Flexible data rate THz-wave communication using Nyquist pulses and optical-domain reception signal processing

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Abstract: We report variable capacity THz-wave communication using Nyquist pulses, which is realized by changing the channel number and optical-domain filtering of received signals. We carried out 10 to 40 Gsymbol/s communication in the 300 GHz-band.
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1. Introduction

Terahertz (THz)-wave communication is suitable for implementing short-reach and high-speed communication [1]-[3]. It can provide wireless communication systems of more than 10 Gbit/s by utilizing its wide bandwidth. One of its application areas is to build-out fiber-to-THz radio bridges, namely, to provide a high-speed wireless link to connect fiber-optic links at a location where it is difficult to lay a fiber-optic cable. While the single-carrier communication is being mainly pursued in the THz-band [1]-[3], the investigation into multi-carrier THz-wave communication including wavelength division multiplexing (WDM), orthogonal frequency division multiplexing (OFDM), and Nyquist WDM is also becoming active in order to increase the data rate and spectral efficiency [4]-[7]. The fixed data rates are adopted in the existing THz-wave communication. While on the other hand, in the prospective THz-wave communication systems, the adaptive transmission, where the minimal bands are flexibly allocated corresponding to the traffic and transmission distance, might be required with a view to saving the power consumption and network resources. This adaptive communication can be realized by changing the number, symbol rate, and/or modulation formats of used channels.

In this paper, we report on wireless communication using Nyquist pulses in the 300 GHz-band, which adopts variable channel number signals and reception signal filtering supported by photonic technology. A 1 x 10 Gbit/s optical Nyquist time division multiplexing signal and 2 x 10 to 4 x 10 Gbit/s optical Nyquist WDM signals were produced by shaping a spectrum of each channel signal with an optical Nyquist filter, and the variable channel number Nyquist signals in the THz-band were generated by high-speed photo mixing. In addition to the THz-wave signal generation using the photonic technology, the received Nyquist signals in the THz-band were also processed in the optical-domain. The signal received at an antenna was down-converted to a radio-frequency (RF) signal with heterodyne detection, and the RF signal was transferred to an optical signal through an optical intensity modulator (IM) to carry out optical-domain filtering. An optical filter has high functionality including center frequency tunability, dynamic bandwidth assignment, and an arbitrary passband shape in contrast to filters for the THz-band. The filtered optical channel was evaluated. Bit error rates (BERs) on the order of less than or equal to 10^{-6} were obtained regarding all the demultiplexed channels from the 1 x 10 to 4 x 10 Gbit/s Nyquist signals.

2. Experimental set-up and operating principle

Figure 1 shows an experimental set-up of the variable channel number communication using Nyquist pulses in the 300 GHz band. The figure indicates an example when 4 x 10 Gbit/s Nyquist WDM communication is carried out. Four lightwaves from laser diodes (LDs) 1 to 4, whose wavelengths ranged from 1552.28 [channel (CH) 1] to 1552.52 nm (CH4) by 0.08 nm, respectively, were independently modulated with non-return-to-zero 10 Gbit/s on-off keying (OOK) data produced by four pulse pattern generators (PPGs). The pseudo-random bit sequence (PRBS) of the data was 2^7-1. The spectra of the generated four signals were shaped with root raised-cosine optical Nyquist filters 1 to 4. Each filter was composed of a bulk grating, and roll-off factors of the filters 1, 2, 3, and 4 were 0.41, 0.41, 0.45, and 0.47, respectively. A 4 x 10 Gbit/s optical Nyquist WDM signal was produced by combining the filtered four signals with optical fiber couplers. The 1 x 10 to 4 x 10 Gbit/s optical Nyquist signals (center frequency: f_{WDM}) were generated by just turning on the requisite LDs. The optical Nyquist signals with the various channel number were mixed with a continuous local lightwave from a local LD5 utilizing a unitraveling-carrier photo-diode (UTC-PD)-type high-speed photo-mixer [8] to generate the variable channel number Nyquist signals in the THz-band. The input intensity of the 4 x 10 Gbit/s optical Nyquist WDM signal into the UTC-PD was 7.0 dBm. The wavelength and input intensity into the UTC-PD were 1550.00 nm and 7.0 dBm, respectively, as for the LD5. The frequency difference between the LD5 frequency f_{LO} and f_{WDM} corresponded to the center frequency f_T of the THz-wave Nyquist signal. The f_T value was set at 295 or 300 GHz as for an odd or an even channel number signal, respectively. The output intensity of the UTC-PD ranged from -12.8 to -13.7 dBm with the decrease of the used

