A Design of Ultra-low Phase Noise Frequency Source Based on High Phase Detection Frequency

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Abstract. This paper introduces a design of ultra-low phase noise frequency source based on high phase detection frequency. Frequency source is a very important part of modern electronic system. Radar, communication, space technology and so on are inseparable from frequency source. Its performance index directly affects the whole electronic system, and phase noise is one of the most important indicators. In this paper, the scheme of phase-locked technology with high phase detection is mainly used, the phase noise is better than -116dBc/Hz@1kHz, -120dBc/Hz@10kHz, -121dBc/Hz@100kHz when the output frequency is 4.5GHz. The technology of high phase discrimination and low phase noise frequency synthesis in this paper can also be extended to higher and more special frequency bands. It provides a solution of ultra-low phase noise for frequency sources of modern radar, electronic jamming and countermeasure systems.

1. Introduction
Frequency source is one of the core components in communication, radar, navigation and other systems. Moreover, the performance of radio frequency system is closely related to the performance of the signal source used. With the development of modern electronic technology, radar, wireless communication, electronic countermeasures and other military and national defense fields require more and more frequency sources. With the development and breakthrough of millimeter wave technology, in radio frequency components and systems in modern military and national defense fields, the phase noise performance of radio frequency microwave signal source is required higher for its anti-jamming ability, communication confidentiality, integration and other functions. Therefore, it is very important to study the frequency synthesis technology of ultra-low phase noise. Frequency synthesis technology is the key technology of modern electronic communication. The frequency synthesizer with low phase noise is a research hotspot in radar and other systems, and it is also the main development trend.
2. Theory of Scheme

2.1. theory analysis
The locking phase-locked loops (PLL) consists of a phase detector (PD), a loop filter, a voltage controlled oscillator (VCO) and a frequency divider. The working principle of PLL is to detect the phase difference between the input signal and the output signal, and convert the detected phase difference signal into the output voltage signal through the phase discriminator. The control voltage of the VCO is formed after filtering by the low-pass filter. The frequency of the output signal of the VCO is controlled, and then the oscillation is controlled by the feedback path. The frequency and phase of the output signal are fed back to the phase detector.

2.2. Phase Noise Analysis
Phase noise can be seen as the modulation of phase by various types of random noise signals. From the frequency domain performance, the spectrum is no longer a discrete line, but with a certain width. It is defined as the ratio of the noise power spectral density to the output signal power within the bandwidth of 1 Hz at the deviation from the center frequency in the unit of \(-\text{dBc/Hz}\).

\[
\theta_r = \frac{G(s)}{s} = \frac{K_{PD}K_{VCO}}{s}
\]

Figure 1. Equivalent model of PLL

Loop filter is between phase discriminator and voltage controlled oscillator, which plays an important role in maintaining the stability of the loop and controlling the noise inside and outside the loop band. The equivalent model of a PLL is shown in Figure 1. The gain constants of phase discriminator, filter and VCO are KPD, K and KVCO, respectively. N is the frequency division ratio of the frequency divider and \(F(s)\) is the transmission function of the loop filter. Let the phase noise generated by reference signal source be \(\theta_r\) and the phase noise generated by VCO be \(\theta_e\). For simplicity, suppose \(F(s) = K = 1\). The open-loop transfer function of PLL is

\[
G(s) = \frac{K_{PD}K_{VCO}}{s} = \frac{K_{PD}K_{VCO}}{s}
\]

Then the loop transfer function for \(\theta_r\) is

\[
\theta_r = \frac{G(s)}{1 + G(s)} = \frac{K_{PD}K_{VCO}}{s} (1 + \frac{K_{PD}K_{VCO}}{N}) = \frac{1}{N(1 + \frac{1}{K_{PD}K_{VCO}})N} \tag{2}
\]

Formula (2) is the form of the transmission function of the low-pass filter, and the time constant is \(1/K_{PD}K_{VCO}\).

For \(\theta_e\), the loop transfer function is

\[
\theta_e = \frac{1}{1 + K_{PD}K_{VCO}/N} = \frac{1}{1 + 1/(1/K_{PD}K_{VCO})N} \tag{3}
\]

Formula (3) is the transmission function form of high-pass filter, and the time constant is \(1/K_{PD}K_{VCO}\). So the phase noise of the loop filter is low-pass to the reference signal and high-pass to the phase noise of VCO. So it is very important to choose the appropriate loop bandwidth for phase noise. Generally, the intersection of phase noise and VCO phase noise in the loop is the best, which not only optimizes the near-end phase noise, but also does not waste the far-end phase noise characteristics of VCO.

The higher the division ratio of the phase-locked loop, the worse the phase noise is. It deteriorates at 6dB per octave, i.e. at \(-20\log N\). The best way to improve the phase noise in the loop is to increase the phase detection frequency and reduce the frequency division ratio.
2.3. Design Scheme

The scheme block diagram of this design is shown in Figure 2. The reference signal is amplified by 100MHz crystal oscillator through an amplifier. There are two choices for frequency doubling: 300MHz or 500MHz, which will be analyzed later. Then the frequency is selected by a band-pass filter, and then the phase is compared with the frequency signal from a voltage controlled oscillator. The output level signal of the phase discriminator is processed by a loop filter and added to the regulator of the VCO. Voltage controlled oscillator generates signal power in two ways, one way amplifies the output, the other way feedback phase detector after frequency divider.

