DESIGN OF A 100 kW SOLID-STATE RF PULSE AMPLIFIER WITH A TE011 MODE RF COMBINER AT 476 MHz

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Abstract

Solid-state rf amplifiers, which have a long lifetime and a small number of failures, are the recent current of medium-power rf sources for particle accelerators. Hence, we designed a 100kW solid-state amplifier with a TE011 mode cavity (Q0=100,000) type power combiner having extreme low-loss, which is operated at 476 MHz and a 50 μs pulse width. The final amplifier module and combiner are to realize a high efficiency of over 60 % of a klystron and to reduce a number of rf solid-state amplification devises, respectively. Developing this amplifier is for replacement of a high-power amplifier using an induction output tube, IOT, in the X-ray free-electron laser, SACLA. In SACLA, highly rf phase and amplitude stabilities of less than 0.01 deg. and 10^{-4} in rms are necessary to stable lasing within a 10 % intensity fluctuation, respectively. The amplifier comprises a drive amplifier, a reentrant cavity rf-power divider, 100 final amplifier modules with a 1 kW output each and a TE011 mode cavity combiner. Water-cooling control within 10 mK and a DC power supply with a noise level of less than -100 dBV at 10 Hz for the amplifier is necessary to realize the above-mentioned stabilities. Based on the experimental results of a 1 kW prototype amplifier module with an efficiency of 60 % and combiner cavities, possibility to realize an output rf-power of 100 kW, the low-loss and the stabilities is large. We report the detail and performance of the amplifier.

INTRODUCTION

In traditional accelerator technology, medium-power rf sources were mainly vacuum tubes, such as triodes, tetrodes [1] and an induction output tube (IOT, klystrodes) [2]. These medium rf-output powers are form 10 kW to 100 kW at a pulse repletion of 60 Hz, if we compare to the output power of a high-power klystron over megawatts. These rf sources mostly drive acceleration cavities around an injector with a low-beta electron or a proton beam and a superconducting cavity [3,4]. In the case of the vacuum tubes, a number of interlocked fault stops by such over current and a lifetime are not negligibly few and long. In the case of a free-electron laser, SACLA, 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 [5]. However, these kinds of the vacuum tubes, which are mainly used in a broadcasting station, is shortage of supply, because of its replacement by solid-state devices. Hence the prices of these devices are nowadays expensive. In these reasons, we decided to replace to our IOT to a solid-state amplifier, since the IOT have some troubles, such as the end of its lifetime.

High-power solid-state rf-amplification devices, like a field effect transistor (FET), recently develop well and increase rf-output power of itself. It can now handle over a 1 kW output [6]. If the output powers of these 100 devices are combined, we have great possibility to realize a solid-state amplifier replaced form the medium-power - sources, such as the IOT. The prices of these devices are not so low. Hence, the out powers of the devices are expensive, In this case, the rf-power loss of an power combining method must be low, since the loss exactly corresponds to many of the output power of the devices. To reduce the costs of the solid-state amplifier, reducing the loss of the rf-combining method is crucial and the FET with the highest output power should be selected for comprising the amplifier. Furthermore, since this amplifier is employed for a free-electron laser machine, like SACLA, ultra-stable rf-output is necessary to obtain stable FEL intensity [5]. For the above-mentioned reasons, we develop a 476 MHz solid-state amplifier with an extreme low-loss rf-power combining method using a TE011 mode rf-cavity. In this paper, we describe the basic design of the amplifier and test results of the final amplifier module before the combinser.

DESIGN

Criteria to Design Amplifier

When we design the amplifier, how we do realize the low loss at the outputs of the individual final-stage amplifier module is very important. Radial rf-power combiners [7] and a TM010 mode cavity rf-power combiner [8] were traditionally used for low-loss rf-power combing. However, these methods still have several % loss. If an rf-output power is 100 kW, the loss is several kW. In this case, this loss power corresponds to several pieces of the 1 kW FET device. This fact cannot be ignorable for the costs to make the amplifier, because of the high price of the FET (more than several thousand dollars per a piece). Therefore, we need an extreme low-loss rf-power combiner. Furthermore, in the case of the 100kW output amplifier, 100 pieces of the FET based on the present technology are necessary. This number is still large, even through, one FET has a 1kW output. Hence, we want to reduce the number of the FET, as small as possible, which correspond to compressing amplifier costs. The amplifier using the 100 FETs and the power combiner need much installation space. For this reason, we want to reduce and to fit the installation space to our present installation space (2 m x 2 m) at the SACLA injector. In addition to

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the above-mentioned items, we must realize amplifier rf-stability demanded by the FEL. Therefore, an extreme stable rf-output with rf phase and amplitude of less than 0.01 deg. and 10^{-4} in rms [5] of the amplifier is necessary, respectively.

