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A Novel Photonic Frequency Down-Shifting Technique for Millimeter-Wave-Band Radio-Over-Fiber Systems

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***Abstract*—A novel photonic frequency down-shifting technique for millimeter-wave-band radio-over-fiber (RoF) systems is proposed and verified by simulation. The frequency shifting is based on subcarrier modulation (SCM). An optical carrier with a subcarrier is injected into the frequency shifter consisting of a Mach–Zehnder modulator (MZM) or electroabsorption modulator (EAM) driven by a radio frequency sinusoidal signal. The frequency-shifted optical carrier with a frequency-shifted subcarrier is, thus, generated by SCM modulation.**

***Index Terms*—Microwave photonics, millimeter-wave (mm-wave), optical fiber communications, radio-over-fiber (RoF).**

I. INTRODUCTION

FUTURE wireless millimeter-wave (mm-wave)-band communication networks are expected to offer broad-band radio access to a large number of subscribers. However, the electrical distribution of such mm-wave-band radio frequency (RF) signals over air is limited due to the high transmission loss. All high RF signals can be transmitted over fiber by applying dense wavelength-division-multiplexing (DWDM) and subcarrier modulation (SCM) techniques and making use of the large available bandwidths and the low transmission losses in optical fibers. Recently, the DWDM technique with the SCM has been investigated for the application to radio-over-fiber (RoF) systems [1]–[5]. However, the subcarriers which carry mm-wave-band RF signals are separated by tens of gigahertz from its optical carrier; thus, it is impossible to apply conventional DWDM optical multiplexers and demultiplexers for the RoF systems, because the frequency separation of the optical carrier and its subcarrier is usually more than DWDM channel spacing and therefore the bandwidth of the multiplexers or demultiplexers. Moreover, it is preferable to generate a low intermediate frequency (IF) directly from the optical signal, avoiding the use of high frequency RF signal processing. Photonic frequency down-shifting (or conversion), by using carrier suppressed modulation with an optical Mach–Zehnder modulator (MZM) [6], [7] has been proposed to overcome this technical difficulty. However, optical modulation depth, the power ratio of optical carrier and its subcarrier, and the most important factor in determining the RoF transmission performance, cannot be adjusted directly.

In this letter, we propose a novel frequency down-shifting technique by the use of SCM with an optical MZM or electroabsorption modulator (EAM).

II. PRINCIPLE OF PHOTONIC FREQUENCY DOWN-SHIFTING

Suppose that an electric field has an optical carrier at f_c which is injected into an MZM (referred to MZM-1), which is driven by a phase-modulated RF signal $V_m\cos[\omega_m t+\theta(t)]$, where V_m is the modulation voltage, ω_m is the RF modulation angular frequency, and $\theta(t)$ is the modulated signal phase. The RF signal is applied to both electrodes of the MZM-1 with $-\pi/2$ phase shift applied to one electrode. A dc bias voltage is also applied to one electrode while the other is grounded; and thus, the MZM-1 is operated at quadrature. The output $E_0(t)$ from the MZM-1 is, thus, given by Bessel series [6], [7]

$$\begin{aligned}E_0(t) =& \frac{A}{2}\left\{\sqrt{2}J_0(\beta\pi)\mathbf{sin}\left[\omega_c t+\phi_c(t)-\frac{\pi}{4}\right]\right.\\ &-2J_1(\beta\pi)\mathbf{cos}\\ &\left.\times\left[(\omega_c-\omega_m)t+\phi_c(t)-\theta(t)\right]+\cdots\right\} \quad (1)\end{aligned}$$

where $\omega_c = 2\pi f_c$; $\omega_m = 2\pi f_m$, f_m—RF modulation frequency; $\beta = V_m/V_\pi$—normalized modulation voltage, V_π—the MZM voltage with a π phase shift; and $\phi_c(t)$ is the laser phase noise. In (1), $J_n(\;)$ is the Bessel function with $n = 0$ or 1. The first term in (1) is the optical carrier and the second term is the lower sideband (LSB) subcarrier, introduced by the single-sideband (SSB) modulation, which carries the transmitting signal. All other higher harmonics are omitted in (1).

