Vector Signal Generation Using a Polarization and a Phase Modulator in a Sagnac Loop

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***Abstract*— A novel technique to generate a microwave vector signal based on a bidirectional use of a polarization modulator (PolM) and a phase modulator (PM) in a Sagnac loop is proposed and experimentally demonstrated. The I/Q data streams of a vector signal are mixed with a microwave carrier and then applied to the PolM and the PM, respectively. A microwave vector signal is generated by combining two microwave signals with one obtained by beating the optical carrier and the $+1^{st}$ order sideband of a phase-modulated signal and the other obtained by beating the optical carrier and the $+1^{st}$ order sideband of an intensity-modulated signal. A quadrature phase is introduced due to the inherent $\pi/2$ phase shift between the optical carrier and the $+1^{st}$ order sideband of the phase-modulated signal. The generation of a 4.5 GHz microwave signal at 625 Msym/s with quadrature phase-shift-keying (QPSK) modulation and the transmission of the signal over a 25-km single-mode fiber are evaluated. An error-free transmission is achieved at a received optical power of 6 dBm. By incorporating I/Q imbalance compensation, an error-free transmission is achieved at a lower received power of 2 dBm.**

***Index Terms*— Microwave photonics, polarization modulation, phase modulation, vector signal generation, radio-over-fiber system.**

I. Introduction

OWING to the fast increasing communication speed, picocell base stations that operate at a much higher frequency to provide a much greater network capacity for wireless access networks have been intensively investigated. Picocell base stations covering a small area provide also the capability for frequency reuse which is important for efficient use of the available frequency spectrum. Since the number of picocell base stations is significantly large, a low-cost solution to effectively generate and distribute microwave signals to base stations is needed. Considering the broad bandwidth and low loss of optical fibers, the distribution of microwave signals over an optical fiber, or radio over fiber, is considered as a solution. In addition, the use of advanced modulation schemes can significantly increase the spectral efficiency and further enhance the performance of an access network [1]. Thus, the generation of high-frequency microwave signals with advanced modulation, and the distributions of the signals over optical fibers have been an active research topic and numerous techniques have been proposed and demonstrated recently [2]–[4].

A microwave signal with advanced modulation can be represented by a vector in the signal space. A microwave vector signal can be generated electronically. To transmit a microwave vector signal over an optical fiber, the signal needs to be converted to the optical domain. For example, an electronically generated microwave vector signal is up-converted to millimeter-wave and transmitted over an optical fiber by modulating the microwave vector signal on one of the two optical carriers obtained based on optical carrier-suppressed (OCS) modulation scheme [2], or a heterodyne OCS modulation scheme [3]. However, for both techniques in [2] and [3] the vector signals need to be electronically generated first then up-converted to millimeter-wave optically. In addition, an optical filter with a well-tailored spectral response is needed to select the required optical carrier and sideband, which may increase the system complexity and cost.

A microwave vector signal can also be generated directly in the optical domain, which may provide some key advantages such as higher frequency and broader bandwidth enabled by modern photonics. A few schemes to generate microwave vector signals in the optical domain have been proposed. For example, in [4], the I/Q data streams of a vector signal combined with two quadrature microwave carriers are applied to a dual-parallel Mach-Zehnder modulator (DP-MZM). After detection at a photodetector (PD), a microwave vector signal is generated. For the scheme reported in [4], two microwave combiners and a microwave 90° hybrid are needed, which will complicate the system. To avoid using a microwave 90° hybrid, in [5] an optical delay is introduced to one of the I/Q channels, giving a 90° phase shift to generate a microwave vector signal. The major limitation of the scheme in [5] is that the I/Q channels are physically separated, thus the phase variations due to environmental disturbance will be translated to the generated microwave vector signal. In addition, the phase shift introduced by the delay line is frequency dependent; when the microwave frequency is changed, the time delay must be re-tuned to make the phase shift identical to 90°.

