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A LOW-COST, NIST-TRACEABLE, HIGH PERFORMANCE DIELECTRIC RESONATOR MASTER OSCILLATOR*

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Abstract

The current CEBAF Master Oscillator (MO) uses a quartz-based 10 MHz reference to synthesize 70 MHz and 499 MHz, which are then distributed to each of the klystron galleries on site. Due to the specialised nature of CEBAF's MO requirements, it has been determined that an in-house design and fabrication would provide a cost-effective alternative to purchasing or modifying vendor equipment. A Global Positioning System (GPS) disciplined, Direct Digital Synthesis (DDS) based MO is proposed which incorporates low-cost consumer RF components, designed for cellular communications. A 499 MHz Dielectric Resonant Oscillator (DRO) Voltage Controlled Oscillator (VCO) is phase-locked to a GPS-disciplined 10 MHz reference, and micro-tuned via a DDS, in an effort to achieve the lowest phase noise possible.

1 INTRODUCTION

The Thomas Jefferson National Accelerator Facility (Jefferson Lab) consists of a 5.5 GeV nuclear physics accelerator (CEBAF) and a 500 watt IR Free Electron Laser (FEL). Both machines have placed tight requirements on their beam parameters, most notably energy spread. Future beam requirements for accelerators used in nuclear physics and as UV FEL drivers will demand stringent timing requirements for the RF MO. In the case of the nuclear physics accelerator, the timing jitter (induced by phase noise) contributes to the overall energy spread of the electron beam[1]. Similarly, in the FEL, the laser cavity performance is affected by the timing jitter between successive light pulses and electron bunches [2]. Typically, accelerator designers have taken a rather easy, but expensive, approach and purchased high-end full-featured frequency synthesizers, most notably from Hewlett Packard. This paper serves as a survey of the many cost-effective oscillator options available to the RF engineer. The paper is divided into three sections; the first is a brief discussion of phase noise / timing jitter, the second is a comparison of four types of resonator-oscillators: crystal, SAW, DRO, and CRO. An attempt is made to simulate the performance with the application of a 2nd-order phase-lock loop (PLL). The paper concludes with a discussion on technology and cost, and a proposed RF MO.

2 OSCILLATOR EVALUATION

Precision oscillators are characterized in both the time and frequency domains. Timing jitter is the relative measure of stability from cycle-to-cycle, over a prescribed interval. The common method for reporting stability, as prescribed by the IEEE, involves averaging differences in consecutive sample pairs (a two-sample variance AVAR), and is known as the Allan Variance [3]. Although small Allan Variance values for long intervals are regarded as good clocks, accelerator applications require a high stability for the brief time a particle is in orbit within the machine.

Jitter is the composite of a large sum of Fourier fractional frequency, or phase, fluctuations about the carrier frequency. In the frequency domain, this is phase noise, and is defined by the IEEE to be the total noise power in a 1 Hz bandwidth, divided by the total carrier power (including sidebands), as measured at a carrier-offset frequency, f:

$$S_{\Phi}(f) = \Delta\Phi(f) * BW^{-1}, \quad \text{Radians}^2 / \text{Hz}$$

Typically, only one sideband is presented, and the units are logarithmic:

$$L(f) = 10 * \log (\tfrac{1}{2} * S_{\Phi}(f)), \quad \text{dBc / Hz}$$

The 1 Hz measurement bandwidth allows a universal comparison to be performed, while the L(f) eliminates restrictions on the values for f. Unnecessary phase noise redistributes carrier energy into the sidebands, where power is wasted. This effect can be quite considerable, as in the case of the Jefferson Lab UV FEL RF control system, which powers the high-Q (10^7) superconducting RF cavities. The UV FEL specification requires a 1497 MHz phase noise envelope of $2.6 \times 10^{-10} / f$ [2].

Measurement of phase noise is accomplished by either an autocorrelation, or a cross-correlation with a known, low-noise reference oscillator. The technique employed to measure phase noise at Jefferson Lab is shown in Figure 1. An ultra-low phase noise Hewlett Packard HP 8663 synthesized microwave signal source was used as a standard, to which the unit under test (UUT) was loosely phase-locked. After the two oscillators are multiplied together, the baseband signal is applied to an FFT spectrum analyzer for analysis. A dBV/Hz readout with a correction for detector gain was used to determine the L(f) in dBc/Hz.

