A Novel Carrier-Eliminated Optical Millimeter-Wave Generation Using a Single Over-Driven Phase Modulator

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Abstract: A carrier-eliminated 40-GHz optical mm-wave generated by over-driving a phase modulator is first proposed. Error-free transmission over 10-km SMF-28 and 3-m wireless is successfully demonstrated with a highly relaxed bandwidth requirement for sideband optical filtering.

OCIS codes: (060.4250) Networks; (060.4510) Optical communications

1. Introduction

Millimeter-wave (mm-wave) radio-over-fiber (RoF) access system has gained lots of attention recently due to its potential ability to offer ubiquitous multi-gigabit wireless services through centralized, simplified remote access units [1]. One of the major challenges for such system is to source a cost-efficient optical mm-wave transmitter at the central office, and so far several approaches employing external optical modulators have been presented [1-4]. Among them, phase-modulator-based optical mm-wave generation is considered one of the most reliable category since a phase modulator (PM) requires no bias control that avoids bias drafting and suffers lower insertion loss compared to a Mach-Zehnder modulator (MZM), and thus it has been recently adopted in a mm-wave RoF field-trial demonstration requiring long-term stability for delivering HD video over hybrid optical-wireless interfaces [5]. No matter using PM or MZM, to suppress optical carrier and double the beating frequency, a narrowband optical filter is usually required. Therefore, in this paper, we propose and experimentally demonstrate an innovative optical mm-wave generation method with optical carrier eliminated by simply over-driving a PM, which highly relax the constraint on the filter bandwidth since a wideband optical filter is used not to select the specific central carrier, but to filter out all the high order sidebands. Characteristics like wavelength detuning range, filter bandwidth requirement, and harmonics fluctuation due to fiber dispersion are also studied.

2. Operating Principle

Fig. 1 illustrates the conceptual diagram of the proposed scheme to generate an optical mm-wave with eliminated carrier by simply using an over-driven phase modulator (OD-PM). By definition, a phase-modulated optical carrier is generated by the phase modulation of a continuous wave (CW) light source $E_0\exp(j\omega_0 t)$ and its complex amplitude is given by

$$E_{PM}(t) = E_0 e^{j\omega_0 t} e^{j\beta\cos\omega t} = E_0 \sum_{n=-\infty}^{\infty} (j)^n J_n(\beta) e^{j(\omega_0 + n\omega)t} \quad (1)$$

, where E_0 and ω_0 are the amplitude and angular frequency of the CW, β is the modulation index, $J_n(\beta)$ is the Bessel function of the first kind of order n, and ω is the angular frequency of the modulating microwave signal. The phase-modualted optical carrier features multiple upper and lower optical sidebands centered at ω_0, and its nth sideband exhibits approximated Bessel amplitude $E_0(j)^n J_n(\beta)$. Inset (a) shows the plot of Bessel function of the first

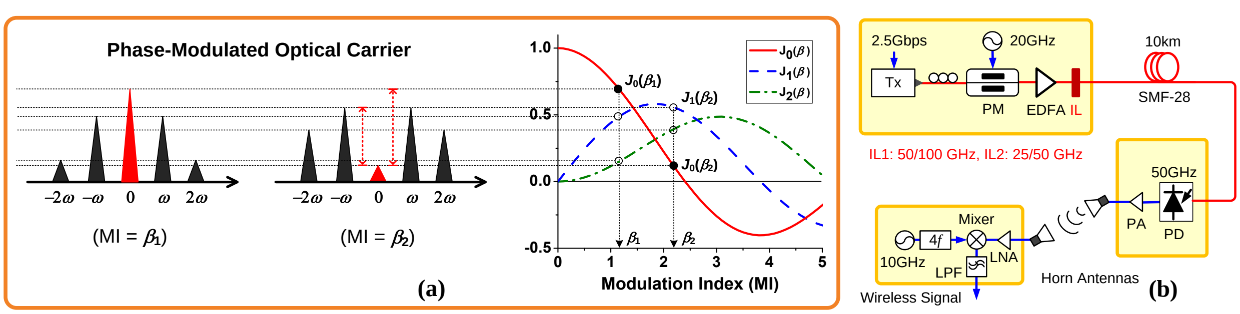

Fig. 1 Conceptual diagram of the proposed optical mm-wave generation with eliminated carrier using an OD-PM.