Now we consider another MZM (referred to MZM-2) which is used for optical frequency shifting, driven by an RF sinusoidal signal $V_{\mathrm{lo}}\cos(\omega_{\mathrm{lo}}t)$, where V_{lo} is the modulation voltage and ω_{lo} is the RF modulation frequency. The MZM-2 is operated at quadrature, too. For a continuous-wave (CW) light with an optical frequency ω_c, the output electric field can be expressed by Fourier series and the optical carrier and LSB subcarrier terms are only considered here, i.e., $E_o(t) \propto e^{j\omega_c t} + \xi e^{j(\omega_c-\omega_{\mathrm{lo}})t}$, where the relative amplitude ξ is normalized to that of the optical carrier, which is increased with the modulation voltage V_{lo}/V_π,

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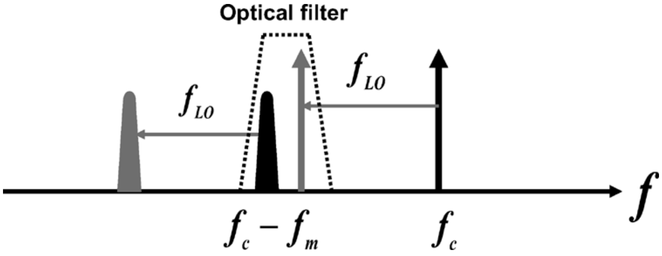


Fig. 1. Optical spectra of the input electric field consisting of an optical carrier and its LSB subcarrier (black lines) and the output electric field consisting of the input (black lines) and frequency-shifted (gray lines) replica of the MZM-2, used for optical frequency down-shifting.

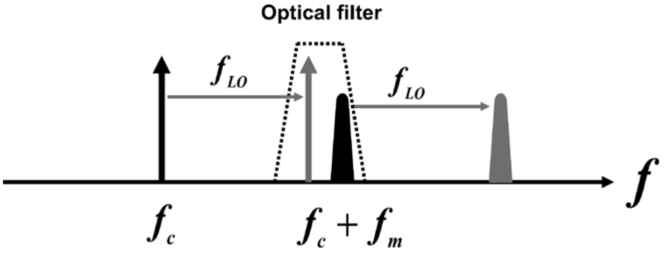


Fig. 2. Optical spectra of the input electric field consisting of an optical carrier and its USB subcarrier (black lines) and the output electric field consisting of the input (black lines) and frequency-shifted (gray lines) replica of the MZM-2, used for optical frequency up-shifting. Others are the same as in Fig. 1.

and $|\xi|^2$ is optical modulation depth. If the electric field expressed by (1) is injected into the MZM-2, the output is then approximated by

$$\begin{aligned} E_0(t) \propto\ & \Big\{\sqrt{2}J_0(\beta\pi)\mathbf{sin}\Big[\omega_c t + \phi_c(t) - \frac{\pi}{4}\Big] \\ & - 2J_1(\beta\pi)\mathbf{cos}\left[(\omega_c - \omega_m)t + \phi_c(t) - \theta(t)\right]\Big\} \\ & + \Big\{\sqrt{2}\xi J_0(\beta\pi)\mathbf{sin}\Big[(\omega_c - \omega_{\text{lo}})t + \phi_c(t) - \frac{\pi}{4}\Big] \\ & - 2\xi J_1(\beta\pi)\mathbf{cos}\Big[(\omega_c - \omega_{\text{lo}} - \omega_m)t \\ & + \phi_c(t) - \theta(t)\Big]\Big\}. \end{aligned} \tag{2}$$

The terms in the first brace represent the input optical carrier and its LSB subcarrier, and the terms in the second brace represent the frequency down-shifted optical carrier and its LSB subcarrier. The optical spectra of the electric fields with (2) are shown in Fig. 1. Thus, the frequency down-shifted optical carrier is about a few of gigahertz far from the input LSB subcarrier; they can be filtered out optically by an optical narrow-band filter and sent to photodetection. Finally, the electrical signal with an IF ($f_{\text{IF}} = f_m - f_{\text{LO}}$) is obtained. It was shown that the performance of RoF systems can be improved by the suppression of optical carrier [8]. As shown in Fig. 1, the frequency down-shifted optical carrier can be suppressed by decreasing V_{lo}/V_{π}.

