Low Phase Noise Laser Synthesizer with Simple Configuration Adopting Phase Modulator and Fiber Bragg Gratings

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Abstract

We introduce a novel laser synthesizer with a simple configuration that contains no phase lock loop. This laser synthesizer generates an optical beat signal by modulating a CW light using a phase modulator and selecting two line spectra from modulation sidebands using serially-connected fiber Bragg gratings. With this configuration, the optical beat signal is obtained from a single laser source by converting CW laser light into an optical beat signal through a single optical path. This enables us to obtain a low phase noise of the optical beat signal which is comparable to that of the RF synthesizer that drives the phase modulator. In addition, polarization stability is also obtained between the two line spectra. The complete frequency range of the optical beat signals required in ALMA can be covered using this laser synthesizer.

Keywords: Laser Synthesizer, Phase Noise, Phase Modulator, Fiber Bragg Grating

1. Introduction

Laser synthesizers that generate optical beat signals with millimeter-wave frequencies will play an important role in radioastronomy [1-3]. In ALMA, one of the critical issues with regard to optical beat signals is finding a way to reduce their phase

noise. When an optical beat signal is generated using two different CW laser sources, the two laser sources must be phase locked to each other. Nevertheless, it is difficult to eliminate the phase noise from the lasers completely [3].

In this memo, we report a laser synthesizer with a novel configuration that contains no phase lock loop (PLL). The optical beat signal is generated from a single CW laser source using a phase modulator and serially connected fiber Bragg gratings (FBGs) [4]. The generated optical beat signal has a low phase noise, which is comparable to that of the RF synthesizer that drives the phase modulator. Moreover, polarization stability is obtained between the two line spectra that constitute the optical beat signal.

2. Configuration of novel laser synthesizer

Figure 1 shows the configuration of our laser synthesizer. First, a CW laser light is coupled into a $LiNbO_3$ phase modulator after amplification using an erbium-doped fiber amplifier (EDFA). The phase modulation generates multiple spectrum sidebands whose spacing is the same as the modulation frequency. Then the modulated light is coupled into a sideband selector, which consists of serially connected multiple FBG filters. Each FBG reflects a different line spectrum and only two line spectra, whose frequency separation is equal to the necessary beat frequency, are transmitted through the sideband selector. Although the light coupled into the sideband selector is a chirped CW light, it is converted into an optical beat signal by eliminating unnecessary line spectra. The beat frequency can be tuned by changing the modulation frequency and by selecting different combinations of the two line spectra. In this case, the reflection wavelength of the FBG is adequately tuned by applying mechanical stress.

The light emitted from the CW laser source has its own phase fluctuation, which leads to a finite spectral linewidth (= approximately 100 kHz for the laser we used). However, the phase fluctuation of the CW light is cancelled out for an optical beat signal that is generated by selecting two line spectra from the modulated light. Therefore, the RF spectrum obtained by detecting the optical beat signal has a very small linewidth (< 10 Hz), which is comparable to that of the RF synthesizer output used to drive the phase modulator.
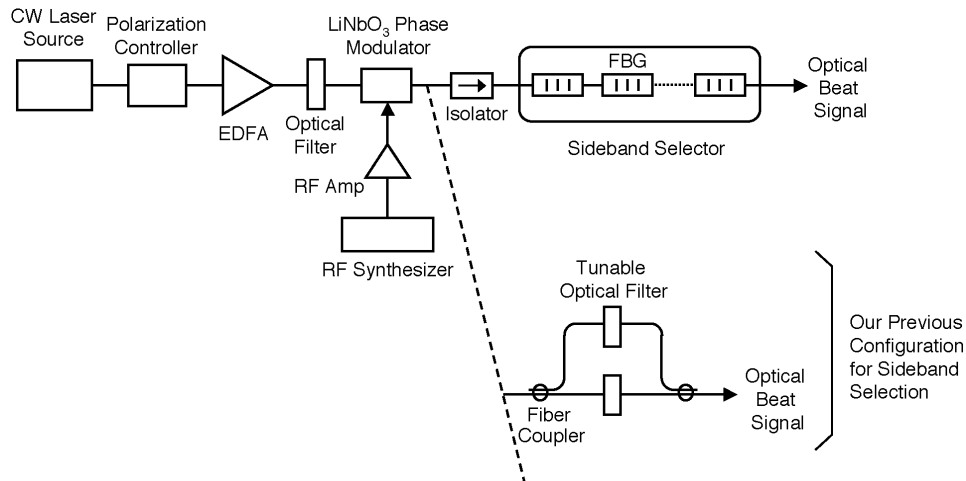
Fig. 1   Configuration of novel laser synthesizer

