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## **Optical beat-note frequency stabilization between two lasers using a radio frequency interferometer in the gigahertz frequency band**

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# Optical beat-note frequency stabilization between two lasers using a radio frequency interferometer in the gigahertz frequency band

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**Abstract.** A beat-note frequency stabilization system using a distributed-feedback laser and external cavity laser diode has become a very important technique for laser spectroscopy, where highly stabilized high-frequency beat notes are required. We have developed a simple and versatile system capable of stabilizing the high-frequency beat notes (3 to 11 GHz) of two lasers using a delayed radio frequency self-heterodyne interferometer and have confirmed its basic operation. The frequency stability of the obtained beat notes is higher than 1 MHz in the 3- to 11-GHz frequency range with an average time of 20 s. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.53.12.124109](https://doi.org/10.1117/1.OE.53.12.124109)]

Keywords: radio frequency self-heterodyne interferometer; beat note; frequency stabilization; photonic generation.

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## 1 Introduction

Frequency-tunable and frequency-stable microwave sources are becoming increasingly important in the fields of measurement/spectroscopy and communications. Microwave signals are usually generated using complicated electronic circuits with multistep frequency multiplication to obtain the desired frequency signal. In contrast to the complicated conventional electronic method, optical generation of microwave signals using optical beat-note generation, i.e., optical heterodyning using two optical sources, with ultrafast photodetectors (PDs)<sup>1</sup> can be performed with simple experimental apparatuses. However, since the frequency of the generated microwave signal directly corresponds to the frequency difference between the two optical sources, frequency fluctuation may arise if the optical sources are unstable. To generate stable microwave signals, the beat-note frequency of the two optical sources used for optical heterodyning must be stabilized. Optical phase-locked loop (OPLL) is a widely used method for beat-note frequency stabilization. In OPLL, the target signal frequency is locked to a stable reference frequency generated by a radio frequency (RF) synthesizer. Using this technique, two independent lasers can be offset locked in atomic spectroscopy.<sup>2-6</sup> The OPLL is also used in ion optical clocks<sup>7,8</sup> for quantum information processing, power combination of high-power lasers,<sup>9</sup> and microwave photonics.<sup>10-13</sup> In previous studies, several other techniques have been used to obtain highly stable and low-phase noise beat notes such as two-mode optical cavity atomic resonances<sup>14</sup> and injection locking schemes.<sup>8</sup> The frequency stabilities of these systems are less than 1 Hz for the best performance, when the stable frequency reference (e.g., ultralow expansion glass optical cavity and ultrastable oscillator) is used. However, these systems require complicated circuits and/or special optical devices

as required in OPLL and the locking range is narrow. The typical locking range of these systems is several megahertz.

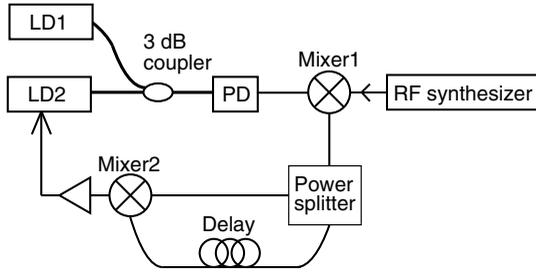
Recently, technological developments in electronics have enabled simple frequency stabilization schemes in high-frequency regions suitable for photonic microwave generation.<sup>15,16</sup> Recently developed circuits can generate microwaves at 810 MHz using a simple technique; however, they have not yet been used to generate a beat note in the gigahertz frequency region.

In this paper, we propose and demonstrate the photonic generation of stabilized microwave frequency signals ranging from 3 to 11 GHz using a loop filter with a delayed RF interferometer. The locking characteristics of the loop filter can be optimized with the help of the interferometer. As a result, compared with the previously reported systems, the frequency locking range of our system extends to several hundred megahertz, while a simpler operation is achieved in the proposed configuration. The frequency stability obtained in our system is higher than 1 MHz, which is sufficient for photonic RF signal generation (e.g., phased array antenna using photonic-generated RF signals<sup>1</sup>) or basic spectroscopic applications. Further improvement of frequency stability, i.e., higher than 10-kHz range stability, will be possible by using a narrow linewidth laser instead of the distributed-feedback laser used in our system.

