

A Miniature YIG Tuned Oscillator/Frequency Divider Achieves Octave Tuning Bandwidth with Ultra Low Phase Noise in S, C, X and Ku Bands

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Abstract —Traditional YIG tuned oscillators use negative resistance type circuits and large magnetic structure to produce excellent phase noise with octave plus tuning ranges, but at the expense of size and weight. This paper describes a revolutionary approach to YIG tuned oscillator design which makes use of a unique combination of a miniaturized magnetic structure, and a GaAs HBT ring oscillator circuit topology, working through a YIG tuned filter to produce octave tuning ranges in X and Ku bands with phase noise less than -125 dBC per Hz at 100 KHz. To cover S and C bands, a digital IC frequency divider is used to divide the output frequency by an integer N. Phase noise is shown to improve by a factor $20\text{Log}(N)$. For $N=4$, and $F_0=12$ GHz, at an output frequency of 3 GHz, the measured phase noise is -137 dBC per Hz at 100 KHz.

I. INTRODUCTION

Traditional YIG tuned oscillators (YTOs) have made use of negative resistance type circuit [1] and very large magnetic structures to produce microwave sources with extremely linear magnetic tuning, and excellent phase noise over an electronic tuning range of 1 to 2 octaves. In many important ways, YTOs offer superior performance relative to other types of oscillators such as voltage controlled oscillators (VCOs) and dielectrically tuned oscillators (DTOs), however size and weight considerations have long prevented the adoption of YTOs by many areas of the electronics industry. This is especially true of YTOs operating in Ku band or higher where the traditional YTO magnetic structures are very large. Varactor tuned VCOs are small and light, but lack the wide linear tuning range and the low phase noise of YTOs. DTOs have excellent phase noise but are limited to fixed tuned applications. Also DTOs remain very expensive due to the high cost of the skilled alignment labor that is required for their manufacture.

This paper describes a very significant advance in the YTO field, offering superior performance by making use of a highly refined miniature magnetic structure tuning a single sphere YIG filter which completes a feedback loop as part of a GaAs HBT ring oscillator circuit topology, of the kind described by Hajimiri and Lee [2]. The magnetic structure is less than $\frac{1}{4}$ of the size and weight of traditional YTOs, but is capable of

tuning the oscillator to 14 GHz and beyond. An IC frequency divider is used to divide the fundamental oscillator output frequency by a integer N, obtaining at the divided frequency the same percentage tuning bandwidth with phase noise reduced by a factor of $20\text{Log}(N)$. Frequency division is an excellent way of producing low frequency outputs, because YIG devices are best used at higher frequencies (above 10 GHz) where they reach their maximum Q and are free of spurious modes. The ring oscillator circuit topology uses a GaAs HBT Darlington amplifier circuit [3] providing nearly flat gain from DC to 15 GHz. Ring oscillator circuits use positive feedback, which can start oscillations over the full operating bandwidth of the amplifier. Providing the parallel feedback around the amplifier produces an open loop gain greater than 0 dB, and an open loop phase of $N(2\pi)$, where N is an integer. As long as these conditions are met, the resulting oscillator can potentially be tuned over the entire bandwidth of the amplifier; which in the case of a GaAs HBT Darlington amplifier could exceed 1 decade [3].

II. A COMPARISON OF YTO CIRCUIT TOPOLOGIES

The phase noise of oscillators constructed with Si Bipolar devices is quite good as a direct result of the low $1/f$ noise associated with this class of transistor [4]. However in the case of GaAs mesfet devices which are most often used in high frequency YTOs, close-in phase noise (in the $1/f^2$ region) is often poor due to the up conversion of the $1/f$ noise produced by surface trapping states associated with this class of transistor [4]. The result is that traditional YTOs can produce excellent phase noise up to 10 GHz, but at higher frequencies their phase noise may be compromised.

