PAD Design for the Phasing System of BEPCⅡ Linac*

GENG Zhe-Qiao[1)] HOU Mi PEI Guo-Xi

(Institute of High Energy Physics, CAS, Beijing 100049, China)

Abstract Phase and amplitude measurement is one of the most important issues for the phasing system of BEPCⅡ linac. Two kinds of PAD, based on analog and digital I/Q demodulator respectively, have been constructed and tested in both laboratory and the klystron gallery of BEPCⅡ linac. A calibration algorithm based on LMS method is used to compensate the mismatches of the analog I/Q demodulator. Experiments show that both kinds of PAD run stably and can meet the requirements of the phasing system.

Key words PAD, phasing system, I/Q demodulator, LMS method

1 Introduction

To reduce the beam energy spread of BEPCⅡ linac to a level of less than 0.4%, the phase fluctuation of each klystron must be less than $\pm 2°$ centered by an optimized phase[1, 2]. So, it is very important to construct a stable and accurate PAD (Phase and Amplitude Detector) for phase and amplitude measurement.

I/Q demodulator can down convert an RF signal to the base band directly. It's easy to be used to measure the phase and amplitude simultaneously, so it's a good choice to construct a PAD. Analog I/Q demodulator suffers from the mismatches such as DC offset, 90° phase imbalance and amplitude imbalance, which may draw remarkable errors to phase and amplitude measurement[3]. A general calibration algorithm based on the adaptive LMS (Least Mean Square) method is used to calibrate the I/Q mismatches to a rather low level[4, 5]. To further reduce the influence of I/Q mismatches, a digital I/Q demodulator[6] is built and tested. It is more accurate but slower than the analog one.

The greatest challenge for PAD is to work in a very noisy environment in the klystron gallery. To minimize the influence of noise, some EMC(Electro Magnetic Compatibility) methods, such as shielding, analog and digital filtering are adopted. All of them run successfully and almost all the noises are removed.

2 PAD design

2.1 Design and calibration of the analog PAD

The block diagram of the analog PAD is shown in Fig. 1. The analog I/Q demodulator is constructed by a microstrip circuit board and two mixers working at the frequency of 2856MHz, which is shown in Fig. 2(a). The I/Q outputs are low pass filtered and then sampled by a virtual oscilloscope with the sampling rate of 50MS/s and 12bit of vertical resolution. The sampled data are transferred to an industrial computer where phase and amplitude are calculated.

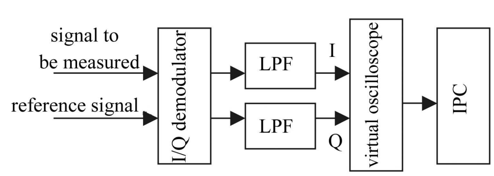

Fig. 1. The analog PAD.

Received 30 May 2005
*Supported by BEPCⅡ project
1) E-mail: gengzq@mail.ihep.ac.cn

The error of PAD is mainly from the mismatches of the analog I/Q demodulator, including DC offset, phase and amplitude imbalances. To compensate the mismatches, the frequency of RF signal is changed to be a little different from the frequency of local oscillator (LO) signal. Then the I/Q outputs will be two sine waves with low frequency. Because of the mismatches, the two sine waves will have different amplitudes and phase error off 90°, and the trace of I/Q will be an ellipse, which is shown in Fig.2 (b).

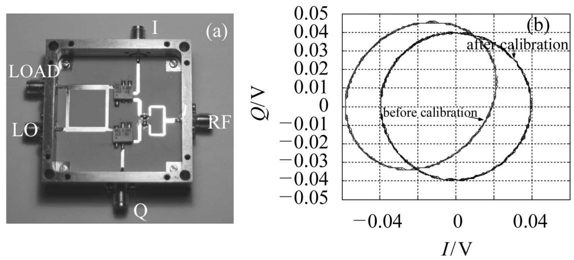

Fig. 2. The analog I/Q demodulator.
(a) I/Q demodulator; (b) I/Q trace before and after calibration.

A calibration algorithm is to draw ideal (I_0, Q_0) values from the distorted (I,Q) values measured in practice, which are voltage signals at the output ports of the I/Q demodulator. The relationship of (I_0, Q_0) and (I,Q) can be written as

$$I_0 = f(I,Q), \quad Q_0 = g(I,Q) \ . \tag{1}$$

where f and g are functions to be decided by evaluating the I/Q mismatches. A convenient way to get f and g is to use the Taylor expansion

$$\begin{aligned} I_0 &= a_0 + \sum_{n=1}^{N} (a_n I + b_n Q)^n + R_I(N), \\ Q_0 &= c_0 + \sum_{n=1}^{N} (c_n I + d_n Q)^n + R_Q(N). \end{aligned} \tag{2}$$

Drop the residual items R_I and R_Q, and combine the unknown coefficients, Eq. (2) can be rewritten as

$$\begin{aligned} I_0 &= a_0 + a_1 I + a_2 Q + a_3 I^2 + a_4 IQ + a_5 Q^2 + \cdots , \\ Q_0 &= b_0 + b_1 I + b_2 Q + b_3 I^2 + b_4 IQ + b_5 Q^2 + \cdots . \end{aligned} \tag{3}$$

where a_n, b_n $(n = 0,1,2,\cdots)$ are coefficients to be decided.

