Flexible capacity wireless communication in THz-band with Michelson interferometer-based THz-wave filter

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Abstract: We report wireless communication in the 300 GHz-band, which uses variable channel number and symbol rate signals. We demultiplexed densely allocated 8 to 32 Gbit/s signals directly in the THz-domain using a Michelson interferometer-based filter.

1. Introduction

Terahertz (THz)-wave communication is being vigorously investigated with a view to realizing high-speed wireless communication of more than 10 Gbit/s with the use of the wideband characteristics in the THz-band [1], [2]. One of methods to further increase the capacity of the THz-wave communication is to employ multi-carrier channels including frequency division multiplexing (FDM) [3], and spectrally efficient (spectral efficiency: 1 symbol/s/Hz) orthogonal frequency division multiplexing (OFDM) [4] and Nyquist wavelength division multiplexing (WDM) [5]. The THz-domain direct filtering of high-speed multi-carrier channels can be significant because it not just boosts signal processing speed at the receiver but also decreases configuration complexity and power consumption of the receiver. The adaptive communication, which employs the requisite minimum bandwidth depending on the traffic and communication distance, is achieved by varying the channel number, symbol rate per channel, and/or modulation formats [6]. This type of communication might be needed in the intending THz-wave communication to conserve the communication resources and power consumption [7]. The combination of the adaptive communication and direct channel filtering is potentially effective in achieving a sophisticated THz-wave communication system.

We utilized a Michelson interferometer (MI)-based THz-wave filter for demultiplexing channels of variable capacity FDM signals in the 300 GHz-band. In this paper, we explain the configuration and operating principle of the filter, and preliminary experimental results on the channel demultiplexing. The filter was composed of bulk devices developed for the THz-band, and the number of the interferometer cascades was two. The filter functions as a discrete Fourier transform (DFT) filter in the THz-band, which can demultiplex the THz-wave OFDM sub-carrier channels directly in the THz-domain. The DFT filter is also useful in demultiplexing densely allocated FDM channels [8]. We show detailed results for channel demultiplexing of various capacity FDM signals (2 x 4 Gbit/s to 4 x 8 Gbit/s signals) in the 300 GHz-band using the filter. Although we do not accomplish demultiplexing of the OFDM channels at the present stage, the obtained spectral efficiency of N x 8 Gbit/s signals was 0.64.

2. Configuration and operating principle of filter, and experimental set-up for channel demultiplexing

Figure 1 shows the configuration of the MI-based THz-wave filter for demultiplexing up to four sub-carrier channels, which consisted of cascaded two MIs with arm length difference of $\Delta L/2$ and $\Delta L/4$. All the demultiplexed channels share one output port for simplicity in the current conditions. The interferometers comprised bulk beam splitters (material: high resistivity float zone silicon) and mirrors (material: gold-covered silica glass) that were developed for the THz-band. One of the mirrors in each interferometer was made movable with a view to adjusting the length difference and phase shift between the two arms. The wavelength of a 300 GHz electromagnetic wave is 1.0 mm, while on the other hand, the resolution of used fine movement stages is about 0.5 μm. Therefore, we can tune the phase shift with an accuracy of less than one thousandth of the wavelength. This accuracy is sufficient for realizing the interferometer with good properties. The filter operates as a DFT filter for demultiplexing OFDM sub-carrier channels in the THz-band, and the filter output signal $O_n(t)$ (n: output channel number, t: time) is expressed as,

$$O_n(t) = \sum_{k=0}^{N-1} I(k\Delta t)\exp(-j2\pi nk/N),\ \Delta t = T/N, \tag{1}$$

where N, $I(t)$, and T are the number of sub-carriers, an input signal, and a period of each sub-carrier signal, respectively [8], [9]. The DFT filter shown in Fig. 1 is also effective in demultiplexing densely allocated FDM channels [8]. We set arm length difference of the first-stage interferometer (MI1) $\Delta L/2$ to 6.0 mm so that the free spectral range (FSR) of MI1 or second-stage interferometer (MI2) became 25.0 or 50.0 GHz, respectively, to demultiplex 12.5 GHz-spaced four sub-carriers. The signal from the filter output was introduced into a Schottky barrier diode (SBD) through a THz-wave biconvex lens (material: polymethyl pentene) and a horn antenna (gain: 27 dBi) and was converted into an electrical signal with envelope detection at the SBD. Each output channel was selected by tuning the phase shift between the MIs arms according to Eq. (1).

