Note on Microwave Oscillators

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Author Di Yu (yudi.0211@foxmail.com)

Genereal structure of microwave oscillators

An oscillator is a device that generates a continuous oscillating signal. Its basic structure consists of a loop with a filter and a broadband gain element, as illustrated in Figure 1. The gain element stimulates and amplifies oscillations, while the filter sets the frequency of the oscillation. This concept is applicable to various types of oscillators, such as lasers and RF oscillators. For example, a laser functions as a resonator loop with optical gain through stimulated emission and a narrowband filter like a grating. Similarly, an RF oscillator is an electrical circuit loop comprising an RF amplifier and a low-pass RF filter. The RF filter suppresses harmonic oscillations and enables single-mode oscillation.

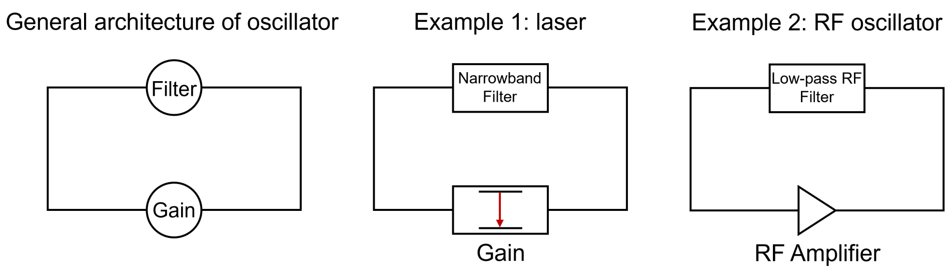

Figure 1: General structure of oscillators.

The key characteristics of microwave oscillators are output frequency and phase noise (frequency instability, explained further later). For most applications, the ideal output frequency varies, but minimizing phase noise is crucial in fields like wireless communication, analog-to-digital signal conversion, and radar. In general, an oscillator's phase noise is inversely proportional to the square of the loop delay (the time for a signal to complete a circulation): $S_\phi(\omega) \propto 1/\tau^2$. This means that a longer loop delay is necessary to achieve low-noise oscillators.

In microwave signal generation, the challenge lies in the significant signal loss in transmission lines, which hinders achieving long loop delays and low phase noise. In a standard GaAs microstrip, often found in monolithic microwave integrated circuits (MMIC), the microwave propagation loss is approximately 0.5 dB/cm at 20 GHz [1], meaning that a loop delay of just 6 cm would lead to a 3 dB loss.

To address the issue of high microwave signal loss, the electronics industry commonly applies frequency multiplication techniques to a frequency-stable reference signal at a lower frequency (typically 50-100 MHz from a quartz crystal piezoelectric oscillator) in order to generate a low-noise microwave signal, instead of directly producing a microwave signal with a microwave oscillator. While the frequency multiplication method has been effective, it faces challenges with increasing phase noise when synthesizing signals at high frequencies (>20 GHz). Each time a signal is frequency doubled, the phase noise increases by 6 dB. This means that when synthesizing mmWave signals (30 GHz - 300 GHz) with multiple stages of frequency doubling, the signal will undergo at least 8 frequency doubling stages, leading to a significant decline in signal purity. Consequently, generating low-noise microwave signals has become a significant research area with practical importance and technical complexities.

Applications of microwave oscillators

Microwaves cover a wide frequency spectrum (300 MHz - 300 GHz) and are integral to various applications including wireless communication, test and measurement tools, and radar systems. In the process of modulating a baseband signal to an RF signal, frequency upconversion is employed where the baseband signal merges with a carrier signal from a local oscillator. Conversely, demodulating an RF signal to a baseband signal involves frequency downconversion which requires another local oscillator. These oscillators need to function at microwave frequencies for applications like 5G, Bluetooth, and Wi-Fi, which operate within the microwave band. For instance, 5G communication spans from 450 MHz to 6 GHz (FR1 or sub-6G) and 24.25 GHz to 52.6 GHz (FR2 or mmWave) [2].

Low-noise microwave oscillators play a critical role in various test and measurement equipment, facilitating high-speed and high-precision analog-to-digital conversion (ADC) crucial for devices like mixed signal oscilloscopes [3]. They are also utilized in network analyzers where a widely tunable microwave source is necessary for S-parameter measurements. For instance, the Keysight PNA-X network analyzer features a microwave source operating from 900 Hz to 67 GHz [4].

Automotive mmWave radar represents a burgeoning application of microwave oscillators, using millimeter-wave signals for accurate range measurements. A typical mmWave radar like the Texas Instruments AWRL1432 automotive mmWave Radar sensor [5] operates within the frequency range of 76 GHz to 81 GHz. To achieve precise ranging, these radars require low-noise microwave oscillators with minimal jitter.