Design of Amplifier

Based on the above-mentioned criteria, we designed the amplifier with a frequency of 476 MHz, an output rf-power of 100 kW, an output pulse width of more than 50 µs. Further details of the amplifier specifications are tabulated in Table 1. The schematic block-diagram of the amplifier configuration is shown in Fig. 1. To reduce the rf-power combing loss, a TE011 mode cavity, which has a quality factor, Q, value of more than 100,000 was selected. This Q value is 2~3 times larger than that of the TM010 mode cavity and the highest value in normal conducting rf-cavities. Form the other point of view; ordinal rf-engineers do not much care about input rf-powers to drive the final stage amplifier, because of not so big rf-power. However, in the case of the 100 kW amplifier with the 100 FET devices, driving total power for the final amplifiers are around 20 W (based on our present design), which is not ignorable small. From this reason, we should also give care of loss of the driving power. Hence, a reentrant cavity type rf power divider is employed, as shown in Fig. 1 and Fig 2.

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	A or AB

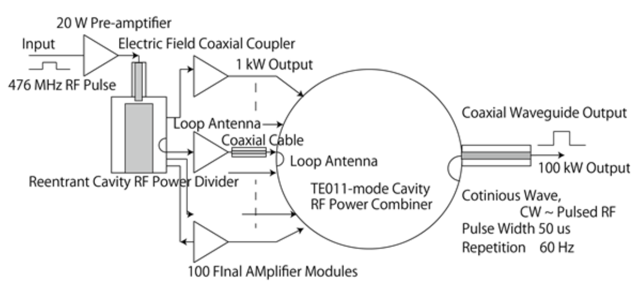

Figure 1: Block-diagram of the amplifier.

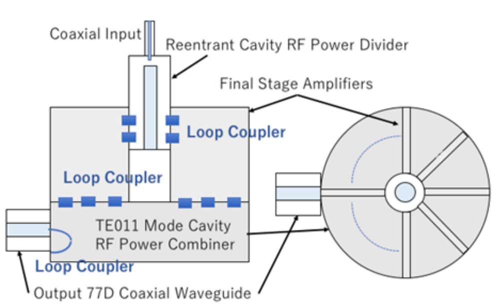

Figure 2: Mechanical configuration of the amplifier.

Why we use this resonant mode, because of its small cavity size.Since the size of the TE011 mode cavity rf-power combiner is very big, we should consider the small size of the divider, otherwise, the whole amplifier system size must be unacceptably very big. On the other hand, the big size of the TE011 cavity combiner has some advantage. This combiner can be used as a support structure for the amplifier modules, as shown in Fig. 2, because of its big size. This fact directly connects to reducing the installation space to fit the previously mentioned SACAL's space, since the extra support for the components of the amplifier including the combiner is eliminated. On the other demand to the amplifier, reducing the number of the FET device is effective to reducing its cost. In this case, we must choose an amplification device with the maximum handing power from commercially well available parts. In state of art rf solid-state technology, the LDMOS and GaN processes to produce device is well developed. From these devices, we choose a LDMOS FET. A push-pull LDMOS device including 2 FET components, as which specifications are described in Table 2, can handle an rf-power of more than 1 kW. This device can effectively reduce a number of the FET to generate a 100 kW rf-power. To obtain the rf stability of the amplifier output demanded for the FEL, we can use the method to reduce ultra-stable (~$2x10^{-5}$) and low-noise (-100 dBV@10 Hz) power supply technique employed for SACLA [9]. Because these techniques almost determine the rf stability and already achieve the rf stabilities of of less than 0.01 deg. in phase and 10^{-4} in rms in amplitude at SACLA [5].

