Photonic THz Generation Using Optoelectronic Oscillator driven Optical Frequency Comb Generator

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Abstract— **We propose and experimentally demonstrate a photonic THz signal generation technique combining a discrete optoelectronic oscillator (OEO) and optical frequency comb (OFC) generator. Using a microwave photonic filter (MWPF), we generate an electrical oscillation up to 18.36 GHz with a phase noise of -103 dBc/Hz at 10 kHz offset frequency. The OEO frequency tunability is obtained by changing the bandwidth of a tunable optical band pass filter (TOBF). This can produce an electrical RF carrier from 6.58 - 18.36 GHz. The OEO driven optical comb generates 22 optical comb lines with a frequency spacing of 17.33 GHz covering a bandwidth of 360 GHz within a 20 dB envelop. By selecting two optical comb lines using a wavelength selective switch (WSS) and beating them in a uni-travelling carrier photodiode (UTC-PD), a THz wave is generated at 242.6 GHz with phase noise of -78 dBc/Hz at 10 kHz offset frequency. This technique would be a potential for use in THz signal generation where it is possible to tune the THz carrier frequency by tuning the RF carrier generated from the OEO.**

Keywords—Optical frequency comb, optoelectronic oscillator, microwave photonic filter, phase noise.

I. INTRODUCTION

Optical heterodyning is a well-known approach to the photonic generation of millimeter wave (mm-wave) and THz signals. One simple implementation is the use of a pair of free-running lasers with a wavelength separation corresponding to the desired RF frequency to be generated, but this approach suffers from frequency and phase fluctuations [1]. In contrast, optical frequency comb (OFC) generators overcome this problem due to their highly phase correlated optical tones with a fixed frequency spacing [2]. By appropriate two comb lines selection, it is possible to generate pure mm-wave and THz signals [3].

Several techniques have been considered to generate OFCs, such as mode-locked lasers, gain-switched lasers, non-linear optics, and external modulation [4]. Conventionally, an external microwave synthesizer is used to provide the seed tone and to determine the frequency spacing in an external modulation based OFC. However, the external synthesizer can be replaced by an optoelectronic oscillator (OEO) which can generate spectrally pure microwave signals with a very low phase noise level [5]. In an OEO, the phase noise is independent of the oscillation frequency while in close-to-carrier, it depends on the *Q*-factor of the optical storage element (either a long optical fiber or whispering gallery mode resonator) used in the OEO loop. In addition, the white noise floor is limited by the shot noise of the photo-detector [6]. A state-of-the-art OEO provides a low phase noise of -163 dBc/Hz at an offset frequency of 6 kHz (for 10 GHz oscillation carrier) [7]. Therefore, the use of an OEO to drive an OFC generator (either directly or via a self-oscillating approach) for subsequent low-phase noise generation of mm-wave and THz signals is a promising concept.

In first-generation of OEOs, a microwave bandpass filter was used to determine the oscillation frequency, with additional techniques such as dual optical loop being used to suppress electrical side modes [8]. OEOs based on a microwave photonic filters (MWPF) have shown the capability to overcome the tunability limitation of their electrical filter counterparts [9], [10]. In [9], a tunable OEO based on stimulated Brillouin scattering (SBS) was proposed to achieve a carrier with a tunable frequency from DC - 60 GHz, while in [10] a tunable OEO (3 - 28 GHz) was implemented in which two optical phase modulators (PMs) were cascaded with a phase shifted fiber Bragg grating (PS-FBG). A relatively simple technique was also reported in [11] to achieve a tunable frequency range from 4.74 GHz - 38.8 GHz based on using an optical PM and a tunable optical bandpass filter (TOBF), where the tunability was realized by changing the optical bandwidth of TOBF. Later, a modified version of [11] was reported for tuning range up to 57.7 GHz [12].

In our earlier work, we experimentally generated a mm-wave signal from a self-oscillating optical frequency comb by using a dual drive Mach-Zehnder modulator (DD-MZM), and a conventional electrical band pass filter in the feedback loop [13], [14]. A 95 GHz mm-wave was generated using this method and a radio over fiber link was implemented to transmit wireless signals modulated with a standard LTE advanced signal. However, this proposed system still lacks of the frequency tunability of the OEO, and thus the generated mm-wave at a fixed carrier.