Alternatively, we consider an optical carrier having an upper sideband (USB) subcarrier. In the MZM-1 and MZM-2, the phase difference between the two arms is $+\pi/2$, instead of $-\pi/2$. Thus, the output electric field from the MZM-1 driven by phase modulated RF signal can be expressed as

$$\begin{aligned} E_0(t) =& \frac{A}{2}\Big\{\sqrt{2}J_0(\beta\pi)\mathbf{sin}\Big[\omega_c t + \phi_c(t) - \frac{\pi}{4}\Big] \\ & - 2J_1(\beta\pi)\mathbf{cos} \\ & \times \left[(\omega_c + \omega_m)t + \phi_c(t) + \theta(t)\right] + \cdots\Big\}. \end{aligned} \tag{3}$$

The first and second terms represent the optical carrier and its USB subcarrier. The output electric field from the MZM-2 for a CW input light can be approximated as $E_o(t) \propto e^{j\omega_c t} + \xi e^{j(\omega_c + \omega_{\text{lo}})t}$, where the first term is the optical carrier and the second term is the USB subcarrier, generated by the SSB modulation. When the electric field given by (3) is injected into the MZM-2, the output electric field from the MZM-2 can be approximated by

$$\begin{aligned} E_0(t) \propto\ & \Big\{\sqrt{2}J_0(\beta\pi)\mathbf{sin}\Big[\omega_c t + \phi_c(t) - \frac{\pi}{4}\Big] \\ & - 2J_1(\beta\pi)\mathbf{cos}\left[(\omega_c + \omega_m)t + \phi_c(t) + \theta(t)\right]\Big\} \\ & + \Big\{\sqrt{2}\xi J_0(\beta\pi)\mathbf{sin}\Big[(\omega_c + \omega_{\text{lo}})t + \phi_c(t) - \frac{\pi}{4}\Big] \\ & - 2\xi J_1(\beta\pi)\mathbf{cos}\left[(\omega_c + \omega_{\text{lo}} + \omega_m)t \right. \\ & \left. + \phi_c(t) + \theta(t)\right]\Big\}. \end{aligned} \tag{4}$$

The optical spectra corresponding to (3) and (4) are shown in Fig. 2.

Now we consider an EAM to replace the MZM-2 and be used for frequency down-shifting. When a CW light is injected into the EAM driven by an RF sinusoidal signal $V_{\text{lo}}\cos(\omega_{\text{lo}}t)$, the output electric field can be approximated by $E_o(t) \propto e^{j\omega_c t} + \xi e^{j(\omega_c - \omega_{\text{lo}})t} + \xi e^{j(\omega_c + \omega_{\text{lo}})t}$, the optical carrier, LSB and USB subcarrier, respectively. When the electric field with (1) is injected into the EAM, the output electric field becomes

$$\begin{aligned} E_0(t) \propto\ & \Big\{\sqrt{2}J_0(\beta\pi)\mathbf{sin}\Big[\omega_c t + \phi_c(t) - \frac{\pi}{4}\Big] \\ & - 2J_1(\beta\pi)\mathbf{cos}\left[(\omega_c - \omega_m)t + \phi_c(t) - \theta(t)\right]\Big\} \\ & + \Big\{\sqrt{2}\xi J_0(\beta\pi)\mathbf{sin}\Big[(\omega_c - \omega_{\text{lo}})t + \phi_c(t) - \frac{\pi}{4}\Big] \\ & - 2\xi J_1(\beta\pi)\mathbf{cos}\left[(\omega_c - \omega_{\text{lo}} - \omega_m)t \right. \\ & \left. + \phi_c(t) - \theta(t)\right]\Big\} \\ & + \Big\{\sqrt{2}\xi J_0(\beta\pi)\mathbf{sin}\Big[(\omega_c + \omega_{\text{lo}})t + \phi_c(t) - \frac{\pi}{4}\Big] \\ & - 2\xi J_1(\beta\pi)\mathbf{cos}\left[(\omega_c + \omega_{\text{lo}} - \omega_m)t \right. \\ & \left. + \phi_c(t) - \theta(t)\right]\Big\}. \end{aligned} \tag{5}$$

