# Terahertz optical clock generation with tunable repetition rate and central wavelength using variable-bandwidth spectrum shaper

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**Abstract:** Recently, a number of high-speed optical clock generation technologies have been developed due to their potential useful applications in different fields. Here, we propose a new terahertz optical clock generation technique with tunable repetition rate and central wavelength. The proposed optical clock generator consists of an frequency comb light source and a variable-bandwidth spectrum shaper (VBS). The VBS can generate arbitrary repetition rate pulse trains and waveform by controlling each spectral mode. We experimentally demonstrated optical clock generation with repetition rates of 1.28, 2.56, 3.0, and 4.0 THz



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## 1. Introduction

Recently, there have been studies of ultrahigh-repetition-rate technologies with THz-order optical clock generation. These are based on the ultrafast and ultrabroadband properties of light. The applications of such THz-repetition-rate optical clocks are broad, including ultrahigh-precision time-resolved measurement exceeding the time resolution.[1], material development [2,3], nonlinear optical phenomena [4], and terahertz order ultrafast photonic networks[5].

Current techniques for THz-repetition-rate optical clock generation are based on pulse compression in highly nonlinear fibers, use of optical time division multiplexers, Fourier synthesis of multiple wavelengths, and mode-locked distributed Bragg reflectors [6–11]. In addition, an ultrafast clock with a repetition rate of 10 THz has been realized by employing molecular motion [12]. However, tunability of the repetition rate and the central wavelength of the optical clock has not yet been achieved using these technologies.

We previously proposed spectral domain processing based on a waveguide-type optical spectrum synthesizer (OSS) using a high-resolution arrayed waveguide grating (AWG) [13]. We have also demonstrated 1.28 THz and 2.56 THz-repetition-rate optical clock generation from a 20 GHz repetition-rate optical clock by using an OSS [14]. However, the programmability of the repetition rate and central wavelength in that system was limited. To generate a THz-repetition-rate optical clock, we had to use each diffraction order of the AWG. Therefore, we could generate only optical clocks with a repetition rate that is a multiple of 1.28 THz. In addition, the central wavelength tunability depends on the properties of the AWG in the OSS.

Therefore, we developed a variable-bandwidth spectrum shaper (VBS) as a high-resolution optical spectrum control system. This system controls optical signals in the spectral domain with 10 GHz resolution for the entire C-band. The optical intensity of each spectral component can be controlled independently.

To date, we have proposed a THz-repetition-rate optical clock generation technique with tunable repetition rate and central wavelength using the VBS, and shown basic properties by the proof-of-principle experiment [15]. In this paper, we report the principle, configuration, and properties of the VBS in detail. The arbitrary THz-repetition-rate optical clock generation using the VBS with a frequency comb (FC) light source is experimentally demonstrated. Demonstration results are verified by computer simulation.

## 2. Principle of THz-repetition-rate optical clock generation based on spectral domain processing

Ultrahigh-speed (more than 100 GHz) optical pulse train processing in the time domain is not easy. In contrast, it is possible to process ultrahigh-speed optical pulse trains in the spectral domain comparatively easily without using ultrahigh-speed devices. Figure 1 shows the principle of spectral domain processing. The pulse repetition rate corresponds to the inverse of the frequency spacing of the spectral components. The mode spacing of an ultrahigh-speed optical pulse train is so broad that it could easily be processed in the spectral domain. The THz-rate optical clock is generated by suppressing the spectral components wider than 8 nm. In principle, it is possible to control the waveform of the pulse train by processing the amplitude and the phase of the spectral components.

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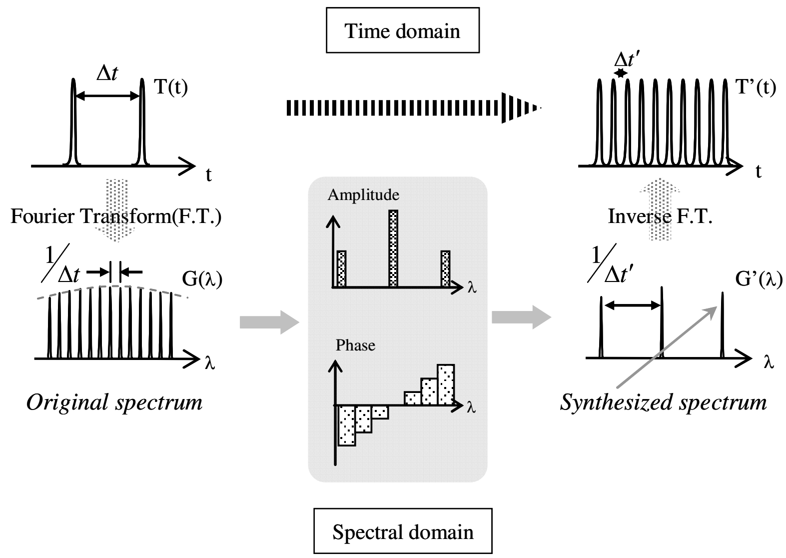


Fig. 1. Principle of pulse processing in the spectral domain.

