

4-2 High-Repetition TDS System

MOROHASHI Isao, SAKAMOTO Takahide, SAITO Shingo,
SOTOBAYASHI Hideyuki, KAWANISHI Tetsuya, SEKINE Norihiko, HOSAKO Iwao,
and TSUCHIYA Masahiro

We have demonstrated ultrafast optical pulse generation using a Mach-Zehnder-modulator-based flat comb generator (MZ-FCG) and an adiabatic soliton compression technique for terahertz-time-domain-spectroscopy. Our pulse generation technique is very simple configuration and has tunability in the repetition rate and the pulsewidth. The MZ-FCG was driven by two radio-frequency sinusoidal signals. Continuous wave lights led to the MZ-FCG were converted to ultraflat comb signals. The comb signals were formed into picosecond pulse trains by compensating the frequency chirp, and the picosecond pulses were compressed into femtosecond pulses by a dispersion flattened-dispersion decreasing fiber. Pulse trains with 200fs-width were successfully generated.

Keywords

Terahertz wave, Time-domain spectroscopy, Optical frequency comb, Mach-Zehnder modulator, Dispersion-flattened dispersion-decreasing fiber

1 Introduction

Electromagnetic waves in the terahertz frequency range can be used to illuminate many interesting characteristics of materials, including optical phonon scattering in solids, plasma frequency, intermolecular interactions, and vibration in solids. Accordingly, this frequency range is a promising one in the study of material properties. Expectations are high for applications in diverse fields, from medical applications such as cancer diagnosis and testing of drugs to security-related applications such as those involving the detection of explosives. This field of research is thus attracting a great deal of attention.

Terahertz pulses can be generated using ultrashort optical pulses. For this reason, photoconductive antennas are used as terahertz emitting devices, where electrodes with antenna structures are fabricated on the surface of a semiconductor with a short carrier lifetime,

such as a low-temperature grown GaAs (LT-GaAs). Ultrashort optical pulse excitation of the antenna applied by a bias field induces an instantaneous current in the antenna, and then a monocycle terahertz pulse is emitted. The photoconductive antenna and the ultrashort optical pulse are also used to detect terahertz pulses. When an ultrashort optical pulse and a terahertz pulse simultaneously enter the photoconductive antenna, carriers generated by the ultrashort optical pulse drift due to the electric field of the terahertz wave, causing a current to flow through the antenna. This current is used to detect the amplitude of the terahertz wave.

In terahertz time-domain spectroscopy (THz-TDS), the femtosecond pulse source is an important component determining performance, specifically in terms of the THz bandwidth, among other properties. This component also plays a significant role in cost and system size. A technique of generating tera-

