Design of a low cost digitally controlled phase shifter

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I. INTRODUCTION

Linac accelerators based on independently phased resonators require precise phase shifters to setup the reference phase of each cavity with respect to the master oscillator. In a linac like ALPI, that has more than 80 resonators in operation (including those of the new PIAVE injector), the cost of such phase shifters represents a significant fraction of the cost of the overall RF control system. In ALPI we have used Merrimac digital phase shifters (series PTB-84A and PTB-84B) at frequencies of 80 and 160 MHz. The cost of these components is very high (around 5000-6000 USD, depending on the frequency and the quantity) but it is justified by the high precision and stability of these components.

After many years of Linac operation we reconsidered the question if phase shifters with less performing characteristics – but also a lower price – could be suitable for providing a phase reference signal to our resonator controllers. Following the promising tests we made on a vector modulator realized using a high speed analog multiplier [1], we decided to further extend that design and use it as building block for a digitally controlled phase shifter. This paper describes the realization of such device and compares its performance to a Merrimac PTB-84B model.

II. DESIGN BASICS

It can be easily demonstrated that a vector modulator can be used as phase shifter. We recall here the basic principle of its operation. A vector modulator is a device in which the input signal is split into a pair of orthogonal components, normally designated as I (in phase) and Q (in quadrature). The amplitude of each component is independently controlled through a couple of linear attenuators, then the output signal is obtained by summing in-phase the I e Q components. Assuming that $V_I$ and $V_Q$ are the control voltages on I and Q ports, the amplitude of the output signal is given by $(V_I^2 + V_Q^2)^{1/2}$, while the phase angle is given by $\arctan(V_Q/V_I)$. So, if we supply the modulator control ports with two signals that represent respectively the sinus and the cosine of an angle $\phi$ and change the value of $\phi$ over the full range 0-360 degrees, we shall see, by trigonometric identity, that the amplitude of the output signal will remain constant, while its phase will track the angle $\phi$. We have also demonstrated, in our previous work, that it is possible to build a vector modulator using an inexpensive analog multiplier like the AD834 to control the signal amplitude along the I and Q branches. This component acts as a biphase attenuator but it is much less costly with respect to mixers or RF attenuators and exhibits a very good linearity up to frequencies exceeding 200 MHz. As said before, the aim of this work was to realize a digital phase shifter that could be used as replacement part for the Merrimac PTB-84B model. This component is a 8 bit device, whose operation is based on delay lines switching. Since the delay lines are made of pieces of cable of weighted length, this method is inherently stable versus aging and temperature.

On the other side, our design is based on an analog building block to which we added the components required to drive it through an 8 bit digital interface.

III. PRACTICAL REALIZATION

Basically, we need to generate two analog signals tracking the functions $\sin \phi$ and $\cos \phi$ where $\phi$ is the phase angle coded on a 8 bit pattern. This can be easily done by using the 8 bit code as the address of two ROM memories containing the look-up tables of the sinus and cosine functions. Then, the data read from the memories are converted to analog signals by means of two DACs. Fig. 1 shows the phase shifter electrical diagram.

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The analog core of the circuit has already been discussed in [1]. We added the two ROMs M27C516 and the two 12 bit DACs AD7245. The DACs have a bipolar output range of –5 to +5 V. The signal at their output is reduced to a –1/+1 V range by a resistor partition and buffered by means of an operational amplifier (AD845).

We also added an RF amplifier (Mini-Circuits AMP77) at input to drive the quadrature splitter PSCQ-2 with an optimal +10 dBm level while maintaining the full compatibility with the RF level we operate the Merrimac phase shifters in our Linac (typically –6 dBm at shifter input). The overall insertion loss of the board is about 4 dB. If more power is needed at the output, we have foreseen the possibility to mount an output driver (an Avantek GPD402 or equivalent device).

A particular care has been taken in decoupling the power supply. The board requires two voltages to operate: +5V and +15V. The +15V is used only for the RF amplifiers AMP77 and GPD402, while the +5V is used only for the digital logic. Then, a 3 Watt DC/DC converter is used to generate, from the +5V input, the +/-12 voltage supplies required by the two DACS and the two operational amplifiers AD845. Finally, two voltage regulators are used to generate, from the +/-12V, the two +/-5V supplies necessary for the AD834 multipliers. The board dimension is 10 x 13 cm; the input connector is pin-to-pin compatible with the equivalent Merrimac model.

IV. PERFORMANCE MEASUREMENTS

The device performance has been tested by connecting it to our standard resonator controller that has a 8 bit port dedicated to drive a digital phase shifter. The controller was connected to a PC through a serial line. Then, phase steps have been applied to fulfill a complete 360 deg. rotation and the response has been sampled using a HP4195 network analyzer connected to the PC through a GPIB interface. Measurement cycles have been repeated for different input levels: it has been verified that the device behavior remains substantially unaffected when input power ranges from –10 to –3 dBm. Finally, a comparison has been done with a Merrimac PTB-84B model.

Fig. 2 shows the phase error, intended as deviation with respect the nominal response, for both the home-made and the Merrimac model. The linearity error of our device appears to be within +/-1.5 degree, that is equivalent to +/-1 LSB (1 LSB means 1.4 degree for a 8 bit device). By other hand, the total error of Merrimac device doesn’t exceed 1.5 degrees, that means +/- ½ LSB, and complies to the component specifications declared by the manufacturer. So, the linearity error exhibited by our phase shifter is worse by a factor of two with respect to the Merrimac one, but the cost is about one tenth. We think that the performance of our device is adequate for many applications and likely it could be used as replacement of Merrimac parts in the Linac RF system with no effects on accuracy of beam transport setup.

We can also observe that, while the integral phase error is clearly worse for our device, the differential error, intended as the maximum error observable when applying a single bit step can be much larger for the Merrimac model. So, when the maximum differential error is an important issue, it can be preferable to use an analog device rather than one based on switched cable technology.

Fig.2  Plot of phase error