZ}/\pi$. At the first step (denoted as #1 in the flow chart), V_{XI} and V_{XQ} are input to the DSP via an analog-digital converter. The first graph (denoted as #1) shows digitized V_{XI} and V_{XQ} vs. time; beat with angular frequency ω_{RZ} is observed. The amplitude and polarity of these beats are determined by $A_{sigX}(t)$, $\varphi_{sigX}(t)$, $A_{sigY}(t)$ and $\varphi_{sigY}(t)$. Next, the DSP calculates $|V_{XI}|^2$ and $|V_{XQ}|^2$ (denoted as #2). Though the amplitude of the beats still depends on the signal pattern, the inverse in polarity has vanished (see the second graph denoted as #2). Consequently, the frequency spectrums of $|V_{XI}|^2$ and $|V_{XQ}|^2$ have a peak at angular frequency $2\omega_{RZ}$. Next, the DSP extracts this frequency component from $|V_{XI}|^2$ and generates the clock with angular frequency ω_{RZ} using a digital frequency divider (see the third graph denoted as #3). In high order-QAM system, the amplitude of $|V_{XI}|^2$ depends on $A_{sigX}(t)$ and $A_{sigY}(t)$. If the amplitude of $|V_{XI}|^2$ is too small, the DSP can generate the clock using $|V_{XQ}|^2$ instead of $|V_{XI}|^2$. Next, the DSP multiplies the generated clock by the original V_{XI} and V_{XQ}. A peak holding and smoothing process yields V_{XI} and V_{XQ} without the beat term (see the last graph denoted as #4). In the same manner as in the previous step, beat terms are removed from V_{YI} and V_{YQ}. After the terms are removed, V_{XI} and V_{XQ} in (6) and (7) become the same as the results obtained with conventional self-homodyne detection of DP-QAM. Because θ_{312} and θ_{412} represent the signal delay between the X and Y components (note that θ_{312} - θ_{412} = θ_{3X} - θ_{4Y}), these terms can be eliminated by using classical digital coherent detection techniques dedicated to polarization mode dispersion (PMD) [11].

IV. Experimental Setup and Results

We measured the Q-factor of the DP-16-QAM signal demodulated by the proposed system after 20-km and 80-km transmission. The experimental setup was the same as that shown in Fig. 1. The linewidth of the CW light source in the TX was less than 100 kHz. To demonstrate the system's tolerance against phase noise φ_{noise}, we also used a dithered CW light source with 45 MHz linewidth. In both cases, wavelength was 1558 nm. Random data patterns XI, XQ, YI and YQ, which are based on a 2^{15}-1 pseudo random bit sequence, were generated by offline processing and an arbitrary waveform generator. The DP-16-QAM baud rate was 3.125 G baud (25 G bps) and $\omega_{RZ}/(2\pi)$ was 6.25 GHz. Note that with this baud rate, classical digital coherent detection systems demand linewidths less than 1 MHz for stable phase recovery of 16-QAM [5]. At the TX output, the optical power values of both the DP-16-QAM signal light and the twin local lights were -20 dBm (total power was -17 dBm). These lights were amplified by optical amplifier #1. The total fiber launch power was controlled by attenuator #1 (ATT #1). The transmission fiber was a 20-km or 80-km standard SMF. Its chromatic dispersion (CD) was 17 ps/nm/km and PMD was negligible. No optical CD compensator was used in the transmission line. In the RX, the local light polarization was manually controlled because of the restrictions of the experimental setup. In practice, an auto polarization control circuit [10] would be used for this purpose. The detected signals were stored in a digital storage oscilloscope and the Q-factor was calculated by offline processing. The oscilloscope's sampling rate was 80 G samples/s.

In the experiments we conducted, we first measured the Q-factor after 20-km transmission. In this experiment, we did not use the pre-amplifier before the RX (Amp. #2 in Fig.1). Fig. 3 (a) and (b) show the constellations generated by the proposed technique. The optical signal noise ratio (OSNR) was larger than 30 dB/0.1 nm and total fiber launched power (summation of the signal and twin local lights) was +8 dBm. The constellations in (a) were obtained by using the CW light source without outer noise (linewidth < 100 kHz) and those in (b) were obtained using dithered CW light source (linewidth = 45 MHz). Clear constellations were achieved in both cases. For comparison purpose, in (c) we show the constellations generated using a classical self-homodyne detection technique with a back-to-back (BtoB) configuration and a dithered CW light source. In this measurement, pulse carver was not used, and tapped CW light was directly launched into the local port of the receiver. Fig. 3 (c) shows that the phase recovery failed because of the phase noise induced by the dithering. Fig. 4 (a) shows the measured Q-factor as a function of the total received

