Title

Multioctave high dynamic range up-conversion optical-heterodyned microwave photonic link

Journal
IEEE Photonics Technology Letters, 16(10)

ISSN
1041-1135

Authors
Wu, Y
Xie, X B
Hodiak, J H
et al.

Publication Date
2004-10-01

Peer reviewed

Multioctave High Dynamic Range Up-Conversion Optical-Heterodyned Microwave Photonic Link

Y. Wu, X. B. Xie, J. H. Hodiak, *Member, IEEE*, S. M. Lord, *Member, IEEE*, and P. K. L. Yu, *Member, IEEE*

***Abstract*—An up-converting microwave photonic link which enables high dynamic range over a multioctave information bandwidth is demonstrated. The improvement in spurious-free dynamic range (SFDR) as compared to conventional links is experimentally demonstrated. The link consists of two heterodyned lasers with one optical carrier modulated by a $LiNbO_3$ Mach–Zehnder modulator biased at the null point. This results in strong optical sidebands, minimum even order distortion, and more than ∼40-dB suppression of the optical carrier. The first carrier's two optical sidebands are heterodyned with the second unmodulated optical carrier. The modulated optical carrier is suppressed reducing noise power and enhancing SFDR. An SFDR of 115 dB/Hz$^{2/3}$ was measured. The detected local oscillator power is also suppressed, easing output filtering requirements.**

***Index Terms*—Optical-heterodyned link, up-conversion, multioctave, radio-frequency (RF) link gain, suppressed-carrier.**

I. Introduction

WIRELESS access networks supporting wide-bandwidth services such as high-data rate mobile access and video delivery will be driven to millimeter wave (MMW) carrier frequencies and numerous small radio cells. Commercial wide-bandwidth networks will require high-dynamic range links to address antennas, similar to the requirement for military applications and broad-band MMW radar. For applications like communications networks, a large number of remote antenna sites will need to be addressed. Addressing remote antenna sites via optical fibers is attractive due to the large transmission bandwidth and low loss at MMW frequencies.

In order to realize these applications, photonic links must exhibit large dynamic range, have relatively simple hardware, and have the capability to transmit broad-band signals over long distances. Numerous photonic links have been proposed to deliver signals to simplified remote antenna units, including optical heterodyning schemes [1]. One photonic up-conversion link suitable to these applications is an optically heterodyned photonic link using a single Mach–Zehnder modulator (MZM) [2]. Such a link is particularly beneficial if combined with null biasing of the modulator. This combination not only converts modulation frequencies achieved by commercially available modulators to MMW frequencies, it also provides large spurious-free dynamic range (SFDR) over multioctave information bandwidths. In addition, it provides radio-frequency (RF) local oscillator (LO) suppression which relaxes the Q factor requirements on the image filters, an SFDR which is not limited by optical power into the modulator, and decoupled sidebands which eliminates the dispersion-induced power penalty (DIPP), thereby allowing for long-distance transmission. Simulation results have proposed that such a link can have an improved SFDR over conventional MZM links [3]. In this letter, we verify this improvement experimentally.

Manuscript received February 5, 2004; revised June 3, 2004. This work was supported in part by the National Science Foundation (NSF) ANIR Program and in part by the Office of Naval Research.

Y. Wu and X. B. Xie are with the Department of Electrical and Computer Engineering, Jacobs School of Engineering, University of California, San Diego, La Jolla, CA 92093-0409 USA (e-mail: ywu@ece.ucsd.edu; xixie@ucsd.edu).

J. H. Hodiak is with SPAWAR Systems Center, San Diego, CA 92152-5001 USA (e-mail: justin.hodiak@navy.mil).

S. M. Lord is with SPAWAR Systems Center, San Diego, CA 92152-5001 USA on sabbatical from the Department of Engineering, University of San Diego, San Diego, CA 92110 USA (e-mail: slord@sandiego.edu).

