

Rapidly frequency-swept optical beat source for continuous wave terahertz generation

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Abstract: We propose a rapidly frequency-swept optical beat source for continuous wave (CW) THz generation using a wavelength swept laser and a fixed distributed feedback (DFB) laser. The range of the sweeping bandwidth is about 17.3 nm (2.16 THz), 1541.42–1558.72 nm. The achieved side mode suppression ratio for both wavelengths within the full sweeping range is more than 45 dB. We observe CW THz signals for tunable optical beat sources using a fiber coupled CW THz measurement system to confirm the feasibility of using our frequency swept optical beat source as a CW THz radiation source. The THz output signal falls to the thermal noise level of the low-temperature grown (LTG) InGaAs photomixer beyond 1.0 THz. The rapidly frequency-swept optical beat source will be useful for generating high-speed tunable CW THz radiation.

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1. Introduction

THz technologies have many potential applications in biomedical imaging, organic inspection, gas sensing, and spectroscopy [1–10]. In particular, the high-speed scanning THz spectrometer has been attracting attention because of its real-time processing. The THz spectrometer has mainly been demonstrated with a femto-second pulse laser in time-domain spectroscopy [4–6]. However, the high-speed scanning THz spectrometer is not easy to demonstrate in the time domain because of the signal process time. On the other hand, a frequency-domain THz spectrometer is a good candidate technology for a high-speed scanning THz spectrometer using a continuous frequency-tunable THz source [7,8]. The tunable optical beat source holds promise as a source of continuously tunable THz radiation. It is typically composed of two tunable distribution feedback (DFB) or distributed Bragg reflector (DBR) laser diodes (LDs) with different operation wavelengths [7,8], [11–15]. Recently, we reported a monolithic 1.55- μm multi-section dual-mode DFB laser and a widely tunable dual wavelength erbium-doped fiber laser as a compact optical beat source for tunable continuous wave (CW) THz radiation [9,10]. However, the high-speed continuous tuning of the optical beat frequency has not yet been realized. For practical application in a real-time measurement THz spectrometer, a wide range of THz radiation should be realized using high-speed continuous tuning. In order to tune the optical beat frequency electronically and continuously, we propose a frequency-scanning optical beat source that consists of a wavelength-swept laser and a fixed DFB laser. Generally, a wavelength-swept laser is used as an optical source for Fourier domain optical coherence tomography or dynamic optical fiber sensors [16–20]. This has been demonstrated by the use of a narrowband wavelength-scanning filter in a laser cavity such as in a fast rotating polygonal mirror, a diffraction grating on a Galvanometer scanner, and a fiber Fabry-Perot tunable filter (FFP-TF). Among these, a conventional wavelength-swept laser with FFP-TF is a promising technique because it does not require any optical alignment with bulk optics.

To the best of our knowledge, this is the first paper to describe a rapidly frequency-swept THz optical beat source consisting of a fiber-based wavelength-swept laser and a fixed DFB laser. A wide bandpass filter is employed in the laser cavity in order to obtain a flat intensity within the bandpass region from the wavelength-swept laser. A sweeping bandwidth of about 17.3 nm is achieved, which corresponds to a sweeping frequency of 2.16 THz, from 1541.42 nm to 1558.72 nm. The achieved side mode suppression ratio (SMSR) of the swept laser is over 45 dB. Furthermore, we measure CW THz waveforms using our developed optical beat source in a fiber-coupled CW THz measurement system.

2. Experiments

Figure 1 shows the experimental setup for frequency swept optical beat source generation using a wavelength-swept laser and a fixed DFB laser. The wavelength-swept laser has a conventional ring laser structure consisting of a 1550-nm semiconductor optical amplifier (SOA), two isolators, a polarization controller (PC), a scanning FFP-TF, a wide bandpass filter 1 (W-BPF 1), and a 30% output coupler. The scanning frequency applied to the FFP-TF is 1 kHz. The output of the wavelength-swept laser is combined with the fixed DFB laser through a 3-dB fiber coupler. Therefore, a frequency swept optical beat source can be obtained. One port of the 3-dB fiber coupler goes to an autocorrelator to measure the optical beat waveform, while the other goes to an optical spectrum analyzer (OSA) to measure the optical spectrum. The center wavelength of the fixed DFB laser is 1559.66 nm. The scanning FFP-TF has a free spectral range of ~160 nm at 1500 nm and an instantaneous linewidth of ~0.15 nm. The optical spectrum is measured using the peak hold mode in the OSA at a resolution bandwidth of 1.0 nm. The W-BPF 1 provides a flat output for the spectral-limited wavelength-swept laser. The bandwidth of the W-BPF 1 is about 19 nm, from 1540.5 nm to 1559.5 nm. In order to measure the autocorrelation trace of the optical beat source, the static voltage from the dc power supply, instead of the function generator, is applied to the FFP-TF. Then, the wavelength-swept laser has a static output wavelength at a certain voltage. Thus, a static optical beat source with a fixed DFB laser can be achieved. The frequency of the optical beat source can be tuned by changing the static voltage applied to the FFP-TF.

