LOW PHASE NOISE AMPLIFIER AND OSCILLATOR USING FEED-FORWARD TECHNIQUE AT 10 GHz[1]

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Abstract - **We discuss the performance of a feed-forward amplifier (FFA) at 10 GHz. The feed-forward method is primarily used to suppress intermodulation distortion in amplifiers to suppress up-converted near-DC noise. The main amplifier in this configuration is a low-noise array of eight amplifiers in parallel and having a phase noise of –165 dBc/Hz at f = 10 kHz. By implementing a feed-forward scheme, we are able to suppress this noise, as well as close-to-carrier noise, by at least another 10 dB. This improved performance surpasses that of other present low-noise microwave amplifiers. We discuss this exceptional performance in the context of trade-offs with other amplifier properties and specifications. We also construct a 10 GHz oscillator using an air-dielectric resonator and the FFA as the loop amplifier. The phase modulated (PM) noise of this particular oscillator is either less than or comparable to the PM noise of several classes of commercial oscillators. Additionally, the AM noise performance is superior to existing oscillators.**

I. INTRODUCTION

The inherent near-DC noise of an amplifier, which is usually flicker noise, is up-converted and projected partially as phase modulated (PM) noise and partially as amplitude modulated (AM) noise onto the signal being amplified [1-2]. This behavior significantly limits the performance of an amplifier used to amplify and/or distribute low-noise, spectrally pure oscillating signals. The feed-forward technique is well known for increasing the linearity of amplifiers and is also a means to reduce amplifier PM and AM noise [3-7].

We have used the feed-forward technique to design a very low flicker PM noise amplifier. We also build an oscillator at 10 GHz using the FFA as the loop amplifier. Section II describes the working principle of the FFA method. In Section III, we describe our two-channel, carrier-suppressed PM noise measurement system that tests the FFA. The PM and AM noise of our FFA is also presented in this section. Section IV describes our FFA oscillator and its PM noise is compared to other oscillators of various types. Finally, a summary is provided in Section V.

II. FEED-FORWARD AMPLIFIER

Figure 1 shows that a feed-forward amplifier consists of signal cancellation and phase-error cancellation signal paths. In the signal cancellation loop, the RF input signal is split after amplification and subtracted from the input signal. Specifically, the main amplifier is sampled with a coupler and compared with the input signal at a subtracting junction where the two signals are combined with equal amplitude and anti-phase. With fine adjustment of amplitude and phase, the reference signal is mostly cancelled leaving an error signal, which is an attenuated version of the noise and inter-modulation distortion (IMD) generated by the main amplifier. In the error cancellation circuit, the error signal is amplified using an error amplifier. Then with appropriate

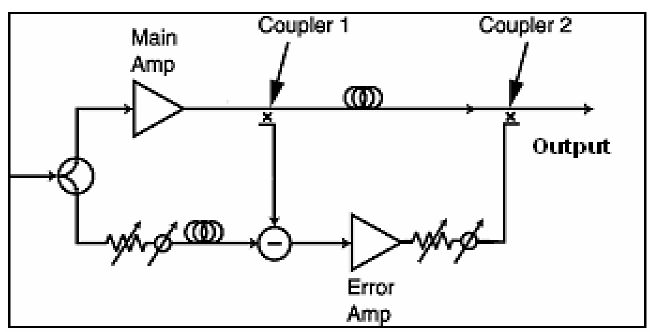

Figure 1. Block diagram of a feed-forward amplifier.

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phase and amplitude match at the output coupler, the noise and IMD is removed by vector subtraction.

Delay lines in each circuit are necessary to compensate for the delay of the main amplifier and the error amplifier. Also, effective noise reduction requires very careful balancing of signal paths.

We used a GaAs array amplifier as our main power amplifier. This amplifier has state-of-the-art PM noise by virtue of a parallel-amplifier architecture. The gain (G), noise figure (NF) and power output at 1-dB compression (P_{1dB}) are 18 dB, 8 dB, and 21 dBm, respectively.

The error amplifier is a lower power amplifier with G = 32 dB, NF = 1 dB and P_{1dB} = 10 dBm. It is very important to keep the carrier power of this error amplifier very low so that its flicker noise contribution is less. It is also very important to choose an error amplifier with low NF to reduce its white noise contribution.

III. TWO-CHANNEL CARRIER-SUPPRESSED MEASUREMENT SYSTEM AND EXPERIMENTAL RESULTS OF FFA

In order to measure the low flicker PM noise of FFA, we used a two-channel carrier-suppressed measurement system [7-10]. This technique was first introduced by Sann [8] to measure near-carrier noise in microwave amplifiers. The block diagram of our two-channel carrier-suppressed measurement system is shown in Figure 2. Carrier suppression measurement systems use a carrier cancellation scheme similar to the FFA configuration as described in the previous section. To reduce or cancel the power at the carrier frequency prior to phase-noise measurement, two signal paths are matched at the carrier operating frequency. The carrier-suppressed signal, which contains mostly the noise of DUT is then split and fed to error amplifiers. The amplified error signal is then fed to RF port of the double balanced mixer (DBM) whereas direct source signal is fed

