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L-BAND RESONANT RING FOR TESTING RF WINDOWS FOR ILC

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Abstract

A resonant ring is widely used for the breakdown test of RF components under high power. It can reach power gain of more than 10 dB, which is limited by the attenuation of the ring. An L-band resonant ring is constructed for testing RF components of International Linear Collider (ILC) which is based on an RF frequency of 1.3 GHz. The target of the high power test is 5 MW. We have finished the test of an input power of 500 W using a solid state amplifier, and the principle of the resonant ring is verified. The resonant ring is tuned to an optimal condition, which is preparation for high power operation. This paper details the principle, construction, and test of the L-band resonant ring.

INTRODUCTION

The International Linear Collider (ILC) is a 250 GeV linear electron-positron collider, based on the 1.3 GHz superconducting radio-frequency technology [1]. Figure 1 shows the power distribution system (PDS) for ILC. Every PDS contains one 10 MW multi-beam klystron and that drives 39 cavities. Based on Fig. 1, the power on RF window, which is next to the variable power divider, is 1.1 MW. Considering the maximal standing wave, the power on the RF window may be 4 times to theoretical value, which is 4.4 MW. Therefore, it is necessary to test the RF window under 5 MW using a long operating period.

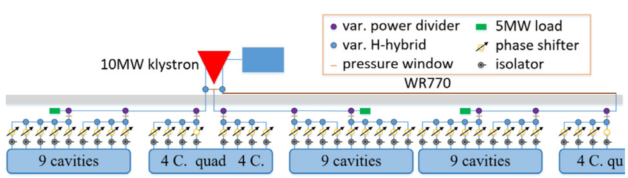

Figure 1: Power distribution system for ILC.

A resonant ring is a closed loop of a waveguide system that can amplify power, and it is widely used for the breakdown test of the RF components under high power [2]. In the superconducting RF test facility (STF), the variable hybrid, the phase shifter and the 500kW circulator have already been developed [3]. Moreover, the 800 kW modulated-anode klystron is developed in the STF, which is employed in the distributed RF system for the ILC [4].

Firstly, we a construct resonant ring with a variable hybrid, a phase shifter and a circulator at a low input power of 500 W from a solid state amplifier. The power gain is compared with one-turn phase of the ring and the coupling factor of the hybrid is tested [5]. The measured result shows that the maximum power gain can reach 10 ~13 dB, and is matched with simulation. A circular power of 5 MW can be achieved by the resonant ring with an input from an 800 kW klystron.

Secondly, considering the high power test of 5 MW circular power, the ring is expected to be pressurized by SF_6 or N_2 for preventing high power breakdown. The variable hybrid and phase shifter cannot be worked as pressurized due to its construction. Therefore, a fixed 11 dB hybrid is used to replace the variable hybrid and the operating frequency is changed to adjust one-turn phase. Moreover, the 500 kW circulator cannot be used at 5 MW due to the power limit. Even a low reflection generated in the resonant ring will be accumulated in the high reflected power. A 3-stub tuner is inserted in the ring to reduce the reflection in the ring. After adjusting the depth of the stub, the reflection is reduced significantly and the resonant ring worked at an optimal condition with a higher forward power gain.

THEORY AND STRUCTURE

The structure of the resonant ring is shown in Fig. 2. It contains a signal generator, hybrid, dummy load, and certain length of the waveguide system.

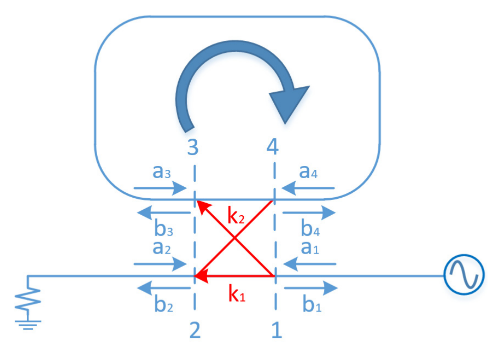

Figure 2: Schematic diagram of the resonant ring.

