Development of a high-power and ultra-high-vacuum waveguide coupler working at C/X band

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Abstract: Waveguide directional couplers working at 5.712/11.9924 GHz are developed. Even holes symmetrical to the structure are drilled along the central line of the narrow-wall of the waveguide, which are used to couple the electromagnetic power from the main-waveguide to the sub-waveguide. The final prototypes have achieved satisfactory performances of high-power, ultra-high-vacuum and high-directivity. The microwave measurement results are also qualified.

Key words: high-power, ultra-high-vacuum, high-directivity, C-band, X-band, waveguide coupler

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1 Introduction

As one of the most widely used microwave components in many microwave systems, a directional coupler is used to divide the input microwave power according to a given ratio. Different from their use in microwave circuits or radars, in accelerator systems [1, 2], directional couplers are mainly used for watching the power continuously or for chain protection together with a power meter and a control box.

Unlike those commonly used in an S-band, prototypes of new C/X band waveguide directional couplers with a central frequency of 5.712/11.9924 GHz have been developed, and are used in CERN's linear accelerator and PSI's (Paul Scherrer Institute) free electron laser (FEL) respectively. The prototypes have a vacuum leakage rate of less than 2×10^{-10} Torr·L/s (ultra-high-vacuum), a directivity of more than 29 dB (high-directivity), and a very good high-power performance.

2 Structure

The structure (also the simulation model in Computer Simulation Technology-CST 2010) of the directional couplers are shown in Fig. 1. Six holes of the C-band coupler (four holes for the X-band coupler) are drilled along the central line of the narrow-wall of the waveguide. The two ends of the main-waveguide are welded with flanges while two shorting walls are used at the two ends of the sub-waveguide, and two N-type joints for the C-band coupler (Sub Miniature A-SMA joints for the X-band coupler) are welded on the wide-wall of the sub-waveguide to pick the microwave power out.

The microwave power comes in from the Input Port and very little power is coupled to the sub-waveguide and finally picked out by the joints.

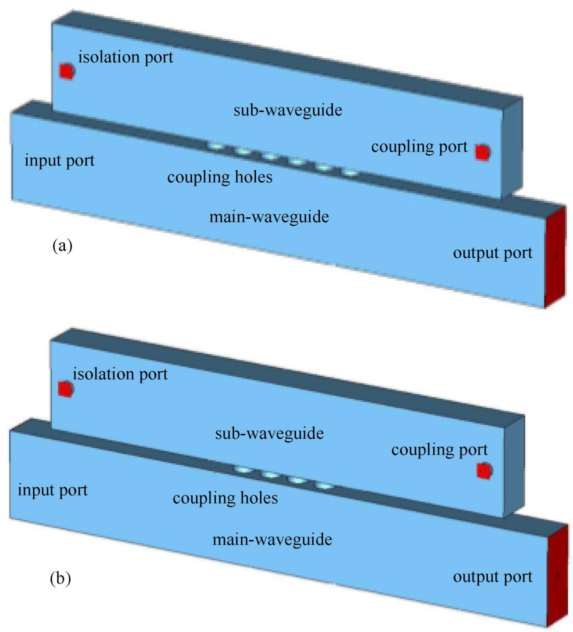

Fig. 1. (color online) Structure (simulation model) of the C/X band waveguide directional coupler. (a) C-band, six coupling holes; (b) X-band, four coupling holes.

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3 Simulation result

The most important parameters of the couplers are the distance between the coupling holes, the diameter of each coupling hole, the distance between the central point of the joint and the shorting wall, and the insertion depth of the joints.

After the simulation and optimization, the developed directional couplers have a directivity of more than 25/31 dB within a bandwidth of 250/430 MHz (5.62–5.87 GHz/11.82–12.25 GHz) while maintaining a Voltage Standing Wave Ratio (VSWR) of less than 1.04/1.04 as well as a variation of the coupling degree less than 0.4/0.4 dB (−59.8 ∼−60.2 dB/−48.5 ∼ −48.9 dB) at the same time in simulation. The frequency response of the directivity of the C/X band couplers are shown in Figs. 2 and 3 respectively.