We carried out direct channel demultiplexing of various capacity FDM signals in the 300 GHz-band using an experimental set-up shown in Fig. 2. In Fig. 2, an output light from a laser diode (LD) 1 (wavelength: 1552.40 nm) was modulated with the use of a $LiNbO_3$ (LN)-based phase modulator. The phase modulator was driven with a 12.5 GHz sinusoidal wave to produce 12.5 GHz-spaced optical frequency combs. Two or four flat spectral components were picked out from the combs with a tunable rectangular-shaped optical filter, and interleaved even and odd channel spectral components were modulated with different LN-based intensity modulators with a view to

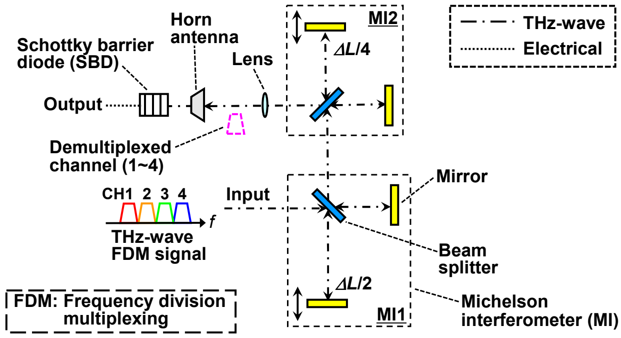

Fig. 1. Configuration of Michelson interferometer (MI)-based THz-wave filter.

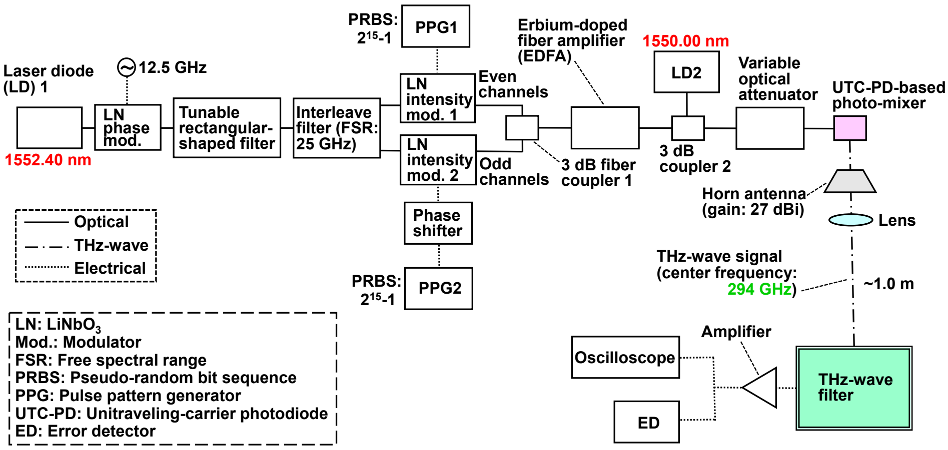

Fig. 2. Experimental set-up for direct channel demultiplexing of various capacity FDM signals in 300 GHz-band.

decorrelating the adjacent channels. Bulk-optic grating-based and MI-based filters were adopted as the rectangular-shaped and interleave filters, respectively. In this experiment, we set each channel bit rate to 4 or 8 Gbit/s, whose pseudo-random bit sequence (PRBS) was 2^{15}-1. We synchronized the symbol timing between the two sets of optical on-off keying (OOK) signals by adjusting the phase difference between two output baseband signals from pulse pattern generators (PPGs). This procedure was necessary because the orthogonality between sub-carrier channels is maintained within just one symbol [8], [9]. We then combined the two sets of OOK signals to generate a two or four-channel optical FDM signal with 12.5 GHz channel spacing and mixed the amplified optical FDM signal with a continuous local LD2 light (wavelength: 1550.00 nm) by using a unitraveling-carrier photodiode (UTC-PD)-based high-speed photo-mixer for THz-wave generation [10]. We tuned the input light intensity into the UTC-PD with a variable optical attenuator. The generated 12.5 GHz-spaced two or four-channel FDM signal with the center carrier frequency of 294 GHz was radiated via the horn antenna and the THz-wave lens. The center carrier frequency corresponded to the difference between the center carrier frequency of the optical FDM signal and the LD2 frequency. The spectral efficiency of the 4 or 8 Gbit/s-based signal was 0.32 and 0.64, respectively. The signal was input into the THz-wave filter in Fig. 1 after 1 m space propagation. The demultiplexed channel at the filter was evaluated with a sampling oscilloscope (bandwidth: 40 GHz) and an error detector (ED).

3. Experimental results

Figure 3 shows examples of measured spectra of the optical FDM signals (2 x 4 Gbit/s and 4 x 8 Gbit/s) and the LD2 for producing the FDM signals in the 300 GHz-band when the input optical intensity into the UTC-PD was maximum. At that time, the signal and local light intensity was both 12.0 dBm, and the intensity of the produced THz-wave signal was -7.8 dBm.

