Broadband IF-Over-Fiber Transmission Based on a Polarization Modulator

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***Abstract*— In this letter, we propose a novel broadband IF-over-fiber transmission system employing a polarization modulator (PolM). PolMs are special phase modulators, which can support both TE and TM modes with opposite phase modulation indices. If a polarizer is placed after the PolM with an angle of 45° to one principal axis of the PolM, then an equivalent intensity modulator (IM) can be achieved. On the other hand, if the direction of the polarizer is parallel to one principal axis of the PolM, an equivalent phase modulator (PM) can be achieved. As a result, we can utilize a PolM to achieve the functions of a parallel IM/PM transmitter, which is previously reported in mobile fronthaul to overcome the dispersion-induced power fading effect. Compared with the conventional parallel IM/PM transmitter based on an IM and a PM, our scheme only needs one modulator, which significantly reduces the cost and avoids the disparity in operation requirements between the IM and the PM. As a demonstration, we successfully transmit 14 × 1 GHz OFDM/OQAM signals with a data rate of 44.7 Gb/s over 25 km of a single-mode fiber.**

***Index Terms*— Mobile fronthaul, IF over fiber, dispersion-induced power fading.**

I. Introduction

The drastic growth of demands for high quality wireless services pushes the mobile communication networks to evolve continuously. Cloud optical radio access network (C-RAN), which is an important advance in LTE-Advanced systems, is expected to play an important role in the next generation mobile communications systems. In the C-RAN architecture, mobile fronthaul places the baseband processing functions inside the BBU pool, which is efficiently shared by multiple remote radio units (RRUs), leading to a great cost reduction. Currently, the mobile fronthaul is primarily based on the Common Public Radio Interface (CPRI) which transmits the digitized in-phase (I) and quadrature-phase (Q) samples of the wireless signals in binary modulation format [1]. One drawback of CPRI is its bandwidth inefficiency due to binary transmission. In future mobile communication systems, the bandwidth and the number of antennas need to support larger cell capacity. Consequently, the CPRI is inadequate for the next generation mobile fronthaul. To achieve cost-effective and bandwidth-efficient mobile fronthaul architecture, intermediate-frequency over fiber (IFoF) transmission scheme has been proposed and studied. In [2], with the employment of a Mach-Zehnder modulator, 12×100-MHz LTE-A-like signals over 40 km of single-mode fiber (SMF) has been demonstrated based on IFoF transmission. Afterwards, 128×100-MHz signals over 20 km SMF has also been demonstrated [3]. In [4], the IFoF transmission has achieved an equivalent CPRI line data rate of 178 Gb/s by transmitting 144-IF carriers of LTE-A signals over 20 km of SMF. In [5], 48 LTE signals and 32 LTE signals have been demonstrated over 5 km SMF transmission, respectively. In [6], 24 filtered orthogonal frequency division multiplexing (f-OFDM) signals have been transmitted over 20 km of SMF. In IFoF transmission systems, IF signals suffer from the chromatic dispersion of SMF, leading to severe power fading at some frequencies. To overcome the dispersion-induced power fading effect, one solution is optical single sideband modulation which can be generated by filtering out one sideband using an optical filter [7] or Hilbert transform [8]. However, the optical filter should have a sharp roll-off profile and fine wavelength tunability, which increases the system cost. As to the Hilbert transform method, 90° phase shift should be applied to all frequency components, which imposes a heavy burden on digital signal processing. Another solution to compensate the dispersion is carrier phase-shifted double sideband (DSB) modulation [9]. By tuning the phase of the carrier, the chromatic dispersion can be overcome. However, the power fading effect can be only compensated in a limited bandwidth, which makes this scheme not suitable for broadband transmission. In addition, Zhang *et al.* [10] have utilized a polarization modulator (PolM) to compensate dispersion. The fading frequencies can be shifted in this scheme, but the compensation bandwidth is still limited. In [11], a broadband dispersion compensation scheme has been proposed employing a parallel intensity modulator (IM) and phase modulator (PM) transmitter since the IM and the PM have complementary responses. The same signal is transmitted through the IM-based and PM-based links, then a broadband companion can be achieved. However, the IFoF transmission was not studied in [11]. Recently, the parallel IM/PM transmitter has been introduced in IFoF systems [12], [13]. In this kind of schemes, multiple IF signals are transmitted by either the IM or the PM using a bandwidth allocation strategy. However, no matter in [11] or [12], [13], two modulators should be used, resulting in an increased cost.