In this paper, we propose and experimentally demonstrate the photonic generation of THz signal based on a frequency tunable dual-loop OEO, and an optical frequency comb generator (OFCG). We use a MWPF-based approach to achieve the OEO frequency tunability (6.58 -18.36 GHz), where a PM and TOBF function together as a MWPF [12]. The system provides the opportunity to generate a tunable low phase noise THz signal without requiring any reference RF input. The proposed system generates a seed RF signal from OEO at 17.33 GHz and a phase noise level of -103 dBc/Hz at 10 kHz offset frequency. This is used as a driving electrical signal to generate 22 optical comb lines, and covering a range of 360 GHz within a 20 dB envelop. By selecting two optical comb lines, and beating them in a uni-travelling carrier

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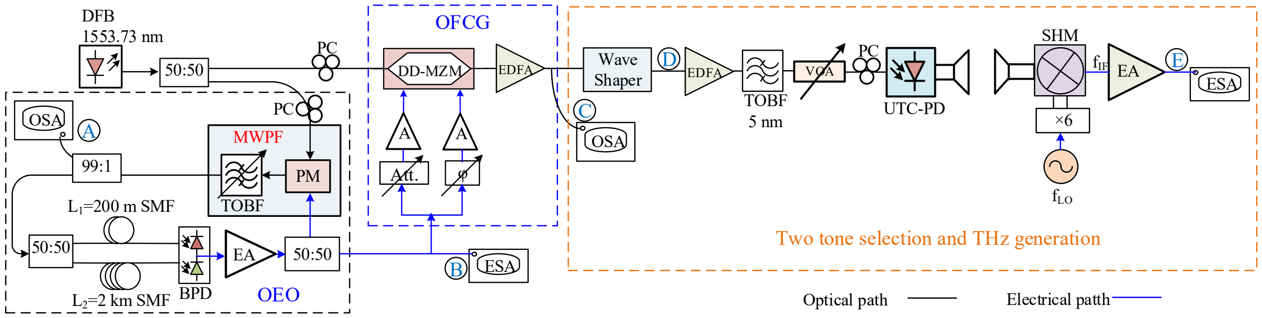


Fig.1. Experimental arrangement of the OEO driven OFC generation and THz wave generation

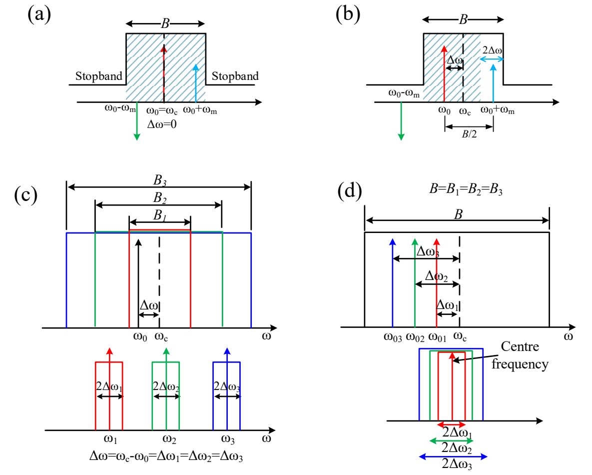
photodiode (UTC-PD), we generate a THz signal at 242.6 GHz. The measured phase noise (after down conversion procedure) is -78 dBc/Hz at 10 kHz offset frequency.

II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement of the proposed concept is shown in Fig. 1. It consists of the OEO section, OFC generation section, and two optical tones filtering and THz wave generation section. The individual sections are described as follows.