## 2 Principle

A schematic for beat-note frequency stabilization is shown in Fig. 1. The purpose of this experiment is to demonstrate the stabilization of the beat note generated by two lasers (LD1 and LD2) to generate a highly stable synthesizer signal. An RF self-heterodyne interferometer is introduced to control the locking characteristics of the servo loop. An error signal proportional to the frequency difference between the beat- and RF synthesizer-signals is converted to a DC signal and applied to LD2 to control its frequency.

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**Fig. 1** Schematic of beat-note frequency stabilization by means of a radio frequency (RF) self-homodyne interferometer. PD: photodetector; LPF: low pass filter.

The RF signal intensity,  $I$ , generated by PD, is proportional to the intensity of the incident light and can be expressed as

$$\begin{aligned} I &\propto |E_1 \cos(\omega_1 t) + E_2 \cos(\omega_2 t)|^2 \\ &= E_1^2 \cos^2(\omega_1 t) + E_2^2 \cos^2(\omega_2 t) \\ &\quad + 2E_1 E_2 \cos(\omega_1 t) \cos(\omega_2 t), \end{aligned} \quad (1)$$

where  $E_1$  and  $E_2$  are the amplitudes of the electric fields of the two beams of light with frequencies  $\omega_1$  and  $\omega_2$ , respectively. By eliminating the DC components in Eq. (1), an RF signal component from the PD,  $I_{\text{RF}}$ , can be obtained as

$$\begin{aligned} I_{\text{RF}} &\propto 2E_1 E_2 \cos(\omega_1 t) \cos(\omega_2 t) \\ &= E_1 E_2 \cdot \{\cos[(\omega_1 - \omega_2) \cdot t] + \cos[(\omega_1 + \omega_2) \cdot t]\} \\ &\approx E_1 E_2 \cdot \{\cos[(\omega_1 - \omega_2) \cdot t]\}. \end{aligned} \quad (2)$$

Since the second term in Eq. (2) represents the higher frequency component and is outside the PD bandwidth, the component cannot be detected by the PD. Thus, only the low-frequency component [i.e., Eq. (3)] can be observed. In the following discussion,  $|\omega_1 - \omega_2|$  is expressed as  $\Delta\omega$  and corresponds to the beat-note frequency.

To stabilize the beat-note frequency to a reference frequency of the synthesizer, the synthesizer signal with frequency  $\omega_{\text{Synth}}$  is multiplied by the beat signal using a frequency mixer. As a consequence of the multiplication, oscillating signals with two frequency components are generated, as indicated in Eq. (4). Because the frequency component  $\Delta\omega + \omega_{\text{Synth}}$  is higher than the cut-off frequency of Mixer1, we can use the last term [Eq. (5)], which is proportional to  $\Delta\omega - \omega_{\text{Synth}}$ , to obtain an error signal

$$\begin{aligned} \cos(\Delta\omega \cdot t) \cdot \cos(\omega_{\text{Synth}} \cdot t) &= \frac{1}{2} \{\cos[(\Delta\omega - \omega_{\text{Synth}}) \cdot t] \\ &\quad + \cos[(\Delta\omega + \omega_{\text{Synth}}) \cdot t]\} \\ &\approx \frac{1}{2} \{\cos[(\Delta\omega - \omega_{\text{Synth}}) \cdot t]\}. \end{aligned} \quad (4)$$