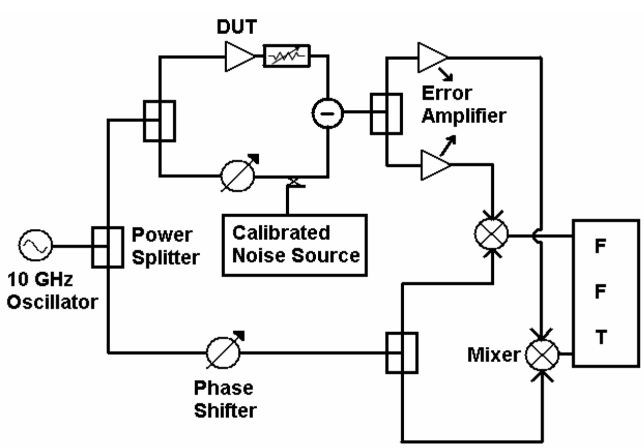

Figure 2. Block diagram of a two-channel carrier-suppressed measurement system.

to the LO port. A phase shifter is used to set true phase quadrature between the two signals of the DBM for PM noise measurement. The effective PM noise of the DUT as seen by the DBM mixers is enhanced by the amount of carrier suppression since the measurement is ratio-metric. The output of the DBM which is used as a phase detector is then amplified and fed to a two-channel fast Fourier transform (FFT) spectrum analyzer. Only the coherent noise, i.e., noise of the DUT that is present in both channels, averages to a finite value whereas the time average of the incoherent noise processes approaches zero as $\sqrt{N}$, where N is the number of averages used in the FFT. A calibrated PM noise source is used to calibrate the gain of the system.

A stable operating environment is required to maintain a very good amplitude and phase match of carrier cancellation loop. The measurement enhancement provided by carrier suppression is improved as environmental effects are reduced.

The measured PM noise of our FFA using the set-up illustrated in Figure 2 is shown in Figure 3. It shows that there is at least 10 dB improvement in the PM noise using feed-forward technique at frequencies below 2kHz. This improved performance surpasses that of other existing low-noise microwave amplifiers. It can also be noted that in the FFA the flicker corner frequency has also moved below the original array amplifier's 10 kHz corner frequency. The noise floor of the measurement system is also shown.

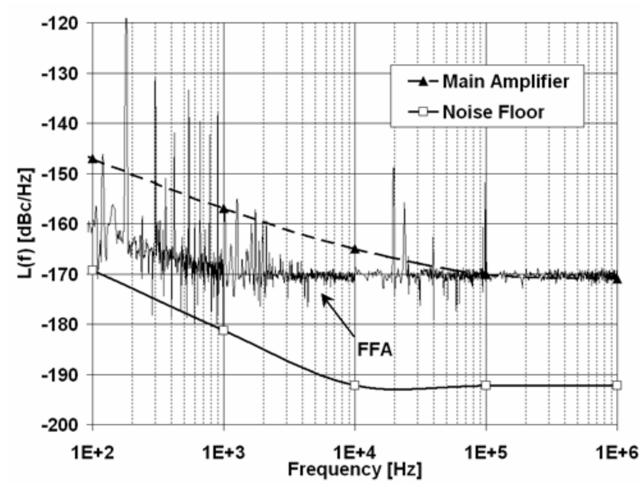

Figure 3. PM noise of main amplifier and FFA.

IV. FEED-FORWARD AMPLIFIER OSCILLATOR

In the design of an oscillator, the sustaining amplifier, also called the feedback or loop amplifier, is often the source of dominant noise. Since a feed-forward amplifier has very low PM noise it can be used to design a very low noise oscillator [11-12]. Therefore, we focused on building and testing an oscillator at 10 GHz using the FFA, the block diagram of which is shown in Figure 4. It consists of an air-dielectric cavity as the resonator [13], the array amplifier for loop gain, and a phase shifter. The loaded quality factor (Q_L) for the cavity is 20,000 with an insertion loss of 6 dB. In order to realize a FFA oscillator, it is important to keep the main amplifier operating in its linear range, at a level below saturation. Excess non-linearity will negate the important phase and amplitude balance in the FFA [11]. Usually a limiter can be used before the amplifier. However, we found that our FFA can also be configured to operate with some compression in the main amplifier [7]. Hence, our FFA oscillator design had the main amplifier operating slightly in compression for best performance. The typical phase noise plots of the oscillator with and without the FFA configuration is shown in Figure 5. One can see a significant improvement in the PM noise of the oscillator using the FFA scheme.

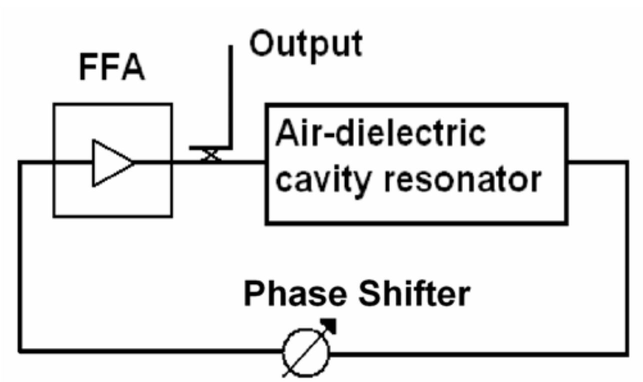

Figure 4. NIST air-dielectric cavity oscillator with FFA.