In our previous experiment described in [2] and [5], two sidebands were selected using two fiber couplers and two tunable optical filters as shown in the lower half of Fig. 1. In this configuration, the modulated light was divided in two using a fiber coupler and two different line spectra were selected using two optical filters and coupled again using a fiber coupler. Although this configuration enables us to select two line spectra with an easy operation, the temperature fluctuation around the setup leads to a fluctuation in the optical fiber length of the two different optical paths through which the two line spectra pass. As a result, a phase fluctuation is generated in the optical beat signal by the fluctuation in the length difference between the two optical paths. Even if the length difference fluctuation is as small as the wavelength of the light (1.55 μm), the phase fluctuation of the optical beat signal reaches as much as 2π, which is a serious problem for application in ALMA. In contrast, such phase fluctuation can be avoided when the two line spectra are selected using the serially connected multiple FBG filters because the two line spectra pass through the same optical path.

In addition, the laser synthesizer configuration shown in Fig. 1 has the advantage of polarization stability. As suggested in [6], the polarization stability of the LO generator is a significant requirement for ALMA. In the laser synthesizer configuration shown in Fig. 1, the polarization stability between the two line spectra is easily preserved because these spectra originate from the same light source and they pass through the same optical path during the process of optical beat signal generation.

3. Modulation index and power of sideband

The optical spectrum of the phase-modulated light spreads symmetrically as we increase the modulation index. Figure 2 shows the power of the line spectrum at the center wavelength and the Nth-order sideband as a function of modulation index. The vertical axis shows the relative optical power of each line spectrum where the power of the CW light at the output of the phase modulator without modulation is set at 0 dB. As shown in Fig. 2, the power of each sideband rises and falls as we increase the modulation index. At a modulation index of 1.43, the power of the first sideband becomes the same as that of the line spectrum at the center wavelength. The first and second sidebands gain their maximum power at modulation indexes of 1.84 and 3.05, respectively.
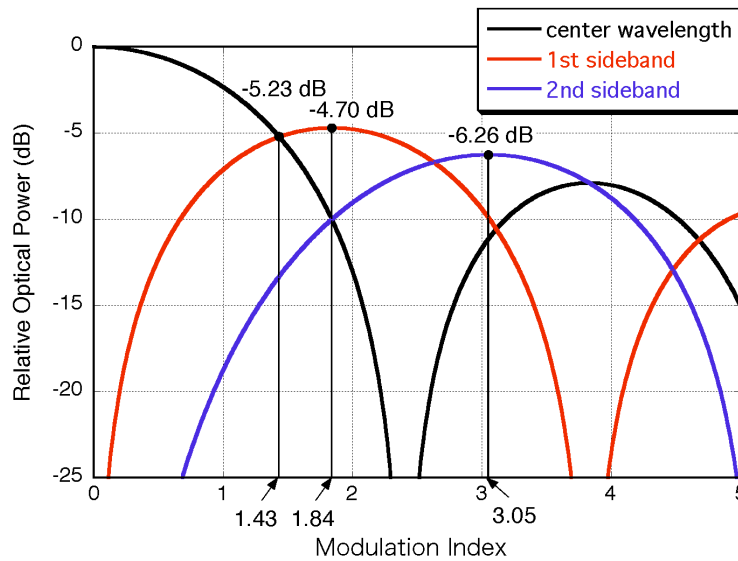
Fig. 2   Sideband power vs. modulation index

Figure 3 (a) - (c) show the calculated optical spectra after phase modulation for modulation indexes of 1.43, 1.84, and 3.05, respectively. The horizontal axis N in Fig. 3 is correlated with the optical frequency ν of each line spectrum by the formula $\nu = \nu_{cw} + N \cdot f_m$, where ν_{cw} is the optical frequency at the center wavelength and f_m is the modulation frequency. From the phase-modulated light shown in Fig. 3 (a), we can obtain an optical beat signal with a frequency equal to the modulation frequency f_m by eliminating the line spectra except for N=0 and 1. Similarly, we can obtain optical beat

