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LOW PHASE NOISE AND SPURIOUS LEVEL IN MULTI-LOOP OPTO-ELECTRONIC OSCILLATORS

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Abstract – **We report on substantial improvements of the phase noise, and especially the spurious level of the opto-electronic oscillator (OEO) by using multiple optical loops. We demonstrated a spurious level reduction of more than 30 dB in a dual loop OEO compared with that of a single loop OEO. We found the OEO's closed loop transfer function to describe very well the spurious pattern and to provide an excellent tool for the design of a low spurious multi-loop OEO. The advantages of the multi-loop OEO configuration for a widely tunable OEO will be discussed as well.**
Keywords - **Opto-electronic oscillator, low phase noise, low spurious level, tunable oscillator**

I. INTRODUCTION

Microwave oscillators are at the heart of modern communications systems providing reference signals to establish or select particular transmission channels; they also enable clock signals for many other electronic systems ranging from microprocessors to wireless base stations, radar, satellite communication link and optical network applications. This technology has advanced only incrementally over the past two decades while oscillator signal quality will become an even more critical factor in the performance of future microwave systems.

The goal of this paper is to report on substantial improvements in the spurious level of the opto-electronic oscillator (OEO) [1,2], initially demonstrated at the Jet Propulsion Laboratory (JPL). This approach has the unique features of providing spectrally pure signals of free running up to 80 GHz, with both electrical and optical outputs. At JPL, different configurations of the opto-electronic oscillator and the coupled opto-electronic oscillator were studied. The phase noise was additionally reduced using the carrier suppression scheme in a dual-loop opto-electronic configuration [3]. The acceleration sensitivity has been studied as well and shown to be as low as the best available commercial oscillator on the market [4].

The outline of this paper is as follows: We will start with a description of the OEO and its characteristics. Then, the low spurious multi-loop OEO will be described. Next, the advantages of the multi-loop OEO configuration for a widely tunable OEO will be discussed and measurement results will be presented.

II. THE OPTO-ELECTRONIC OSCILLATOR

The most common OEO is an active feedback loop in the form of a single-loop oscillator (see Fig. 1). It consists of a semiconductor laser injecting light into an optical fiber through an optical modulator. The detected modulated light in the high-speed photodetector is then amplified electronically to compensate for loss around the loop. Before the loop is closed, the signal is filtered by a microwave filter to select the desired frequency of interest among the possible modes of the oscillator (having mode spacing of ~c/nL, where c is the speed of light, n is the effective refractive index of the optical fiber and L is the fiber length).

The OEO is characterized by high spectral purity due to the long optical storage time provided by the long fiber in a closed loop. An important advantage of the OEO is that the quality factor (Q) is proportional to the oscillation frequency, leading to noise level performance that is independent of frequency. In fact the only limitation to achieve low phase noise at high frequencies is the availability of RF and optical components at these frequencies.

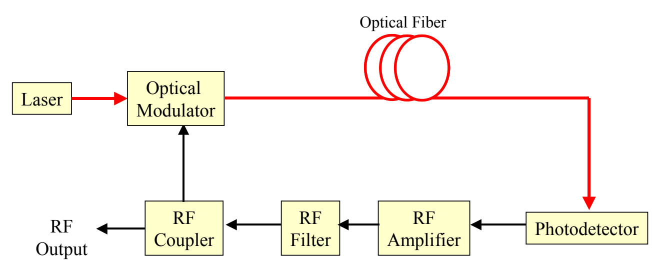

Fig. 1. Schematic diagram of an OEO.

The mode selection and spurious level are determined by the RF filter (see Fig. 2). The mode closest to the peak frequency of the filter will oscillate. Spurious will show up at other frequencies of the natural modes with the highest spurious level for the modes closest to the oscillating mode. The spurious level at higher offset frequencies drops following the filter transmission spectral shape. Clearly, the spurious level will depend on the filter bandwidth. Using a higher Q filter will result in lower spurious level. Note also, that with a tunable filter any of the modes chosen will provide the same phase noise.