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

Frequencies	1.6 ~ 500 MHz
Handing Power	1250 W (CW or Pulse)
Gain	27 dB at Maximum
Efficiency	84 % at 81 MHz, Maximum,

FEASIBILITY CHECK

To check feasibility of our designed amplifier based on the above-mentioned criteria, we numerically simulated functions of the key components of the amplifier, such as the TE011-mode cavity-type rf-power combiner, which decides main rf-loss. The final amplifier module was also and preliminary tested by using a prototype circuit board, which decides the output powers and a number of the amplifier modules. These power and number directly reflects to the costs. Figure 3-(a), (b) and (c) show simulated results of the TE011-mode rf-power combiner with a 1 output and 4 inputs by HFSS (High-frequency structure simulator [10]). Why we only simulated the 4-input case, because it does not so easily to simulate the previously-mentioned 100 input case. These simulation results are, (a) an electric-field distribution, (b) an rf-return loss of the S11 value of the combiner output and (c) an rf-transmission loss of the S12 between the input and output of the cavity.

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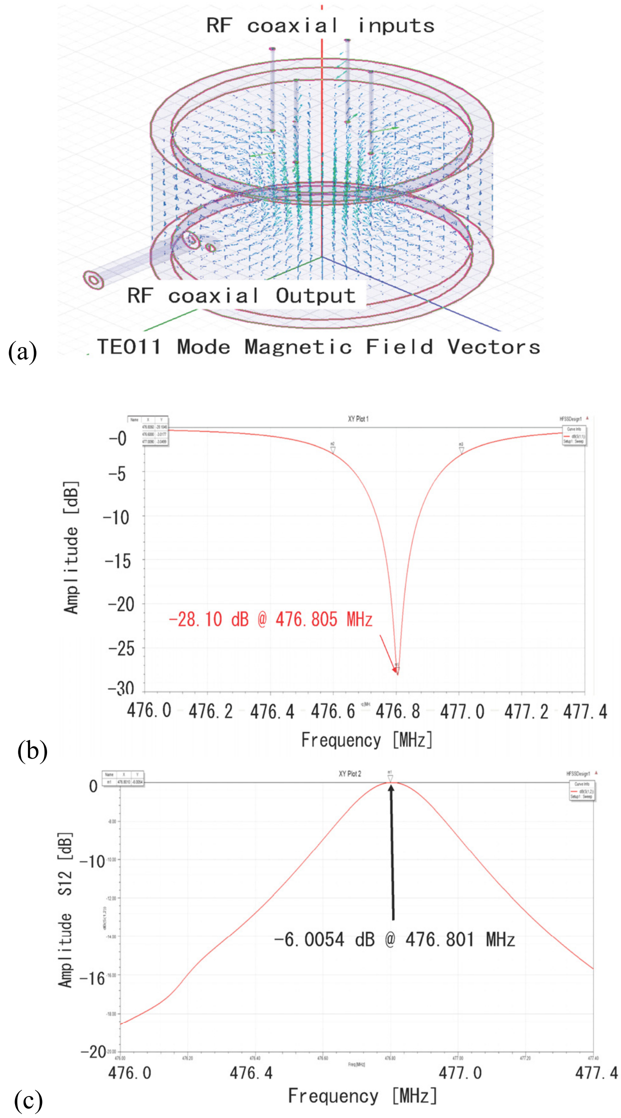

Figure 3 : (a) Magnetic field vectors of the TE011 mode cavity combiner, (b) an rf-return loss of the S11 value of the combiner output and (c) rf-power transmission (S12) from one of the inputs to the output. A transmission ratio of -6.0054 dB is close to the ideal value of – 6 dB (meaning low loss).

The results describe that an rf excitation of the cavity is an almost pure TE011-mode, the S11 is a very small value of about -28 dB and the S12 is about –6 dB, which means to be close to a theoretically proper dividing ratio of the combiner without rf loss, when it is used as a divider. Figure 4-(a), (b) and (c) show a schematic circuit diagram of the final amplifier module using a FET, the input and output relation of its rf-power amplification and, the efficiency and drain current of the module in the case of NXP, MRF6VP61K25HR6. 2 kinds of the FETs (both LDMOSs) of Ampleon and NXP [6,11] were actually tested. Both FET rf-output powers are values of more than 1kW, respectively. The output power of NXP's FET was larger than Ampleon's one. Therefore, we choose NXP's one, which gives a further operation margin of rf handing power by the amplifier module.

