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Sub-THz radio-over-fiber signal generation using external modulation

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Abstract: This paper describes photonic technologies for millimeter-wave generation and distribution. External modulation would be useful for stable and high-quality radio-over-fiber signal generation, where frequency stability and spurious suppression are very important for radio services such as mobile communications, radio locations etc. This paper provides outline of radio-over-fiber signal generation techniques. Precise and high-speed lightwave optical modulation would play important roles for suppression of undesired spectrum components. Photonic harmonic generation would be useful for very high-frequency signals. Reciprocating optical modulators consisting of optical modulators and fiber Bragg gratings can provide optical modulation by sub-THz signals.

Keywords: radio over fiber, optical modulation, millimeter-wave

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

Millimeter-wave including sub-THz region would be attractive for various radio services, such as very high-speed wireless links, high-resolution radars, etc., because wide radio-wave spectra are available in millimeter-wave bands, such as V-band (50–75 GHz), E-band (60–90 GHz) and W-band (75–110 GHz), while it is rather difficult to reserve such wide bands in microwave regions. Unlicensed bands in 60 GHz attract much attention for high-speed short distance telecommunications. However, 60 GHz bands are not suitable for moderate or long distance links due to oxygen absorption. On the other hand, in the range from 70 GHz to 110 GHz (E- and W-bands), atmospheric attenuation of millimeter-waves is much smaller than in 60 GHz bands, as shown in Fig. 1 [1]. Attenuation in dry air is the lowest at 94 GHz in the frequency region higher than 60 GHz. In this range, 71–76 GHz, 81–86 GHz, 92–94 GHz, 94.1–100 GHz and 102–109.5 GHz are internationally allocated for fixed or mobile radio services (95–100 GHz is only for mobile services in USA). In total, 25.4 GHz wide frequency bands can be used for moderate distance wireless telecommunication services in Europe and Japan, where over 100 Gb/s wireless links can be constructed with modulation formats with spectral efficiency larger than 3.94 bit/s/Hz [2]. In these bands, a 8 GHz wide continuous spectrum from 92 GHz to 100 GHz is available for radar applications, such as high-resolution imaging for foreign-object debris (FOD) detection, which is required to increase safety in transportation infrastructure including runways in airports and facilities along railway tracks [3].

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Propagation loss of E- or W-band millimeter-wave signals would be smaller than in V-band, however, lager than in microwave bands. In millimeter-wave radio systems, many antenna units would be required to cover wide areas such as runways, railway trucks, etc., so that cost of implementation and operation would be issues in such systems. Radio-over-fiber (RoF) technologies would be solutions for reduction of cost for millimeter-wave signal generation and distribution, where RoF signals whose envelops are modulated by millimeter-wave radio waveforms as shown in Fig. 2. RoF signals generated by high-speed optical modulators can be distributed over optical fibers connecting antenna units. Transmission loss in optical fibers is much smaller than in coaxial cables for high-frequency signals. We can easily distribute or switch such RoF signals by using photonic devices developed for passive optical networks (PONs) or wavelength-domain-multiplexing (WDM). Total performance of RoF systems largely depends on high-speed electric-to-optical (EO) conversion devices (optical modulators) [4, 5] or optical-to-electric (OE) conversion devices (photodetectors) [6, 7]. In radio service applications, precise lightwave control and detection at the devices would be very important for suppression of undesired spectral components to observe radio regulations.

This paper focuses on optical modulation techniques for RoF signal generation, because high-speed and precise optical signal generation is one of the most important key issues. High-speed optical modulators have been developed for high-speed digital transmission systems, however, they are designed for bandwidths narrower than 40 GHz [5]. In addition, requirement for preciseness is not so high, because simple modulation formats such as on-off-keying (OOK) and quadrature-phase-shift-keying (QPSK) are commonly used in commercial transmission systems. Various optical modulation devices and sub-systems have been proposed to achieve stable millimeter-wave signal generation [4, 8, 9, 10]. We may use two laser sources with fixed frequency separation for millimeter-wave signal generation [11, 12], however, it is rather difficult to achieve stable operation due to phase and frequency fluctuation of the laser sources. On the other hand, optical modulation can provide very stable operation, where spectrum components are stably phase-locked in the optical output. Phase noise of the beat note between the spectrum components depends on that of electric signal fed to the modulator, in principle. Thus, EO modulation would be a promising candidate for millimeter-wave band RoF signal generation technique.