If the hybrid is assumed to be lossless and symmetrical, with no reflection, then the power gain (G) will be as given in equation (1), where k_1 and k_2 are transmitted and coupling coefficients of the hybrid at voltage respectively; α, β, and L are the attenuation coefficient, phase coefficient, and length of the resonant ring respectively.

$$G = \frac{|b_3|^2}{|a_1|^2} = \frac{k_2^2}{1 + k_1^2 e^{-2\alpha L} - 2k_1 e^{-\alpha L}\cos\beta L} \tag{1}$$

It is obvious that the power gain reaches a maximum when βL=2nπ, where n is an integer. This means that the wave in the ring will be superposed at an optimum condition [6].

$$G_{\max} = \frac{k_2^2}{1 + k_1^2 e^{-2\alpha L} - 2k_1 e^{-\alpha L}} = \frac{1 - k_1^2}{\left(1 - k_1 e^{-\alpha L}\right)^2} \tag{2}$$

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If the transmitted coefficient k_1 is a variable that corresponds to the variable hybrid, then the eventual maximal power gain is obtained using equation (3) when $k_1=e^{-\alpha L}$.

$$G'_{\max} = \frac{1}{1-e^{-2\alpha L}} \tag{3}$$

SIMULATION AND MEASUREMENT OF THE RESONANT RING

The resonant ring is constructed with a phase shifter, variable hybrid, 500 kW circulator, and an input of 500 W to verify the principle. Figure 3 is the structural diagram of the resonant ring. The maximal power gain relative to k_1 and one-turn phase is measured. Further, the simulation is compared with the measurement.

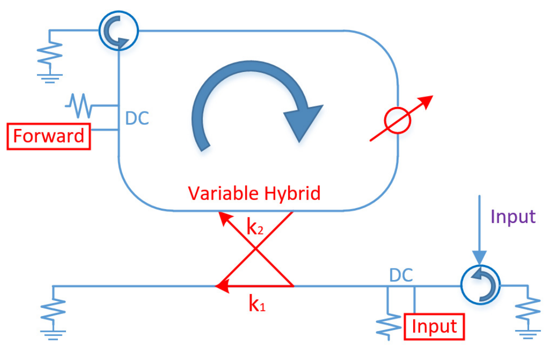

Figure 3: Structure diagram of the resonant ring.

Figure 4 shows the simulated power of the resonant ring compared with time. The parameters for the simulation are obtained from the measurement of the constructed resonant ring, such as one-turn phase, on- turn loss (A) and the transmitted coefficients (k_1^2) of the hybrid are set to 11 times 2π, -0.21 dB and -0.21 dB, respectively. The maximal power gain is 21.18 times (13.26 dB) and the rising time of the forward power from 10% to 90% is 0.89 µs. This showed that the power in the ring is accumulated to a high value by many turns and reaches saturation when the one-turn loss is equal to the coupling input.

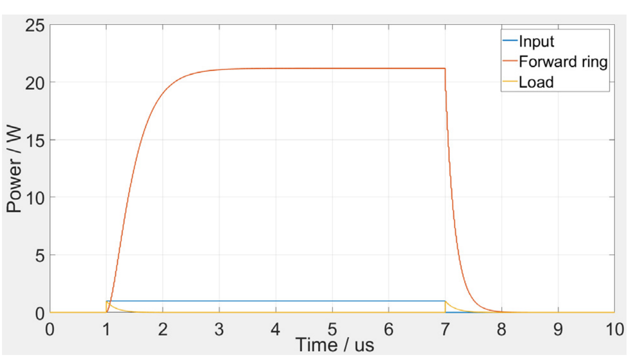

Figure 4: Simulated power with time.

