MULTI-BUNCH BEAM SIGNAL GENERATOR FOR FEEDBACK RECEIVER DEVELOPMENT*

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Abstract

Bunched beam signals from button-style Beam-Position Monitor (BMP) electrodes can have spectral content up to 20-30 GHz and structure of narrow impulsive trains in time-domain. Multi-bunch feedback systems require receivers to process such beam signals and generate ΔX, ΔY, and ΔZ beam motion signals. To realistically test these receivers, we have developed a 4-bunch programmable impulse generator, which mimics the signals from a multi-bunch beam. Based on step-recovery diode techniques, this simulator produces modulated 100-ps impulse signals. The programmable nature of the system allows us to mimic Betatron and Synchrotron signals from 4 independent bunches with adjustable beam spacing from 1 to 8 ns. Moreover, we can observe nonlinear effects and study the noise floor and the resolution of the receiver. This paper presents the design of the system and shows typical achieved results.

INTRODUCTION

Beam Position Monitors to measure beam transverse coordinates and longitudinal coordinate are fundamental diagnostics. The BPM detects the centroid of the beam. The oscillatory component of the coordinate is useful for the feedback systems (the average position is useful for orbit measurements). For any of these purposes, the typical signals generated at button-type or stripline beam pick-ups are impulsive and have frequency components going out to high frequencies of order 1/(bunch length). The wideband signals with so many high frequency harmonics makes the design of the coordinate circuits interesting because non-linear effects may be present from the high frequency components. Filters can help remove harmonics out of the detection band but the feed-through and attenuation in these filters can effect the coordinate measurement.

One traditional way to lab test BPM and feedback systems is via narrowband sine waves. While convenient, this does not really explore the non-linear performance and system characteristics with signal that look very much like what we see from the real BPM. For this purpose, we investigated and put together a beam simulator that we can use to test various receivers.

METHODS

DIODE

The heart of our system is a step-recovery diode that makes impulsive signals at the RF driving frequency. Also called a snap diode, a p-n junction is doped to exploit the minority carrier storage inherent in the diodes. [2] It makes use of the abrupt transition from on to off that occurs once the stored charge has been removed and produces signals with extremely fast rise-time (~100 ps).

With a periodic input, the output spectrum consists of harmonics of the input fundamental. This way, a 100-MHz input signal can be used to generate gigahertz outputs. Step-recovery diodes are often used to make circuits such as frequency comb generators. The diode is typically used with a tuned bias circuit which has roughly 10% bandwidth, so that a given diode and tuned bias circuit is useful over a 10% operating fundamental bandwidth. Using the step-recovery diode, we are able to generate a train of narrow, high amplitude pulses, shown in Figure 1. We can clearly see this sharp 100-ps impulse generated by HP-33002 in Figure 1.

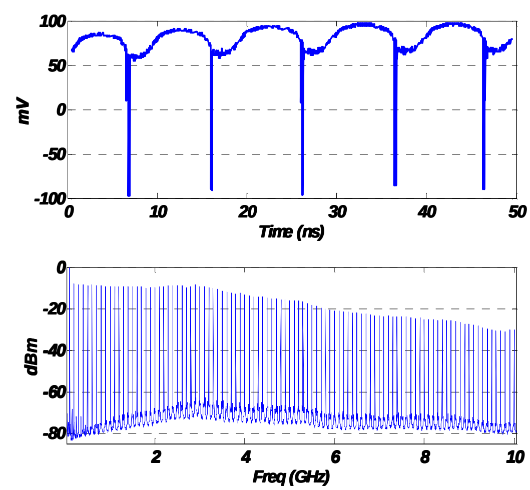

Figure 1: The impulse train generated using the 100 MHz HP-33002 snap diode in time domain (above, with 30 dB attenuation) and spectrum content (bottom, showing the 100 MHz comb)

The MODULATORS

We can modulate the impulsive output signal from the diode properly to mimic different beam oscillations, i.e. phase modulation for Synchrotron oscillation and amplitude modulation for Betatron oscillation. The next step is to make a good phase modulator and amplitude modulator.