This paper is organized as follows. In section 2, we describes some examples of system applications of RoF techniques, to show roles of EO devices in such RoF systems. Section 3 provides frequency multiplication techniques using Mach-Zehnder modulators (MZMs), where precise optical modulation would be very important to suppress undesired spectral components [4, 10, 13]. In Section 4, we review reciprocating optical modulation (ROM), which can generate high-order harmonics inside modulators, by using reciprocation of lightwaves in the devices [14, 15, 16, 17].

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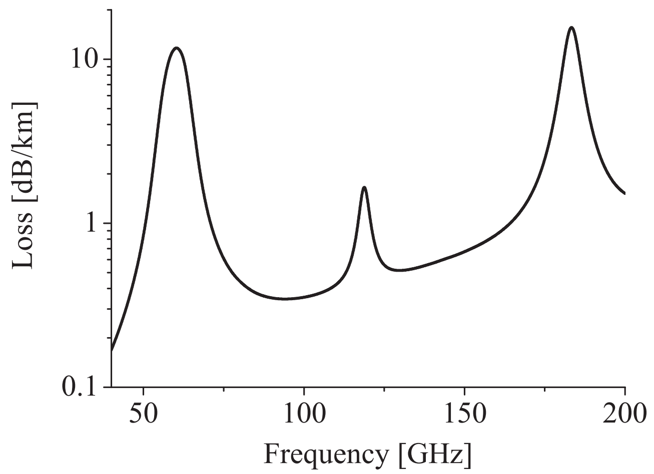

Fig. 1. Atmospheric attenuation of millimeter-wave [1]

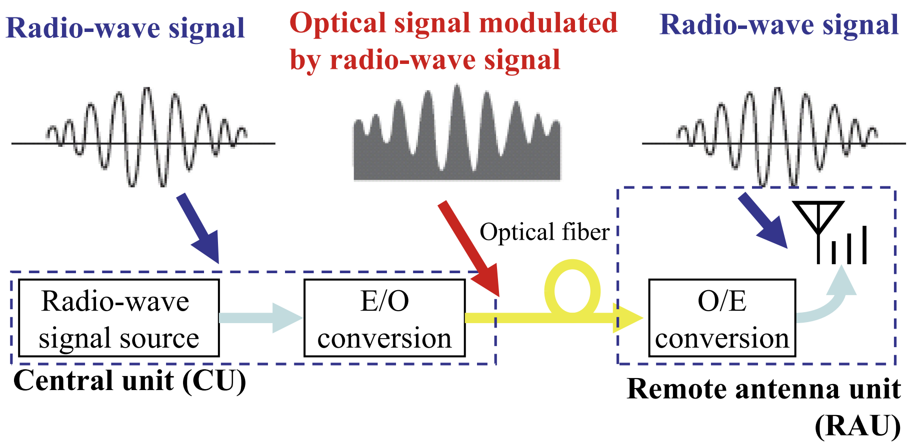

Fig. 2. Schematic of RoF systems

2 RoF system examples

2.1 Wired and wireless seamless links [18]

As shown in Fig. 3, wired and wireless seamless links consist of optical fiber and radio-wave wireless links. Wireless-to-wired or wired-to-wireless media converters (WWMCs) convert optical signals into radio-wave signals and/or radio-wave signals into optical signals. RoF can transmit optical signals with waveforms over optical fibers. "Seamless" means that waveforms on optical signals in fibers can be transparently converted into millimeter-waves at WWMCs, without using complicated digital signal processing. A WWMC comprising an OE converter and a radio front-end (FE), can act as an optical-to-radio (O/R) converter, while a radio-to-optical (R/O) converter also can be constructed by a radio FE and an EO converter. A high-speed photodetector in the WWMC seamlessly transforms optical signals from a RoF transmitter (Tx) directly into radio signals. On the other hand, the use of optical digital coherent detection techniques at the receiver (Rx) can completely compensate for transmission impairments such as media dispersion.