The signal proportional to  $\Delta\omega - \omega_{\text{Synth}}$  is transformed into a DC signal for frequency stabilization used in the feedback loop. This is done by splitting the signal with  $\Delta\omega - \omega_{\text{Synth}}$  frequency into two equal components and

multiplying them by Mixer2 (bandwidth: 200 MHz), while one signal passes through an additional delay line. A coaxial cable is used as a delay line to create a delay time  $\tau$  (5 ns for a 1-m cable) between the two signals. The delay time  $\tau$  is equivalent to a phase shift  $\phi$  of  $\tau \cdot (\Delta\omega - \omega_{\text{Synth}})$ . The output signal  $S$  from Mixer2 is

$$\begin{aligned} S &\propto \cos[(\Delta\omega - \omega_{\text{Synth}}) \cdot t] \cdot \cos[(\Delta\omega - \omega_{\text{Synth}}) \cdot t + \phi] \\ &= \frac{1}{2} \{\cos \phi + \cos[2(\Delta\omega - \omega_{\text{Synth}}) \cdot t + \phi]\}. \end{aligned} \quad (6)$$

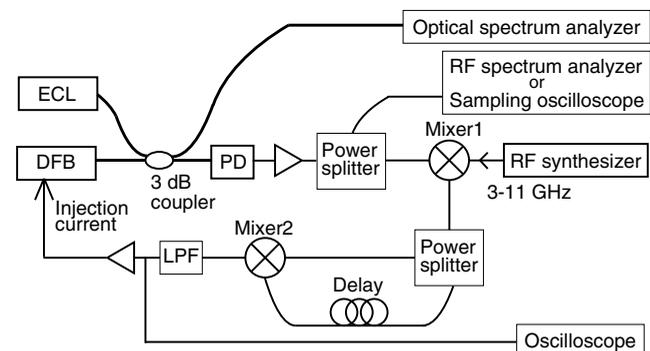
Equation (6) consists of a DC part proportional to the phase shift and an AC part, which can be filtered out by a low pass filter (LPF). As a result, the error signal is obtained as

$$\begin{aligned} S &\propto \cos \phi \\ &= \cos[\tau \cdot (\Delta\omega - \omega_{\text{Synth}})]. \end{aligned} \quad (7)$$

By scanning the frequency of LD1 or LD2 (i.e., changing  $\Delta\omega$ ), the error signal traces a cosine curve with a finite width corresponding to the bandwidth of Mixer2. The error signal has several zero crossing points, and one of these points is used as a locking point. The neighboring locking points are separated by  $2\pi/\tau$ . By changing the cable length  $l$  of the delay line, the locking points and the slope at the zero crossing points can be changed. The locking bandwidth is given by approximately  $2\pi/\tau$ , so a shorter delay line gives a wider locking bandwidth and lower discrimination gain (i.e., derivative of the error signal at the zero crossing point), and vice versa.

### 3 Experiment

The experimental setup of the photonic generation of an RF signal in the gigahertz region is shown in Fig. 2. An external cavity diode laser (ECL) and a distributed feedback (DFB) laser are used as optical sources to create an optical beat note. The ECL (Photonics: TUNICS-PRI, linewidth: 0.5 MHz) is used for coarse tuning of the beat-note frequency, since its tuning range is wide (approximately 16 THz, corresponding to 1470 to 1599 nm). The DFB (Fitel: FRL15DCWx-A8x-W1510, linewidth: 3.3 MHz) laser is used for fine tuning of the beat frequency, together with the servo system, since its optical frequency can be controlled by an injection current. The optical output signals of the ECL and the DFB laser are



**Fig. 2** Experimental setup. PD: photodetector; LPF: low pass filter.

combined by a  $2 \times 2$  3-dB coupler. One of the output optical signals from the coupler is measured by an optical spectrum analyzer (Advantest, U3772). The beat note (the other output signal from the coupler) is detected by a fast (typically 40-GHz) photodiode (Picometrix, P-40HPA) and converted to an RF signal. The RF signal is amplified by RF amplifiers (Avantec, APT10566 and Anritsu, A3HB3102) to the range between  $-10$  and  $+4$  dBm. The amplified signal is subsequently divided by a power splitter (Anritsu, K241C). One of the divided signals is measured by an RF spectrum analyzer or a sampling oscilloscope, while the other is mixed with the output of an RF synthesizer (Anritsu, MS9030A +MS9703) using a frequency mixer (Mini Circuits, ZX05-153+). The bandwidth of the mixer (3 to 15 GHz) is sufficient for photonic generation in the 10-GHz range. The signal, generated by mixing the beat note and RF synthesizer output, is split by a power splitter (Anritsu, K241C). One of the split signals is delayed by a coaxial cable (Hitachi Cable, MW3.00-FF-3000; length, 3 m) and multiplied by another split signal using a mixer (Mini Circuits, ZLW-3+, bandwidth: 200 MHz). The mixed signal is then amplified and used as an error signal for a feedback system. The residual RF component created by the down conversion process is eliminated by a 5-MHz LPF placed before the amplifier.