To get the unknown coefficients in Eq. (3), we sample the I/Q sine waves mentioned above. The I waveform can be fitted to be a Fourier series (the residual item has been dropped)

$$I(t) = I_{\mathrm{DC}} + \sum_{i=1}^{M} (m_i \cos(\mathrm{i}\omega t) + n_i \sin(\mathrm{i}\omega t)). \tag{4}$$

Assume the desired values of the I/Q waves measured by PAD to be

$$\begin{aligned} I_{\mathrm{d}}(t) &= \sum_{i=1}^{M} (m_i \cos(\mathrm{i}\omega t) + n_i \sin(\mathrm{i}\omega t)) , \\ Q_{\mathrm{d}}(t) &= \sum_{i=1}^{M} (m_i \cos(\mathrm{i}\omega t - \pi/2) + n_i \sin(\mathrm{i}\omega t - \pi/2)) . \end{aligned} \tag{5}$$

Note that the order N and M selected in Eqs. (2) and (5) is decided by the requirement of accuracy.

Define the vectors

$$\begin{aligned} \tilde{a} &= [a_0, a_1, a_2, a_3, a_4, a_5, \cdots]^{\mathrm{T}} , \\ \tilde{b} &= [b_0, b_1, b_2, b_3, b_4, b_5, \cdots]^{\mathrm{T}} , \\ \tilde{u} &= [1, I, Q, I^2, IQ, Q^2, \cdots]^{\mathrm{T}} , \end{aligned} \tag{6}$$

then the adaptive LMS method is used to get the unknown coefficients in Eq. (6). For example, to get the coefficients $\tilde{a}$, follow the steps

i) $\tilde{a} = 0$.

ii) $k = 1, 2, \cdots$

$$\begin{aligned} e_I(k) &= I_{\mathrm{d}}(k) - \tilde{a}^{\mathrm{T}}(k-1)\tilde{u}(k), \\ \tilde{a}(k) &= \tilde{a}(k-1) + \mu_I \tilde{u}(k) e_I(k). \end{aligned} \tag{7}$$

where e_I is the error item and μ_I is the convergence factor.

The I/Q trace after calibration is shown in Fig. 2(b). Most of the mismatches are canceled by the calibration algorithm.

2.2 Design of the digital PAD

It is very hard to improve the accuracy of the analog PAD. After calibration, the analog PAD still has a phase error of about 1.2° (Fig. 4). A PAD using the digital I/Q demodulator is constructed to reduce the phase error.

Fig. 3(a) shows the diagram of the digital PAD. Both the reference signal and the RF signal to be measured are down converted to intermediate frequency signals. The two intermediate frequency (IF) signals are band pass filtered and then digitized directly by a virtual oscilloscope. In the industrial computer, digital algorithms are used to demodulate the signals and then calculate the phase and amplitude.

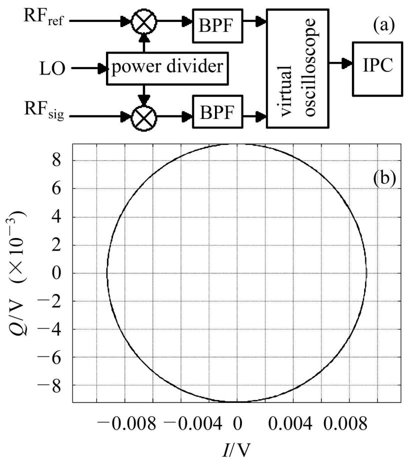

Fig. 3. The digital PAD.
(a) Diagram of the digital PAD; (b) The I/Q trace of the digital PAD.

The DC offset is canceled by a digital high pass filter. Hilbert transformation is used to get an accurate 90° phase shift of the reference IF signal, and the 3-dB power divider of the I/Q demodulator can be realized by simply dividing the two IF signals by $\sqrt{2}$. With these digital algorithms, the phase error of the PAD is reduced to a level of less than 0.5° (Fig. 4). Fig. 3(b) shows the I/Q trace of the digital PAD.

