2 Light Source Technology

2-1 Fourier Synthesis of Optical Pulses

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With the rapid progress made recently in the field of optical communication technology, much attention is being focused on the techniques for generating ultrafast optical pulses with an ultra-high repetition frequency. Fourier synthesis is one of the most promising techniques for doing this, because, unlike in conventional techniques such as mode-locking, there is no limitation on having an arbitrarily high repetition frequency. Fourier synthesis is also used to synthesize arbitrary waveforms based on the inverse process of Fourier-series expansion. We have demonstrated the generation of ultrafast optical pulses with repetition frequencies from 9.6 GHz to as high as 1.8 THz by synthesizing the outputs from three independently oscillating semiconductor lasers. We have also demonstrated that the Fourier-synthesized pulses could be synchronized to an external optical clock. This paper describes the outlines of the above experiments as well as a technique for successive generation of arbitrary bit streams.

Keywords
Generation of optical pulses, Fourier synthesis, Optical phase-locked loops, Semiconductor lasers, Four-wave mixing

1 Introduction

Development of a high-quality optical-pulse source which emits optical pulses with highly controllable repetition frequency will prove indispensable in next-generation, large-capacity optical communication systems. Particularly in the serial-processing type of all-optical TDM system [1], highly stable optical pulses whose repetition frequency is in a THz region are desired as an optical carrier on which a number of slower data streams are successively multiplexed. Although optical pulses have been generated at 1.54 THz [2] by using a mode-locked laser and at 1.28 THz [3] by using a planar lightwave circuit (PLC), the repetition frequencies of these pulses were limited by the lengths of resonators and could not be changed arbitrarily. Moreover, in the PLC approach, jitters between pulses attributed to the machining accuracy of the waveguides limits the enhancement of the repetition frequency.

Fourier synthesis is currently attracting attention as a method of optical-pulse generation that is free from these restrictions. In Fourier synthesis, three or more continuous-wave (cw) lasers are used as light sources, where outputs of these lasers are superposed with accurate control of phases, allowing for the synthesis of optical pulses with desired waveforms based on the inverse process of the Fourier-series expansion. The repetition frequency of the optical pulses generated by the Fourier synthesis is equal to the frequency difference between the oscillation frequencies of the individual lasers that act as Fourier components, and is not dependent on the resonator length of each laser. Moreover, since the repetition frequency can be easily tuned by simply changing the oscillation frequencies of the individual lasers, theoretically there are no restrictions on the repetition frequency.

Fourier synthesis was realized for the first time by Hayes *et al.* [4] in 1977. They succeeded in generating optical pulses with a repetition frequency of 120 MHz using five carbon-dioxide cw lasers as light sources, by setting the frequency difference in oscillation frequencies among the lasers to 120 MHz and synchronizing the phases through the application of the conventional electronics. In this approach of direct control of the beat signals between adjacent lasers by using the conventional electronics, the response speed of the electronic devices gives the virtual upper limit of the repetition frequency.

To generate higher-repetition-frequency optical pulses exceeding this limit, in 1993 Mukai *et al.* [5] proposed a novel method involving optical wavelength conversion in the visible wavelength range, and successfully demonstrated the synthesis of optical pulses using three cw lasers. They compared the phase of the second-harmonic lightwave from one laser with that of the sum frequency of the lightwaves from the remaining two lasers, and formed a negative feedback loop such that the difference between these phases became a constant value. Since they obtained the phase-error signal by comparing the beat signal with an external reference voltage, the phase difference did not become zero, and the maximum repetition frequency obtained was limited to 600 MHz.

We started our study for the purpose of applying the Fourier-synthesis method to generate a stable optical-pulse train with a THz repetition frequency in the 1.5-μm wavelength range adopted by practical optical communication systems. To achieve this purpose, it was essential to improve the phase-locking technique and to mitigate the phase-matching conditions associated with nonlinear wavelength conversion.

First, with respect to nonlinear wavelength conversion, we focused our attention on four-wave mixing (FWM), which is a kind of third-order nonlinear effect, instead of on second-harmonic generation (SHG). Since FWM generally requires a less stringent phase-matching condition than SHG, the entire optical system can be constructed with single-mode optical fibers, and the complete wavefront matching can easily be realized. In particular, in the 1.5-μm wavelength range, a semiconductor optical amplifier (SOA) that will feature an excellent FWM function [6] is under development, which is well-suited to the purpose of this study. On the other hand, it was found that a semiconductor laser oscillating in the 1.5-μm wavelength range generally features a narrow frequency-modulation bandwidth, which is unsuited for use in an optical phase-locked loop (OPLL). We therefore devised a design of a laser so that an electrooptic crystal was installed in the resonator. The crystal was restrained with low-compliance members, eliminating mechanical resonance due to piezo-electric effect. In these efforts we were successful in ensuring a modulation bandwidth sufficient for constructing an OPLL. Moreover, we also developed a method of ensuring high OPLL performance even with a faint FWM signal, where the FM sideband heterodyne technique was used to detect the weak beat signal.

In this report we will first review the principles of Fourier synthesis, then provide an outline of an experiment in which 1.81-THz optical pulses were generated by this method. Furthermore, we will describe an experiment in which a Fourier-synthesized optical-pulse train of 40 GHz was synchronized with an external 8-GHz clock signal. Finally, we will introduce a method of generating an arbitrary bit pattern and dark pulses as an example of an application of the Fourier synthesis.

