SSBI-Free Photonic Armstrong Method for Ultra-Wideband PM Signal Generation

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Abstract *We propose a novel scheme to generate a wideband PM signal using a photonic Armstrong method, accomplishing both bandwidth expansion and the total elimination of SSBI simultaneously. We experimentally confirm the validity of the concept and demonstrate a 60-GHz-class PM signal generation.*

Introduction

Signal generation using frequency modulation (FM) and phase modulation (PM) is the key fundamental function for various types of applications, such as radar (e.g., FMCW radar systems [1]) and analogue communication systems. Wideband FM/PM signal generation is practically important, especially in analogue communication systems, since FM/PM systems reduce the amount of noise and thus improve signal quality significantly by spectral expansion [2]. For example, FM systems have been commercially employed in cable television (CATV) systems since the 1990s [3]. Moreover, recent studies have shown that FM/PM systems can also support high-quality signal transmission without incurring signal-to-signal beat interference (SSBI) [4,5]. By using an SSBI-free PM system, signal transmission with high order QAM, up to 1024 QAM, targeting analogue mobile fronthaul links, was demonstrated with an optical phase modulator (PM). However, such wideband PM signal generation requires an extremely high input voltage, usually much greater than V_π, to the optical PM, which would effectively make such a system impractical. Various attempts at a device level for reducing V_π of optical modulators have been reported [6,7]. However, such modulators are still under development and are not available as off-the-shelf devices at this time. On the other hand, there exist several FM/PM bandwidth expansion techniques at a system level. For example, in classical theories of communication, there is a wideband FM/PM generation method, namely, the Armstrong indirect method [2]. In this method, a narrowband signal is first generated and then converted to a wideband signal with the help of a frequency multiplier. Therefore, by using such a system-level approach, we can also increase signal bandwidth without incurring a high-voltage problem.

In this paper, we demonstrate the Armstrong method enabled by direct detection (DD) for the photonic generation of wideband PM signals. The proposed photonic Armstrong method has two significant benefits: (i) it can easily expand signal bandwidth to double that of the SSBI-free PM system reported in [4,5], and (ii) it never incurs the SSBI components as with the SSBI-free system in the bandwidth expansion process. Namely, the proposed Armstrong method accomplishes both bandwidth expansion and the complete elimination of SSBI simultaneously. We experimentally confirm the validity of the concept and demonstrate a 60-GHz-class PM signal generation.

Working principle

If the input to a second-order nonlinear device is a narrowband PM signal expressed as $s(t)=\cos[\omega_{RF}t+\theta(t)]$, where ω_{RF} is the angular frequency of the PM carrier and $\theta(t)$ is the original signal, the output is given as $\cos^2[\omega_{RF}t+\theta(t)]=\frac{1}{2}+\frac{1}{2}\cos[2\omega_{RF}t+2\theta(t)]$. As a result, we can double the frequency deviation of the PM signal without losing information of the original signal $\theta(t)$. Since DD naturally induces such a second-order nonlinearity, it can be utilized as a second-order multiplier. In the photonic Armstrong method, the optical PM signal $e^{j\omega_c t}\cos[\omega_{RF}t+\theta(t)]$ is detected by a single PD, where ω_c is the angular frequency of the optical carrier. The output current is given as:

$$
\begin{aligned}
I_{PD} &\propto \left|e^{j\omega_c t}\cos[\omega_{RF}t+\theta(t)]\right|^2 \\
&= \frac{1}{4}\left|e^{j\{(\omega_c+\omega_{RF})t+\theta(t)\}}+e^{j\{(\omega_c-\omega_{RF})t-\theta(t)\}}\right|^2 \\
&= \frac{1}{4}\left|e^{j\{(\omega_c+\omega_{RF})t+\theta(t)\}}\right|^2+\frac{1}{4}\left|e^{j\{(\omega_c-\omega_{RF})t-\theta(t)\}}\right|^2 \\
&\quad +\frac{1}{2}\mathrm{Re}\left[e^{j\{2\omega_{RF}t+2\theta(t)\}}\right]
\end{aligned}
\tag{1}
$$

The first and second terms in the last equation are SSBI components of the upper and the lower sidebands of the PM signal. Note that the sideband components are complex conjugate pairs. As with the SSBI-free PM system, since