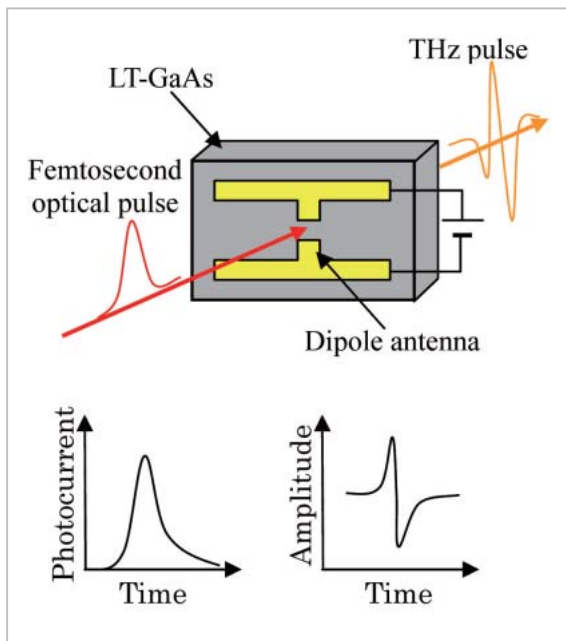


Fig. 1 Terahertz radiation from photoconductive antenna

terahertz waves by irradiating femtosecond optical pulses to a photoconductive switch was proposed and demonstrated by Auston *et al.* in 1984[1]. This research project initially employed colliding pulse mode locking dye lasers. Dye lasers are large and feature complicated structures. Moreover, these lasers do not operate stably and are thus generally unreliable. The required combination of diverse dyes and solvents also gives rise to significant safety issues. An alternative method arose with the subsequent development of the highly operable mode-locked Ti: sapphire laser, resulting in a significant contribution to research on terahertz waves. The wavelength in a Ti:sapphire laser can be tuned from approx. 700 nm to approx. 1,000 nm. The laser provides stable femtosecond optical pulses with high beam quality using component devices made of solids, including the excitation laser. With the relative increase in output power of the femtosecond optical pulses and the improvements to the terahertz wave generation device, the output power of the terahertz waves increased accordingly[2][3]. Further, with the reduction in the pulsewidth of the femtosecond optical pulses, terahertz waves could be generated within a wider frequency

range[4]. However, a Ti:sapphire laser is expensive, relatively large, and difficult to handle. The fiber laser is an alternative ultrashort pulse source that may serve as a replacement for the mode-locked Ti:sapphire laser. A number of terahertz-wave-generation experiments have been performed to date using such fiber lasers[5][6]. At the same time, research is also progressing on terahertz-wave generation and detection using the standard communication wavelengths[7][8]. THz-TDS systems based on fiber lasers are already commercially available and are used as easily operable terahertz spectroscopic systems aimed at researchers who are not specialists in terahertz waves. Although the fiber laser is smaller than the mode-locked Ti: sapphire laser, it is less flexible in respect of various properties, such as wavelength tunability, and the device remains expensive. As the cavity length determines the repetition rate, this rate is only slightly adjustable and any changes require precise control. Pulse generation methods based on step-like dispersion fiber and comb-like dispersion fiber have been reported as useful in the generation of ultrashort optical pulses using a nonlinear pulse compression method[9]-[11]. However, these methods require fiber optics specially designed for pulse shaping and compression.

It has recently been reported that the optical frequency comb generation method can generate pulses within a simple system configuration[12]-[14]. This method uses a Mach-Zehnder modulator (MZM) driven by a radio-frequency (RF) signal with large amplitude; here, an ultraflat optical comb signal is generated. Chirp compensation of the optical comb signal is then performed to generate an optical pulse. The chirp in the optical comb signal is linear, such that chirp compensation becomes easy using a normal single-mode fiber (SMF). As the bandwidth and mode interval of the optical comb signal can be easily controlled using the frequency and power of the RF signal input to the modulator, the pulsewidth and repetition rate of the generated optical pulse can also be easily controlled. In addition, the

generated optical pulse can be further shortened using a nonlinear compression method.

This article mainly reports on femtosecond optical pulse generation using the Mach-Zehnder-modulator-based flat comb generator (MZ-FCG) and the soliton compression method.

2 Ultrashort optical pulse generation using optical frequency comb generator

Figure 2 shows a schematic diagram of the MZ-FCG. The MZ-FCG consists of a continuous wave (CW) light source, an MZM, and an RF circuit used to drive the modulator. The MZM is a dual-drive modulator with independent modulation electrodes on both arms. The two arms are driven by large-amplitude sinusoidal signals at slightly different amplitude values. The CW light input to the MZ-FCG is modulated by the arms and generates side bands on both sides of the basic component.

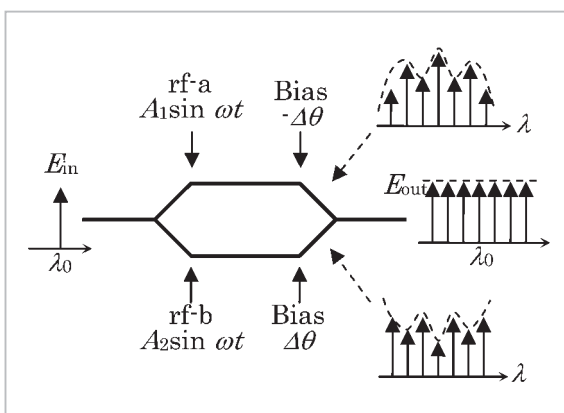


Fig.2 Principle of optical comb generation based on MZM

The frequency interval of the side bands agrees with that of the RF modulation signal, and the number of these bands depends on the power (amplitude) of the RF signal. After the modulation signals generated in both arms are applied with a DC bias, which creates a phase difference, they are multiplexed, and then output. As a result, the optical comb signal output from the MZ-FCG features an interval corresponding to that of the modulation signal, with bandwidth determined by modulation frequency and power. As the amplitude of each component of the optical comb signal generated by the MZ-FCG is determined by the Bessel function, the signal does not generally yield a flat spectral form. However, when the condition

