Phase Noise Investigation of Multicarrier Sub-THz Wireless Transmission System Based on an Injection-Locked Gain-Switched Laser

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***Abstract*— We propose a multi-carrier THz wireless communication system using an injection-locked gain-switched laser as an optical comb source. The phase noise of the 192 GHz signal resulting from the beating of two optical comb lines is theoretically analyzed and experimentally examined. Moreover, a three channel, 10 Gbaud QPSK THz signal is generated, and transmission over 40 km standard single mode fiber (SSMF) is experimentally demonstrated.**

***Index Terms*— Phase noise, gain-switched laser, optical comb, frequency multiplication**

I. Introduction

Data rates in wireless communications have been increasing exponentially over recent decades. However the spectral resources are extremely limited because of the heavy use of today's conventional frequency range up to 60 GHz. High-speed terahertz (THz) wireless communications have attracted great interest for short distance ultrahigh data rate mobile applications [1]. A photonic solution is a promising technique for high-frequency RF signal generation and transmission, as it enables the distribution of high-frequency RF signals over long distance through optical fiber, and makes the system compact and light [2].

Several systems have been demonstrated based on heterodyne detection for increasing the bit rates up to 100 Gbit/s [3-7]. A multicarrier based system with optical subcarriers was demonstrated in the W-band to maximize the overall channel data rate, and achieve high spectral efficiency [3]. The wireless transmission window in the 200 GHz band is of strong interest due to low atmospheric transmission losses. Recently 75 Gbit/s multichannel transmission at 200 GHz carrier frequency using two free running lasers and a digital coherent receiver has been experimentally demonstrated [4,5]. However, the frequency spacing between two lasers is not constant and their phases fluctuate continuously. To stabilize the carrier frequencies, an optical frequency comb-based signal generation is the most effective approach [6-8]. A. Kanno et al. [6] and T. Nagatsuma et al. [7] have experimentally demonstrated 16 quadrature amplitude modulation (QAM) and quadrature phase shift keying (QPSK) systems in the W-band using optical frequency comb-based signal generation. Both of the optical combs used in these works were based on external modulation. The large insertion loss of the multiple cascaded modulators, coupled with the modulation efficiency and the instability induced by bias drift can prove prohibitive for broader optical comb generation. In [8], a 100 Gb/s THz system using a mode-locked laser (MLL) as an optical comb source is proposed. Although this technique can generate multi-carrier signals spanning over a wide bandwidth, it inherently suffers from cavity complexity due to the use of a MLL, and does not offer free spectral range (FSR) tunability since the comb line spacing is fixed by the cavity length of the laser.

Previously, we reported on the use of gain-switching to generate an optical comb [9]. Such a comb source enables simple and cost efficient generation of lightwaves with precisely controlled channel spacing. Different 60 GHz radio over fiber (RoF) systems using the gain-switched comb source have been proposed and demonstrated [10, 11], with the data rate limited to 25 Gb/s due to the limited bandwidth of the 60 GHz technology [11].

In this paper, we propose a multi-carrier THz wireless transmission system using the externally injected gain-switched laser as an optical comb source. The phase noise of the 192 GHz signal resulting from the beating of two optical comb lines is theoretically analyzed and experimentally examined. Moreover, three 10 Gbaud QPSK sub-THz channel signals (with total data rate of 60 Gbit/s) are generated and transmitted over 40 km standard single mode fiber (SSMF) before wireless transmission.

The article is organized as follows. In section II, the principle of THz generation using a gain-switched comb source is explained and the phase noise of the THz signal generated by

Manuscript received Jan. 1st, 2015. This work was supported in part by the SFI PI grant 09/IN.1/I2653 and 10/CE/I1853, the HEA PRTLI 4 INSPIRE Programs, the Engineering and Physical Sciences Research Council programme grant Coherent Terahertz Systems (COTS) (EP/J017671/1), and by the European Commission through the European project iPHOS (grant agreement no: 257539).

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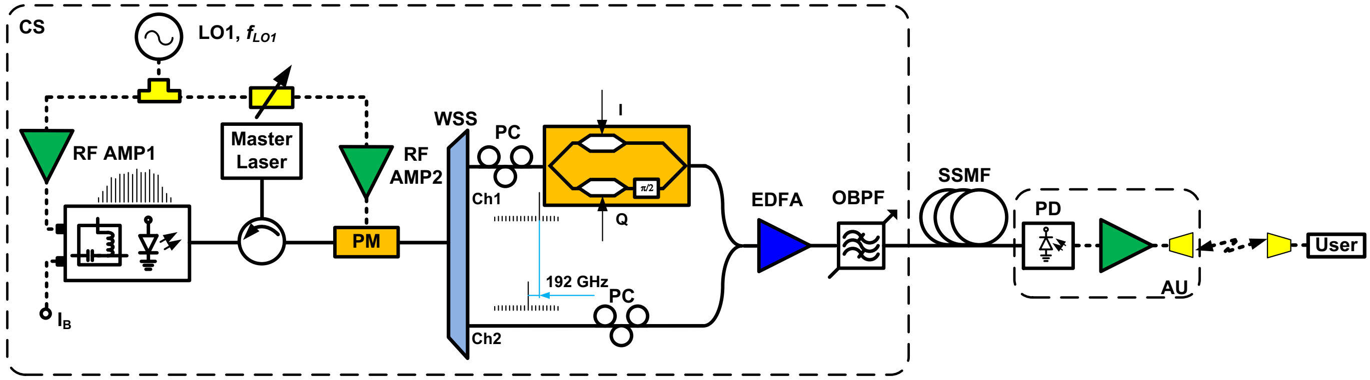


Fig. 1 Principle of the proposed THz-over-fibre system based on a gain-switched laser.

the photonic-RF frequency multiplication is theoretically analyzed and experimentally demonstrated. In section III, a multi-carrier wireless communications THz system based on the gain-switched comb source is experimentally demonstrated. Finally our conclusions are presented in section IV.