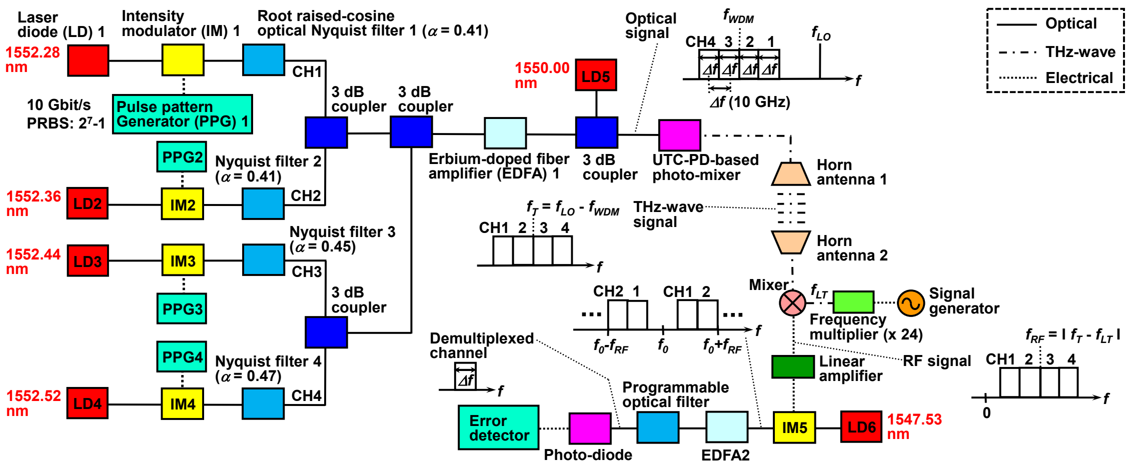

Fig. 1. Experimental set-up of variable channel number communication using Nyquist pulses in 300 GHz band.

channel number. The THz-wave signal was radiated to a free-space link through a horn antenna 1, and was received at an antenna 2. The gain of both antennas was 27 dBi, and the wireless link length was 0.5 m.

The received signal was mixed with a local sinusoidal wave (frequency: f_{LT}) with a view to obtaining a down-converted RF signal with the center frequency of f_{RF}. The f_{LT} values of 255, 265, 325, 335, and 340 GHz were utilized depending on the used channel number and the channel to be demultiplexed. The f_{RF} values changed from 30 to 45 GHz with 5-GHz increments in between. The linearly amplified RF signal was again up-converted into an optical signal (wavelength: 1547.53 nm) through a modulator IM5 (bandwidth: 30.3 GHz, half-wavelength voltage V_π: 3.0 V). The bandwidths of the mixer and linear amplifier were 40 and 65 GHz, respectively. The bias of the IM5 was set at a null point, and, under this bias setting condition, a spectrum at the IM5 output showed two main sidebands around the optical carrier frequency f_0. The center frequency difference between the sidebands became $2f_{RF}$ [9]. The desired channel was extracted from one of the sidebands with a programmable optical filter consisting of a bulk grating and a spatial light modulator [10], and the filtered optical channel was evaluated. The programmable filter was set so that each filtered channel finally had a raised-cosine spectral shape.

3. Experimental results

Figure 2 shows measured spectra of the optical Nyquist signals with the various channel number and the LD5 for producing the THz-wave Nyquist signals. The frequency difference between the center frequency of the Nyquist signal and the LD5 was 295 or 300 GHz for an odd or an even channel number signal, respectively.