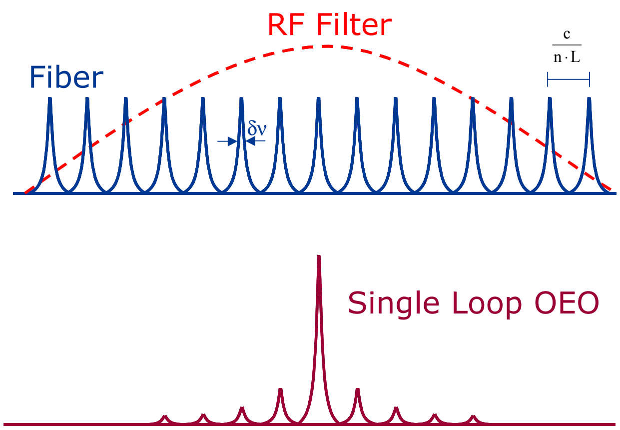

Fig. 2. Illustration of the mode selection and spurious level in a single loop OEO. The RF modes due to the long loop (top solid curve) are shown with the filter spectra (dashed curve) leading to the OEO oscillating spectrum at the bottom.

In a single loop OEO, the phase noise can be improved by increasing the fiber length (Q is proportional to L). However, at the same time the mode spacing becomes narrower, leading to a relatively high spurious level due to the limited ability to filter other super modes. For example, we have previously demonstrated a 10 GHz reference with phase noise level of –143 dBc/Hz at 10 kHz offset frequency [5, 6] and spurious level of –66 dBc (at 45 kHz), a level that is relatively high for some applications (see Fig. 3).

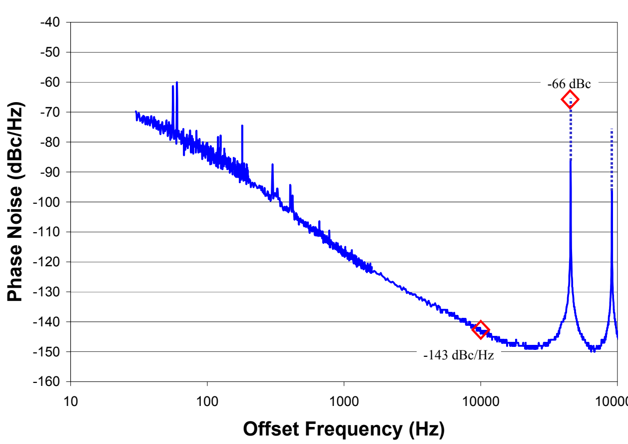

Fig. 3. Phase noise of single loop OEO with RF filter having Q=4,000. Solid curve describes phase noise measurement in units of dBc/Hz. Dotted line describes highest spurious measured in units of dBc.

As mentioned, a higher Q microwave filter will reduce the spurious level. We have demonstrated a reduction of about 30 dB in the spurious level for the first side mode (see Fig. 4), and significantly reduced the number of spurious by using a homemade microwave filter having Q of 38,000 at a carrier frequency of 8.98 GHz. Note however, that such filters are not always available at low cost and are harder to make at multi-GHz frequencies.

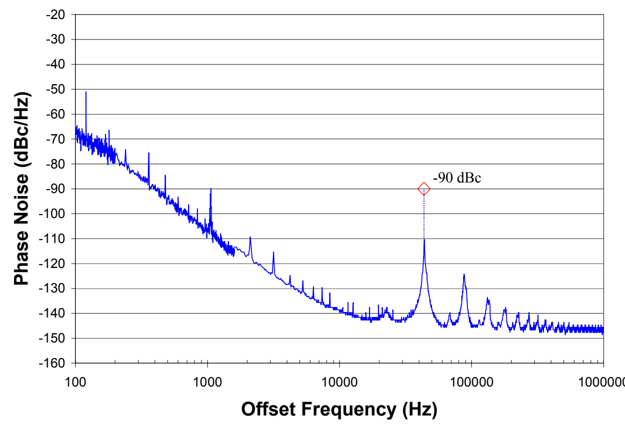

Fig. 4. Phase noise of single loop OEO with RF filter having Q=38,000.

III. Multi-loop OEO

Another method to reduce the spurious level, suggested before by Yao and Maleki [2], is by implementing a multi-loop OEO configuration. This method uses the natural structure of the OEO cavity to obtain additional filtering through an additional fiber loop or loops (having shorter lengths) in parallel with the long fiber loop. For example, as is illustrated in Fig. 5 for a dual optical loop OEO, the optical signal is split into two fibers having different lengths. Due to interferences between the two combined signals at the RF coupler, the multi-loop OEO will be characterized by strong mode selectivity and low spurious level.