II. Principle of THz System and Investigation of Phase Noise

In this part, we will present the principle of the proposed THz signal generation and transmission system using a gain-switched laser as an optical comb source. Then the phase noise of the THz signal resulting from the beating of two optical tones of the gain-switched laser is theoretically analyzed and experimentally demonstrated.

A. Principle of the THz system based on gain-switched laser

Fig. 1 shows the proposed THz multi-carrier transmission system employing the gain-switched laser. A distributed feedback (DFB) laser is used to generate a comb by gain switching the laser. A master laser is used for external injection into the gain switched laser in order to reduce the linewidth of optical comb lines and mitigate the chirp [9]. Moreover, the injection locking can enhance the relaxation oscillation frequency of the slave laser and thus improve the flatness of the optical comb [9]. An optical phase modulator is employed to broaden the spectrum of the optical comb. The spacing between the subcarriers is controlled by the driving RF frequency. A wavelength selective switch (WSS) is used to select two comb lines, into two different optical channels. One optical tone in channel 1 (Ch1) is fed into a dual parallel Mach-Zehnder modulator (DP-MZM) and modulated with a QPSK signal. The other optical tone in channel 2 (Ch2) is used as an optical local oscillator (LO) for THz signal generation. The recombined signal is then amplified with an EDFA and transmitted over standard single-mode fiber (SSMF) to the antenna unit (AU).

At the AU, the optical LO source beats with the modulated optical signal on an unpackaged uni-travelling carrier (UTC) photodiode [12] to generate the THz modulated multichannel signal. The modulated THz signal is radiated to the end user through a pair of horn antennas.

B. Investigation of the phase noise

The phase noise performance of the THz signal generated by the beating of two optical comb lines is firstly examined. The free spectral range (FSR) of the optical comb is initially set at 16 GHz. Two optical tones with the frequency spacing of 192 GHz are selected into two optical channels of the WSS. The QPSK data is not applied to the DP-MZM in order to initially measure the phase noise of the resultant 192 GHz signal. The 192 GHz signal is down-converted to an intermediate frequency (IF) using a sub-harmonic mixer. The LO signal at 17 GHz, from a RF synthesizer, is firstly frequency multiplied by using a sixth harmonic electronic multiplier and then applied to the sub-harmonic mixer to down-convert the resultant 192 GHz signal to 12 GHz.

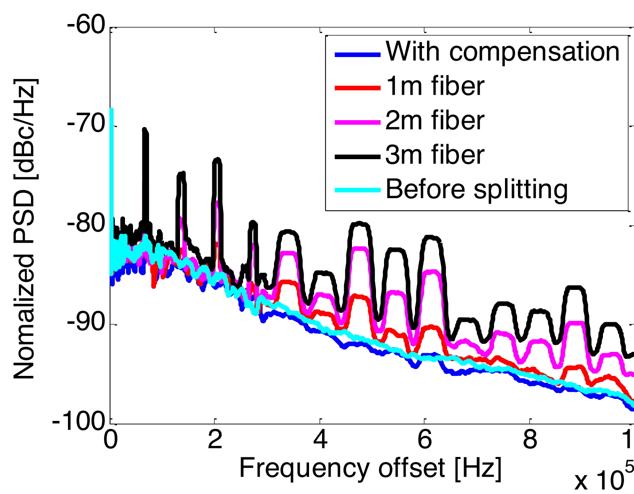


Fig. 2 Phase noise measurement of the resultant 192 GHz signal.

We have previously demonstrated that a time delay between the two optical channels will induce significant phase noise due to the phase decorrelation of the two optical tones [10]. Therefore the delay between the two path lengths is accurately compensated with the study of the spectrum of the resultant THz signal [10]. Additional 1 m, 2 m or 3 m delay fibers are applied to Ch2 to examine the phase noise impact due to the optical phase decorrelation. Fig. 2 shows phase noise measurements of the down-converted THz signal. In order to examine the delay compensation, the phase noise of the 192 GHz signal generated by the beating of the two optical tones without splitting is also measured. In this case, both of the two optical tones with 192 GHz frequency spacing are selected by one port of the WSS. Therefore, no additional optical delay is applied between the two optical tones.

From Fig. 2, it can be seen that the phase noise of the 192 GHz signal is increasing as the time delay between the two optical channels is increased. Comparing the cyan line and the blue line in Fig. 2, the phase noise performance of the THz signal with delay compensation and without optical splitting is the same. Thus it is evident that the phase noise induced by the optical phase decorrelation can be highly mitigated with the delay compensation technique.