**4 Results**

Figure 3 shows the measured optical spectra of the ECL and DFB laser using an optical spectrum analyzer (Advantest, Q8384). The wavelengths of the ECL and DFB laser are 1549.18 and 1549.26 nm, respectively. Using an RF spectrum analyzer, the measured frequency of the generated beat note is obtained as 9.983 GHz, as shown in Fig. 4. The obtained beat-note frequency is consistent with the difference between the two optical frequencies of the ECL and DFB laser. When the frequency of the ECL is scanned over 1 GHz, the beat-note frequency is also swept together with the frequency of ECL. According to Eq. (7), this results in a cosine variation of the error signal.

Figure 5 shows the measured results of the error signal as a function of  $\Delta\omega - \omega_{\text{Synth}}$  using an oscilloscope. In the servo loop, one of the zero crossing points of the error signal is used to lock the frequency difference between the ECL and DFB laser. A proportional integral derivative servo (bandwidth: 10 kHz) is used to control the injection current of the DFB laser. When the servo loop is closed, the beat

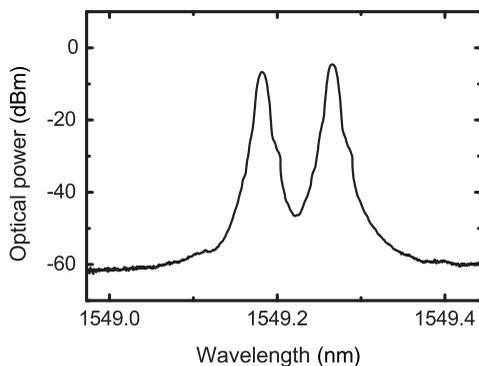


Fig. 3 Optical spectrum of ECL and DFB laser.

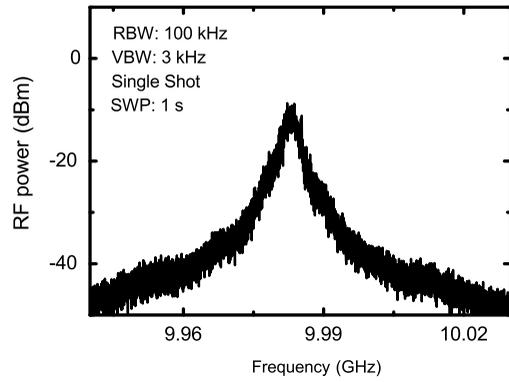


Fig. 4 Beat note generated from the two lasers.

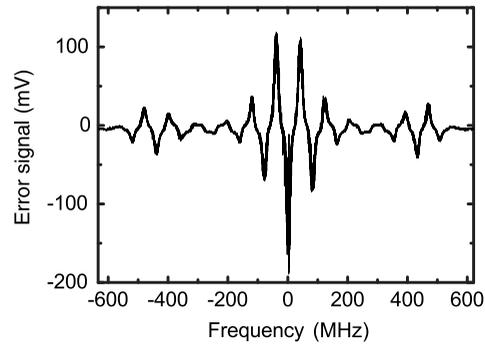


Fig. 5 Error signal.

frequency spectrum becomes stable, as shown in Fig. 6. For comparison, a measured free running beat frequency spectrum is shown in Fig. 7. The drift of the beat frequency is estimated to be around 22 MHz. To investigate the effect of our stabilization method, the time-domain beat note is measured by a sampling oscilloscope.