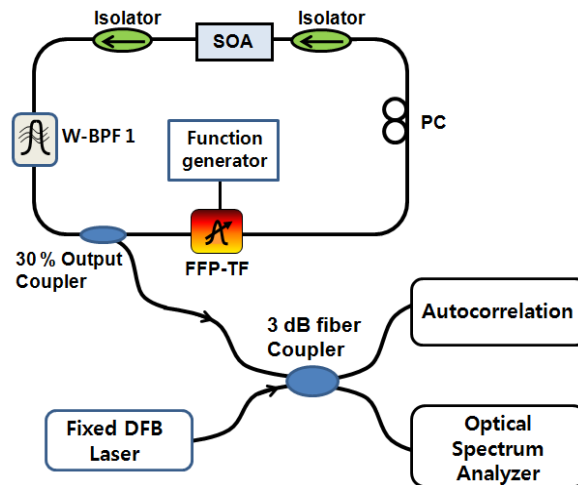


Fig. 1. Configuration of experimental setup for frequency-scanning optical beat source.

The optical spectrum of the wavelength-swept laser without the W-BPF 1 is shown in Fig. 2(a). The full scanning 3-dB bandwidth is about 134 nm, from 1465 nm to 1599 nm. When the W-BPF 1 is inserted into the laser cavity, the output spectrum is limited to within the bandpass region, as shown in Fig. 2(b). Figure 2(b) shows the optical spectrum of the frequency swept optical beat source between the spectrum-limited wavelength-swept laser and the fixed DFB laser. The scanning frequency of the optical beat source is 1 kHz, which is same as that of the wavelength swept laser. The bandwidth of the spectrum-limited wavelength-swept laser is ~19 nm, which is the result of the W-BPF1. The right peak in Fig. 2(b) represents the output of the fixed DFB laser at 1559.66 nm. The SMSR is over 45 dB in the case of both lasers. The output of the 3-dB fiber coupler in Fig. 1 will deliver the frequency-scanning optical beat sources.

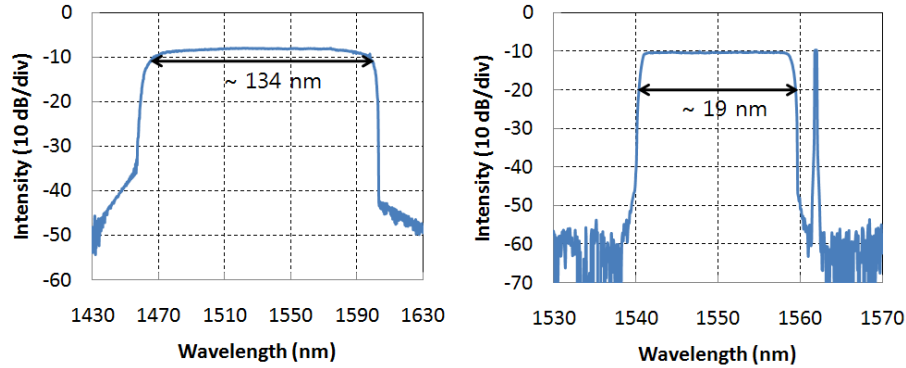


Fig. 2. (a) Optical spectrum of wavelength-swept laser and (b) output spectra of spectrum-limited wavelength-swept laser and fixed DFB laser.