A 12.5 Gbaud QPSK signal is then applied to the DP-MZM. Fig. 3 (a), (c) and (e) show the constellations and error vector magnitude (EVM) of the 192 GHz QPSK signal with different levels of phase noise due to the phase decorrelation by varying the time delay between the two channels. It is important to note that there is no phase correction applied in the DSP. It is evident that the compensation of the time delay between the two channels can partially reduce the phase noise impact. Nevertheless Fig. 3 (a) also shows that the 192 GHz QPSK signal still suffers from some level of phase noise even though the optical delay is fully compensated. Fig. 3 (b), (d) and (f) show constellations of the QPSK signal with different fiber delay where digital phase estimation is applied in the DSP process to mitigate the phase noise impact [13].

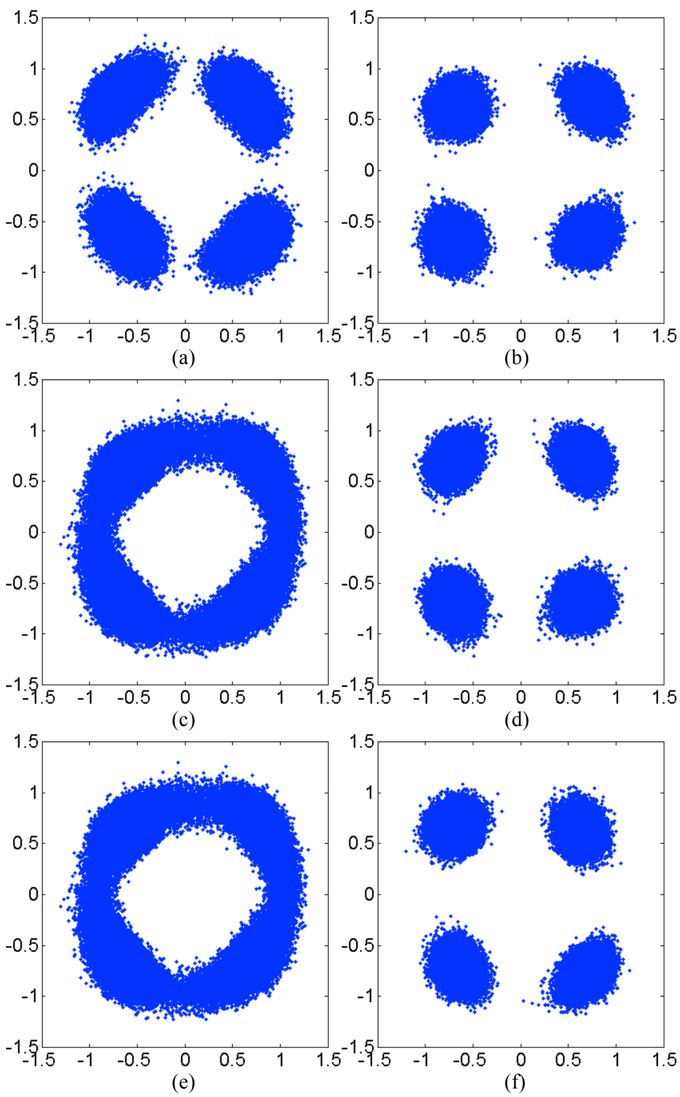


Fig. 3 Constellations of the 192 GHz QPSK signal with different delay. (a) with delay compensation, without DSP phase correction, EVM=19.1% (b) with delay compensation, with DSP phase correction, EVM=14.6% (c) 1 m fiber delay, without DSP phase correction, EVM= 20%, (d) 1 m fiber delay, with DSP phase correction, EVM= 14.3% (e) 3 m fiber delay, without DSP phase correction, EVM=22.4% (f) 3 m fiber delay, with DSP phase correction, EVM=14.5%.

It can be seen from the constellation shown in Fig. 3 (a) that there is some level of phase noise impact even though the optical delay is fully compensated. Previously, we have demonstrated a 60 GHz RoF system employing a high-linewidth gain-switched laser [11]. It has been proven that the phase noise impact can be highly mitigated by compensating the time delay between the two channels even if a high-linewidth (60 MHz) gain-switched laser without external injection is employed in the system. Compared to the 60 GHz system, the proposed THz system using the gain-switched comb source is based on a higher-order photonic-RF frequency multiplication. The output of the gain-switched laser can be expressed as:

$$E_{GS}\left(t\right)=I\left(I_{DC}+E_{LO1}\left(t\right)\right)\exp\left(j2\quad f_0 t+\ {}_0\left(t\right)\right) \tag{1}$$

where $E_{GS}(t)$ is the output of the gain-switched laser. $I(\bullet)$ represents the relationship between bias current of the laser with the amplitude of the optical output. I_{DC} is the DC bias of the gain-switched laser. f_0 and $\phi_0(t)$ are the central frequency and phase noise of the master laser respectively as the gain-switched laser is injection-locked by the master laser. $E_{LO1}(t)$ is the electrical field of the LO1, which can be expressed as:

$$E_{LO1}\left(t\right)=I_{LO1}\cos\left(2\quad f_{LO1}t+\quad {}_{LO1}\left(t\right)\right) \tag{2}$$