## 3. Variable-bandwidth spectrum shaper (VBS)

Figure 2 shows the configuration of the VBS and the principle of pulse processing in the spectral domain. The VBS can process spectral components in the entire C-band.

The VBS consists of a collimating lens, a grating serving as a functional dispersion device, a lens, a reflector, a polarizer, and a spatial light modulator (SLM). Spectrum distribution is controlled by the SLM in the wavelength range between 1530 nm and 1570 nm with the channel spacing and channel number of 10GHz and 480ch, respectively. And the insertion loss of  is less than 6 dB.

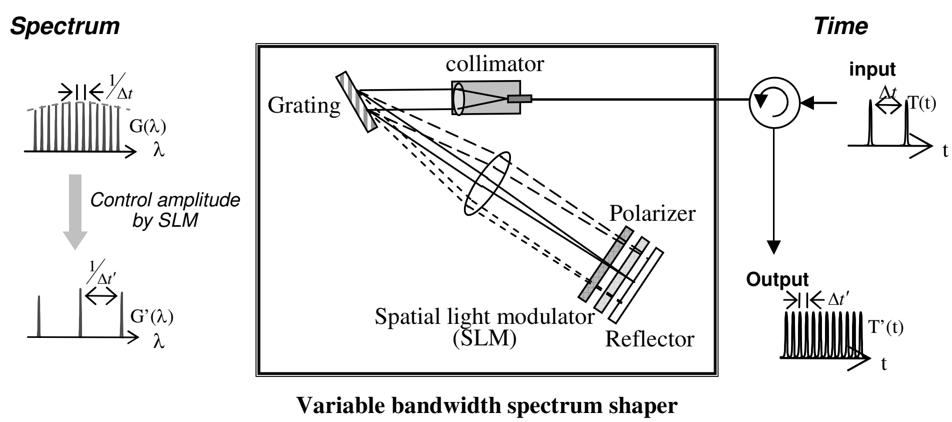


Fig. 2. Configuration of VBS and principle of pulse processing in the spectral domain.

Input pulses are propagated as collimated light from the collimator, through the optical circulator, and the intensities of the spectral components are suppressed by the SLM and polarizer with the extinction ratio of 15 dB. The processed spectral components are reflected at the reflector and coupled by the collimator. A synthesized signal is output from the VBS via

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the optical circulator. The SLM is based on liquid crystal, which can spatially modulate the light intensity in combination with a polarizer. This SLM system has two liquid crystal microdisplays for controlling the intensity. The liquid crystals have parallel orientation. The cell pitch is 20 μm. To control the intensity, the orientation direction is tilted at 45 degree to the direction of polarization. The polarization state of the spectral components is tuned by phase control, and the intensity is controlled in combination with the polarizer. The liquid crystal microdisplays are controlled independently. Based on these design concepts, we realized a VBS with a resolution of 10 GHz (480 channels) at C-band wavelengths.

## 4. Demonstration results

We generated 1.28 THz, 2.56 THz, 3.0 THz, and 4.0 THz optical clocks with the VBS, a spectrum equalizer (SE), and a FC light generator. Optical clocks with sharp spectral components with 1.28, 2.56, 3.0, and 4.0 THz mode spacing were demonstrated. Figure 3 shows the experimental set-up used for generating the THz-repetition-rate optical clocks.

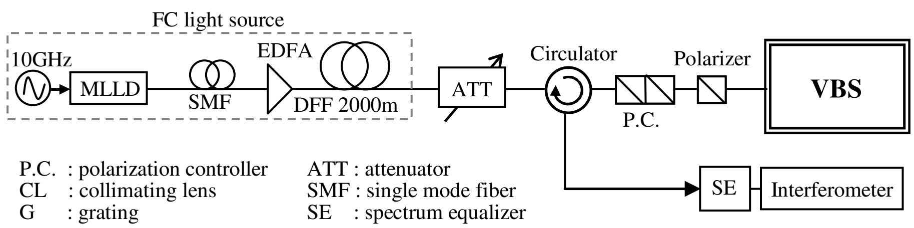


Fig. 3. Experimental set-up for THz-repetition-rate optical clock generation.

