Simultaneous Generation of Baseband and Radio Signals Using Only One Single-Electrode Mach–Zehnder Modulator With Enhanced Linearity

Chun-Ting Lin, Wei-Ren Peng, Peng-Chun Peng, Jason (Jyehong) Chen, Cheng-Feng Peng, Bi-Shiou Chiou, and Sien Chi

***Abstract*—We experimentally demonstrate a simultaneous generation of baseband (BB) and RF signals, using only one single-electrode Mach–Zehnder modulator (SD-MZM) based on double-sideband with optical carrier suppression (DSBCS) scheme. With optimal modulation index (MI = $V_{\mathrm{p-p}}/2V_{\pi}$) equal to 0.43 for driving MZM, the receiver sensitivity of the RF signal can have 1-dB improvement. Based on this result, only one SD-MZM is needed to generate optical microwaves using DSBCS scheme, thus eliminating the requirement of a high-cost dual-electrode MZM without degrading the signal performance. Following 75-km standard single-mode fiber, the power penalties of both BB and RF signals are less than 0.3 dB.**

***Index Terms*—Mach–Zehnder modulator (MZM), microwave, millimeter-wave (mm-wave), radio-over-fiber (RoF).**

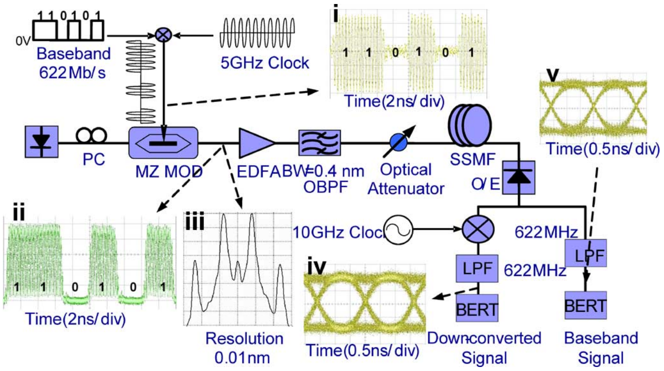


Fig. 1. Experimental setup for optical microwave generation based on DSBCS modulation scheme using one MZM. (i) Mixed electrical signal; (ii) generated optical microwave; (iii) spectrum of generated microwaves; (iv) eye diagram of DC signals; (v) eye diagram of BB signals.

I. Introduction

WITH THE ubiquitous popularity of handheld devices, the demands on wireless and wired-line capacity have grown rapidly. Facing quickly increased capacity demand, one of the best solutions is to use fiber as the transmission medium. In addition, wireless signals suffer the insufficient bandwidth and serious loss problems in traditional coaxial cable. Therefore, radio-over-fiber (RoF) becomes a promising scheme to simultaneously transmit baseband (BB) and RF signals due to the broad bandwidth and lower loss of optical fiber [1]–[4].

The microwave and millimeter-wave (mm-wave) generations are key techniques in RoF systems. The optical mm-waves using external Mach–Zehnder modulator (MZM) based on double-sideband (DSB), single-sideband (SSB), and DSB with optical carrier suppression (DSBCS) modulation schemes have been demonstrated [4]–[6]. Generated by setting the bias voltage of MZM at quadrature point, the DSB modulation experiences performance-fading problems due to fiber dispersion, resulting in degradation of the receiver sensitivity. The SSB signal is generated when a phase difference of $\pi/2$ is applied between the two RF electrodes of the dual-electrode MZM (DD-MZM) biased at quadrature point. Although the SSB modulation can reduce the impairment of fiber dispersion, it suffers worse receiver sensitivity than DSB modulation [6]. In [5], DSBCS modulation is demonstrated at the mm-wave range with the best receiver sensitivity, lowest spectral occupancy, lowest bandwidth requirement for RF signal, electrical amplifier, and optical modulator, and smallest power penalty of receiver sensitivity after long transmitted distance. In the conventional DSBCS modulation scheme, the BB signal is generated using a single-electrode MZM (SD-MZM) biased at quadrature and then up-converted using a DD-MZM biased at the minimum transmission point [5]. In order to get high optical carrier suppression ratio (OCSR), the electrical RF signal with full swing $(2V_{\pi})$ for MZM is necessary so that DD-MZM is needed to generate the mm-wave. In this letter, we propose a novel and simple method to generate the mm-wave DSBCS signal using only one MZM. We study the relationship between the RF modulation index $(\mathrm{MI} = V_{\mathrm{p-p}}/2V_{\pi})$ for DD-MZM and the receiver sensitivity. When MI is set to 0.43, there is 1-dB improvement for the receiver sensitivity of the RF signal. Based on this result, only one SD-MZM is needed to generate the mm-wave based on DSBCS scheme, which is more compact and cost-effective.