![Block diagram](image)

In the scheme, HMC3716, which supports high phase detection frequency, is selected as the phase detector. It’s phase noise base: \(-145\text{dBc/Hz}@1\text{kHz}\). Because the dividing ratio \(N = \frac{4500}{500} = 15\), because there is no integrated divider inside the phase discriminator, the dividing ratio \(N\) must be realized by using an external divider. The normalized phase noise base is \(PN_{\text{final}} = -145\text{dBc/Hz}@1\text{kHz}\) - \(10\log 10^6 = -225\text{dBc/Hz}@1\text{kHz}\). The theoretical value of 4.5GHz phase noise without considering the influence of reference signal noise.

\[
PN_{\text{final}} = -225\text{dBc/Hz}@1\text{kHz} + 20 \log 15 + 10 \log 100 * 10^6 \approx -121.5\text{dBc/Hz}@1\text{kHz}
\]

The reference frequency is realized by frequency doubling. The phase noise of 100 MHz crystal oscillator at 1 KHz offset is about -158 dBc/Hz, which will deteriorate by \(-20\log N\) after frequency doubling. That is to say, the theoretical phase noise of 300MHz after 3-fold frequency is as follows. \(PN_{300\text{MHz}} = -158\text{dBc/Hz} + 20\log 3 = -148\text{dBc/Hz}@1\text{kHz}\). The 500 MHz phase noise after 5-fold is \(PN_{500\text{MHz}} = -158\text{dBc/Hz} + 20\log 5 = -143\text{dBc/Hz}@1\text{kHz}\). However, in fact, noise will be introduced in the process of frequency doubling and amplifier amplification, so the actual 300 MHz phase noise is only \(-145\text{dBc/Hz}@1\text{kHz}\), while the 500 MHz phase noise is \(-140\text{dBc/Hz}@1\text{kHz}\). The actual reference noise is substituted into the simulation software to simulate the phase noise. The results are shown in figs. 3 and 4.

![Phase noise at 4.50GHz](image)

Figure 3. Phase noise simulation at 300 MHz phase discrimination frequency
From the observation of figs. 3 and 4, it can be seen that the phase noise at 1 KHz offset is not much different, but it is much better when 500 MHz phase discrimination frequency is used at 10 KHz offset and 100 KHz offset. So 500 MHz is chosen as the final phase detection frequency.

The output circuit of this phase discriminator is UP DN without charge pump. The maximum output voltage is 2V. It cannot meet the requirement of the voltage controlled oscillator's tuning range. So the loop filter adopts the form of active loop filter. The circuit form is shown in Figure 4. Compared with passive loop filter, active loop filter can introduce noise, but it can amplify the output voltage of phase discriminator to the available range by using the operational amplifier in the loop filter. The loop bandwidth is as wide as possible because the phase discrimination frequency is 500 MHz, so the phase noise in the loop will be better.

3. Test results and analysis
After the simulation and theoretical analysis, the final test of the object is carried out. Considering the influence of different power of reference signal on phase noise, the reference signals of different power of frequency source are given. The test results are shown in Fig. 5-8.
After analysis, the reference signal power decreases, and the phase noise of the output signal becomes worse: the phase noise shows the shift of the center frequency in the frequency domain, and the random fluctuation of the signal phase in the time domain. The phase discriminator works by comparing the phase difference between the reference signal and the voltage controlled oscillator feedback signal. That is to say, the phase detector grabs a certain phase point of the reference signal to compare with the phase of the signal fed back by the voltage controlled oscillator. Because this phase point is not ideal, it has random jitter, which is transmitted to VCO as offset of the central frequency, that is, phase noise. The reference signal is usually provided by crystal oscillation, usually sinusoidal wave. The larger the power of the signal, the higher the amplitude of the sinusoidal wave and the more shaking the sinusoidal wave is. The larger the amplitude of sinusoidal wave is, the smaller the random change of phase is. The smaller the random offset of center frequency is, the better the phase noise is. Therefore, the higher the power of the reference signal, the better the phase noise of the output signal. It is ideal to use square wave as the reference signal.
From figs. 6 to 9, it can be seen that the phase noise of the frequency source is the best when the reference signal power is 5 dBm, which is -116 dBc/Hz@1kHz, -120 dBc/Hz@10kHz.
-121 dBc/Hz@100kHz. When the power drops to 0 dBm, the phase noise begins to deteriorate. It deteriorates about 3 dB at 1 kHz offset and 2 dB at 10 kHz and 100 kHz offset. When the power drops to -10 dBm, deteriorating 8 dB at 1 kHz offset and 7 dB at 10 kHz and 100 kHz offset.

There are errors between the test results and the simulation results. The main reason is that the simulated reference signal is simulated by the ideal square wave of 500 MHz. Now it is impossible to provide a square wave with good phase noise ratio, and only sinusoidal wave can be used as the reference signal to replace it. In order to achieve better phase noise, some learning improvements of square wave will be made in the future.

4. Concluding remarks

In this paper, a design method of ultra-low phase noise frequency source based on high phase detection frequency is presented by using PLL frequency synthesis technology. Finally, the ultra-low phase noise index is achieved, which is better than -116 dBc/Hz@1kHz, -120 dBc/Hz@10kHz, -121 dBc/Hz@100kHz. This method can also be extended to higher and more special frequency bands. It provides a solution of ultra-low phase noise for the frequency synthesizer of modern radar, electronic jamming and countermeasure electronic systems.

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