Phase noise spectrum

Basics

Let's begin by defining the phase noise power spectral density (PSD), also known as the phase noise spectrum, mathematically. For a real signal $x(t) \in \mathbb{R}$, we can obtain its complex representation using the Hilbert transform: $\tilde{x}(t) = x(t) + j\mathcal{H}[x(t)]$ [6]. In this complex representation, the positive-frequency components of the original signal are doubled, while the negative-frequency components are removed. For instance, if $x(t) = \cos(t) = (e^{jt} + e^{-jt})/2$, then the complex representation is $\tilde{x}(t) = e^{jt}$.

The complex representation allows us to define the instantaneous phase of the signal as $\phi(t) = \arg(\tilde{x}(t))$, and the instantaneous frequency as $f(t) = d\phi(t)/dt$. Assuming that the signal $x(t)$ consists of a single-frequency carrier wave with added noise and is continuous rather than transient, the instantaneous phase $\phi(t)$ can be expressed as $\phi(t) = f_c t + \delta\phi(t)$, where $f_c t$ represents the carrier wave phase, and $\delta\phi(t)$ represents phase fluctuations. The phase fluctuation $\delta\phi(t)$ can be considered a random signal with an average value of zero and finite power. The two-sided phase noise spectrum of $x(t)$ is defined as the power spectral density of $\delta\phi(t)$ [7]:

$$S_\phi(f) = \lim_{T\to\infty} \frac{1}{T} |\tilde{\delta\phi}_T(f)|^2 = \lim_{T\to\infty} \frac{1}{T} |\int_{-\infty}^{\infty} e^{-j2\pi f t} \delta\phi_T(t) dt|^2.$$

In this context, $\delta\phi_T(t)$ represents the instantaneous phase fluctuation at time t for a truncated signal $x_T(t)$. This truncated signal equals $x(t)$ for the interval $t_0 - T/2 < t < t_0 + T/2$ around an arbitrary time t_0, and it is zero outside this interval.

When plotting a phase noise spectrum, the x-axis typically shows the offset frequency relative to the carrier frequency, and the y-axis is represented on a logarithmic scale with units of dBc/Hz. The term 'dBc/Hz' indicates the ratio of noise power in a 1-Hz bandwidth at a specific frequency offset to the total power of the carrier wave, expressed in decibels.

To understand this better, let's consider a signal with a small phase variation: $X(t) = X_0 \sin(\omega_c t + \phi_0 \sin(\omega_n t))$, where $\phi_0 \ll 1$ [8]. The instantaneous phase fluctuation is $\delta\phi(t) = \phi_0 \sin(\omega_n t) = (\phi_0 e^{j\omega_n t} - \phi_0 e^{-j\omega_n t})/2j$. The power spectral density (PSD) of the phase fluctuation is given by $S_\phi(f) = \frac{\phi_0^2}{4}[\delta(f - \frac{\omega_n}{2\pi}) + \delta(f + \frac{\omega_n}{2\pi})]$.

We will demonstrate that this phase noise spectrum represents the power ratio of noisy sidebands to the carrier wave. The original signal $X(t)$ can be approximated as:

$$X(t) \approx X_0 \sin(\omega_c t) + X_0 \phi_0 \cos(\omega_c t) \sin(\omega_n t)$$
$$= X_0 \sin(\omega_c t) + \frac{X_0 \phi_0}{2} \sin((\omega_c + \omega_n)t) - \frac{X_0 \phi_0}{2} \sin((\omega_c - \omega_n)t).$$

This shows that the signal has two sidebands at frequencies $\omega_c + \omega_n$ and $\omega_c - \omega_n$, with power ratios to the carrier wave of $\phi_0^2/4$. These power ratios match the phase noise spectrum, confirming our explanation.

In summary, we have shown that the phase noise spectrum represents the power ratio of a noise Fourier component in a 1-Hz bandwidth at a given offset frequency to the carrier power. This justifies using the unit 'dBc/Hz' for the phase noise spectrum.

In engineering, the one-sided (or single-sided) phase noise spectrum is commonly used. It is defined as:

$$S_\phi^{\text{one-sided}}(f) = S_\phi^{\text{two-sided}}(f) + S_\phi^{\text{two-sided}}(-f).$$

The one-sided phase noise spectrum is 3 dB higher than the two-sided spectrum at positive frequencies due to symmetry around the zero offset frequency. It's important to understand that the one-sided spectrum, while defined only at positive frequencies, accounts for the total phase noise intensity at both positive and negative frequencies.

