Optical Millimeter-Wave Generation or Up-Conversion Using External Modulators

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***Abstract*—We have experimentally compared the performances of optical millimeter-wave generation or up-conversion using external modulators based on different modulation schemes. The generated or up-converted optical millimeter wave using the optical carrier suppression (OCS) modulation scheme shows the highest receiver sensitivity, highest spectral efficiency, and smallest power penalty over long-distance delivery. Moreover, the OCS modulation scheme has a simple configuration and low-frequency bandwidth requirement for both electrical and optical components. Employing an OCS modulation scheme, 16-channel dense wavelength-division multiplexing signals at 2.5-Gb/s per channel have been up-converted to a 40-GHz carrier simultaneously.**

***Index Terms*—All-optical up-conversion, optical carrier suppression modulation, optical millimeter generation, radio over fiber.**

I. Introduction

OPTICAL millimeter-wave generation and all-optical up-conversion are key techniques in radio-over-fiber (ROF) systems. Recently, a few new schemes for realizing these functions have been reported [1]–[10]. Among them, the simplest and the most accurate scheme to generate optical millimeter wave at high frequency up to 40 GHz is to use external intensity modulation [2]. People have demonstrated the millimeter-wave generation using external modulators based on different modulation schemes including double-sideband (DSB), single-sideband (SSB), and optical carrier suppression (OCS) [4]–[8], but there is lack of experimental comparison and investigation at a system level, especially for multiple-channel and ultrabroad-band systems up to 2.5 Gb per channel. For example, most investigations of [6] focus on a generalized study when different modulation schemes are used, and there is no experimental result for a complete system.

SSB modulation is superior to DSB on extending the delivery distance for the optical millimeter wave due to its reduced effects in suffering dispersion in a single-mode fiber (SMF), but the receiver sensitivity for SSB is relatively low because the dc component at the central wavelength is very large [5]. In order to improve the receiver sensitivity, a fiber Bragg grating (FBG) can be used to suppress the dc component [5]. However, the FBG is sensitive to temperature, which will need a complex control system to stabilize its operation. Moreover, most power will be lost due to the FBG reflection.

A dual-mode lightwave can be generated when a single-mode laser is transmitted over an $LiNbO_3$ modulator (LN-MOD) based on optical carrier suppression (OCS) modulation [2]. Using an optical filtering technique, the dual-mode lightwaves are separated before one mode is used to carry the optical millimeter wave. Since the FBG filters or other optical components are used, the configuration of this optical millimeter-wave source is complex and unstable for long-term operation.

In this letter, we experimentally compare the performances of the optical millimeter-wave generation or up-conversion based on different modulation schemes using external modulator. We will demonstrate that the optical millimeter wave generated by the OCS modulation scheme possesses the highest receiver sensitivity, lowest spectral occupancy, lowest bandwidth requirement for RF signal, electrical amplifier (EA), and optical modulator as well as smallest power penalty over la ong delivery distance. The OCS modulation scheme can be easily implemented and upgraded with a large number of dense wavelength-division multiplexing (DWDM) channels simultaneously without any power saturation or other nonlinear impact [9], [10]. Relying on this method, we experimentally demonstrate 16 $\times$ 2.5 Gb/s DWDM signals in a seamlessly integrated ROF optical network with record setting on both the overall capacity and reach.