In this letter, we propose and experimentally demonstrate a broadband IFoF transmission system using a PolM which can achieve an equivalent parallel IM/PM transmitter. The PolM is a special phase modulator which can support both

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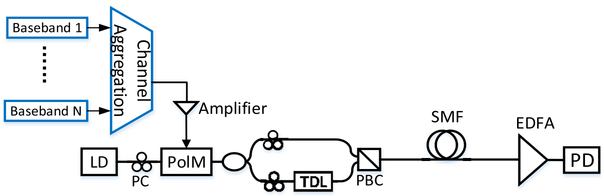

Fig. 1. Experimental setup for IFoF transmission using a PolM.

TE and TM modes with opposite phase modulation indices. With a polarizer oriented with an angle of 45° to one principal axis of the PolM, an equivalent IM can be obtained. On the other hand, if the direction of the polarizer is parallel to one principal axis of the PolM, an equivalent PM can be achieved. Therefore, we can implement an equivalent parallel IM/PM transmitter using one PolM. Compared with the previous parallel IM/PM transmitter using an IM and a PM, our system cost is significantly reduced. Furthermore, since only one modulator is used, the IM/PM bandwidth allocation strategy is avoided. Recently, OFDM using offset quadrature amplitude modulation (OFDM/OQAM) has been introduced in mobile fronthaul as an alternative waveform to achieve better spectral efficiency than conventional cyclic-prefix OFDM (CP-OFDM) [14], [15]. In our experiment, we successfully transmit 14×1 GHz OFDM/OQAM signals corresponding to wireless throughout of 44.7 Gb/s over 25 km SMF using our PolM transmitter.

II. Principle

The schematic diagram of the proposed scheme is shown in Fig. 1. A laser diode (LD) generates a linearly polarized lightwave which can be expressed as $\exp(j\omega_c t)$. Then the lightwave is oriented with an angle of 45° to the principal axis of the PolM. If the PolM is modulated by a microwave signal with an angular frequency of ω_m, the output optical signal along the TE- and TM-axes can be expressed as $E_x = (\sqrt{2}/2)e^{j\omega_c t + j\gamma\cos\omega_m t}$, $E_y = (\sqrt{2}/2)e^{j\omega_c t - j\gamma\cos\omega_m t}$, where γ is the phase modulation index. The modulated signal after the PolM is split by a 3-dB optical coupler into two branches. One branch is directed to a polarization controller (PC) while the other branch is directed to another PC followed by a tunable delay line (TDL). Then the two branches are combined by a polarization beam combiner (PBC). In the upper branch, the PC is adjusted to align the axis of the PBC with 45° to the principal axis of the PolM, then the signal in the upper branch after the PBC can be expressed as

$$E_{IM} = (\sqrt{2}/2)\left(E_x e^{j\varphi} + E_y\right) = e^{j\omega_c t}e^{j\varphi/2}\cos\left[\gamma\cos(\omega_m t) + \varphi/2\right], \quad (1)$$

where φ is the phase difference between E_x and E_y, which can be changed by adjusting the DC bias of the PolM or the PC. As can be seen from (1), an equivalent IM is achieved. In the lower branch, the PC is adjusted to align the axis of the PBC parallel to one principal axis of the PolM, then the optical signal can be expressed as $E_{PM} = E_x$, leading to an equivalent PM. We adjust $\varphi = -\pi/2$ to bias the equivalent IM at the quadrature point and assume small signal modulation, then the upper signal can be expressed as

$$E_{IM} = (\sqrt{2}/2)\left[J_0(\gamma) + J_1(\gamma)e^{j\omega_m t} + J_1(\gamma)e^{-j\omega_m t}\right]e^{j\omega_c t}e^{-j\pi/4}. \quad (2)$$

If the signal is transmitted through an optical fiber, group-velocity dispersion (GVD) will change the phases of the sidebands. The transmitted signal can be expressed as

$$E'_{IM} = \frac{\sqrt{2}}{2}\begin{bmatrix} J_0(\gamma)e^{-j\theta_0} + J_1(\gamma)e^{j\omega_m t}e^{-j\theta_{+1}} \\ +J_1(\gamma)e^{-j\omega_m t}e^{-j\theta_{-1}} \end{bmatrix} e^{j\omega_c t}e^{j\varphi/2}, \quad (3)$$

where θ_0, θ_{+1}, θ_{-1} are dispersion-induced phase shifts of the optical carrier, the upper and lower sidebands, respectively. Expanding the propagation constant β in Taylor series, we have $\theta_0 = z\beta_0$, $\theta_{+1} = z\beta_0 + \tau_0\omega_m + D_\omega\omega_m^2/2$ and $\theta_{-1} = z\beta_0 - \tau_0\omega_m + D_\omega\omega_m^2/2$, where z is the transmission distance, $\tau_0 = z\beta'$ is the group delay, $D_\omega = z\beta''$ is the GVD with respect to the optical angular frequency, and β' and β'' are the first- and second-order derivatives of β. After optical-to-electrical conversion at a photodetector (PD), the generated electrical signal can be given by

$$I_{IM} \propto \left|E'_{IM}(t)\right|^2 = 2J_0(\gamma)J_1(\gamma)\cos(D_\omega\omega_m^2/2)\cdot\cos[\omega_m(t-\tau_0)]. \quad (4)$$

