A Photonic-Link Millimeter-Wave Mixer Using Cascaded Optical Modulators and Harmonic Carrier Generation

C. K. Sun, R. J. Orazi, S. A. Pappert, and W. K. Burns

Abstract—**Efficient frequency conversion into and out of the millimeter wave frequency band has been demonstrated using photonic link signal mixing with cascaded optical modulators. By adjusting the modulator bias point and RF drive power to the modulator introducing the local oscillator signal at $f_{\mathrm{LO}} = 8.8$ GHz, frequency conversions from f_s to $f_{\mathrm{LO}} \pm f_s$, $2f_{\mathrm{LO}} \pm f_s$, and $4f_{\mathrm{LO}} \pm f_s$ with respective losses of 4.8, 6.3, and 7.5 dB have been demonstrated. The direct phase noise measurement of the optical RF signal at $2f_{\mathrm{LO}} = 17.6$ GHz with 1 kHz offset shows -89 dBc/Hz, limited by the RF drive source.**

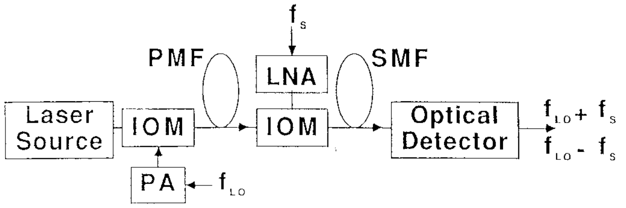


Fig. 1. Schematic of the photonic link mixer with cascaded modulators.

ANALOG photonic links are potentially useful for many applications requiring high-speed antenna remoting or RF signal distribution. Size, weight, bandwidth, and low optical transmission loss are the primary advantages of optically transmitting high-frequency analog information. However, as the frequency of operation increases, limitations in optical modulation and detection efficiency result in high RF insertion loss for single modulator broadband transmission. For suboctave bandwidth transmission systems operating at high center frequency, another approach is possible. A millimeter wave (MMW) photonic mixer composed of a cascaded optical modulator link [1]–[4] or a single modulator link with heterodyned lasers [5] can be used to increase the overall link efficiency. Eliminating the intermediate electronic conversion from RF to MMW, this photonic mixer approach benefits from using a low half-wave voltage (V_π) modulator to introduce the information signal for upconversion and an efficient photodetector to recover the information signal for downconversion. This letter focuses on the cascaded modulator approach to achieve efficient MMW frequency translation.

A schematic of the cascaded integrated optical modulator (IOM) photonic mixer is shown in Fig. 1. In this case, polarization-maintaining fibers (PMF's) are used to connect a polarized optical laser source to the cascaded IOM's and the modulated output after the second IOM is remoted through a standard single-mode fiber (SMF) to a photodetector. A low noise amplifier (LNA) is required to obtain RF transparency at f_s and a power amplifier (PA) is required to achieve a high modulation depth local oscillator (LO) optical signal at f_{LO}.

Past work has used this photonic link signal mixing approach to demonstrate upconversion or downconversion at $f_{\mathrm{LO}} \pm f_s$ [1]–[4]. In this paper, the cascaded modulator approach is used with the LO signal derived from either the fundamental, second, or fourth harmonic of the modulator RF output to produce efficient conversion to $Nf_{\mathrm{LO}} \pm fs$ where $N = 1$, 2 or 4. With the LO modulator driven at 8.8 GHz and RF powers ranging from +25 to +35 dBm, a 1.1 GHz information signal is upconverted to 9.9, 18.7, and 36.3 GHz with measured conversion loss of 4.8, 6.3, and 7.5 dB, respectively. Using the fourth harmonic of the LO modulator signal driven at 8.8 GHz, downconversion from 36.3 GHz to 1.1 GHz with a loss of 7.0 dB has also been measured.

Aside from RF link loss at f_s, the cascaded modulator photonic link with an RF overdriven Mach–Zehnder modulator biased at quadrature has previously achieved a 4.7-dB conversion loss from f_s to $f_{\mathrm{LO}} \pm f_s$ [4]. A drawback of using this MMW frequency converting photonic link technique is that a modulator with a low V_π near the desired transmit frequency is required to maintain a reasonable electrical drive power for minimum conversion loss. A 10 V half-wave voltage already implies an input MMW electrical drive power exceeding +30 dBm to optimally overdrive the modulator. As the modulation frequency is increased, the modulator half-wave voltage increases resulting in a decrease of the modulation efficiency. An optical modulator with adequate MMW modulation response has been an elusive device although some encouraging results have been reported [6], [7].

