Tunable, Ultra-Low Phase Noise YIG Based Opto-Electronic Oscillator

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Abstract – **We will describe a YIG tuned Opto-Electronic Oscillator with extremely low phase noise. The oscillator can be tuned from 6 to 12 GHz in steps of 3 MHz, and exhibits a phase noise of –128 dBc/Hz at 10 KHz away from the carrier. This is nearly a 30 dB improvement over conventional YIG oscillators, and is derived from the novel approach of the Opto-Electronic Oscillator. To our knowledge, this is the lowest noise performance of any YIG tuned oscillator previously reported.**

I. Introduction

Tunable oscillators are a workhorse of test and measurement technology, and are the heart of synthesizers, signal generators, spectrum analyzers, and other test equipment. Since wide tunability is a requirement for these applications, virtually all oscillators in the GHz regime are based on the use of YIG filters. Thus tunability in the range of 2 to 18 GHz is readily obtained, and the achievable tunability range is only limited by the range of the filter. Despite this versatility, YIG filters are relatively low Q devices that, when used in the conventional electronic oscillator configurations lead to relatively poor phase noise performance. Typical YIG-tuned oscillators perform at about –100 dBc/Hz at 10 KHz from the carrier (10 GHz), and the phase noise performance varies with the carrier frequency, degrading with increasing frequency.

The Opto-Electronic Oscillator (OEO) [1] is a fundamentally different approach to the generation of spectrally pure reference frequency that has demonstrated very high spectral purity, -143 dBc/Hz at 10 KHz from a 10 GHz carrier [2]. The previous realization of the OEO has been primarily focused on the generation of fixed frequencies, although tunability over a limited range using a filter bank has also been demonstrated [3], or by varying the filter temperature [2]. In the present work we have utilized a YIG filter to extend the tunability range of the OEO to a significantly wider regime. This approach preserves the high spectral purity of the OEO, and results in, to our knowledge, the highest performance YIG-tuned oscillator ever developed. In part II we will review the principle of operation of the OEO, and describe some of the salient features of this approach for generation of millimeter wave and microwave frequencies. In part III a description and results of the YIG-tuned OEO will be made. A conclusion is presented in part IV.

II. Principle of Operation of the OEO

The OEO is based on an opto-electronic feedback loop that directly converts light energy to spectrally pure microwave oscillation, and has been described in detail previously [1]. The oscillator begins with a continuous wave laser that acts as the source of energy. The laser output passes through an electro-optic modulator, followed by a long fiber delay and a photo-detector, which converts the light energy into electrical output. This output in turn is amplified and filtered before being introduced to the electrical port of the modulator, completing the feedback loop. This configuration, depicted in Figure 1, leads to self sustained oscillation when the loop gain is larger than losses, and the waves going around the loop add up in phase.

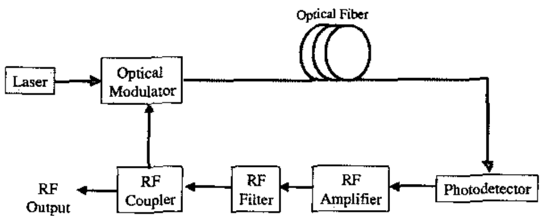

Figure 1. Schematic diagram of an OEO.

The long fiber delay (typically one or more kilometers) with the length L provides the large Q through $Q = \pi\tau f_0$, where f_0 is the oscillator frequency, and $\tau = nL/c$ is the time it takes for light with velocity c to pass through the fiber with index of refraction n. The feedback loop is inherently multi-mode, with mode spacing related to the length of the

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fiber with a corresponding frequency equal to $1/\tau$. The insertion of the filter in the loop then allows the selection of a particular mode for single frequency oscillation. Thus the same OEO can operate at any frequency supported by the modulator by simple selection of the filter. OEO's operating with frequency in excess of 40 GHz have been previously demonstrated [4].

Since the optical elements in the loop have a fixed loss and dispersion across a few nm, they have the same loss for the modulated sidebands of the carrier. Thus an OEO operating at, say, 5 GHz, has the same noise performance as one operating at 50 GHz, assuming the same amplifier noise for the two examples. This is an extremely useful and unique feature of the OEO, which results in the absence of degradation in phase noise performance with increasing frequency, in contrast to conventional oscillators.

