Covert Photonics-Enabled Millimeter-Wave Transmitter

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Abstract — Military communications are at a high risk of interception and detection and operate in regions with intentional jamming. Covert communication systems can reduce the probability of intercept and detection and increase robustness against jamming by employing spread-spectrum waveforms. To observers, a spread-spectrum signal appears as random noise, whereas to intended users the data can be recovered by using a shared key. Since spread-spectrum signals require large bandwidths, millimeter-wave (mmW) frequencies offer ideal bands for operation. Long-distance covert communications can use the W-band (75–110 GHz) and efficiently employing spread-spectrum signals at W-band is the focus of this paper. Specifically, our work uses photonic components in the analog front end of a transmitter to communicate covertly in the W-band. In this manner, high bandwidth, low-loss photonic components replace performance-limited RF components. The end result is a photonics-enabled spread-spectrum W-band transmitter demonstrated at 83 GHz and spreading the signal over a 4 GHz bandwidth.

Keywords — covert communications, microwave photonics, millimeter-wave, spread spectrum.

I. INTRODUCTION

On the battlefield, it is desirable to have low probability of detection (LPD) and low probability of intercept (LPI) of military communications. One way of reducing the probability of detection and intercept is through the use of spread spectrum systems where the data being transmitted are divided into chips of pseudo random noise (PRN) and appear as noise in the passband. Though the process of encoding the data and spreading them over large bandwidths is spectrally inefficient, spread-spectrum systems provide resistance to multi-path, interference, and jamming [1] and is a natural choice for multiple-user access schemes [2].

Spectrum in the millimeter-wave (mmW) regime is particularly attractive in point-to-point high-data-rate applications due to the availability of small-size high-gain antennas and wide bandwidths. Due to the relatively small wavelengths in the W-band, it is possible to manufacture physically small antennas that allow for narrow beamwidths with high gain which help to conceal transmitted signals from unintended recipients.

Ideally, the V-band (40–75 GHz) is useful for covert communications because a signal is rapidly attenuated by atmospheric gases [3] but is only practical in short-distance links. For long-distance links, much work in the mmW regime uses the W-Band (75–110 GHz) where attenuation by atmospheric gases can be as low as 0.4 dB/km [3] and total losses (including path-loss [4]) is less than that in the V-band (for long-distance links). To improve resiliency against jamming and interception, it is best to utilize the entire W-band (35 GHz) which requires the use of extremely broadband components at the transmitter and receiver.

Photonics-enabled systems have several advantages over their RF counterparts and are inherently broadband, allowing for a single hardware setup to span many bands without the need for multiple lower bandwidth, higher loss RF mixers [5], [6]. Furthermore, photonics-aided up and downconversion eliminates the need for mmW electronic oscillators. Photonic conversion provides inherent signal to local oscillator isolation, carrier frequency flexibility, and better spurious responses as compared to mixer-based systems [7], [8]. The low loss (≈ 0.2 dB/km), light weight, and flexibility of fiber optic cables compared to mmW transmission lines and waveguides enables separation of signal generation and processing hardware from the antenna [9]. Millimeter-wave arrays with tight element spacing requirements can especially benefit from having signals fed through fiber optic cables [10].

This paper demonstrates a direct-sequence spread-spectrum (DSSS) W-band transmitter using photonic signal upconversion for application in long-range point-to-point covert communication systems with high gain antennas. The technique used in the receiver for downconversion is nearly the same and has been previously demonstrated [9], [10]. This paper uses a BPSK modulated waveform to demonstrate the operation of spread spectrum systems. Signals with chip to data ratios of up to 500, with signal bandwidths up to 4 GHz, are demonstrated to illustrate the technique and highlight the unique benefits of photonics for covert mmW systems.

II. SPREAD SPECTRUM SYSTEMS

A. Direct-Sequence Spread-Spectrum

Spreading is the process of using a pseudo-random noise binary sequence to divide the data bits into multiple PRN chips resulting in a signal that appears as noise and occupies a larger bandwidth than a data stream that has not been spread. Direct-sequence refers to the modulation scheme where the data is modulated onto a carrier followed by the application of the PRN spreading sequence [11].

As the chip ratio (CR, the number of chips per data bit) increases, the bandwidth of the transmitted signal increases. The data rate remains the same while the chip rate (raw pulse rate) increases. The receiver, with knowledge of shared PRN code, recovers the signal from the noise floor and performs conventional demodulation to decode the information bits.

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Fig. 1. Spread-spectrum (a) transmitter and (b) receiver with photonic conversion.

