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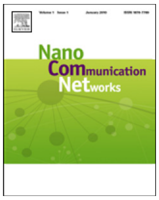

Ultrashort optical pulse source using Mach–Zehnder-modulator-based flat comb generator

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ABSTRACT

We reported ultrashort pulse generation using a Mach–Zehnder-modulator-based flat comb generator (MZ-FCG) and a dispersion-flattened dispersion-decreasing fiber (DF-DDF). Our source has high stability, low jitter, and independent control of the repetition rate and center wavelength. 80 fs-order ultrashort pulse generation was demonstrated. The phase noise of the ultrashort pulse train is determined by that of the microwave signal driving the MZ-FCG, which was -110 dBc/Hz at the offset frequency of 100 kHz. The rms timing jitter of the femtosecond pulses was 80 fs, and the frequency stability evaluated with Allan deviation was in the order of 10^{-13}.

1. Introduction

To meet the growing demand for high speed wireless communication, the development of frequency bands in terahertz (THz) waves and standardization of high speed transmission over 10 Gbps in the THz frequency range are now progressing [1]. Since a field trial of high speed wireless transmission using the 120 GHz-band had been demonstrated by Hirata et al. [2], the carrier frequency has raised to 300 GHz- [2–4] and 600 GHz-bands [5]. To improve both the spectral efficiency and the total capacity, multilevel modulation schemes such as quadrature phase shift keying (QPSK) [6,7] and quadrature amplitude modulation (QAM) [8] were adopted. By using multilevel modulation formats, the total capacity of 100 Gbps has been achieved.

As another modulation scheme, impulse radio including ultra-wideband (UWB) is widely studied [9,10]. The major advantages of impulse radio include large bandwidth, low power spectral density (PSD), multipath immunity, high data rate capacity, and low-cost equipment. In the receiver side of impulse radio, the envelope detection is generally used, which is simpler than the heterodyne detection system used in the multilevel modulation schemes. Thus, impulse radio can reduce the cost for the detection system. 10 Gbps transmission experiments using an InP high electron mobility transistor (HEMT) device [11] and photonics-based systems [12,13] were demonstrated.

Because photonics can easily generate THz waves than electronics (especially the high-frequency region), photonics-based transmitter systems were proposed by many groups. For the communications application, optical sources are required to have high coherence, high frequency stability, and low timing jitter. In addition, to increase the bitrate in the impulse radio system or to use the higher frequency bands in the coherent system, it is important that optical pulse sources serve femtosecond pulses with a high repetition frequency in the order of gigahertzes. Optical comb sources based on optical modulators are good candidates for flexible and high repetition frequency sources [14]. These sources have no cavity configuration, so that they can operate stably. As an optical modulator-based pulse sources, a Mach–Zehnder-modulator-based flat comb generator (MZ-FCG) has been proposed [15–17]. The MZ-FCG generates ultraflat comb which can be easily converted to picosecond pulses only by compensating the chirp using a single-mode fiber (SMF). By using a soliton compression techniques, the pulsewidth of the picosecond pulses can compressed to femtosecond ones [18,19]. The benefits of this system are high stability, low jitter, and independent control of the repetition rate and center wavelength. This system can also operate with alignment-free and with turn-key starting.

In this paper, we report on ultrashort pulse, broadband comb generation and the performance on the timing jitter and frequency stability in the MZ-FCG pulse source combined with a soliton compression technique.

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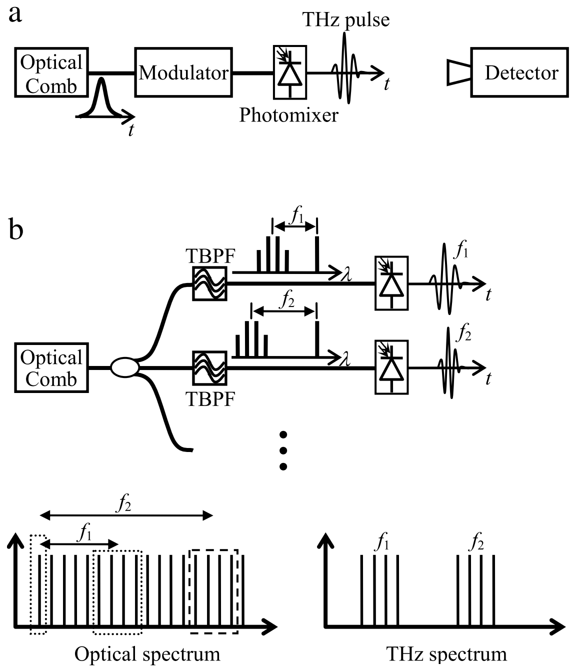

Fig. 1. The concept for THz impulse radio. (a) The basic configuration using ultrashort optical pulse trains. The ultrashort optical pulse trains directly converted to THz pulse trains by using a photomixer. (b) The concept for multi-band THz impulse radio. Broadband optical comb provided by ultrashort optical pulses were spectrally-sliced by tunable bandpass filters (TBPFs). The individual components converted to THz pulses at different center frequencies.