While the multi-mode feature of the OEO provides for a valuable versatility allowing the selection of the operating frequency at any mode, it nevertheless results in the presence of side modes to the operating frequency. These side modes, in principle, can be eliminated if the bandpass of the filter is comparable to the mode separation frequency, which for a four kilometer fiber is 50 KHz. Such a high-Q filter is difficult to realize at GHz range, with readily available high-Q filters having a 3-dB bandwidth of a few MHz. Thus in practice side modes in the OEO persist, and show up in the phase noise spectrum at a frequency corresponding to the mode separation, and its subsequent harmonics. As an example the highest peak in the noise spectrum of a typical OEO with 4.4 kilometers of fiber and a 3 MHz filter is about –65 dBc. While suitable for many applications, this level of noise is unacceptable for high performance test and measurement equipment.

A simple solution to the above problem is the use of multiple fiber loops. Since waves in all loops in such a configuration must add up in phase for sustained oscillation, only modes that coincide in frequency in each loop survive, resulting in significant reduction of the peaks in the phase noise spectrum [5]. The addition of a second loop with 1.2 km of fiber to the above mentioned 4 km loop reduces the side mode peaks by about 30 dB.

We close this short review of the principle of operation of the OEO by mentioning that the performance of the free running oscillator is limited only by the flicker noise of the amplifier and the bandwidth of the filter. Improved amplifiers and filters will simply result in better performance.

III. THE YIG-TUNED OEO

From the above discussion it is clear that a tunable filter will allow the OEO to oscillate at any modal frequency. Based on this we fabricated and tested a YIG-tuned OEO. This tunable 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 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 hoping 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 Figure 2).

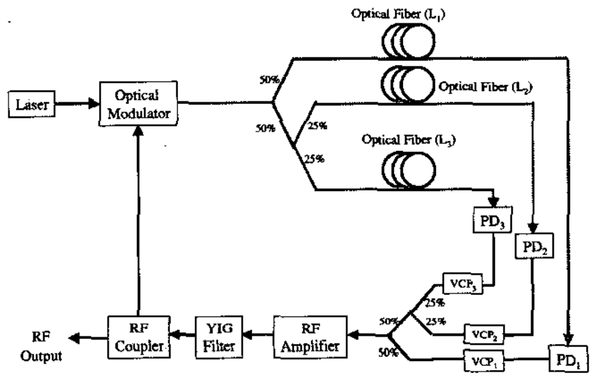

Figure 2. Schematic diagram of the three loop YIG-tuned OEO.

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 shifter (VCP). The VCP continuously tunes the oscillator through a frequency corresponding to the mode separation of the loop length. As is shown in Figure 2, three VCPs were used, controlled through voltage dividers, in order to compensate for the different tuning range of the three different loop lengths. This configuration allows for the synchronization of the frequency shift at the three different loops providing continuous tuning. The final tuning range is set by the smallest mode spacing. In our configuration, this spacing is 45 KHz, corresponding to continuous tunability of >50 KHz, which is adequate for phase locking the oscillator to a stable reference and frequency modulation. The noise performance of the YIG-tuned OEO is shown in Figure 3 as the power spectral density of phase noise. Note that the actual spurs 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.

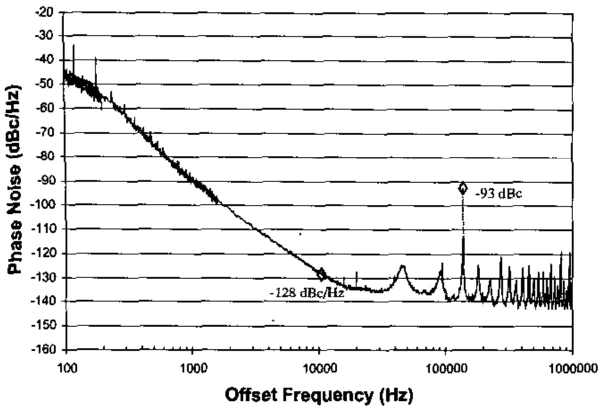

Figure 3. SSB Phase noise of the YIG-tuned OEO at 10 GHz, measured by the heterodyne method. Similar phase noise levels were measured across the tuning range between 6 to 12 GHz.

IV. Conclusions

We have designed and demonstrated a high performance free-running YIG-tuned oscillator with a phase noise performance exceeding conventional YIG-tuned oscillators by about 30 dB. This oscillator is based on a unique opto-electronic feedback loop, the performance of which is limited by the performance of the amplifier and the YIG filter. Thus we believe that higher performance for a 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.

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