2 Principles of Fourier synthesis

We will first consider the temporal waveform of an optical pulse train generated by Fourier synthesis using three sinusoidal electric fields of lightwaves having an equal amplitude *A*. If the phase of the electric field of lightwave *i* (i = 1, 2, and 3) is represented by Φ_i, the nominal angular frequency by ω_i ($\omega_1 > \omega_2 > \omega_3$), and the phase fluctuation by $\phi_i(t)$, the electric field $E_i(t)$ of lightwave *i* can be expressed, using the complex notation, as

$$E_i(t) = A\exp[j\Phi_i] \tag{1}$$

and

$$\Phi_i = \omega_i t + \phi_i(t). \tag{2}$$

The temporal waveform $I(t)$ of the lightwave formed as a superposition of the three component lightwaves is obtained by calculating $|\Sigma E_i(t)|^2$ and expressed as

$$I(t) = 3I_0^2 + 4I_0^2\cos(\Delta\phi/2)\cos[\Omega(t+\delta t)] + 2I_0^2\cos[2\Omega(t+\delta t)], \tag{3}$$

where

$$\Omega \equiv \omega_1 - \omega_2 = \omega_2 - \omega_3, \tag{4}$$

$$\Delta\phi \equiv \phi_1 - 2\phi_2 + \phi_3, \tag{5}$$

$$\delta t \equiv \frac{\phi_1 - \phi_3}{2\Omega}, \tag{6}$$

and I_0 is the intensity of one of the three component lightwaves. Equation (3) indicates that when $\Delta\phi$ is a constant, $I(t)$ becomes a stationary pulse train with a repetition frequency $f = \Omega/2\pi$, accompanied by a timing jitter δt. Figure 1 shows the calculated waveforms $I(t)$ by using (3) with $\delta t = 0$, where the waveforms were drawn over four periods for several values of $\Delta\phi$. The symbol $\Delta\phi$ determines the waveform $I(t)$ in a period of 4π.When $\Delta\phi$ is either zero or an integer multiple of 2π, the peak value of each pulse becomes the maximum and the width of each pulse becomes the minimum, thus forming an ideal pulsed waveform.

Equation (4) indicates that the three component lightwaves must maintain equal frequency intervals. Furthermore, $\Delta\phi$ becomes a constant when the following phase-locked state

$$\Phi_1 - 2\Phi_2 + \Phi_3 = \Delta\phi = const. \tag{7}$$

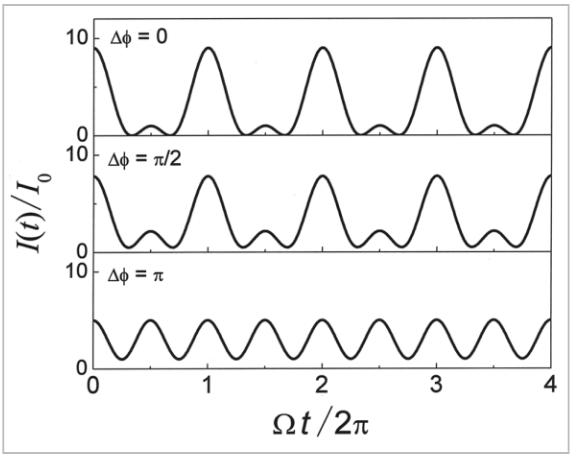

Fig.1 Temporal waveforms of optical-pulse trains formed from three phase-locked laser lightwaves. For $\Delta\phi$, refer to the text.

is established. This state can be produced by combining an effect of nonlinear wavelength conversion such as FWM, and one OPLL. Figure 2 is an illustration of this principle. When E_2 and E_3 are made to enter a medium of third-order nonlinearity simultaneously, FWM occurs, generating anti-Stokes wave E_{AS} on the high-frequency side and Stokes wave E_S on the low-frequency side. The angular frequency of the anti-Stokes wave is precisely $2\omega_2 - \omega_3$. The OPLL technique involves maintaining a constant phase difference between two lightwaves via optoelectronic negative-feedback control. When this technique is used, E_1 of angular frequency ω_1 is phase-locked to E_{AS}, and (7) is thus satisfied.

The full-width-at-half-maximum (FWHM)

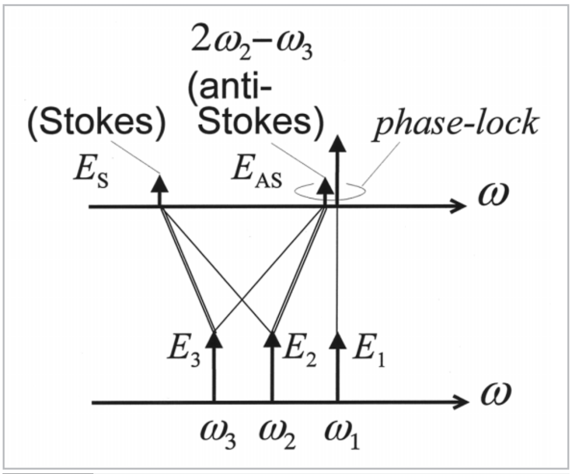

Fig.2 Principle of phase-locking using four-wave mixing.

value Δt of an optical pulse obtained by Fourier synthesis of three independent lightwaves becomes the minimum when $\Delta\phi = 0$, resulting in $\Delta t \approx 0.311/f$.

When N lightwaves are mutually phase-locked to form an optical pulse train, the minimum number of OPLLs required is N - 2. In this case, the phases of N - 2 lightwaves are completely controlled by OPLLs, with two lightwaves remaining free-running. To ensure that the pulses are generated stationarily in the faithful repetitive manner, the lasers must be in a phase-locked state such that the angular frequency differences between adjacent lasers are all equal to Ω. The temporal waveform of an optical pulse train obtained by synthesizing N lightwaves with equal intensities can be expressed as

$$I(t) = \left|\sum_{i=1}^{N} \exp\left[j(\omega_i t + \phi_i)\right]\right|^2 = \left[\frac{\sin\frac{N\Omega}{2}(t-t_0)}{\sin\frac{\Omega}{2}(t-t_0)}\right]^2, \qquad (8)$$

where t_0 is the timing jitter, which is equivalent to

$$t_0 = \frac{\phi_m - \phi_n}{(n-m)\Omega}, \qquad (9)$$

assuming that the m-th and n-th lasers ($m<n$) remain free-running and that the other lasers are perfectly phase-locked. The FWHM pulse width Δt becomes approximately $0.886/Nf$ when N is sufficiently large. The error of this approximation for $N = 3$ is about 5%.