A. MWPF based tunable OEO

A light source from a distributed feedback (DFB) laser with a centre wavelength of 1553.73 nm and linewidth of 10 kHz is routed via a 50:50 optical coupler to an OEO loop, and an OFCG. In the OEO loop, a PM serves two functions: (i) as an electrical-to-optical (E/O) converter, and (ii) as a MWPF when combined with a tunable optical bandpass filter (TOBF) [15]. When the PM is modulated with an external RF carrier, it generates optical sidebands with opposite phase around the optical carrier. If an optical bandpass filter with a center frequency equal to the optical carrier frequency is placed after the PM, then the anti-phased sidebands are symmetrically transmitted as shown in Fig. 2(a). If they beat immediately in a photo-detector a zero response is generated. However, if the centre frequency of the optical carrier (ω_0) is slightly shifted from the centre frequency of the optical filter (ω_c), this gives asymmetrical sidebands suppression as shown in Fig. 2(b). The beating between the remaining of the unbalanced sidebands and the optical carrier will only be detected by the photodiode. This will generate a single sideband RF response, where the centre frequency and the bandwidth are determined by the spectral response of TOBF. The centre frequency in the electrical domain is equal to the half of the bandwidth of TOBF ($B/2$) and the bandwidth in electrical domain is equal to the twice of the offset between laser oscillation frequency and TOBF centre frequency ($\Delta\omega=\omega_c-\omega_0$), as shown in Fig 2(b). Tunability can be obtained by changing the wavelength, and bandwidth of TOBF. By changing the bandwidth of the TOBF, the centre frequency of the RF filter changes (Fig. 2(c)), while the bandwidth of the RF filter changes with the changes of offset frequency (Fig. 2(d)). A Yenista Optics XTM-50 (with a minimum and maximum bandwidth of 6.25 GHz, and 120 GHz, respectively) is employed as the TOBF, with a 99:1 optical coupler being used to monitor the optical spectrum after the TOBF. A dual loop balanced detection configuration is used in the feedback loop of the OEO, with short and long fiber lengths of L_1 = 200 m and L_2 = 2 km, respectively, which is fed into a balanced photodiode (DSC730, with a 3-dB bandwidth of 25 GHz, and responsivity of 0.60 A/W). Two electrical amplifiers are cascaded to compensate for the E/O and O/E conversion losses, and meet the loop gain condition for the OEO. The output of this amplifier chain is then fed back to the PM via a 50:50 electrical coupler, while the other coupler output is connected to 10:90 coupler. 10% of the output is used as monitoring in electrical spectrum analyzer, and 90% is used to drive the DD-MZM (model PSI-3600D1) for optical comb generation.



Centre frequency can be tuned from ω_1 to ω_3 by changing optical filter bandwidth from B_1 to B_3

Bandwidth can be tuned from $2\Delta\omega_1$ to $2\Delta\omega_3$ by changing laser oscillation frequency from ω_{01} to ω_{03}

Fig. 2. (a) Symmetrically transmitted sidebands (b) Asymmetrically transmitted sidebands (c) Centre frequency tuning by changing the optical bandwidth (B) of the TOBF, and (d) Bandwidth tuning by changing the laser wavelength.

B. OFC generation

The DFB laser is injected into a DD-MZM after being split by a 50:50 coupler and polarization controlled by a polarization controller (PC) as shown in Fig. 1. The optical frequency comb is generated by driving the two RF ports of the DD-MZM with RF signal of different amplitudes and phases [16]. The generated OEO electrical signal is further split into two signals, electrically amplified, and then connected to the two RF ports of the DD-MZM. Prior to amplification, the RF signal of one arm is attenuated while the other arm is phase shifted in order to satisfy the flat spectrum condition [16]. The output optical signal is optically amplified and split for monitoring by using an optical spectrum analyser, and the other output used for THz signal generation in the next section.

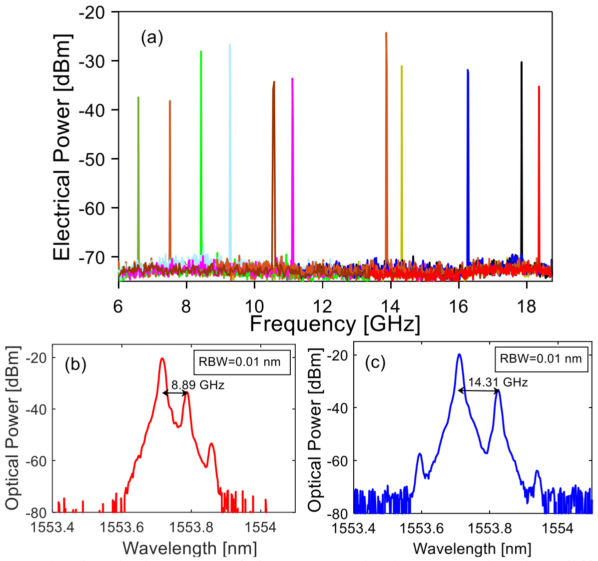


Fig. 3. (a) Electrical spectra of the generated microwave signal at different frequencies at point **B** of Fig.1; (b) and (c) optical spectra at the output of the TOBF for the oscillating frequency 8.89 GHz, and 14.31 GHz, respectively at point **A** of Fig.1.