Figures 8 and 9 show the measured sampling oscilloscope traces with frequency stabilization with 2-event averaging (Fig. 8) and 100-event averaging (Fig. 9). The sampling scope was self-triggered by a beat-note RF signal. In each figure, three traces are measured at 60-s intervals, three times. As shown in these figures, the three traces almost overlap, which is clear evidence that a stable beat signal has been successfully generated in our system. From these

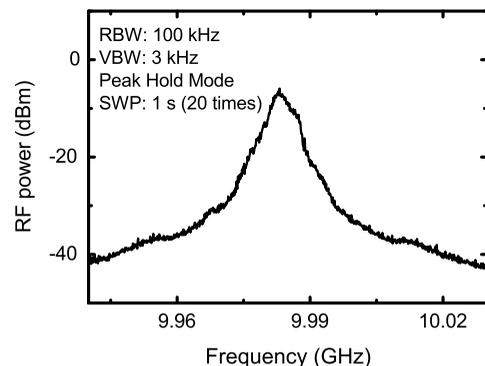


Fig. 6 Beat note with frequency stabilization.

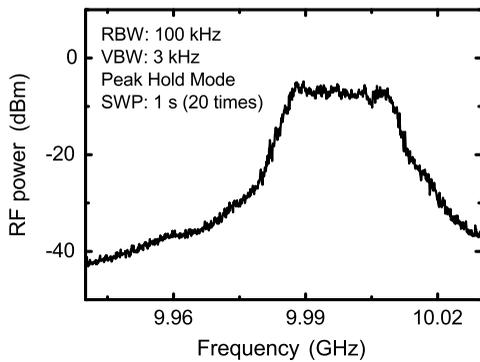


Fig. 7 Beat note without frequency stabilization.

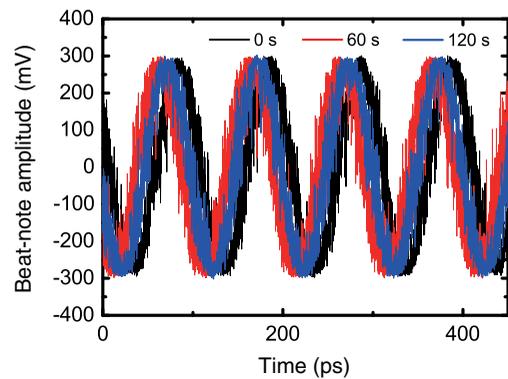


Fig. 10 Beat note without frequency stabilization measured by a sampling oscilloscope (2-event averaging).

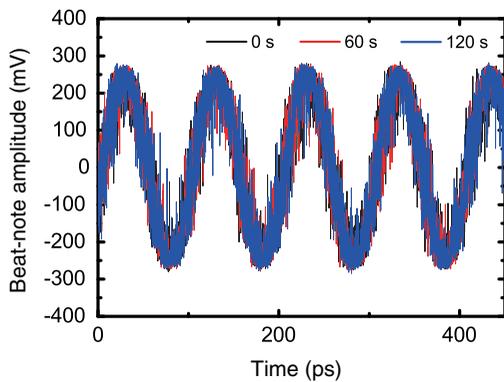


Fig. 8 Beat note with frequency stabilization measured by a sampling oscilloscope (2-event averaging).

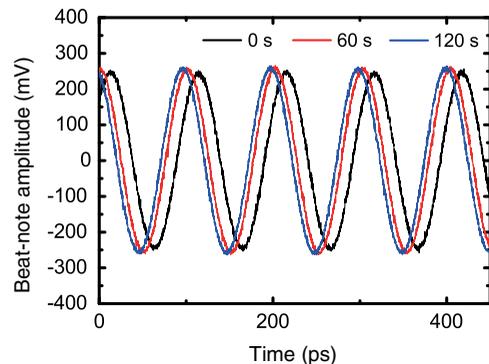


Fig. 11 Beat note without frequency stabilization measured by a sampling oscilloscope (100-event averaging).