If the repetition frequency exceeds a few tens of GHz, it becomes impossible to observe the temporal waveform directly with a conventional oscilloscope. In such a case, the temporal waveform is estimated indirectly using an autocorrelation waveform. In cases in which the optical pulses are synthesized from three lightwaves of equal intensities, the autocorrelation function of the waveform becomes, by using (3),

$$\Gamma_I(\tau) \equiv \langle I(t)I(t+\tau)\rangle = 9I_0^2 + 4I_0^2\cos(\Omega\tau)\left[1 + \langle\cos\Delta\phi\rangle\right] + 2I_0^2\cos(2\Omega\tau), \qquad (10)$$

where it is assumed that variations in $\Delta\phi$ and δt are sufficiently slow and negligible during the delay time τ. $\Delta\phi$ is usually a non-stationary process, however, when phase-locking is established, the variance in $\Delta\phi$ converges to a finite value and $\Delta\phi$ obeys a stationary Gaussian statistics. By representing its average value as $\Delta\phi_{av}$ and its variance as $V_{\Delta\phi}$, (10) can be rewritten as

$$\Gamma_I(\tau) = 9I_0^2 + 4I_0^2\cos(\Omega\tau)\left[1 + \gamma\cos(\Delta\phi_{av})\right] + 2I_0^2\cos(2\Omega\tau) \qquad (11)$$
$$\gamma \equiv \exp\left(-\tfrac{1}{2}V_{\Delta\phi}\right),$$

where the Gaussian moment theorem [7] was used. Hereafter, $\Delta\phi_{av}$ is simply rewritten as $\Delta\phi$, and $V_{\Delta\phi}$ is regarded as the residual phase fluctuation in the phase-locked state. Parameter γ can be regarded as unity when $V_{\Delta\phi}$ is less than 0.1 rad^2, since $\gamma = 0.951$ for $V_{\Delta\phi} = 0.1$ rad^2.

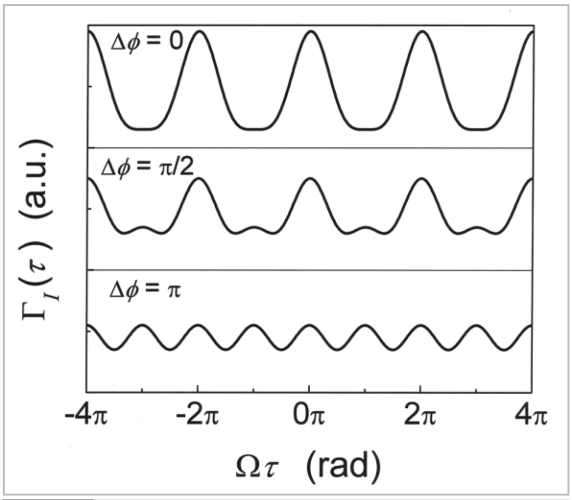

Fig.3 Autocorrelation waveforms of optical-pulse trains formed from three laser lightwaves (calculation with $\gamma = 1$). For $\Delta\phi$, refer to the text.

Figure 3 shows the autocorrelation waveforms calculated by using (11) for several different values of $\Delta\phi$. The autocorrelation waveform varies as a function of $\Delta\phi$ in a period of 2π. When the phases of the component lightwaves are not synchronized, the average value of $\cos\Delta\phi$ in (10) becomes zero, and hence the autocorrelation waveform does not change its shape at all. On the contrary, when the phases of the component lightwaves are synchronized, the autocorrelation waveform changes its shape to a great extent as a function of $\Delta\phi$ as shown in Fig. 3. Such a change in shape ensures that the Fourier synthesis is being properly carried out. When γ = 1 can be assumed, the FWHM correlation width $\Delta\tau$ of the autocorrelation waveform becomes 0.411/f in the case $\Delta\phi$ = 0, which is 1.32 times the actual pulse width. Table 1 compares some of the waveform parameters for several typical pulse shapes. This table indicates that the optical pulses obtained by Fourier synthesis of lightwaves of equal intensities exhibit intermediate properties between those of rectangular-shaped pulses and those of Gaussian pulses.

Table 1 Comparison of waveform parameters between typical pulsed waveforms. Δt, $\Delta\nu$, and $\Delta\tau$ are the full width at half maximum of the temporal waveform, spectrum, and autocorrelation waveform, respectively.

$I(t)$	$\Delta\tau/\Delta t$	$\Delta\nu\cdot\Delta t$
Rectangular	1	1
Fourier synthesized	**1.32**	**0.622**
Gaussian	1.41	0.441
$sech^2$	1.55	0.315
Lorenzian	2	0.221

3 Experimental setup for Fourier synthesis

3.1 Wavelength-tunable semiconductor laser

Figure 4 shows the configuration of a wavelength-tunable external-cavity semiconductor laser used in the experiment. The laser resonator is of a Littrow type consisted of an InGaAsP semiconductor laser chip, a collimating lens (L_1) with a numerical aperture of 0.47, and a diffraction grating of 1,200 lines/mm. The laser oscillates in a single longitudinal mode in a wavelength range centered at 1.53 μm, delivering a typical output power of 3 to 3.5 mW. The facet of the laser chip on the grating side is anti-reflection coated, and the facet on the opposite side is as cleaved, functioning as an output mirror. The axis of rotation P of the diffraction grating is set at a fixed distance from the optical axis, enabling continuous frequency-tuning operation for over 100 GHz without mode hopping. The operating current was set to 70 mA, or approximately three times the threshold value, and the temperature of the laser chip was maintained at 22℃. The spectral linewidth of the laser measured by the beat spectrum of two independent lasers is spread over more than several hundred kHz, due to acoustic noise. However, the real oscillation linewidth for which the effect of acoustic noise is eliminated is estimated at approximately 17 kHz by the delayed self-heterodyne method [8]-[10], in which white noise and 1/f noise are assumed as causes of frequency fluctuation.

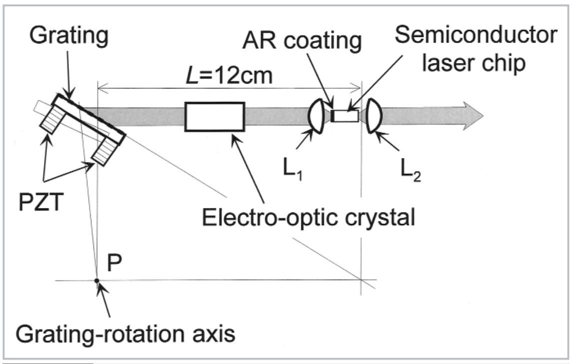

Fig.4 Configuration of an external-cavity semiconductor laser.