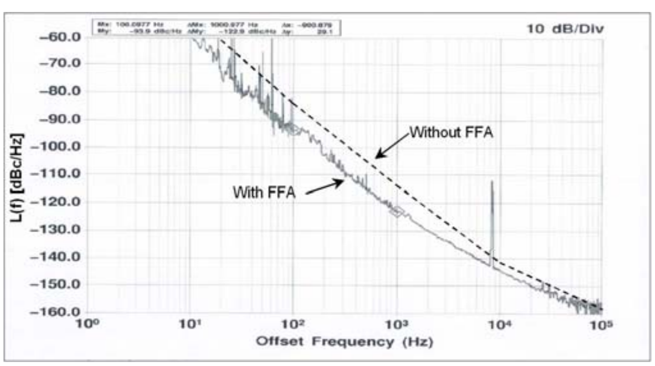

Figure 5. PM noise of NIST air-dielectric cavity oscillator with and without FFA.

We also calculated the theoretical value of the FFA oscillator's PM noise using Leeson's model [14]. The results, given in Table - I, show very good agreement between theory and the actual measurement of the PM noise.

TABLE I

Q_L=20,000, Insertion Loss = 6 dB
Main Amplifier Gain =18 dB
Noise Figure= 8.2 dB
Corner Frequency = 500 Hz

PM noise -L (f) [dBc/Hz]		
Offset Frequency [Hz]	**Theory**	**Actual**
100	-95.1	-93.9
1000	-121.1	-122
10,000	-142.6	-144
100,000	-162.2	-158 Limited by the noise floor of digital phase noise measurement system [15].

We then compared the PM noise of our FFA oscillator with the PM noise of different commercial oscillators [16-18], and this comparison is as shown in Figure 6. The PM noise of FFA oscillator is either better than or comparable with most commercial oscillators while being less expensive and in many cases less complex.

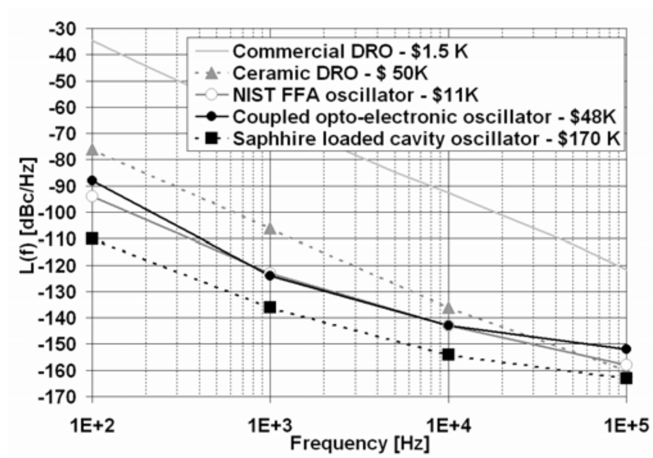

Figure 6. PM noise of different classes of oscillators at 10 GHz.

Finally, we measured the AM noise of the FFA oscillator. The results are compared with that of a sapphire loaded cavity oscillator (SLCO). The AM noise is 20 to 30 dB lower than the SLCO as shown in Figure 7. The AM noise performance of the FFA oscillator is lower than the AM noise of any existing oscillators at 10 GHz of which the authors are presently aware.

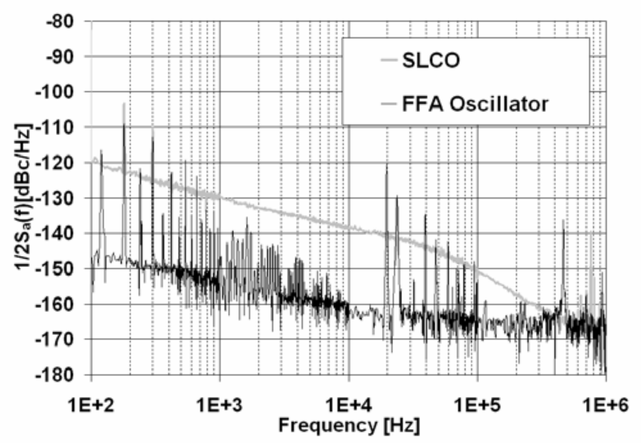

Figure 7. AM noise of FFA oscillator and SLCO.

V. SUMMARY

We designed a FFA whose PM noise performance is superior to existing commercial microwave amplifiers. The exceptional PM and AM noise performance of the FFA however, comes with the cost of large power consumption by the main amplifier, an array of eight parallel amplifiers. We also designed a FFA oscillator at 10 GHz with outstanding AM noise performance. The present performance of our FFA and oscillator is limited by several factors such as vibration sensitivity, low resonator Q_L and loss in the loop. We expect to improve the PM noise of the FFA oscillator by at least 7 to 10 dB at and below a 100 Hz offset frequency.

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