P. K. L. Yu is with the Department of Electrical and Computer Engineering, Jacobs School of Engineering, University of California, San Diego, La Jolla, CA 92093-0407 USA (e-mail: yu@ece.ucsd.edu).

Digital Object Identifier 10.1109/LPT.2004.834454

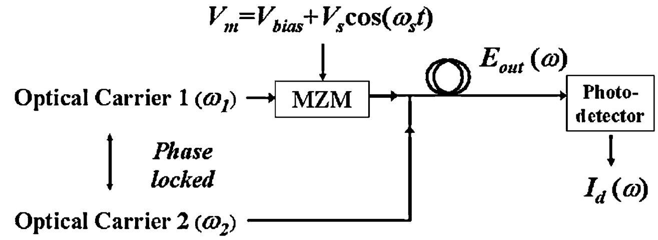


Fig. 1. Schematic of the MZM optical-heterodyned link.

II. Analysis

A schematic of our photonic link is shown in Fig. 1. The link consists of two phase-locked optical carriers which generate an optical LO. One of the optical carriers (Optical Carrier 1) is modulated by a $LiNbO_3$ MZM biased at its null point and then combined with the second unmodulated carrier (Optical Carrier 2). Biasing an MZM near the null has been shown to increase the dynamic range of a photonic link [4], [5]. This is primarily due to decreasing the dc photocurrent and thus the noise floor.

In our link, the null bias is combined with optical heterodyning to provide additional benefits. The combined optical field under first-order small signal approximation is

$$E_{\rm out}\approx\sqrt{P_2}\cos(\omega_2\cdot t)+\left[\cos\left(\frac{\pi}{2}\cdot\frac{V_{\rm bias}}{V_\pi}\right)\right]\sqrt{P_1}\cos(\omega_1\cdot t) - \left[\sin\left(\frac{\pi}{2}\cdot\frac{V_{\rm bias}}{V_\pi}\right)\frac{\pi}{4V_\pi}\right]V_s\sqrt{P_1} \cdot\{\cos[(\omega_1+\omega_s)\cdot t]+\cos[(\omega_1-\omega_s)\cdot t]\} \quad (1)$$

where P_1 and ω_1 (P_2 and ω_2) are the power and angular frequency of the modulated (unmodulated) optical carrier, V_π is the modulator's half-wave voltage, $V_{\rm bias}$ is the dc bias voltage on the modulator, and V_s and frequency ω_s are the amplitude and frequency of the modulation signal. The RF power at the LO frequency $\omega_{\rm LO} = \omega_1 - \omega_2$ is

$$P_{\rm LO} \propto \left\{\cos\left(\frac{\pi}{2V_\pi}\cdot V_{\rm bias}\right)V_s\right\}^2 P_1P_2\Omega_1\Omega_2 \quad (2)$$

where $\Omega_1(\Omega_2)$ is the total power loss in the link for the modulated (unmodulated) optical carrier. The RF output from the mixing of Optical Carrier 2 (at ω_2) with either optical sideband of Carrier 1 at $\omega_{\rm LO} \pm \omega_s$ is

$$P_{\rm LO} \propto \left\{\sin\left(\frac{\pi}{2V_\pi}\cdot V_{\rm bias}\right)\frac{\pi}{4V_\pi}V_s\right\}^2 P_1P_2\Omega_1\Omega_2. \quad (3)$$

Eqations (2) and (3) show that when the MZM is null-biased ($V_{\rm bias} = V_\pi$), the RF output power is maximum and the RF LO power ($P_{\rm LO}$) is suppressed. Fig. 2(a) shows the transfer characteristic for an MZM. Fig. 2(b) shows the optical field spectra of the input to the photodiode and the corresponding photocurrent spectra at quadrature and null biases.