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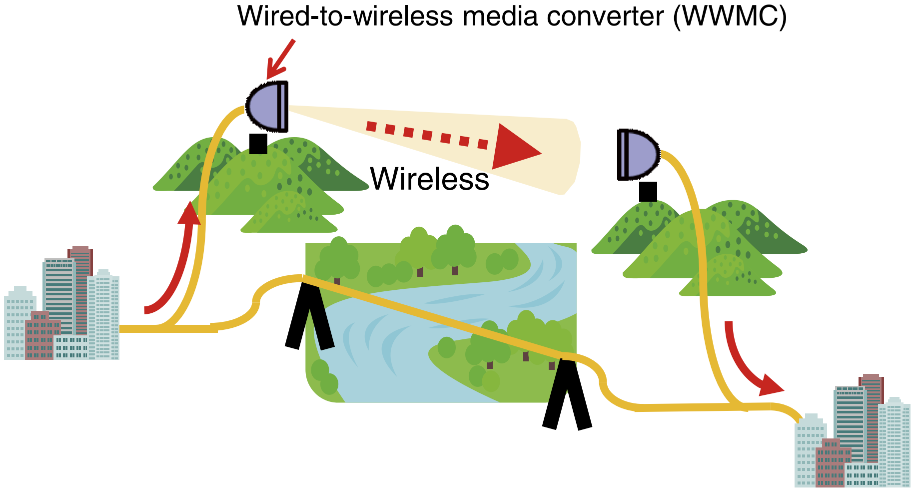

Fig. 3. Schematic of wired and wireless seamless links [2]

2.2 Millimeter-wave distribution systems for radar systems

High resolution imaging which can detect metal objects as small as a few centimeters would be needed to ensure take-off and landing safety in airports where the typical length and width of runways are 60 m and 3000 m, respectively. Areas along tracks longer than 100 km should be scanned with resolution much smaller than 1 m, to monitor railway facilities. However, millimeter-wave attenuation in the air is not small enough to achieve radar range long enough for airport or railway facility surveillance. Required radiation power is proportional to the fourth power of the radar range. It is rather difficult to achieve high-power millimeter-wave signals by semiconductor devices. We may consider another option to increase the radar range: to use a number of radar units (radar heads) installed close to the areas under surveillance. For a linear area along to a railway track or runway (linear cell), N units can cover N times longer area, while a system with a radar unit needs at least N^4 times larger radiation power to achieve N times longer range. A radar system consisting of many radar heads can largely reduce total radiation power of the system and required millimeter-wave output at each unit, so that the high-resolution imaging for long area coverage can be achieved by low-cost semiconductor devices. However, the system needs many high performance millimeter-wave oscillators for radar ranging by each unit. A RoF system comprising one or a few master generators and radar heads connected by optical fibers has been proposed to overcome this problem, where RoF signals can be delivered from a central office to each remote radar head through optical fibers network [3].

3 Over 100 GHz RoF two-tone signal generation using Mach-Zehnder modulators [10, 13]

Mach-Zehnder modulators (MZMs) can generate stable upper sideband (USB) and lower sideband (LSB) components, by feeding sinusoidal electric signals. The output spectrum depends on the dc bias voltage applied on the electrode in the MZM. When the bias is set to a minimum transmission point, double-sideband suppressed carrier (DSB-SC) optical modulation can be achieved, where the output

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has the first order LSB and USB. The frequency separation between the two spectral components is precisely equal to double the modulating signal frequency [4]. The spectral components generated by optical modulation are always phase-locked, so that we can easily construct robust systems without using complicated feedback control techniques. However, the modulation frequency is limited by the frequency response of the modulator. A typical 3 dB bandwidth of a modulator is 30 GHz, so that the frequency upper limit of the two-tone signal generated by DSB-SC modulation can not be larger than 100 GHz. An MZM whose bias was set to a maximum transmission point was used to generate the second order LSB and USB. By using this technique, we can easily obtain a high-frequency two-tone signal, however, the suppression ratio of undesired components depends on the extinction ratio of the MZM. Recently, we proposed ultra high extinction-ratio modulation technique by using an integrated MZM having intensity trimmers [4].

