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Design and simulation of an S-Band tunable solid-state power amplifier as an RF injector into a miniature ECR ion source

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HIGHLIGHTS

- A high-power RF MOSFET transistor is utilized to design a solid-state power source.
- The RF transistor is internally matched to 50 ohms and doesnt need any bias sequence circuit.
- The proposed RF source can deliver 57 dBm of power into the ECR ion source.

ABSTRACT

A continuous-wave solid-state-based power amplifier is designed and simulated in this paper to work as an RF injector into an ECR ion source chamber. Employing a solid-state radio frequency power amplifier, instead of microwave tubes, leads to having higher efficiency, lower price, compact size, and longer lifetime. Also, a modular design can be achieved for designing higher output power by repeating lower power sources and combining them. The proposed solid-state source can deliver more than 200 W power to the ion chamber with a single high-power transistor. The selected Doherty high-power transistor is internally matched to 50 ohms and does not need a bias sequence circuit. Two gain stages are applied to drive the high-power transistor. The designed RF source is simulated using the Advanced Design System (ADS) based on the measured scattering parameters of components. Simulations show an output power of more than 57 dBm with a tunable frequency bandwidth from 2.3 to 2.5 GHz.

KEYWORDS
Power amplifier
Solid-state transistors
Power efficiency
RF source
Ion source

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1 Introduction

Transistor-based power amplifiers are much more efficient than microwave tubes like magnetrons and have a longer lifetime, higher efficiency, and more compatibility to be designed with other electronic components (Piel et al., 2005). It significantly improves the minimization of size, cost and can have better control over power management and impedance matching (Nakatani and Ishizaki, 2015). As a result, these features give them the ability to be utilized in miniature Electron Cyclotron Resonance (ECR) ion sources (Fatkullin et al., 2018; Wen et al., 2018).

The main solid-state-based design considerations are the number of high-power transistors for reaching the desired output power, bias sequence control, frequency stability, efficiency, and matching networks (Bondarenko et al., 2019; Latrasse et al., 2017; Piel et al., 2005; Tuo et al., 2009). Usually, microstrip-based matching networks are used for delivering the maximum output power. Also, the number of high-power transistors is important because several power combiners should be used which can dissipate power before reaching load (Chen et al., 2017; Duc et al., 2018).

In the present work, we hired an internally matched transistor, on both the output and input sides which can deliver up to 57 dBm power at S-band frequencies. In our previous work, we proposed a power chain in which the main power transistor needed negative gate voltage. Rf transistors with negative gate voltage need bias power-up and power-down sequence control. As the selected high-power transistor in this paper works with positive gate voltage, it does not need any bias sequence circuit and additional matching networks. As a result, the design procedure becomes simple and more reliable. Using an internally matched transistor with high efficiency which requires a positive gate voltage is the main novelty of our structure. The dimension of the target plasma chamber is considered 50×50 mm^2. It utilizes an alumina window

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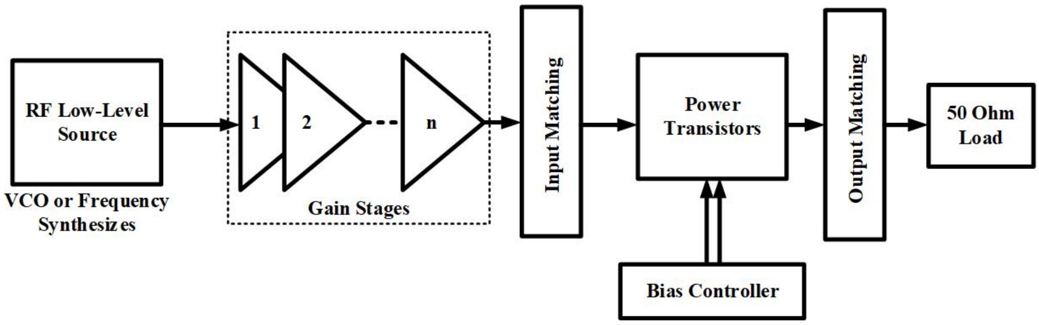

Figure 1: Basic block diagram of a solid-state based RF source.

as a lens for microwave power coupling to focus the wave into the chamber.

This article is organized as follows: Section 2 describes different types of high power sources. The proposed solid-state source is expressed in detail in Section 3. Results are shown in Section 4 and finally, the paper ends with a conclusion and references.