where f_{LO1} and $\phi_{LO1}(t)$ present the central frequency and the phase noise of the LO1 signal respectively, I_{LO1} is the amplitude of the LO1 signal. The optical field of the gain-switched laser in equation (1) can be derived using Taylor series:

$$\begin{aligned}&E_{GS}\left(t\right)=\exp\left(j2\quad f_0 t+\ {}_0\left(t\right)\right)\left[A_0+\right.\\&A_1 E_{LO1}\left(t\right)+A_2 E_{LO1}^2\left(t\right)+\ldots+A_n E_{LO1}^n\left(t\right)+\ldots\end{aligned} \tag{3}$$

where A_0, A_1,…A_n,… are constant. Assuming that the optical power of the gain-switched laser is mainly distributed over 11 optical lines, equation (3) can be rewritten as:

$$\begin{aligned}&E_{GS}\left(t\right)=\exp\left(j2\quad f_0 t+\ {}_0\left(t\right)\right)\left[B_0+\right.\\&B_1\exp\left(j2\quad f_{LO1}t+\quad {}_{LO1}\left(t\right)\right)+B_1\exp\left(\quad j2\quad f_{LO1}t\qquad {}_{LO1}\left(t\right)\right)+\ldots+\\&B_5\exp\left(j10\quad f_{LO1}t+5\quad {}_{LO1}\left(t\right)\right)+B_5\exp\left(\quad j10\quad f_{LO1}t\quad 5\quad {}_{LO1}\left(t\right)\right)\end{aligned} \tag{4}$$

where B_0, B_1,…,B_5 are constants. The output of the gain-switched laser is sent to an optical phase modulator for spectral broadening. The optical comb at the output of the phase modulator can be thus expressed as:

$$E_{comb}(t) \propto E_{GS}(t)\exp\left(j\frac{\pi E_{LO1}(t)}{V_{\pi}}\right) \quad (5)$$

By using Jacobi-Anger expansion, equation (5) can be derived as:

$$E_{comb}(t) \propto E_{GS}(t)\sum_{n=-\infty}^{+\infty} j^{n}J_{n}(I_{LO1})\exp\left(jn\left(2\pi f_{LO1}t+\varphi_{LO1}(t)\right)\right) \quad (6)$$

where $Jn(\bullet)$ is the n[th] Bessel function. Substituting (4) into (6), the output of the optical comb containing 13 optical tones can be expressed as:

$$\begin{aligned} E_{comb}(t) &= \exp\left(j2\pi f_0 t+\varphi_0(t)\right)[C_0 + \\ & C_1\exp\left(j2\pi f_{LO1}t+\varphi_{LO1}(t)\right)+C_1\exp\left(-j2\pi f_{LO1}t-\varphi_{LO1}(t)\right)+\ldots+ \\ & C_6\exp\left(j12\pi f_{LO1}t+6\varphi_{LO1}(t)\right)+C_6\exp\left(-j12\pi f_{LO1}t-6\varphi_{LO1}(t)\right)] \end{aligned} \quad (7)$$

where C_0, C_1,…,C_6 are constants. In the experiment, the THz signal is generated by a beating of two comb lines spaced by 192 GHz ($12\times f_{LO1}$). Therefore the two optical comb lines can be expressed as:

$$\begin{aligned} E_{comb1}(t) &\propto \exp\left(j\left(2\pi\left(f_0+6f_{LO1}\right)t+\varphi_0(t)+6\varphi_{LO1}(t)\right)\right) \\ E_{comb2}(t) &\propto \exp\left(j\left(2\pi\left(f_0-6f_{LO1}\right)t+\varphi_0(t)-6\varphi_{LO1}(t)\right)\right) \end{aligned} \quad (8)$$

The photocurrent of the UTC-PD is:

$$\begin{aligned} i_{UTC-PD} &\propto \left|E_{comb1}(t)+E_{comb2}(t)\right|^2 \\ &= I_{DC}+2\cos\left(24\pi f_{LO1}t+12\varphi_{LO1}(t)\right) \end{aligned} \quad (9)$$

The resultant THz signal is:

$$i_{THz} \propto \cos\left(24\pi f_{LO1}t+12\varphi_{LO1}(t)\right) \quad (10)$$

More generally speaking, the phase noise of the resulting RF signal can be simply linked to the phase noise of the LO1 signal as:

$$\varphi_{Photonic-RF} = n\varphi_{LO1}(t) \quad (11)$$

where $\phi_{Photonic\text{-}RF}(t)$ represents the phase noise of the resulting RF signal. Here we define a random phase change of the LO1 signal and resulting RF signal between t and $t+\tau$ as:

$$\begin{aligned} \Delta\varphi_{LO1}(\tau) &= \varphi_{LO1}(t+\tau)-\varphi_{LO1}(t) \\ \Delta\varphi_{Photonic-RF}(\tau) &= n\left[\varphi_{LO1}(t+\tau)-\varphi_{LO1}(t)\right] \end{aligned} \quad (12)$$