The noise floor, SFDR, and RF gain ($G_{\rm RF}$) of this link may be derived using (1) and (3)

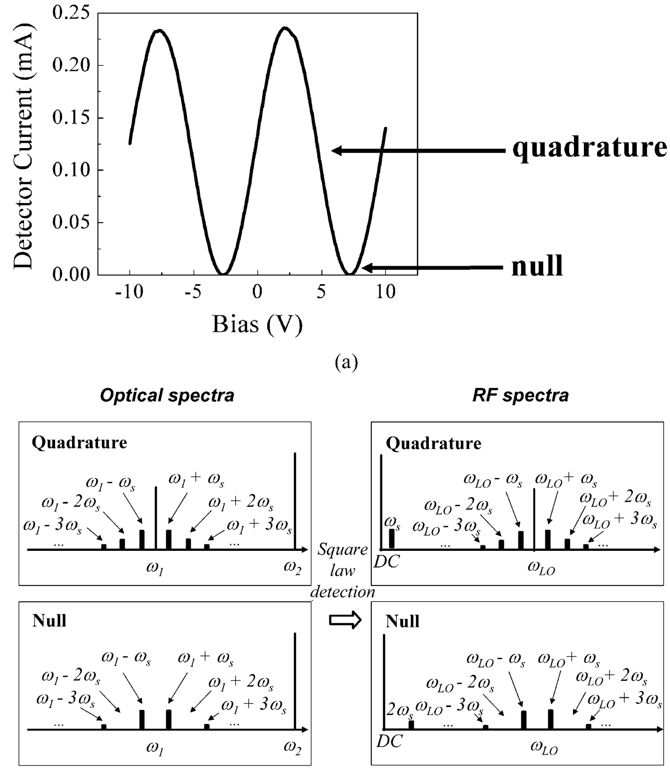
$$\begin{aligned}\mathrm{SFDR(dB)} = &\frac{2}{3}\left[10\log\left(4P_1P_2\Omega_1\Omega_2\eta^2R_{\rm out}\right)\right.\\ &\left.- \mathrm{NoiseFloor(dBm)}\right] \quad (4a)\end{aligned}$$

$$\begin{aligned}\mathrm{NoiseFloor(dBm)} = 10\log\Big(&kTB + 2qI_{\rm DC}R_{\rm out}B\\ &+10^{\mathrm{RIN}/10}I_{\rm DC}^2R_{\rm out}B\Big) \quad (4b)\end{aligned}$$

$$\begin{aligned}G_{\rm RF}(\mathrm{dB}) = 10\log\Bigg\{&P_1P_2\Omega_1\Omega_2\left[\sin\left(\frac{\pi V_{\rm bias}}{2V_\pi}\right)\frac{\eta\pi}{2V_\pi}\right]^2\\ &\times R_{\rm in}R_{\rm out}\Bigg\} \quad (5)\end{aligned}$$

where P_1 and P_2 are the modulated and unmodulated optical carrier powers, $I_{\rm DC}$ is the dc photocurrent and equals $P_2\Omega_2\eta$, $R_{\rm in}$ and $R_{\rm out}$ are the input and output resistances, respectively, B is the bandwidth, and η is the responsivity of the photodiode. These equations suggest that high gain and SFDR are possible by using a large first optical carrier power (P_1) which is limited by the power handling of $\mathrm{LiNbO_3}$ modulators. With a small modulation depth consistent with the small signal approximation, larger RF power gain is possible for a given photocurrent and the same modulator in this link compared to intensity modulated direct detection (IM-DD) links with an MZM biased at quadrature. The second optical carrier power (P_2) fixes the photocurrent but an optical power $P_1 > P_2$ can be used to increase the gain in this scheme [see (5)]. In IM-DD links at quadrature, the gain is proportional to P_1^2 so increasing P_1 to increase the gain also increases the photocurrent. In our link, improved RF gain resulting from large optical power P_1 is not accompanied by significant noise floor degradation. The noise floor is governed primarily by P_2, not P_1. This allows for larger SFDR in contrast with IM-DD links with an MZM biased at quadrature, where the link typically becomes relative intensity noise (RIN)-limited well before reaching the power handling limit of the modulator.