2 Types of high-power sourc

There are different types of high-power RF sources that can be categorized into two main parts; microwave tubes and solid-state power amplifiers. Travelling Wave Tubes (TWT), klystron tubes, and magnetrons are different types of microwave tubes. Microwave tubes are usually utilized to reach an output power in the range of mega wats while solid-state power amplifiers can be applied for lower power ranges. Output power, frequency bandwidth, power efficiency, frequency stability, and lifetime are usually the main parameters of an RF source. Usually, solid-state amplifiers have a higher power efficiency, longer lifetime, lower cast, and smaller size in comparison with microwave tubes. Also, magnetrons and klystrons need a high voltage while solid-state amplifiers work with much lower voltages. Indeed, solid-state amplifiers in ion source accelerator applications are a good choice for delivering medium power ranges of about several kilowatts. As the target load in this article is a compact electron cyclotron resonance ion source and can be triggered by at least 200 W to 1 kW, the best choice is a solid-state power source.

Figure 1 shows a basic block diagram of a solid-state RF source. It usually needs a local oscillator or frequency synthesizer as a low-level RF source. This power at the specific frequency will be amplified with several gain stages to drive the main power transistors. Input and output matching networks can be utilized to maximize the output power. There are two types of high-power metal-oxide-semiconductor field-effect transistor (MOSFET); enhanced mode and depletion mode. In enhanced mode MOSFET transistors, a positive voltage should be applied to the gate while in depletion mode a negative gate voltage with a particular bias sequence should be applied. In our previous work, we utilized a depletion-mode transistor with a bias sequence to achieve the desired output power. In this paper, we utilized an enhanced mode transistor which needs a positive gate voltage. As a result, a bias control part of Fig. 1 can be eliminated and the reliability of the proposed source can be improved considerably. The proposed structure of the power source is explained in the next section.

3 The Proposed RF Source

The block diagram of the proposed structure is shown in Fig. 2. The proposed chain consists of Voltage Controlled Oscillator (VCO), Variable Gain Amplifier (VGA), preamplifier, 90-degree hybrid power combiner, and Doherty power amplifier. As the selected power amplifier

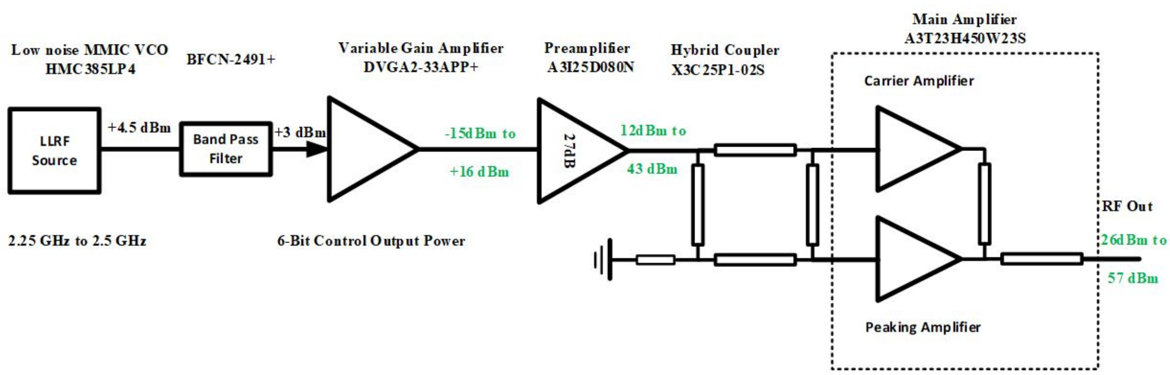

Figure 2: Block diagram of the proposed RF high-power source.

does not need negative gate voltage, there is no need to design a bias sequence for it and the source will become more reliable. All part numbers and power limit values are shown in this figure.

Although frequency synthesizers are more stable in the desired working frequency, a voltage-controlled oscillator is selected as the low-level RF source for design simplicity. A monolithic microwave integrated circuit (MMIC) VCO is used with a frequency range of 2.25 to 2.5 GHz. The output power of the VCO is about 4.5 dBm and its supply current is less than 40 mA with 3 V bias voltage. The utilized VCO has output harmonics in which the second and third harmonics are 7 dB and 23 dB lower than the fundamental tone. As a result, a bandpass filter should be added to suppress these harmonics. The utilized filter can reject the second and third harmonics, more than 30 dB. A controllable gain amplifier in cascade with a preamplifier is chosen as a gain stage to drive the main power amplifier. 6-bit digital pins can control the gain value of the first amplifier with a resolution of 0.5 dB. The maximum and minimum attenuation value is obtained as follows:

$$Att = 2^n \times Res \quad (1)$$

where n is the number of bits and Res is the resolution step value. As a result with six control bits, the maximum attenuation value is about 32 dB.

