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DESIGN STUDIES ON A HIGH-POWER WIDE-BAND RF COMBINER FOR CONSOLIDATION OF THE DRIVER AMPLIFIER OF THE J-PARC RCS

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Abstract

A power upgrade of the existing 8-kW solid-state driver amplifier is required for the acceleration of high intensity proton beams on the J-PARC 3-GeV Rapid Cycling Synchrotron. The development of a 25-kW amplifier with gallium nitride (GaN) HEMTs, based on 6.4-kW modules is ongoing. The combiner is a key component to achieve such a high output power over the wide bandwidth required for multi-harmonic RF operation. This paper presents the preliminary design of the combiner. The circuit simulation setup and results, including the realistic magnetic core characteristics and frequency response of the cable, are reported.

INTRODUCTION

In the J-PARC 3-GeV Rapid Cycling Synchrotron (RCS), the consolidation of the amplifier chain of the RF system is desired [1]. The solid state amplifier is one of the important components of the amplifier chain. The output power and bandwidth of the existing solid state amplifier are 8 kW and 450 kHz–5.1 MHz, respectively. For the high power beam acceleration, improvements in both the output power and bandwidth are desired.

The development of the 25-kW amplifier with gallium nitride (GaN) HEMTs is ongoing. The target bandwidth is 100 kHz–10 MHz. The 25-kW amplifier consists of four 6.4-kW amplifier modules and one 25-kW combiner as shown in Fig. 1. In the current design, the bandwidth of the 6.4-kW amplifier module sufficiently covers our requirements. Hence, the realization of the high power combiner with the target bandwidth is the key of the development of the amplifier.

Transmission line transformers (TLTs) are the primary component of the 25-kW combiner. TLTs have wide bandwidths and high transmission efficiencies. A typical TLT consists of magnetic cores and transmission lines. To realize a wide bandwidth, it is necessary to design TLTs with a short cable length and a large number of winding turns.

Beyond 1 kW, the TLT design is challenging. Since high power coaxial cables are generally thick and stiff, the cable length and winding turn of the coil are inevitably longer and fewer. Furthermore, the power loss in the magnetic core should also be taken into account. We develop the TLT model using the electric circuit simulator, which can evaluate the bandwidth and power loss in the core considering the actual cable characteristics and complex permeability. A preliminary design of the 25-kW combiner is presented.

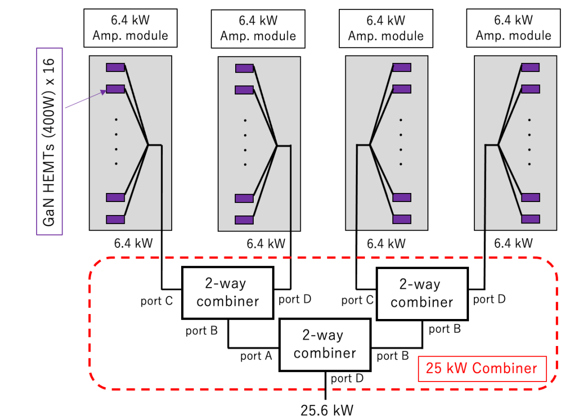

Figure 1: The configuration of 25-kW GaN amplifier.

OVERVIEW OF THE 25 KW COMBINER

The 25-kW combiner consists of three 2-way combiners as shown in Fig. 1. The 2-way combiner has four ports and consists of six TLTs as shown in Fig. 2. When P_A and P_B are input to ports A and B, ports C and D output $1/2(\sqrt{P_A}-\sqrt{P_B})^2$ and $1/2(\sqrt{P_A}+\sqrt{P_B})^2$, respectively. When P_C and P_D are input to ports C and D, ports A and B output $1/2(\sqrt{P_C}-\sqrt{P_D})^2$ and $1/2(\sqrt{P_C}+\sqrt{P_D})^2$, respectively.

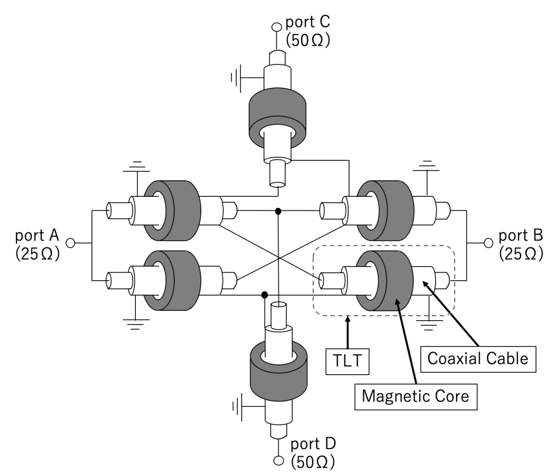

Figure 2: The configuration of the 2-way combiner [2].

The bandwidth of the 25-kW combiner depends on the TLT design. The cable attenuation due to the skin effect degrades the high frequency response. Cables with a low attenuation and short length should be employed. The isolation of the TLTs is associated with the low frequency response.