An additional important feature of null-biasing is that it minimizes the even-order distortion generated by the modulator



(b)

Fig. 2. (a) Measured transfer characteristic of a 1.3-μm MZM with dc V_π of 4.95 V. (b) Schematic of spectral components of the optical heterodyned link showing relevant distortion terms at quadrature (top) and null bias (bottom). Photodiode input spectra ($E_{\rm out}(\omega)$) is shown on the left; RF spectra of the photocurrent ($I_d(\omega)$) is on the right.

[see Fig. 2(b)]. When null-biasing is used in a direct detection scheme, the signals are not recoverable due to the carrier suppression. However, when the null bias is combined with a heterodyne scheme, as shown in Fig. 1, the link can transmit and up-convert a multioctave information bandwidth with high dynamic range.

In this optically heterodyned link, the two optical sidebands decouple into two RF frequencies so that no DIPP results due to the absence of two sideband interference, an important feature when transmitting intensity-modulated MMW signals over conventional optical fiber at 1550 nm where the DIPP is severe. A self-heterodyne technique which makes use of the same principle as the link shown in Fig. 1 was demonstrated to increase transmission distance; however, the benefits of this approach for multioctave high dynamic range links were not analyzed [6]. Finally, LO suppression in this link also simplifies the system hardware. The Q factor requirement on the image filters is relaxed with the suppression. Whether the filter is implemented in the optical or microwave domain, the selectivity specification is eased.

III. Experimental Results

The link RF performance was verified using two phase-locked LightWave Electronics 1319-nm lasers with a beat frequency ($f_{\rm LO}$) of about 15.9 GHz forming the optical LO. The optical powers of the modulated and unmodulated carriers were 14.48 and 10.17 dBm, respectively. The higher

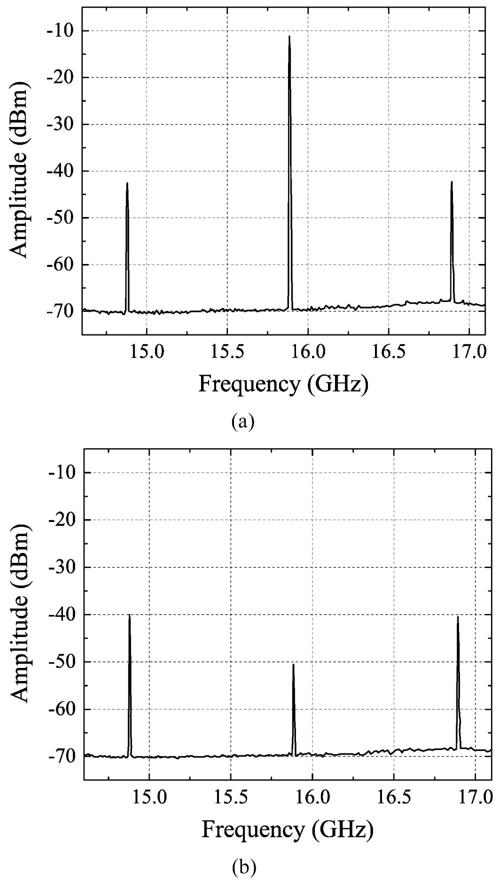


Fig. 3. RF output of the optical-heterodyned link with MZM biased at (a) quadrature and (b) null.

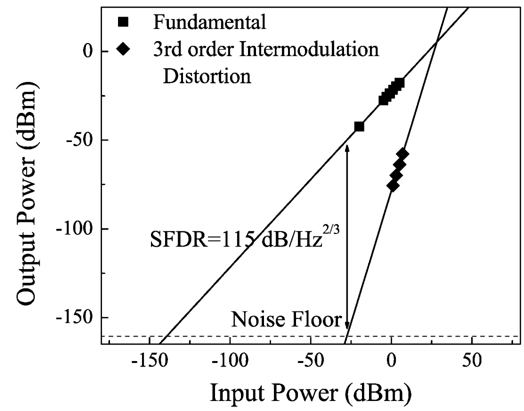


Fig. 4. Two-tone SFDR measurement of the optical-heterodyned link. The output fundamental frequency and the third-order intermodulation distortion were at 14.9 and 13.88 GHz, respectively.