The variance of the random phase change between t and $t+\tau$ of the LO signal ($\sigma_{\Delta\phi LO}{}^{2}(\tau)$) is related to the PSD of the instantaneous angular frequency fluctuation $S_f(\omega)$ of the LO1 signal [14]

$$\sigma^2_{\Delta\varphi LO1}(\tau) = \frac{\tau^2}{2\pi}\int_{-\infty}^{+\infty}\left(\frac{\sin\frac{\omega\tau}{2}}{\frac{\omega\tau}{2}}\right)^2 S_f(\omega)\,d\omega \quad (13)$$

The instantaneous frequency fluctuation here is considered as white noise, which means the PSD of the frequency fluctuation is a constant ($S_f(\omega)=C$), the variance of the random phase change between τ delay ($\sigma_{\Delta\phi LO}{}^{2}(\tau)$) is represented as

$$\sigma^2_{\Delta\varphi LO}(\tau) = 2\gamma_{LO}|\tau| \quad (14)$$

where $2\gamma_{LO1}$ are the angular full linewidth of the LO1 signal. The variance of the random phase change between t and $t+\tau$ of the resulting RF signal ($\sigma_{\Delta\phi Phtonic\text{-}RF}{}^{2}(\tau)$) can be expressed as:

$$\begin{aligned} \sigma^2_{\Delta\varphi Photonic-RF}(\tau) &= n^2\sigma^2_{\Delta\varphi LO}(\tau) \\ &= 2n^2\gamma_{LO}|\tau| \end{aligned} \quad (15)$$

And the linewidth of the resulting RF signal can be expressed as:

$$\gamma_{Photonic-RF} = n^2\gamma_{LO1} \quad (16)$$

where $2\gamma_{Photonic\text{-}RF}$ is the angular full linewidth of the resulting RF signal. It can be seen from equation (10) and (11) that the RF signal generated by high-order frequency multiplication suffers from a higher level of phase noise induced by the LO signal. In other words, the phase correlation among the optical comb lines based on the gain-switched laser is not even. If we assume that the dominant frequency jitter component of the RF signal and LO1 signal is white noise, the normalized power spectral density (PSD) of the resulting RF signal and the LO1 signal follows the Lorentzian slope if the delay of the two channels are well compensated [15]:

$$\begin{aligned} S_{LO1}(f) &= 10\log_{10}\frac{\gamma_{LO1}}{\gamma^2_{LO1}+4\pi^2 f^2} \\ S_{Photonic-RF}(f) &= 10\log_{10}\frac{n^2\gamma_{LO1}}{\left(n^2\gamma_{LO1}\right)^2+4\pi^2 f^2} \end{aligned} \quad (17)$$

Here it is important to note that the THz signal is firstly mixed with another THz signal in the sub harmonic mixer, for electrical down-conversion before sending it to the electrical spectrum analyzer for phase noise measurement. Therefore the phase noise of the down-converted signal shown in Fig. 2 contains a contribution both from LO1 and LO2 signals. Similarly the THz signal generated by 12[th] order RF frequency multiplication of LO2 signal can be expressed as:

$$i_{THz\_LO} \propto \cos\left(24\pi f_{LO2}t+12\varphi_{LO2}(t)\right) \quad (18)$$

where f_{LO2} and $\phi_{LO2}(t)$ present the central frequency of the LO2 signal respectively. Thus the down-converted THz signal can be expressed as:

$$i_{IF} \quad \cos\left(2 \quad \left(12 f_{LO2} \quad 12 f_{LO1}\right)t + 12\left(\quad_{LO2}(t) \quad \quad_{LO1}\right)\right) \qquad (19)$$

Fig. 4 shows the normalized PSD of the 192 GHz signal which is down-converted to 12 GHz, the 16 GHz signal which is generated by the beating of a two neighboring tones, the electrical LO1 signal, and the electrical LO2 signal. It can be seen that the phase noise of the 192 GHz signal is about 20 dB larger than the 16 GHz signal which is a result of the beating of a pair of neighboring optical tones. It is also shown that the phase noise of the LO2 signal is smaller (>3dB) than LO1 signal. It is evident that the dominant phase noise contribution of the down-converted THz signal is from the LO1 signal.

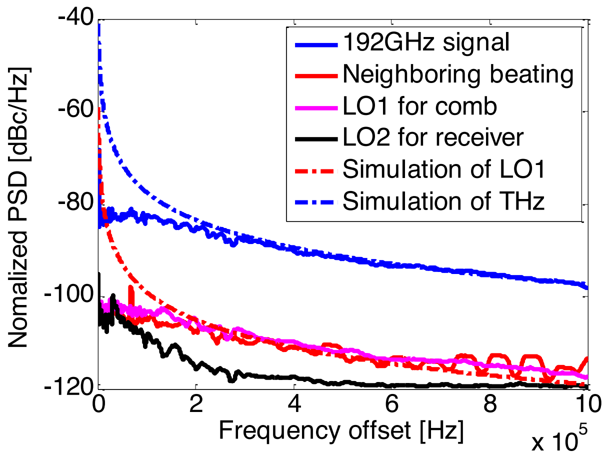


Fig. 4 Phase noise comparison of the THz signal and the neighboring beating.