II. Experimental Setup

Fig. 1 shows the experimental setup used for optical microwave generation and transmission based on DSBCS

Manuscript received July 17, 2006; revised September 22, 2006. This work was supported by the National Science Council of R.O.C. under Contract NSC 95-2752-E-009-009-PAE, NSC 95-2221-E-009-085, NSC 95-2221-E-155-072, NSC 95-2112-M-260-001-MY2, and NSC 95-2221-E-155-059

C.-T. Lin, W.-R. Peng, J. Chen, and C.-F. Peng are with the Department of Photonics and Institute of Electro-optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan 300, R.O.C.

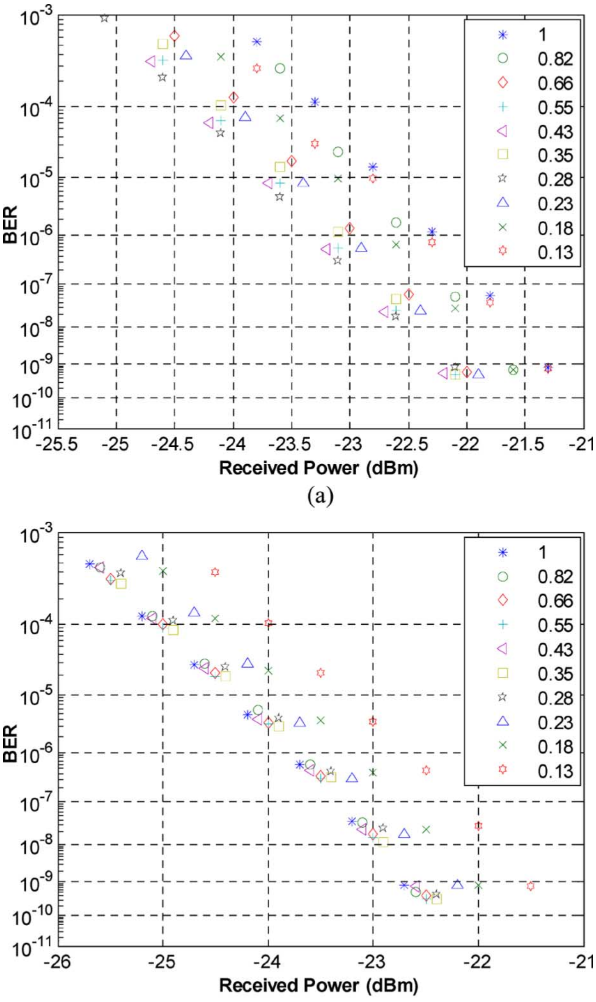
P.-C. Peng is with the Department of Applied Materials and Optoelectronic Engineering, National Chi Nan University, Taiwan 545, R.O.C.

B.-S. Chiou is with the Department of Electronics Engineering and Institute of Electronics, Innovative Packaging Research Center, National Chiao-Tung University, Hsinchu, Taiwan 300, R.O.C.

S. Chi is with the Department of Photonics and Institute of Electro-optical Engineering, National Chiao-Tung University, Hsinchu, Taiwan 300, R.O.C., and also with the Department of Electrical Engineering, Yuan-Ze University, Chung Li, Taiwan 320, R.O.C. (e-mail: jinting@ms94.url.com.tw).

