

Frequency stabilization of two orthogonally polarized external cavity laser diodes using a novel γ -type optical configuration consist of a phase modulator and a Faraday rotator mirror

Tomoyuki Uehara^{a)}, Kohei Hagiwara, Toshihide Tanigaki, Kenichiro Tsuji, and Noriaki Onodera

Department of Communications Engineering, National Defense Academy of Japan, 239–8686, Japan

a) uehara@nda.ac.jp

Abstract: We propose a novel method to stabilize two external cavity lasers for optical generation of microwave and millimeter wave signals. In our method, two 1550-nm, servo-locked external cavity laser diodes (ECLDs) are simultaneously locked to two resonance frequencies of a single Fabry-Perot optical cavity. The stabilization of two lasers are realized by introducing classical FM sideband technique. In γ -type optical configuration, two wavelengths from the ECLDs with orthogonal polarization are simultaneously phase modulated by a phase modulator with a Faraday rotator mirror. The γ -type optical configuration is designed as a compact, stable and double-pass phase modulation apparatus with same modulation index for two orthogonally polarized signals transmitted through a polarization maintaining fiber. We obtain short-term stability of 200 kHz at an averaging of 10 ms, which is measured with the square root of the Allan variance from the beat note between frequency stabilized lasers.

Keywords: photonic generation, microwave, FM sideband technique, frequency stabilization, γ -type configuration

Classification: Optoelectronics, Lasers and quantum electronics, Ultrafast optics, Silicon photonics, Planar lightwave circuits

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1 Introduction

Recently, the generation of electrical signals using photonic techniques have attracted great interest for its possibilities in wide variety applications [1, 2]. Photonic approaches are suitable for high frequency electrical signal generation since various high speed optical devices, such a photodetectors and intensity/phase modulators, have been developed and widely available. Additionally, polarization of optical waves can be easily controlled and transmitted using various optical components and fibers employed in optical communication systems. Therefore, the photonic approaches are very attractive methods for obtaining versatile micro- or millimeter wave signals. The easiest and costeffective way to generate phase-coded micro- or millimeter waves [3] would be the beat-note generation between two lasers. However, wavelength fluctuations of these two lasers make the generated electrical signal unstable. It is well known that in laser cooling or trapping experiments, lasers are stabilized to an atomic or a cavity resonance frequency [4, 5]. Since only one laser is used as a light source in these experiments, the frequency stabilization is required only for the laser with one reference frequency. On the other hand, in applications of photonic micro- or millimeter wave signal generation using beat note generation, it is required to stabilize two lasers to some stable reference frequencies for stable signal generation.

In this paper, we propose and demonstrate the simple frequency stabilization technique using double-pass phase modulation with FM sideband technique [6] utilized in newly developed γ -type optical configuration. The γ -type configuration with double-pass phase modulation technique is simple and effective technique which utilize optical phase modulator [7] and optical components.

2 Principle

We briefly describe the principle associated with this work: FM sideband technique and a γ -type optical configuration consist of a phase modulator and a Faraday rotator mirror.







Fig. 1. Schematic of FM sideband modulation technique.

