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A HIGH-SPEED VOLTAGE-CONTROLLED OSCILLATOR FOR THE FERMILAB BOOSTER LOW-LEVEL RF SYSTEM

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SUMMARY

This paper describes the design, development and test results of a high-speed VCO with an output frequency range from 29 MHz to 54 MHz. The use of high-speed and low-noise techniques throughout the unit enable the VCO to slew at greater than 5 MHz/μsec, while maintaining high spectral purity and phase stability. These characteristics allow the Booster phase-lock system to operate at a high gain setting while using a wide loop bandwidth.

INTRODUCTION

A primary requirement of components used within phase-locked loops is that the parasitic poles generated by the inherent bandwidth restrictions of each individual component be high in frequency with respect to the dominant loop compensation poles, so as not to interfere with the stable operation of the loop. For this reason a VCO for the booster RF system was developed with a design small-signal FM bandwidth of 1 MHz.

To minimize errors due to non-linear effects, a linearity specification of ± 2% was adopted. Good spectral purity and a high degree of phase stability were required over the frequency range of nearly an octave.

Refer to separate papers with regard to other loop components and overall system concepts.[1]

SYSTEM DESCRIPTION

Figure 1 is a block diagram of the oscillator. In order to minimize low-index close-in phase modulation, low-noise regulators were used to supply voltages to critical points. These regulators displayed a measured noise level of 140 μV RMS, integrated from 10 Hz to 10 MHz. Isolation from power supply load variations of other components in the NIM crate is also achieved with the regulators.

The summing amplifier of figure 1 performs two tasks. Primarily, the amplifier matches the varactor tuning characteristics of 7.4 MHz/Volt to the required input constant of 3 MHz/Volt. A low-noise operational amplifier followed by a current buffer form the amplifier network. Secondly, the summing amplifier also acts as an isolation device between the VCO and the external inputs, i.e., disallowing reverse feedback of RF energy from the VCO to the loop phase detector.

The actual voltage-controlled oscillator circuit consists of a Motorola MC1648 oscillator chip, tuned with an MV1404 varactor diode resonated with a fixed inductor. Since the oscillator is tuned with a tank circuit of fairly high Q, it shows superior performance in phase stability compared to packaged multivibrator-type oscillators.

Two problems were encountered in selecting a varactor tuning diode; the requirement for an octave-wide frequency range and a frequency vs. voltage linearity specification of ± 2%. Since for a resonant circuit:

$$f_r \propto \frac{1}{\sqrt{LC}}$$

then:

$$\Delta C \propto (\Delta f_r)^2$$

Therefore, for an octave change in f_r, a factor of 4 change in C is required. The diode used has a capacitance tuning ratio of 10:1. A diode with a hyperabrupt junction was chosen because for this junction profile,[2]

$$C_j \propto (V_r)^{-2}; \quad C_j = \text{junction capacitance}, \quad V_r = \text{applied reverse voltage}$$

Therefore for a tank circuit tuned with a hyperabrupt varactor:

$$f_r \propto \frac{1}{\sqrt{LC}} \propto V_r$$

This indicates that a linear tuning function can be expected over a fairly large capacitance range for a hyperabrupt junction diode.

A buffer amplifier following the VCO serves to isolate the oscillator from the remainder of the system, reducing frequency-pulling effects due to the non-constant driving-point impedance of the lowpass filter and eliminating reverse RF leakage to the oscillator.

Filters are used to improve signal purity by attenuating harmonics of the fundamental oscillator frequency and low-frequency spurious noise. A sixth-order Butterworth approximation was chosen for the filters for its relatively good combination of attenuation and phase linearity. An amplifier is also placed between the filters to buffer against interaction due to driving-point impedance variations.

TEST RESULTS

Figures 2 and 3 show the harmonic content of the oscillator output at 30 MHz and 54 MHz, respectively. It can be seen that the worst-case harmonic levels are -32 dbc at 30 MHz and -35 dbc at 54 MHz.

The oscillator's inherent phase stability at both ends of the frequency range is illustrated in figures 4 and 5. At an offset-from-carrier frequency of f_m, the single-sideband RMS phase noise-to-signal ratio per Hertz bandwidth, $\alpha(f_m)$, is approximated as,[3]

$$\alpha(f_m) \cong \left.\frac{\text{single-sideband noise power}}{\text{signal power}}\right|_{\Delta B_x} - 10\log_{10}(\Delta B_x) \text{ db/Hz}$$

where: ΔB_x = bandwidth used for measurement.

Therefore, at 10 KHz away from the carrier the VCO shows the following results:

$\alpha(10\text{KHz}) \cong -91$ db/Hz @ 29 MHz

$\alpha(10\text{KHz}) \cong -89$ db/Hz @ 54 MHz

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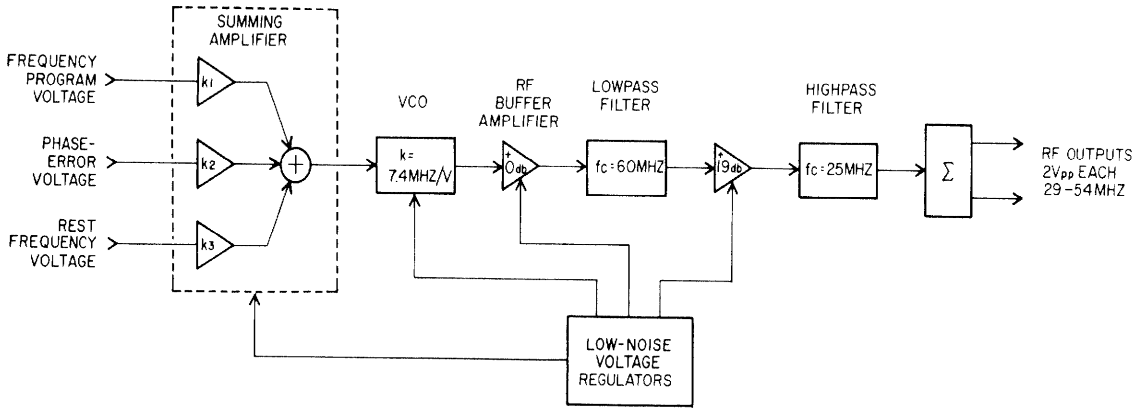

Fig. 1. Oscillator Block Diagram.

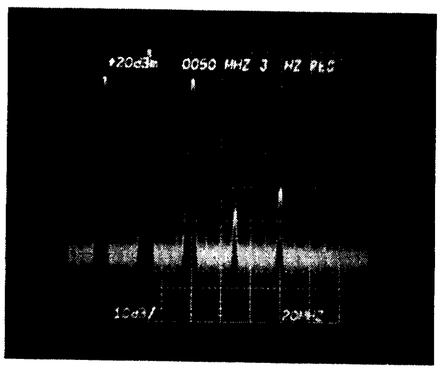

Fig. 2. Output Spectrum at 30 MHz.
Center: 50 MHz. BW: 3 MHz. Scan: 20 MHz/div.
Vert.: 10 db/div.

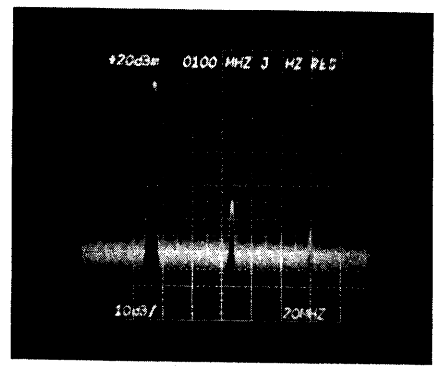

Fig. 3. Output Spectrum at 54 MHz.
Center: 100 MHz. BW: 3 MHz. Scan: 20 MHz/div.
Vert.: 10 db/div.

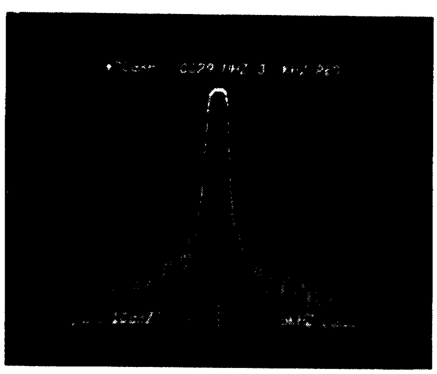

Fig. 4. Phase Stability at 29 MHz.
Center: 29 MHz. BW: 3 KHz. Scan: 5KHz/div.
Vert.: 10 db/div.

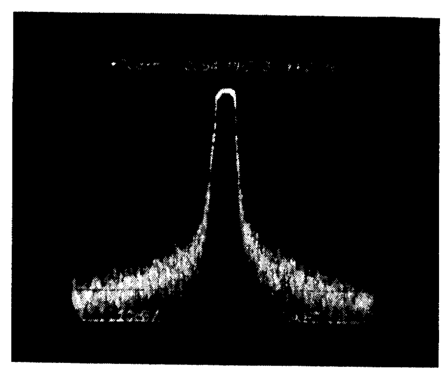

Fig. 5. Phase Stability at 54 MHz.
Center: 54 MHz. BW: 3 KHz. Scan: 5 KHz/div.
Vert.: 10 db/div.

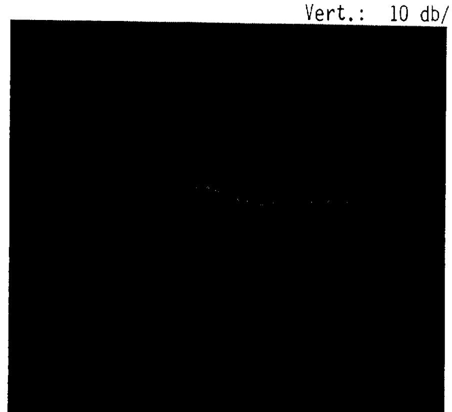

Fig. 6. Oscillator Step Response from 39.5 MHz to 40.5 MHz. Horiz.: 200 ns/div.

The program linearity was measured to be within ± 2% of the best straight line over the entire frequency range. A fast frequency discriminator was used to measure the response of the VCO to a step change in program voltage. The response to a 1 MHz step from 39.5 MHz to 40.5 MHz is shown in figure 6. From the figure it is seen that a slew rate of at least 5 MHz/μsec was achieved, and that the small-signal FM cutoff frequency, f_c, is approximately:

$$f_c \approx \frac{1}{2t_r} = \frac{1}{500\text{ns}} = 2\text{ MHz}$$

The oscillator is housed in a 2-wide NIM module.

ACKNOWLEDGMENTS

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