SAWTOOTH WAVE GENERATION FOR PRE-BUNCHER CAVITY IN ISAC

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Abstract

Two phase-locked loops operating with a reference frequency of 11.667 MHz are used to generate the Fourier components for a sawtooth waveform with a repetition frequency of 11.667 MHz. These frequencies are combined at signal level, amplified and used to power a set of parallel plates inside the pre-buncher cavity up to 600 V_{p-p}. The resultant sawtooth waveform is feedback regulated by I/Q regulation of its individual Fourier components.

1 INTRODUCTION

A pre-buncher cavity is used in the ISAC low energy beam transport line to increase the energy acceptance[1]. This cavity consists of a set of parallel plates that is driven by a 600 V_{p-p} sawtooth waveform at 11.667 MHz. The sawtooth waveform is synthesized by summing the fundamental to 4th harmonics Fourier components. Two phase-locked loop frequency synthesizers are used to generate these frequency components. The In-phase and Quadrature phase of each frequency component are individually regulated by a digital signal processor to produce a stable sawtooth waveform at the cavity. These frequency components are summed together at signal level. The summed output is predistorted, compensating for the group dispersion and nonlinearity caused by the components downstream, to obtain a sawtooth waveform at the cavity. A single 125 W MOSFET rf power amplifier is used to raise the combined signal to 220 V_{p-p} at 50 Ω. Coaxial cable transmits the rf power to the cavity. The rf is then stepped up to 600 V_{p-p} at 450 Ω with a 1:9 balun mounted on the outside of the cavity. The unbalanced-to-balanced transformation also allows the rf power to be fed effectively into a set of parallel plates inside the cavity. The sawtooth voltage is feedback regulated. Pickup probes at each plate monitor the waveform at the cavity. A digital signal processor regulates the In-phase and Quadrature-phase components of each of the Fourier frequencies of the sawtooth waveform, which are obtained by a set of 4 bandpass filters.

Modular design is used in the hardware architecture. Circuits for different functions are housed in separated modules. All the signal level modules, including the waveform synthesizer, the feedback controller, safety interlocks and local supervisory controller, are housed in a VXI mainframe. The rf power amplifier, due to its different power requirements, is housed in another chassis with its own power supplies. The pre-buncher cavity with its impedance matching balun/transformer, is located in the beam line 10 m away.
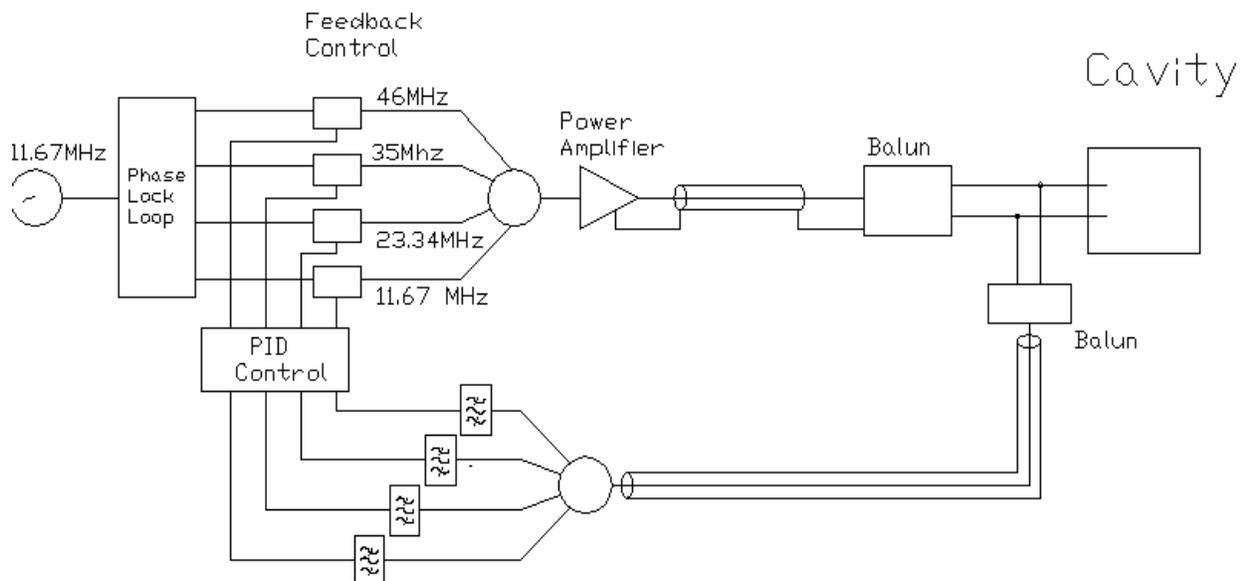
Figure 1. Block diagram of sawtooth wave generator