II. Comparison of Different Modulation Formats

The experimental setup for optical millimeter-wave generation and transmission is shown in Fig. 1. A continuous wave (CW) lightwave was generated by a distributed feedback laser diode (DFB-LD) at 1554.7 nm and modulated via an LN Mach–Zehnder modulator (LN-MZM) driven by 2.5-Gb/s pseudorandom bit sequence electrical signal with a word length of $2^{31} - 1$. A dual-arm LN-MZM modulator (D-LN-MZM) biased at v_π and driven by two complementary 20-GHz clocks was used to realize OCS. The carrier suppression ratio is larger than 25 dB, the repetitive frequency of the generated LO optical signal is 40 GHz, and the duty cycle of the LO is 0.6. The optical spectrum and the eye diagram after OCS are insets (i) and (ii) in Fig. 1, respectively. Then, the generated millimeter optical wave was amplified by an erbium-doped fiber amplifier

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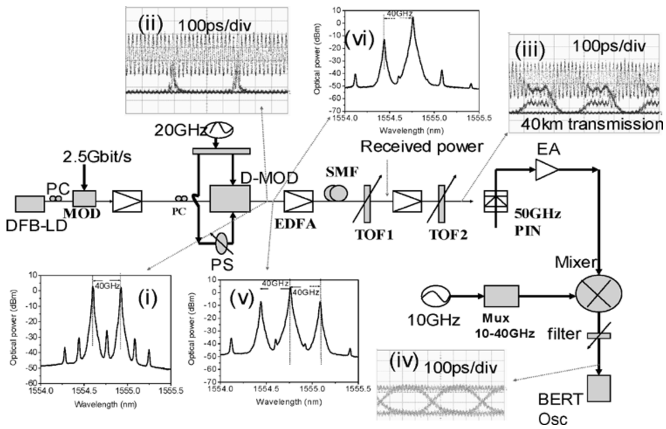

Fig. 1. Experimental setup for optical millimeter-wave generation by using OCS modulation scheme. PC is polarization controller, D-LN-MOD is dual-arm LN-modulator, TOF is tunable optical filter, and PS is phase shifter. Resolution for all optical spectra is 0.01 nm.

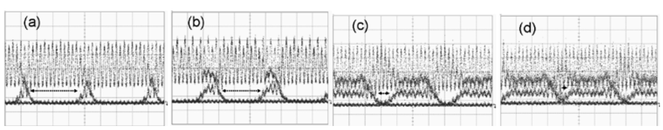

Fig. 2. Optical eye diagrams after optical millimeter-wave transmission over (a) 10-, (b) 20-, (c) 50-, and (d) 60-km SMF (100 ps/div).

(EDFA) to get a power of 5 dBm before it was transmitted over various lengths of SMFs. Fig. 2 shows the eye diagrams at different distances. The eye diagrams were measured by using an oscilloscope with a 50-GHz bandwidth. Inset (iii) in Fig. 1 is the eye diagram of the signal after transmission over 40-km SMF. For a dual-mode millimeter wave, [1] has shown that the RF power of the optical millimeter wave after transmission over 60 km is still high, even though the carrier frequency is 60 GHz. Since the optical millimeter wave has two peaks after OCS modulation, as shown in inset (i) of Fig. 1, it will suffer from dispersion in fiber when it is transmitted in SMF. The pulsewidth of the 2.5-Gb/s signal carried by the optical millimeter wave is approximately 400 ps. The two peaks with a wavelength spacing of 0.32 nm will have a walkoff time of 400 ps caused by fiber dispersion after the millimeter wave was transmitted over 74-km SMF with a group velocity dispersion of 17 ps/nm/km, which means that the eye will be fully closed after transmission over this distance. While considering the limited rise and fall times of the optical receiver and electrical amplifier, the maximum delivery distance will be shorter. Fig. 2 clearly shows this evolution due to the fiber dispersion. The unflat amplitudes of the optical carriers at 40 GHz as shown in Fig. 2(b) are caused by fiber dispersion. References [1] and [3] show that fiber dispersion causes the amplitude fluctuation of the carrier, but the RF power at 40 GHz does not disappear when the carrier is a pure dual-mode lightwave. Fig. 2(d) shows that the eye is almost closed after the optical millimeter wave was transmitted over 60 km.