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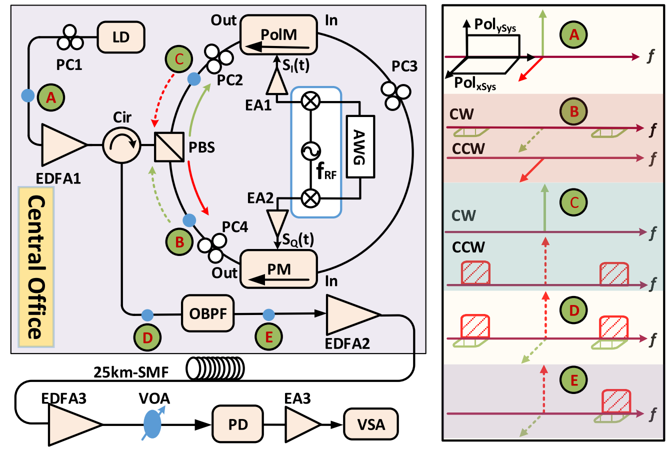

Fig. 1. Experimental setup. CO, central office; LD, laser diode; EDFA, erbium-doped fiber amplifier; Cir, circulator; PBS, polarization beam splitter; PolM, polarization modulator; PM, phase modulator; EA, electronic amplifier; PC, polarization controller; OBPF, optical band-pass filter; VOA, variable optical attenuator; PD, photodetector; VSA, vector signal analyzer.

In this letter, we propose a novel approach to generating a microwave vector signal using a simplified system with better stability. In the proposed system, a linearly polarized light wave is split by a polarization beam splitter (PBS) and sent to a Sagnac loop in which a polarization modulator (PolM) and a phase modulator (PM) are incorporated. For the Sagnac loop, as the light waves traveling along the clock-wise and counter clock-wise directions are in the same fiber, they experience identical environmental vibrations, thus the phase variations will be cancelled and the stability is not affected. The I/Q data streams of a vector signal are mixed with a microwave carrier, and then applied, respectively, to the PolM and the PM. Both the PolM and the PM are traveling-wave devices that support efficient modulation for a light wave traveling in one direction due to the match of velocities of the light wave and the microwave along that direction. For the other direction, due to the velocity mismatch, the modulation is very weak and can be negligible [6], [7]. At the output of the Sagnac loop, the optical signal generated by the PolM is combined with the orthogonally polarized phase-modulated signal. The optical signals are then filtered by an optical bandpass filter (OBPF) to filter out the -1^{st} order sidebands. After transmission over a single-mode fiber (SMF), the optical signals are applied to a PD. A microwave vector signal is generated by combining two microwave signals obtained from the phase-modulated and PolM-modulated signals at the output of the PD. A quadrature phase is introduced due to the inherent $\pi/2$ phase shift between the optical carrier and the $+1^{st}$ order sideband of the phase-modulated signal. The proposed approach is experimentally evaluated. The photonic generation of a 4.5 GHz microwave vector signal at 625 MSym/s with QPSK modulation and the transmission of the signal over a 25-km SMF are evaluated. An error-free transmission is achieved at a received optical power of 6 dBm. By incorporating I/Q imbalance compensation, an error-free transmission is achieved at a lower received power of 2 dBm.

II. Operation Principle

Fig. 1 shows the schematic diagram of the proposed microwave vector signal generation and transmission system. At the central office (CO), a light wave from a laser diode (LD) is sent through a polarization controller (PC1) to an erbium-doped fiber amplifier (EDFA1), and then launched into a Sagnac loop via a PBS. The Sagnac loop consists of a PolM, a PM, and three PCs (PC2, PC3, and PC4). The joint operation of the PolM, PC2 and the PBS corresponds to an MZM with the bias point determined by the static phase introduced by PC2 [8]. Two orthogonally polarized optical carriers are fed into the Sagnac loop via the PBS, enabling one carrier traveling along the clockwise direction and the other along the counter-clockwise direction. Note that both the PM and PolM are traveling wave devices; for a light wave launched in to a device from its output port, the velocity of the light wave and that of the modulating signal are mismatched, thus the modulation is very weak and can be neglected. As shown in Fig. 1, the input port of the PolM is connected to the input port of the PM. The clockwise optical carrier will pass through the PolM without modulation and be modulated at the PM, while the counter-clockwise optical carrier will pass through the PM and be modulated at the PolM. Unlike the conventional microwave quadrature upconversion, where the I/Q data streams of a vector signal are mixed with a pair of quadrature microwave carriers [9], in the proposed scheme the I/Q data streams of a vector signal are mixed with two identical microwave carriers, thus no 90° microwave hybrid is needed.