3 PAD test

3.1 PAD test in laboratory

To evaluate the phase errors of PAD, we insert a phase shifter, which is calibrated by the HP8720ES network analyzer, into the RF channel of PAD. Tune the phase shifter and measure the phase change with both kinds of PAD, then compare it with the results calibrated by the network analyzer, and the phase errors of both kinds of PAD are shown in Fig. 4.

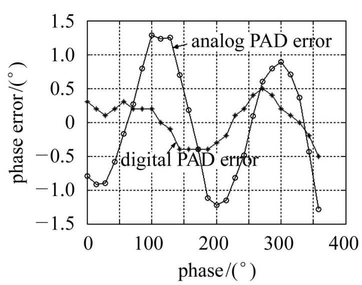

Fig. 4. Phase errors of PAD.

The digital PAD has a phase resolution of 0.15°, and the analog one is more sensitive, it has a phase resolution of 0.05°. Both kinds of PAD are not sensitive to the environment temperature. The phase drift due to the temperature change is less than 0.1°/℃, so both kinds of PAD are stable enough for the phasing system of BEPCⅡ linac.

The dynamic range of the PAD can be evaluated by measuring the phase errors for different RF input power. Fig. 5 shows that the analog PAD has a dynamic range of about 20dB, while the digital PAD has a dynamic range of more than 25dB.

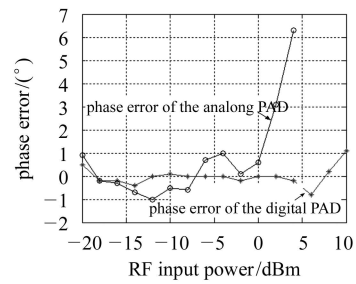

Fig. 5. The dynamic range of PAD.

The I/Q demodulator can measure the phase and amplitude of the input RF signal simultaneously. The amplitude errors of the analog and digital PAD are shown in Fig. 6.

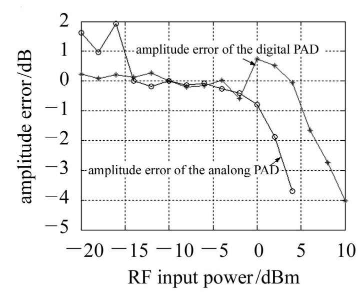

Fig. 6. Amplitude errors of PAD.

From the above test results we can see that the analog PAD has a higher resolution and speed but a lower accuracy and smaller dynamic range, while the digital PAD has a lower resolution and speed but a higher accuracy and larger dynamic range. Both of them run well when the input RF power is between −15dBm to −5dBm.

3.2 PAD test in the klystron gallery

To reduce the influence of the klystron noises, the following measures are adopted in the PAD chassis

1) Power filter is used to remove the noises in the supply power.

2) A new shielding box is used to avoid the radiation noises into the virtual oscilloscope.

3) Two band pass filters are added into the two 2856MHz channels.

4) Adaptive digital filters are adopted in the phasing program to remove the residual random noises.

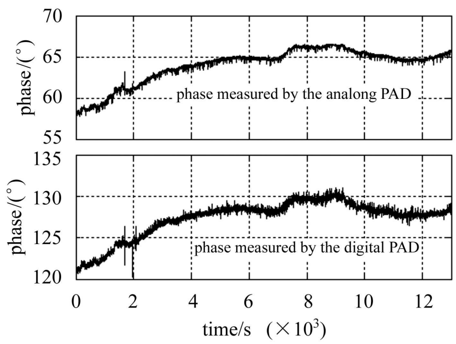

Fig. 7. Phase measured by the analog and digital PAD.

With these measures, almost all the noises are removed. Fig. 7 shows the phase of the klystron #1 measured by both the analog and digital PAD in the klystron gallery.

4 Summaries

I/Q demodulator is a good unit to form a PAD, but it suffers from the mismatches. A LMS calibration algorithm can reduce the phase error to a low level. Digital I/Q demodulation algorithms can further reduce the phase error. Both kinds of PAD run stably and successfully, and they can meet different requirements of the phase and amplitude measurement.

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BEPCⅡ直线加速器相控系统PAD的研制*

耿哲峤[1] 侯汨 裴国玺

(中国科学院高能物理研究所 北京 100049)

摘要 相位和幅度测量是BEPCⅡ直线加速器相控系统中最重要的部分之一. 基于模拟和数字I/Q解调器, 构建了两种PAD, 并分别在实验室和速调管长廊进行了测试. 基于LMS方法的校准算法用于补偿模拟I/Q解调器的各种不匹配误差. 实验证明, 两种PAD都能正常稳定地运行, 可以满足相控系统对相位和幅度测量的要求.

关键词 PAD 相控系统 I/Q解调器 LMS方法

2005 – 05 – 30 收稿

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1) E-mail: gengzq@mail.ihep.ac.cn