Now we will look into making a good phase modulator to replicate Synchrotron oscillation. Phase modulation can be done by using a voltage controlled phase shifter.

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Applying a DC voltage plus 100 KHz small modulation applies phase modulation, as shown in the Figure 2.

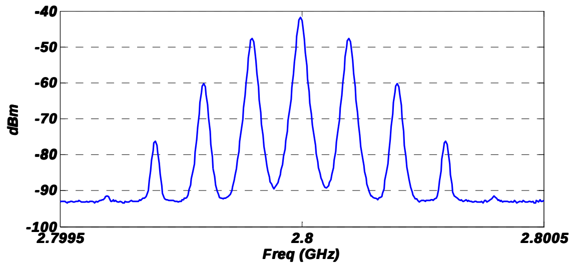


Figure 2: Simulated Synchrotron oscillation (DC voltage with 100 KHz modulation)

On the other hand, to simulate Betatron motion requires making a good amplitude modulator. If we want to look at signals with DC components and AC components, we have to think about the performance of the modulator in terms of small modulation with big DC offset. Let's look at some double-balanced mixers as modulators. We identify several mixers; each one is useful for a certain range of frequency, but none of them can be working in all bands. Figure 3 depicts how DC attenuation with a small amplitude modulation would affect the shape of the impulse.

In the lab, we tested three mixers: double balanced mixers M1G/M1J from M/A-COM and Marki M8 series mixer. We measure the frequency response of the mixers by passing a small modulation with DC value on both spectrum analyzer and network analyzer.

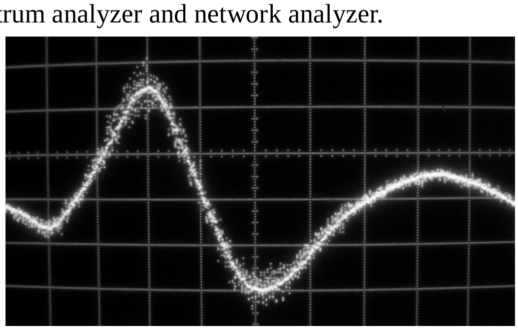


Figure 3: Close-up at the 100 KHz 20% amplitude-modulated impulse (notice the fuzzy samples around the tip of the impulse due to very small amplitude modulation, scale 10mV/div, time scale 100 ps/div)

Marki M8-0412 is specified from 4 GHz to 12 GHz. This is a high-level mixer (12 dBm drive level) and we were curious if it would behave differently than the standard 7 dBm level M1J and M1G. It has very flat response from 4 to 10 GHz, shown in Figure 4.

M1J Mixer from M/A-COM is specified in the frequency band ranging from 300 MHz to 2 GHz. It has relatively flat response in low frequency band and thus is useful for detection frequencies from 200 MHz up to 2 to 3 GHz.