SIGINT, a numerical method used to transform the phase noise spectrum into a time-domain description of frequency stability, was developed at NIST, which allows

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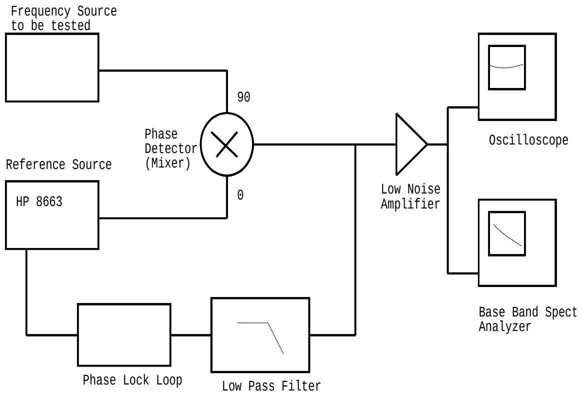
the designer to accurately predict oscillator performance [4].

Figure 1. Phase noise test fixture.



3 RESONATOR OPTIONS

3.1 Crystal Oscillator

Historically, quartz-crystal resonators have been used to construct high-stability oscillators which exhibit good phase noise, particularly close to the carrier. In addition, recent availability of Global Positioning Satellite (GPS) technology permits easy phase-lock capability, with NIST traceability [5]. Their frequency use is restricted to the 1-20 MHz range, with 5 MHz being the optimum frequency for phase noise performance [6]. Frequency multiplication is required above these ranges. Although phase noise is a non-linear phenomenon, scaling to other carrier frequencies is possible if integrated phase noise values of less then 0.2 Radians are obtained [7]. A naïve scaling can then be applied:

$$L(f)_{\nu_2} = L(f)_{\nu_1} + 20 * \log (\nu_2/\nu_1)$$

To move from a carrier frequency of 5 MHz to a frequency of 499 MHz, the entire L(f) spectrum is scaled by 34 dB. Although the close-in performance is retained, an ultimate high-frequency limit of –130 dBc/Hz is reached for Fourier frequencies above 1kHz. For this reason, it is desirable to use the close-in behavior of quartz as a synthesizer reference, but appeal to other resonators which might exhibit better high-frequency characteristics.

3.2 Surface Acoustic Wave

The Surface Acoustic Wave (SAW) oscillator is well suited for the 500 MHz - 1GHz portion of the RF spectrum, due mainly to its small size. The SAW device tested at Jefferson Lab was an off-the-shelf component sampled by a vendor. A free-running center frequency of 500 MHz was measured. The tuning port was terminated in 50 Ohms to minimize frequency drift. The SAW possessed a high resistance to microphonics, short of tapping directly on the enclosure.

3.3 Dielectric Resonant Oscillator

Dielectric Resonant Oscillators (DRO) have become popular as potential low-noise microwave sources. They serve to provide high-Q resonators, of relatively small size. Phase noise performance is suggested to be optimized for the 1-2 GHz range.

A DRO was fabricated at TJNAF, primarily in accordance with Loboda et al. and technical briefs from the dielectric supplier [8]. Two software models were employed to determine cavity dimensions and coupling schemes. Copper was chosen, due to its superior RF characteristics.

Raw measurements produced Q and insertion loss (IL) values of 10,000 and –4 dB. Minimal attempts were made to optimize cavity coupling. Final values for loaded-Q and IL, to be used in the test DRO oscillator were 15,000 and -10 dB, respectively.

A transmission type of oscillator was assembled using the high-Q cavity, a low-noise amplifier, and a coaxial transmission line of appropriate electrical length to sustain oscillation.

Phase noise performance was carefully measured by acoustically isolating the cavity from surroundings, minimizing susceptibility of environmental effects. Microphonics were prevalent, adding to the close-in phase noise.

3.3.1 Frequency Divider for DRO

A 499 MHz DRO presents a cavity structure too large for most practical applications, so a tradeoff of 1497MHz was employed. A divider scheme is required to arrive at the 499 MHz operating frequency.

Prescalers are susceptible to additional phase noise, mostly from amplitude fluctuations. A Miller divider, first proposed in 1939, employed a regenerative feedback approach to achieve a divide by (N+1) output. Recently, NIST engineers have applied the Miller circuit to microwave oscillators, appearing in Figure 5, and achieving exceptional PM performance [9]. Since the overall divide ratio is N+1, a divide-by-two scheme requires no multiplier, improving reliability. This configuration was selected for its simplicity, in order to determine feasibility.