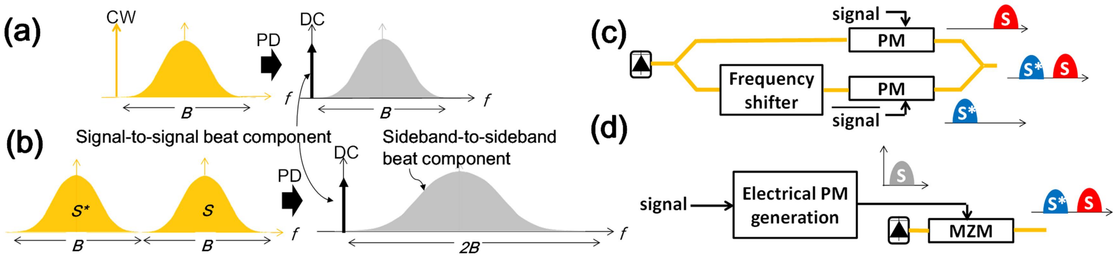

Fig. 1: Schematic spectra in the PM generation process: (a) the carrier-assisted PM system and (b) the Photonic Armstrong method. The right figures show the architectures of (c) optical and (d) electrical photonic Armstrong modulators.

the amplitudes of the sideband components are always constant, their SSBI terms become just direct-current (DC) components and never mix with the desired signal. On the other hand, the third term is a sideband-to-sideband beat component. Such a component severely degrades performance in a typical intensity-modulated double-sideband system. However, if we limit the discussion to the PM system, it brings a significant benefit of bandwidth expansion. In fact, as can be seen in Eq. (1), DD accomplishes bandwidth expansion double that of the original PM signal.

Figure 1(b) shows the schematic spectra in the PM generation process. In contrast to the conventional carrier-assisted PM system shown in Fig. 1(a), the optical signal in the photonic Armstrong method has a conjugated component instead of the carrier. Therefore, after PD detection, the sideband-to-sideband beat component, or the beat component between the original and the conjugated signals, appears with the double frequency deviation without incurring the SSBI components, as confirmed in Eq. (1). Figures 1(c) and (d) show two possible architectures of the photonic Armstrong modulator. The PM signal is generated optically in Fig. 1(c), while it is generated electrically in Fig. 1(d). In the former architecture, a two-tone signal is generated first, and then an optical PM modulates each tone. Since one of the sideband components needs to be the complex conjugate of the other one, the driving signal needs to have a polarity opposite to that of the other port. This architecture is quite similar to the push-pull configuration of a Mach-Zehnder modulator (MZM). However, in contrast to MZM, the signals at the two arms have different wavelengths. In the latter architecture, the electrically generated PM signal is injected into an MZM biased at the null transmission point. This architecture can easily generate the conjugated signal since the modulated optical signal has a double sideband. However, since the spectrum is already expanded in the electrical domain, the MZM bandwidth needs to be large enough to accommodate the bandwidth-extended electrical signal.

Experiments

We experimentally confirmed the validity of the concept of the principle above. The experimental setup is shown in Fig. 2(a). Note that we employed the architecture shown in Fig. 1(c). A light source at 1550 nm was divided into two using an optical coupler. One of the light sources was injected into an optical frequency shifter (OFS), consisting of an intensity modulator (IM) driven by a 30-GHz sinusoidal wave and an optical band-pass filter (OBPF) for eliminating one of the sidebands and the original component. Therefore, the frequency of the tone signal was shifted by 30 GHz. Then the signal was injected into an optical PM, which was driven by an arbitrary waveform generator (AWG) operating at 100 GS/s. On the other path, the light was directly injected into another optical PM. The PM was also driven by the same signal but with an opposite polarity to generate the conjugated signal. The path lengths were carefully adjusted using optical variable delay lines (VDLs). After combining the two outputs from the PMs, the signal was amplified by an erbium-doped fiber amplifier (EDFA), and then detected by PD. Finally, the output from the PD was captured by a digital sampling oscilloscope (DSO) operating at 160 GS/s.

First, we quantitatively confirmed the concept by evaluating error-vector magnitude (EVM) values. We generated an orthogonal-frequency-division-multiplexed (OFDM) signal having a bandwidth of 1 GHz, and sent the signal to the AWG. The signal consisted of 880 subcarriers modulated in 16QAM and 176 subcarriers modulated in QPSK for pilots. At the receiver side, the PM demodulation was performed first, and then the OFDM signal was demodulated. Finally, the EVM value was measured. We also measured the EVM values using the conventional carrier-assisted PM system for comparison. In the carrier-assisted PM system, one of the two carriers must remain unmodulated. Thus, we stopped one of the two