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If the isolation is insufficient, common mode signals are excited in the coaxial cables which causes the degradation of the low frequency response. Thus, a large number of turns and low loss magnetic core should be preferred to realize the required low frequency response.

CIRCUIT SIMULATION MODEL OF TLT

A circuit simulation model of TLTs is developed with LTspice [3]. Our model contains the skin effect, common mode propagation, and complex permeability, which are not trivial in LTspice simulations, to evaluate the bandwidth and core loss. The details of the TLT model are described below.

The developed TLT model consists of the coaxial cable model and core model. Figure 3 depicts the coaxial cable model. To simulate the skin effect, the parallel circuit consists of multiple resistors ($R1$–$R6$) and inductance ($L2$–$L6$) is introduced [4]. This parallel circuit represents a conductor line divided into multiple concentric circles. The number of stages in the parallel circuit varies depending on the accuracy and the upper frequency limit. In this case, the number of the stages is six. The values of each resistance and inductance are determined by the property of actual cables. Details in derivation of each resistance and inductance are described in Ref. [4], and Ref. [5] provides the computational programs.

The coaxial cable model also includes the technique to simulate the common mode propagation. LTspice provides "TLINE" for simulating the signal propagation in a transmission line. However, "TLINE" only supports a single transmission line mode. To calculate the common mode signal propagation, we use two "TLINE" as shown in Fig. 3, which is recommended in the example simulation code provided by LTspice.

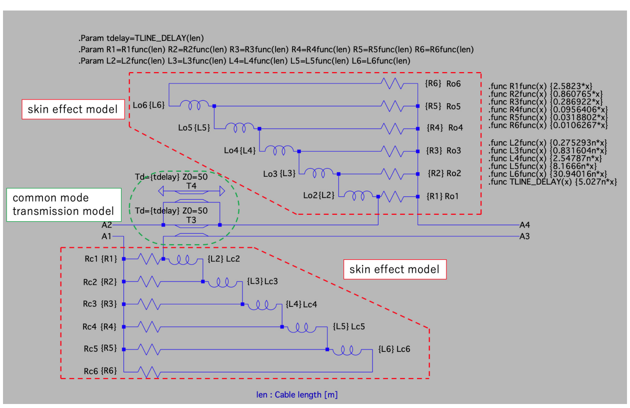

Figure 3: The coaxial cable model considering the skin effect and common mode signal propagation with LTspice. Parameters shown in this figure is for LMR-400-FR cable.

Magnetic cores with the complex permeability ($\mu = \mu' - j\mu''$) can be represented by an equivalent circuit, which consists of resistance and inductance varying with frequencies. In LTspice, "arbitrary behavioral voltage source" is used to simulate the frequency-dependent resistance and inductance. Figure 4 shows the toroidal coil model considering the complex permeability. Toroidal cores are represented by the "arbitrary behavioral voltage sources" [6]. The behavior of the voltage source $V(s)$ can be controlled using the Laplace variable $s = j\omega$. $V_L(s)$ and $V_R(s)$, corresponding to the inductance and resistance of toroidal cores, are

$$V_L(s) = s\mu' \frac{\mu_0 t N^2}{2\pi} \left(\ln \frac{b}{a}\right) (I_1(s) + I_2(s)) \quad \text{and} \tag{1}$$

$$V_R(s) = s\frac{-s}{|s|} \mu'' \frac{\mu_0 t N^2}{2\pi} \left(\ln \frac{b}{a}\right) (I_1(s) + I_2(s)), \tag{2}$$

where μ_0 is the magnetic permeability in vacuum, a, b and t are the inner and outer radius and thickness of toroidal cores, respectively, $I_1(s)$ and $I_2(s)$ are the current inner and outer conductors of coaxial cables, and N is the number of turns.

The parameters μ' and μ'' are introduced to the simulation model using the fitting function $g(x)$, which is given in Ref. [6] as

$$g(x) = \frac{10^{k_2 \log_{10} x + l_2}}{1 + 10^{(k_2 - k_1)\log_{10} x + (l_2 - l_1)}}, \tag{3}$$

where k_1, k_2, l_1, l_2 are the parameters derived from the curve fitting of complex permeability data. Figure 4 shows the magnetic core model for FINEMET (FT-3L) core [7]. The curve fitting is performed on the complex permeability data of FT-3L in the frequency range of 10 kHz–10 MHz.

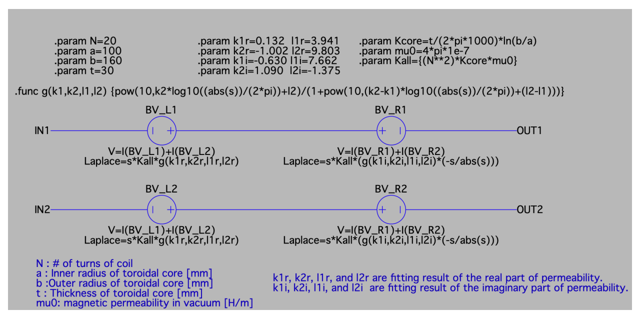

Figure 4: The toroidal core model considering the complex permeability with LTspice. Parameters shown in this figure are for FINEMET (FT-3L).