When the bias of the MZM is at the maximum transmission point, the odd order sideband components were suppressed. Thus, the output would have the zeroth order component, whose optical frequency is identical to that of the input, and the second order components (LSB and USB), when the higher order components can be neglected. By eliminating the zeroth order component, we can obtain a two-tone lightwave signal of $4f_m$, where f_m is the frequency of the rf signal applied to the modulator. The frequency separation between the zeroth and second order components is $2f_m$. When $f_m > 10$ GHz, the frequency separation would be large enough to eliminate the zeroth order by using a conventional optical filter. The suppression ratio of the first order components depends on the extinction-ratio of the MZM. By using the modulator with intensity trimmers, we can suppress, largely, the first order components, which cause undesired spurious signal generation. 40 GHz sinusoidal signal was fed to the modulator. The optical output had the zeroth and second order components, where the suppression ratio of the first order components with respect to the zeroth order was 34 dB. The zeroth order component was eliminated by the optical band rejection filter whose bandwidth was 25 GHz. The optical signal was boosted by the optical amplifier, where a 5 nm band-pass filter was used to suppress spontaneous emission noise. As shown in Fig. 4, we successfully obtained a two-

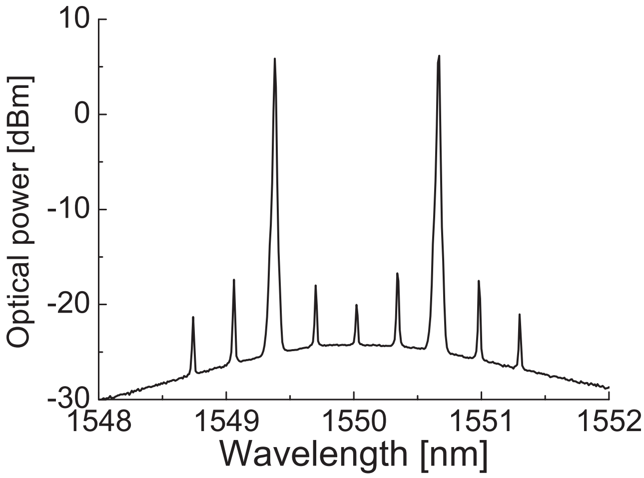

Fig. 4. Optical spectrum of 160 GHz two-tone signal generated by a high extinction ratio MZM

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tone lightwave signal whose frequency separation was 160 GHz. We also measured a time domain profile of the two-tone signal by using an optical sampling oscilloscope (ANDO AQ7750). The output was quite stable, where the period was 6.25 ps and the extinction ratio was larger than 10 dB, as shown in Fig. 5.

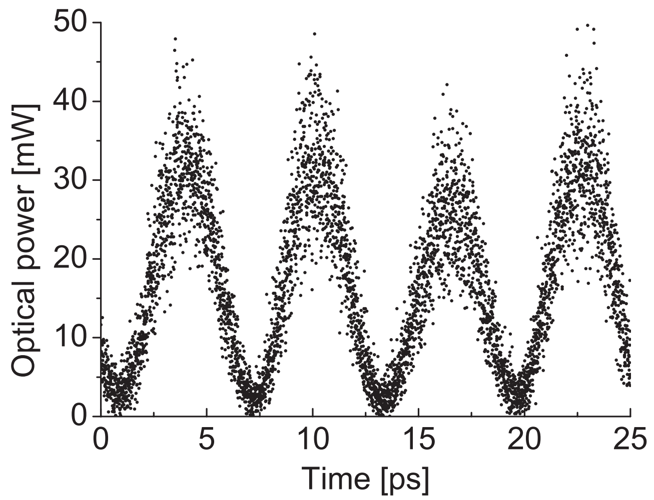

Fig. 5. Time domain profile of 160 GHz two-tone signal generated by a high extinction ratio MZM