The diffraction grating is equipped with a piezo-electric transducer (PZT) element to control the laser-oscillation frequency by negative-feedback control. The oscillation frequency is fine-tuned by changing the voltage applied to the PZT; however, the response speed is insufficient for the construction of an OPLL. Subsequently, a $LiNbO_3$ electrooptic (EO) crystal (length: 25 mm) placed between L_1 and the diffraction grating is used to control the oscillation frequency for a wider frequency bandwidth. The crystal is sandwiched between an acrylic plate and a brass plate, both of which are 6-mm thick and tightened firmly with six stainless-steel screws. This contrivance is designed to suppress mechanical resonance induced in the crystal; its effectiveness is illustrated in Fig.5. Figure 5 (a) shows the frequency transfer function of the laser-oscillation frequency, measured with a $LiNbO_3$ crystal without the mechanical constraint (unrestrained movement), in which multiple acoustic resonance structures can be recognized clearly in both amplitude and phase. Figure 5 (b) shows the frequency transfer function of the laser-oscillation frequency, measured using a $LiNbO_3$ crystal with the mechanical constraint (restrained movement) in the *z*-axis direction with a pressure of 15×10^5 N/m^2. This figure indicates that the resonance structures are almost completely suppressed [11]. There is no evident resonance structure in the frequency range of 3 kHz or less, indicating a flat frequency transfer function with a 3-dB bandwidth of 25 MHz. This frequency bandwidth is sufficient for constructing most OPLLs.

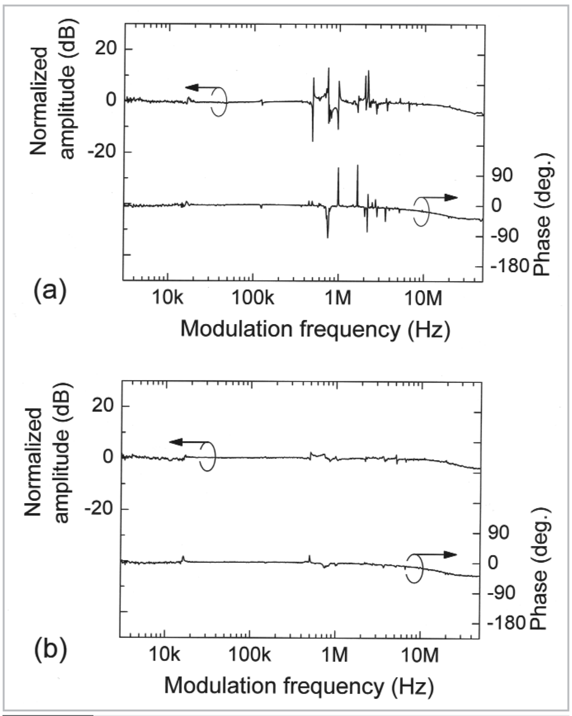

Fig.5 *Effect of mechanical restraint. (a) Frequency transfer function with the application of mechanical restraint. (b) Frequency transfer function without restraint.*

3.2 Optical phase-locked loop (OPLL)

The OPLL technique involves automatic control of the phase difference between two laser lightwaves, allowing this difference to be maintained at a constant value. This control is performed through electronic processing of the beat signal obtained through the interference of the two laser lightwaves. The beat signal is then fed back to control the oscillation frequency of one of the lasers. Cases in which a constant frequency difference is obtained between the two laser lightwaves are referred to as “heterodyne OPLL,” whereas cases in which no frequency difference is obtained and phase difference is temporally constant are referred to as “homodyne OPLL.” The latter is particularly required for Fourier synthesis. In order to construct an accurate homodyne OPLL, a contrivance is required for detection of the beat signal generated by two input lightwaves.

In the often-applied balanced-type detection technique, the two laser lightwaves are mixed and branched by a 50:50 beam splitter where two photodetectors of equal characteristics are placed at the two output ports, and the difference between the two output photocurrents is used as a phase-error signal. Although this technique offers advantages in that the beat signal can be detected accurately with a relatively simple configuration, it is generally difficult to maintain an accurate balance between the two photodetectors, so that the common-mode noise can only be reduced by 20 to 30 dB. Further, in cases in which the two input lightwaves differ significantly in intensity (as in Fourier synthesis), this method cannot be used.

In the FM sideband heterodyne technique, frequency modulation of several hundred MHz is applied to one of the input lightwaves in advance (this step is often replaced with phase modulation), a beat signal between the sideband of this modulation and the other input lightwave is detected with a certain offset frequency, and this signal is electrically demodulated to obtain the base-band error signal. In the single-sideband (SSB) heterodyne technique, one input lightwave is subjected to SSB modulation instead of frequency modulation. In either case, the residual AM component induced by the modulator gives the detection limit of the beat signal. In particular, in the FM sideband heterodyne technique, the detection limit can easily reach -60 dB. Note that in cases in which the FM sideband heterodyne technique is used to construct an OPLL, the phase difference between the two input lightwaves can be obtained only as zero or π, whereas in the SSB heterodyne technique, an arbitrary phase difference from zero to 2π can be obtained by installing a phase shifter just before a demodulator. Both the FM sideband heterodyne technique and the SSB heterodyne technique were used properly in this study.

To construct an adequate OPLL, optimization of the loop filter, which determines the transfer function of the loop, is also important. In the OPLL used in this study, the phase-error signal is distributed to the PZT and the EO crystal, with the crossover frequency set to 106 Hz. The control loop containing the PZT is of the integral type at low frequencies (10 Hz or lower), and the control loop containing the EO crystal uses an active lag-lead filter with a pole and a zero at 14 kHz and at 960 kHz, respectively. Considering that the marginal frequency determined by the loop-propagation delay time was about 5 MHz, the natural frequency of the loop was set to approximately 1 MHz and the damping factor was set to about 0.95.

The stability of the OPLL is estimated by measuring the residual phase fluctuation of the beat signal generated by two laser lightwaves. The root-mean-square (rms) value of the phase fluctuation in $\Delta\phi$ of the beat signal is estimated by [12]

$$\sqrt{V_{\Delta\phi}} = \sqrt{2\int_{f_{low}}^{f_{high}} L(f)\,df} \qquad (12)$$

where, $L(f)$ is the power spectral density (PSD) of the beat signal (measured with an RF spectrum analyzer) normalized with the electric power contained in the carrier, and f denotes the offset frequency measured from the center frequency f_0 of the beat signal. When the frequency of the beat signal is too large to measure $L(f)$ directly, $L(f)$ can be evaluated indirectly using the beat signal observed within the loop by using the following equation [13],

$$L(f) = L_m(f) - \frac{1}{2} S'_{n_a}(f+f_0)\left(1 + \left|1 - H(j2\pi f)\right|^2 - \left|H(j2\pi f)\right|^2\right) \qquad (13)$$

where $L_m(f)$ is the normalized PSD measured within the loop, $S'_{n_a}(f+f_0)$ is the normalized PSD of an additive noise, and $H(j2\pi f)$ is the closed-loop transfer function of the OPLL. By using (13), phase fluctuation can be estimated accurately regardless of the phase-detector gain factor and the noise level of the local oscillator. Note that since the carrier does not appear in the beat signal in the case of the FM sideband technique, the signal obtained by demodulating the beat signal must be measured. Accordingly, the conversion gain of the phase discriminator and the phase-noise spectrum of the local oscillator must also be measured.