In the analysis, we take the two orthogonal directions of the principal axes of the PBS as the reference directions of the system. As shown in Fig. 1, the two principal axes of the PolM are aligned with the reference directions while the principal axis of the PM is aligned with the horizontal reference direction. Both PC2 and PC3 introduce a 45° rotation of the polarization to the bi-directionally traveling light waves, while PC4 is used to fine tune the polarization direction to make the output optical signals orthogonally polarized. The two optical signals at the output of the PBS are sent to an OBPF to filter out the -1^{st} order sidebands. After being amplified by a second EDFA (EDFA2), the optical signals are sent to a base station over the SMF. At the PD, a microwave vector signal is generated by combining the two beat signals obtained from the phase-modulated and the PolM-based intensity-modulated signals. Due to the inherent quadrature phase between the optical carrier and the $+1^{st}$ order sideband of a phase-modulated signal, a 90° phase shift is introduced to the Q component at the output of the PD, thus a microwave vector signal is generated. Mathematically, the microwave I/Q signals can be expressed as

$$S_I(t) = \sum_{n=0}^{\infty} A_{In}(t)\cos(\omega_{RF}t)\mathrm{Rect}\,(t-nT) \qquad (1.1)$$

$$S_Q(t) = \sum_{n=0}^{\infty} A_{Qn}(t)\cos(\omega_{RF}t)\mathrm{Rect}\,(t-nT) \qquad (1.2)$$

where $A_{In}(t)$ and $A_{Qn}(t)$ are the information-bearing signal amplitudes of the quadrature carrier, ω_{RF} is the angular frequency of the microwave carrier, and Rect(t) is given by

$$\text{Rect}(t) = \begin{cases} 0, & t < 0, \quad t > T \\ 1, & 0 < t < T \end{cases} \tag{2}$$

The electric field of the optical signal at the output of the OBPF can be expressed as

$$\begin{bmatrix} E_{xSys} \\ E_{ySys} \end{bmatrix} = \sum_{n=0}^{\infty} \text{Rect}\,(t - nT) \times \begin{bmatrix} E_{ySys0}\left\{J_0\left[\beta_{PM}A_{Qn}(t)\right]\cos(\omega_0 t) - J_1\left[\beta_{PM}A_{Qn}(t)\right]\cos\left[(\omega_{RF}+\omega_0)\,t - \frac{\pi}{2}\right]\right\} \\ \frac{\sqrt{2}}{2}E_{xSys0}\left\{J_0\left[\beta_{PolM}A_{In}(t)\right]\cos(\omega_0 t + \frac{\pi}{4}) - J_1 \times \left[\beta_{PolM}A_{In}(t)\right]\cos\left[(\omega_{RF}+\omega_0)\,t + \frac{\pi}{4}\right]\right\} \end{bmatrix} \tag{3}$$

where E_{xSys0} and E_{ySys0} are the amplitudes of the electrical fields of the incident light waves along the reference directions, ω_0 is the angular frequency of the light wave, β_{PolM} and β_{PM} are given by $\pi/2\text{V}_{\pi PolM}$ and $\pi/2\text{V}_{\pi PM}$, where the $\text{V}\pi_{\text{PolM}}$ and $\text{V}\pi_{\text{PM}}$ are the half-wave voltages of the PolM and the PM, respectively, and J_0 and J_1 are the Bessel functions of the first kind of orders 0 and 1.

The in-band photo-current generated at the PD is given by

$$i_{out}^{RF}(t) \propto \sum_{n=0}^{\infty}\text{Rect}\,(t-nT) \times (-1) \times \left\{ \begin{array}{l} \frac{1}{2}E_{xSys0}^2 J_0\left[\beta_{PolM}A_{In}(t)\right] J_1\left[\beta_{PolM}A_{In}(t)\right] \times \cos\left(\omega_{RF}t\right) \\ +E_{ySys0}^2 J_0\left[\beta_{PM}A_{Qn}(t)\right] J_1\left[\beta_{PM}A_{Qn}(t)\right] \times \cos\left(\omega_{RF}t - \frac{\pi}{2}\right) \end{array} \right\} \tag{4}$$

As can be seen from (4) a vector signal with an amplitude of $\frac{1}{2}E_{xSys0}^2 J_0\left[\beta_{PolM}A_{In}(t)\right] J_1\left[\beta_{PolM}A_{In}(t)\right]$ for the I component, and that of $E_{ySys0}^2 J_0\left[\beta_{PM}A_{Qn}(t)\right] J_1\left[\beta_{PM}A_{Qn}(t)\right]$ for the Q component at a carrier frequency of ω_{RF} is generated. As the recovered microwave I/Q components are exclusively generated by beating between the optical carrier at ω_0 and the $+1^{\text{st}}$ order sideband at $\omega_0 + \omega_{RF}$, thus the generated microwave vector signal is immune to the chromatic-dispersion-induced power fading.