4 Reciprocating optical modulation for over 300 GHz signal generation [17]

A reciprocating optical modulator (ROM), consisting of a pair of optical filters and an optical phase modulator, as shown in Fig. 6, can generate high-order sideband components effectively, where one of the optical filter is placed at the optical input port (input filter), and the other is at the output port (output filter) [14]. In ROMs, some of the sideband components are fed to the optical modulator again, in order to obtain effective generation of specific sideband components. The desired sideband components are taken out from the modulator, without recycling to the modulator. This is in contrast to mode-locked lasers, where all generated sideband components are recycled into the modulators. ROMs can generate very stable and low-phase noise signals by using hybrid integration [15, 16].

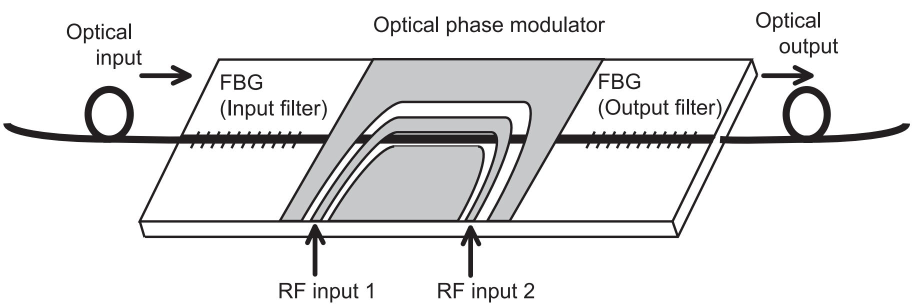

Fig. 6. Schematic of ROM

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In order to obtain very high-frequency components over 300 GHz, input and output filters should have wide reflection bands. For effective high order sideband generation, the filters should have steep reflection band edges. However, it is not easy to design optical fibers having wide reflection bands and very steep band edges. FBGs with apodization techniques would be useful for suppress undesired side lobes adjacent to the main reflection band. On the other hand, uniform FBGs would have side lobes, but there is a very narrow passband between the main reflection band and a side lobe. We fabricated an integrated reciprocating optical modulator, consisting of a z-cut $LiNbO_3$ phase modulator and two uniform FBGs, where the FBGs were fixed on SiO_2 substrates and directly attached to the phase modulator chip. The uniform FBGs have narrow passbands near the edges of the main reflection bands, as shown in Fig. 7. The bandwidth of the main reflection band was slightly narrower than 320 GHz, where the passbands were at 1550.9 nm and 1553.5 nm. Designed frequency of modulating signal fed to the phase modulator was 40 GHz. When an input lightwave wavelength is close to 1550.9 nm, the eighth-order sideband whose wavelength would be close to 1553.5 nm can be taken out from the output filter. The optical phase modulator had a traveling-wave electrode to achieve high-speed operation, where halfwave voltage of the modulator was 4.1 V at dc and 7.8 V at 40 GHz. The modulator had a pair of rf input ports, RF input 1 and 2 in order to obtain bidirectional modulation. In ROM sideband generation process, sideband components in the reflection band reciprocate between the FBGs, and pass the modulator several times, so that the bidirectional modulation is indispensable for effective high-order sideband generation.