In order to measure the autocorrelation trace of the optical beat source of our system, the output of the optical beat source needs to be static. A static output can be obtained for the spectrum-limited wavelength-swept laser by applying a static voltage to the FFP-TF. With changing the static voltage to the FFP-TF, the static wavelength can be changed continuously. Figure 3(a) shows the sweeping range of the spectrum-limited wavelength-swept laser. It can be swept over 17.3 nm, from 1541.42 nm to 1558.72 nm. The corresponding sweeping frequency range is 2.16 THz. The wavelength of the right peak in Fig. 3(a) represents the output of the fixed DFB laser, which is 1559.66 nm. Figure 3(b) shows the optical spectra of three cases for the static optical beat source. The intervals of the spectra at the top, middle, and bottom are 1.76 nm, 3.6 nm, and 7.92 nm, respectively. These correspond to 0.22 THz, 0.45 THz, and 0.99 THz, respectively. The SMSR of the static wavelength is almost 50 dB, as shown in Fig. 3(b). The autocorrelation traces of these three static beat frequencies are measured, as shown in Fig. 3(c). The autocorrelation trace of the optical beating signal frequency depends on the polarization states of two optical inputs. The linewidth of the wavelength swept laser is an important factor to analyze the performance of the frequency swept optical beat source. The measured instantaneous linewidth of the wavelength swept laser is less than 0.1 nm. Even though the output of the wavelength-swept laser does not have a single longitudinal oscillation mode, the beat frequency between the static output of the wavelength-swept laser and a fixed DFB laser can be achieved, as shown in Fig. 3(c).

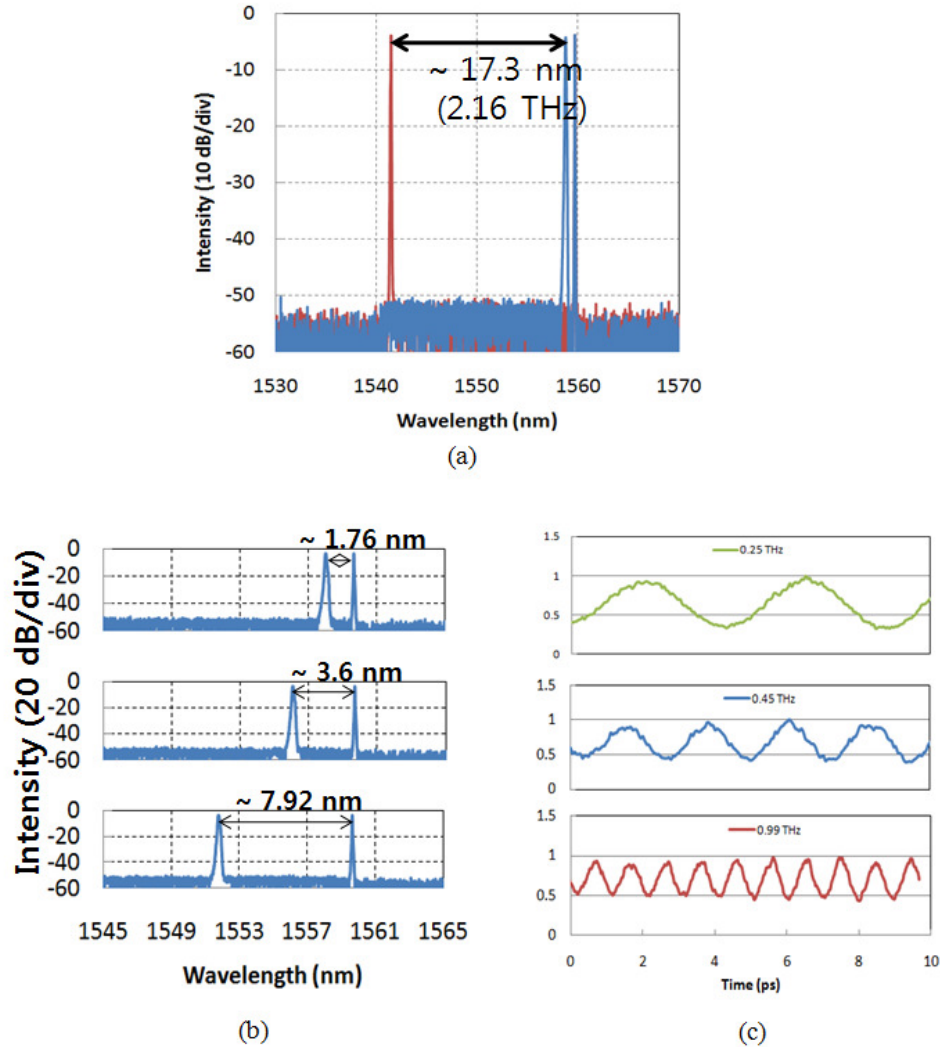


Fig. 3. (a) Sweeping range of spectrum-limited wavelength-swept laser, (b) optical spectra of three static optical beat sources, and (c) autocorrelation traces of their beat frequencies.

