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90 kW SOLID-STATE RF AMPLIFIER WITH A TE011-MODE CAVITY POWER-COMBINER AT 476 MHz

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Abstract

Solid-state rf amplifiers, which have long lifetimes and small failures, are the recent trend as reliable and stable high-power rf sources for particle accelerators. Hence, we designed a 90kW solid-state amplifier with an extreme low-loss TE011 mode cavity (Q0=100,000) power-combiner operated at 476 MHz and a 50 us pulse width. Developing this amplifier is for replacement of an IOT rf amplifier, at the X-ray free-electron laser, SACLA. In SACLA, highly RF phase and amplitude stabilities of less than 0.02 deg and 10^{-4} in rms are necessary in order to obtain stable lasing within a 10 % intensity fluctuation. The amplifier comprises a drive amplifier, a reentrant cavity rf power divider, 100 final amplifiers with a 1 kW output each and a TE011 mode cavity combiner. Water-cooling with precise temperature regulation at 10 mK and a DC power supply with a noise of less than -100 dBV at 10 Hz for the amplifier are necessary in order to realize the previously mentioned stabilities. Based on the test results of the amplifier, the above-mentioned specifications with the extreme low-loss are confirmed. The amplifier also allows us to operate in pulsed and CW rfs for linacs and ring accelerators.

INTRODUCTION

Medium-power rf sources comprising vacuum tubes, such as triodes, tetrodes [1] and an induction output tube (IOT, klystrodes) [2] based on the traditional rf technology, usually drive acceleration cavities for proton and injectors. These medium rf-output powers are form 10 kW to 100 kW, if it is compared with the output power of a high-power klystron over mega-watts. In the case of an X-ray free-electron laser (XFEL), SACLA [3], a 476 MHz IOT having a 100 kW rf-output power with a 50 µs pulse width is unexceptionally used to drive a booster cavity, which accelerates an electron beam up to 1 MeV [4]. We recently decided to replace from our IOT to a solid-state amplifier, since the IOT had some troubles, such as the end of its lifetime, shortage of its supply.The reference [5], which mentions the design of this amplifier, describes the detail reason of the replacement.

Based on the design concept described in the reference [5], we developed a 90 kW, 476MHz rf solid-state amplifier with a pulse width of 50 µs using a field effect transistor (FET) with a 1 kW output each [6]. Therefore, this amplifier used these 100 FETs in order to generate 90 kW. Furthermore, because of this FET could work in a continuous wave (CW) mode, we also aimed for diverting this amplifier to ring accelerator rf sources. This CW operation mode is one of the development concepts [5]. Concerning use of this amplifier as the CW rf source, an extreme low-loss rf cavity combiner using a TE011 resonant mode (Q0=100,000) was employed. Since the rf combing loss exactly corresponded to many of the output power of the FETs, in order to reduce the costs of the solid-state amplifier, reducing loss by an rf-combining method is important. The intended combing loss of the rf power combiner including the loses of rf connectors and cables is 0.1 dB [5]. On the other hand, since SACLA is going to use this amplifier, ultra-stable rf-output is also indispensable feature in order to realize stable XFEL intensity [3]. Highly rf phase and amplitude stabilities of less than 10^{-4} and 0.02 deg. in rms are necessary for stable lasing within a 10 % intensity fluctuation. An ultra-low noise DC power supply technique for realizing the rf stability already established in SACLA [7] is also needed. Realization of the 90 KW, 476 MHz amplifier had great possibility in the design stage in order to obtain the demanded XFEL intensity stability, since, in the design stage, we already obtained a 1kW rf output of the final amplifier module [5]. Furthermore, because of environmental temperature change largely affected the rf phase and amplitude changes of the amplifier, counter measures in order to reduce the temperature change are crucial. Hence, to employ a precise temperature controller originally developed for SACLA [8] having a temperature regulation within 10 mK is a big candidate. In addition to the above-mentioned requirements, because the SACLA building did not have a sufficient-big space for installing the amplifier instead of the IOT, the compactness of the amplifier was also important.