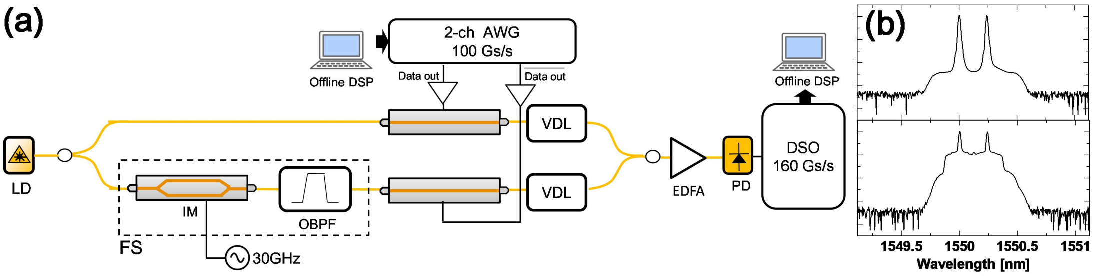

Fig. 2: Experimental setup (a) and the observed optical spectra before modulation (top) and after modulation (b).

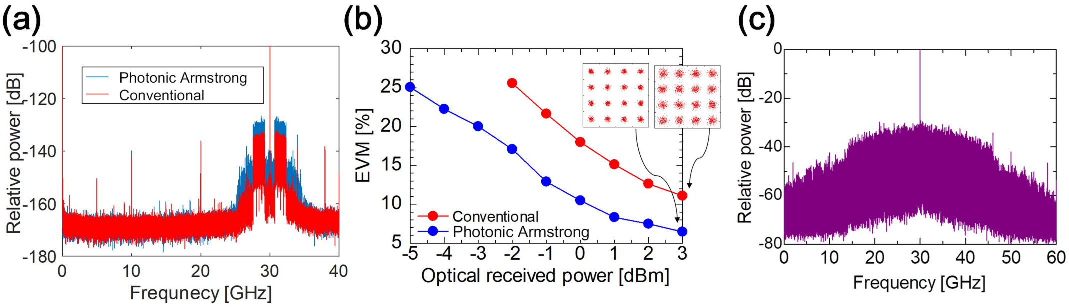

Fig. 3: (a) Observed spectra after PD detection, (b) the measured EVMs, and (c) the spectrum of the 60-GHz-class PM signal when using the photonic Armstrong method.

AWG outputs.

Figure 3(a) shows the observed spectra after PD detection. The blue plot shows the spectrum of the photonic Armstrong method, while the red plot shows that of the conventional carrier-assisted method. It can be seen that the Armstrong method could successfully broaden the spectrum. Moreover, the SSBI components which usually appear around the DC region were not observed in either case as theoretically predicted in Eq. (1). Figure 3(b) shows the measured EVMs as a function of received optical power with insets showing constellations. The blue dots indicate the EVMs when using the photonic Armstrong method, while the red dots indicate those when using the carrier-assisted method. As can be seen in the figure, the Armstrong method improved the EVM performance by 3 dB compared with the carrier-assisted method. It is known that the FM/PM systems can improve the SNR performance by 6 dB for each doubling of the signal bandwidth [8]. Since the output electrical power increases with the square of the received optical power, this 3-dB improvement corresponds to a 6-dB improvement of the electrical power. Therefore, the 3-dB improvement of the received optical power is clear evidence that the Armstrong method doubled the signal bandwidth. Note that we found that the dominant noise source in this system was noise induced in DSO. Therefore, the noise level was always the same regardless of received optical power during the measurements.

Next, we demonstrated ultra-wideband PM signal generation using the Armstrong method. First, we generated a 16-Gbaud QPSK signal, and then filtering was performed using a raised-cosine filter with a roll-off factor of 0. It was up-converted to a centre frequency of 8 GHz. Since the up-converted signal had a bandwidth of 16 GHz, there was no gap from the DC. At the receiver side, the signal was equalized using the decision-directed least-mean-square (DD-LMS) algorithm [6] after PM demodulation and down-conversion to the baseband. The EVM value of the QPSK signal was measured to be 8.2 %, while the EVM measured using the carrier-assisted method was 9.5 %. It should be noted that the EVM in the electrical back-to-back (B2B) case was already around 8 %. Therefore, we could not improve the EVM value even with the PM system. However, we believe that if we can further improve the electrical B2B performance, the EVM value can also be improved by using the Armstrong method. Figure 3(c) shows the electrical spectrum after PD detection. We observed that the PM signal occupied bandwidth of 60 GHz.

Conclusions

We have proposed an SSBI-free photonic Armstrong method, accomplishing both bandwidth expansion of PM signals and the complete elimination of the SSBI components. We experimentally confirmed the validity of the concept and demonstrated a 60-GHz-class PM signal generation by using the photonic Armstrong method.

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