Optical FM-CW Signal Generation for a Terahertz Radar System by Higher-order Optical Modulation

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Abstract— In this paper, optical frequency-chirped signal generation using a high-order optical modulation technique is investigated. An optical frequency comb generator based on optical modulation is utilized as a frequency multiplier. Its multiplication factor of 12 allows designing a 300 GHz terahertz-band radar system. An input signal at the central frequency of 25 GHz with a chirp bandwidth of 1 GHz, 2 GHz, and 3 GHz provides 6 GHz, 12 GHz, and 18 GHz optical signals at 6th-order harmonics, respectively. A frequency separation of the +6th and −6th-order components is equal to 300 GHz, with a chirp bandwidth of 12 GHz and 24 GHz. The proposed technique can be used to design high-precision imaging systems.

1. INTRODUCTION

Precise imaging technology using terahertz waves plays an important role in enhancing civil security. In fact, at security check points of most airports, body scanners based on millimeter-wave imaging are used to detect concealed and hidden metal materials [1]. Although the millimeter-wave imaging technique is interesting, it has a limitation in the image resolution, owing to the used wavelength. For example, the wavelength of the 60 GHz frequency is equal to 5 mm. However, small object detection requires short wavelength radio signals. The terahertz band is a promising alternative for high-resolution imaging for detecting concealed objects [2]. In addition, the available bandwidth in the terahertz band is much broader than that in microwave and millimeter-wave bands. Consequently, the range resolution in radar systems would increase. For example, in a frequency-modulated continuous-wave (FM-CW) radar system, the range resolution can be approximated as

$$\Delta R \sim \frac{c}{2f_{BW}} \tag{1}$$

where ΔR, c, and f_{BW} denote the range resolution, speed of light, and bandwidth of the FM-CW signal, respectivel [3]. In this regard, and because the resolution is inversely proportional to the bandwidth of the radar signal, a high-range resolution is provided by high-frequency carrier signals. However, particularly in the terahertz band, the high-precision signal generator cannot be configured using only electronic devices. Therefore, terahertz frequency band devices have not been achieved until now.

Photonics technology is a potential solution to provide terahertz signal generation with high precision. In the 100-GHz band, modulation with an external optical modulator can generate high-frequency signals using second-order harmonics [4]. This modulation technique is operated as a frequency multiplier with a factor of 4, and has small degradation on a single-sideband (SSB) phase noise. However, for terahertz signal generation, such as 300-GHz signals, higher-order harmonic components are required to realize a higher-order multiplication. Therefore, optical frequency comb generation using modulation is recommended for signal generation.

In this paper, we demonstrate 300-GHz optical signal generation for the FM-CW radar system using optical frequency comb generation. Using a push-pull-type optical intensity modulator, the generated optical frequency comb with a separation of 25 GHz is obtained. Electrically synthesized FM-CW signals, with 1-GHz chirp bandwidth launched into the modulator, provide 300-GHz FM-CW signals, which are characterized by a 12-GHz bandwidth, using 6th-order harmonics components.

2. DEMONSTRATION

2.1. Setup

Figure 1 shows an experimental setup for FM-CW signal generation at 300 GHz, based on photonics technology. The original FM-CW signal is generated electrically by an arbitrary waveform generator (AWG), with a sampling rate of 50 Gsa/s (gigasamples per second). The signal form is a sawtooth-type frequency chirp signal that spreads from the frequency of 12.25 GHz to 12.75 GHz (12±0.25 GHz), with a chirp duration of 10 µs. For broader bandwidth signal generation, 12.5±0.5-GHz and 12.5±0.75-GHz signals are also used with the same pulse duration. Using a frequency doubler (×2), the FM-CW signal is multiplied to become a 25 GHz signal. An amplifier boosts the signal, and then, a bandpass filter (BPF) suppresses the unwanted sidebands and noises. A 180-degree hybrid (180° hy) split into two signals is realized. The latter signals are fed to the input ports of a dual-drive Mach-Zehnder interferometer-type optical intensity modulator (DD-MZM). This configuration provides a push-pull operation on the modulator. In the optical domain, a tunable laser diode (TLD) operated at a wavelength of 1550.11 nm is launched into the DD-MZM. Then, the modulated signal, that is an optical frequency comb signal, is amplified by an erbium-doped fiber amplifier (EDFA). In order to obtain the terahertz-wave signal, an optical two-tone signal should be picked up from the optical frequency comb one. An optical filter bank (OFB), which is composed of an optical grating and a liquid crystal on silicon that allow to configure a flexible optical filter, suppresses unnecessary components from the optical frequency comb signal [5]. The filtered optical signal has two components, with a frequency separation of 300 GHz. The generated optical terahertz signal is boosted up again by the EDFA. Then, the optical BPF (OBPF) suppresses the amplified spontaneous emission noise generated by the EDFA. A photomixer (PM) converts the optical signal into its corresponding terahertz-wave signal using square-law detection. The PM is based on a unitraveling-carrier-photodiode, and has an output port with a standard waveguide WR-3.4 [6]. It should be noted that the launched power into the modulator is approximately 25 dBm, and the half-wavelength voltage of the modulator, denoted by $V\pi$, is approximately 1.7 V (approximately 9 dBm). As a consequence, higher-order harmonic components are generated by the modulation.