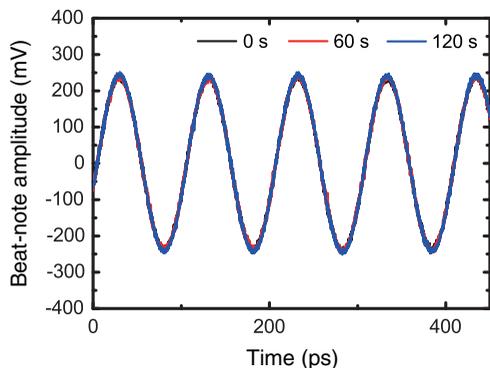


Fig. 9 Beat note with frequency stabilization measured by a sampling oscilloscope (100-event averaging).

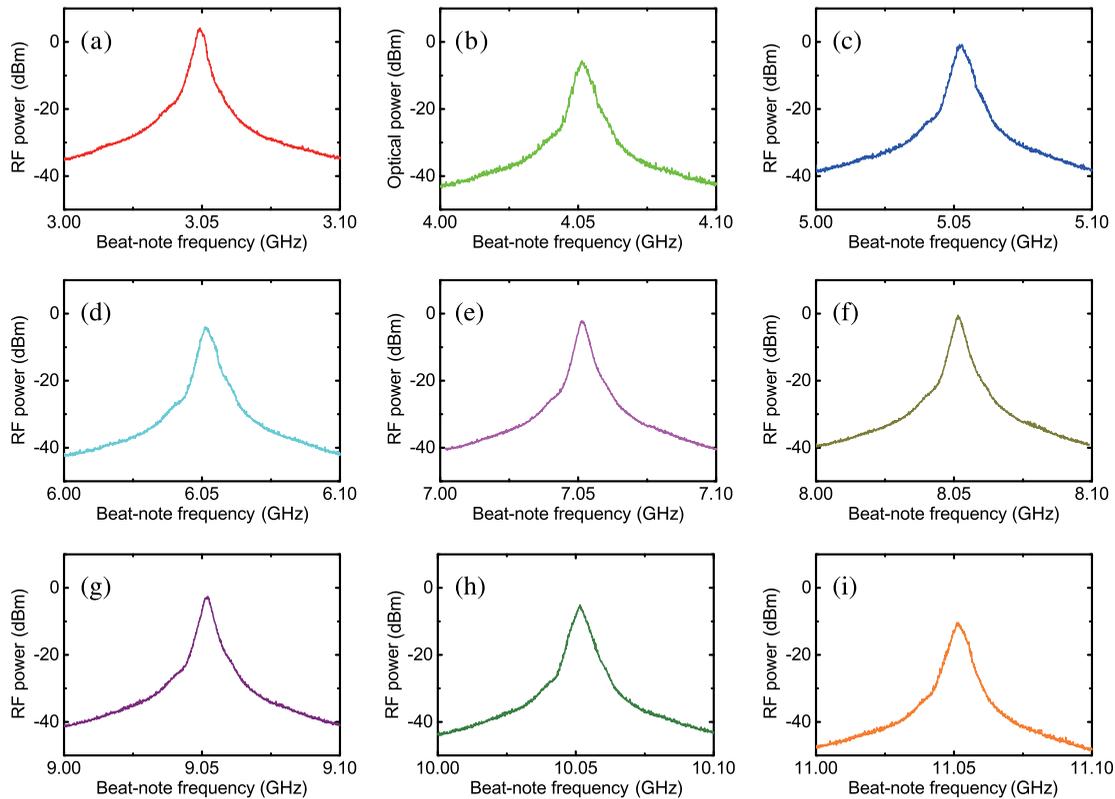
figures and the RF spectrum shown in Fig. 6, it can be concluded that the frequency noise of the beat note is reduced to almost the same level as the frequency noise of the RF synthesizer. The same measurements were then performed for the beat signal without frequency stabilization.