Although a spread signal does not improve performance against additive white Gaussian noise [12], it does provide anti-jamming capabilities. An intentional interferer may be successful at jamming the ability to receive a transmission given a static carrier frequency, bandwidth, and power. However, for DSSS, the interferer must increase the jamming bandwidth and power to maintain a jam-signal power (J/S) ratio. With DSSS, the information spreads over the entire signal bandwidth while the receiver "de-spreads" the signal power of the intended transmission before demodulation.

B. DSSS Transmitter and Receiver

The data and PRN sequences are modulo-2 added together [12] before modulation providing that the binary integers 0, 1 map to 1, −1, respectively. If \( x(t) \) is the binary data sequence, \( p(t) \) is the binary PRN sequence, and \( A \) is the carrier power level. First, \( x(t) \) and \( p(t) \) are modulo-2 added together and then the resulting binary sequence is converted to a pulse value of ±1. This sequence is then modulated onto a carrier with angular frequency \( \omega_c \). The resulting transmit signal is

\[
s(t) = \sqrt{2A}x(t)p(t)\cos(\omega_c t).
\]

(1)

The received signal, \( r(t) \) without channel noise is

\[
r(t) = G\sqrt{2A}x(t-T)p(t-T)\cos[\omega_c(t-T) + \phi)]
\]

(2)

where \( G \) is the system gain, \( T \) is the actual propagation delay, and \( \phi \) is the phase angle (random). To accurately recover the signal from the noise floor, \( r(t) \) must be multiplied by a perfectly generated replica of the transmitted PRN code \( p(t-T) \) where \( \hat{T} \) is the propagation delay estimated by the receiver. Together the PRN code generator, mixer, and filter form the correlator. The locally generated PRN sequence shifts until both PRN codes perfectly align (i.e., the correct propagation delay). The output of the correlator is

\[
h(t) = G\sqrt{2A}x(t-T)p(t-T)
\]

\[
p(t-\hat{T})\cos[\omega_c(t-\hat{T}) + \phi)].
\]

(3)

When the locally generated and received PRN sequences are perfectly aligned \( T = \hat{T} \) (the actual time delay is found) and the product \( p(t-T)p(t-\hat{T}) = 1 \). Afterwards, demodulation can take place to extract \( x(t) \) from the remaining signal components. Many orthogonal codes can exist to satisfy the conditions, a fact that is leveraged when different users of the same bandwidth are assigned a unique PRN sequence in code-division-multiple-access (CDMA) systems [11], [13].

III. PHOTONICS-ENABLED SYSTEMS

A. Photonic Upconversion and Downconversion

The DSSS signal is created by the process described in Section II-B at an intermediate frequency (IF) \( f_{IF} \ll f_{mmW} \). Fig. 1 illustrates the two stage process that brings the signal in and out of the mmW regime. The photonic upconversion stage requires the input of a low phase noise electronic local oscillator (LO) at \( \omega_{LO}/n \) (\( n \) is an integer) such that the final carrier frequency \( \omega_c = \omega_{LO} + \omega_{IF} \) or \( \omega_{LO} - \omega_{IF} \), as the photonic converter multiplies the \( \omega_{LO}/n \) signal or uses it as a frequency reference. The DSSS signal is also input to the upconverter, and the output is the signal at the desired mmW frequency \( \omega_c \) which can then be filtered, amplified, and transmitted. For the receiver the opposite process is employed [9], [10], with the appropriate frequencies selected for the LO and IF. The output of the downconverter is the DSSS signal sent to the correlator and demodulator. Photonic conversion allows all signal generation and reception to be achieved using low frequency electronics.

A key element of the converter is photonic heterodyne mixing. When two optical tones are received by a photodiode, the signals interact nonlinearly, producing frequencies at the sum and difference of the optical tones. The sum frequency and the frequencies of the optical carriers are filtered out by the bandwidth of the photodiode and difference frequency remains.

There are different methods of setting the carrier frequency. The simplest is dual-wavelength optical signal generation, but this requires complex control circuitry. One laser cavity...
emits two optical frequencies spaced by the desired mmW frequency. In this method, the optical cavity, not the optical pump or the electrical oscillator, determines the noise power. This method is especially attractive for applications requiring carrier frequency tuning, as the phase noise is independent of the generated RF frequency [14].

This paper uses a different method for carrier selection, known as double-sideband suppressed-carrier signal generation [15]. In this method, the \( \omega_{LO}/n \) signal drives an electro-optic Mach-Zehnder modulator biased at its null point. The null bias suppresses the optical carrier, and the modulation creates sidebands at even multiples of the input. For example, if \( n = 2 \), the first two sidebands will be spaced by \( \omega_{LO} \). When these two sidebands mix on a photodiode, the electrical signal contains the separation frequency. This solution is convenient, as it requires a single laser, and a low- to moderate-frequency modulator and oscillator. By delay matching the full paths of the two sidebands, the impact of the laser linewidth is minimized and the phase noise is set by the phase noise of the electronic oscillator.