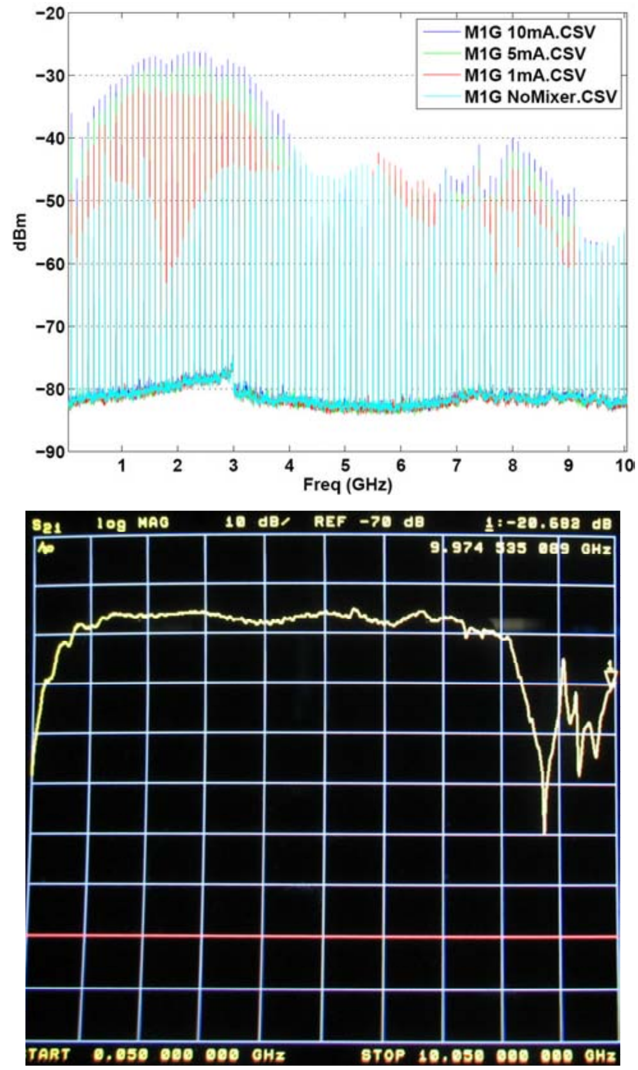


Figure 4: Lab measurement results of Marki M8-0412. The top figure is measured on the spectrum analyzer by driving M1J with a small modulation and a DC current of 1 mA (red), 5 mA (green), and 10 mA (blue). The bottom figure is from the network analyzer, frequency spanning from 50 MHz to 10.05 GHz, 10 dB/div.

M1G Mixer from M/A-COM is specified in the 1 GHz to 4.2 GHz frequency band. It has relatively flat response in wide frequency band and could be useful for detection frequencies of 1 to 4 GHz.

In summary, we identify several modulators; each one is useful for a certain range of frequency, but not for all. In low frequency band (200 MHz - 2 GHz), M1J is a good choice. M1G has better frequency performance in the 1 – 4 GHz band. On the other hand, Marki works well for higher frequency bands up to 10 GHz.

Selecting the Operation Point

We need to operate in the linear region of the mixer to represent Betatron motion. Thus we measured the DC attenuation characteristic of Marki M8-0412 at 2.865 GHz.

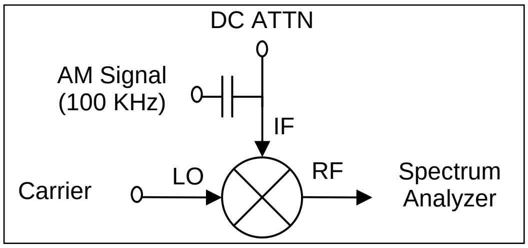


Figure 5: Lab setup to measure the DC attenuation characteristics

In the lab, the equipment is set up as Figure 5 describes. We put an amplitude-modulated signal (100 KHz) into the mixer and observe the carrier-to-sideband ratio on the spectrum analyzer. If the mixer is linear, we should expect the carrier-to-sideband ratio is going up because we have a fixed DC control current and increasing modulation depth. As we keep increasing the modulation depth, we gradually saturated the mixer and reach the limit of the carrier-to-sideband ratio. Figure 6 describes how the DC attenuation varies with different mixer drive level. If we put big DC control current (> 5 mA) into the mixer, we will saturate the mixer. We want good linearity and don't want to work in the saturation region. In Figure 7, we are operating in the linear region of the mixer.