In the following discussion, when we refer to the phase noise spectrum, we will be discussing the one-sided phase noise spectrum unless explicitly stated otherwise.

Example

Figure 2 shows the phase noise spectrum of the internal RF source of the Keysight PNA-X network analyzer [4]. Note that the phase noise for a continuous wave (CW) at 20 GHz is about 6 dB higher than that for a CW at 10 GHz. Similarly, the phase noise for a CW at 10 GHz is about 6 dB higher than that for a CW at 5 GHz, measured at a 10 kHz offset frequency. This dependency of the phase noise spectrum on the carrier frequency suggests that a frequency doubling technique is used in the network analyzer to synthesize these microwave signals.

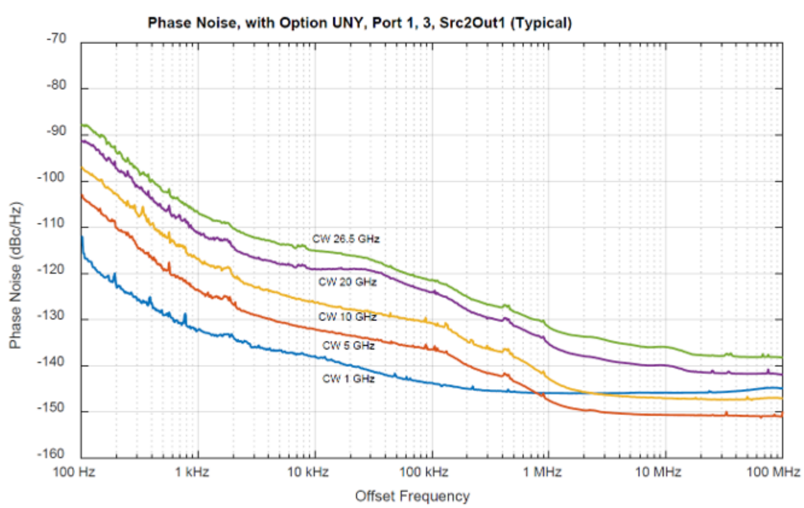

Figure 2: Phase noise spectrum of internal oscillator in Keysight PNA-X network analyzer.

Overview of commercial microwave oscillators

Microwave oscillators are available from companies like Renesas, Texas Instruments, and Analog Devices in the form of packaged chips. The specifications and unit prices of some of the latest commercial microwave oscillators are listed in Figure 3. These oscillators typically have a maximum output frequency of about 20 GHz, with a phase noise of around -110 dBc/Hz at a 10 kHz offset. All these integrated oscillators come in a standardized 7 mm x 7 mm package, and their unit prices range from 60 to 160 USD.

Model	Max. Frequency	Phase Noise @10 kHz (Scaled to Max. Freq.)	Dimensions	Unit Price	Year of Release
Renesas 8V97003	18 GHz	-107 dBc/Hz	7x7 mm	60 USD	2020
Texas Instruments LMX2820	22.6 GHz	-104 dBc/Hz	7x7 mm	70 USD	2020
Analog Devices ADF4382A	20 GHz	-117 dBc/Hz	7x7 mm	160 USD	2023

Figure 3: Specifications of commercial integrated microwave oscillators.

We also present the parameters of some commercial bulky microwave oscillators in Figure 4. These oscillators can achieve an output frequency of up to 67 GHz with a phase noise of around -110 dBc/Hz at a 10 kHz offset.

Model	Max. Frequency	Phase Noise @10 kHz (Scaled to Max. Freq.)	Dimensions	Unit Price	Year of Release
Keysight N5247B PNA-X	67 GHz	-111 dBc/Hz	Bulky	NA	2017
Berkeley Nucleonics 870A	54 GHz	-114 dBc/Hz	Bulky	NA	2023

Figure 4: Specifications of commercial bulky microwave oscillators.

These commercial microwave oscillators can serve as a baseline for developing new oscillators. Any new oscillator should outperform the existing ones in either frequency range, phase noise, compactness, or cost to justify their practical significance.

Reference

1. Zhang, M., Wu, C., Wu, K., & Litva, J. (1992, June). Losses in GaAs microstrip and coplanar waveguide. In 1992 IEEE MTT-S Microwave Symposium Digest (pp. 971-974). IEEE.
2. What Is the 5G Spectrum? Definition
3. Clocking high-speed data converters - Texas Instruments
4. Keysight PNA-X Network Analyzers
5. Texas Instruments AWRL1432 automotive mmWave Radar sensor
6. Analytical signal - Wikipedia
7. Spectral density - Wikipedia
8. Introduction to Phase Noise