QUADRATURE DIRECTIONAL COUPLING METHOD FOR PRECISE RF POWER MEASUREMENT*

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Abstract

The directional coupler is used in the RF transmission and distribution system of accelerator, to measure the forward and backward power. Due to the finite directional isolation of the coupler (20-30dB normally), the crosstalk exists between the bi-directional coupling output signals. For the typical isolation of 26dB, if the bi-directional crosstalk signals are in- or anti- phase, the error of input or reflected power measurement is 10% in case of total reflection, whilst the error of reflected power measurement is 100% in case of VSWR 1.1. A method of quadrature directional coupling measurement is developed to solve the isolation problem. A pair of directional couplers with 90 ° phase difference are employed to measure the RF power. The influence of the directional crosstalk would be reduced significantly by processing the measurement data. The prototype of quadrature directional couplers is constructed to verify this method. The results showed that the measurement accuracy of quadrature coupler pair after data process is better than 2% for forward measurement, even if the error of single coupler is over 6%. The paper also analyses the error caused by non-ideal quadrature.

INTRODUCTION

High precision power measurement is demanded in the RF transmission and distribution system, control and feedback system of accelerator. Directional coupler is extensively used for power measurement. Single coupler has big error by reason that the finite directional isolation lead to the crosstalk exists between the bi-directional coupling output signals, especially when it is used to measure low reflected signal. The quadrature coupling method is developed to achieve high accuracy. The test results show that the quadrature method can achieve the accuracy of 2% and 5% with forward and backward measurement respectively.

PRINCIPLE OF QUADRATURE DIRECTIONAL COUPLING METHOD

The quadrature directional coupling measurement system is shown in Fig. 1 which consists of a pair of directional coupler, between which the phase difference is 90° at the working frequency. In order to adjust the phase for wide frequency range measurement, a phase shifter may insert between the couplers.

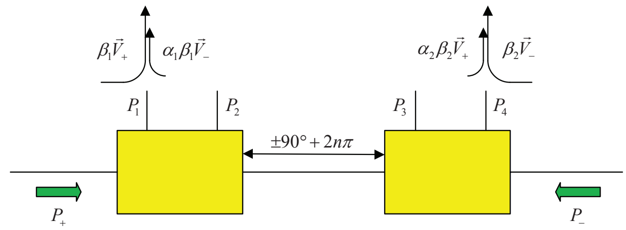

Figure 1: Structure of Quadrature coupling method.

In the ideal condition, the output ports no.1 or 3 is only coupling with the incident signal P_+. But due to the finite directional isolation, the reflected signal will be coupled and mixed into the output signal [1]. The same situation also takes place on the backward measurement ports no.2 or 4. The relations of the coupling output voltage to the forward V+ and backward V- can be expressed as [2]

$$\begin{cases} \overrightarrow{V_1} = \beta_1 V_+ + \alpha_1\beta_1 V_- e^{j(\varphi+\Delta\varphi)} \\ \overrightarrow{V_2} = \alpha_1\beta_1 V_+ + \beta_1 V_- e^{j(\varphi+\Delta\varphi)} \\ \overrightarrow{V_3} = \beta_2 V_+ e^{j\Delta\varphi} + \alpha_2\beta_2 V_- e^{j\varphi} \\ \overrightarrow{V_4} = \alpha_2\beta_2 V_+ e^{j\Delta\varphi} + \beta_2 V_- e^{j\varphi} \end{cases} \tag{1}$$

Where β_i is the voltage coupling factor and corresponding power coupling factor β_i^2 (normally expressed in dB unit as $10\lg\beta^2$), α_i is the voltage isolation factor ($10\lg\alpha^2$ for power coupling), φ is the phase difference of $\overrightarrow{V_+}$ and $\overrightarrow{V_-}$, $\Delta\varphi$ is the phase difference between two couplers.