III. Experiment

An experiment based on the setup given by Fig. 1 is performed. A light wave with a wavelength of 1552.034 nm and an optical power of 7 dBm from the LD is sent through PC1 to EDFA1, which has an output saturation power of 12 dBm and is employed to boost the power of the light wave before sending it to the Sagnac loop via the PBS, with the vertically polarized light wave traveling along the clockwise direction and the horizontally polarized along the counter-clockwise direction. The I/Q data streams of a vector signal at 625Mb/s with on-off keying modulation are generated and up-converted to 4.5 GHz by an AWG (Tektronix AWG7102). Due to the velocity mismatch, the clockwise light wave is modulated by the Q component at the PM, and the counter-clockwise light wave is modulated by the I component at the PolM. The optical signals are combined at the PBS and sent to the OBPF (Finisar WaveShaper 4000S) to filter out the -1^{st} order sidebands for both polarizations. The effect of the OBPF is illustrated in the Fig. 2, where the -1^{st} order sidebands of both polarizations are filtered out by the OBPF. Then, the filtered signals are amplified by EDFA2 and sent to the base station via the 25-km SMF. To evaluate the quality of the received signal as a function of the received optical power, after transmission over the 25-km SMF, the power of the signals are adjusted by a third EDFA (EDFA3) and a variable optical attenuator. The signals are photo-detected at the PD (Discovery Semiconductors DSC740). The beating between the optical carrier and the co-polarized sideband for each polarization direction will recover a microwave signal, and the combination of the recovered signals would produce a microwave vector signal with QPSK modulation at 4.5 GHz. In the experiment, the generated QPSK signal is amplified by a 20-dB electrical amplifier (Agilent 83006A), and sent to a vector signal analyzer (VSA) to evaluate the signal transmission performance. Note that the VSA is implemented using a high-performance real-time oscilloscope (Agilent DSOX93204A) and its associated software (Agilent 89600).

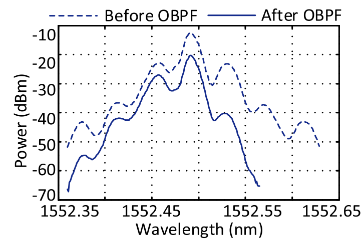

Fig. 2. The optical signals of both polarizations before and after the OBPF.

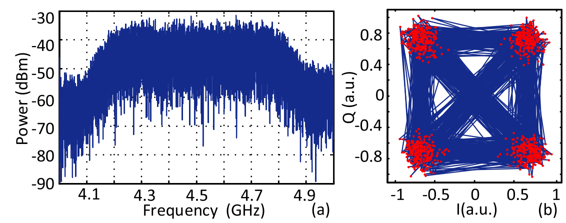

Fig. 3. Experimental results for the generation of a microwave vector with a signal symbol rate of 625 MSym/s. (a) The spectrum of the generated QPSK. (b) The constellation of the generated QPSK signal.

In the experiment, when the optical power at the input of the PD is 2 dBm, the spectrum of the generated QPSK signals at 4.5 GHz is shown in Fig. 3(a), and the back-to-back (BTB) constellation of the generated microwave vector signal is shown in Fig. 3(b). The EVM is 15.77%, corresponding to a BER of 1.15×10^{-10}, which is calculated based on the equation given in [10].

The transmission performance is then evaluated. Fig. 4(a) shows the constellation of the microwave vector signal after transmission over 25-km SMF for a received power of 2 dBm. As can be seen, the amplitude mismatch and phase misalignment between the recovered I/Q signals are observed, which are the major deterioration factors affecting the signal quality. The amplitude mismatch is mainly resulted from the difference

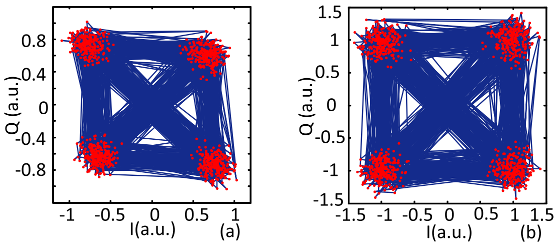

Fig. 4. Experimental results for the transmission of the generated microwave vector over a 25-km SMF (a) Without the GSOP, and (b) with the GSOP.