$$\Delta A \pm \Delta \theta = \pi/2 \quad (1)$$

is satisfied, the optical comb signal after multiplexing is flattened (the “optical comb flattening condition”). Here, ΔA is the amplitude difference between the two RF signals, and $\Delta \theta$ is the phase difference between the modulation signal light in the two arms. In the optical comb flattening condition, the phase of each comb component is proportional to the square of the mode order. Thus, this condition results in a characteristic that is the reverse of dispersion of the SMF; it is this characteristic that enables compensation.

Figure 3 shows the flow of ultrashort optical pulse generation based on the MZ-FCG. The ultrashort pulse generation system used in this research consists of (1) an MZ-FCG based on a LiNbO₃ MZM, (2) an SMF for chirp compensation of the generated optical comb

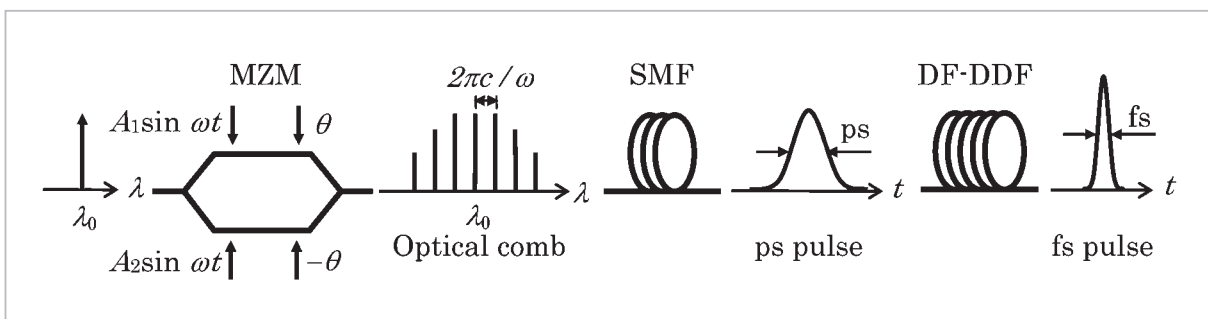


Fig.3 Flow of ultrashort optical pulse generation

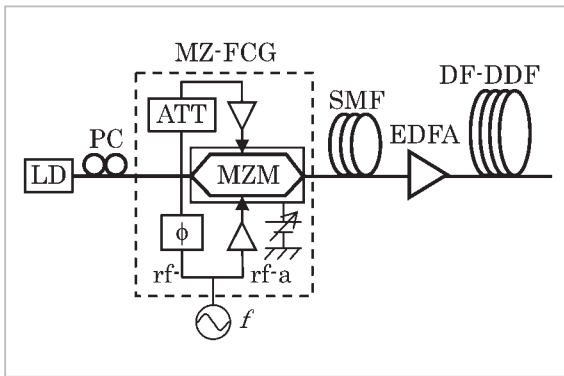


Fig.4 Experimental configuration of femtosecond optical pulse generation

signal, and (3) a dispersion-flattened dispersion-decreasing fiber (DF-DDF) for compressing the shaped optical pulse. When the MZM is driven by a sinusoidal RF signal ($\sin \omega t$) such that Equation (1) is satisfied, continuous wave light input at a wavelength of λ_0 becomes the flat optical comb signal, in which the interval between each component is $\Delta \lambda = 2\pi / \omega$. When the generated optical comb signal is input to the SMF, compensation is applied to the chirp of the optical comb signal, and an optical pulse with a time width corresponding to the bandwidth is generated (i.e., a picosecond pulse). When the optical pulse is input to the DF-DDF, the optical pulse is output after the pulse width is compressed (to the femtosecond order) by adiabatic soliton compression.

