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 $f_{LO} = 8.8$ GHz, frequency conversions from $f_s$ to $f_{LO} \pm f_s$, $2f_{LO} \pm f_s$, and $f_{LO} \pm f_s$ 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 $2f_{LO} = 17.6$ GHz with 1 kHz offset shows $-89$ dBC/Hz, limited by the RF drive source.

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 ($V_n$) 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 optical 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 $f_{LO} \pm f_s$ [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 $N f_{LO} \pm f_s$ 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 $f_{LO} \pm f_s$ [4]. A drawback of using this MMW frequency converting photonic link technique is that a modulator with a low $V_n$ 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...
modulator at minimum optical transmission ($V_b = V_s$) 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 $V_s = 3.3$ 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 ($V_b = V_s/2$), 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 $f_{LO}$ to $2f_{LO}$ $+ f_s$ and $4f_{LO}$ $+ f_s$, 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, ..., 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 $V_s$) using the above approach for $N = 1$ through 10 are summarized in Table I, although experimental verification has been limited to $N = 1, 2, 4$ 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.

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 $V_s$ of 2.5 times or greater than that of the low-

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**TABLE I**

<table>
<thead>
<tr>
<th>N</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drive voltage ($V_s$)</td>
<td>0.59</td>
<td>1.3</td>
<td>2.1</td>
<td>2.7</td>
<td>3.4</td>
<td>0.97</td>
<td>1.7</td>
<td>2.4</td>
<td>3.1</td>
<td>3.7</td>
</tr>
<tr>
<td>Converter loss (dB)</td>
<td>4.7</td>
<td>7.2</td>
<td>8.5</td>
<td>9.4</td>
<td>10.1</td>
<td>6.3</td>
<td>8.0</td>
<td>9.6</td>
<td>9.8</td>
<td>10.4</td>
</tr>
</tbody>
</table>

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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.

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 $V_s$ of 2.5 times or greater than that of the low-
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 7-dB insertion
loss and a 15-V half-wave voltage at 34.1 GHz is used along
with low phase noise harmonic carrier generation
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.

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