Using the similar derivation, the generated electrical signal of the lower branch after transmission can be expressed as

$$I_{PM} \propto |E_{PM}(t)|^2 = 2J_0(\gamma)J_1(\gamma)\sin(D_\omega\omega_m^2/2)\cdot\cos[\omega_m(t-\tau_0-\tau_d)], \quad (5)$$

where τ_d is the time delay introduced by the TDL. As can be seen from (4) and (5), the IM and PM links have complementary responses. Consequently, the parallel IM/PM transmitter can flatten the null frequencies caused by the chromatic dispersion [13]–[15]. In our scheme, the two branches are polarization multiplexed by the PBC, then the generated signal is the sum of the two electrical signals, which can be expressed as

$$I = I_{IM} + I_{PM} = 2J_0(\gamma)J_1(\gamma)\sqrt{1+\sin(D_\omega\omega_m^2)\cos(\omega_m\tau_d)} \cdot \cos\left[\omega_m(t-\tau_0) + \psi(\omega_m)\right], \quad (6)$$

where ψ is the phase shift with respect to ω_m. So the frequency response of the power of the microwave signal is $1 + \sin(D_\omega\omega_m^2)cos(\omega_m\tau_d)$. Previous investigations have shown the time delay can smooth out the response [12]. We define the optimal time delay as the time delay which induces the minimum frequency response variation within a determined frequency range. Then the optimal time delay from 0 to 18 GHz and the corresponding minimum variation are calculated and shown in Table I. We can see from Table I that the serious power fading effect induced by the chromatic dispersion is eliminated and the residual amplitude variation can be compensated by pre-emphasis [12], [13]–[15]. The simulated frequency responses of the IM, the PM and the parallel IM/PM over 25 km of SMF can be shown in Fig. 2. As can be seen, the response of the parallel IM/PM transmitter is flattened by the complementary response of the IM and the PM, resulting in broadband dispersion compensation. Furthermore, since two links are combined, an optical multipath channel is generated. The delay spread of the multipath channel is τ_d, so the coherence bandwidth can be written as $B_c = 1/\tau_d$. The calculated coherence bandwidth is also given Table I. For the analog mobile fronthaul, multicarrier modulation signals are transmitted. The multicarrier modulation can send bit stream over many different subchannels.

TABLE I
OPTIMAL TIME DELAY

Fiber length	Optimal time delay	Minimum variation	Coherence bandwidth
20 km	19 ps	3.2 dB	26.3 GHz
25 km	69 ps	3.4 dB	7.2 GHz
30 km	76 ps	3.4 dB	6.6 GHz
35 km	88 ps	4.0 dB	5.7 GHz
40 km	97 ps	4.6 dB	5.2 GHz

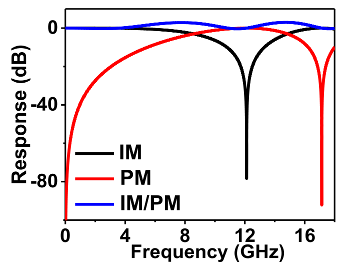

Fig. 2. Simulated frequency responses of IM, PM and parallel IM/PM-based links over 25 km SMF.

Since the coherence bandwidth of the optical channel is much larger than the conventional bandwidth of each subchannel (e. g. 15 kHz for LTE), the subchannels experience flat fading. Thus, the inter-symbol interference (ISI) on each subchannel can be neglected and one-tap equalizer can efficiently equalize each subchannel.