One means of circumventing the modulator bandwidth limitation is to drive the appropriately biased modulator introducing the LO signal at $1/N$ the desired LO frequency, N an integer, and rely on the efficient harmonic carrier generation that can be obtained with these devices. In this manner, efficient modulator response is only required at $1/N$ times the desired transmit frequency range. Taking the case of $N = 2$ and $N = 4$ as an example, biasing the LO

Manuscript received January 22, 1996; revised May 20, 1996.

C. K. Sun, R. J. Orazi, and S. A. Pappert are with the NCCOSC RDT&E Division, Code 895, San Diego, CA 92152-5000 USA.

W. K. Burns is with the Naval Research Laboratory, Code 6571, Washington, DC 20375-5320 USA.

Publisher Item Identifier S 1041-1135(96)06559-7.

TABLE I
SIMULATED MINIMUM CONVERSION LOSSES FROM f_s TO $Nf_{LO} \pm f_s$ OF THE CASCADED MODULATOR MIXER WITH RESPECTIVE OPTIMUM MODULATOR RF DRIVE VOLTAGES (PEAK AMPLITUDE) AND BIAS CONDITIONS

IOM Bias	quadrature					max. or min. transmission				
N =	1	3	5	7	9	2	4	6	8	10
Drive voltage (V_π)	0.59	1.3	2.1	2.7	3.4	0.97	1.7	2.4	3.1	3.7
Conver. loss (dB)	4.7	7.2	8.5	9.4	10.1	6.3	8.0	9.0	9.8	10.4

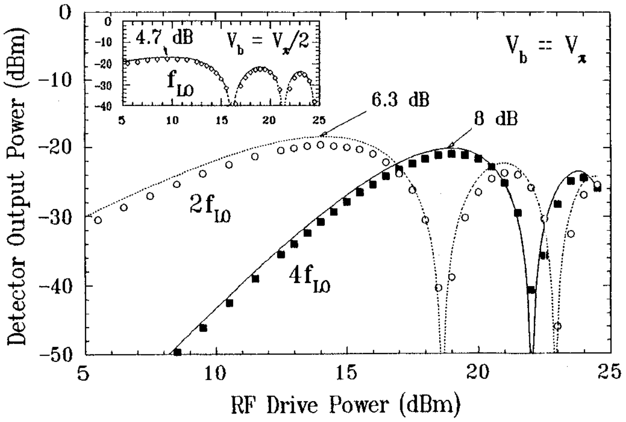
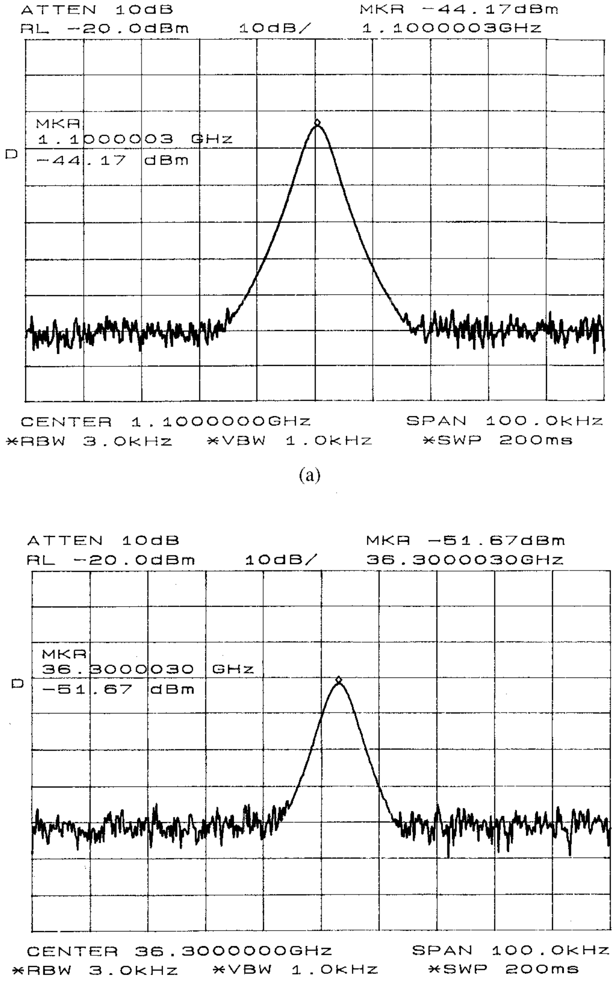


Fig. 2. Simulation (symbols) and experimentally measured (lines) photodetector output power of the $2f_{LO}$ and $4f_{LO}$ optical signals as functions of the modulator RF drive power. The modulator is biased at minimum optical transmission. For modulator biased at quadrature, the f_{LO} detector output power as a function of the RF drive power is shown in the inset.