In order to confirm the feasibility of using our frequency swept optical beat source as the THz radiation for frequency-domain THz spectroscopy, a fiber-coupled CW THz measurement system is constructed, as shown in Fig. 4. This THz measurement system consists of an erbium-doped fiber amplifier (EDFA), isolator, optical wide bandpass filter 2 (W-BPF 2), 1×2 optical splitter, emitter, detector, computer-controlled delay line, function generator, and lock-in amplifier. The lock-in amplifier is used to enhance the detection sensitivity. The emitter or receiver module is composed of a hyper-hemi-spherical Si lens, a log-spiral antenna-integrated low-temperature grown (LTG) InGaAs photomixer chip electrically mounted on a printed circuit board, and a fiber assembly. In order to measure the THz radiation signal, the static optical beat source is used as previously discussed. Therefore, the static voltage from a dc power supply is applied to the FFP-TF in the wavelength-swept laser to generate a static optical beat source. The optical beat source from the 3-dB fiber coupler is launched into the EDFA after an optical isolator to increase the output power to 15 dBm. The amplified spontaneous emission (ASE) noise from the EDFA is filtered out using

optical W-BPF 2. A single mode fiber coupled emitter and receiver made of our LTG-InGaAs photomixers are used to generate and detect THz radiation, respectively.

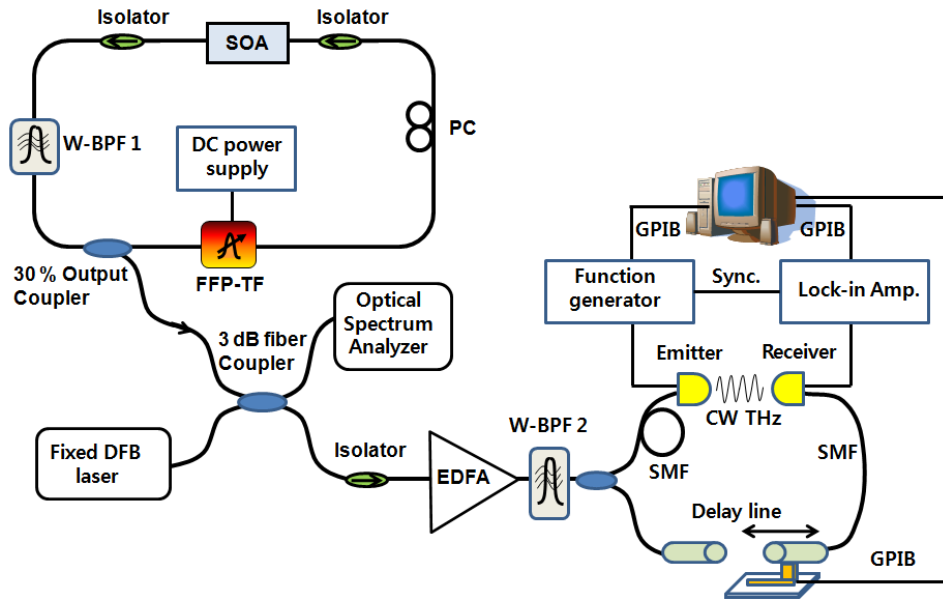


Fig. 4. Experimental setup for CW THz measurement system using frequency swept optical beat source; W-BPF: wide-bandpass filter; PC: polarization controller; FFP-TF: Fiber Fabry-Perot tunable filter; EDFA: erbium doped fiber amplifier; SOA: semiconductor optical amplifier; SMF: single mode fiber

The frequency-swept optical beat sources as the CW THz generation are launched into the CW THz measurement system to measure the THz radiation output signal. The photocurrent in the LTG-InGaAs emitter is measured using a lock-in amplifier at a modulation frequency of 11 kHz. The dark resistance of the photomixer, the total optical input power, and the operation bias voltage on the photomixer are $\sim 10 \text{ k}\Omega$, $\sim 30 \text{ mW}$, and 1.2 V, respectively. Figure 5 shows the continuous frequency tuning of the CW THz radiation emitted from the fabricated LTG-InGaAs photomixers using the frequency swept optical beat source. The CW THz frequency is tuned from 0.3 to 1.0 THz with 4.5 GHz step. The THz output signal falls to the thermal radiation level of the LTG-InGaAs photomixer beyond 1.0 THz. This is caused by the long carrier lifetime of the homemade LTG-InGaAs layer as well as the background ASE from the EDFA. In CW-THz measurement, integration and acquisition time of 1 s / 2 s for each point are used. Figures 6(a-d) show the measured several THz waveforms of 350 GHz, 460 GHz, 820 GHz, and 1.15 THz, respectively. In the Fig. 6(d), the amplitude of THz waveform is almost same as the noise level. Note that the THz radiation can be detected even though the wavelength-swept laser has multi-longitudinal mode oscillation.