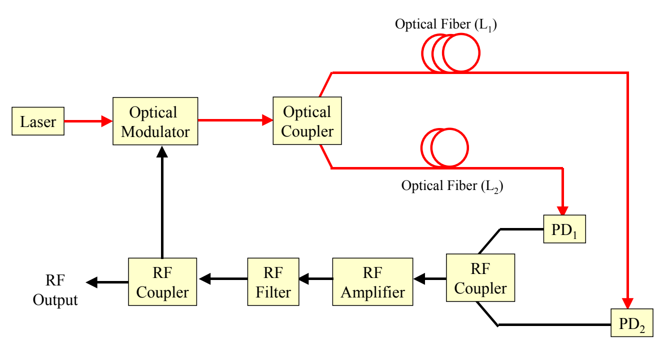

Fig. 5. Dual optical loop OEO configuration.

This effect is illustrated in Fig. 6. Since the OEO consists of two fibers having two lengths, not every mode of each loop can oscillate. Many of the modes corresponding to the long loop will meet low transmission at the short loop that due to interferences will result in low spurious. In this example, the modes of the two loops closest to the filter peak frequency will oscillate since they have constructive interferences. However, the nearest modes of the long fiber are now suppressed by the short fiber. Similarly, the nearest modes of the short fiber are suppressed by the long fiber. Only the second nearest modes of the short fiber and the fifth modes of the long fiber can oscillate in this example (this will depend on the ratio between the lengths of the fibers). However, these are at the roll off of the filter. Nevertheless, they might show up as the highest spurious in the phase noise of the oscillator.

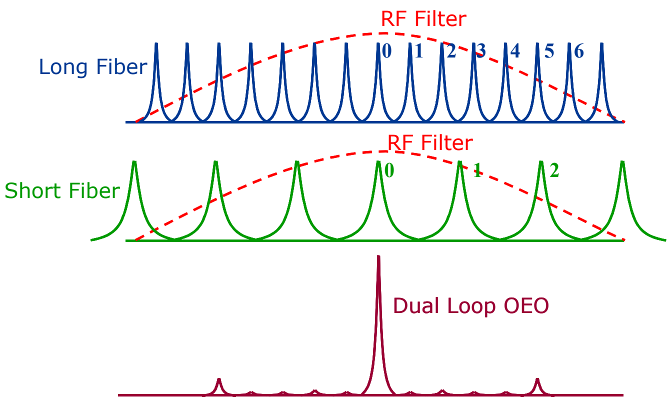

Fig. 6. Illustration of the mode selection and spurious level in a dual loop OEO. The RF modes due to the long fiber loop are shown with the filter spectra (dashed curve) and the short fiber loop RF spectra. This leads to the OEO oscillating spectrum at the bottom.

We have studied experimentally the effect of the multi-loop OEO on the phase noise and spurious level. First we have measured the phase noise of a single loop OEO using 4.4km fiber. The results are illustrated in Fig. 7 obtaining phase noise of –136 dBc/Hz at 10 kHz offset for 10 GHz carrier and spurious level of –61 dBc for the first spur at 45 kHz offset. At offset frequencies corresponding to multiples of the mode spacing, the spurious level drops, and its envelope follows (as $1/f^2$) the shape of the microwave filter passband. Note that the dotted line is to distinguish the spurious measured by dBc from that of phase noise measured by dBc/Hz.

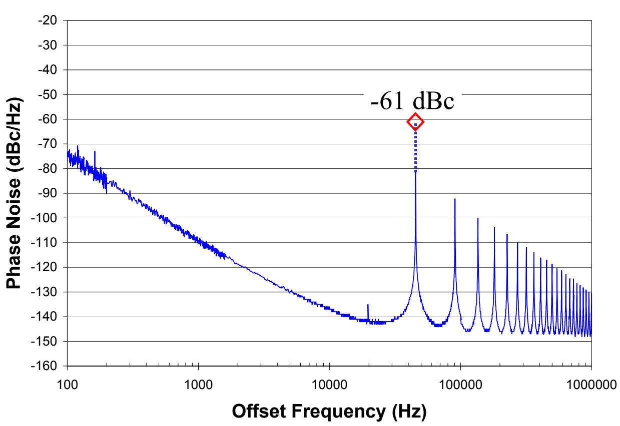

Fig. 7. SSB phase noise of a single loop OEO measured by the heterodyne method. The solid curve describes phase noise measurement in units of dBc/Hz. The dotted line describes highest spurious measured in units of dBc.