Figure 5 shows the measured and the simulated power gain compared with transmitted coefficient k_1^2. The optimal condition is to make k_1^2 equal to A, and the power gain will decrease faster when k_1^2 is larger than A. Figure 6 shows the measured and simulated power gain compared with one-turn phase drift ($k_1^2 = A$ = -0.21 dB). The delta phase of the x-axis is the phase difference obtained from the optimum condition. The maximal simulated power gain is 13.26 dB with a one-turn loss of -0.21 dB and the maximal measured power gain is 14.12 dB, which corresponds to the one-turn loss of -0.17 dB. This may due to the measuring error of one-turn loss. The 3 dB width is 5.4° for simulation and 4.0° for measurement. If the one-turn phase cannot be adjusted to be an integer times 2π precisely, it is expected to be within the 3 dB width to ensure sufficient power gain.

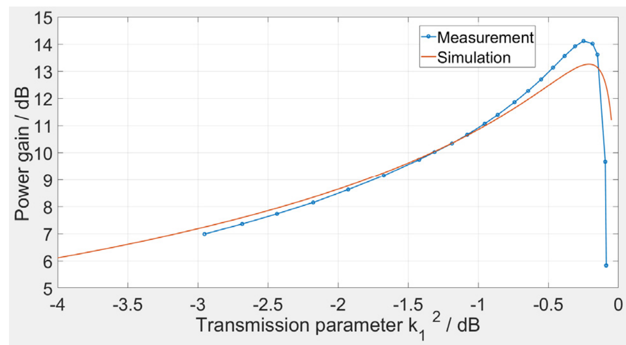

Figure 5: Measured and simulated power gain compared with transmitted coefficient k_1^2.

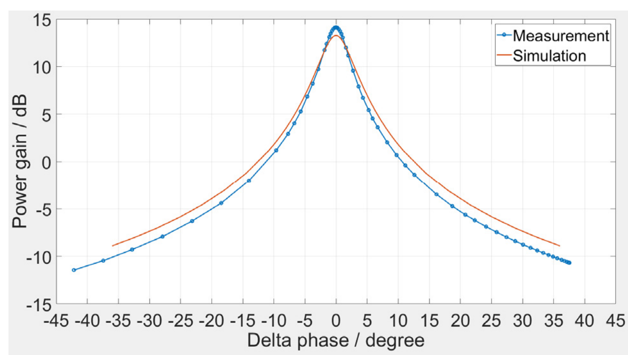

Figure 6: Measured and simulated power gain compared with one-turn phase drift.

PREPARATION FOR HIGH POWER OPERATION

To prevent breakdown at high power, the resonant ring should be pressurized; however, the variable hybrid and phase shifter cannot be used in this condition. The operating frequency is shifted to change the circular phase to adjust the resonant ring to its optimal condition. The fixed hybrid of the coupling coefficient, which is -11.15 dB at 1.3 GHz, replaces the variable hybrid. The reflection due to the hybrid is typically higher than -20 dB around 1.3 GHz.

The circulator cannot be used for the 5 MW case. We find that even small reflections generated in the resonant ring accumulate to cause high reflected power. It is therefore challenging to measure the power of the device under test owing to the serious standing waves generated by the

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high reflected power. Thus, it is necessary to suppress or compensate this reflected power in the ring.

A 3-stub tuner is commonly used to match impedance and decrease reflection [7]. Figure 7 is the schematic diagram of the resonant ring with a 3-stub tuner.

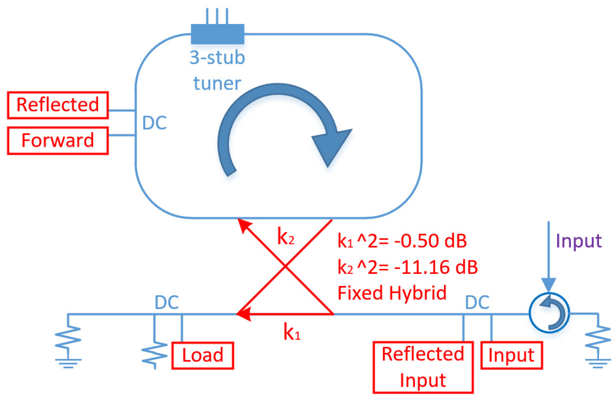

Figure 7: Resonant ring with 3-stub tuner.