Figure 3 shows measured BERs of all the demultiplexed 10 Gbit/s channels. Figures 3 (a) to (d) are characteristics relating to the 1 x 10 to 4 x 10 Gbit/s Nyquist signals, respectively. Figure 4 indicates a measured eye diagram of the demultiplexed channel at the lowest BER in each channel number communication. From Fig. 3, BERs in the order of less than or equal to 10^{-9} were attained regarding all the demultiplexed channels from the Nyquist signals with the one to three channel number. While on the other hand, in the four channel number communication, the achieved lowest BER of CH1 was 1.7 x 10^{-6} (the lowest BERs of other three channels: less than 10^{-6}). The power penalties also increased when the channel number rose. The degradation of the BER characteristics with the increase of the channel number was mainly attributed to interchannel crosstalk, which was caused by the non-linear response of the optical modulator IM5. Other factors were crosstalk between the original Nyquist WDM channels and limited bandwidths of the used RF components. Figure 5 shows two examples of spectra relating to the denultiplexed channels. The spectra did not show complete raised-cosine shapes. This stemmed from the difference

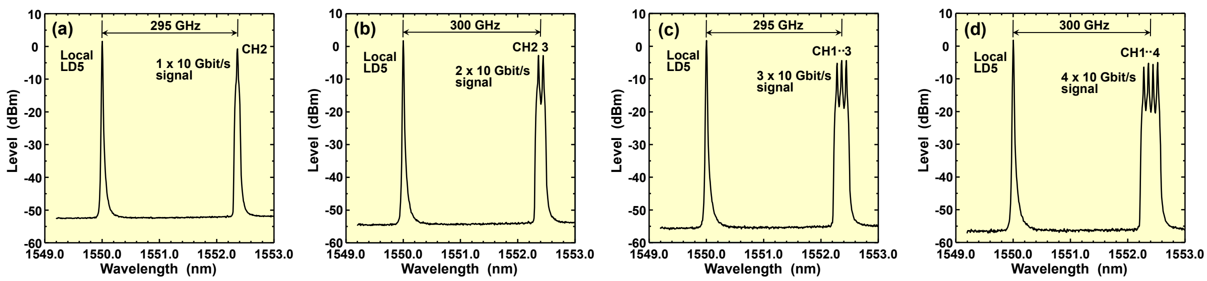

Fig. 2. Spectra of various channel number optical Nyquist signals [(a) one, (b) two, (c) three, and (d) four channel signals] and local LD5.

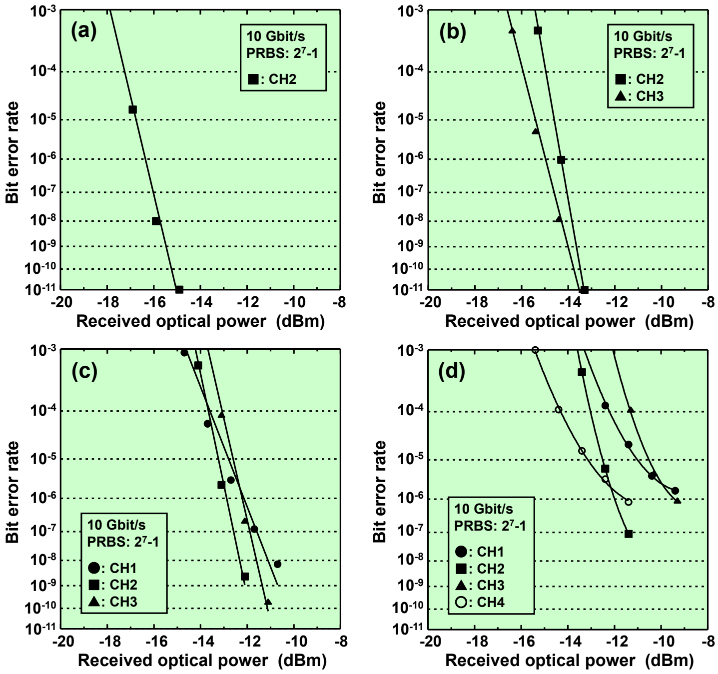

Fig. 3. BERs of all demultiplexed 10 Gbit/s channels from (a) one, (b) two, (c) three, and (d) four channel number Nyquist signals.