After the measurement, a full phase-locked-loop (PLL) was induced, in order to evaluate in-situ performance. No attempt was made to optimize the loop filter, other than to achieve stability.

The measured SAW, divided DRO phase noise, locked DRO and UV FEL specification, scaled for 499 MHz, are all summarized in Figure 2. The test fixture appears to have an ultimate noise floor at ~ -130 dBc, providing a worst-case performance bound. Despite that, the trends of each of the oscillators is evident. Loboda, et al. Have demonstrated 1.5 GHz DRO phase noise performance of –130 dBc at 1kHz, further supporting their use[8].

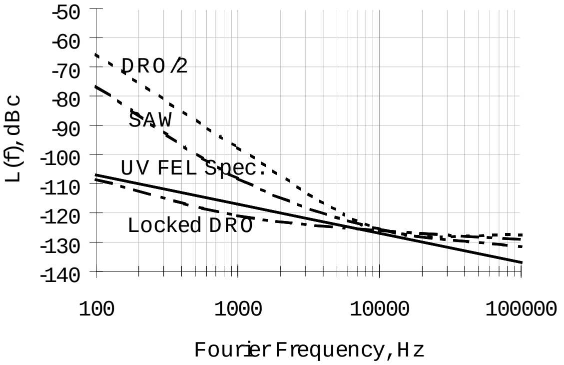


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Figure 2. Phase noise summary of SAW and DRO oscillators

3.4 Coaxial Resonator

Another trend in the communications industry is the use of coaxial resonant oscillators (CRO), which employ a ¼-wave coaxial dielectric structure as a feedback element. They are commonly used at UHF frequencies, and have typical Q values of less than 1000. Therefore low phase-noise performance is difficult to achieve, without the use of loop filters of high-order (>5). These filters permit the designer to tailor resultant phase noise by optimizing poles and zeros within the control loop, but often present an enigmatic design challenge.

4 CONCLUSION

Of the four options explored, the most attractive appears to be the DRO oscillator. Although the SAW exhibited excellent noise, along with immunity to microphonics, its cost per unit is quite high. At the time of this manuscript, a typical price for an off-the-shelf SAW, for standard frequency dies, was ~$2000. Custom frequencies incur an additional engineering-setup charge which could be as high as $8000. Conversely, the DRO material is relatively inexpensive (~$30 per puck) in small quantities. Additional cost would exist for optimizing puck dimensions for a specific frequency, with the remaining cost embedded in cavity fabrication. Despite the susceptibility of the cavity to microphonics, little was required to eliminate with the use of a PLL. Additionally, the proliferation of software tools for DRO applications made cavity designs particularly easy. Popularity of these devices surely rests on having these design tools available.

The unit cost for CRO elements is by far the least expensive ($1.00 / unit), and the same software as was used in the DRO design is applicable to CROs. Given the requirement for complex loop filters to minimize phase noise, the CRO would not be the first choice for a precision UHF oscillator. However, software simulation packages such as MatLab or Elanix would certainly reduce design time.

The use of a crystal-only arrangement would demand that a ~5-10 MHz oscillator be multiplied to the necessary frequency, achieving an ultimate phase noise floor of ~-130 dBc, not achieving Jefferson Lab specifications.

Finally, a system diagram of a proposed low-cost Master Oscillator, exhibiting high stability, low phase noise, Global Positioning Satellite (GPS) reference, and limited frequency agility is demonstrated in figure 3. Estimated cost for such a system is less than $10,000.

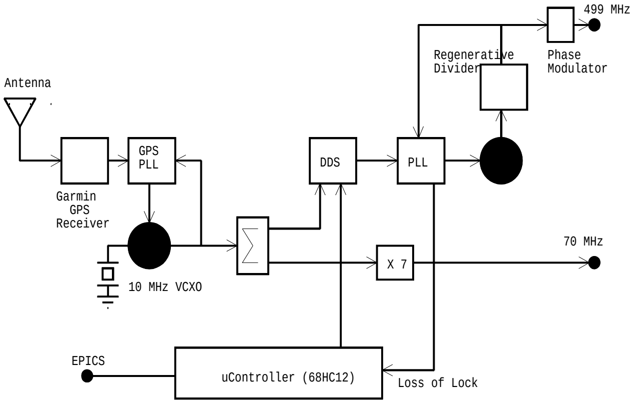

Figure 3. Proposed Master Oscillator

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