Figure 4 shows the experimental configuration for femtosecond optical pulse generation. We generated an RF signal (at frequency f and output of 16 dBm) to drive the MZM using a synthesizer and split the signal into halves (denoted as rf-a and rf-b). The rf-a signal was amplified to 29 dBm and input to one of the arms of the MZM. The rf-b signal was adjusted to be in-phase with the rf-a signal using a mechanical delay device, given a different amplitude from that of the rf-a signal using the attenuator, amplified to 28 dBm, and input to the other arm of the MZM. This measurement used a fixed attenuation rate for the rf-b signal and adjusted the DC bias to satisfy the optical comb flattening condition expressed in Equation (1).

The CW light from the single mode semiconductor laser was input to the MZ-FCG to generate the optical comb signal. The generated signal was processed with frequency chirp compensation using the SMF and was shaped into a picosecond pulse. As the amount of chirp of the optical comb signal varies depending on the frequency of the modulation signal, the length of the SMF that produces the optimum pulsewidth differs depending on the modulation signal. The generated picosecond pulse was amplified to 24 dBm using an erbium-doped fiber amplifier (EDFA) and was processed with adiabatic soliton compression through the DF-DDF. We used a 2-km DF-DDF with an input dispersion value of 9.1 ps/nm/km, an output dispersion value of 0.53 ps/nm/km, and a dispersion slope of 0.03 ps/nm/km/nm at 1,550 nm. We observed the time and spectral shapes of the generated optical pulse with the two-photon absorption type autocorrelator and a spectrum analyzer.

Figure 5 shows the autocorrelation trace and spectrum of the seed pulse light on the SMF output terminal. The frequency of the modulation signal input to the MZM was 10 GHz. As indicated in Fig. 3 (b), we obtained a flat optical comb signal in MZ-FCG output. The interval of the optical comb signal agreed with the modulation frequency of the MZM, and 18 modes displayed intensity values in the range of 5 dB. When this optical comb signal was input to the 1.5-km SMF (with a total dispersion value of 22.5 ps/nm), we obtained a picosecond pulse [Fig. 2 (a)]. The pulsewidth (full width at half maximum) under the assumption of the sech^2 waveform was 3.52 ps. The pedestal component was small, with a value of 19.6 % of the total.

Figure 6 shows the autocorrelation trace and spectrum of the optical pulse after soliton compression when the picosecond pulse obtained in Fig. 5 was used as the seed pulse. The pulse compression produced a wide wavelength bandwidth of 10 nm or more in the 20-dB-reduction range. The pulsewidth (full width at half maximum) assuming a sech^2 waveform was 203.0 fs. The pedestal compo-