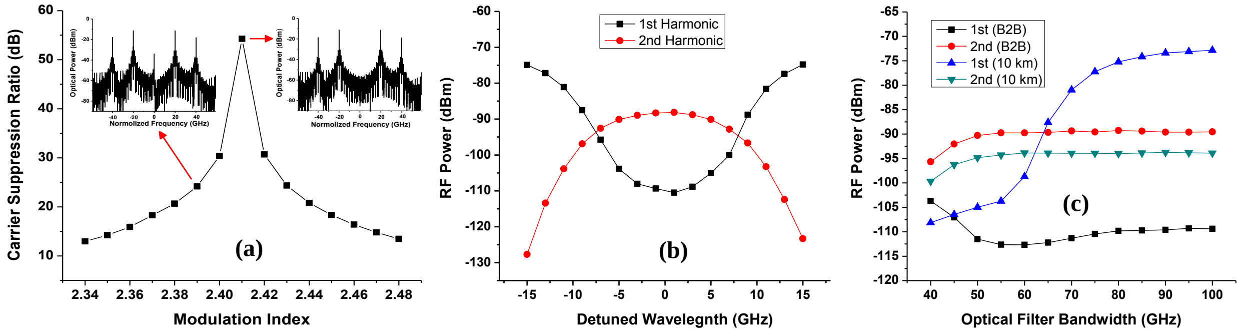

Fig. 2 Simulation analysis of (a) carrier-suppression radio versus modulation index, (b) wavelength drafting/offset tolerance, and (c) 3-dB filter bandwidth requirement for the proposed OD-PM optical mm-wave generation scheme.

kind for orders n=0, 1, and 2, and details its relationship to the normalized amplitude of each sideband, where relative sideband frequencies are displayed. As can be seen, when the modualtion index (MI) increases from β_1 to β_2, the amplitude of central optical carrier will decrease accordingly from $J_0(\beta_1)$ to $J_0(\beta_2)$, which means high driving voltage will help to suppress or even entirely remove the optical carrier in such phase-modulator-based optical mm-wave generation. Note that although the proposed scheme allows ease of carrier suppression without traditionally required bias control and narrow-band optical notch filter, the enhanced higher order sidebands (as illustrated in Fig. 1) will still require a optical filter with a wide 3-dB bandwidth at least two times of the swept frequency ω to reduce them especially for WDM applications, which is, however, more easily available.

We conducted simulation analysis via *VPItransmissionMaker 8.0*. Fig. 2(a) shows that the carrier-suppression ratio (CSR) of a generated a 40-GHz optical mm-wave can be higher than 25 dB with MI between 2.39 and 2.43, and can ultimately go up to 55 dB at MI = 2.41. Fig. 2(b) displays the RF power variation of the 1st (20-GHz) and 2nd (40-GHz) harmonics versus the wavelength offset of the OD-PM optical carrier, where the swept frequency was 20 GHz, and a 100-GHz 4th order Gaussian optical filter was considered. The 2nd to 1st harmonics suppression ratio (HSR) is larger than 15 dB within the detuning range of ±5 GHz. Fig 2(c) depicts that 50 to 100 GHz filter bandwidth is ideal to generate a 40 GHz carrier with HSR of larger than 20 dB in back to back (B2B) case; however, in 10-km fiber transmission case the HSR will gradually reduce and become negative as the filter bandwidth increases. This is because in B2B case two 1st order sidebands of the OD-PM carrier are π out-of-phase in nature, and 1st harmonic will not exist since the beating between 1st and 2nd upper sideband, and that between 1st and 2nd lower sideband will be cancelled with each other, but his is not the case when that π out-of-phase condition is violated by fiber dispersion-induced phase rotation. Nevertheless, we found that the RF power of the 2nd harmonic (40-GHz) after 10-km fiber will remain constant regardless of the change in filter bandwidth.

3. Experimental Setup and Results

Fig. 1(b) shows an experimental setup to generate and deliver a carrier-suppressed optical mm-wave at 40-GHz using OD-PM technique. A 2.5-Gbps pseudorandom binary sequence (PRBS) baseband signal with a word length of 2^{31}-1 directly modulated an optical transmitter (Tx) at 1553.2 nm, and was then fed into a $LiNbO_3$ optical PM with half-wave voltage less than 4V driven by a 20-GHz sinusoidal wave at 6.4V_{pp} to achieve carrier-suppressed optical upconversion. A 50/100-GHz optical interleaver (IL1) was used to select 1st order upper and lower sidebands and to suppress higher order ones. After 10-km fiber transmission, the 40-GHz optical mm-wave was directly detected by a 50-GHz photodiode (PD), boosted by a power amplifier (PA) and transmitted through a 40-GHz horn antenna with 20-dBi gain. The optical input power to the PD is about 2 dBm and the equivalent isotropically radiated power (EIRP) is around 17 dBm. 40-GHz mm-wave was detected by a direct-downconversion receiver comprising a low noise amplifier (LNA), a mixer, a 10-GHz synthesizer, a 1×4 multiplier and a 2.8-GHz low-pass filter (LPF). For comparison, we also evaluated the traditional scheme by replacing the IL1 with a 25/50-GHz optical interleaver (IL2) functioning as a narrow-band carrier-suppressing filter and reducing the RF voltage to about 4.3 V_{pp}. Fig. 3(a) and (b) illustrates the measured optical spectra of the generated optical carrier with and without OD-PM. Over 35-dB CSR were observed for both cases. In Fig. 3(c), the bit error rate (BER) performance for both cases in wireline transmission was compared. After 10-km SMF-28, the measured power penalties were 1.4-dB and 1.2-dB with and without OD-PM at 10^{-9} BER, respectively. The 0.2-dB penalty difference is mainly caused by the residual high-order sidebands as shown in Fig. 3(a). This can be further improved by employing non-periodic filers, which is even better