If only one coupler such as the first one in Fig. 1 is used to measure power, the measurement value P_1 outputted from port 1 will represent the incident power, and P_2 from port 2 represents the reflected power. We have

$$P_1 = \frac{V_1^2}{\beta^2} = (1+\alpha^2\Gamma^2 + 2\alpha\Gamma\times\cos\varphi)V_+^2 \tag{2}$$

$$P_2 = \frac{V_2^2}{\beta^2} = \left(1+\frac{\alpha^2}{\Gamma^2} + 2\frac{\alpha}{\Gamma}\times\cos\varphi\right)V_+^2 \tag{3}$$

Where Γ is voltage reflection coefficient.

The relative error of power measurement is

$$D_+ = \frac{|P_+ - P_1|}{P_+} = \left|\alpha^2\Gamma^2 + 2\alpha\Gamma\cos(\varphi)\right| \tag{4}$$

$$D_- = \frac{|P_- - P_2|}{P_-} = \left|\frac{\alpha^2}{\Gamma^2} + 2\frac{\alpha}{\Gamma}\cos(\varphi)\right| \tag{5}$$

The error of single directional coupler measurement is depending on α, Γ and φ obviously. The error will be

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maximum when $\vec{V_-}$ is in- or anti- phase with $\vec{V_+}$ ($\varphi = 0, \pi$), and minimum when the two singles are quadrature. Considering the typical isolation of 26 dB[3], the error of forward or backward power measurement is in the range from 5% to 10% in the case of total reflection($\Gamma = 1$), and the error of reflection measurement is even more than 100% when VSWR=1.1 ($\Gamma = 0.048$).

The Eq. 1 can't be solved to analytical results if $\Delta\varphi$ is arbitrary value. But in the case of $\Delta\varphi = \pm 90°$ (quadrature), we can find out the approximate value (marked as P_+' and P_-') of the forward and backward power. The relationship between them and the measured value P_i is.

$$P_+' \approx \left[\frac{\left(\alpha_2 P_1^* + \alpha_1 P_3^*\right)}{\left(\alpha_2 + \alpha_1\right)} - \alpha_1\alpha_2 \frac{\left(\alpha_2 P_2^* + \alpha_1 P_4^*\right)}{\left(\alpha_2 + \alpha_1\right)}\right] \quad (6)$$

$$P_-' \approx \left[\frac{\left(\alpha_2 P_2^* + \alpha_1 P_4^*\right)}{\left(\alpha_2 + \alpha_1\right)} - \alpha_1\alpha_2 \frac{\left(\alpha_2 P_1^* + \alpha_1 P_3^*\right)}{\left(\alpha_2 + \alpha_1\right)}\right] \quad (7)$$

Where $P_{1(2)}^* = \frac{P_{1(2)}}{\beta_1^2}$, $P_{3(4)}^* = \frac{P_{3(4)}}{\beta_2^2}$.

The error due to the approximation is less than 0.01% even though the isolation of two couplers is worse to 20dB. In Eq. 6, the second term is less than the first term because the backward power must be less than input power, the equation can be replaced by Eq. 8 when the accuracy requirement of input power measurement is about 1%.

$$P_+' \approx \frac{\left(\alpha_2 P_1^* + \alpha_1 P_3^*\right)}{\left(\alpha_2 + \alpha_1\right)} \quad (8)$$

ERROR OF NON-IDEAL QUADRATURE

It is no easy to keep the coupler-pair in ideal quadrature in practice. The error will take place due to non-ideal quadrature, which tends to be serious when $\vec{V_-}$ is in- or anti- phase with $\vec{V_+}$ ($\varphi = 0, \pi$). According to the calculation, in the case of $\varphi = 0, \pi$, the error of non-ideal quadrature can be expressed as

$$D_+' = \left|\Gamma \times \frac{2\alpha}{1+\alpha^2} \times \cos\Delta\varphi\right| \quad (9)$$

$$D_-' = \left|\frac{1}{\Gamma} \times \frac{2\alpha}{1+\alpha^2} \times \cos\Delta\varphi\right| \quad (10)$$

Where D_+' and D_-' are the forward and backward error caused by the phase deviation away from quadrature.