We compare these YTO characteristics with what can be obtained with the ring oscillator topology. The ring oscillator is composed of a GaAs HBT Darlington amplifier and a YIG tuned filter closing a parallel feedback path around the amplifier. A second identical Darlington amplifier serves as a buffer amplifier, reducing load-pulling effects and raising the output power. Fig. 1 shows the block diagram of the ring oscillator followed by the digital divide by N circuit. As long

as the open loop gain and phase requirements for oscillation are satisfied, this circuit can oscillate over the full frequency range of the amplifier. Like their Si bipolar counterparts, GaAs HBTs are bipolar transistors making them far less subject to $1/f$ noise than GaAs mesfets. Therefore we expect this circuit topology to yield excellent phase noise up to a fundamental frequency of 20 GHz and beyond

III. RING OSCILLATOR TOPOLOGY

The ring oscillator is composed of a very wide band Darlington amplifier plus a YIG tuned filter. This filter, which is configured as two half loops, is a natural differential circuit. The filter's behavior is critical to the overall operation of the YTO because it is this magnetically tunability of the filter, which selects the frequency at which oscillations may start.

A. The YIG filter

The YIG filter consists of two half-wire loops, one running under the YIG sphere and the other running over the top of the sphere. The clearance between the sphere and the loops is 10 mils. YIG resonance is a direct result of a quantum mechanical phenomenon called spin precession [1]. Unlike circuit element resonators, such as those found in varactor tuned, VCOs, YIG resonators, by virtue of their quantum mechanical nature, maintain high Q factors to extremely high frequencies, and in fact work better at high frequencies than at low frequencies. The result is low phase noise over extremely wide tuning bandwidths. The spin precession resonant frequency of YIG is set by a Z directed DC magnetic field, H_{dc} . The RF magnetic field vector, which is in the X-Y plane, rotates at right angles to the DC magnetic field, which is aligned along the Z-axis. H_{rfX} and H_{rfY} , are the X and Y directed components of the rotating RF magnetic field associated with spin precession. Because RF currents flow in opposite directions within the two (top and bottom) coupling loops, a natural 180-degree phase shift occurs between the same-sided filter inputs and outputs. Since the physical plane of the top loop is rotated by 90 degrees relative to the physical plane of the bottom loop, a natural 90 degree phase shift occurs between the loops because one of them is always experiencing a peak of the RF magnetic field occurring at 90 degrees relative to the other. Therefore a total phase shift of 270 degrees is directly associated with the YIG filter. The filter's 3 dB bandwidth is about 25 MHz. For simulation purposes, this YIG filter is modeled as a differential Bessel filter coupled to the surrounding loop elements by two ideal transformers. The bandwidth of each filter is set to 25 MHz, which implies a Q factor of about 600 at 12 GHz.

B. The Gain Block Amplifier

The gain block amplifier makes use of a Darlington topology [2] and GaAs/InGaP HBT fabrication technology. The amplifier's two bipolar transistors have emitter

dimensions of 2 microns x 20 microns and 2 microns x 40 microns respectively. This amplifier, whose overall dimensions are 350 microns x 500 microns, has nearly flat gain from DC to 15 GHz and a very constant phase shift over frequency. The amplifier's outstanding performance is due to its small size and freedom from parasitic elements.

A model for the Darlington amplifier, including layout parasitic elements is used to simulate the performance of the ring oscillator. Agreement between the measured and simulated amplifier performance is excellent. Phase shift of S_{21} is a nearly constant 180 degrees over a bandwidth exceeding one octave. The amplifier was fabricated on a 6 inch GaAs/InGaP HBT process at the Knowledge On foundry in South Korea.

C. Open Loop Gain and Phase Simulations

The open loop gain and phase of the oscillator is simulated to determine the conditions necessary for start of oscillation. If we simply add up the individual phase contributions around the loop, we get 2π plus 90 degrees. However component interactions and the affect of the tuning stub, which is connected to the differential YIG filter's unused port, reduces this total significantly.

The simulated open loop gain is greater than 0 dB, and the associated phase shift is centered at 0 degrees (i.e. $1 \times 2\pi$), and is adjustable with the length of a coplanar wave-guide stub connected to the unused port of the YIG filter. This transmission line stub serves as a phase adjustment, providing an easy way to set the center frequency of the desired band of oscillations. At 12 GHz, the open loop phase shift may be adjusted by ± 40 degrees with this stub. Adjustment of the stub's length is the only alignment step required during the manufacture of this YTO, leading to low manufacturing costs. The simulated open loop gain and phase fulfill all of the conditions for start oscillation. In their physical realization, the circuit elements are mounted on a ceramic substrate, which has a cutout allowing the YIG sphere to be mounted in the middle of two orthogonal half coupling loops (one on the top and one on the bottom of the YIG sphere).