signals with frequencies of $2f_m$ and $4f_m$ from the phase-modulated light shown in Fig. 3 (b) and (c), respectively.
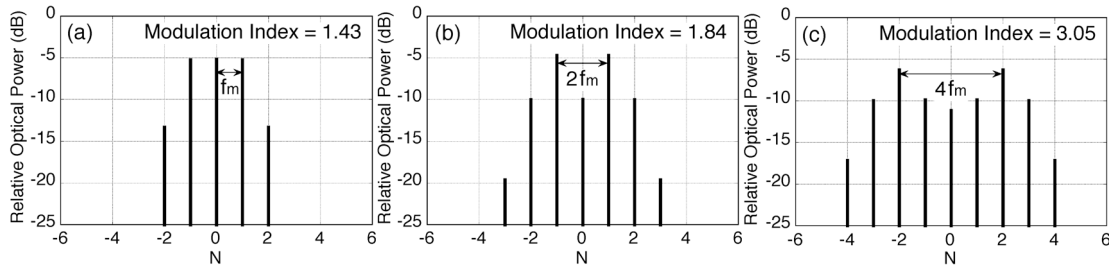

Fig. 3   Calculated optical spectra after phase modulation

Table 1 shows an example of the modulation index and modulation frequency setup needed to obtain the optical beat signal frequencies required for ALMA. By changing the modulation frequency between 22.5 and 45 GHz, we can obtain the necessary optical beat signal frequency.

Table 1   Setup for the generation of necessary optical
beat signal frequencies in ALMA

Modulation Index	Modulation Frequency (GHz)	Multiplication Number	Optical Beat Signal Frequency (GHz)
1.43	27 - 33	1	27 - 33
1.84	32.5 - 45	2	65 - 90
3.05	22.5 - 35	4	90 - 140
3.05	27.5 - 42.5	4	110 - 170

4. Optical beat signal generation experiment

4.1   Experimental setup

We generated optical beat signals with frequencies of 80 and 102 GHz using the experimental configuration shown in Fig. 1. The output wavelength of the CW light source was 1547.2 nm. The output power of the EDFA positioned in front of the phase modulator was set at 16 dBm. The phase modulation frequencies were set at 20 and 25.5 GHz, and the modulation index was set at 3.05 in both cases. With this

modulation index, the second sideband pair gains the maximum power, and we can obtain an optical beat signal with four times the modulation frequency. In this experiment, seven FBGs were used to eliminate the unnecessary seven line spectra.

4.2 Optical spectrum

Figure 4 shows the optical spectra at the phase modulator output ((a),(b)) and sideband selector output ((c),(d)) for modulation frequencies of 20 GHz ((a),(c)) and 25.5 GHz ((b),(d)). Figure 4 (a) and (b) show the optical spectra that correspond to the calculated result shown in Fig. 3 (c). As shown in Fig. 4 (c) and (d), the relative power of the unnecessary line spectra was suppressed to less than -20 dB as compared with the two line spectra consisting of an optical beat signal.
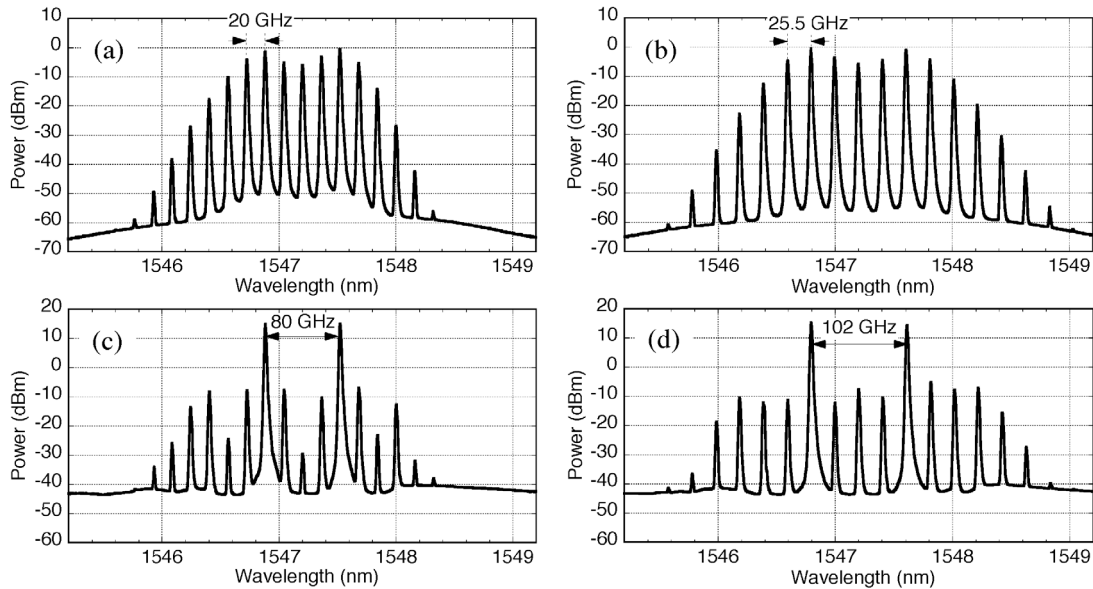
Fig. 4   Optical spectra