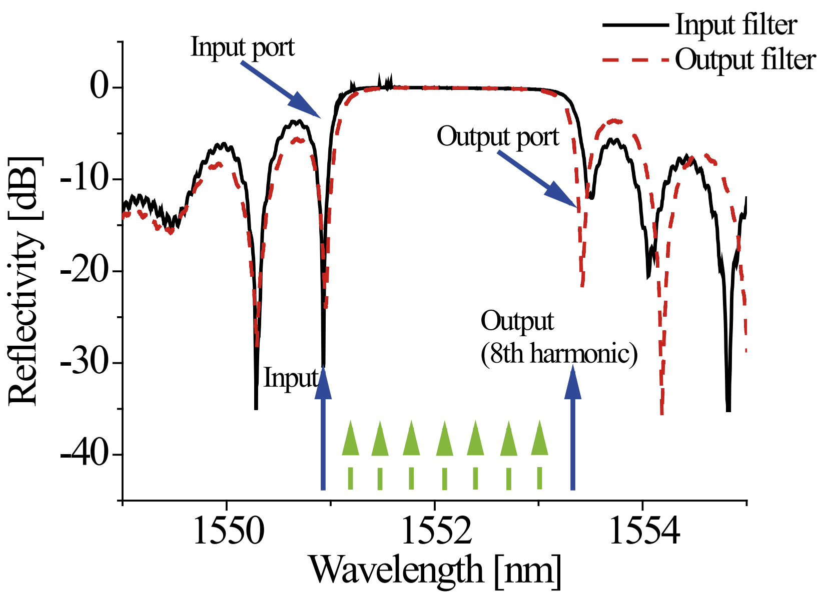

Fig. 7. Filters in ROM

Fig. 8 shows an experimental setup for high-speed optical clock signal generation with ROM. High-order LSB components were successfully obtained as shown in Fig. 9. The optical input power and wavelength were 5 dBm and 1550.908 nm, respectively, where the input lightwave was in the passband at

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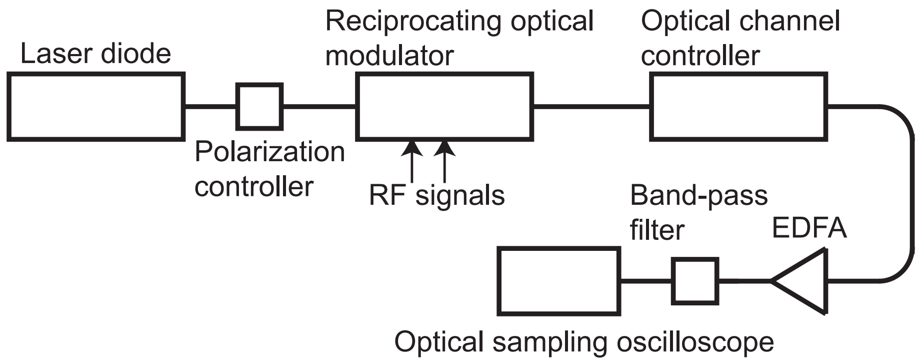

Fig. 8. Experimental setup for 470 GHz signal generation

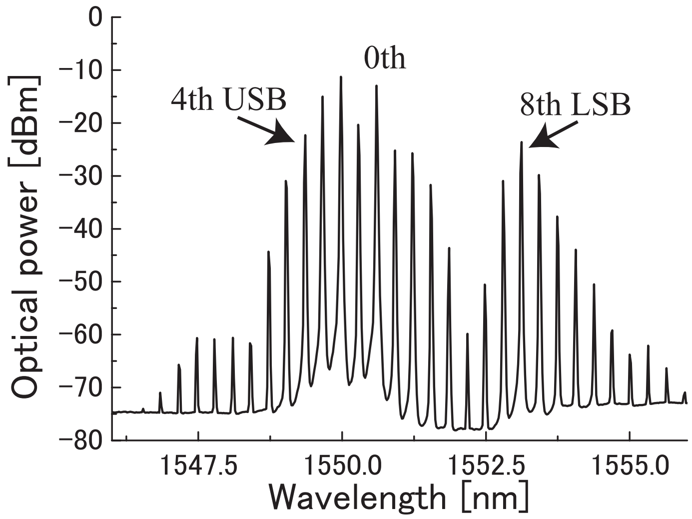

Fig. 9. Modulator output spectrum

1550.90 nm. The rf-signal power at the rf input ports of the ROM was 27.4 dBm. The modulator was designed for 40 GHz rf-signal, however, high-order sideband generation efficiency of a fabricated modulator became maximum when the rf-signal frequency was 39.07 GHz. This is due to the difference between designed and actual group delays in the FBGs. The eighth order LSB, which was in the narrow passband at 1553.5 nm, was enhanced. USB components were also obtained by harmonic generation in conventional phase modulation, however, high-order components around the eighth order were much smaller than in LSB. We selected these two spectral components by using an optical channel controller (Peleton QTM-050C), in order to generate an optical clock signal consisting of two phase-locked spectral components. As shown in Fig. 10, undesired components were highly suppressed. The frequency separation between the fourth USB and the eighth LSB was 468.84 GHz. We measured a time domain profile of the high-speed optical clock signal by using an optical sampling oscilloscope (ANDO AQ7750), where the period of the signal was 2.13 ps, as shown in Fig. 11.