C. *Optical two tone selection, and THz wave generation*

The generated optical comb after amplification is passed through a programmable wavelength selective switch (WSS) from Finisar to select two optical tones with the desired wavelength spacing. Then, the output signal is amplified, and filtered to remove the amplified spontaneous emission (ASE) noise before heterodyning at the UTC-PD. The UTC-PD is unpackaged device with an integrated coplanar waveguide (CPW). The output of the photodiode is emitted through a 20 dBi horn antenna (WR-5.1) using a coplanar mm-wave probe. Another identical horn antenna is placed to receive the transmitted THz signal. In order to measure the phase noise of the received THz signal, we down-converted it to a microwave IF frequency within the range of RF components by using a sub-harmonic mixer (SHM). The local oscillator (LO) from Rohde&Schwarz (SMA100A) is electrically multiplied (× 6) and mixed with THz signal in the SHM. The IF signal is then amplified and connected to an electrical spectrum analyser to measure the phase noise performance.

III. EXPERIMENTAL RESULTS AND DISCUSSION

As described earlier, the PM-TOBF combination functions as a tunable MWP filter. By tuning the bandwidth of the TOBF filter, we were able to generate microwave signals from 6.58 GHz - 18.36 GHz – typical spectra of the generated RF carriers measured at a point **B** of Fig.1 are shown in Fig.3 (a). The optical spectrum after the TOBF is measured at point **A** in Fig. 1 with an optical spectrum analyzer of the resolution bandwidth of 0.01 nm and is depicted in Fig.3 (b) and Fig.3 (c) for 8.89 GHz, and 14.31 GHz, respectively.

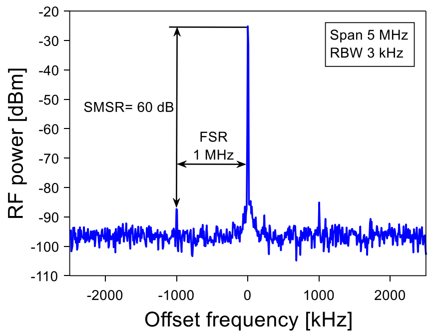


Fig.4. Electrical spectrum of the generated RF signal from OEO at 17.33 GHz signal with span of 5 MHz and RBW of 3 kHz (measured at point **B** of Fig.1).

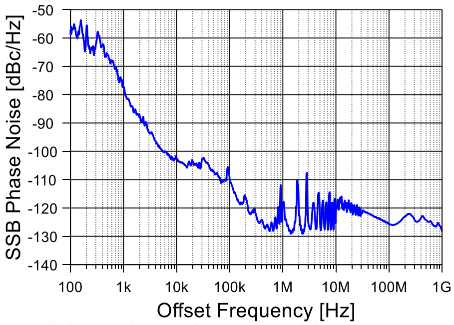


Fig. 5. Measured electrical SSB phase noise of the 17.33 GHz oscillation.

For THz signal generation, the OEO oscillation frequency was set to 17.33 GHz by adjusting the bandwidth of the TOBF. The electrical spectrum of the generated signal was then measured from the 10% electrical splitter (at point **B** in Fig. 1) and is shown in Fig. 4. Side modes at an offset frequency of 1 MHz from the carrier was observed at 60 dB suppression, and these correspond to the short fiber length (L_1=200 m). The single side band (SSB) phase noise of the generated 17.33 GHz signal was also measured. The phase noise level of -103 dBc/Hz was found at 10 kHz offset frequency as shown in Fig. 5.