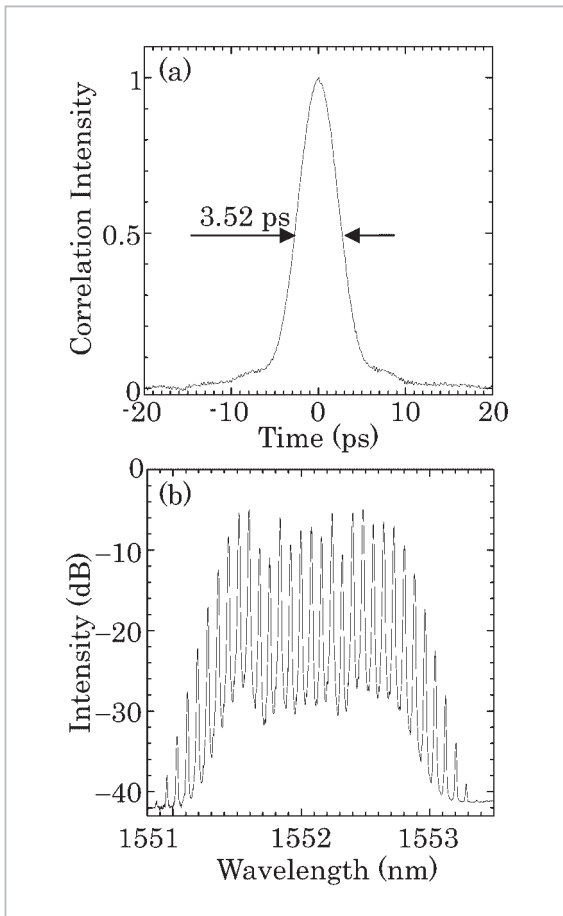


Fig.5 Autocorrelation trace and spectrum of SMF output pulse

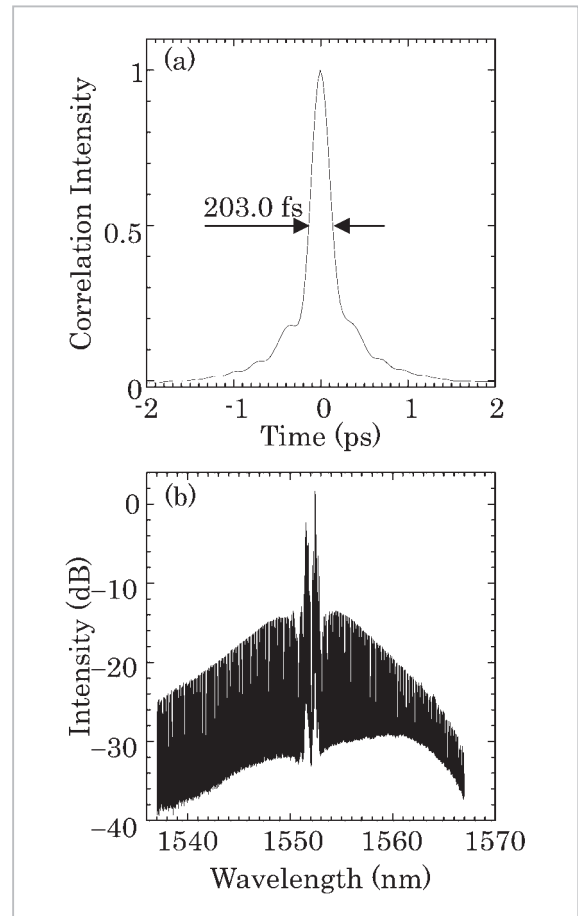


Fig.6 Autocorrelation trace and spectrum of output pulse after soliton compression

nent represented 57.2% of the total.

Figure 7 shows the modulation frequency dependence of the pulsewidth for the picosecond seed optical pulse and the compressed femtosecond optical pulse. Here, the intensity of the modulation signal input to the MZM is held constant. In the case of the seed optical pulse, we obtained picosecond pulses in the range from 5 GHz to 17 GHz; here, pulsewidth rapidly decreased with increasing frequency. This result is attributable to the increase in the spectrum bandwidth due to a greater mode interval in the optical comb signal accompanying the increase in the frequency. A pulsewidth of 2.15 ps was obtained with a modulation frequency of 17 GHz. We were able to obtain picosecond pulses within such a wide range because we used a low driving-voltage MZM. In this measurement, the tunable range of the modulation frequency depends on the bandwidth of the RF amplifier.