III. Transmission Experiment

Fig. 1 shows the experimental setup. The output lightwave of the LD at 1550 nm with a power of 10 dBm is directed to a PolM with an integrated polarizer whose direction has an angle of 45° with respect to one principal axis of the PolM. The PC placed before the PolM is adjusted to align the lightwave in the direction of the integrated polarizer. The lightwave after the PolM is split into two branches by a 3-dB coupler. Each branch has a PC which is adjusted to achieve the equivalent IM or PM, respectively. One of the branches has a TDL to tune the time delay between the two branches. The two branches are combined by a PBC to achieve the equivalent parallel IM/PM transmitter. The optical signal after the PBC is transmitted over 25 km of SMF. At the RRU, the optical signal is firstly amplified by an Erbium-doped fiber amplifier (EDFA) to compensate the transmission loss. A variable optical attenuator (VOA) is placed after the EDFA to adjust the optical power. Finally, the optical signal is received by a PD with a bandwidth of 60 GHz for optical-to-electrical conversion. In the experiment, we firstly disconnect the lower branch of the parallel transmitter and adjust the PC in the upper branch to form an equivalent IM. The frequency responses of the equivalent and real IMs are measured by a vector network analyzer, and the measured results are shown in Fig. 3(a). We can see the equivalent IM exhibits a same frequency response as that of the real IM. Then we disconnect the upper branch and adjust the PC in the lower branch to form an equivalent PM. The frequency responses of the equivalent and real PMs are measured as well, and the measured results are shown in Fig. 3(b). We can also see the equivalent PM functions the same as the real one. Then we combine the two branches and adjust the time delay to the optimal value to minimize the amplitude variation. The measured frequency response is shown in Fig. 3(c) and the amplitude

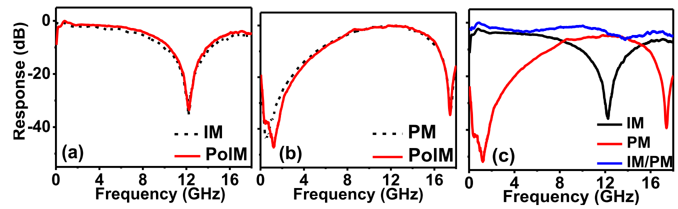

Fig. 3. Measured frequency responses of (a) IM, (b) PM and (c) parallel IM/PM.

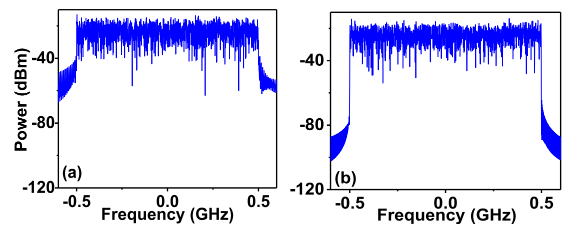

Fig. 4. Simulated electrical spectrum of (a) CP-OFDM and (b) OFDM/OQAM.

variation is measured within 6.5 dB. In our experiment, we use OFDM/OQAM instead of CP-OFDM as the baseband signal [14], [15]. Compared to CP-OFDM, OFDM/OQAM uses proto-type filters to define the time-frequency window of each subcarrier. As a result, the undesired sidelobes of subcarriers are significantly suppressed, enabling the system to seamlessly aggregate asynchronous carriers from different users, services without interference.

Firstly, we generate 14 OFDM/OQAM signals with the IFFT/FFT size of 1024 points. Each OFDM/OQAM signal consists of 1022 subcarriers with 16-QAM-modulated symbols and 2 subcarriers as the guard band. The subcarrier spacing is set at 0.97656 MHz. Thus, the baseband sampling rate is 1 GSa/s. The root raised cosine filter with a length of 4 times of symbol duration and a roll-off factor of 1 is used for pulse shaping, leading to the transition time of 3 symbol duration. The preamble configuration of IAM3 using two symbols proposed in [16] is utilized for channel estimation. In the experiment, 20 OFDM/OQAM symbols are transmitted, so the throughput is 1 GSa/s$\times$1022/1024$\times$4bit/s$\times$20/(20+5)$\times$14 = 44.7 Gb/s. Fig. 4 shows the electrical spectra of CP-OFDM and OFDM/OQAM signals. It can be clearly observed that the sidelobe suppression ratio of OFDM/OQAM is more than 35 dB compared to the CP-OFDM. Then we generate 14 OFDM/OQAM channels and aggregate them in the IF band. The interval between center frequencies of adjacent IF channels is set to be 1 GHz, so the channel spacing is only 2 subcarriers which can be seen as quasi-gapless carrier aggregation [14], [15]. An arbitrary waveform generator (AWG) with a sampling rate of 64 GHz is employed to generate the aggregated signals. The generated signals are amplified by a 12.5 Gb/s driver amplifier and applied to the PolM. The measured frequency spectrum of 25 km transmission of the equivalent IM link is shown in Fig. 5(a). We can see there is severe power fading at about 12 GHz which is also indicated in Fig. 3(a). The measured frequency spectrum of the equivalent parallel IM/PM link based on the PolM is shown in Fig. 5(b) where the several power fading is eliminated. Nevertheless, there is still a small variation within the bandwidth. Pre-emphasis is further implemented to flatten the frequency response and the frequency spectrum after pre-emphasis is shown in Fig. 5(c).