Color versions of Figs. 1–3, 5, and 6 are available at http://ieeexplore.ieee.org.

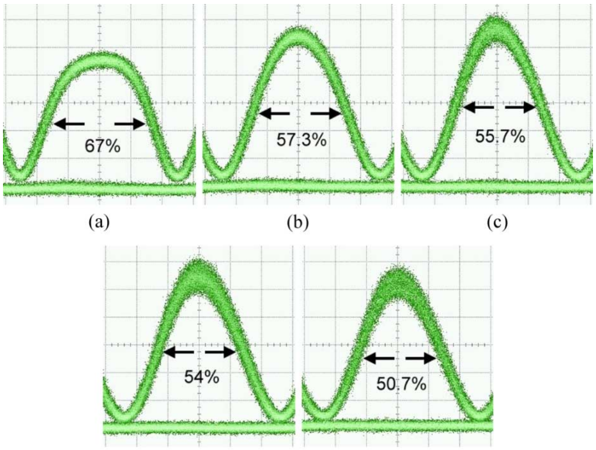
Digital Object Identifier 10.1109/LPT.2006.887233



(a)

(b)

Fig. 2. BER curves of (a) DC and (b) BB signals for different MI.



(a) (b) (c)

(d) (e)

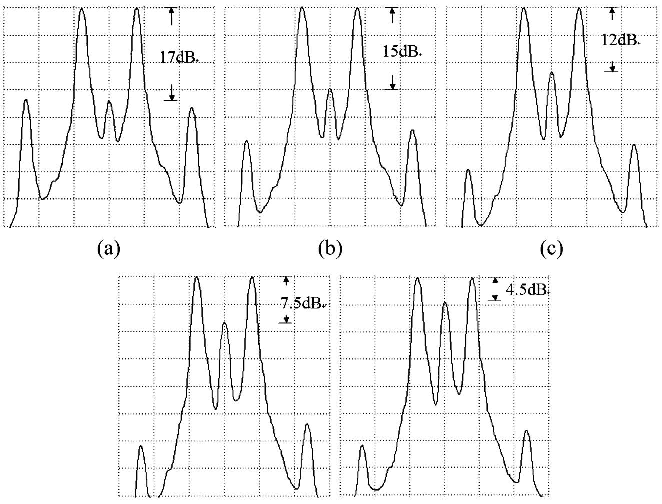
Fig. 3. Duty cycles of optical microwaves based on DSBCS modulation. The optical microwave power is 1 dBm. The optical power scale is 0.8 mW/div and the time scale is 20 ps/div. The MI is set at (a) 1, (b) 0.66, (c) 0.43, (d) 0.28, and (e) 0.18.

modulation scheme. Due to lack of high-frequency components in our laboratory, we use a 622-Mb/s optical BB signal carrying a 10-GHz optical microwave. The continuous-wave (CW) laser is generated by a distributed feedback laser, and the emission wavelength is 1540 nm. The BB signal is 622-Mb/s pseudorandom bit sequence signal with a word length of $2^{31} - 1$ and up-converted with the 5-GHz clock as shown in inset (i) of Fig. 1. The up-converted signal is amplified to maximum peak-to-peak voltage $(V_{\mathrm{P-P}})$ of 7 V, limited by the commercial RF amplifier (Picosecond 5865). The CW laser is modulated via external SD-MZM or DD-MZM with half-wave voltage (V_π) of 5 V. In order to realize DSBCS modulation, the MZM is biased at the minimum transmission point. The repetition frequency of the generated optical microwave is 10 GHz. The optical microwave and spectrum are shown in insets (ii) and (iii) of Fig. 1, respectively. The generated optical signal is amplified by erbium-doped fiber amplifier and then filtered by a tunable optical filter with a bandwidth of 0.4 nm. After transmitted over standard single-mode fiber (SSMF), the transmitted optical microwave signal is converted into an electrical microwave signal by a PIN photodiode with a 3-dB bandwidth of 38 GHz, and the converted electrical signal is amplified by an electrical amplifier. In the BB path, a low-pass filter with a 3-dB bandwidth of 622 MHz is inserted to reject the undesired RF components. In the other path, the microwave signal is down-converted (DC) by a mixer with a 10-GHz clock, and then passes through a low-pass filter with a 3-dB bandwidth of 622 MHz. The eye diagrams of the DC and BB signals are shown in insets (iv) and (v) of Fig. 1, respectively. Both the DC and BB signals are tested by a bit-error-ratio (BER) tester. We set the fiber length to be 25, 50, and 75 km.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Fig. 2(a) and (b) shows the variation of the receiver sensitivities of the BB and DC signals with MI, respectively. For the DC signal, the receiver sensitivity increases first and then decreases when MI ranges from 1 to 0.13, and the best sensitivity is at MI equal to 0.43. For the BB signal, no receiver sensitivity penalty is observed when MI decrease from 1 to 0.43. As MI changes from 0.43 to 0.28, the sensitivity degradation is only 0.3 dB at BER of 10^{-9}.