We have finally built a 90 kW, 476 MHz pulse solid-state amplifier with an extreme low-loss rf-power combining method using a TE011 mode rf-cavity. In this paper, we describe the test results and the final characteristics of the amplifier.

CONFIGURATION OF AMPLIFIER

In this summer, we finished to build the 100 kW, 476 MHz pulse solid-state amplifier. Table 1 tablets the specifications of the amplifier. Figure 1 shows electrical configuration of the amplifier using the FET described in Table 2. The amplifier comprises a 20 W amplifier in order to drive the final stage amplifier modules through a re-entrant type cavity power divider. Following the driving amplifier, there are 100 final stage amplifier modules

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including 2 FETs of a push-pull configuration in one package, which can handle a 1 kW rf output power. After the final amplifiers, a TE011 mode cavity rf power combiner is connected to the final amplifier modules. On the other hand, the amplifier equips auxiliary instruments, such as extreme low-noise DC power supplies and a control module using a programable langrage controller (PLC). To obtain the rf stability of the amplifier output demanded for the XFEL, we can use a method of the ultra-stable (~$2x10^{-5}$) and low-noise (-100 dBV@10 Hz) power supply technique employed for SACLA [7]. Because the technique almost determines the rf stability and already achieve the rf stabilities of of less than 0.01 deg. in phase and 10^{-4} in amplitude in rms at SACLA [7]. The extreme low-noise DC power supply for this amplifier uses the technique. Installation of the precise temperature control system having control performance within +/- 10mK is planned, when this amplifier is going to be placed in the SACLA's klystron gallery. This control system greatly helps in order to achieve the demanded rf amplitude and phase stabilities. However, we do not presently and unfortunately install the control system yet.

Table 1: Specifications of the 476 MHz Amplifier

Frequency	476 MHz
Output Power	90 ~ 100 kW
Pulse Width	50 µs
Repetition	60 pps
Amplification Class	AB

Table 2: Specifications of the LDMOS FET (MRFE6VP61K25H, NXP)

Frequencies	1.8 ~ 600 MHz
Handing Power	1250 W (CW or Pulse)
Gain	27 dB at Maximum
Efficiency	58 % at 500 MHz, at maximum

Figure 2 describes the actual fabrication condition of the amplifier. Since the amplifier should fit an installation space (2 m x 2 m) at the SACLA injector, the rf power combiner is used as a support structure for the amplifier modules, as shown in Fig. 2. Hence, the extra support for the components of the amplifier is eliminated. On the other hand, we devised the following items for easy maintenance (quick replacement of the modules), because of the many final amplifier modules. The top plate of the combiner has roles of cooling water ducts and a cooling water distribution header. The water-cooled 100 final-amplifier modules attach on the top plate through quickly-detachable water joints [9], which realize ease replacement of the module. Furthermore, the top plate has another role as an rf power transmission lines using striplines with air insulator (Air line) in order to connect among the final amplifier modules and the input ports of the rf combiner on it. These air lines are to reduce the rf loss. These air lines through the inside of the top plate structure are connected with quickly-detachable rf connectors [10] for easy replacements of the module.

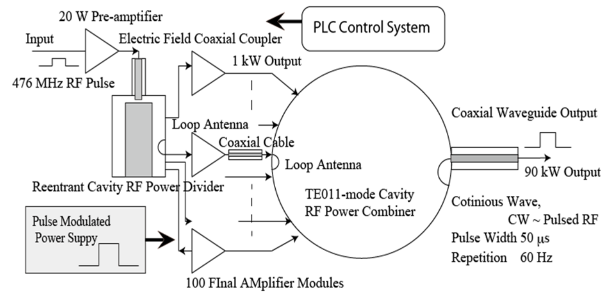

Figure 1: Block-diagram of the amplifier.