A QPSK transmission with or without the impact of the phase noise due to high-order frequency multiplication is simulated. The angular linewidth of the LO1 signal γ_{LO1} is set to 50 rad/s, which corresponds to the simulation of the PSD of the LO1 signal. The baud rate of the QPSK signal is set to 12.5 Gbaud and the length of the sequence is 1.2×10^5 symbols, which correspond to the experimental setup (experimental results are shown in Fig. 3). Signal-to-noise ratio is set to 15.5 dB. Fig. 5 shows the constellations of the QPSK signal with or without the phase noise impact due to the high-order frequency multiplication. It can be seen that the phase noise due to high-order frequency multiplication can highly degrade the QPSK signal transmission. The EVM results of the simulation agree well with the experimental results that are shown in Fig. 3 (a) and (b).

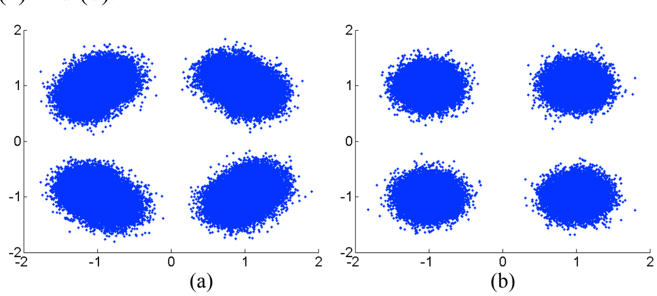


Fig.5 Constellations of the simulated QPSK signal with or without phase noise impact due to high-order frequency multiplication. (a) with phase noise impact, EVM=19.4% (b) without phase noise impact, EVM=14.6%.

Based on the theoretical analysis and experimental demonstration of the phase noise of the THz signal, it can be concluded that:

1) The phase noise induced by the optical phase decorrelation between the two optical tones due to the time delay can be highly mitigated by delay compensation.

2) The THz signal may suffer some level of phase noise impact due to the high-order frequency multiplication even if the optical delay is compensated. This requires DSP techniques to mitigate the residual phase noise impact. However it is worthwhile to pointing out that the frequency stability and phase noise performance is much better than that of the THz produced by the beating of two free running lasers [4]. For example, in Ref. [4], the authors employed a laser source with 3-dB linewidth of 15 kHz as the transmitter and an external cavity laser (ECL) with the 3-dB linewidth of 100 kHz as the receiver. In this case, the linewidth of the resultant THz signal can be estimated around 115 kHz, while the linewidth of the resultant THz in our experiment is much smaller (please see Fig. 4). In our experiment, no particular frequency offset estimation is required in the DSP.

III. Experimental Demonstration of Multi-carrier THz System Based on a Gain-switched Laser

In this section, an experimental demonstration of a multi-carrier THz system is presented. Three QPSK THz signals with a total data rate of 60 Gb/s are generated and transmitted over 40 km SSMF.

A. Experimental setup

Fig. 6 shows the proposed THz multi-carrier transmission system employing the gain-switched comb source. A distributed feedback (DFB) laser at a wavelength of 1551 nm was used to generate a comb by gain switching the laser with the aid of a 24 dBm RF signal. A master laser with a linewidth of 300 kHz was used for external injection into the gain switched laser in order to reduce the linewidth of optical comb lines [9]. An optical phase modulator is employed to broaden the spectrum of the optical comb for higher frequency signal generation. After amplifying the optical signal using an Erbium-doped fiber amplifier (EDFA), a WSS is used to select two or several comb lines, into two different optical channels. The WSS employed in the experiment is basically a commercially available programmable optical filter (Finisar WaveShaper 4000S) based on liquid crystal on silicon (LCoS) technology. There are four output ports the frequency response (both amplitude and phase) of which can be programmed independently. One or a group (3 comb lines) of the optical tones in channel 1 (Ch1) are fed into a DP-MZM and modulated with a 10 Gbaud QPSK signal. The I and Q signals are generated by a pulse pattern generator (PPG) with 2^{11}-1 pseudo-random bit sequence (PRBS) patterns. The other optical tone in channel 2 (Ch2) is used as an optical local oscillator (LO) for THz signal generation. The unmodulated and modulated signals were combined in an optical coupler, aligning their polarizations by using a polarization controller (PC). The optical power of the unmodulated optical tone is controlled by a variable optical attenuator (VOA) to match the