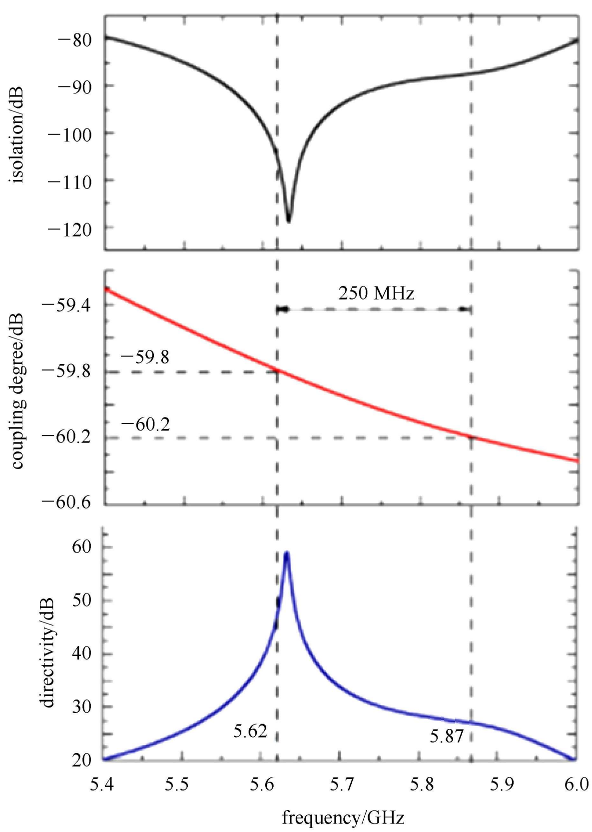

Fig. 2. (color online) Frequency response of directivity, coupling degree and isolation for the C-band coupler.

4 Measurement results

The prototypes of the C/X band couplers are shown in Fig. 4, and the comparison between the simulation and measurement results of the C/X band couplers at their central frequencies are shown in Tables 1 and 2 respectively. Note that the A/B in the tables mean that the results are obtained when the microwave power comes inside from the left (Input port)/right (Output port) port (see Fig. 1).

The C-band waveguide directional coupler has been accepted by PSI's FEL for meeting their requirements as: bandwidth of 5712±3 MHz, VSWR less than 1.04,

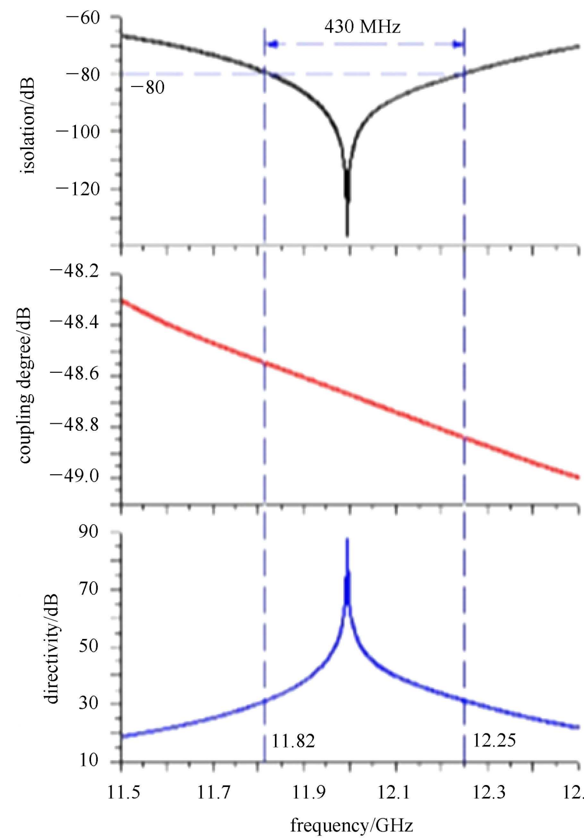

Fig. 3. (color online) Frequency response of directivity, coupling degree and isolation for the X-band coupler.

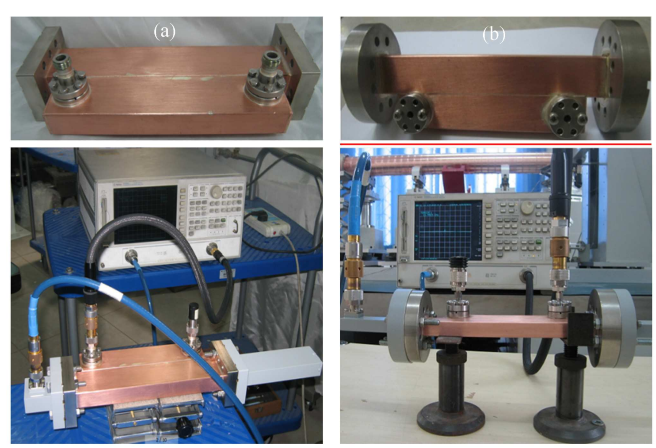

Fig. 4. (color online) Prototype and testing of the waveguide directional couplers. (a) C-band coupler; (b) X-band coupler.

coupling degree within (−60±0.2) dB, directivity more than 25 dB at the same time. A high power test of the C-band coupler has been performed in the PSI C-band test facility TRFCB01 from the end of March to the beginning of May 2014. A schematic diagram of the test is shown in Fig. 5. The conditioning took 4 weeks, during which the pulse length was increased from 100 ns to 3000 ns by steps of 100 ns when keeping the vacuum pressure always below 1×10^{-7} mbar. After that, the test at constant power took 5 weeks. The power from the klystron was set as a rectangular pulse with a pulse width of 3 μs and a peak power of 40 MW (average power 12 kW for a repetition rate of 100 Hz). The vacuum pressure was always below 1×10^{-8} mbar.