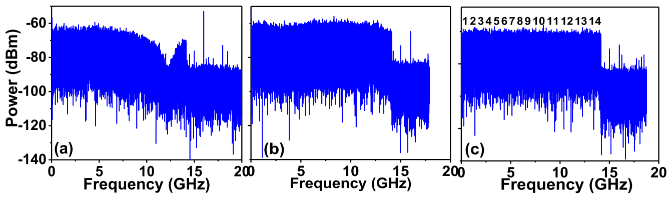

Fig. 5. Received electrical spectra: (a) the equivalent IM, (b) before and (c) after pre-emphasis of the PolM transmitter.

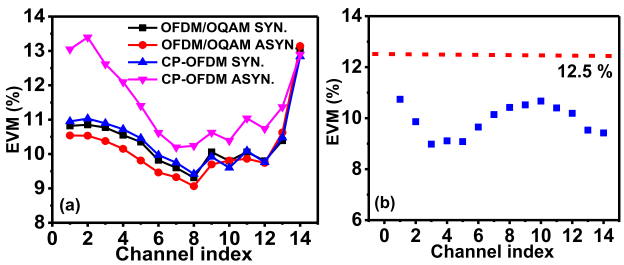

Fig. 6. (a) EVM versus channel index before pre-emphasis, (b) after pre-emphasis.

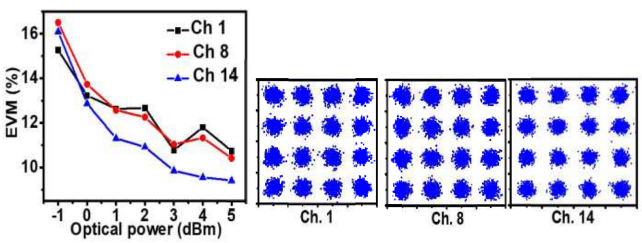

Fig. 7. EVMs of Channel 1, 8 and 14 versus the received optical power, Insets show the constellation when the optical power is 5 dBm.

We also generate 14 IF CP-OFDM signals with the IFFT/FFT size of 1024 points where 1022 subcarriers are used to carry 16-QAM symbols and 2 subcarriers are used as the guard band. The subcarrier spacing is also set to be 0.97656 MHz, so the symbol duration is 1.024 μs and 12.5% CP is added. To simulate the asynchronous transmission between adjacent channels, a delay of 0.25 × 1.024 μs is introduced between the odd and even channels. Then the asynchronous and synchronous transmission of OFDM/OQAM and CP-OFDM signals with a received optical power of 5 dBm is shown in Fig. 6(a). As can be seen, for the OFDM/OQAM signal, the asynchronous and the synchronous transmission have similar performance. However, the asynchronous transmission performance of CP-OFDM is degraded. For the transmission of OFDM/OQAM signals, pre-emphasis is implemented to further compensate the residual amplitude variation. The EVMs of all the 14 channels after pre-emphasis at a received power of 5 dBm is shown in Fig. 6(b). We can confirm all the channels satisfy the 12.5% threshold for 16 QAM which is specified in 3GPP requirements. The EVMs of the 14 channels versus the optical power are also measured, and the results are shown in Fig. 7. The constellations of the channel 1, 8 and 14 at a received optical power of 5 dBm are also shown in Fig. 7 and the EVMs are 10.74%, 10.42%, and 7.42%, respectively.

IV. Conclusion

In summary, we proposed and demonstrated an efficient IFoF transmission system using a simple PolM. Since the PolM is a special phase modulator with opposite modulation indices for TE and TM modes, equivalent IM and PM functions can be achieved if a polarizer is aligned to the principal axis of the PolM with 45° and 0°. As IMs and PMs have complementary transmission responses, a parallel IM/PM transmitter can be achieved by one PolM to compensate the chromatic dispersion induced power fading effect. Compared with the previous reports of parallel IM/PM transmitters implemented by independent IM and PM, our scheme is more cost-efficient. Furthermore, the procedure of bandwidth allocations to the IM and the PM for the IF signals is also eliminated since only one modulator is used. We successfully demonstrated 14 × 1 GHz OFDM/OQAM signals over 25 km SMF using the PolM. We believe the proposed scheme is suitable for the next generation IFoF mobile fronthaul link to support 5G mobile communication systems.

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