Figures 10 and 11 show the measured sampling scope traces of the beat signal without frequency stabilization, corresponding to Figs. 8 and 9, respectively. Compared with a beat note which is frequency stabilized to the RF synthesizer signal, the beat note without frequency stabilization shown in Figs. 10 and 11 has drifted. This can be explained as follows.

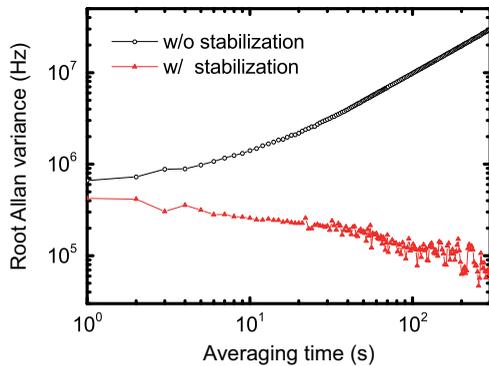
Without the frequency stabilization, the frequency of the ECL drifts, as shown in the beat-note RF spectrum (Fig. 7). In this situation, it is likely that the phase of the laser light shifts/jumps randomly over time. A simple mathematical calculation shows that the phase of the beat note is closely linked with the phase difference between the two optical sources used for the beat-note generation. Thus, when the phase of the RF beat signal changes because of the unstable optical phase of the laser light, the trigger timing may be changed for self-triggered oscilloscope measurements. This may be the reason for the drifting scope traces shown in Figs. 10 and 11.

The similarity between the frequency-stabilized beat notes from 3 to 11 GHz is shown in Fig. 12, and the frequency stability at 10-GHz RF synthesizer frequency is shown in Fig. 13. Frequency fluctuations observed in these beat notes are less than 1 MHz over an average time of 20 s and are currently limited by the linewidth of the DFB laser. The frequency stability of the beat note was also measured using an RF spectrum analyzer. The long-term stability is improved by 1/100 compared with the free running operation.

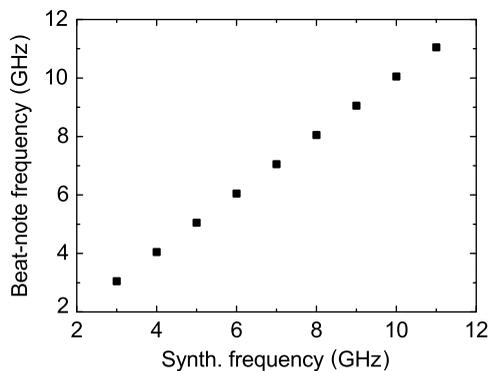
To confirm the locking characteristics of the beat note frequency on the external RF signal, locked beat-note frequencies were measured as a function of the RF synthesizer frequency. The results, shown in Fig. 14, demonstrate that from 3.05 to 11.05 GHz, the beat-note frequency is precisely locked to the RF synthesizer frequency.



**Fig. 12** Beat note between two lasers in frequency stabilization. RF synthesizer frequency set at (a) 3 GHz, (b) 4 GHz, (c) 5 GHz, (d) 6 GHz, (e) 7 GHz, (f) 8 GHz, (g) 9 GHz, (h) 10 GHz, and (i) 11 GHz.



**Fig. 13** Frequency stability of generated beat note at 10-GHz RF synthesizer frequency.



**Fig. 14** RF-synthesizer frequency versus beat-note frequency.

### 5 Summary

We have developed and demonstrated a simple and versatile system to generate RF signals using optical beat generation. Since the frequency of the generated RF signal, which corresponds to the frequency difference between the two lasers, is locked to the stable external RF signal, it is not necessary to achieve absolute frequency locking of the lasers used in the beat-note generation. In our experiments, the beat-note frequency between the ECL and DFB laser is stabilized within the range 3 to 11 GHz using a delayed RF self-homodyne method combined with the stable reference frequency of the RF synthesizer. The beat-note frequency fluctuation is reduced to 1/20 (short term) and 1/100 (long term) compared with the fluctuation obtained by free running lasers. The proposed system will be applicable to stable and tunable gigahertz frequency range photonic generation of RF signals.

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