D. The Magnetic Structure

The miniature YTO uses a permanent magnet ring and field focuser to define a very narrow air-gap, typically 100 mils, in which the YIG sphere is located. The permanent magnet determines the quiescent operating frequency. The main tuning coil surrounding the permanent magnet has 2200 turns providing a tuning rate of 25 MHz per mA. Tuning current will raise or lower the frequency. A shield magnet above the field focuser prevents magnetic flux from flowing in the outer shell, greatly reducing the affects of mechanical vibration and phase hits occurring at temperature extremes. The YTO's overall size (including outer shell) is .75 inches in diameter and .60 inches high. Its weight is 25 grams. This structure can easily be adapted to surface mount packaging technology.

VI. CLOSED LOOP OSCILLATOR PERFORMANCE

By closing the ring oscillator's loop, it is possible to simulate the YTO's power output, waveform and phase noise over a range of frequencies. According to Hajimiri and Lee [2] it is very important for ring oscillators to maintain a highly symmetric output waveform in order to keep to a minimum that portion of the phase noise caused by up converted $1/f$ noise. Since HBT devices generate very little $1/f$ noise due to their bulk effect structure, a highly symmetric waveform provides double protection against $1/f^3$ low frequency phase noise associated with the up converted $1/f$ noise. Simulations indicate a nearly sinusoidal waveform over a wide range of operating frequencies.

Strong oscillations are predicted by simulation to occur in the octave from 7 GHz to 14 GHz., with power output in excess of +10 dBm. Under closed loop conditions, the simulated phase noise at 12 GHz is less than -125 dBC per Hz at 100 KHz, which is a 10 dB improvement over mesfet YTOs operating at this frequency.

Measured power from 7 GHz to 14 GHz is about +10 dBm, in agreement with simulations. The center frequency of the YTO's tuning bandwidth may be adjusted inversely with stub length. The measured phase noise at 12 GHz is -125 dBC per Hz at 100 KHz offset, in close agreement with simulations. Following the YTO with a divide by 4 digital IC divider, the measured phase noise at the divided frequency (3 GHz) is -137 dBC per Hz at 100 KHz offset, in almost perfect agreement with the $20\text{Log}(N)$ phase noise reduction rule for frequency dividers. A graph of measured phase noise for both

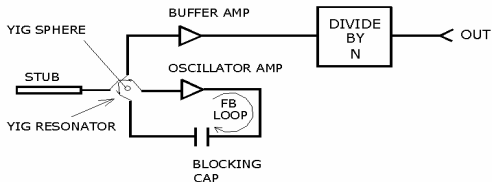


Fig. 1 Block diagram of Ring Oscillator and Divide by N IC

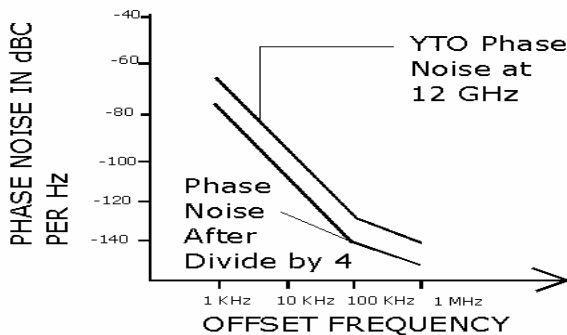


Fig. 2 Phase noise before and after dividing by 4 (3 GHz)

the fundamental oscillations at 12 GHz, and the divided by 4 signal at 3 GHz are shown in Fig. 2. The phase noise delta between the two signals is in excellent agreement with $20\text{Log}(4)=12$ dB.

VII. CONCLUSIONS

The YTO reported in this paper represents a significant step forward in YIG source technology. By combining a ring oscillator topology with GaAs/InGaP HBT device technology, plus a miniature YIG filter, the new oscillator to be described in this paper is capable of operating well into Ku band at its fundamental frequency with superior phase noise and power output. By using a frequency divider IC, to divide the YTO's fundamental output frequency by a integer N, the same percentage tuning bandwidth is maintained at the lower frequencies while the phase noise is reduced by a factor of $20\text{Log}(N)$. Also, because the oscillator's circuit elements are very forgiving, alignment labor is kept to a minimum, translating into efficient, lower cost of manufacturing.

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