The MZM nonlinearity and OCSR are closely related to MI. As RF MI for MZM decreases, the MZM nonlinearity and OCSR decrease. The reduction of the MZM nonlinearity makes the duty cycle of optical microwaves closer to 0.5, as shown in Fig. 3. At the same optical power, smaller duty cycle of optical microwaves has higher peak power, resulting in better receiver sensitivity of the DC signal. However, low OCSR means that the RF component of optical power is relatively low and the dc component of optical power at the center wavelength is relatively high, as shown in Fig. 4. This incurs worse receiver sensitivity of the DC signal. Therefore, there is a tradeoff for the receiver sensitivity of the DC signal between the MZM nonlinearity and OCSR when we decrease MI. When the optimal MI is 0.43, the receiver sensitivities of the BB and DC signals at BER of 10^{-9} are -22.6 and -22.7 dBm, respectively. The receiver sensitivity of the DC signal has 1-dB improvement when MI changes from 1 to 0.43. After optical microwaves with optical power of 0 dBm, using the optimal MI equal to 0.43, are transmitted over 25-, 50-, and 75-km SSMF, no power



(a) (b) (c)

(d) (e)

Fig. 4. OCSR of optical microwaves based on DSBCS modulation. The resolution is 0.01 nm. The MI is set at (a) 1, (b) 0.66, (c) 0.43, (d) 0.28, and (e) 0.18.

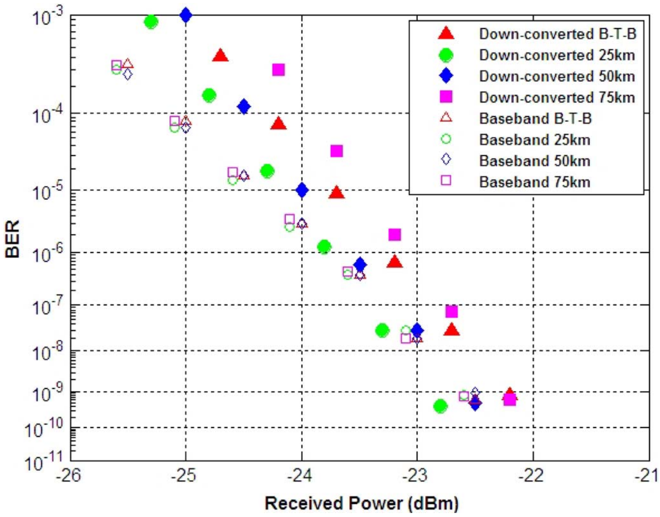


Fig. 5. BER curves using one DD-MZM with MI of 0.43 after transmitted over 25-, 50-, and 75-km SSMF.

penalty for the receiver sensitivities of the BB and DC signals at BER of 10^{-9} is observed, as shown in Fig. 5.