3.3 Four-wave mixing

To generate a high-repetition-frequency optical-pulse train by Fourier synthesis, efficient FWM is required. FWM takes place through the modulation of the refractive index of a medium, where the modulation is induced by incident lightwaves via third-order optical nonlinearity. In principle, although FWM can be expected with any medium having third-order nonlinearity, a semiconductor optical amplifier (SOA) is often used as an efficient FWM generator in the 1.5-μm wavelength range. The third-order nonlinearity in semiconductor gain media is attributed to carrier-density and carrier-temperature modulations induced by beating of the incident lightwaves in the gain media, where both kinds of the carrier modulations leads to the modulation of the refractive index.

Figure 6 shows the results of measurement of FWM conversion efficiency of the SOA used in this study. An SOA with a gain of 25 dB manufactured by ALCATEL was selected as the FWM device. Figure 6 (a) shows the optical spectrum obtained at the SOA output by injecting two superposed laser lightwaves (λ_2, λ_3) at frequencies differing by 1.8 THz into the SOA [14], indicating clearly that Stokes wave and anti-Stokes wave are generated at frequencies separated from the laser lightwaves by the same interval. Figure 6 (b) shows the measurement results for optical powers of the FWM signals as a function of the frequency difference between the two incident lightwaves, indicating that FMW signals are obtained up to roughly 4 THz, with sufficient powers for implementing Fourier synthesis.

Since phase-coherent wavelength conversion is essential for Fourier synthesis, it is possible to apply the cascade $\chi^{(2)}$ effect [15], in which second-order nonlinear effects occur successively in the same medium. However, the use of $\chi^{(2)}$ renders the phase-matching condition particularly strict relative to FWM.

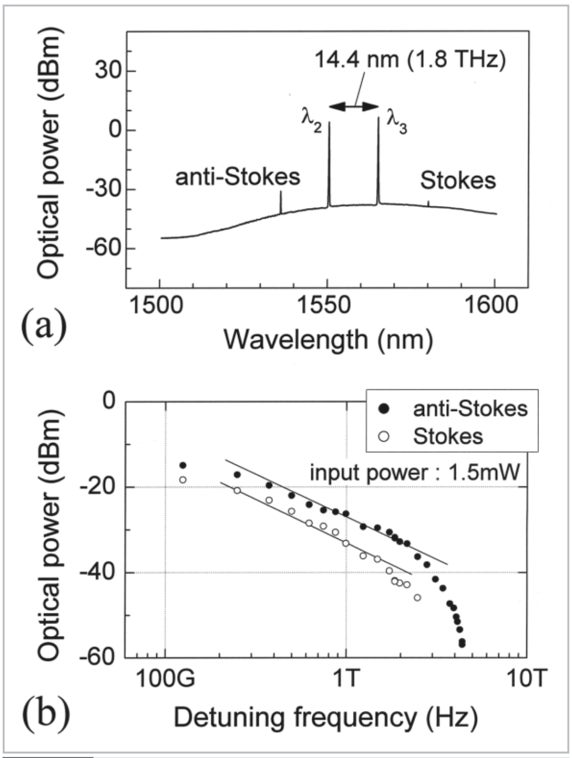

Fig.6 Four-wave mixing (FWM) obtained by injecting two lightwaves with equal intensities into a semiconductor optical amplifier (SOA). (a) Spectrum of SOA output. (b) Optical powers of FWM signals measured as a function of the frequency difference between two injected lightwaves.

4 Experiments on Fourier synthesis

4.1 Fourier synthesis of 1.8-THz optical pulse trains

Figure 7 shows the experimental setup for Fourier synthesis. The three external-cavity semiconductor lasers described in the previous section are used as the light sources, and are represented in the figure as Lasers 1, 2, and 3. These three lasers feature the same resonator structure, but only Lasers 1 and 2 have EO crystals in their resonators. Outputs from Lasers 2 and 3 are mixed and branched with a fiber coupler FC3, and one of the outputs of this component is fed to the SOA (SOA1) to generate FWM signals. The output from the SOA is made to pass through an optical bandpass filter (BPF), which extracts only an anti-Stokes wave; this lightwave is then fed via FC2 to a photodetector (PD1) having a 1.5-GHz frequency bandwidth. On the other hand, one of the output lightwaves from Laser 1 passing through the FC1 is subjected to phase modulation of 480 MHz with a phase modulator (PM); a certain amount of phase difference $\Delta\phi$ is then applied by an optical delay (OD), and the signal is subsequently fed to the PD1. The PD1 generates a beat signal between the lightwave from Laser 1 and the anti-Stokes wave, subsequently the output is demodulated by a DBM and processed by the loop filter. The output of the loop filter is fed back to the EO crystal of Laser 2 and the PZT, resulting in completing an OPLL (OPLL1).

When the frequency difference between the three laser lightwaves was set to 1.8 THz, the residual phase fluctuation in $\Delta\phi$ estimated from the error signal of the OPLL1 was 160 mrad ($V_{\Delta\phi}$= 0.026 rad^2). The remaining outputs from FC1 and FC3 are mixed by FC4 and amplified by an erbium-doped fiber amplifier (EDFA). The waveform of the amplified lightwave is observed using an autocorrelator with a delay-time resolution of 30 fs. If the OPLL1 is closed, a pulsed waveform with a repetition frequency of 1.8 THz is observed by the autocorrelator, however, the waveform is maintained only for a few seconds, due to fluctuation in fiber length induced through the vibration and the change in operation temperature. The fluctuation in fiber length is therefore canceled through the following steps: part of the lightwaves mixed in FC4 is introduced to another SOA (SOA2) to generate FWM signals, then the slight variation in the intensity of lightwave from the SOA2 (a response to variation in the waveform) is detected by a lock-in amplifier and returned to the OD as negative feedback. By use of this auxiliary OPLL (OPLL2), the waveform is thus dramatically improved. Moreover, even when the Fourier-synthesized waveform is stable, the optical pulse deteriorates significantly in the waveform after propagation of only a few meters, due to wavelength dispersion in the optical fiber and the EDFA. Therefore, a single mode fiber (SMF) of a suitable length is inserted just before the EDFA for compensating overall dispersion such that the optimal pulsed waveform is obtained at the autocorrelator. Moreover, the overall optical system is composed of polarization-maintaining fibers, and the optical system is carefully aligned such that the polarization directions of all the laser lightwaves coincide. Furthermore, although not shown in the figure, optical isolators are used in several locations to completely remove the light reflected from the fiber facets.