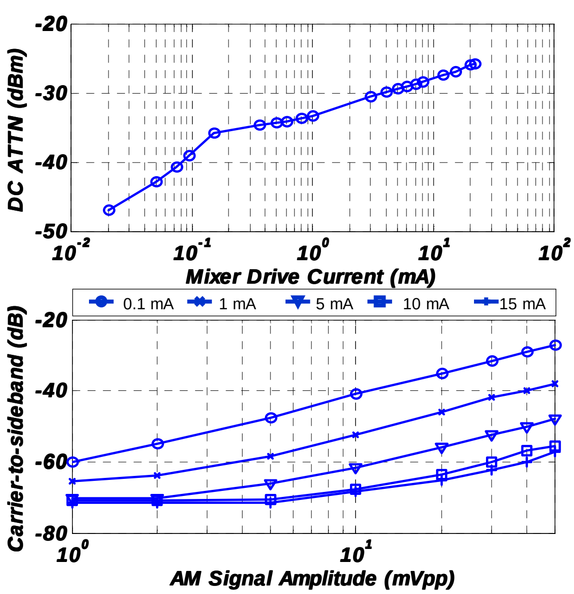


Figure 6: DC attenuation characteristic of Marki M8-0412 at 2.865 GHz

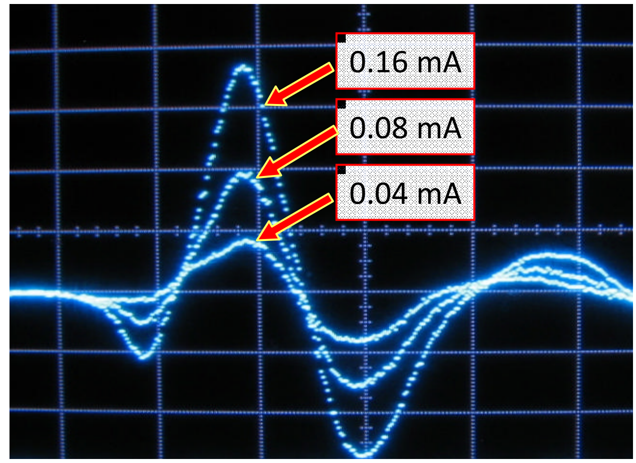


Figure 7: Linear Response of the Modulator. Snapshot of the impulse when the mixer is operating at DC control currents of 0.04 mA, 0.08 mA, and 0.16 mA. Time scale 10 mV/div, time scale 100 ps/div.

To test high resolution receiver, we want to generate beam signals that can be modulated with very small signal. For the chosen mixer, we have to carefully choose the operating point to achieve the high dynamic range. High dynamic range corresponds to high resolution, i.e. 60dB dynamic range will allow us to mimic <10 micron motion in 1 cm aperture. Figure 8 is typical result we achieved in the lab. The 60dB carrier-to-sideband ratio can be further improved by increasing the resolution of the spectrum analyzer and lowering the noise floor in the system.

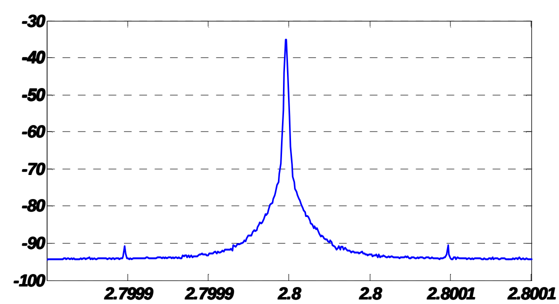


Figure 8: 60 dB carrier-to-sideband ratio, centered at 2.865 GHz, sidebands 100 KHz apart

One Bunch Block Diagram

Figure 9 shows the first bunch of our bunch signal simulator. A step-recovery diode driven at 100 – 125 MHz makes fast impulses; a phase modulator mimics Synchrotron oscillation. The 1-to-4 divider splits the signal into 4 button signals, each can be amplitude modulated by Betatron motion. This bunch signal repeats at the frequency the step-recovery diode is running at.

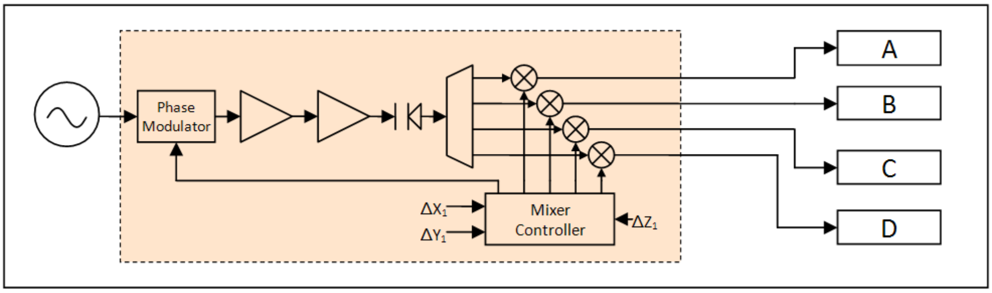


Figure 9: One Bunch system block diagram.