2. Concepts of THz impulse radio system using ultrashort optical pulses

Fig. 1 shows a concept for THz impulse radio using ultrashort optical pulses. Fig. 1(a) shows a system based on direct conversion to THz pulse trains. In this system, ultrashort pulse trains generated by an optical comb source are modulated with data and launched into a photomixer. For the modulation, modulation techniques such as on–off keying and pulse position modulation and so forth can be used. At the photomixer, the modulated ultrashort pulse trains are converted to THz pulse trains. For the photomixer, uni-traveling carrier photodiodes, photoconductive antennas can be used. The THz pulse trains are received by a detection system based on a Schottky barrier diode and so forth. The data rate in this system can be increased by increasing the repetition rate of the optical pulse train. To realize data rates of 100 Gbps or higher, high-speed optical modulators have to be used.

As another scheme, Fig. 1(b) shows a multi-band THz impulse radio. In this system, broadband optical combs are sliced in the frequency domain by using tunable bandpass filters (TPBFs), which extract a mode (single-tone) and several modes (multi-tone). The multi-tone signal preserves the pulse shape but the pulsewidth is elongated from the original pulse. By mixing them using a photomixer, the optical pulse trains are down-converted to THz pulse trains. The envelope of the optical pulses is preserved to the THz pulses. The carrier frequency is corresponds to the frequency difference between the center frequencies of the filters, and the pulsewidth is proportional to that of the optical pulse (i.e. the bandwidth of the multi-tone signal) [20]. Ultrashort optical pulse trains in the order of femtoseconds provide extremely broadband optical combs, so that the center frequency of THz pulses can be broadly tuned. In addition, by using an array of TBPFs, multi-band THz impulse signals can be generated.

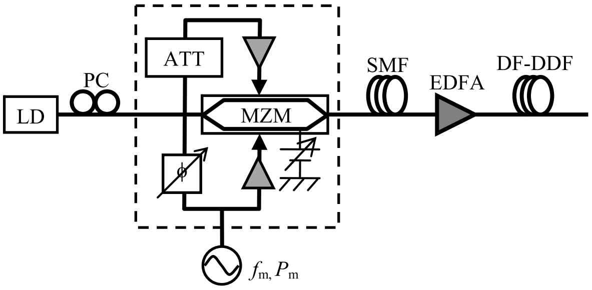

Fig. 2. The configuration of ultrashort pulse source. ϕ, rf phase shifter; PC, polarization controller; ATT, rf attenuator; SMF, single-mode fiber; DF-DDF, dispersion-flattened dispersion-decreasing fiber.

3. Generation of ultrashort pulses using MZ-FCG and pulse compression

Fig. 2 shows the configuration of ultrashort pulse source using the MZ-FCG. This system consists of three stages: the first stage is the MZ-FCG, the second stage is a chirp compensator which converts the comb into a picosecond pulse train, and the third stage is a pulse compressor which compresses the picosecond pulses into femtosecond ones. In the MZ-FCG, a dual-drive-type MZM, which fabricated on a z-cut $LiNbO_3$ crystal and has a half wavelength voltage (V_π) of 2.2 V at 10 GHz, is driven by two microwave signals (driving signals) with the frequency of f_m and the power of P_m. The details of the operation principle and the driving conditions are described in the previous papers [15–19]. A cw light from a laser diode (LD) input to the MZ-FCG is converted to a comb. By launching the comb into an SMF, the comb is formed into a pulse train by chirp compensation. The spacing of the comb is directly related to f_m, and the number of the modes depends on the power of the driving signal. Thus, the bandwidth of the comb and the pulsewidth is decided by f_m and P_m.

Fig. 3 shows results of numerical simulation of comb and pulse generation using the MZ-FCG. In this simulation, values, $f_m = 18$ GHz and $A_1 = 3.2\pi$, were used. In the case of single-arm drive shown in Fig. 3(a), a comb with low intensity flatness is output. When the flat spectrum condition [16] is satisfied by setting to $\Delta A = \pi/2$, $\Delta\theta = \pi/2$, the intensities of the comb modes are flattened out (Fig. 3(b)). As shown in Fig. 3(c), a phase change of the comb in the flat spectral region is quadratic (i.e. linear chirp), so that the comb can be formed to a picosecond pulse train by chirp compensation as shown in Fig. 3(d).

Fig. 4(a) shows experimental results of comb and pulse generation. The driving signal was set to $f_m = 18$ GHz, $P_m = 16$ dBm, and a cw light with a wavelength of 1550 nm and a power of 10 dBm was fed into the MZ-FCG. By setting the driving condition of MZ-FCG to the flat spectrum condition by tuning the power balance of the driving signals and the bias voltage, a comb with high intensity flatness was generated. The spectral shape of the generated comb was consistent with the numerically calculated one (Fig. 3(b)). In Fig. 4(a), 40 modes were clearly observed, and the 10 dB bandwidth was 468 GHz. A MZM with a low half wavelength voltage makes the bandwidth of the comb broader, because of increase of the modulation depth. By chirp compensation using a 200 m-long SMF (group velocity dispersion (GVD) $= 4.0\ \mathrm{ps}^2$), a 1.77 ps-width pulse was generated, as shown in Fig. 4(b). The time-bandwidth product (TBP) was 0.51, which was close to the Fourier-transform limit.

The obtainable pulse width directly from the MZ-FCG is in the order of picoseconds. Pulse compression techniques are effective in generation of femtosecond pulses. Dispersion-managed fibers such as a comb-like profiled fiber (CPF) [21] and a dispersion-decreasing fiber (DDF) [22,23] were developed. In the CPF, specially designed

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