power carrier was coupled to a $LiNbO_3$ MZM with a Pine Photonics MBC-2 bias controller stabilizing the operating bias point. The modulator had an insertion loss of 2.4 dB and an RF V_π of 2.5 V. The second optical carrier was combined with output of the MZM using a 3-dB coupler and sent to a high power Discovery Semiconductor (DSC50) photodiode terminated in 50 Ω. The photodiode had a responsivity of 0.8 A/W and a saturation power of 14 dBm.

Fig. 3(a) and (b) shows the RF power spectrum of the output of the optical heterodyned link at quadrature and null biases, respectively. The 3-dB difference in the RF output at either sideband between Fig. 3(a) and (b) is shown and agrees with (3). Most importantly, a 40-dB suppression of the RF LO power is observed between Fig. 3(a) and (b).

The RF gain of the link was experimentally determined to be -22.6 dB. This compares well with the expected gain of -21.9 dB obtained using (5). A two-tone test using intermediate frequency (IF) input tones at 1.0 GHz and 980 MHz yielded the results shown in Fig. 4. The noise floor was experimentally measured to be -165 dBm/Hz. This agrees within ± 0.5 dBm with the theoretical prediction using (4b), a detector photocurrent of 2.1 mA, and an RIN of -165 dB/Hz. From this data, the noise figure was extracted to be 31.4 dB. An SFDR value of 115 dB/Hz$^{2/3}$ was obtained from Fig. 4. If the optical input into the MZM could be increased to the 200-mW limit, the best SFDR achievable would be 121 dB/Hz$^{2/3}$ with a link gain of -15 dB at 4 mW of optical power input into the photodiode from the second optical carrier.

IV. Conclusion

We have experimentally demonstrated a suppressed-carrier optical heterodyned up-conversion link with two optically heterodyned lasers and a single MZM, requiring only the IF bandwidth. This link utilizes the optical power handling potentials of both the MZM and the photodiode to improve the RF gain and SFDR. The noise floor is nearly independent of the input power to the MZM. Using the null bias minimizes the even order distortion and maximizes the powers of the optical sidebands, thereby maximizing the multioctave SFDR. This experiment demonstrates good link gain and broad-band operation. Additional features of the link are low DIPP and LO suppression due to a suppressed optical carrier. These features make this link promising for signal transmission in the MMW band.

References

[1] S. A. Pappert, R. Helkey, and R. T. Logan Jr., "Photonic link techniques for microwave frequency conversion," in *RF Photonic Techonology in Optical Fiber Links*, W. S. C. Chang, Ed: Cambridge Univ. Press, 2002, pp. 293–333.

[2] R. T. Logan Jr., "Remote millimeter-wave antenna fiber optic communication system using dual optical signal with millimeter-wave beat frequency," U.S. Patent 5710 651, Jan. 1998.

[3] W. B. Bridges, U. V. Cummings, and J. H. Schaffner, "Linearized modulators for analog photonic links," in *IEEE MWP'96 Tech. Dig.*, Dec. 1996, pp. 61–64.

[4] M. L. Farwell, W. S. C. Chang, and D. R. Huber, "Increased linear dynamic range by low biasing the Mach-Zehnder modulator," *IEEE Photon. Technol. Lett.*, vol. 5, pp. 779–782, July 1993.

[5] M. J. LaGasse, W. Charczenki, M. C. Hamilton, and S. Thaniyavarn, "Optical carrier filtering for high dynamic range fiber optic links," *Electron. Lett.*, vol. 30, pp. 2157–2158, Dec. 1994.

[6] R. A. Griffin, P. M. Lane, and J. J. O'Reilly, "Dispersion-tolerant subcarrier data modulation of optical millimeter-wave signals," *Electron. Lett.*, vol. 32, pp. 2258–2260, Nov. 1996.