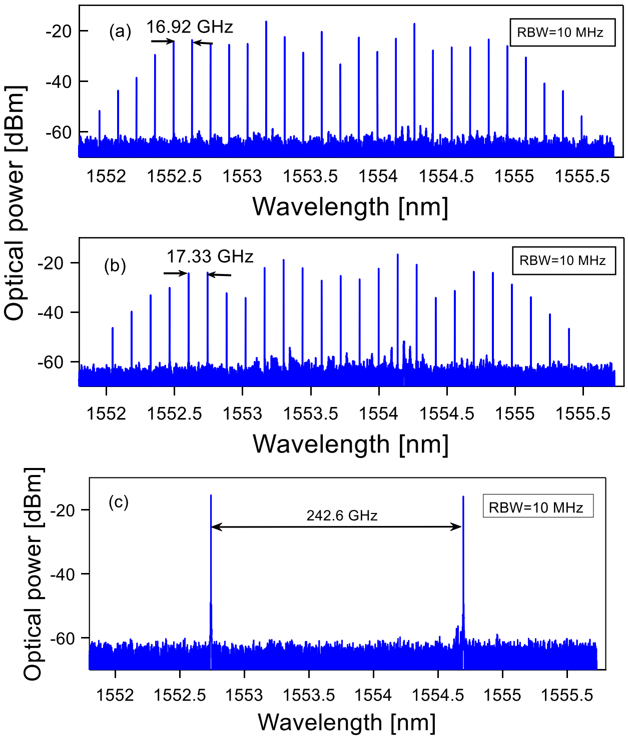


Fig.6. Optical spectra of the generated optical frequency combs with a frequency spacing of (a) 16.92 GHz and (b) 17.33 GHz at the center wavelength of 1553.73 nm (measured with an OSA at point **C** in Fig.1; (c) Optical spectrum of the selected comb lines (measured with an OSA at point **D** in Fig. 1).

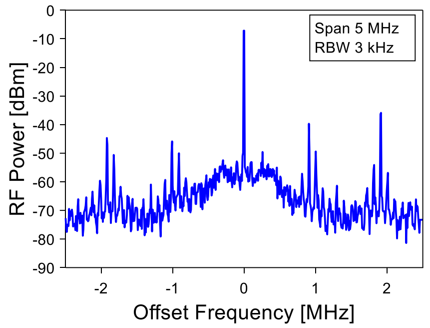


Fig.7. Electrical spectrum of the generated 242.6 GHz signal after down-conversion, measured at point **E** of Fig.1.

The optical comb signal for two different OEO oscillation frequency of 16.92 GHz, and 17.33 GHz are shown in Fig. 6 (a) & (b). A spectrum of 22 optical tones with a spacing of 17.33 GHz are observed (Fig. 6(b)), covering a bandwidth of 360 GHz within a 20 dB envelope. By selecting two optical comb lines, it is possible in principle to generate THz signals up to 360 GHz through heterodyne detection at UTC-PD. Using a programmable WSS, we selected two optical comb lines separated by 14 lines to generate a THz signal at 242.6 GHz. Fig. 6(c) shows the optical spectra of the selected optical tones. The electrical spectra of the down-converted signals are shown in Fig. 7. We found ~1 MHz spaced side modes (corresponds to short length L_1=200m) around the carrier and ~100 kHz spaced side modes (corresponds to the long length L_2=2 km) with relatively low amplitude around the ~1 MHz spaced side modes. The SSB phase noise of the down-converted signals were measured as shown in Fig. 8. The SSB phase noise is -78 dBc/Hz at 10 kHz offset frequency which is degraded by 25 dB. This degradation also includes the phase noise addition during the down-conversion process coming from optical and electrical amplifiers. Although the SSB phase noise of our OEO is comparable to other reported designs, the SSB phase noise of the system could be improved by using a long fiber. In addition, the long-term stability of the set-up could be improved by thermal stabilization. The refractive index of the fiber depends on temperature, hence temperature variation results in frequency drift of the OEO oscillation. This oscillation frequency drift could be controlled by using a temperature stabilized box or by phase locking with an external reference. Recently, hollow core photonic band gap (HC-PBG) fiber have been considered in OEO implementations to enhance long term stability, and improve the temperature stability by a factor of more than 15, as compared to standard single mode fiber [17].

IV. CONCLUSION

We have demonstrated a low phase noise THz generation technique in which a tunable OEO is used to drive an OFC generator. The demonstrated system can generate a tunable THz signal with low phase noise by tuning the OEO oscillation frequency. We generated THz signal at 242.6 GHz with a phase noise level of -78 dBc/Hz at 10 kHz offset when the OEO oscillation frequency was 17.33 GHz. The system has the potential to apply in multi-carrier or multi-band radio over fiber link with reconfigurable THz carrier frequency. The signal stability of generated THz signal depends on the OEO stability.

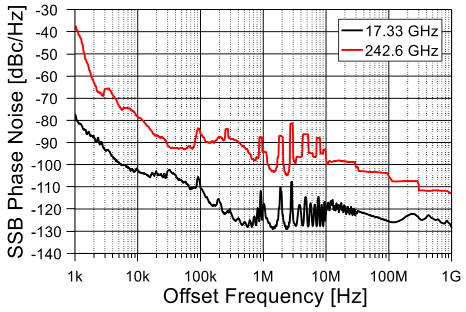


Fig.8. SSB phase noise of the generated 242.6 GHz signal (after down-conversion)

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