### B. Photonic Data Encoding

Data can be introduced by optically filtering one of the desired sidebands and phase modulating that tone with the data to be upconverted. The required bandwidth of the electro-optical phase modulator is generally low and is determined by the bandwidth of the data and by \( \omega_{IF} \). The unmodulated sideband can be path-matched with added fiber. The photodiode receives the two recombined sidebands. The output of the photodiode includes the data at the desired carrier frequency, \( \omega_c \). In the downconversion process, the two sidebands are again filtered and path matched, the received mmW signal is input to the phase modulator, and after optical recombination and mixing on the low-frequency photodiode, one of the output terms is the data at \( \omega_{IF} \). In this method, the only two components that require mmW bandwidths are the transmit photodiode and the receive modulator.

### IV. Results

#### A. Experimental Setup

With an arbitrary waveform generator (Tektronix AWG7122B, 12 GSa/s) programmed with a DSSS test signal, photonics-enabled upconversion has been successfully demonstrated. The test signal, generated in MATLAB, consists of a DSSS BPSK modulated waveform and the resulting pulse stream was upconverted to the desired IF at 3.0 GHz. Fig. 2 shows the transmitter architecture and Fig. 3 shows the experimental setup. The 80 GHz LO is generated using an optical C-band semiconductor external cavity laser (ECL, linewidth < 5 kHz), and an intensity modulator biased at null driven by an RF source at 40 GHz. This suppresses the optical carrier and produces two sidebands spaced 80 GHz apart. After amplification with an erbium-doped fiber amplifier (EDFA), a demultiplexer (DEMUX) filters the optical sidebands and matched sideband path lengths suppress laser phase noise. An optical phase modulator driven by the output of the AWG encodes one sideband. A multiplexer (MUX) recombines the modulated and unmodulated sidebands, which then mix on a photodiode (PD, \( f_{3dB} > 100 \text{ GHz} \), 0.43 A/W responsivity) to upconvert the data onto the 83 GHz carrier. A spectrum analyzer (Agilent PXA-N9030A) with a W-band mixer receives the output of the photodiode. This experiment is repeated to illustrate the effect of increasing the chip ratio to various values.

#### B. Experimental Results

To demonstrate spreading of a BPSK modulated signal we chose a variety of chip ratios with a maximum of \( CR = 500 \). As CR is increased, the bandwidth of the main lobe increases and the maximum power decreases. Fig. 4 illustrates this effect using a BPSK signal with a data rate of 4.0 Mbps with different chip ratios. In Fig. 4(a), the additional peak at 82.4 GHz is caused by a combination of mixing spurs and quantization errors in the AWG. Table 1 lists the properties of each signal.

### V. Conclusion

In this paper, we presented a photonics-enabled spread-spectrum transmitter at 83 GHz using the BPSK modulation format. Chip rates up to 2000 Mcps were
achieved while keeping the data rate constant at 4.0 Mbps by using an AWG programmed with a MATLAB script to output an IF DSSS signal. The IF signal was upconverted to 83 GHz using an optical carrier. The photonics upconverter was able to double our LO frequency to 80 GHz with minimal noise and power loss. The resulting signal, fed to a photodiode for conversion to the electrical domain, was viewed on a spectrum analyzer. Our results confirm that an increase in CR further spreads the signal and pushes it into the noise floor and would appear as random noise to an observer.

Table 1. Tx Waveform Properties

<table>
<thead>
<tr>
<th>Chip Ratio</th>
<th>Data Rate (Mbps)</th>
<th>Chip Rate (Mcps)</th>
<th>Bandwidth (MHz)</th>
<th>Carrier Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.00</td>
<td>4.00</td>
<td>8</td>
<td>83</td>
</tr>
<tr>
<td>5</td>
<td>4.00</td>
<td>20.00</td>
<td>40</td>
<td>83</td>
</tr>
<tr>
<td>50</td>
<td>4.00</td>
<td>200.00</td>
<td>400</td>
<td>83</td>
</tr>
<tr>
<td>500</td>
<td>4.00</td>
<td>2000.00</td>
<td>4000</td>
<td>83</td>
</tr>
</tbody>
</table>

Fig. 4. Measured spectrum of a DSSS transmitter with photonic upconversion for various chip ratios (a) $CR = 1, 5$ and (b) $CR = 50, 500$.