DESIGN OF 25-kW COMBINER

The overview of the 25-kW combiner is shown in Fig. 5. Two types of TLTs are designed, corresponding to each transmission power. For the TLT at the output port (TLT-A), the transmission power is 25.6 kW. For the other TLTs (TLT-B), the transmission power is less than 6.4 kW.

For coaxial cables, LMR series from Amphenol [8], which have a high power handling and flexibility, are employed. LMR-900-FR and LMR-400-FR are employed for the TLT-A and TLT-B, respectively. For the magnetic core, FT-3L, which has a high relative permeability with a low core loss, is employed.

For the TLT-B, a toroidal coil with a single core is designed thanks to the small minimum bend radius (25.4 mm) of LMR-400-FR. For the TLT-A, the minimum bend radius

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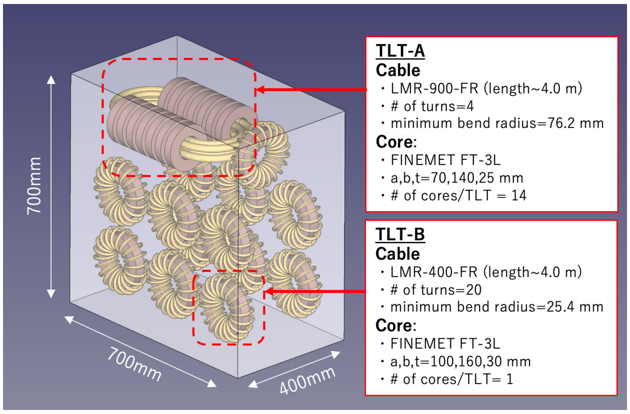

Figure 5: Overview of the 25 kW combiner.

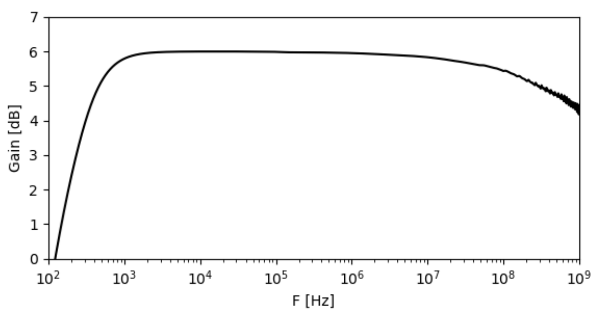

Figure 6: Bandwidth of the designed 25-kW combiner calculated using LTspice.

of LMR-900-FR is not sufficiently small (76.2mm) to implement a single core configuration. Therefore, a coil with multiple magnetic cores is designed. The cable length is set to 4 m. The number of turns for each TLT is 4 and 20 for the TLT-A and TLT-B, respectively.

The LTspice model of the 25-kW combiner is developed using the TLT model described in the previous section. The simulated bandwidth of the combiner is shown in Fig. 6. To observe the bandwidth clearly, the frequency range is set to 100 Hz – 1 GHz. In the frequency range out of 10 kHz – 10 MHz, for the complex permeability, the extrapolation of the fitting results is used. The drop in the gain at the higher frequency side is due to the skin effect, while the low frequency side is due to the common mode propagation. The bandwidth of the designed 25-kW combiner sufficiently covers our requirement, from 100 kHz to 10 MHz. Figure 7 shows the core loss. The core loss is expected to be very low, approximately 10 W maximum.

SUMMARY

The development of the 25 kW amplifier with GaN HEMTs is ongoing for the consolidation of the RF system in the RCS. Design studies for the 25-kW combiner, which is a key component of the 25-kW amplifier, are conducted. Circuit simulator models that include the skin effects, common mode propagation, and complex permeability, which are essential for evaluating bandwidth and core loss of the combiner, have been developed. The preliminary design of the 25 kW combiner is established. The circuit simulation result shows that the designed 25-kW combiner has a wide bandwidth and a low core loss, which covers our requirements. A prototype of the 25kW combiner is to be constructed.

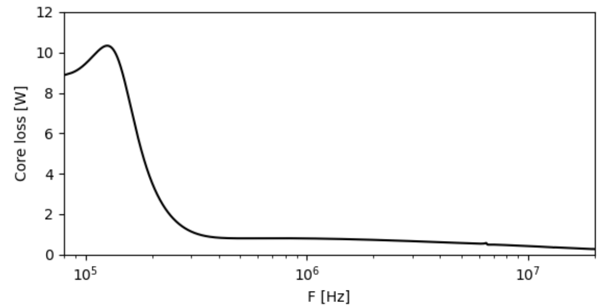

Figure 7: Core loss of the designed 25-kW combiner calculated using LTspice.

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