The error is calculated in the conditions that the relative power isolation is typical value of 20dB, 26dB, 30dB and $\Delta\varphi$ is in the range from 80° to 100°, and shown in Fig. 2 and Fig. 3.

The following analysis is based on the condition that $\Delta\varphi$ is in the range from 85° to 95° and the relative power isolation A is 26dB. Forward measured accuracy can achieve 1% with any reflection coefficient. Backward accuracy can achieve 2% with reflection being 0.5, 4% with 0.25, 9% with 0.1, 19% with 0.048 theoretically.

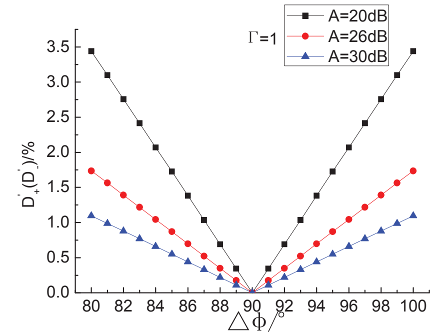

Figure 2: Forward and backward error at Γ=1.

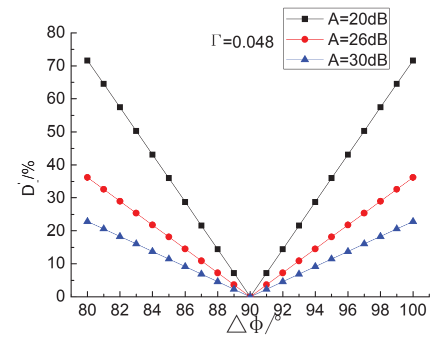

Figure 3: Backward error at Γ=0.048.

The analysis indicates that the forward measurement accuracy has much higher tolerance with $\Delta\varphi$. But backward accuracy is sensitive to the phase deviation away from quadrature, especially when the reflection is small.

PHASE DIFFERENCE MEASUREMENT

Since the power measurement accuracy is sensitive to $\Delta\varphi$, it is important to measure precisely the $\Delta\varphi$. we develop a method to determine the phase difference between two couplers on the working frequency. The network analyzer is used to measure the transmission parameter S_{21} from the forward port to coupling port 1 or 3, Meanwhile the backward port is shorted. The principle of this measurement is shown in Fig. 4.

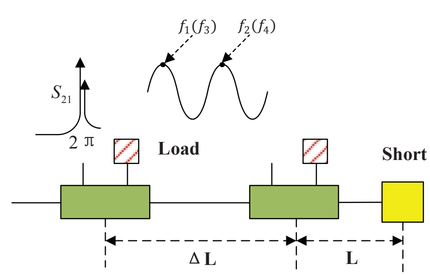

Figure 4: Structure of measurement.

We find out the frequency f_1 and f_3 which are corresponded to the adjacent S_{21} peak value on port 1, and f_2, f_4 on port 3 [4]. Then we have

$$2\frac{\Delta L\times f_1}{c}+2\frac{L\times f_1}{c}+\frac{\pi}{2}=2n\pi \tag{11}$$

$$2\frac{\Delta L\times f_2}{c}+2\frac{L\times f_2}{c}+\frac{\pi}{2}=2(n+1)\pi \tag{12}$$

$$2\frac{L\times f_3}{c}+\frac{\pi}{2}=2m\pi \tag{13}$$

$$2\frac{L\times f_4}{c}+\frac{\pi}{2}=2(m+1)\pi \tag{14}$$

The phase difference of a pair of directional couplers at arbitrary frequency f is

$$\Delta\varphi=\frac{\Delta L}{c}\times f=\pi\times f\times\left[\frac{1}{(f_2-f_1)}-\frac{1}{(f_4-f_3)}\right] \tag{15}$$

TEST RESULTS

The test model was built as Fig. 5. The type of couplers is ZGDC20-33HP+ produced by Mini-Circuits Company. The frequency range is from 300MHz to 3000MHz. The backward coupling port is inside terminated and unused. Therefore twice measurements should be made, one for forward, and then reverse the couplers direction for backward. We measure the phase difference between couplers, which infers that the quadrature frequency should be 1.76GHz [5]. The power coupling factor is 20dB and the relative power isolation is 26dB at this frequency.