2.1 FM sideband technique

Fig. 1 shows laser frequency control system using FM sideband generation to achieve high frequency stability of laser by reducing frequency drift. In this system, the phase modulation sidebands are reflected back from the optical resonator which is used as a reference cavity. The electrooptic phase-modulator produces modulation sidebands which are located outside the resonator passband. These FM sidebands are totally reflected from an input mirror of the reference cavity and are steered to a photodetector by a polarization beam splitter and a $\lambda/4$ plate. The carrier frequency of the laser matches the cavity resonance frequency and this leads to a buildup of intracavity standing-wave at the laser frequency. This technique is the so-called Pound-Drever-Hall stabilization [6]. The two reflected fields, one is directly reflected field from the coupling mirror to the beam splitter with residual carrier, and the other field is the reflected carrier from inside the cavity, are superimposed in antiphase. The cancellation of two carriers at the input mirror leads to a small residual and fluctuating carrier with a phase shift which is frequency dependent in the vicinity of the resonance. These two fields, the reflected field and the leakage field, result in a line spectrum and broadened components at the modulation frequency. The shape of the phase signal obtained by heterodyne detection circuit, is similar to the derivative of cavity leakage field. The phase signal becomes antisymmetric around the cavity resonance frequency, thus we use the phase signal as an error signal. To retrieve the phase information, we use the two modulation sidebands. By a modulation with frequency of f_m , the two sidebands with the imaginary component of carrier are generated. By using an electronic mixer, the phase information can be extracted. An electronic mixer is a device that essentially multiplies two signals together; multiplying the signal detected from the sideband signal at the photodetector and the local oscillator signal will result in a DC component and a $2f_m$ component. To get





the error signal, a LPF is used to eliminate the DC component. Once an error signal is obtained, the signal is fed back to the laser through a proportional-integral-derivative (PID) servo loop filter to control wavelength of the laser.

2.2 γ -type optical configuration

To achieve phase modulation for two laser lights without using two phase modulators and an optical beam combiner, we propose the simple γ -type optical configuration. The γ -type configuration is a novel structure for simultaneous phase modulation of the orthogonally polarized two lights with different wavelength. The γ -type configuration consists of an optical circulator, one phase modulator and a Faraday rotator mirror as shown in Fig. 2. All those components have PM fiber pigtails. The two laser lights, $\lambda 1$ and $\lambda 2$, are coupled into the slow axis and fast axis of the circulator's port 1, respectively. Then, both lights pass through the phase modulator and reflected back to the circulator by the Faraday rotator mirror. On the way to the Faraday mirror, $\lambda 1$ is largely phase modulated by the modulator but $\lambda 2$ is not since the axis of the modulator is aligned to the slow axis. On the way back from the mirror, λ^2 is now largely phase modulated since polarization is rotated by 90 degree by the mirror. As a result, both lights are simultaneously phase modulated and sent to the output port (port 3) of the circulator with the same modulation index. In the technique, we use only one phase modulator and one RF synthesizer for two-frequency locking system described later.



Fig. 2. Dual wavelength, orthogonal polarization frequency modulation in γ -type configuration.

3 Experimental setup

Using the previously described FM sideband technique and γ -type configuration, we lock the laser frequencies of two commercially available external cavity laser diodes (ECLD1 and 2) to a single optical cavity. Fig. 3 shows our frequency locking system of two ECLDs. Two resonant modes of a Fabry-Perot optical cavity are used as stable reference frequencies for frequency locking of the two ECLDs. At first, we briefly explain experimental procedure using Setup#1 in Fig. 3.

Optical power (6 mW) from a 1550 nm external cavity diode laser (ECLD1) is divided by a 3 dB coupler. Half of the power is sent to an optical







Fig. 3. Experimental setup using γ -type configuration with FM sideband technique.

spectrum analyzer and the photo detector together with the output from the ECLD2 to create and detect the beat note signal. The remaining power is sent to a LiNb0₃ phase-modulator. The modulator is driven by a 18 MHz RF signal $(0.5 V_{pp})$ to generate FM sidebands. After passing through a circulator, the modulated light is reflected back from a Faraday mirror with the rotation angle of 90 degree. The light passes a second circulator and enters an optical cavity (FSR: 300 MHz, finesse: 200) which is used as a reference cavity in FM sideband technique. As previously mentioned, the reflected field (modulation sidebands and residual carrier) and the leakage field pass the second circulator and a polarization beam splitter. At the polarization beam splitter, the light from the ECLD1 is steered to a photodetector in Setup#1 and the light form those photodetectors, the two lasers are independently locked to two different resonant modes of one reference optical cavity using heterodyne detection in Setup#1 and Setup#2.