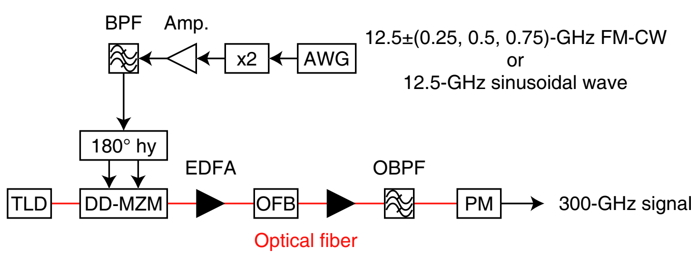

Figure 1: Experimental setup for terahertz FM-CW signal generation.

3. RESULTS

The generated optical frequency comb signal under the 12.5-GHz CW input condition is shown in Fig. 2; the input frequency to the DPMZM is 25 GHz. The observed optical signal has 9th-order harmonics within a carrier: 19 comb lines in total. ±6th-order harmonics for 300 GHz signal generation have a signal-to-noise ratio larger than 40 dB. A transmission characteristic of the OFB is also presented in Fig. 2. Indeed, the suppression ratio is larger than 40 dB and the associated insertion loss is approximately equal to 7 dB. Finally, a two-tone signal with a frequency separation of 300 GHz is obtained with a suppression ratio larger than 35 dB observed at the front of the PM. The degradation could be caused by the noise generated by the EDFAs. The optical power dip, observed at a wavelength of 1550.11 nm is caused by the OBPF characteristic. It does not affect the 300 GHz signal.

In order to evaluate the generated signal quality, SSB phase noise spectra are observed by a 300 GHz heterodyne receiver and an electrical spectrum analyzer, set at the output side of the PM, as shown in Fig. 3. The heterodyne receiver is configured with a 300 GHz subharmonic mixer, characterized by a multiplication factor of 12, and the local oscillator is set to the frequency 24.56 GHz. The LO frequency of the mixer is 294.72 GHz. The behavior of the observed SSB phase noises on the 300 GHz signal and the original signal inputs into the DD-MZM (frequency equal to 25 GHz), respectively, are similar at an offset frequency smaller than 1 MHz. The phase noise degradation in the frequency band 10–100 kHz is approximately equal to 22.5 dB. This result agrees well with the theoretically calculated value of 21.5 dB. Ideally, a phase noise degradation by multiplication is expressed by $20 \log m$, where m is the multiplication factor. When m is equal to

12, the expected degradation is equal to 21.5 dB. An additional 1 dB degradation could be caused by the noise generated by the EDFAs. Indeed, the phase noise degradation at an offset frequency larger than 1 MHz is worse than that for a frequency smaller than 1 MHz. This is due to the EDFAs' amplified spontaneous emission noise observed at the wavelengths between 1549 nm and 1551 nm, which could cause the signal degradation in the high frequency region. The degradation is dominated by the multiplication effect, and insignificant degradation can be caused by other factors. This photonics technology is seen as an ideal frequency multiplier.

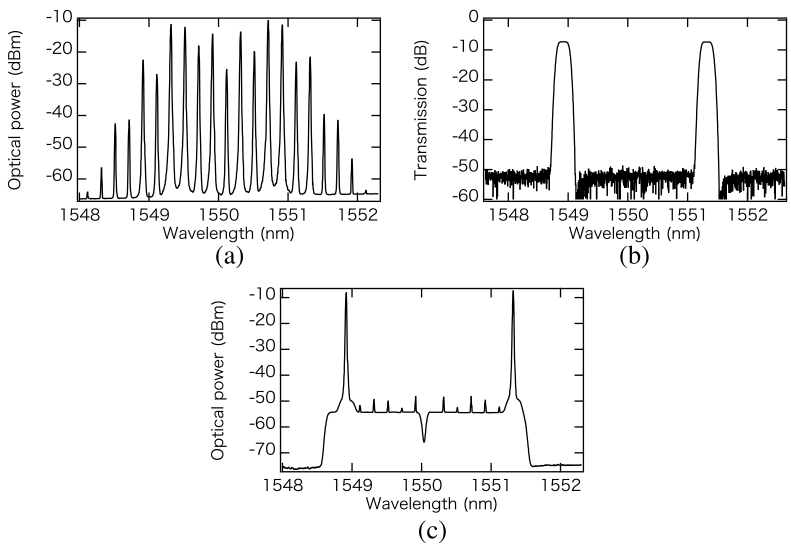

Figure 2: (a) Optical spectrum of optical frequency comb with 25-GHz spacing, (b) transmission spectrum of an optical filter bank, and (c) optical spectrum of the filtered 300-GHz optical signal.

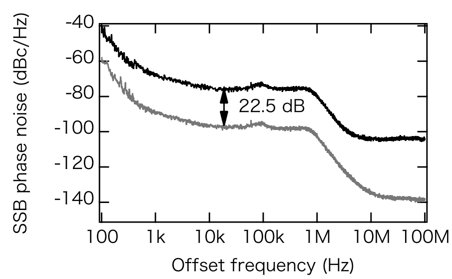

Figure 3: Observed SSB phase noise spectra of (black) generated 300-GHz comb signal and (gray) 25-GHz electrical signal launched into the DD-MZM.