For the process of tuning in the preliminary step, a network analyzer is inserted in place of the H-corner near the 3-stub tuner to pre-tune the ring. In the second step, the resonant ring is constructed integrally and an oscilloscope is used to monitor the waveform of the reflected signal in the ring.

Figure 8 shows the measured and simulated response of the fully tuned resonant ring with an input of 500 W. The optimal or peak frequency is found to be 1.3017 GHz. The difference between the forward and reflected power values of the ring is 56.31 dB, as shown in Fig. 9. With the measured one-turn loss of ring A, transmitted coefficient k_1^2, and coupling coefficient k_2^2 are -0.04 dB, -0.50 dB, and -11.16 dB, respectively, and the measured and simulated maximal power gain values are 14.80 dB and 13.26 dB, respectively. We consider two possible causes for this difference. First, the measured one-turn loss may be less than the true loss value. Second, if k_1 is not changed and k_2^2 is equal to one subtract k_1^2, the expected G will be 14.76 dB, which is close to the measured G of 14.80 dB. This means that when the resonant ring is tuned well, all the input power except that delivered to the load will be accumulated as the forward power in the ring. This will make the estimated value of k_2 larger than the measured value, and the hybrid will be operated as the ideal model. For the ideal model of the hybrid, power will only be delivered to the straight and coupling ports but not the isolated port.

Unloaded quality factor Q_{unload} can be calculated using equation (4), where v_g is the group velocity [6]. Measured and simulated Q_{unload} values are 6505 and 3176, respectively. The reason for the difference here is that the measured G and power across load are higher than the simulated values.

$$Q_{\text{unload}} = \frac{\pi f}{\alpha v_g} \frac{G(1-A^2)}{1-P_{load}/P_{input}} \tag{4}$$

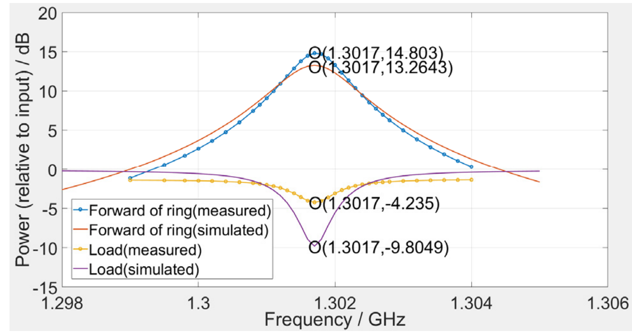

Figure 8: Measured and simulated responses of fully tuned resonant ring with input of 500 W.

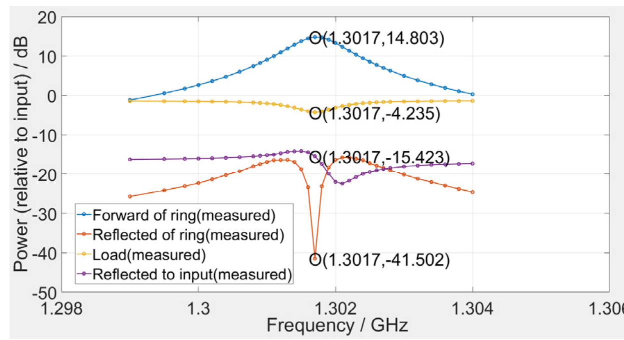

Figure 9: Measured responses of fully tuned resonant ring with input of 500 W.

CONCLUSION

The maximal power gain reached 14.80 dB with an input power of 500 W after the resonant ring was tuned by 3-stub tuner. An 800 kW klystron can satisfy a target of circular power of 5 MW with this power gain. A high power test was conducted after the preparation and a new RF window for PDS of ILC was designed simultaneously.

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