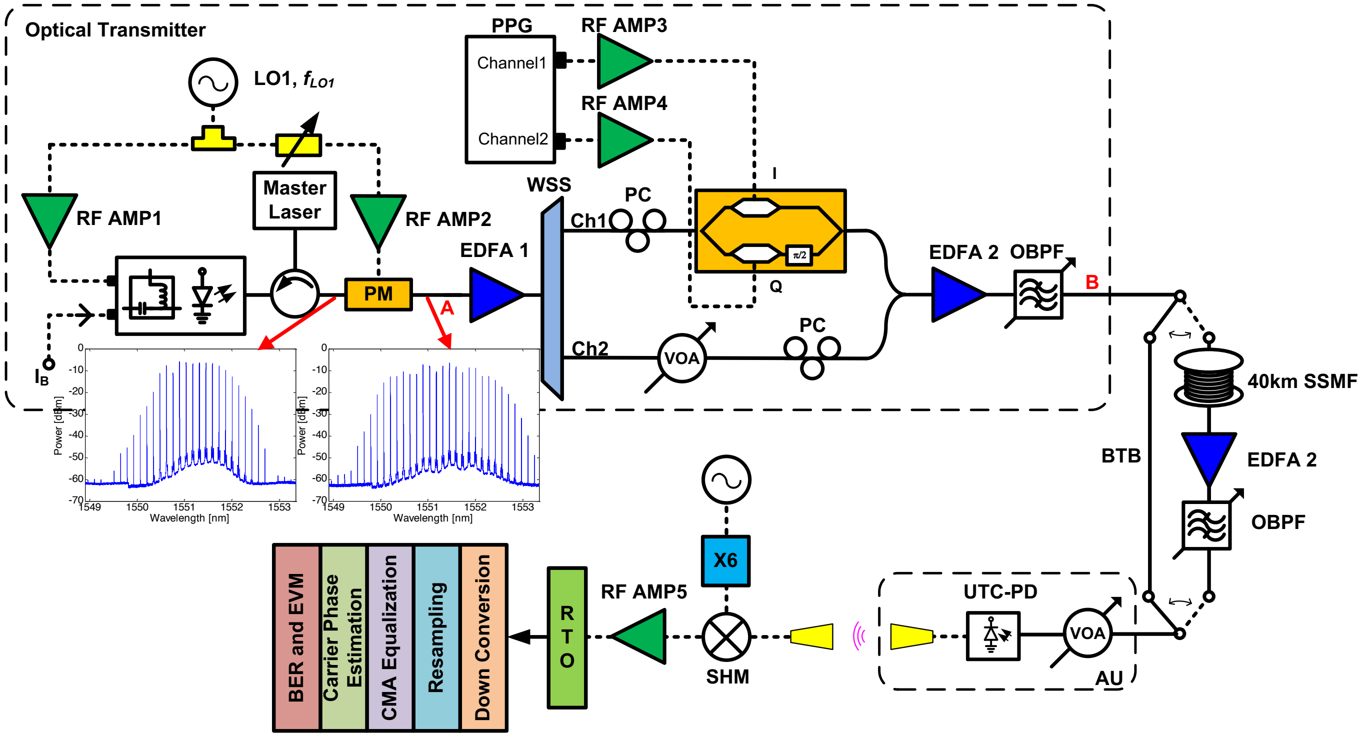


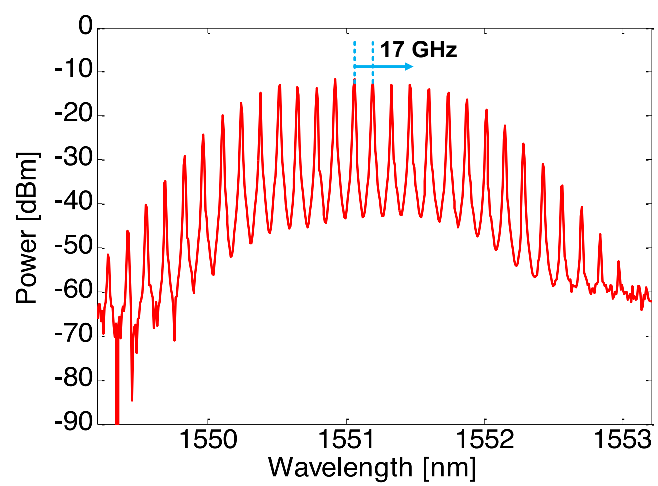
Fig. 6 Experimental setup of the multi-carrier THz system based on a gain-switched laser.

optical power of the other channel. The recombined signal is then amplified with an EDFA and filtered with a 3 nm optical bandpass filter (OBPF) to reject out-of-band amplified spontaneous emission (ASE). The combined optical signal is transmitted over either a section of back-to-back SSMF or a 40 km SSMF to the antenna unit (AU). Another EDFA is employed to compensate the loss of the fiber transmission.

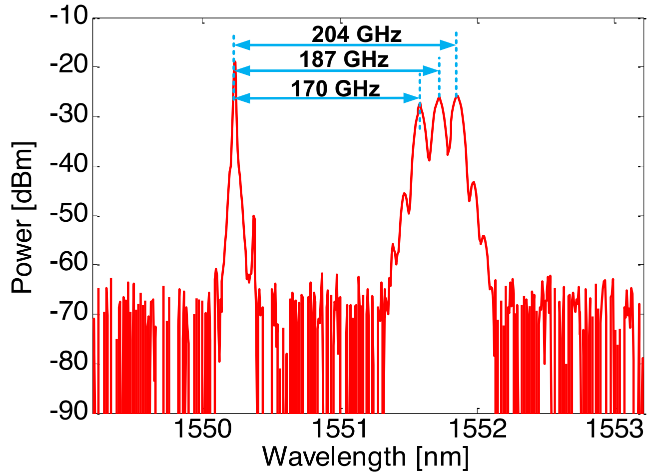
At the AU, the optical LO source beats with the modulated optical signal on an unpackaged uni-travelling carrier (UTC) photodiode to generate the THz modulated multichannel signal [12]. An optical amplifier and VOA were used before the AU to evaluate the system performance. The modulated THz signal was radiated from the 20 dBi horn antenna and propagated over a 2 cm wireless channel to a receiving 20 dBi horn antenna. The received THz signal was initially down-converted to a microwave IF by using a sub-harmonic mixer. The LO signal at f_{LO2}, from a RF synthesizer, is firstly frequency multiplied by using a sixth harmonic electronic multiplier and then applied to the sub-harmonic mixer to down-convert the resultant THz signal. The down-converted IF signal is then amplified and sent to the real time oscilloscope (RTO) for analog-to-digital conversion. The sampling rate and bandwidth of the RTS are 80 GSample/s and 36 GHz, respectively. An offline digital signal processing (DSP) including downconversion, downsampling, equalization [16], and phase estimation [13] is applied to demodulate the QPSK IF signal using Matlab. It is worthwhile noting that there is no particular frequency offset estimation required in the DSP as the carrier frequency of the THz signal generated by the beating of the two optical comb lines is very stable.