Next we have studied the multi-optical loop OEO. The phase noise and spurious level of a dual optical loop OEO with fiber lengths of 8.4 and 2.2km is illustrated in Fig. 8. The phase noise is improved by 4 dB at 10 kHz offset (-140 dBc/Hz) due to the long fiber, while the spurious level is improved by more than 30 dB. Note also that the highest spurious is shifted to a higher offset frequency.

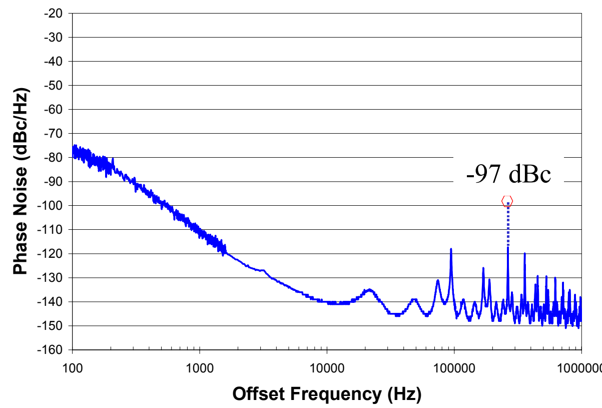

Fig. 8. SSB phase noise of a dual optical loop OEO measured by the heterodyne method.

The multi-loop OEO does not necessarily require longer total fiber length compared with the single-loop OEO. For example, the dual loop OEO (with total fiber length of L_1+L_2), illustrated in Fig. 5, can be implemented using two fiber spools (L_2, L_1-L_2), as is shown in Fig. 9, with total fiber length of only L_1.

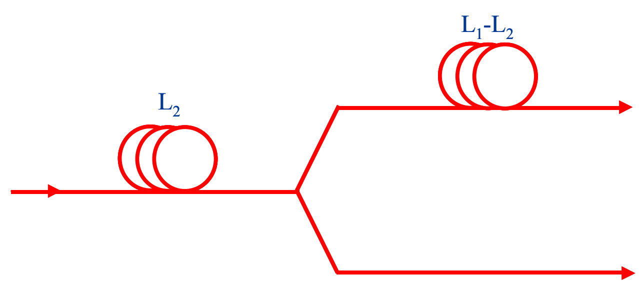

Fig. 9. Equivalent dual optical loop configuration with shorter fiber length.

IV. MODELING THE SPURIOUS PATTERN

In our effort to model the phase noise of the OEO at high offset frequencies, we have discovered that the spurious pattern can be represented by the closed loop transfer function multiplied by one over the square root of the offset frequency (f) as is given in equation (1):

$$\left|1 - A(\omega)\cdot \exp(i\omega\tau)\right|^{-2} \cdot \omega^{-1/2}, \qquad (1)$$

where $\omega=2\pi f$, τ is the fiber delay time ($\tau=nL/c$), and $A(\omega)$ is the RF filter's transmission spectra given approximately by:

$$A(\omega) = \frac{\omega_0}{\omega_0 - i \cdot \omega} \ . \quad (2)$$

$\omega_0 = 2\pi f_0$, and f_0 is the filter's HWHM transmission spectra, when it was assumed as a single pole filter close to the peak frequency. Note that the factor $\omega^{-1/2}$ most likely includes both, a noise source and a correction to the assumed filter spectra given in equation (2). Additional study is required to clarify this issue.

A plot of the phase noise compared with our analytical model given by equation (1) with L=4.4 km and f_0=1.25 MHz is illustrated in Fig. 10. Note the excellent matching between the two for offset frequencies between 1 kHz to 1 MHz.

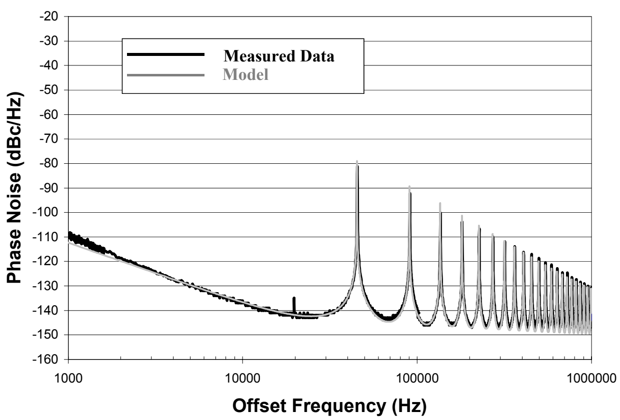

Fig. 10. Comparison between analytical model (gray curve) and phase noise of single-loop OEO (black curve). A relatively low Q filter was used (Q=4,000).