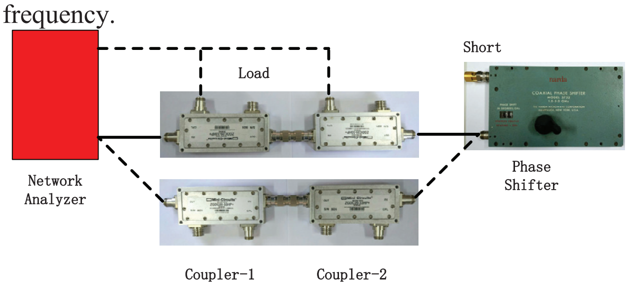

Figure 5: Test model.

We measure and calculate the forward and backward power at 1.76GHz, and also 1.9GHz as comparison, the variation of frequency may lead the $\Delta\varphi$ to change about 12°. The results are shown in Fig. 6 and Fig. 7.

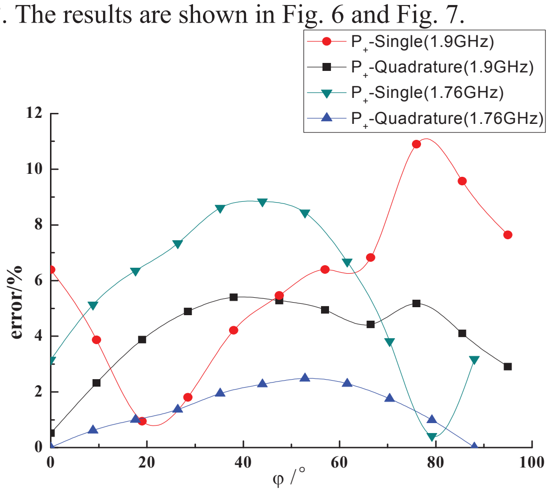

Figure 6: Forward measured comparison.

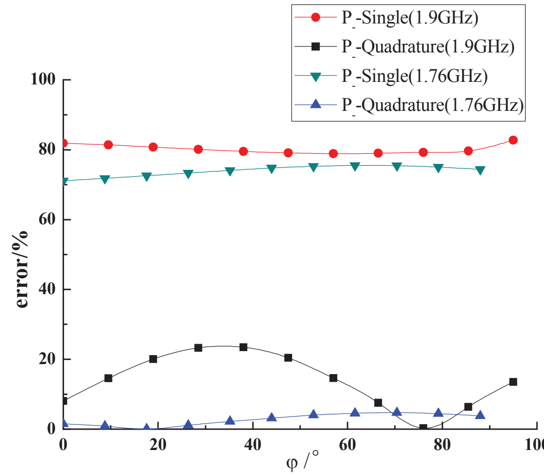

Figure 7: Backward measured comparison.

The test results show that the forward measured accuracy is improved to 2% on 1.76GHz and 5% on 1.9GHz. But the backward measured accuracy is influenced seriously by $\Delta\varphi$, it can be improved to 5% on 1.76GHz but only 25% on 1.9GHz, meanwhile the reflection is 20%. The test proves that the quadrature coupling method can really archive high accuracy in both forward and backward measurement with small phase deviation away from quadrature. The deviation has allowable tolerance which is determined by the needed accuracy.

CONCLUSION

The quadrature directional coupling method can significantly eliminate the influence of directional cross-talk, and improve the accuracy of forward and backward power measurement. When two couplers are in the perfect quadrature situation, the method will give out the satisfying measurement results. In the imperfect quadrature situation, the tolerant phase deviation away from quadrature is ±5 degrees, in order to obtain the accuracy of ±1% for the measurement of forward power, and ±20% for the measurement of very low reflected power, meanwhile the coupler's isolation should be over 26dB. The test experiments demonstrate that, the power measurement accuracy can be obtained to 2% for forward, and 5% for low reflection in case of 26dB coupling isolation.

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