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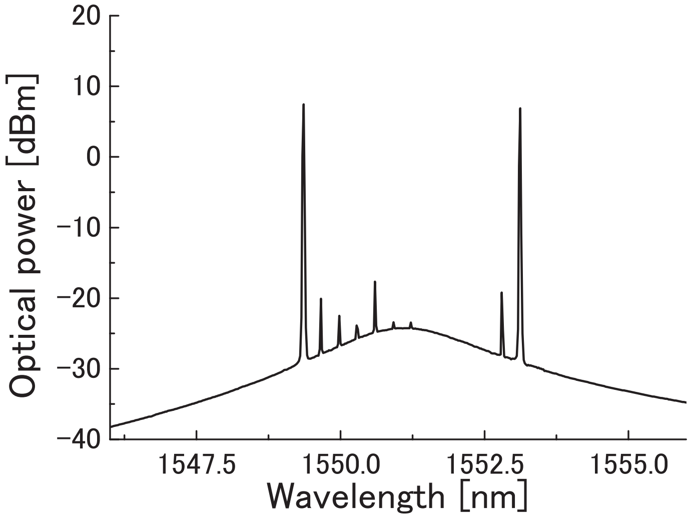

Fig. 10. Spectrum of 470 GHz two-tone signal

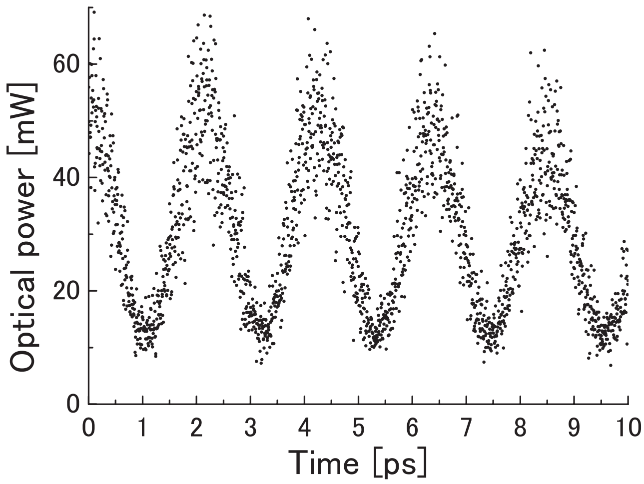

Fig. 11. Time domain profile of 470 GHz signal

5 Conclusion

We reviewed a couple of radio systems using RoF technologies, where generation of RoF signals would play important roles. External modulation can provide stable and low-phase noise signal generation, however, the bandwidths of conventional external modulators are narrower than 40 GHz. In this paper, we focused on two particular external modulation techniques to generate high-order harmonics for very high-frequency RoF applications.

One is 4th-order harmonic generation using high-extinction ratio MZMs, where suppression ratio of undesired components depends on extinction ratio of the modulators. MZMs with a maximum transmission bias point can generate the second order USB and LSB components. Thus, we can obtain the 4th-order harmonic from the USB and LSB with large spurious suppression. Stable 160 GHz signal generation was demonstrated by using a simple setup consisting of a high extinction-ratio MZM and a fixed optical filter.

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The other is high-order harmonic generation using ROMs. A 470 GHz optical clock signal was effectively generated from a 39 GHz signal, where the sideband components were stationary phase-locked each other without using feedback loop control. We can expect that a stable and robust low phase-noise sub-THz signal can be generated by feeding the optical output to a high-speed photodetector, so that this technique would be also useful for sensing and broad-band communications in sub-THz wave band.

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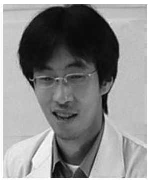

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