As shown in Fig. 3, the set-up consists of a 10 GHz mode-locked laser diode (MLLD) with a central wavelength of 1550.0 nm, an erbium-doped fiber amplifier (EDFA), a dispersion flattened fiber (DFF), a polarization controller (PC), a polarizer, a circulator, a VBS, an SE, and a Michelson interferometer. The 10 GHz FC light generated by the DFF is based on a 2 ps, 10 GHz pulse train from the MLLD, as shown in Fig. 4 (a). Figure 4 (b) shows the spectrum of the generated 10 GHz FC light. Figure 4 (c) shows a close up of the spectrum. To generate THz-repetition-rate optical clock, we need FC spectrum with broad-band over C-band, flat distribution, and high SN. In this experiment, we generate FC spectrum using 2km DFF and 10GHz pulse with 13.5 dBm average power. This 10 GHz FC spectrum was synthesized by the proposed VBS.

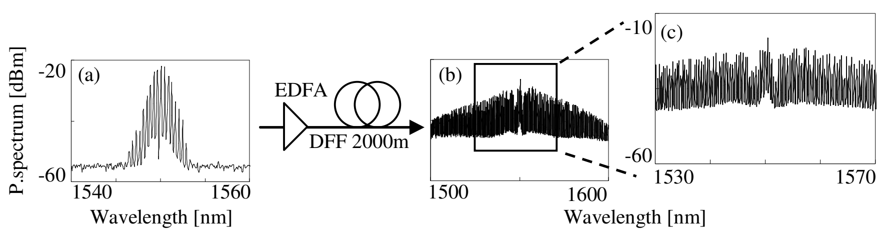


Fig. 4. FC light generation. (a) Spectrum of 10 GHz repetition-rate optical pulses. (b) Spectrum of generated FC light. (c) Close-up of FC light spectrum.

Figure 5 shows a comparison of the simulation results with the experimental results for the 1.28 THz rate optical clock, and the tunability of the central wavelength. Figures 5(a) and (b) show simulated results of the generated 1.28 THz rate optical clock. These simulations were calculated by MATLAB. We calculated sech$^2$ pulses as optical pulse train. The pulse width is 0.1614ps, and repetition rate of 10GHz. The number of sample was 65536, sample spacing was 9.15 fs. In this simulation, all spectral components in the output from the MLLD were suppressed by the VBS except for these three spectra. Figure 5 (b) shows the autocorrelation. The spacing between two adjacent peaks is 0.781 ps, corresponding to a repetition rate of 1.28 THz. Therefore, it was possible to generate a THz-rate optical clock using the VBS. Figures 5(c) and (d) show the experimental results of the generated optical clock with a repetition rate of 1.28 THz. The central wavelength of these optical clocks is 1547.7 nm, and the spectral mode spacing is 10.21 nm. Figure 5(d) shows the autocorrelation measured by the Michelson interferometer. The spacing between two adjacent peaks is 0.234 mm, corresponding to a repetition rate of 1.28 THz. In the experimental autocorrelation results, peaks of the autocorrelation function degrade gradually. The experimental result Fig. 5(d) corresponds to the simulated results in Fig. 5(b). The results indicate that the waveforms of the generated optical clocks are very stable. In Fig. 5(d), there is noise between the peaks, because it was difficult to completely suppress the spectral components in practice. But we can decrease the noise as much as possible by improved design of the optical system in VBS and improvement of the extinction ratio.

In addition, by changing the spectral component of the optical clock processed by the VBS, it is possible to tune the central wavelength. Figures 5(e) and (f) show the spectrum and autocorrelation for the 1.28 THz repetition-rate optical clock with a central wavelength of 1549.7 nm. The central wavelength can be tuned by the maximum range of 20 nm with the step of 0.08nm, in this trial experimental case. The maximum tunability is able to control by changing the repetition rate of generated optical clock and the channel number of VBS.