Fig. 3 shows the optical spectra of the electric field in each brace of (5). The frequency down-shifted optical carrier and the input LSB subcarrier are optically filtered out and sent to photodetection; thus, an electrical signal with a low IF is obtained. A similar frequency conversion can be applied to a signal with a USB subcarrier. An EAM used for frequency shifting has an advantage of polarization insensitive to the input signal polarization and, thus, no polarization control is required. On the contrary, MZM is required to have polarization control at input. Hence, frequency

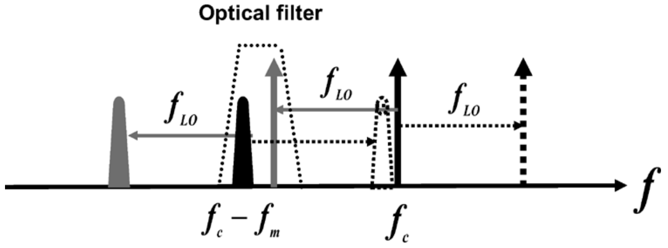


Fig. 3. Optical spectra of the input electric field consisting of an optical carrier and its LSB subcarrier (black lines), and the output electric field consisting of the input (black lines), frequency down-shifted (gray lines) and frequency up-shifted replica (dashed lines) of the EAM, used for frequency down-shifting.

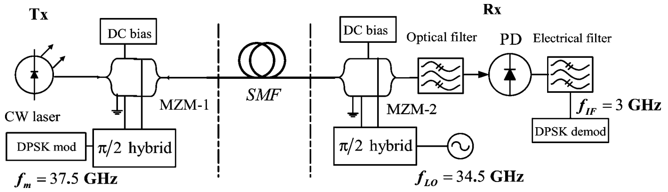


Fig. 4. Verification setup for simulation. Tx: Optical transmitter. Rx: Optical receiver. PD: Photodiode. DPSK mod: DPSK modulator which generates the DPSK signal at RF f_m. DPSK demod: DPSK demodulator.

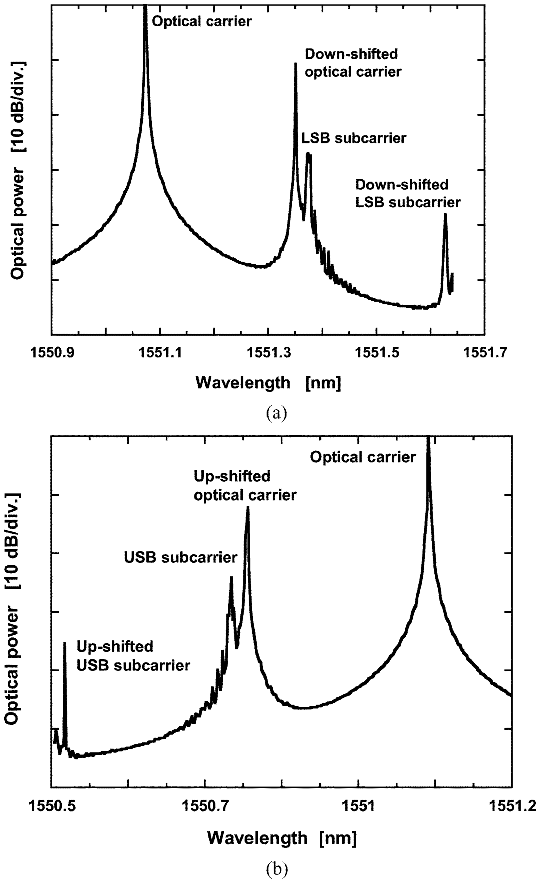
down-shifting using an EAM can be applied to DWDM RoF systems.