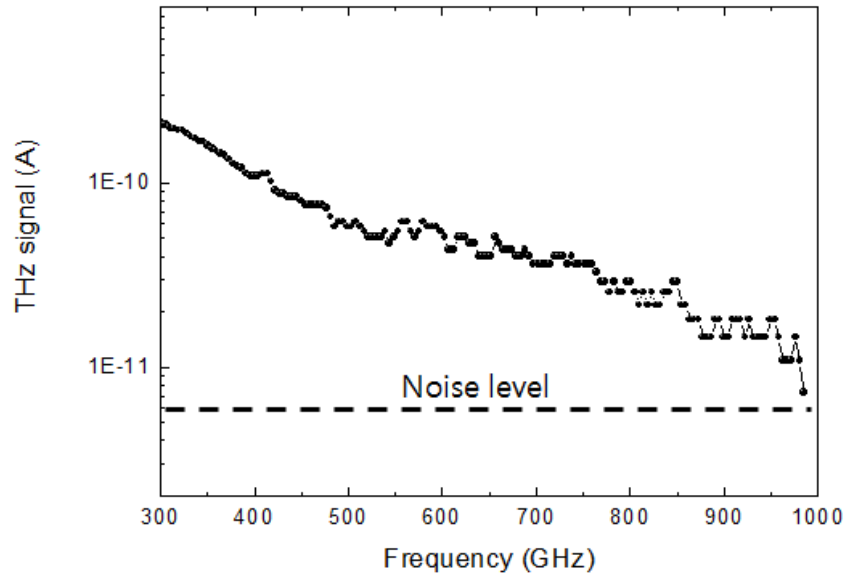


Fig. 5. Frequency tuning characteristic of THz emission from LTG-InGaAs photomixers illuminated by the frequency swept optical beat sources (steps 4.5 GHz)

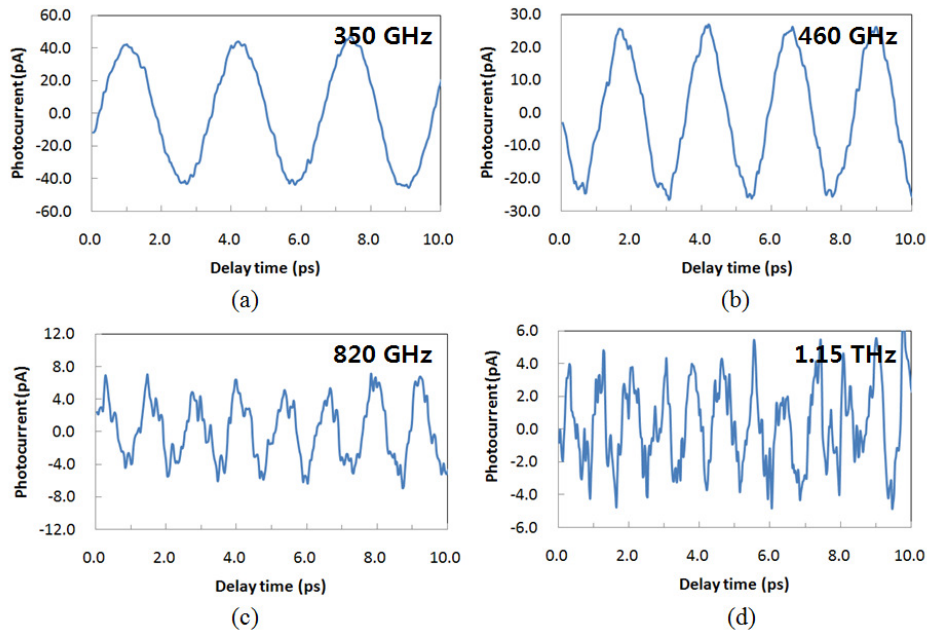


Fig. 6. Measured THz waveforms of (a) 350 GHz, (b) 460 GHz, (c) 820 GHz, and (d) 1.15 THz.

3. Summary

We successfully demonstrated the rapidly frequency-swept optical beat source generation of CW THz radiation using a spectrum-limited wavelength-swept laser and a fixed DFB laser.

The sweeping range was over 17.3 nm, which corresponded to a sweeping frequency of 2.16 THz. The side mode suppression ratio achieved was more than 45 dB for both lasers. We measured THz output signals from the frequency swept optical beat sources using a fiber-coupled CW THz measurement system. The THz output signal fell to the thermal radiation level of the LTG-InGaAs photomixer beyond 1.0 THz. We confirmed that if high-speed signal processing is provided, our frequency-scanning optical beat source could be useful in frequency-domain CW THz spectroscopy.

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