Four Button Signal Controller

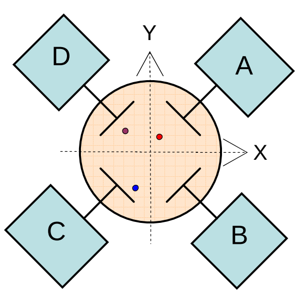
We need an appropriate way to modulate the signals depending on the beam orientation at the pick-up. Thus we have built an analog baseband circuit to control the 4 modulators to generate desired voltage level on the four buttons. With this building block, we are able to simulate one bunch with Synchrotron oscillation and Betatron oscillation. It's going to be a bunch at the repetition rate of the step-recovery diode.

Figure 10 shows a typical button-style beam position monitor. For small displacements from the center of the beam duct, the beam position in terms of voltages on the four buttons is calculated by difference-over-sum algorithm [1]:

$$\Delta X = \frac{b}{2}\frac{(V_A+V_B)-(V_C+V_D)}{(V_A+V_B)+(V_C+V_D)}$$

$$\Delta Y = \frac{b}{2}\frac{(V_A+V_D)-(V_B+V_C)}{(V_A+V_D)+(V_B+V_C)}$$

With some math expression manipulation, we obtain the following equation for the voltage on the four buttons.



$$V_A = K_A - \frac{\Delta X - \Delta Y}{4}$$

$$V_B = K_B + \frac{\Delta X + \Delta Y}{4}$$

$$V_C = K_C + \frac{\Delta X - \Delta Y}{4}$$

$$V_D = K_D - \frac{\Delta X + \Delta Y}{4}$$

Figure 10: Button-style Beam-Position Monitor and the relationship between the Four-button voltages and the Beam Position

The analog baseband modulator is built with op-amps and has a bandwidth of 10 MHz, which is more than enough for the modulation we want to mimic. Potentiometers are used to adjust K_A, K_B, K_C, and K_D and signal Inputs represents ΔX and ΔY signals.

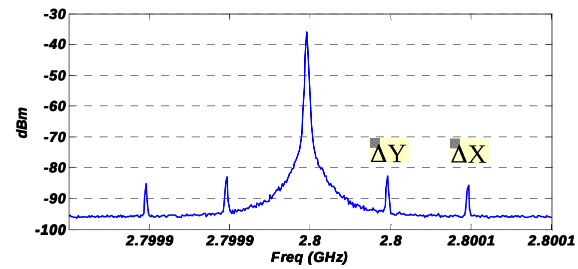


Figure 11: Spectral content of the one bunch signal with oscillations on ΔX and ΔY.

Combining Four Bunches

If we want to put more bunches and move them closer or a high frequency modulation pattern, what we do is to take four of these and combine them. Shown in the above diagram, for a 500 MHz system, we can operate each bunch at 125 MHz and superimpose the 4 signals. One advantage of doing this is the flexibility of choosing the bunch separation interval. Additionally this allows us to modulate each bunch's coordinates at relatively low baseband frequency (simulating coupled-bunch motion, and adjusting the phase between the 4 modulation oscillators to adjust high or low frequency coupled bunch mode). This is easier rather than modulating a single diode at 4 times the RF frequency over the full bandwidth of all coupled-bunch modes.

By selecting either 100, 119, 125, or 250 MHz as the base RF, we can simulate various machines with 100 to 525 MHz RF, and filling patterns up to every bucket. The system block diagram that combines four bunches is shown in Figure 12.

SUMMARY

In this paper, we present the design of a reprogrammable four-bunch beam signal generator system. Using step-recovery diode techniques, the simulator produces modulated 100-ps impulse signals that mimic realistic beam signals to test high-resolution BPM receivers. Our system generates a four-bunch beam impulse signal and the beam spacing can be individually re-configured for each bunch to adapt to different accelerators. The programmable nature of the system allows us to modulate the bunch signals in amplitude to simulate the transverse beam motion of low and high frequency coupled-bunch modes and in phase for longitudinal beam motion. Since the system is working at RF/4 frequency, it increases the flexibility of the system and ease the modulation bandwidth requirement. It further allows testing and measurement of bunch-to-bunch coupling and isolation in multi-bunch feedback via use of 4 different modulation frequencies.