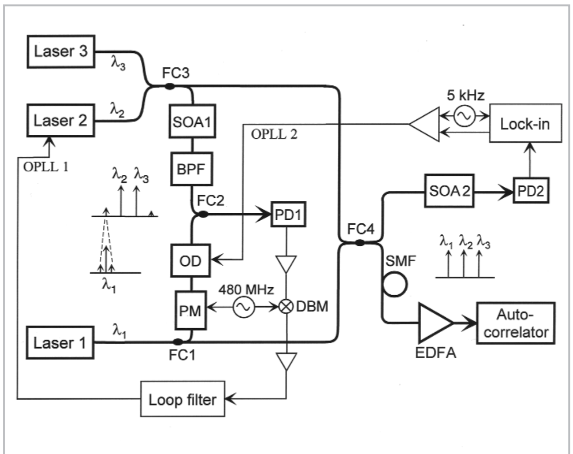

Fig.7 *Experimental setup for Fourier synthesis, where FC1 to FC4 are 3-dB fiber couplers, SOA is a semiconductor optical amplifier, BPF is an optical bandpass filter, PM is a phase modulator, OD is an optical delay, PD1 and PD2 are photodetectors, SMF is a single-mode fiber, EDFA is an erbium-doped fiber amplifier, and DBM is a double-balanced mixer.*

The oscillation frequency difference among the three lasers was firstly set to 9.6 GHz, and the waveform of the optical pulses generated by Fourier synthesis was observed. On this occasion, a fast photodetector with a frequency bandwidth of 45 GHz was used along with a sampling oscilloscope, in place of the EDFA and autocorrelator included in the experimental setup shown in Fig.7. Figure 8 represents the temporal waveform of the observed optical pulses [16]. The observed waveform was in good agreement with the calculation for the case of $\Delta\phi = 0$ depicted in Fig.1. However, the waveform was accompanied by an apparent background, because the sensitivity of the photodetector decreased by 35% at 9.6 GHz and by 40% at 19.2 GHz. The dotted line is the theoretical waveform calculated taking this frequency response into consideration; this waveform shows excellent correspondence with the experimental results. If the photodetector presented flat frequency characteristics, the background would not appear. The measured temporal waveform shows strong dependence on $\Delta\phi$. For $\Delta\phi = 0°$, the desired pulsed shape is obtained. For $\Delta\phi = 100°$, the satellite pulse begins to be noticeable, and for $\Delta\phi = 180°$, the satellite pulse can no longer be distinguished from the main pulse with the waveform reduced to a sinusoidal wave with a doubled repetition frequency. These waveform features agree well with the calculation depicted in Fig.1.

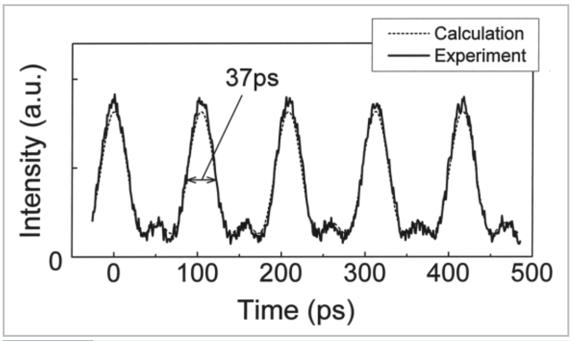

Fig.8 *Waveform of 9.6-GHz optical pulses.*

Next, Fourier synthesis of optical pulses was conducted by increasing the differences in oscillation frequencies among the three lasers to 106 GHz, 257 GHz [17], 504 GHz, 1.25 THz, and 1.81 THz [14][18]. Figure 9 shows the optical spectrum observed at the output of the EDFA in the experiment of synthesizing the optical pulses at 1.81 THz. Three lasers oscillate with almost equal intensities, maintaining a frequency difference of 1.81 THz. Background level, increasing in the wavelength range from 1,535 nm to 1,570 nm, is due to spontaneous emission from the EDFA. Figure 10 shows the autocorrelation waveforms for optical pulses of 1.81 THz [14]. Figure 10 (a) is obtained with $\Delta\phi = 0$, while Fig.10 (b) is obtained with $\Delta\phi = \pi$. The dashed curves represent the predicted waveforms calculated using (11). These predicted curves are in good agreement with those obtained in the experiment.

Although the pulse repetition frequency in this study was limited by EDFA bandwidth, we have confirmed that the OPLL itself functions adequately up to 3.75 THz. If a wider gain bandwidth of about 60 nm had been employed, a pulse train of 3.75 THz could have been synthesized. It is extremely difficult to generate such an ultrafast pulse train using conventional techniques such as with mode-locked lasers.

4.2 Synchronization of Fourier-synthesized optical-pulse train

The repetition frequency of the optical-pulse train synthesized using the method described in the previous section fluctuates with the frequency fluctuations of lasers operating in free-running mode. The most practical way to stabilize the repetition frequency is to synchronize the synthesized pulse train with a stable external clock. In this context we focused on a technique of extracting a low-frequency elementary clock from a fast optical-pulse train using FWM [19]-[21]. Based on this technique we attempted to synchronize the Fourier-synthesized fast pulse train with a low-frequency reference clock.