In servo system, the 18 MHz RF signal from the photodetector is amplified to 0 dBm. This signal and phase-shifted 18 MHz RF signal taken from the signal source are fed into a doubly-balanced mixer. When the optical input frequency (carrier signal) is in the vicinity of the cavity resonance frequency, the output of the balanced mixer shows an antisymmetric resonance curve which can be used as an error signal. After passing through a LPF (cutoff: 2.5 MHz), the error signal is sent back to the laser to control the operating current and the angle of the grating for fast and slow frequency control, respectively. A servo unity gain frequency above 150 kHz is achieved in the servo system. Currently, the bandwidth is limited by the characteristics of the used ECLDs. The two ECLDs are frequency-locked to two different cavity resonance frequencies.





The outputs of the ECLD1 and ECLD2 are superimposed and sent to measurement systems. The beat signal created by a photodetector is sent to a RF spectrum analyzer and a frequency counter to evaluate the frequency stability.

4 Results

Fig. 4(a) shows measured transmitted signal detected by the photodetector placed behind the cavity end mirror. Since the amplitude of second sideband of a phase-modulated electric field is proportional to the second order Bessel function, the modulation index was estimated to be 0.5 from the Fig. 4(a).

The Fig. 4(b) shows the error signal obtained after the LPF previously shown in Fig. 3. FM sideband technique provides the lock point at the resonance center shown in Fig. 4(b) and by using the point, good performance of the locking can be achieved [6]. So, the laser frequency was locked to the zero cross point of the error signal as indicated in the Fig. 4.

To evaluate the frequency stability, two ECLDs were frequency-locked to two different resonance frequencies (approximately 8 GHz apart) of the optical cavity using γ -type configuration. The beat signal was measured using a fast photodetector. The fluctuation of the beat signal was converted to an intermediate frequency of several hundred MHz and the intermediate frequency was measured by the frequency counter. The frequency counter was interfaced to data acquisition system to obtain the intermediate frequency data. Total of 800 data points were collected every 10 ms sampling time τ of the frequency counter. A quantitative measurement of frequency stability was obtained by calculating Allan variance from the measured beat frequency and can be expressed as

$$\sigma^{2} = \frac{1}{2} \left\langle \left| \Delta \nu(t) - \Delta \nu(t - \tau) \right|^{2} \right\rangle \tag{1}$$

where $\langle \rangle$ indicate average time, σ^2 is Allan variance, τ is the sampling time, $\Delta\nu(t)$ and $\Delta\nu(t-\tau)$ are beat frequencies at time t and $t-\tau$ respectively. The definition can be rewritten to calculate the value from the measured data as

$$\sigma^2 = \frac{1}{2(N-1)} \sum_{i=1}^{N} (\Delta \nu_{i+1} - \Delta \nu_i)^2, \qquad (2)$$











Fig. 5. Frequency stability of beat-note between two ECLDs.

where $\Delta \nu_i$ is the beat frequency at time $t_i = i\tau$ and N is the number of beat frequency data. Fig. 5 shows a plot of σ as a function of time τ when the two lasers were locked using FM sideband technique with γ -type configuration. The plot shows that σ stays almost constant over the averaging time for locked lasers. This indicates that frequency difference between the two lasers keeps constant value while they drift over time. The achieved frequency stability was under 200 kHz at square root of the Allan variance for τ from 0.01 s to 1 s.

5 Conclusion

For optical beat generation of microwave and millimeter wave signal, we have developed a new type of frequency stabilization technique for two independent lasers using the FM sideband technique with γ -type optical configuration. In the method, the achieved stability, estimated from the value of square root of the Allan variance for τ from 0.01 s to 1 s, was less than 200 kHz. By increasing the bandwidth of the external cavity laser diodes as well as by reducing the frequency fluctuations of the reference cavity, the frequency stability may be further improved. The obtained result shows that the proposed method can be utilized in stabilization of independent lasers for highly-stable microwave signal generation using optical beat method.