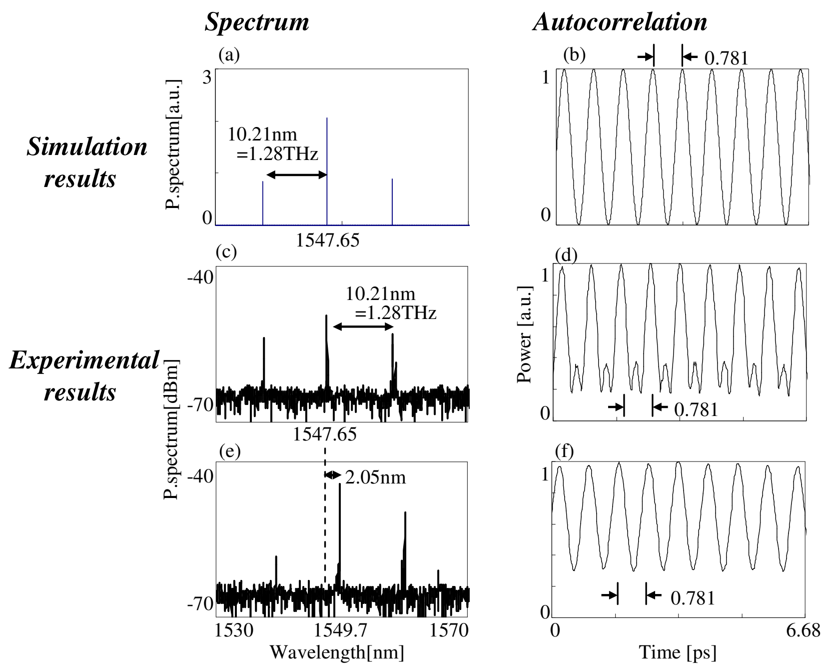


Fig. 5. Simulated and experimental results for 1.28 THz repetition-rate optical clock. (a), (b) Spectra and utocorrelation for simulated results. (c), (d) Spectra and autocorrelation for experimental results. (e), (f) Spectra and autocorrelation for experimental results (at central wavelength of 1549.7 nm).

Figures 6(a), (c), and (e) show the measured spectra with mode spacings of 2.56–4.0 THz. The central wavelength of these optical clocks is 1547.7 nm. The spectral spacings of the THz rate optical clocks are 20.30 nm, 23.73 nm, and 31.49 nm, respectively. Figure 6(b), (d) and (f) show autocorrelations for the generated optical clocks with repetition rates of 2.56–4.0 THz, measured by the Michelson interferometer. The spacings between two adjacent peaks

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are 0.391 ps, 0.333 ps, and 0.250 ps, respectively. These correspond to the 2.56 THz, 3.0 THz, and 4.0 THz repetition rates. The peak spacings of autocorrelations correspond to 2.56–4.0 THz. In the experimental results of autocorrelation, the peaks of the autocorrelation function degrade gradually, meaning that the waveforms of the generated optical clocks are very stable. These results show that the THz-repetition-rate optical clock generation with arbitrarily repetition rate and central wavelength is successfully demonstrated.

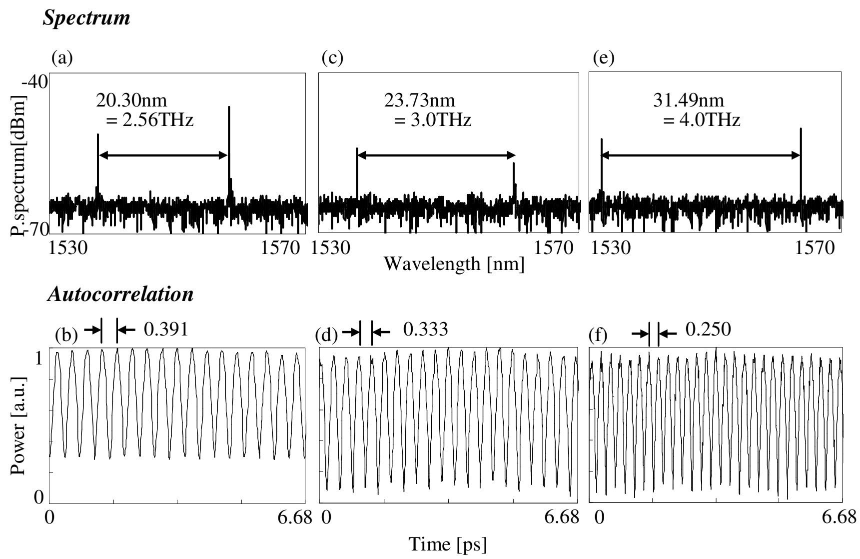


Fig. 6. Spectra and autocorrelations for generated optical clocks. (a) Spectrum and (b) autocorrelation for 2.56 THz repetition rate. (c) Spectrum and (d) autocorrelation for 3.0 THz repetition rate. (e) Spectrum and (f) autocorrelation for 4.0 THz repetition rate.

## 5. Conclusions

We reported the principle, configuration, and properties of the VBS. VBS can control intensity and phase of optical spectrum with 10 GHz resolution. And we also demonstrated the arbitrary THz-repetition-rate optical clock generation using the VBS with a FC light source by simulation and experiment. Demonstration results were verified by computer simulation. We generated 1.28 THz, 2.56 THz, 3.0 THz, and 4.0 THz optical clocks using a VBS, a spectrum equalizer, and FC light source. Optical clocks with two and three sharp spectral components with 1.28 THz, 2.56 THz, 3.0 THz, and 4.0 THz mode spacing were demonstrated. This technique enables the ability optical clocks generation with widely tunable repetition rate and central wavelength. These results clearly demonstrate the capability that our proposed THz rate optical clock can be applied to various fields and application.

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