2 WAVEFORM SYNTHESIZER

The waveform synthesizer occupies two VXI modules. One module houses two analogue phase-locked loops. With an input reference of 11.667 MHz, one loop produces the 2nd and the 4th harmonics frequencies of 23.334 MHz and 46.667 MHz, while the other loop produces the 3rd harmonic frequency of 35.000 MHz. Small scale integration and medium scale integration emitter-coupled logic circuits are used in the digital part of the loops. In particular, synchronous counters are used in frequency division to reduce phase jitter. The phase comparator is a type 4 Phase-Frequency detector[2]. First order loop filters are used for both loops, and the bandwidths of the filters are 2 kHz. The loop filter circuitry has a special feature which prevents large frequency excursions during locking and unlocking of the loop. Figure 1 shows a simplified schematic of one of the loop filters. An analogue-to-digital converter controlled by a microcontroller continuously duplicates the output of the loop filter at a digital-to-analogue converter. A pulse detector, not shown in the figure, detects the presence of the reference signal. A level detector monitors the pump-up/pump-down signal from the frequency-phase detector. When the reference input pulse detector cannot detect the presence of the reference signal, the voltage oscillator circuit is biased by the output of the digital-to-analogue converter, whose voltage is the last VCO control voltage before the reference is lost. Transition into this operating mode is glitchless
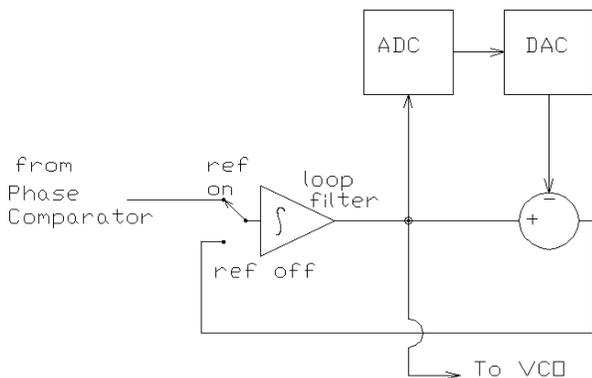
Figure 2. Phase-locked loop bumpless switching block diagram

since the output of the digital-to-analogue converter has been tracking the output of the loop filter. Furthermore, the loop filter capacitor remains in the circuit to achieve bumpless switching when switching back to the phase locked mode. Upon reacquisition of the reference, the reference frequency is usually far enough from the VCO frequency that the Phase-Frequency detector operates in the frequency mode. The microcontroller monitors the difference in frequency via a second detector. The VCO

bias is stepped up or down by the microcontroller until the frequency error from the phase comparator is smaller than a prescribed value. The error voltage from the phase comparator again becomes input to the loop filter, and the output frequency is allowed to lock the reference. The output is cleaned up by a combination of a second order bandpass and a third order lowpass filters. Low power rf amplifier modules isolate the output from the phase locked loops and provide output levels of 6 dBm.

