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Coherent photonic Terahertz transmitters compatible with direct comb modulation

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ABSTRACT

We present a novel approach to coherent photonic THz systems supporting complex modulation. The proposed scheme uses a single optical path avoiding the problems of current implementations, which include: phase decorrelation, 3-dB power loss, and polarization and power matching circuits. More importantly, we show that our novel approach is compatible with direct modulation of the output of an optical frequency comb (i.e., not requiring the demultiplexing of two tones from the comb), further simplifying the system and enabling an increase in the transmitted RF power for a fixed average optical power injected into the photodiode (PD).

Introduction

Terahertz (THz) frequency bands (100 GHz - 1 THz) have transmission windows with unregulated widths of several tens of GHz. These bands are considered a key resource to combat the spectrum congestion at lower radio frequencies (RFs). Hence, THz communications have become a very active research topic in the past few years⁹. The highest transmission rates reported in Terahertz (THz) communications have been enabled by coherent photonic systems supporting complex modulation formats²,³. To date, the most common architecture of these systems is the one depicted in Fig. 1 (a). Unlike photonic systems operating at lower mm-wave frequencies – which can generate phase correlated tones with the required frequency spacing by using the suppressed-carrier technique – THz systems rely in an optical frequency comb generator (OFCG)⁴. A wavelength selective switch (WSS) is then used to demultiplex two tones from the OFCG. One of them is encoded with the data and the other is left unmodulated to act as local oscillator (LO) in the photomixing process that takes place in the photodiode (PD). Before recombining the two optical modes, it must be ensured that both have the same polarization state and optical power⁵.

Figure 1. THz transmitters: (a) heterodyne transmitter, (b) proposed single-path THz transmitter with DSB receiver. DSB: double sideband, WSS: wavelength selective switch.

The arrangement described before presents several problems for practical implementation: first, as the two comb tones
travel through different optical paths, they become decorrelated increasing the phase noise of the generated THz signal. The mitigation of this phenomenon has been the subject of numerous studies, leading to very complex analog or digital phase-noise mitigation systems. Second, the system in Fig. 1 (a) leads to a 3-dB optical loss due to need of first splitting the two OFCGs modes with the WSS and then recombining them with an optical coupler. Furthermore, the need to match both the polarization state (requiring automatic polarization tracking circuits) and the power level (through the use of a variable optical attenuator) of both signals makes the system rather complex.

In this paper, we present a novel approach to coherent photonic THz systems supporting complex modulation that avoids all these problems by using a single optical path. Furthermore, as shown in Fig. 1 (b), our scheme only uses one port of the WSS, allowing a two-fold increase in the number of transmitters. We show that our approach is compatible with the direct modulation of the OFCG (i.e., not requiring the WSS), further simplifying the system and enabling an increase in the transmitted RF power for a fixed average optical power injected into the PD.

System details

The obstacle to using one single optical path in coherent photonic THz transmitters lies in the square-law detection of the PD, which destroys the phase information if both optical tones are modulated with the same baseband complex signal. However, one can turn to a technique commonly used in direct-detection (DD) optical systems to avoid this problem: the use of single sideband with carrier (SSB-C) modulation. As shown in Fig. 1 (b), by using SSB-C modulation, both optical tones from the comb can be modulated simultaneously and still produce a signal after the PD that preserves the phase information. Upon photodetection, the PD generates a double-sideband (DSB) signal which can be recovered using a traditional DSB receiver.

For the generation of the SSB-C signal several techniques can be used. The most common one is the intensity modulation (IM) technique (shown in Fig. 2 (a)), in which the IQ modulator is biased close to the quadrature point to keep a linear relation between the power of the optical signal and the electrical signal driving the modulator. Alternatively, one can bias the modulator in the null point and add the carrier digitally (see Fig. 2 (b)). The advantage of the latter (in this paper referred to as field SSB-C) is that it halves the required digital-to-analog converter (DAC) bandwidth compared to the IM SSB-C technique.

As shown in Fig. 1 (b) inset III, the generated THz DSB signal also contains signal-signal beat interference (SSBI) terms, which distort the data-carrying signal (see section S1.1.1 of the supplementary information). A simple way to mitigate the SSBI is by allowing a guard band (GB) between optical carrier and data signal. If the GB has the same bandwidth as the signal, the SSBI is totally neutralized as shown in Fig. 2 (c). This technique, however, requires doubling the bandwidth of the DAC and analog-to-digital converter (ADC) compared to the case where no GB is used and halves the efficiency of the system. To avoid this, one can use one of the many digital techniques used in DD optical networks to mitigate the SSBI. One that is especially attractive for the system shown in Fig. 1 (b), is the transmitter-based pre-distortion. This technique is based on digitally calculating the SSBI and subtracting it from the original signal so that a SSBI-free signal is produced at the PD (see Fig. 2 (d)). The advantage of this technique over receiver-based linearization algorithms is that it mitigates the SSBI before the interference arises, and therefore it minimizes the amount of unwanted signal that gets transmitted over the wireless channel.
Simulations
In order to assess the sensitivity of the single-path photonic THz Tx, transmission simulations were implemented in Matlab using 10-GBd 16-QAM signals and following the structure shown in Fig. 3 (a). The block with the × 2 multiplication accounts for the 3-dB amplitude gain that is achieved with DSB demodulation. The signal-to-noise (SNR) was set by varying the amplitude of receiver noise. Three different SSB-C systems were compared: (a) IM SSB-C with no SSBI compensation, (b) field SSB-C with pre-distortion together and varying widths of GBs, and (c) field SSB-C with a GB as wide as the signal bandwidth. The performance of the heterodyne transmitter depicted in Fig. 1 (b) was also simulated. In such case, differential detection was implemented to account for the phase decorrelation between the two optical paths.