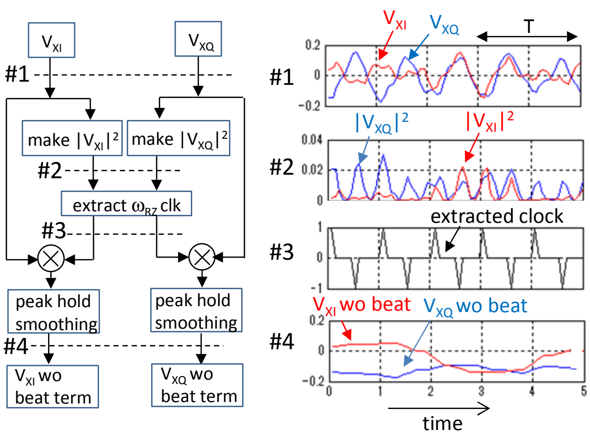

Fig. 2. Process of removing the beat term for received DP-high order QAM. In-processing digitaized data are also shown as the function of the time. T is the symbol duration time.

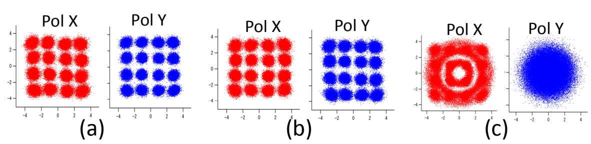

Fig. 3. Measured constellations. (a): after 20-km transmission using proposed system. Linewidth of the CW light was less than 100 kHz. (b): after 20-km transmission using proposed system with dithered CW light source. (c): BtoB configuration using classical self-homodyne detection with dithered CW light source.

power. The latter, including the power of the twin local lights, was measured at the RX input. The total received power and fiber launched power were controlled by ATT #1; the latter was 4 dB higher than the former. The squares and triangles in the figure correspond to the 20-km transmission and the Xs correspond to the BtoB configuration. Black symbols correspond to using the CW light source without outer noise and red symbols correspond to using the CW light source with dithering. Transmission penalty was negligible though the dithered CW light source slightly degraded the Q-factor (red triangles). In this experiment, the OSNR was very high (> 30 dB /0.1 nm) and the Q-factor was almost completely determined by the circuit noise of the storage oscilloscope. Fig. 4(a) shows that the Q-factor was improved at high launched power. This means that optical nonlinear effects (e.g., stimulated Brillouin scattering in local light, self-phase modulation in QAM signal, etc.) did not occur in the measured power range.

Next, to demonstrate the compensation for CD, we measured the Q-factor as the function of the OSNR after 80-km transmission (1360 ps/nm). In this experiment, we utilized the pre-amplifier before the RX (Amp. #2 in Fig. 1) to compensate for fiber loss. The total fiber launched power was fixed to 0.5 dBm. OSNR was controlled by ATT #2 (see Fig. 1). The optical power values of the signal and twin local lights in the DP 90-degree optical hybrid were respectively set to 3.5 dBm and 3 dBm. Fig. 4(b) shows the OSNR tolerance of the proposed system after 80-km transmission. The crosses in the figure correspond to BtoB configuration with a dithered CW light source. The other symbols mean the same as in Fig. 4(a). Since OSNR is defined as the power ratio of signal to noise, the power of the local lights was not included here. The transmission penalty was almost negligible though the dithered CW light source slightly degraded the Q-factor. This means that CD compensation can be achieved with the proposed technique.

V. Conclusion

This paper described a novel optical dual polarization (DP) high order quadrature amplitude modulation (QAM) transmission system for high-speed short link. The system enabled a 3.125G baud DP-16-QAM signal to be successfully demodulated after 20-km and 80-km transmission without using a coherent light source in the system's receiver. The techniques the system used provide tolerance against chromatic dispersion and phase noise in the continuous wave light source inside the system's transmitter.

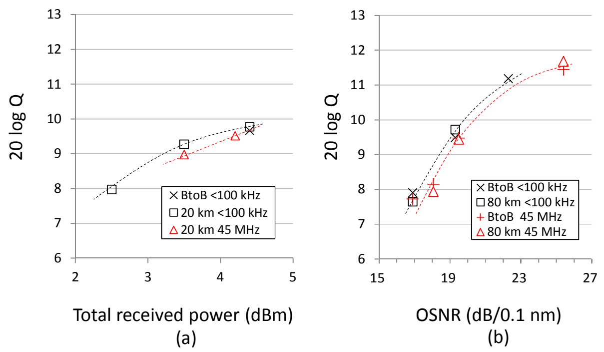

Fig. 4. Measured Q factor. (a): 20-km transmission without pre-amplifier. (b): 80-km transmission with pre-amplifier. Cross and Xs represent BtoB, squares and triangles represent transmission. Black symbols represents CW light soure w/o dithering (linewidth <100 kHz), red symbols represents CW light source with dithering (linewidth = 45 MHz).

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