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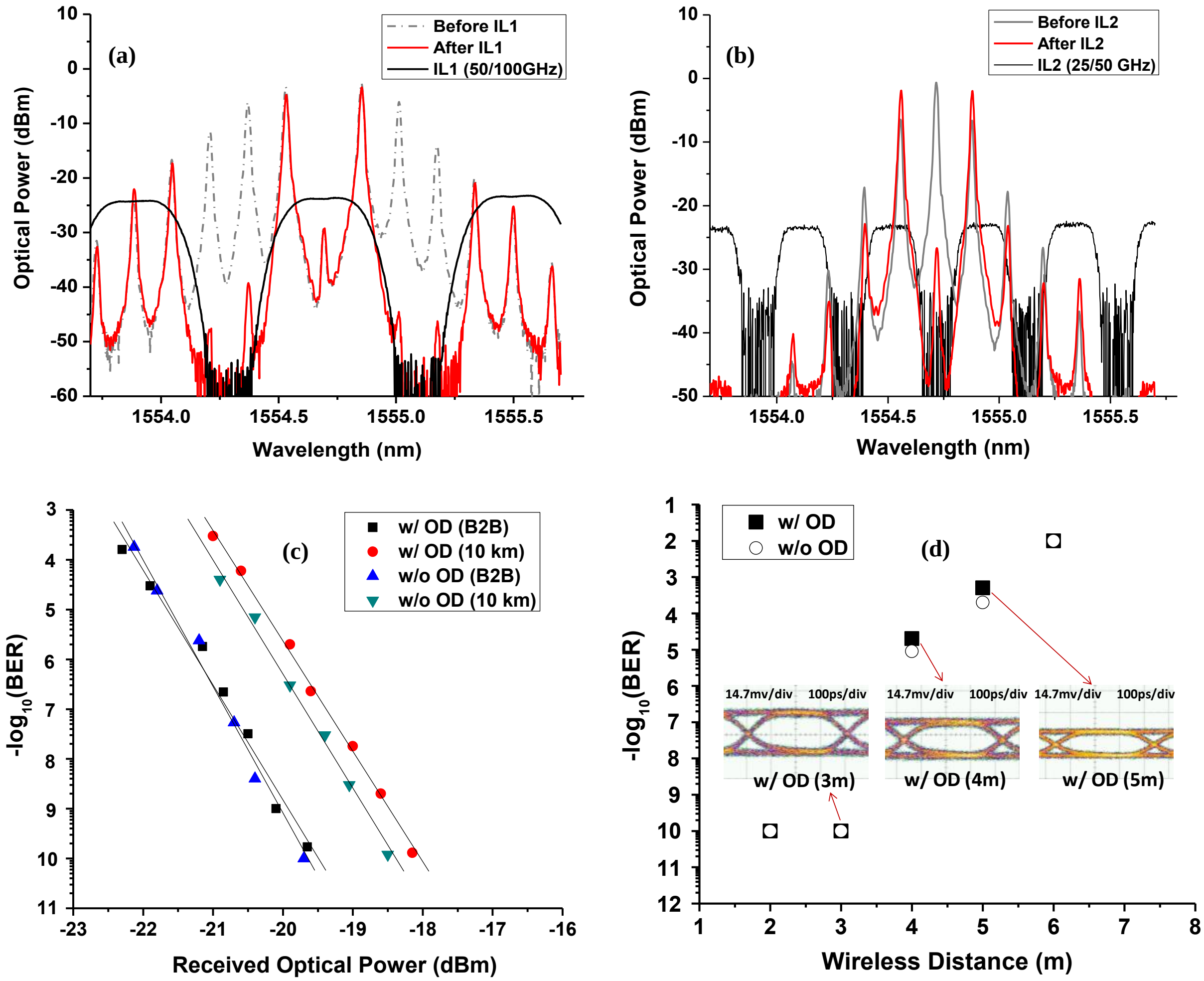

Fig. 3 Measured optical spectra of the optical mm-wave generation scheme (a) with and (b) without OD-PM, BER performance of (c) wireline only transmission and (d) hybrid optical-wireless link with and without OD-PM.

in terms of availability. Fig. 3(d) displays the BER performance as a functional of wireless propagation distance for both cases after 10-km SMF-28. Both cases have similar performance of achieving 3-m error-free distance at the same EIRP, and the rapid BER drop reflects the free-space loss characteristic of a 40-GHz radio at a given transmitting power. In addition, the insets show the measured 2.5-Gbps downconverted signal at different distances for the OD-PM case.

4. Conclusions

We propose and experimentally demonstrate an innovative carrier-eliminated optical mm-wave generation scheme using an over-driven phase modulator (OD-PM). No carrier-suppressing filter is required, but a wideband optical filter is needed to cut off high order sidebands for WDM applications. 40-GHz optical mm-wave carrying 2.5-Gbps signals with and without OD-PM exhibited equivalent link performance with error-free transmission over a combined link of 10-km SMF-28 and 3-m wireless, and only 0.2-dB difference in receiver sensitivity is observed at 10^{-9} BER.

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