B. *Experimental results*

Fig. 7 shows the optical spectra of the comb (point A in Fig. 6) and the recombined optical tones (point B in Fig. 6). After the photo detection, 170 GHz, 187 GHz and 204 GHz QPSK signals with a total data rate of 60 Gb/s are generated.

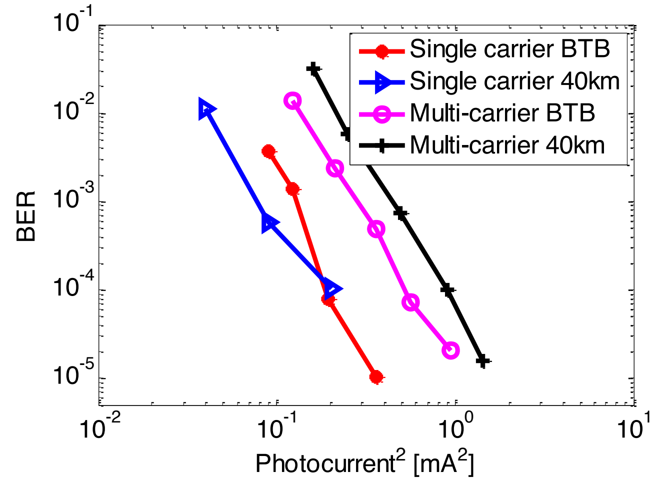


(a)



(b)

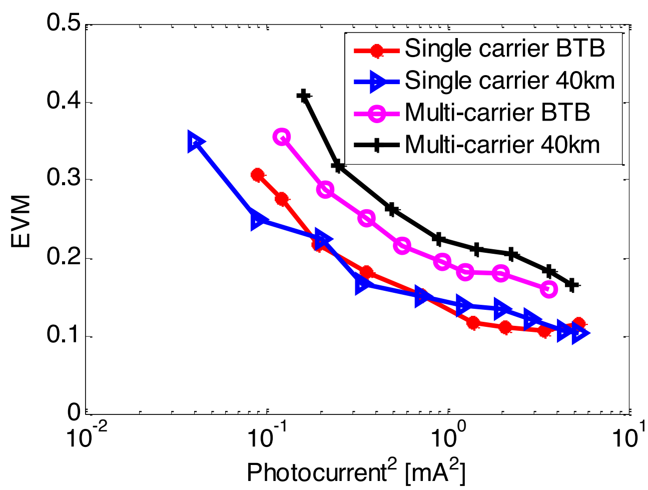
Fig. 7 Optical spectra of the THz system. (a) optical comb, (b) recombined optical signal. Resolution bandwidth: 0.1nm.



(b)

Fig. 8 EVM and BER as a function of the photocurrent. (a) EVM, (b) BER.

Fig. 8 (a) and (b) show the EVM and BER as a function of the photocurrent of the UTC-PD respectively. Due to the high phase noise induced by the high-order frequency multiplication, DSP is applied to mitigate the phase noise impact. The optical power into the UTC-PD is varied between 0 to 10 dBm. Here we do not show the EVM or BER as a function of input optical power to the UTC-PD, as the photo receiver is not packaged and the optical coupling efficiency is not stable. For experimental simplicity, we only examine the beat of the LO with the central channel (187 GHz signal) as this would suffer the highest cross-talk (worst performing channel) in the system. An EVM as low as 14.7% is achieved for 3-carrier transmission over 40 km SSMF. It is shown in Fig. 8 that the power penalty induced by the 40km SSMF is negligible for single carrier transmission system, while the 40 km SSMF transmission causes some power penalty in the multi-carrier case, since the fiber chromatic dispersion induced channel decorrelation increased impact of the cross talk.



(a)

IV. Conclusion

In this paper, we proposed a multi-carrier THz generation and transmission system employing a gain-switched laser as an optical comb source. The phase noise induced by the higher-order frequency multiplication has been theoretically analyzed and experimentally demonstrated. It has been demonstrated that the phase noise induced by the optical phase decorrelation due to optical delay between the two optical tones can be highly reduced by delay compensation. However the resulting THz signal may suffer from phase noise due to higher-order frequency multiplication which requires DSP phase correction in the digital transmission system. Furthermore, three 10 Gbaud QPSK THz signal generation and transmission over 40 km SSMF is experimentally demonstrated, with an EVM as low as 14.7% achieved for the multi-carrier THz transmission system. The phase noise impact is highly mitigated by using the DSP.

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