Figure 3. (a) Structure of the simulations, \( h(t) \) and \( h'(t) \) are defined in the supplementary information (see S5 and S6); (b) signal-to-noise ratio per symbol (SNR\(_S\)) required to achieve a bit error rate (BER) of \( 3.8 \times 10^{-3} \) vs. number of iterations in the pre-distortion technique; (c) optimum carrier-to-sideband power ratio (CSPR) vs. efficiency for each of the SSB-C signals simulated; and (d) sensitivity vs. efficiency of each signal (including the heterodyne system – black-filled square) at the HD-FEC limit of \( 3.8 \times 10^{-3} \).

Fig. 3 (b) shows the SNR per symbol (SNR\(_S\)) required to achieve a bit error rate (BER) of \( 3.8 \times 10^{-3} \) (hard decision-forward error correction (HD-FEC) limit) against the number of iterations in the pre-distortion technique. As two iterations were found to achieve saturated compensation, this was the number of iterations used in the subsequent simulations. It is important to mention that the investigation on the minimum required number of iterations was only preformed for the case with no GB between carrier and sideband. For the cases with a GB, an even lower number of iterations may suffice. Fig. 3 (c) shows the optimum carrier-to-sideband power ratio, CSPR (see S8 in the supplementary information for its definition), for each of the SSB-C signals simulated. As expected, for increasing values of GB, the optimum CSPR value decreases. This is because the SSBI term overlaps less with the useful signal and more power can be allocated to the data-carrying signal in the SSB-C modulation.

Fig. 3 (d) plots the required SNR\(_S\) at the HD-FEC limit against the THz efficiency for each signal and system (including the heterodyne system). As can be seen, the complexity reduction associated with the single-path scheme comes at the expense of lower efficiency and sensitivity compared to the heterodyne approach. The lower THz efficiency is due to the transmission of a DSB signal, whereas the reduced efficiency is explained due to the energy lost in the unmodulated carrier and also the residual SSBI. In spite of this, we note that the simultaneous use of a GB and pre-distortion with the field SSB-C modulation can be a powerful technique to achieve a good trade-off between sensitivity and efficiency in the single-path Tx.

Direct comb modulation
The main advantage of using SSB signalling is that is compatible with direct comb modulation as shown in Fig. 4 (a). This further simplifies the setup in Fig. 1 (b) as not demultiplexing device is needed. Furthermore, if the comb produces near transform-limited pulses, this scheme can increase – compared to the two-line modulation described in the previous section – the emitted THz power for a fixed level of optical power (or photocurrent). A theoretical gain of up to 6 dB was reported here with experimental results in reference, matching quite well this theoretical value. Calculations in these two references focused on the case where wireless generation is performed at the fundamental repetition frequency. However, as shown in
Fig. 4 (b), comb modulation allows for RF generation at the harmonics of the fundamental frequency, relaxing the requirements on the comb repetition frequency. Following the procedure in reference\(^8\), one can derive the gain expression for different multiplication factors (the same result is obtained when incorporating SSB-C modulation into the analysis as shown in section S1.1.4 in the supplementary information):

\[
4 \left(1 - \frac{X}{N}\right)^2,
\]

where \(X\) and \(N\) are the multiplication factor and the number of comb lines, respectively. It is important to note that Eq. 1 gives the theoretical value according to ideal square-law detection and perfect phase correlation between comb lines; in practice, the maximum multiplication may be limited by PD saturation effects or phase decorrelation\(^8\). In Fig. 4 (c), the gain curves for 1\(\times\), 2\(\times\) and 3\(\times\) multiplication factors are shown, highlighting the respective achieved gain for a 10-line comb. As can be seen, for a finite number of lines the gain decreases with multiplication factor. However, all curves approach the same value of 6 dB when the number of lines tends to infinite.

**Figure 4.** (a) Direct-comb-modulation THz transmitter and spectra of the signal before and after the PD, (b) signal multiplication in a comb-based THz transmitter, and (c) gain achieved for different comb frequency multiplications (inset shows the gain achieved with a 10-line comb and different multiplication factors).