III. VERIFICATION BY SIMULATION

To verify the validity of our proposed technique, an RoF system with our proposed frequency down-shifting technique is simulated, as shown in Fig. 4. In the optical transmitter, a CW laser, having a central wavelength of ~1551.1 nm and line-width of 10 MHz, is connected to an MZM (i.e., MZM-1). An RF signal with 155-Mb/s differential phase-shift keying (DPSK) data at $f_m = 37.5$ GHz drives the MZM-1 to generate an LSB (or USB) at 37.5 GHz. The optical carrier with its subcarrier transmits over 25-km single-mode fiber. Another optical MZM (i.e., MZM-2) driven by a sinusoidal signal with $f_{\mathrm{LO}} = 34.5$ GHz is used for frequency down-shifting. The optical spectra after optical frequency shifting are shown in Fig. 5(a) and (b) for the cases of the optical carrier having an LSB or USB subcarrier, respectively. The frequency-shifted optical carrier and input subcarrier are filtered out optically, and injected into a photodiode; then, the electrical signal with an IF of 3 GHz is obtained.

IV. CONCLUSION

A novel frequency down-shifting technique for mm-wave-band RoF systems has been proposed and verified by simulation. The frequency shifting is based on SCM modulation. It was shown that our proposed frequency down-shifting technique has the advantage that the optical modulation depth can be increased/decreased easily by adjusting the modulation voltage of the frequency down-shifter, and thus, RoF system performance can be optimized. Moreover, when an EAM is used, polarization-insensitive frequency down-shifting can be achieved; thus, an EAM can be used for all DWDM channel frequency down-shifting.



(a)

(b)

Fig. 5. Optical spectra of (a) an optical carrier with an LSB subcarrier and their frequency down-shifted replica, and (b) an optical carrier with a USB subcarrier and their frequency up-shifted replica.

REFERENCES

[1] C. Lim, A. Nirmalathas, D. Novak, R. Waterhouse, and G. Yoffe, “Millimeter-wave broad-band fiber-wireless system incorporating baseband data transmission over fiber and remote LO delivery,” *J. Lightw. Technol.*, vol. 18, no. 10, pp. 1355–1363, Oct. 2000.

[2] A. Nirmalathas, D. Novak, C. Lim, and R. Waterhouse, “Wavelength reuse in the WDM optical interface of a millimeter-wave fiber-wireless antenna base station,” *IEEE Trans. Microw. Theory Tech.*, vol. 49, no. 10, pp. 2006–2012, Oct. 2001.

[3] K. Kitayama, “Architectural considerations of fiber-radio millimeter-wave wireless access systems,” *Fiber Integr. Opt.*, vol. 19, pp. 167–186, 2000.

[4] C. Lim, A. Nirmalathas, M. Attygalle, D. Novak, and R. Waterhouse, “On the merging of millimeter-wave fiber radio backbone with 25-GHz WDM ring networks,” *J. Lightw. Technol.*, vol. 21, no. 10, pp. 2203–2210, Oct. 2003.

[5] H. Toda, T. Yamashita, T. Kuri, and K. Kitayama, “Demultiplexing using an arrayed-waveguide grating for frequency-interleaved DWDM millimeter-wave radio-on-fiber systems,” *J. Lightw. Technol.*, vol. 21, no. 8, pp. 1735–1741, Aug. 2003.

[6] T. Kuri and K. Kitayama, “Novel photonic downconversion technique with optical frequency shift for millimeter-wave-band radio-on-fiber systems,” *IEEE Photon. Technol. Lett.*, vol. 14, no. 8, pp. 1163–1165, Aug. 2002.

[7] T. Kuri, H. Toda, and K. Kitayama, “Dense wavelength-division multiplexing millimeter-wave-band radio-on-fiber signal transmission with photonic down conversion,” *J. Lightw. Technol.*, vol. 21, no. 6, pp. 1510–1517, Jun. 2003.

[8] A. Attygalle, C. Lim, G. Pendock, A. Nirmalathas, and G. Edvell, “Transmission improvement in fiber wireless links using fiber Bragg gratings,” *IEEE Photon. Technol. Lett.*, vol. 17, no. 1, pp. 190–192, Jan. 2005.