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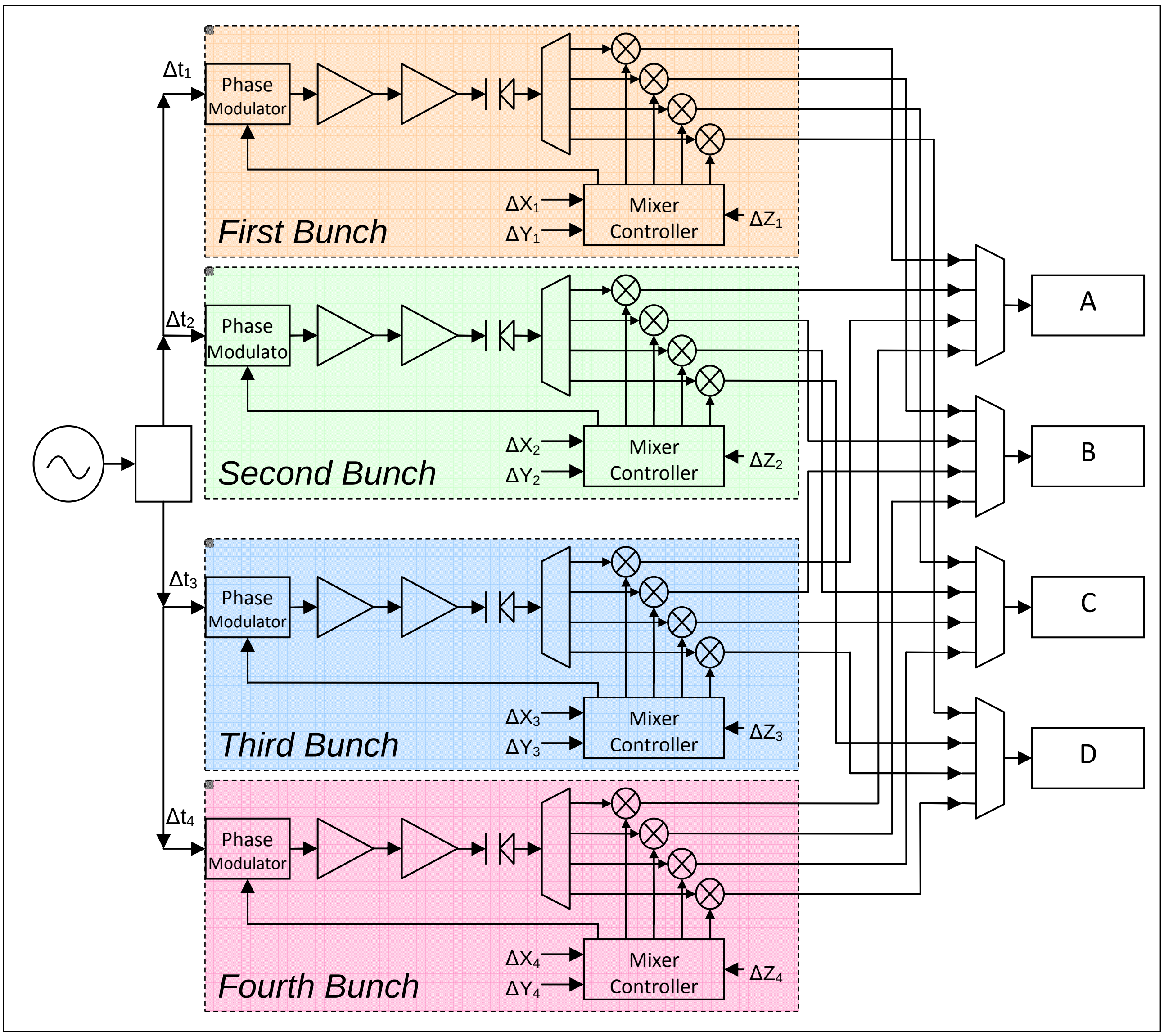

Figure 12: System (four-bunch) Block Diagram. Each dashed box is a separate bunch.