Figure 11 shows the experimental setup for the optical-pulse synchronization experiment. The three lasers used in the Fourier

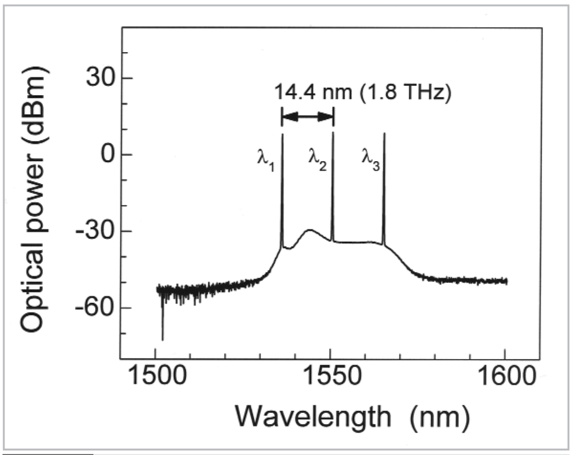

Fig.9 Spectrum of 1.8-THz optical pulses.

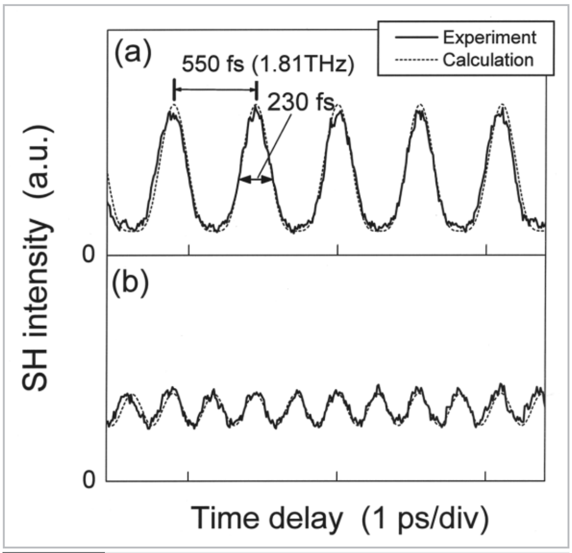

Fig.10 Autocorrelation waveforms of 1.81-THz optical pulses. (a) $\Delta\phi = 0$. (b) $\Delta\phi = \pi$. The solid line is the waveform obtained in the experiment; the dashed line is the waveform calculated using (11).

synthesis described above are also used as light sources in this experiment. The SOA1 generates an FWM signal from the output lightwaves from Lasers 2 and 3. The output lightwave is fed to an SSB modulator driven at 447 MHz, which shifts the frequency of the FWM signal. The optical power in the single sideband is about 2% of the optical power contained in the carrier. The beat signal of the frequency-shifted FWM signal and the lightwave from the Laser 1 is converted to an electrical beat signal by the PD1 and is then demodulated by the DBM to become the phase-error signal for Fourier synthesis. The

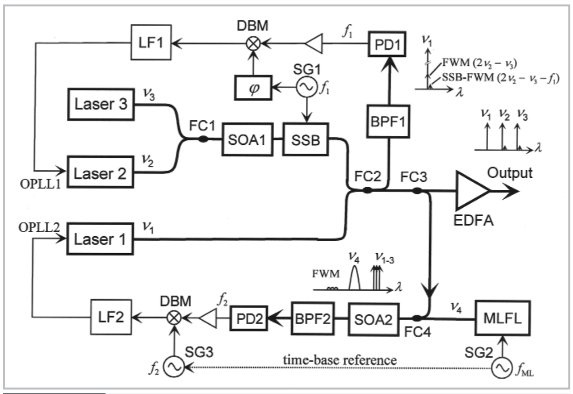

Fig.11 *Experimental setup for optical-pulse synchronization experiment, where SSB is a single sideband modulator, φ is a phase shifter, MLFL is a mode-locked fiber-ring laser, and SG1 to SG3 are signal generators. For other symbols, refer to the explanation in Fig. 7.*

phase-error signal is processed by using the loop filter (LF1), and is fed back to control the oscillation frequency of Laser 2. Since the FWM signal in this case has been subject to SSB modulation, the phase parameter $\Delta\phi$ of the synthesized optical pulse can be set to an arbitrary value by adjusting the phase difference φ just before the demodulation, and consequently the auxiliary OPLL used in Fig.7 becomes unnecessary. The repetition frequency of the synthesized pulses can be continuously varied with the waveform remaining unchanged, by sweeping the oscillation frequency of either Laser 1 or Laser 3 while the OPLL1 is in operation. A part of the Fourier-synthesized optical pulses is mixed with the optical pulses from the mode-locked fiber laser (MLFL) using FC4. The MLFL can operate in a wavelength of 1,547 nm, generating stable clock pulses with a repetition frequency f_{ML} of 8.0027 GHz and a pulse width of 9.6 ps. The two pulse trains are fed to the SOA (SOA2) simultaneously, generating an FWM signal at 1,544 nm. Since the intensity of this FWM signal strongly depends on the relative phase difference between the two pulse trains, (i.e., on timing jitter), if an OPLL is constructed to treat this intensity variation as a phase-difference signal and the output of the OPLL is fed back to control the oscillation frequency of Laser 1, the two pulse trains can be synchronized. In order to construct this OPLL, only the FWM signal is extracted from the output from the SOA2, using a bandpass filter (BPF2); the variation in intensity of this lightwave is then converted to an electrical signal with PD2. In order to improve the signal-to-noise ratio, heterodyne detection (f_2 = 100 MHz) is implemented. The two pulse trains will thus be synchronized, with a frequency difference of 100 MHz.

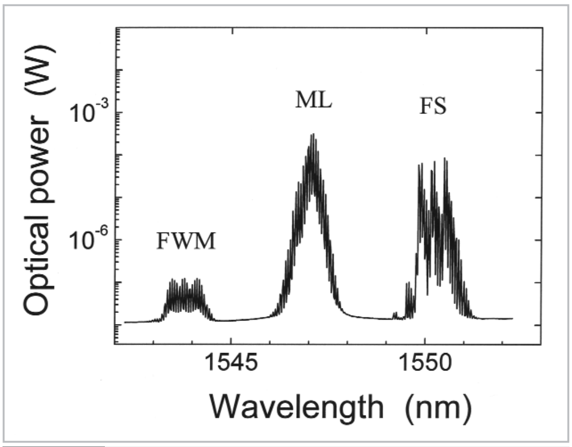

Fig.12 *Optical spectrum of SOA2 output. FS denotes the Fourier-synthesized pulses, MLFL denotes the pulses from a mode-locked fiber laser, and FWM denotes four-wave mixing.*