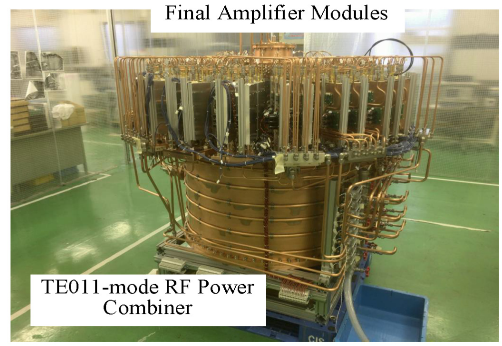

Figure 2: Actual fabrication condition of the amplifier.

TEST AND PERFORMNCE

We built the 90 kW, 476 MHz pulse solid-state amplifier in this summer and tested it. The performances of the amplifier, such as the 90 kW peak output rf power, the low loss, the rf phase and amplitude stability, were checked. Figure 3 shows an rf output power change of the amplifier of up to 109 kW, as a function of an input rf power. Rf phase and amplitude measurement apparatus are also connected through rf couplers for monitoring at the rf input and output ports. Figure 4 describes the rf output power trend for 8 hours. The amplifier rf output in the figure is 90 kW at peak with a pulse width of 50 µs and a pulse repetition rate of 20 pps. In this experiment, a cooling water temperature for the amplifier was controlled within +/- 0.5 K. From the trend data, an rf phase stability is +/- 0.4 deg. and an rf amplitude stability is 1 %, respectively. Rf amplitude and phase jitters are 0.036 %/min. and 0.044 deg./min. in rms, respectively. An oscilloscope takes these jitter data for 1 minute. Because of a cooling water temperature change is +/- 1 K, the previously mentioned rf amplitude and phase drifts are reasonable values, which correlated to the temperature change. If the temperature is controlled within ~ 10 mK, like SACLA's case, the rf phase and amplitude drifts could be ~0.004 deg. and ~10^{-4}, respectively. The reflection loss distribution of the 108 input ports of the combiner are shown in Fig. 5. The average reflection loss and its standard deviation (STD) value are -20.469 dB and 0.105 dB, respectively. The total average insertion loss in rms of the

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combiner is -0.135 dB. Phase displacement values distribution at the 108 output ports of the combiner is shown in Fig. 6. The rms phase deviation is 2.71 deg.. These representative rf-loss related data and some experimental results of the amplifier are tabulated in Table 3.

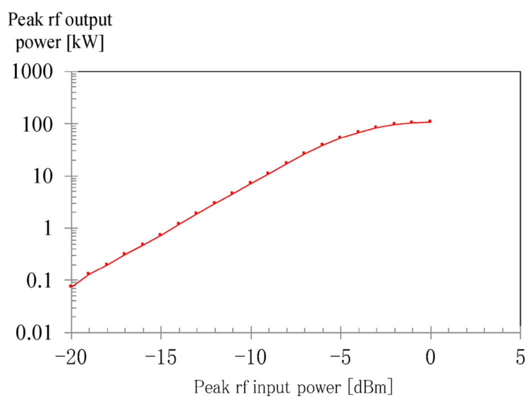

Figure 3: Rf output power as a function of the input rf power. The rf output power reaches 109 kW at peak.