4. 3   Phase noise characteristics of optical beat signal

The generated 80 and 102 GHz optical beat signals were amplified using an EDFA and injected into a uni-traveling-carrier photodiode (UTC-PD) [7]. The millimeter-wave emitted through the W-band waveguide attached to the UTC-PD was mixed with an N x 600 MHz signal, which was generated using an ultra-low-noise oscillator and multipliers. The frequency of the harmonic mixer output was less than 1.3 GHz. Figure 5 shows the phase noise characteristics of the optical beat signal derived from the harmonic mixer output. For comparison, we show the phase noise of the RF

synthesizer output, which we measured for a 15 GHz output and calibrated to frequencies of 80 and 102 GHz. Phase noise saturation is observed for offset frequencies above 500 kHz. One possible reason for the saturation is the phase noise of the oscillator that drives the harmonic mixer. For offset frequencies below 500 kHz, we observed no degradation in the phase noise as compared with the RF synthesizer output. The superficial improvement in the phase noise of the optical beat signal between 2 and 100 kHz may be attributed to the variation in the RF synthesizer characteristics during measurement.
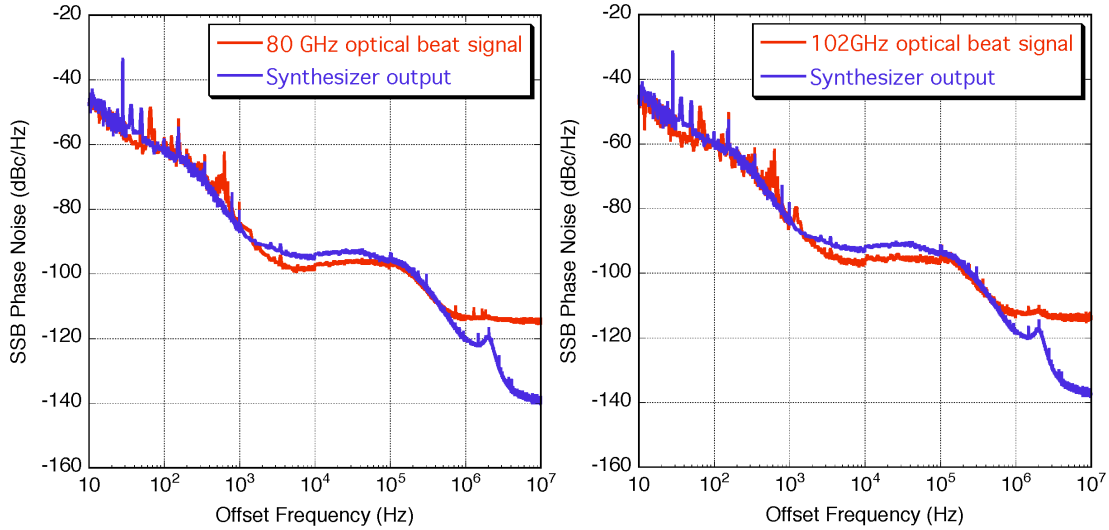

Fig. 5   Phase noise characteristics of the optical beat signal

5. Conclusion

We realized a laser synthesizer with a simple configuration that contains no PLL by utilizing a phase modulator and serially connected FBGs. Modulation sidebands were generated using the phase modulator and two line spectra were selected using the serially connected FBGs. An optical beat signal was generated from a single laser source by converting CW laser light into an optical beat signal through a single optical path. This configuration realized the low phase noise of the optical beat signal that was comparable to that of an RF synthesizer. In addition, this configuration realized polarization stability between the two line spectra. The optical beat signal frequency required in ALMA can be obtained using a single set of this laser synthesizer.

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