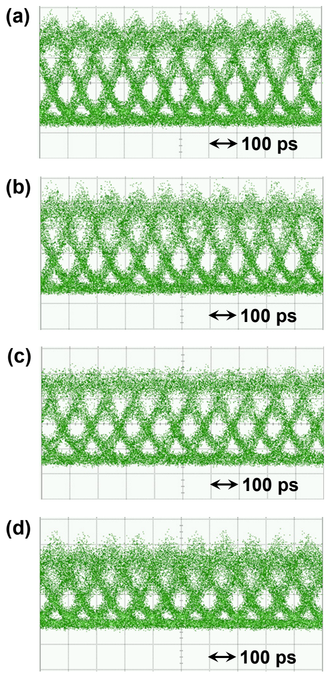

Fig. 4. Eye diagrams of demultiplexed channels. (a) CH2, (b) CH2, (c) CH3, and (d) CH2 of one, two, three, and four channel number Nyquist signals, respectively.

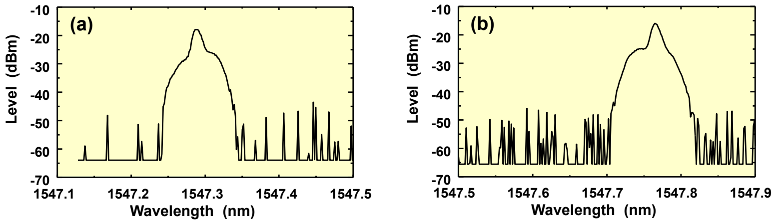

Fig. 5. Two examples of demultiplexed channels spectra. (a) CH2 and (b) CH2 of two and four channel number Nyquist signals, respectively.

between the set and obtained shapes of the programmable filter due to its resolution limit. The incomplete spectral shape caused residual aperture distortion to the demultiplexed signal, which deteriorated the BERs. We however carried out the first variable channel number THz-wave communication using Nyquist signals to our knowledge, and all the obtained BERs were below the limit of 7 % overhead hard-decision forward error correction (3.8×10^{-3}) [11].

4. Summary

We carried out flexible data rate wireless communication using Nyquist pulses in the THz-band. 1 x 10 to 4 x 10 Gbit/s THz-wave Nyquist signals were flexibly and successfully demultiplexed with signal processing supported by photonics. The obtained results can contribute to the progress on the prospective adaptive THz-wave communication.

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5. References

[1] A. J. Seeds et al., "Terahertz photonics for wireless communications," J. Lightwave Technol. **33**, 579-587 (2015).
[2] A. Kanno et al., "High-speed coherent transmission using advanced photonics in terahertz bands," IEICE Trans. Electron. **E98-C**, 1071-1080 (2015).
[3] T. Nagatsuma et al., "Advances in terahertz communications accelerated by photonics," Nature Photonics **10**, 371-379 (2016).
[4] H. Shams et al., "100 Gb/s multicarrier THz wireless transmission system with high frequency stability based on a gain-switched laser comb source," Photon. J. **7**, 7902011 (2015).
[5] X. Yu et al., "160 Gbit/s photonics wireless transmission in the 300-500 GHz band," APL Photonics **1**, 081301 (2016).
[6] K. Takiguchi, "Real-time wireless OFDM communication in THz-band using optical DFT processing," MWP'17 **We2.4**, Beijing, China.
[7] K. Takiguchi, "Spectral-efficient and high-speed THz-wave communication using 40 Gsymbol/s channel-based Nyquist WDM," CLEO'19 **SW4F.7**, San Jose, USA.
[8] T. Ishibashi et al., "Unitraveling-carrier photodiodes for terahertz application," J. Select. Topics Quantum Electron. **20**, 3804210 (2014).
[9] K. Takiguchi, "Method for converting a high-speed and spectrally efficient terahertz-wave signal into an optical signal," Opt. Express **27**, 6598-6606 (2019).
[10] M. A. Roelens et al., "Dispersion trimming in a reconfigurable wavelength selective switch," J. Lightwave Technol. **26**, 73-78 (2008).
[11] C. Xie et al., 960-km SSMF transmission of 105.7-Gb/s PDM 3-PAM using directly modulated VCSELs and coherent detection," Opt. Express **21**, 11585-11589 (2013).