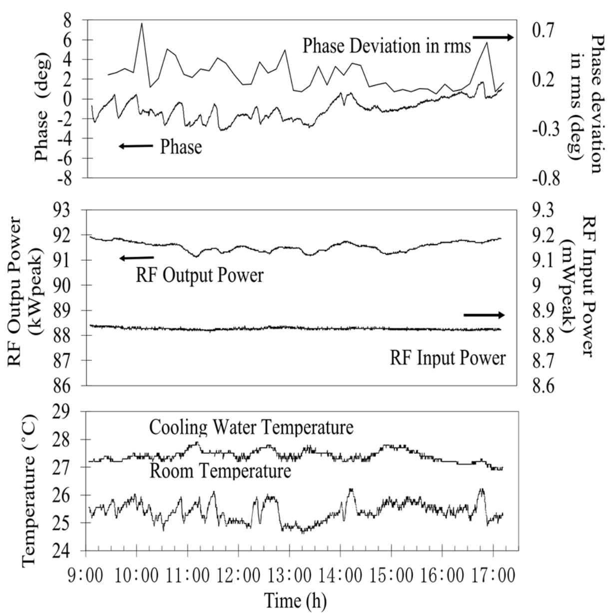

Figure 4: Rf power trend of the phase and amplitude of the amplifier output for 8 hours. Each point data are 10 minutes average of each 1 second data. The phase deviation of the most upper graph shows the rms phase jitters taken from the phase measurement points data for each 10 minutes.

CONCLUSION

We successfully built a 90 kW, 476 MHz rf pulse amplifier. The amplifier was tested to confirm its performances. The idea in order to reduce rf loss for adapting CW operation of the amplifier by using a TE011 mode cavity type rf combiner was evaluated with fruitful results. The rf power combining loss is -0.135 dB in total, which is almost our requirement. Furthermore, this our development technically established elaborated stabilities of the output rf phase and amplitude of the amplifier for driving stable XFEL intensity. The phase and amplitude stabilities are +/- 0.4 deg./1K and +/- 5x10^{-3} /1K, respectively. These could correspond to about +/- 0.004 deg./10mK and about +/- 5x10^{-5}/10 mK, respectively. On the other hand, in order to reduce installation space for the amplifier, the large size of the combiner works well as a support structure for many final amplifier modules, as which we originally intended. From the above-mentioned results, we think this development successfully finished. The amplifier will be installed in SACLA's building for user operation.

Table 3: Summary of the Measured Parameters of the Amplifier

Rf output power	109 kW
Rf amplitude stability in rms for 8 hours	+/- 0.5 % /K
Rf phase Stability in rms for 8 hours	+/- 0.4 deg./K
Total insertion loss of the combiner	- 0.135 dB
Standard deviation of the losses (combiner input)	0.105 dB
Rms deviation of the phases (combiner input)	2.71 deg.

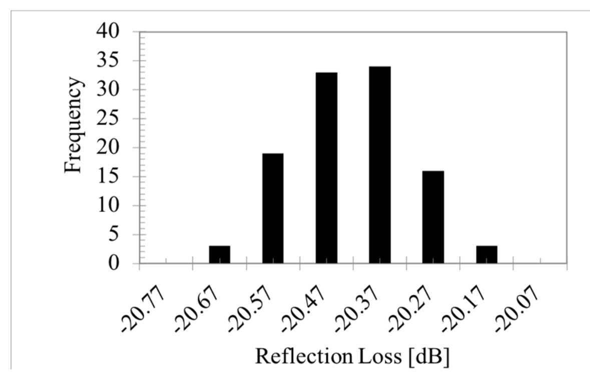

Figure 5: Reflection-loss values distribution of the 108 input ports of the rf power combiner. These values were measured by S21. The average reflection loss and its STD value are -20.469 dB and 0.105 dB, respectively.

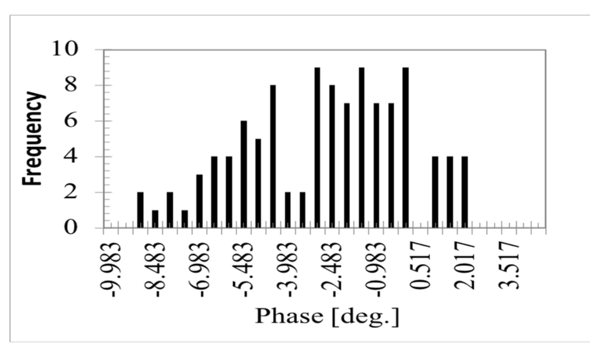

Figure 6: The phase deviation values distribution from the ideal at the 108 input ports of the rf power combiner. These values were measured by S21.

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