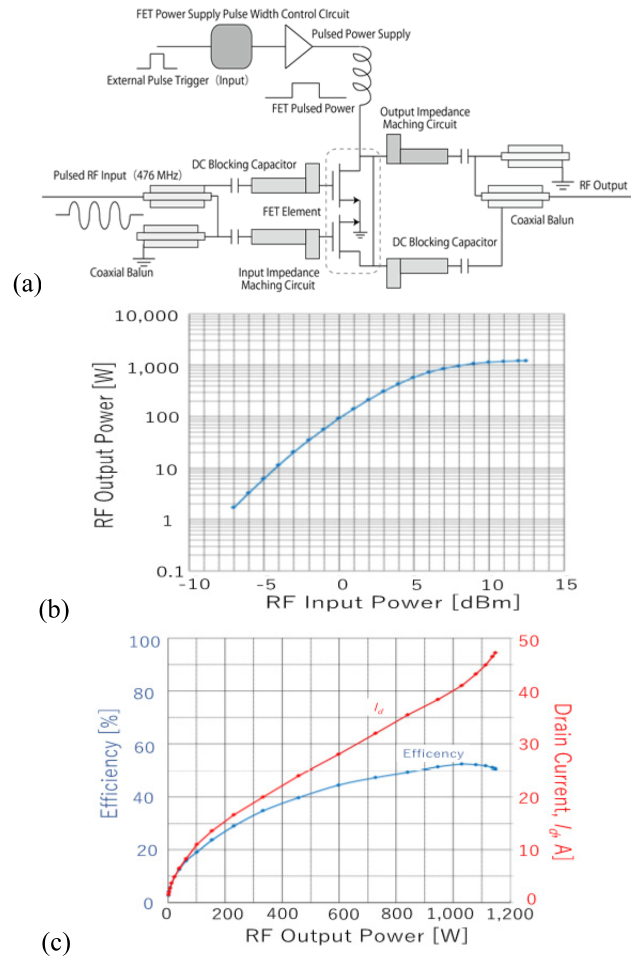

Figure 4: (a) Block-diagram of the final stage amplifier module, (b) input-to-output characteristic of the final stage amplifier (NXP, MRF6VP61K25HR6) and (c) the efficiency and drain current of the amplifier, as functions of the input/output power.

SUMMARY

We designed a 476 MHz, 100 kW solid-state rf-pulse amplifier to replace the present IOT amplifier at SACLA and checked feasibilities of the key components comprising the solid-state amplifier by numerical simulations. Design and simulated results, such as low loss of a TE011 mode combiner and an output power level at the final rf amplifier module by the preliminary test, show that our design is feasible to realize the amplifier. The big combiner size is also shows the possibility of using as a support for the amplifier modules to fit the space at SACLA. This amplifier system will be extended to apply to the CW rf sources of ring accelerators and especially to the ARES system [12] at KEK.

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REFERENCES

[1] A. S. Gilmour, Jr, Microwave Tubes, Chap. 8, 191 (1986).
[2] A. S. Gilmour, Jr, Microwave Tubes, Chap. 8, 196 (1986).
[3] W. Pirkl, Choice of rf Frequency, CAS -CERN Accelerator School: Radio Frequency Engineering, 336-350 (2005).
[4] R. G. Cater, Review of rf Power Sources for Particle Accelerators, CAS -CERN Accelerator School: Radio Frequency Engineering, 107-145 (2005).
[5] H. Hanaki et al., Injector System for X-ray FEL at Spring-8, Proc. of EPAC08, MOPC010, 85-87 (2008).
[6] http://www.nxp.com/products/rf/rf-power-transistors/rf-broadcast-and-ism/1.8-600-mhz-1250-w-cw-50-v-wideband-rf-power-ldmos-transistors: MRFE6VP61K25H
[7] A. Jain *et al.,* "High-power, Low-loss, Radial rf Power Divider/Combiner", Proc. of APAC2007, WEPMA143, 520-522 (2007).
[8] Yuji Otake *et al.,* "Cavity Combiner for S-band Solid-state Amplifier for The High-power Klystron at SLAC", SLAC-PUB-5197, March (1990).
[9] Y. Otake et al., PRAB, 19, 022001-1-22001-20 (2016).
[10] http://www.ansys.com/products/electronics/ansys-hfss
[11] http://www.ampleon.com/products/broadcast/0-500-mhz-transistors/BLF188XR.html
[12] Kageyama *et al.,* "Development of High-power ARES Cavities", Proc. of PAC1997, 2092-2094 (1997).

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