modulator at minimum optical transmission ($V_b = V_\pi$) and electrically driving this modulator at f_{LO}, the detector output power versus electrical drive power for the resulting $2f_{LO}$ and $4f_{LO}$ signals are shown in Fig. 2. For demonstration purposes, the experimental points were obtained using $f_{LO} =$ 100 MHz and an LO Mach–Zehnder modulator with $V_\pi =$ 3.3 V. Excellent agreement is found between experiment and simulation which is based on calculating Fourier expansions of the modulator output power similar to that previously discussed [4]. Compared to operation at f_{LO} with the modulator biased at quadrature ($V_b = V_\pi/2$), which is displayed in the inset of Fig. 2, a reduction in detector power at the respective optimum electrical drive powers of only 1.6 dB and 3.3 dB are incurred at $2f_{LO}$ and $4f_{LO}$, respectively. This translates into added conversion losses of 1.6 dB and 3.3 dB to extend the link frequency response from $f_{LO} \pm f_s$ to $2f_{LO} \pm f_s$ and $4f_{LO} \pm f_s$, respectively. Operating at a frequency of $4f_{LO}$ with near optimum modulator drive power and minimum transmission modulator bias, the odd harmonics, 1, 3, 5, $\cdots$, vanish, as well as the $2f_{LO}$ term. This implies a clean MMW spectrum out to $4f_{LO}$ is possible which reduces the potential intermodulation distortion problem associated with undesired frequency components. The predicted attainable conversion losses and the corresponding RF drive voltages (listed in terms of V_π) using the above approach for $N = 1$ through 10 are summarized in Table I, although experimental verification has been limited to $N = 1$, 2, and 4 for this letter.

To verify these frequency conversion results in the MMW range, an LO frequency of 8.8 GHz and a signal frequency of 1.1 GHz have been chosen. For upconversion, the experimental setup includes a lithium niobate Mach–Zehnder information modulator with 4 dB optical insertion loss and 4.5-V half-wave voltage at 1.1 GHz, a lithium niobate travelling-wave LO modulator with 6-dB optical insertion loss and 11-V half-wave voltage at 8.8 GHz, a 45-mW Nd:YAG solid-state laser emitting at 1.32 μm, and a 45-GHz optical detector with a fiber-coupled responsivity of approximately 0.25 A/W. Optimum LO modulator electrical drive powers of +26 dBm, +31 dBm, and +35 dBm have been used to produce the signals at 9.9, 18.7, and 36.3 GHz, respectively. The spectrum analyzer traces showing the link output powers at 1.1 and 36.3 GHz are displayed in Fig. 3. After the detector frequency response has been calibrated out, conversion losses of 4.8, 6.3, and 7.5 dB are measured for 9.9, 18.7, and 36.3 GHz upconverted signals, respectively.



(a)

(b)

Fig. 3. Spectrum analyzer traces of (a) the information signal at 1.1 GHz and (b) the upconverted signal at 36.3 GHz.

Compared with single modulator link transmission at 36.3 GHz, the above upconverting link transmission approach becomes attractive if the MMW modulator operating at 36.3 GHz has a V_π of 2.5 times or greater than that of the low-

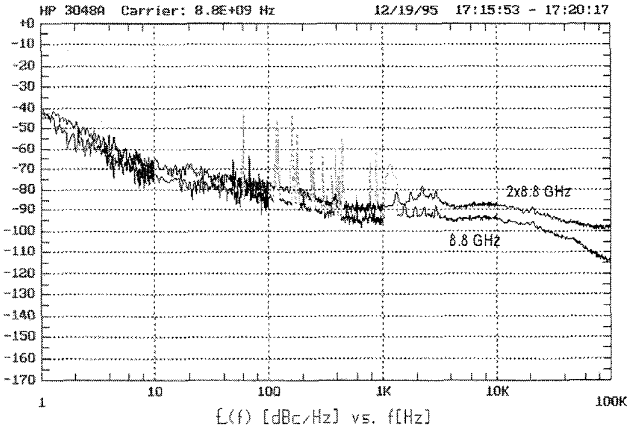


Fig. 4. Phase noise measurement results of the optical signals at f_{LO} (= 8.8 GHz) and $2f_{\mathrm{LO}}$.

frequency information modulator. This comparison excludes electronic mixer loss to convert the signal from 1.1 GHz to 36.3 GHz for single-modulator MMW transmission. Based on the above analysis, a MMW modulator with a V_π at 36.3 GHz of <2.5 V would be required to surpass the advantage of using the photonic mixer approach, given an achievable information modulator V_π of 1 V. A MMW modulator with this performance is not a standard device. Further improvements on the MMW modulator efficiency will only extend the usefulness of this technique to frequencies greater than 100 GHz.