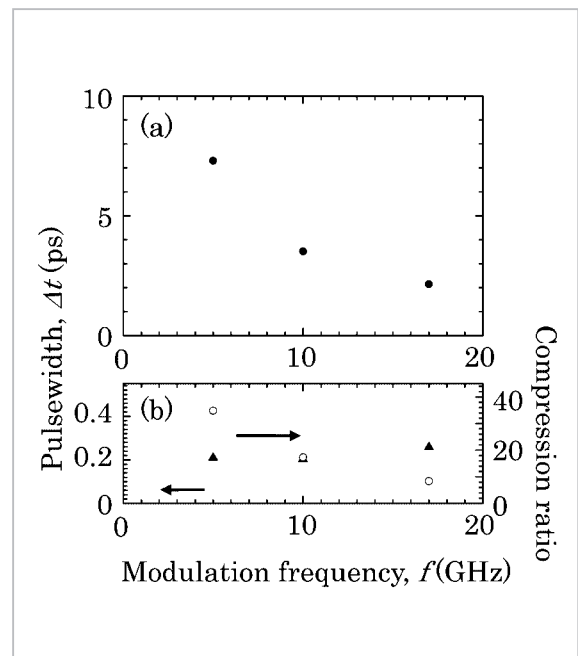


Fig.7 MZM driving frequency dependence of pulsewidth of the output pulse

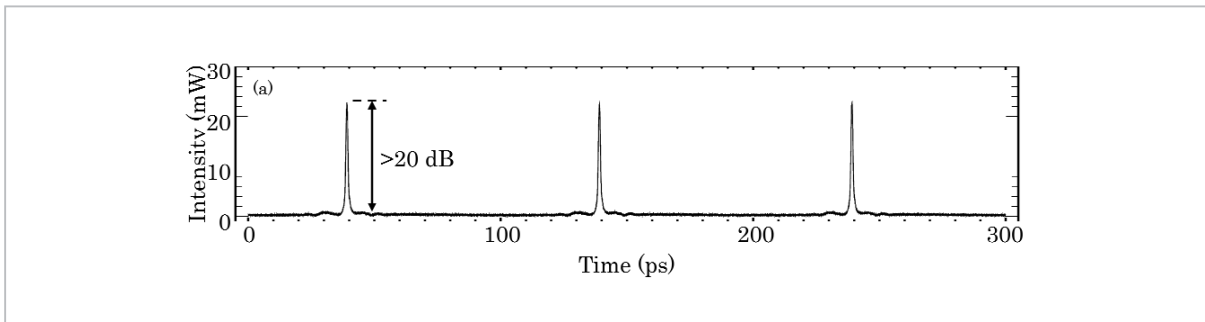


Fig.8 Optical sampling waveform of femtosecond pulse trains

(The bandwidth of the RF amplifier used in this measurement is from 6.0 GHz to 18 GHz.) Thus, by replacing the RF amplifier, pulsed light can also be generated in other frequency ranges. On the other hand, the optical pulses after compression displayed a pulsewidth of approximately 200 fs regardless of the modulation frequency. When the modulation frequency increased from 5 GHz to 17 GHz, the pulse compression rate decreased from 35 to 8.

Figure 8 shows the waveform of the femtosecond optical pulse trains observed by an optical sampling oscilloscope. Here, as the time resolution of the sampling oscilloscope is 1.1 ps in nominal, the observed pulsewidth of the femtosecond pulse is larger than the actual pulsewidth. The optical pulses obtained with this method feature a uniform waveform, and we obtained a satisfactory extinction ratio of 20 dB or greater. These results indicate that almost all the energy of the optical comb signal is compressed into the optical pulse by the SMF and DF-DDF. The fluctuation of peak power was extremely small, at 2.53 %. This experiment thus demonstrated that the optical pulse generation method based on MZ-FCG can produce stable picosecond and femtosecond pulses.

3 THz-TDS system based on MZ-FCG

The ultrashort optical pulse generation method based on the MZ-FCG does not rely on a cavity structure, and all processes take place in the fiber optics. Thus, this method

allows for the generation of stable ultrashort optical pulses impervious to mechanical vibration and provides for tunable wavelength and repetition rate, which is a difficult task in conventional fiber lasers. Given these characteristics, this method is expected to enable the construction of a stable, flexible THz-TDS system.

Figure 9 shows the configuration of the THz-TDS system based on the MZ-FCG. When the MZ-FCG is driven by an RF signal at frequency f , femtosecond optical pulse trains are generated at repetition rate f . This optical pulse is radiated to the free space using the fiber collimator and is divided in half by the beam splitter. One of the beams (the pump light) is irradiated to the emitter photoconductive switch to emit the terahertz waves. The terahertz waves emitted are collimated with a pair of parabolic mirrors for input to the detector photoconductive antenna. The other beam (the probe light) is given a delay time of τ with respect to the pump light according to the applicable stage of the delay process, and input to the photoconductive antenna of the detector. Plotting the current in the detector photoconductive antenna versus delay time provides a waveform of the electric field of the terahertz waves.

The repetition rate of the ultrashort optical pulse trains generated by the MZ-FCG can be changed by controlling the frequency of the driving RF signal, and the wavelength can be changed by controlling the wavelength of the CW light input to the MZ-FCG. Thus, we can construct a flexible system that allows us to change the wavelength and repetition rate to