Another VXI module has four manually adjustable delay lines, operating on the four frequency components from the previous module, and combines them after the delay lines. Electronic modulators located in the In-phase and the Quadrature-phase path will fine tune the amplitude and phase of each frequency component to obtain the desired sawtooth wave shape. Figure 3 shows the frequency spectrum of the composed sawtooth waveform. It shows the individual frequency components and their relative magnitude. Figure 4 uses an expanded frequency scale and shows the spectral purity of the 3rd harmonics alone. The desired frequency component appears as a sharp peak at 35 MHz. The frequency stability of this peak is better than the resolution (10 Hz) of the spectrum analyzer used. Two broad noise bands at -60 dBc extending to 25 kHz on either side of the central peak are results of the phase detector and loop filter noises. Thermal noise is the main contributor to these noises. At frequency offsets beyond the unity gain bandwidth of the phase-locked loop the VCO noise shows the expected $1/f^2$ dependence.

2 POWER AMPLIFIER AND BALUN

Since the pre-buncher operates from 11.667 MHz to 46.667 MHz, wide band designs are necessary in the power amplifier and the cavity termination. The power amplifier is a 2 stage, transformer coupled wide band solid
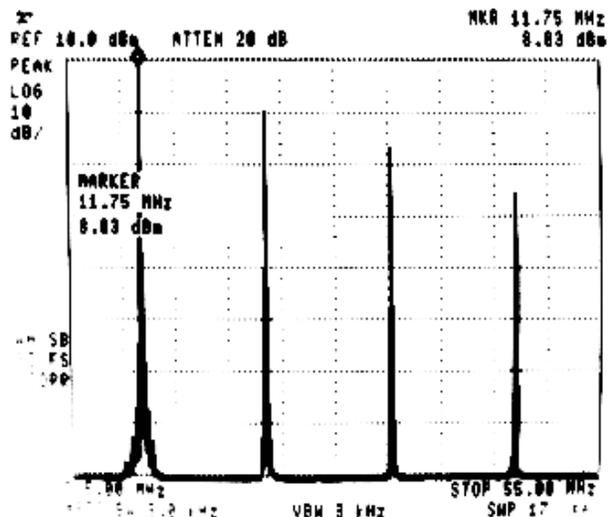
Figure 3. Frequency spectrum of sawtooth waveform
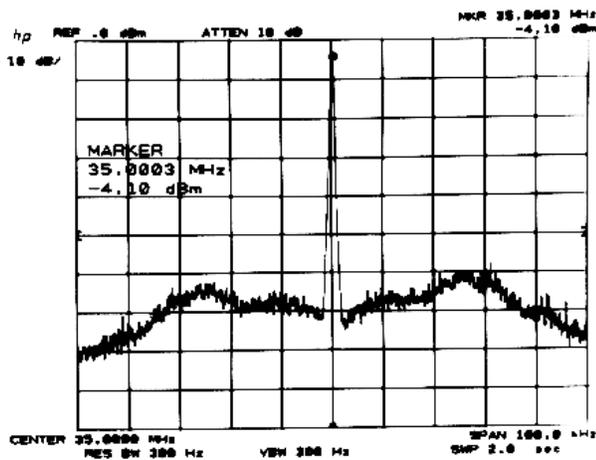
Figure 4. 3rd harmonic output from frequency synthesizer