Frequency downconversion is also possible with the cascaded modulator approach. Using the fourth harmonic of the 8.8-GHz driving signal as the high-side LO signal, a 34.1-GHz signal is introduced to a MMW optical modulator and the downconverted signal at 1.1 GHz is recovered. A lithium niobate travelling-wave modulator with a 7-dB optical insertion loss and a 15-V half-wave voltage at 34.1 GHz is used for this downconversion configuration. A conversion loss of only 7.0 dB has been measured which is slightly better than simulation predicted. For these frequency conversion loss measurements, an experimental uncertainty of ±0.2 dB is estimated. The discrepancy between measurement and simulation as well as the difference in the measured upconversion and downconversion losses is not clear at this time. The 15-V half-wave voltage of the MMW optical modulator used for this experiment results in high-RF link loss for the MMW transmission. This approach for downconversion will become more attractive as efficient MMW optical modulators and reduced MMW link loss become available.

To fully exploit the benefit of the cascaded modulator approach, the frequency stability of the optical MMW signals have been studied. For all of the optical signals generated by the overdriven LO modulator, we measure the frequency drift over an hour to be within 1 Hz, which is limited by instrumentation resolution. To further characterize the signal quality, a direct phase noise measurement has been conducted using a phase noise test set (HP 3048A + HP 8662A) and a programmable microwave downconverter (HP 11729C). Due to the limited bandwidth (18 GHz) of the microwave downconverter, only 8.8- and 17.6-GHz signal phase noise are measured as shown in Fig. 4. From Fig. 4, the phase noise of the 8.8- and 17.6-GHz signals at 1 kHz offset are −95 and −89 dBc/Hz respectively. These phase noise results are as good as the measured phase noise of the electrical signals obtained from the LO driving source (HP 8341B) at the respective frequencies. A residual phase noise measurement comparing the LO driving signal and the optical signal at $f_{\mathrm{LO}} = 8.8$ GHz shows an output of −130 dBc/Hz at 1 kHz offset, revealing ultra low added phase noise to the LO drive source. At lower frequency, a premium 1.28 GHz synthesizer (HP 8662A) has also been used as an LO drive source and synthesizer limited phase noises of −107 and −119 dBc/Hz at 1 kHz offset have been measured for optical signals generated at $4f_{\mathrm{LO}}$ and f_{LO} ($f_{\mathrm{LO}} = 1.27$ GHz), respectively. The phase noise increments of the optical signals from both f_{LO} to $2f_{\mathrm{LO}}$ and f_{LO} to $4f_{\mathrm{LO}}$ are about 6 dB and 12 dB, respectively. Thus the effect of optical frequency multiplication by N results in phase noise power increase by N^2, similar to an electronic frequency multiplier [8]. This also implies the phase noise for the 35.2-GHz signal at 1 kHz offset should be −83 dBc/Hz using the HP 8341B as the drive source at 8.8 GHz. Better phase noise could be obtained at this frequency if a premium source operating at 8.8 GHz is available.

In summary, a cascaded optical modulator link has been used along with low phase noise harmonic carrier generation to produce efficient MMW upconversion and downconversion. This approach is useful for extending the operating frequency of analog photonic links beyond the limit presently imposed by the modulation efficiency of MMW optical modulators.

REFERENCES

[1] G. K. Gopalakrishnan, W. K. Burns, and C. H. Bulmer, "Microwave-optical mixing in LiNbO3 modulators," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 2383–2391, 1993.
[2] G. K. Gopalakrishnan, R. P. Moeller, M. M. Howerton, W. K. Burns, K. J. Williams, and R. D. Esman, "A low-loss downconverting analog fiber-optic link," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2318–2323, 1995.
[3] A. C. Lindsay, G. A. Knight, and S. T. Winnall, "Photonic mixers for wide bandwidth RF receiver applications," *IEEE Trans. Microwave Theory Tech.*, vol. 43, pp. 2311–2317, 1995.
[4] C. K. Sun, R. J. Orazi, and S. A. Pappert, "Efficient Microwave Frequency Conversion Using Photonic Link Signal Mixing," *IEEE Photonics Technol. Lett.*, vol. 8, pp. 154–156, 1996.
[5] R. T. Logan, Jr., and E. Gertel, "Millimeter-wave photonic downconverters: Theory and demonstrations," in *Proc. SPIE*, 2560, pp. 58–69, 1995.
[6] G. K. Gopalakrishnan, C. H. Bulmer, W. K. Burns, R. W. McElhanon, and A. S. Greenblatt, "40 GHz, low half-wave voltage Ti:LiNbO3 intensity modulator," *Electron. Lett.*, vol. 28, pp. 826–827, 1992.
[7] D. Noguchi, H. Miyazawa, and O. Mitomi, "75 GHz broadband Ti:LiNbO3 optical modulator with ridge structure," *Electron. Lett.*, vol. 30, pp. 949–951, 1994.
[8] W. P. Robins, *Phase Noise in Signal Sources, IEE Telecommunications Series 9.* London, U.K.: Peter Peregrinus Ltd., 1984, pp. 78.