Table 1 summarizes obtained minimum bit error rates (BERs) of all the demultiplexed channels (CHs). Figure 4 shows examples of measured eye diagrams of the demultiplexed channels from various capacity signals when the minimum BERs were achieved. From Table 1, the BERs below the 7% overhead hard-decision forward error correction (FEC) threshold (3.8×10^{-3}) [11] were achieved in all the demultiplexed channels. Table 1 and Figure 4 also indicate that the BER and eye diagram characteristics of the demultiplexed channels became deteriorated with the increase of the channel number and bit rate per channel. The deterioration stemmed largely from the increase of crosstalk from other channels, which was caused by the limited extinction ratio of the filter (about 14 dB). In addition, we did not extract effective time 20 ps of the filtered signals with gating, which was shown as Δt in Eq. (1) [8], [9], [12]. This was also the deterioration cause aside from the deficiency in the sensitivity and bandwidth performance of the used SBD. In the four-channel communication, the BERs of the CHs 1 and 4 were slightly

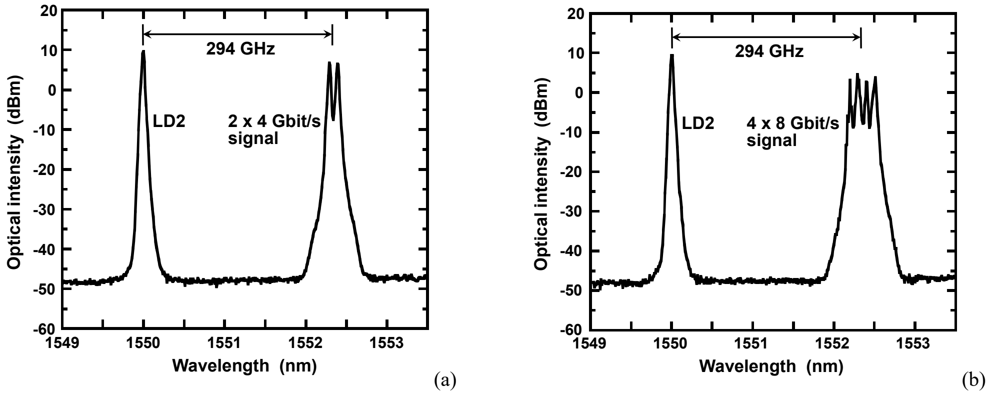

Fig. 3. Examples of measured spectra of optical FDM signals and LD2. Spectra containing (a) 2 x 4 Gbit/s and (b) 4 x 8 Gbit/s optical signals.

Table 1. Obtained minimum BERs of all demultiplexed channels

Signal capacity	Spectral efficiency	BER of CH1	BER of CH2	BER of CH3	BER of CH4
2 x 4 Gbit/s	0.32	1.8×10^{-5}	1.0×10^{-5}		
2 x 8 Gbit/s	0.64	9.2×10^{-4}	8.8×10^{-4}		
4 x 4 Gbit/s	0.32	2.3×10^{-4}	3.0×10^{-4}	3.2×10^{-4}	2.5×10^{-4}
4 x 8 Gbit/s	0.64	3.2×10^{-3}	3.7×10^{-3}	3.8×10^{-3}	3.1×10^{-3}

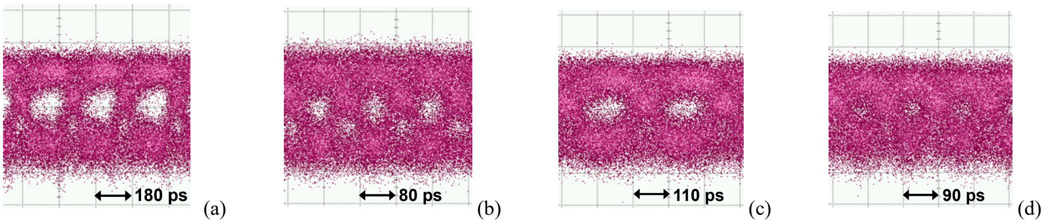

Fig. 4. Examples of measured eye diagrams of demultiplexed channels from various capacity signals. (a) CH2 of 2 x 4 Gbit/s signal, (b) CH2 of 2 x 8 Gbit/s signal, (c) CH1 of 4 x 4 Gbit/s signal, and (d) CH4 of 4 x 8 Gbit/s signal.

smaller than the CHs 2 and 3 because the outer channels received the smaller crosstalk than the inner channels. The BERs when we used just one sub-carrier channel were 6.2×10^{-8} and 4.2×10^{-6} for 4 and 8 Gbit/s-based communications, respectively. We also demultiplexed a 25 GHz-spaced 2 x 8 Gbit/s FDM signal (spectral efficiency: 0.32) with a conventional one-stage MI filter (FSR: 50 GHz) and obtained BERs were 1.7×10^{-3} and 1.5×10^{-3}. This also indicates that the DFT filter was effective in demultiplexing the densely allocated FDM signal.

4. Summary

We presented direct channel demultiplexing of variable capacity and densely allocated FDM signals (2 x 4 Gbit/s to 4 x 8 Gbit/s signals) in the 300 GHz-band with the use of a Michelson interferometer-based THz-wave DFT filter. The spectral efficiency of N x 8 Gbit/s signals was 0.64. The BERs of all the demultiplexed channels were below the 7% overhead hard-decision FEC threshold (3.8×10^{-3}).

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5. References

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