The gain values highlighted in Fig. 4 (c) can be used to determine the gain in THz SNR\(_S\) required by a 10-line comb system to achieve a BER of \(3.8 \times 10^{-3}\) taking as reference the SNR\(_S\) required by the heterodyne system at that BER level and for a fixed level of average photocurrent. For this, the signals in Fig. 3 (c) must be first normalized in terms of average photocurrent (the required scaling factor for the SSB-C and heterodyne signals is derived in sections S1.1.3 and S1.2.3, respectively, of the supplementary material). After average photocurrent normalization, the resulting THz energy of each signal must be computed and compared to that of the heterodyne signal (note that, since the energy and average photocurrent normalizations yield the same expression for the heterodyne signal – see sections S1.2.2 and S1.2.3 of the supplementary material – its THz energy after photocurrent normalization is one). Fig. 5 (a) shows the gain of each of the SSB-C signals employed in the simulations. The decrease in gain with efficiency is linked to the deviation from a value of 0 dB of the optimum CSPR as the GB is narrowed (see Fig. 3 (c)).

**Figure 5.** (a) Direct-comb-modulation THz transmitter and spectra of the signal before and after the PD, (b) achieved gain for 2-line and 10-line comb modulation.
The total gain required, \( G_{\text{req}} \), at the \( X \)th harmonic of the fundamental frequency of a 10-line comb is then:

\[
G_{\text{req}} = (\text{SNR}_{\text{SSB-C}} - \text{SNR}_{\text{Het}}) - G_{\langle IPD \rangle} - 10 \cdot \log_{10} \left[ 4 \left( 1 - \frac{X}{10} \right)^2 \right],
\]

(2)

where \( \text{SNR}_{\text{SSB-C}} \) and \( \text{SNR}_{\text{Het}} \) are the SNRs shown in Fig. 3 (d) for the SSB-C and heterodyne signals, respectively, and \( G_{\langle IPD \rangle} \) is the energy gain shown in Fig. 5 (a). Fig. 5 (b) shows \( G_{\text{req}} \) for both 2-line modulation and the modulation of a 10-line comb. As can be seen, even for a \( 3 \times \) multiplication and a modest GB, \( G_{\text{req}} \) becomes negative, which means that the SNR achieved is higher than that required to produce a BER of \( 3.8 \times 10^{-3} \). This increase in link budget may be used to extend the transmission distance of the THz link or achieve a lower BER.

**Gaussian pulses**

In the previous section, a perfectly flat comb it is assumed. In reality, typical pulsed sources do not produce this type of spectral envelope. One of the most common optical pulses is the Gaussian pulse. The amplitude gain at the fundamental frequency of a pulsed Gaussian source is derived in eq. (9) of reference\(^{10} \). From this equation, the power gain for different multiplication factors can be easily derived. Fig. 6 shows the power gain achieved with a Gaussian source vs. the normalized pulse width for different multiplication factors. The normalized pulse width is the pulse width multiplied by the fundamental repetition frequency. As can be seen, the gain also approaches 6 dB when the normalized pulse width tends to 0 (this limit would correspond to having an infinite number of comb lines). For a known normalized pulse width and multiplication factor, the gain required to produce a BER of \( 3.8 \times 10^{-3} \) can be calculated by replacing the last term in (2) by the gain shown in Fig. 6.

As an example, let us consider the 60-GHz pulse source (i.e. without the optical clock multiplier) in reference\(^{10} \), and assume we want to transmit at 120 GHz (i.e., a \( 3 \times \) multiplication factor is required). The normalized pulse width (taking the narrowest pulse width value reported in such reference – 1.8 ps) is 0.108. The value of the \( 3 \times \) curve in Fig. 6 at 0.108 is approximately 2.8 dB. This value would then be used as the last term in 2 to find \( G_{\text{req}} \). In this case, the SSB-C signal with a THz efficiency of 1.54 (bit/s)/Hz would already have a SNR higher than that required to produce a BER of \( 3.8 \times 10^{-3} \).

**Figure 6.** Power gain achieved with a pulsed Gaussian source vs. normalized pulse width for different multiplication factors.

**Discussion**

We have presented a photonic THz system compatible with complex modulation that offers several advantages over the typical heterodyne transmitter. By using only one optical path our proposed system solves the most important drawbacks associated with the latter, namely: phase decorrelation of the optical modes, 3-dB power loss, and the necessity for both polarization- and power-matching circuits. Furthermore, as the proposed system uses only one port of the demultiplexing device, it allows a two-fold increase in the number of transmitters. We have also discussed ways to mitigate the SSBI, which arises due to the beating of the two sidebands and can distort the data-carrying signal. We found out that the joint employment of a GB with the pre-distortion technique can achieve a good trade-off between efficiency and sensitivity. Finally, we show that the proposed system is compatible with direct comb modulation. This feature is probably the most important one, not only because it allows a further simplification of the system (no demultiplexing device is required) but also because it enables an increase in the transmitted THz power for a fixed average optical power injected into the photodiode (PD).

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Author contributions statement

L.G.G conceived the system architecture, run the simulations and wrote the paper; G.C. assisted in the interpretations of the results. Both authors reviewed the manuscript.

Additional information

To include, in this order: **Accession codes** (where applicable); **Competing interests** (mandatory statement).

The corresponding author is responsible for submitting a **competing interests statement** on behalf of all authors of the paper. This statement must be included in the submitted article file.
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