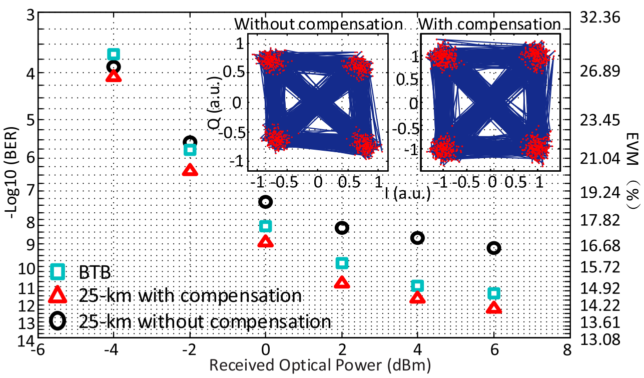

Fig. 5. EVM and BER measurements for the generated QPSK signal.

between the half-wave voltages of the PM and the PolM. The phase misalignment is mainly resulted from the path difference due to the birefringence of the link. The I/Q imbalance in the recovered signal can be corrected by the Gram-Schmidt orthogonalization procedure (GSOP) [11]. Fig. 4(b) shows the corrected constellation after using the GSOP. The EVM of the received signal is 17.16% without the GSOP, corresponding to a BER of 2.8×10^{-9}, which is improved with the GSOP to 15.19%, corresponding to a better BER of 2.3×10^{-11}.

Then, the EVMs of the generated QPSK signals as a function of the received optical power for BTB, 25-km SMF transmission without and with the GSOP are measured. The EVM measurements and the converted BERs are shown in Fig. 5. As can be seen, an error-free transmission over a 25-km SMF can be achieved at a received power of 2 dBm with the GSOP and 6 dBm without the GSOP.

The constellations for the received microwave vector signal after 25-km transmission without and with the GSOP for a received optical power of 6 dBm are also shown in Fig. 5. The corresponding BERs are 4.03×10^{-10} and 7.09×10^{-13}. The relatively high optical power required to achieve an error free transmission is due to the large system loss, including the insertion losses introduced by the PolM and the PM which are about 4.5 dB and 5 dB, respectively. In the experiment, the loss is compensated by three EDFAs. If the system is implemented using a photonic integrated circuit (PIC) including the PM and the PolM and other polarization maintaining components, the loss will be greatly reduced.

IV. Discussion and Conclusion

In the experiment, the microwave frequency is set at 4.5 GHz, which is limited by the sampling rate of the AWG. The bandwidth of the OBPF is more than 10 GHz (0.08 nm), which is too wide to filter out the unwanted sideband without introducing a loss to the optical carrier and the wanted sideband, which would limit the performance of the system. If an OBPF with a smaller bandwidth is used, the performance can be further improved. In addition, the microwave frequency can be doubled without the need to increase the bandwidth of the PM and PolM if the OCS technique is used, similar to what we did in [2]. Thus, it is viable to generate a microwave vector signal at a much higher frequency using low-frequency opto-electronic components.

In the analysis we assume that the PolM and the PM have effective forward modulation and zero reverse modulation. If the reverse modulation is not small enough and cannot be ignored, the crosstalk introduced from counter-propagating signals for both the I and Q components would lead to a reduced signal quality. A detailed theoretical analysis and experimental verifications will be reported elsewhere.

In conclusion, a novel approach to generating a microwave vector signal based on a bi-directional use of a PolM and a PM in a Sagnac loop was proposed and experimentally demonstrated. The fundamental concept of the approach was the use of a PM to produce a phase-modulated signal with an inherent quadrature phase between the optical carrier and the $+1^{\text{st}}$ order sideband, which was used to introduce the quadrature phase to the microwave signals at the output of the PD without the need for a wideband 90° hybrid. The photonic generation of a 4.5 GHz microwave vector signal at 625 MSym/s with QPSK modulation and the transmission of the signal over a 25-km SMF were evaluated. An error-free transmission was achieved at a received optical power of 6 dBm. By incorporating the GSOP, an error-free transmission was achieved at a lower received power of 2 dBm.

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