state amplifier. Each stage consists of a pair of MOSFETs operating class AB in push-pull mode. Overall power gain from 10 MHz to 30 MHz is 38 dB, and the gain reduces at higher frequencies. Although the 3rd and the 4th harmonics lie outside this range, the power requirements for 3rd are 16 dB down from the fundamental, and 4th harmonic is 25 dB down. Their reduced power requirement is low enough such that this power amplifier can still have sufficient gain in order to produce a sawtooth waveform. Overall power output capability is 125 W. A temperature sensor and VSWR monitor protect the power transistors by removing the power supply in abnormal conditions. Since the cavity is located 10m from the amplifier, coaxial cable is used to transfer the power from the amplifier to the cavity. In order to develop 500 Vp-p at the cavity plates, a 1:9 impedance transformer/balun is used to step up the voltage and to provide unbalanced-to-balance transformation. The balun is constructed from three ferrite loaded $\lambda/4$ transmission lines. A 200W, 500 Ω resistor provides termination for the proper operation of the balun. The balun and the resistor are mounted on a large heat sink and cooled by forced air. The top trace of Figure 5 shows the resultant summed sawtooth waveform at the input of the power amplifier. The trace is a distorted sawtooth, but has been adjusted to give an undistorted sawtooth at the cavity plate. This signal level waveform has been predistorted to allow for the group dispersion characteristics of the balun and the cavity plates, as well as for the nonlinearity of the power amplifier. The bottom trace of Figure 5 shows the amplified voltage at one of the plates in the pre-buncher cavity, where the trace has good resemblance to a sawtooth waveform. The actual voltage across the two plates in the pre-buncher cavity would be twice the voltage as shown in the figure.
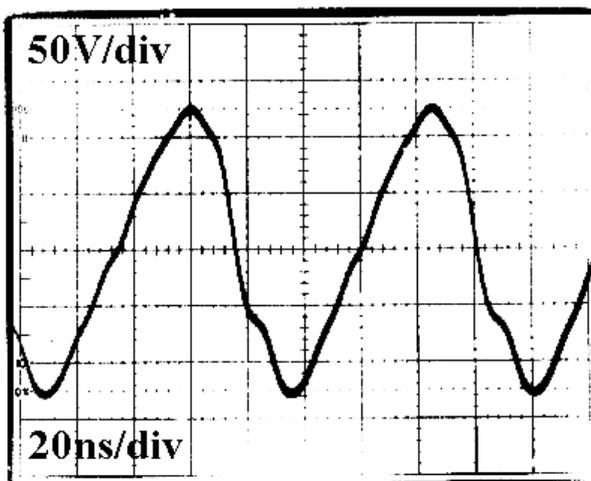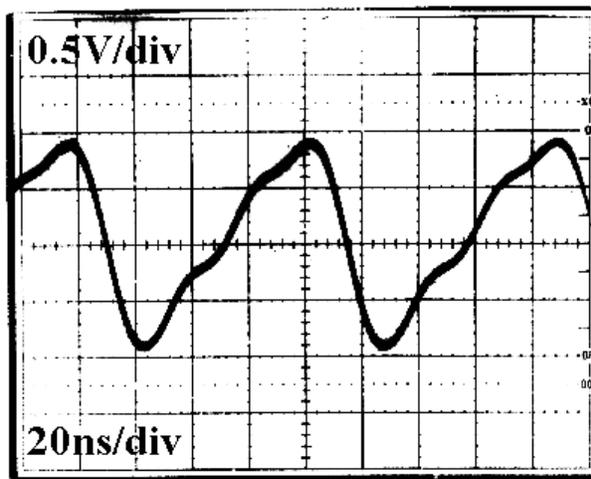
Figure 5. Top trace shows the predistorted waveform at the input of the power amplifier. Bottom trace shows the voltage at one of the plates in the pre-buncher cavity

3 CONCLUSION

There are numerous ways to generate a 400 V_{p-p} sawtooth waveform. In order to achieve an undistorted sawtooth waveform at the cavity one has to pre-distort the waveform at the input of the power amplifier. For ease of tuning we have chosen to synthesize the sawtooth waveform from its Fourier components, and maintain control on the shape of the final waveform by adjustments of the amplitude and phase of the component frequencies.

4 ACKNOWLEDGMENTS

REFERENCES

[1] S. Koscielniak et al, 'Beam Dynamics Studies on the ISAC RFQ at TRIUMF', this proceedings.
[2] Best, R. E., 'Phase-locked Loops', published by McGraw-Hill, 1984.