In order to evaluate FM-CW signal generation in the 300 GHz band, we assess in Fig. 4 the optical spectra using the FM-CW signals with a bandwidth of 1 GHz, 2 GHz, and 3 GHz at a center frequency of 25 GHz, respectively. These bandwidths represent the bandwidths of the signal fed into the DD-MZM. Resultant bandwidths of the FM-CW signal at the 300 GHz frequency band are 12, 24, and 36 GHz, respectively. On one hand, at the 1-GHz bandwidth input, clear optical comb separation is observed for ±6th-order harmonics. Signals are at wavelengths 1548.8 nm and 1551.4 nm respectively. On the other hand, 2-GHz bandwidth input signals have smaller guard bands between neighboring harmonics. Particularly, for the 3-GHz bandwidth signal input, targeted components overlap with neighboring ±5th and ±7th order harmonics, owing to the frequency separation of the 25 GHz comb signals. Thus, a 3-GHz bandwidth signal is not suitable for FM-CW signal generation at the 300 GHz frequency band by this technique. However, because the bandwidth of the FM-CW signal can be optimized by the AWG, the maximum bandwidth for the FM-CW signal (potentially 20 GHz), will be generated by this configuration.

Quality of the FM-CW signal is absolutely important for the design of the radar system. Fig. 5 shows a temporal evolution of the FM-CW signal as a spectrogram. For clarity, we configured a 300-GHz receiver comprised of a heterodyne detector and a high-speed digital oscilloscope [7]. The analog bandwidth and sampling rate of the oscilloscope are equal to 33 GHz and 80 Gsa/s, respectively. The LO of the heterodyne receiver is set at 286.8 GHz. This parameter is realized by the subharmonic LO input of 23.9 GHz. The observable frequency range of the receiver is 286.8–319.8 GHz. In the spectrogram of Fig. 5, the sawtooth-type behavior of the signal in the frequency band 294–306 GHz, with a pulse duration of 10 μs, is clearly shown with small fluctuations. Larger fluctuations in the frequency domain are observed away from the central frequency of the FM-CW signal 300 GHz. This could be caused by the poor bandwidth of the used AWG. In fact, the 3 dB bandwidth of the AWG is approximately 14 GHz, and therefore, the uncertainty of the signal becomes larger. This issue could be solved by optimizing the electrical signal generation technique.

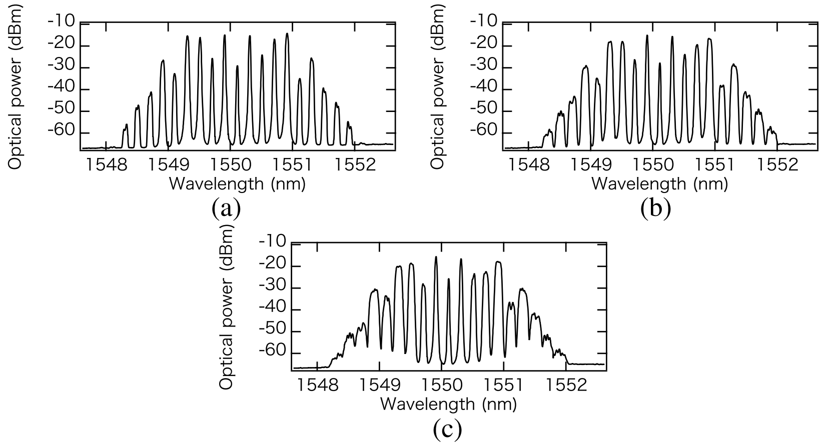

Figure 4: Observed FM-CW signal with the input signal bandwidth of (a) 1 GHz, (b) 2 GHz, and (c) 3 GHz.

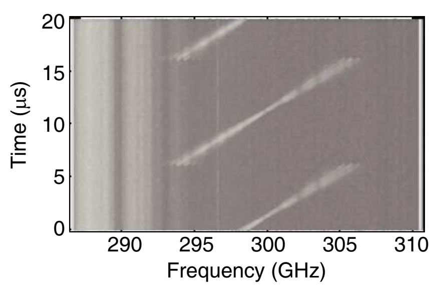

Figure 5: Obtained spectrogram of 12-GHz-bandwidth sawtooth-type FM-CW signal.

4. CONCLUSION

In this paper, we demonstrated and evaluated the 300 GHz radar signal generation using optical modulation technique. The generated signal by the optical frequency comb generator, with a comb separation of 25 GHz, presents an identical phase noise degradation, caused by frequency multiplication. For FM-CW signal generation, 12-GHz bandwidth signals have a moderate frequency response and frequency chirp characteristics, when a pulse duration of 10 μs is used. This technique is can generate possibly 20-GHz FM-CW signals. The proposed photonics-based signal generation technique for imaging is applicable to advanced distributed antenna systems, directly connected to optical fiber networks [7].

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