Next we compared equation (1) with the phase noise of a single loop OEO having high Q filter (f_0=112 kHz). The analytical model again fit very well with the measured phase noise (see Fig. 11).

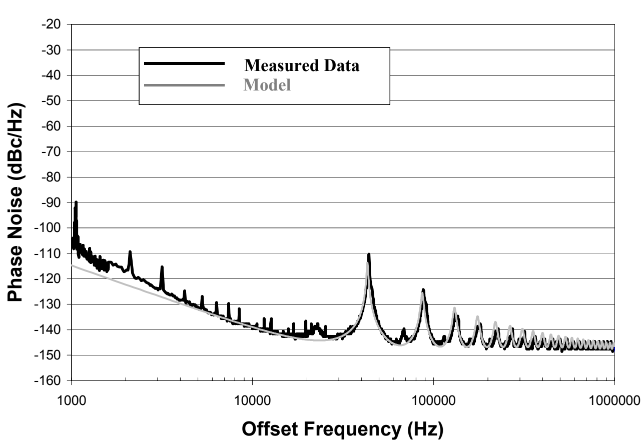

Fig. 11. Comparison between analytical model and (gray curve) phase noise of single-loop OEO. A relatively high Q filter was used (Q=38,000).

The closed loop transfer function of dual loop OEO should now include the lengths of the two fibers. In this case, equation (1) is now replaced with the following:

$$\left|1 - A(\omega) \cdot \left[\exp(i\omega\tau_1) + \exp(i\omega\tau_2)\right]/2\right|^{-2} \cdot \omega^{-1/2}, \quad (3)$$

where τ_1 and τ_2 are the delay times of the two fibers. Equation (3) with L_1=8.4 km, L_2=2.2 km and f_0=1.25 MHz is now compared with the phase noise of a dual loop OEO as illustrated in Fig. 12. Again, we obtained good agreement between the experimental data and the analytical model.

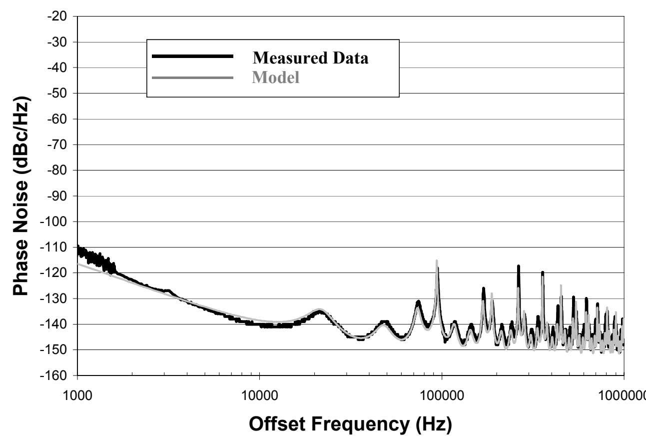

Fig. 12. Comparison between analytical model and (gray curve) phase noise of dual-loop OEO (black curve). Relatively low Q filter was used (Q=4,000).

We conclude that the analytical model that consists of the closed loop transfer spectra multiplied by one over the square root of the offset frequency is a simple and efficient tool to describe the spurious pattern and to use for the design of a low spurious OEO.

V. Tunable Opto-Electronic Oscillator

Since the multiple-loop OEO has stronger mode selection and lower spurious level, it can be used with lower Q RF filters, for example a YIG filter. The YIG filter, however, has the advantage of being able to be tuned across a wide range of frequency bandwidth. We have used the YIG filter to implement a widely tunable low noise OEO. The tunable opto-electronic oscillator was constructed with a commercial semiconductor laser and electro-absorption modulator in a single package. The modulator can be operated at frequencies up to 20 GHz. We used a commercial 2-stage YIG filter that is tunable from 2 to 18 GHz. However, the amplifier used in our set up limits the operation of the oscillator to a 6-12 GHz range.

Since the transmission spectral bandwidth of our YIG filter is about 36 MHz, a large number of modes survive in a single fiber loop, and while stable single mode operation is achievable, the oscillator was prone to mode hopping upon tuning, and the side mode spurs at –45 dBc were unacceptably high. We therefore implemented a three-loop configuration with fiber loops of 4.4, 3, and 1.2 km (see Fig. 13).