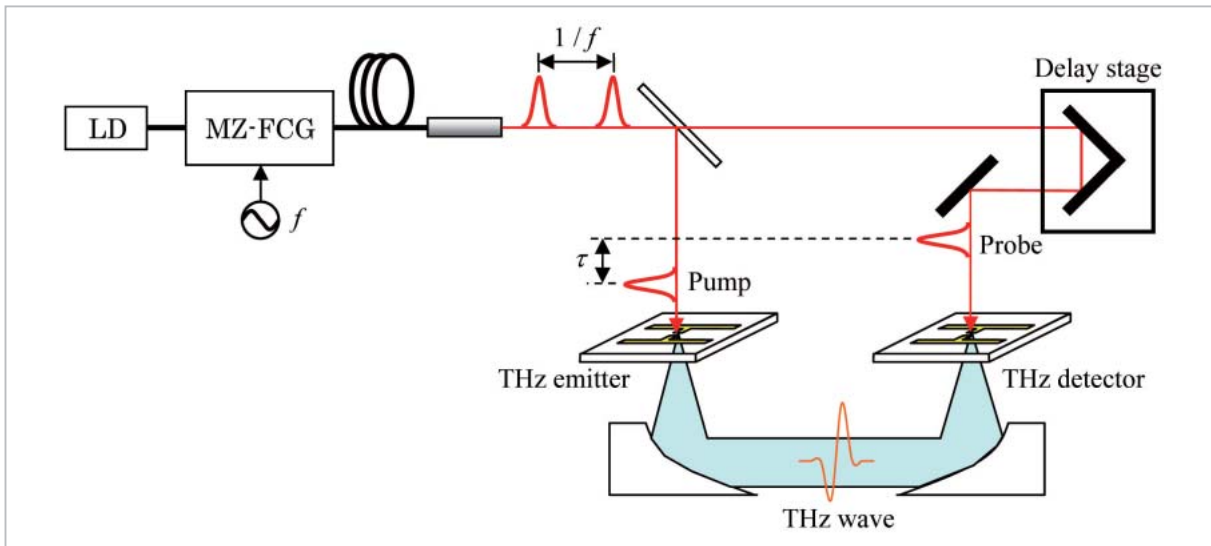


Fig.9 Configuration of THz-TDS system based on MZ-FCG

suit the measurement target and the characteristics of the terahertz-wave emitter and detector devices.

4 Conclusions

We generated femtosecond optical pulses using an MZM-based flat comb generator and the soliton compression technique. By performing frequency chirp compensation on the optical comb signal generated by an optical comb generator, we obtained optical pulses of

2 ps to 7 ps in the modulation frequency range of 5 GHz to 17 GHz. By performing soliton compression of the generated picosecond pulse using the DF-DDF, we obtained an optical pulse of approximately 200 fs. Femtosecond pulse generation based on this method makes use of an extremely simple configuration and enables flexible tuning of pulsewidth and repetition rate. Applying this ultrashort pulse generator to the THz-TDS is expected to allow for the construction of a stable and flexible THz-TDS system.

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MOROHASHI Isao, Dr. Eng.
*Expert Researcher, Advanced
 Communications Technology Group,
 New Generation Network Research
 Center
 Optoelectronics*



SAKAMOTO Takahide, Ph.D.
*Researcher, Advanced Communication
 Technology Group, New Generation
 Network Research Center
 High-Speed Lightwave Modulation*



SAITO Shingo, Ph.D.
*Senior Researcher, Advanced
 Communication Technology Group,
 New Generation Network Research
 Center
 THz Spectroscopy*



SOTOBAYASHI Hideyuki, Dr. Eng.
*Senior Researcher, Advanced
 Communication Technology Group,
 New Generation Network Research
 Center
 Ultrafast Photonic Processing,
 Photonic Network, Photonic Device*



KAWANISHI Tetsuya, Ph.D.
*Research Manager, Advanced
 Communication Technology Group,
 New Generation Network Research
 Center
 High-Speed Lightwave Modulation*



SEKINE Norihiko, Ph.D.
*Senior Researcher, Advanced
 Communications Technology Group,
 New Generation Network Research
 Center
 The Physical Properties of
 Semiconductor Nanostructures in the
 Terahertz Regime and Their
 Application to Terahertz Devices*



HOSAKO Iwao, Ph.D.
*Research Manager, Advanced
 Communications Technology Group,
 New Generation Network Research
 Center
 Terahertz Semiconductor Devices and
 Their Application to Measurement
 Systems*



TSUCHIYA Masahiro, Dr. Eng.
*Group Leader, Advanced
 Communication Technology Group,
 New Generation Network Research
 Center
 Photonics, Electronics*