At the receiver, the millimeter wave was filtered by a tunable optical filter (TOF1) with a bandwidth of 0.5 nm before it was preamplified by a regular EDFA with a small-signal gain of 30 dB. It was then filtered by TOF2 with a bandwidth of 0.5 nm before O/E conversion via a PIN PD with a 3-dB bandwidth of 60 GHz. The receiver is the same as that used in [10] and [11].

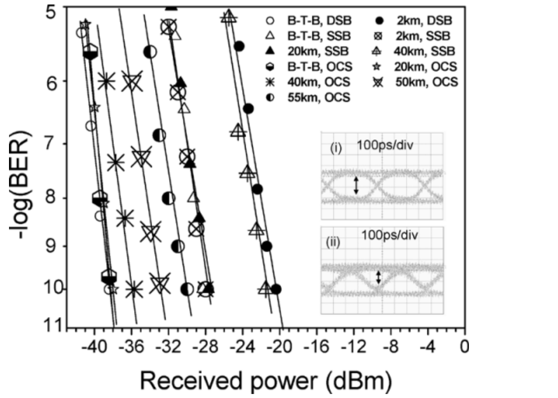

Fig. 3. BER curves and eye diagrams: (i) after 10 km and (ii) after 50 km.

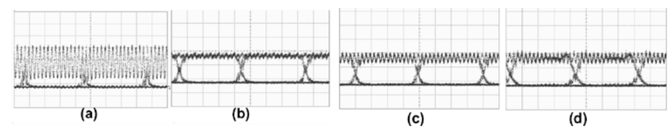

Fig. 4. Optical eye diagrams before and after optical millimeter-wave transmission (100 ps/div): (a) DSB, B-T-B, (b) DSB, 2 km, (c) SSB, B-T-B, and (d) SSB, 40 km.

The down-converted 2.5-Gb/s signal was detected by a bit-error rate (BER) tester, and its eye diagram without fiber transmission is inserted in Fig. 1 as inset (iv). The measured BER curves are shown in Fig. 3. For a BER of 10^{-9}, the receiver sensitivity is -39.7 dBm. The power penalty after 20-km transmission is negligible. After 40 km, the power penalty is 2 dB. However, the power penalty is increased largely when the signal is transmitted over 50 km, and there appears an error-floor of 10^{-6} after it is transmitted over 60 km. For comparison, we also generated DSB and SSB millimeter waves by using almost the same configuration as Fig. 1.

For DSB modulation scheme, only one arm of the D-LN-MOD was driven, the D-LN-MOD was biased at 0.5 v_π and the frequency of the driven RF signal was 40 GHz. Inset (v) in Fig. 1 shows that the generated millimeter wave occupies over 80-GHz bandwidth since it has two sidebands. Because the two sidebands have different velocities in SMF, the RF power at 40 GHz will disappear after transmitting over a certain length of SMF [2]. As an example, the eye diagram before and after a transmission over 2 km is shown in Fig. 4(a) and (b), respectively. It can be seen that RF power at 40 GHz is almost faded, which leads to a large power penalty after transmission. The measured BER curves in Fig. 3 show the power penalty is 17 dB at a BER of 10^{-9} after 2-km transmission. These results indicate that the DSB modulation-based scheme is not suitable for a large area access network.

For SSB modulation, the two electrical RF signals at 40 GHz to drive a D-LN-MOD have a phase shift of 90°, and the dc bias is 0.5 v_π. The generated optical millimeter wave covers only 40-GHz bandwidth, as shown in inset (vi) in Fig. 1, but the optical carrier to sideband ratio (CSR) is generally larger than 15 dB, which means it contains many dc components at the center wavelength; hence, the signal results in low receiver sensitivity. The optical eye diagram of the SSB modulation scheme is shown in Fig. 4(c) and (d) for back-to-back (B-T-B) and 40-km transmission, respectively. Fig. 3 shows that the