Based on the result of DSBCS modulation using one DD-MZM, we can generate DSBCS microwaves using only one SD-MZM with MI equal to 0.43. The V_{π} of the SD-MZM at 5 GHz is 5 V, and the $V_{\mathrm{p-p}}$ for the MI of 0.43 is 4.3 V. Fig. 6 shows the receiver sensitivities of the BB and DC signals with optical power of 0 dBm after they are transmitted over 25-, 50-, and 75-km SSMF. The power receiving penalties for both the BB and DC signals at BER of 10^{-9} are less than 0.3 dB.

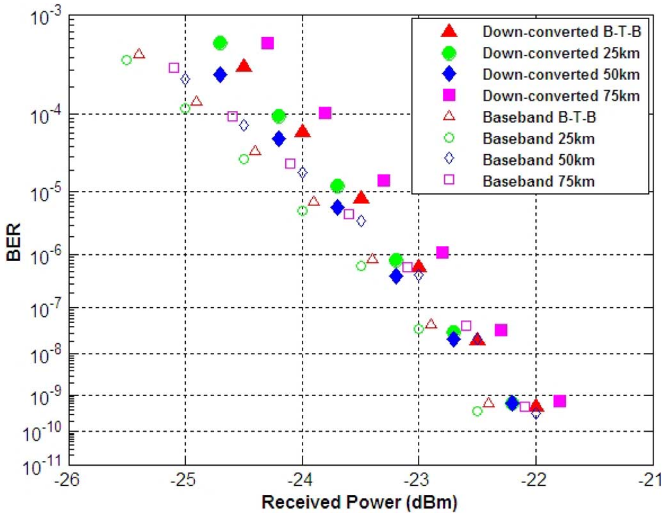


Fig. 6. BER curves using one SD-MZM with MI of 0.43 after transmitted over 25-, 50-, and 75-km SSMF.

IV. CONCLUSION

In this investigation, we experimentally demonstrate a simultaneous generation of BB and RF signals based on DCBCS modulation scheme using only one MZM. The optimal MI level for driving DD-MZM is 0.43 with 1-dB sensitivity improvement for DC signals, and there is no receiver sensitivity penalty after transmitted over 75-km SSMF. Based on the optimal MI of 0.43, we can generate DSBCS microwave using only one SD-MZM, which is more compact and cost-effective. The receiver sensitivity penalty is less than 0.3 dB after transmitted over 75-km SSMF.

REFERENCES

[1] T. Kamisaka, T. Kuri, and K. Kitayama, "Simultaneous modulation and fiber-optic transmission of 10 Gb/s baseband and 60 GHz band radio signals on a single wavelength," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 10, pt. 2, pp. 2013–2017, Oct. 2001.

[2] K. Ikeda, T. Kuri, and K. Kitayama, "Simultaneous three band modulation and fiber-optic transmission of 2.5-Gb/s baseband, microwave-, and 60-GHz-band signals on a single wavelength," *J. Lightw. Technol.*, vol. 21, no. 12, pp. 3194–3202, Dec. 2003.

[3] K. Kojucharow, M. Sauer, H. Kaluzni, D. Sommer, F. Poegel, W. Nowak, A. Finger, and D. Ferling, "Simultaneous electrooptical upconversion, remote oscillator generation, and air transmission of multiple optical WDM channels for a 60-GHz high-capacity indoor system," *IEEE Trans. Microw. Theory Tech.*, vol. 47, no. 12, pp. 2249–2256, Dec. 1999.

[4] A. Martinez, V. Polo, and J. Marti, "Simultaneous baseband and RF optical modulation scheme for feeding wireless and wireline heterogeneous access network," *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 10, pt. 2, pp. 2018–2024, Oct. 2001.

[5] J. Yu, Z. Jia, L. Yi, G. K. Chang, and T. Wang, "Optical millimeter-wave generation or up-conversion using external modulators," *IEEE Photon. Technol. Lett.*, vol. 18, no. 1, pp. 265–267, Jan. 1, 2006.

[6] M. Attygalle, C. Lin, G. J. Pendock, A. Nirmalathas, and G. Edvell, "Transmission improvement in fiber wireless links using fiber Bragg grating," *IEEE Photon. Technol. Lett.*, vol. 17, no. 1, pp. 190–192, Jan. 2005.