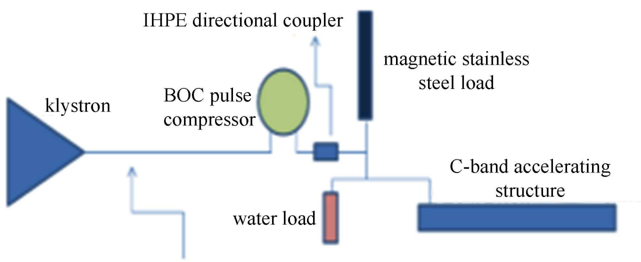

Fig. 5. (color online) The schematic diagram of the high power test in PSI.

From Table 1, it can be seen that the simulated and measured results match well, which means the C-band coupler is a successful one. However, the measured insertion loss is a little bigger than usual but still acceptable. It is possibly caused by the fabrication error of one or more sizes of the coupler, so a deeper consideration of the fabrication process in the future is worth considering. From Table 2, the measured results of the X-band coupler is acceptable but worse than the simulated results. For the very strict requirement of accuracy of the fabrication in the X-band, even a very small fabrication error will result in a very large deviation from the simulation results.

Table 1. Comparison of simulation and measurement results of C-band coupler at 5.712 GHz.

	simulation	measurement
VSWR	1.01/1.01	1.02/1.02
insertion Loss/dB	−0.1/−0.1	−0.5/−0.4
coupling degree/dB	−60.0/−60.0	−58.5/−59.4
isolation/dB	−93/−93	−90/−92
directivity/dB	33/33	32/33

∗ Left port input/ Right port input.

The prototypes have a vacuum leakage rate of less than 2×10^{-10} Torr·L/s and the C-band coupler has a vacuum value better than 1×10^{-8} mbar (7.5×10^{-9} Torr) during the high power test, so the prototypes have a good ultra-high-vacuum performance. Furthermore, the results of the high power and the microwave tests showed that the prototypes are of good high-power and high-directivity (directivity of more than 32/29 dB for C/X band couplers respectively) performances as well.

Table 2. Comparison of simulation and measurement results of the X-band coupler at 11.9924 GHz.

	simulation	measurement
VSWR	1.04/1.04	1.07/1.04
insertion loss/dB	−0.002/−0.002	−0.1/−0.1
coupling degree/dB	−48.7/−48.7	−47.0/−47.4
isolation/dB	−117/−117	−79/−76
directivity/dB	68/68	32/29

∗ Left port input/ Right port input.

5 Error analysis

For a better understanding of the requirement of the fabrication accuracy for some key sizes of the C/X band couplers, some simulations have been done. Three key sizes (the diameter of each coupling hole - R, the distance between the central point of the joint and the shorting wall - D, the insertion depth of the joints - L) of the couplers are studied and the requirements of their fabrication accuracy are listed in Tables 3 and 4 for the C/X band coupler respectively. Note that the number in the table means the influence of the size on the performance, for example, the number in the row 'S11' and column 'R' means the performance of S11 can be guaranteed if the size R is within the indicated error ('/' means the influence is negligible). The results can also be theoretically used as a guide during fabrication.

Table 3. Error analysis for key sizes of C-band coupler (Unit: mm).

	R	D	L
S11 (return loss)	/	/	/
S21 (insertion loss)	/	/	/
S41 (coupling degree*)	±0.02	/	/
directivity (>30 dB)	±0.2	±0.2	±0.1
allowed error/mm	±0.02	±0.2	±0.1

∗ Coupling degree needs to be within ±0.5 dB from the simulated value at central frequency.

Table 4. Error analysis for key sizes of X-band coupler (Unit: mm).

	R	D	L
S11 (return loss)	/	/	/
S21 (insertion loss)	/	/	/
S41 (coupling degree*)	±0.03	/	/
directivity (>30 dB)	±0.15	±0.05	±0.07
allowed error/mm	±0.03	±0.05	±0.07

∗ Coupling degree needs to be within ±0.5 dB from the simulated value at central frequency.

6 Conclusion

The C/X band waveguide directional couplers developed have advantages such as high-power, ultra-high-vacuum, high-directivity, stable coupling degree, wide bandwidth, etc. The high power test of the C-band coupler has been done at the PSI, and the result is satisfactory. However, for the X-band directional coupler, even a very small fabrication error may cause a very large deviation between the measured and simulated results because of the high accurate requirement of fabrication. So it is very important to control the fabrication errors during future processing.

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