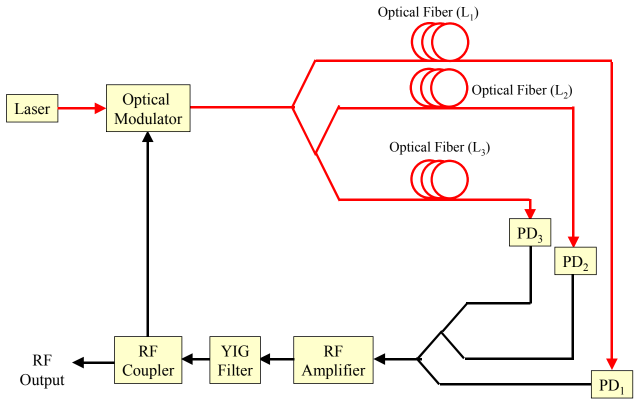

Fig. 13. Schematic diagram of the three loop YIG-tuned OEO.

This configuration resulted in an extremely robust oscillator that can smoothly and reliably be tuned at 3 MHz steps, by tuning the voltage to the YIG filter driver (0-10V). The step size is the result of the combined mode spacing of the three loops and is determined by the particular choice of the fiber lengths. At each frequency, though, the oscillator can be fine tuned using a voltage controlled phase shifters (VCPs). Three VCPs, located at each of the loops, continuously tune the oscillator through a frequency corresponding to the mode separation of the long loop length (45 kHz).

The noise performance of the YIG-tuned OEO is shown in Fig. 14 as the power spectral density of phase noise. Note that the actual spur level is lower than –90 dBc. The oscillator performance is independent of the oscillator frequency and is –128 dBc/Hz at 10 kHz for any carrier frequency between 6 and 12 GHz.

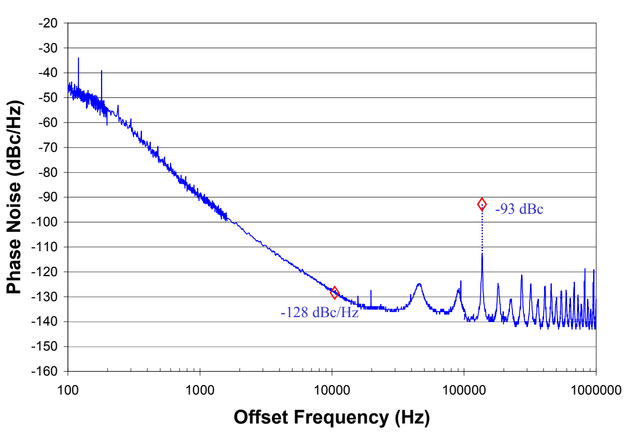

Fig. 14. SSB Phase noise of the YIG-tuned OEO at 10 GHz, measured by the heterodyne method. Similar phase noise levels were measured across the tuning range between 6 to 12 GHz.

Table 1 summarizes the other performance characteristics of the tunable OEO.

Table 1. Summary of other characteristics of the YIG tunable OEO.

Parameter	Value
Frequency	6-12 GHz
Output Power	> 15 dBm
Harmonics	Better than –30 dBc
Spurious	Better than –85 dBc
Step Tune	3 MHz
Fine Tuning Range	50 kHz
FM	Available
Package Size	19 inch rack mount

VI. Discussion and Conclusions

We have described the multi-loop OEO configuration and its efficient mode selection and reduced spurious level. The dual loop OEO can reduce the spurious level by more than 30 dB and shift the highest spurious to higher offset frequency. The OEO's closed loop transfer spectra multiplied by one over the square root of the offset frequency, describes accurately the spurious pattern and is an efficient tool for designing a multi-loop low spurious OEO.

Using a triple-loop OEO and a YIG filter, we have designed and demonstrated a high performance widely tunable OEO with a phase noise performance exceeding conventional YIG-tuned oscillators by about 30 dB. The performance of the tunable OEO is limited by the performance of the amplifier and the YIG filter. Thus we believe that a higher performance YIG-tuned OEO is possible. While the oscillator we demonstrated has a range of 6 to 12 GHz, with the choice of the proper components any oscillation in a range supported by the YIG filter is readily achievable.

Acknowledgment

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