The repetition frequency of the Fourier synthesized pulses resulting in synchronization is governed by the width of the clock pulse. In our experiment this frequency was 40 GHz, with a pulse width of approximately 8 ps. Figure 12 shows the results of observation of the spectrum of SOA2 output. The FWM signal (anti-Stokes component) was obtained with a conversion efficiency of approximately 0.1%, with fine structures of 8 GHz and 40 GHz due to the cross-gain modulation effect in connection with the SOA2. Figure 13 shows the spectrum of the electrical signal [22] obtained by receiving the Fourier-synthesized optical pulses with a photodetector, which corresponds to the power spectrum of the fundamental frequency component of the pulse envelope. Greater purity in this spectrum indicates a more stable pulse repetition frequency. The dashed line represents the case in which the OPLL2 is not in operation; the spectrum fluctuates significantly, reflecting the frequency fluctuation of the laser operating in free-running mode. The solid line corresponds to the case in which the OPLL2 is operating; a high-purity signal component appears at a frequency of 40.1135 GHz. This frequency is exactly equal to the value of $5f_{ML} + f_2$, indicating that the Fourier synthesized pulses is exactly synchronized to a frequency five times that of the clock pulse plus f_2. Using the spectrum designated by the solid line in Fig.13, phase fluctuation is estimated to be 109 mrad, which translates into the timing jitter of 0.43 ps. Comparison of this value with the ns-level timing jitter seen in cases in which the pulse is out of synchronization attests to the dramatic improvement represented by these results. In addition, the phase-locked state of the pulses can be sustained for periods of over 1 hour.

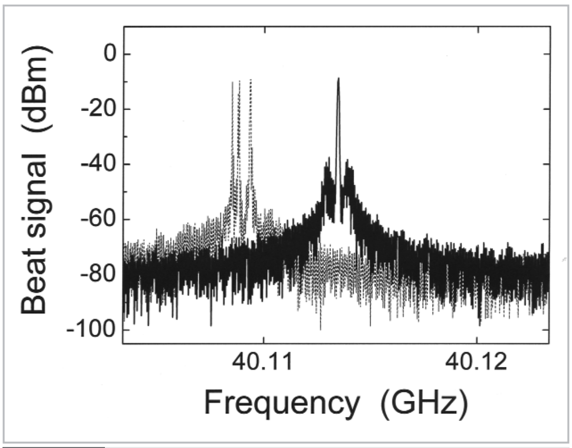

Fig.13 *Comparison of electrical-signal spectra between Fourier-synthesized optical pulses. The solid line designates a state of synchronization; the dashed line designates the non-synchronized state. RBW is 30 kHz.*

5 Arbitrary waveform generation

Above we described experiments in which optical pulses were synthesized using three independent laser lightwaves. When more laser lightwaves are used, synthesis of an arbitrary waveform is enabled. Figure 14 (a) is an illustration of the use of nine laser lightwaves to synthesize an arbitrary 8-bit string consisted of zeros and ones, in this case arranged as {01100111} [23]. The left-hand figure shows the amplitudes and phases of each laser lightwave, and the right-hand figure shows the temporal waveform of the synthesized lightwave. The waveform consists of RZ pulses in which each bit is free from chirp and the optical intensity becomes zero between neighboring bits. Although it is difficult to change such a bit pattern dynamically, this scheme is considered useful in rooting systems or the like, in which the same bit pattern is used repeatedly. Figure 14 (b) presents an example in which a dark pulse train is synthesized. With this particular pulse train, the optical phase at a valley of each dark pulse changes significantly, which is indispensable in exciting a dark soliton. To date it has proven difficult to generate a dark pulse train such as the one shown using methods other than Fourier synthesis.

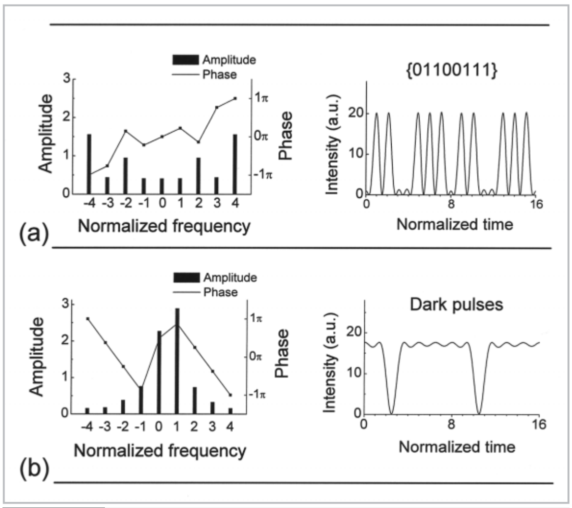

Fig.14 *Results of simulated arbitrary-waveform generation. (a) An arbitrary bit string. (b) A dark pulse train.*

6 Conclusions

In order to generate an ultrafast optical-pulse train - widely viewed as difficult to obtain using conventional methods - we focused attention on the technique referred to as Fourier synthesis, developing a method of generating a stable ultrafast pulse train by superposing three or more independent laser lightwaves. Consequently, we have succeeded in synthesizing ultrafast optical-pulse trains whose repetition frequency can be set to an arbitrary value between 9.6 GHz and 1.8 THz using three semiconductor lasers oscillating in wavelengths in the 1.5-μm range. Moreover, we have demonstrated that the synthesized pulse train can be synchronized with stable external clock pulses, and that such synchronization offers remarkable improvement in terms of stability of the repetition frequency. Moreover, we have proposed a method of synthesizing an arbitrary bit string as well as a dark pulse train, as examples of applications involving the generation of an arbitrary waveform using Fourier synthesis.

The concept behind Fourier synthesis has also been applied to the generation of ultrashort light pulses of durations from femtoseconds to attoseconds, attesting to the versatility and practicality of this technique. Generally, it is often the case that a combination of multiple high-performance apparatuses leads more readily to superior performance than an attempt to develop a single ultra-high-performance device. The application of Fourier synthesis is fully consistent with this approach to design. In closing, this study focused on the generation of an ultrafast pulse train with a view to applications in light sources for optical communications. In this context, the use of a mode-locked laser as a light source for Fourier synthesis must eventually allow for pulse width to be readily shortened; future research on this issue thus merits significant attention.

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