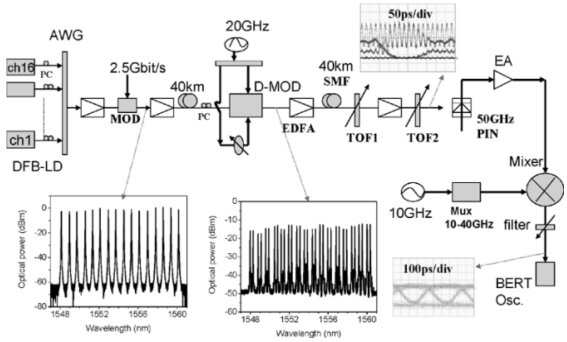

Fig. 5. Experimental setup for 16 × 2.5-Gb/s signal up-conversion using OCS. AWG is arrayed waveguide grating.

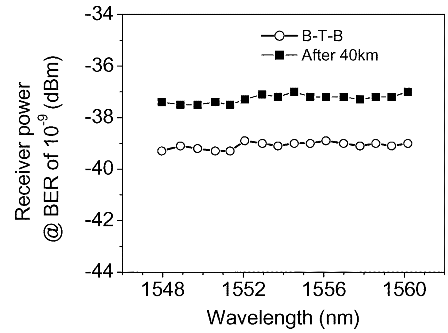

Fig. 6. Receiver sensitivity of 16 up-converted signals.

receiver sensitivity of B-T-B for SSB modulation is around 10 dB lower than that for DSB modulation. Although there is no power penalty after 20-km transmission, it increases to more than 5 dB after 40-km transmission due to fiber dispersion and large CSR.

III. 16 × 2.5-Gb/s DWDM Optical Millimeter-Wave Simultaneous Up-Conversion and Transmission

Since WDM offers huge capacity and has been widely used in current optical networks, it is desirable to seamlessly integrate the WDM transport networks with ROF access systems. All-optical up-conversion of WDM signals for ROF provides an effective way to realize this function [10], [13]. In this section, we demonstrate that 16 × 2.5-Gb/s DWDM signals are simultaneously up-converted based on the OCS technique in an LN-MOD and transmitted over 40 km. The experimental setup for DWDM signal transmission, up-conversion, and post-transmission is shown in Fig. 5. A 16-DFB laser array was used to achieve 16 wavelength signals from 1548–1560.2 nm with 100-GHz spacing. An arrayed waveguide grating (AWG) was used to combine the 16-CW lightwaves before these CW lightwaves were modulated by an LN-MZM. The generated 16×2.5 Gb/s signals were transmitted over 40 km before they were up-converted by using a dual-arm LN-MOD based on the OCS technique. We used 40-km SMF transmission to simulate a metro optical network range. The optical spectra of the original WDM signals before up-conversion and the up-converted signals are inserted in Fig. 5. The up-converted millimeter optical waves were then amplified by an EDFA to obtain a power of 17 dBm before they were transmitted over various lengths of SMF. At the receiver, TOF1 with a bandwidth of 0.5 nm was used to select the desired channel, and TOF2 with the same bandwidth was employed to further suppress the neighboring channels. The down-converted 2.5-Gb/s signal was detected by a BER tester. We set the fiber length for the up-converted signal to be 20 or 40 km. The receiver sensitivities for all channels after 40-km transmission were measured and are shown in Fig. 6. There is no power penalty for all channels after 20-km transmission, which is not shown in this figure. The average power penalty for all channels is roughly 2 dB after 40-km SMF delivery. We turned off the 15 channels and only kept one central channel on while reducing the launch power into the SMF to be 5 dBm; a similar result was observed compared to the multichannel scenario.

IV. Conclusion

We have experimentally compared the performances of optical millimeter-wave generation or up-conversion using external modulators based on different modulation schemes. The up-conversion signals based on OCS modulation scheme have shown the best performance such as the highest receiver sensitivity, the highest spectral efficiency, and the smallest power penalty over long-distance delivery (0 dB at 20 km, 2 dB at 40 km).

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