The main power amplifier is Doherty type and is internally matched at both input and output sides. The block diagram of a Doherty amplifier is shown in Fig. 3. An amplitude-modulated input signal is divided into two paths: the envelope of the input signal and its phase. According to Fig. 3, the envelope of the input signal is applied to the carrier amplifier and the phase of the input signal which has a constant envelope is applied to the carrier amplifier. Finally, they are combined, leading to a linear amplification with high power efficiency. As the peaking amplifier can be nonlinear with higher power efficiency, this way is usually used in linear high-efficient applications.

According to the datasheet of the selected Doherty amplifier, the input signal should come from a hybrid power coupler which is depicted in Fig. 2. The utilized hybrid coupler is X3C25F1 which is designed for Doherty applications (X3C25F1-03S, 2022). A schematic of the selected hybrid coupler is shown in Fig. 4. The isolated port of the hybrid coupler is termed to the ground and the other ports are applied to the Doherty amplifier as it is shown in Fig. 2.

A3T23H450W23SR6 which is selected as the high-power transistor has two main advantages (A3T23H450W23S, 2022). The first one is that it does not need any matching network on the input and output sides. As a result, the design will be much simple and more reliable than the block diagram in Fig. 1. The second feature is that as the gate voltage of the selected amplifier is positive, there is no need to utilize sequential circuits for the device start-up procedure.

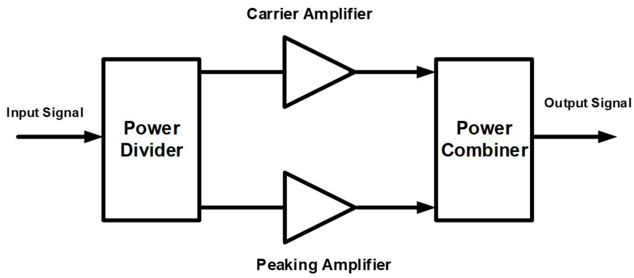

Figure 3: Block diagram of a Doherty power amplifier.

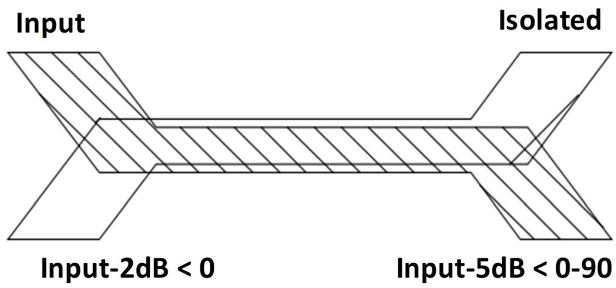

Figure 4: Schematic of a hybrid coupler.

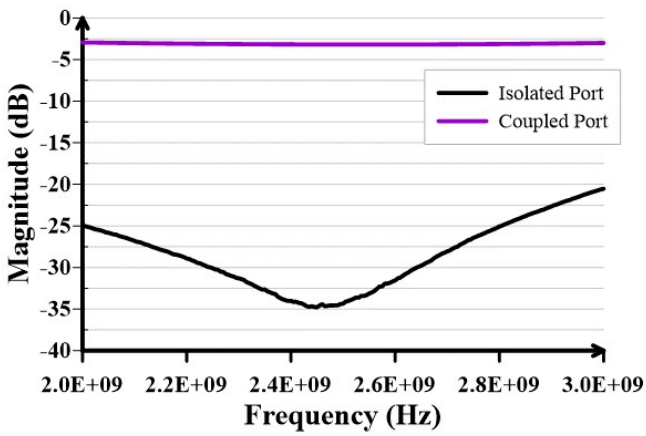

Figure 5: Frequency response of the hybrid coupler.

4 Results and discussion

The simulations were performed by the momentum RF simulator of the Advanced Design System and the precise and practical model of the components in the S-Band. Rogers RO4350B with a thickness of 20 mils and 3.66 dielectric constants is selected as the substrate of the proposed solid-state source. The output power of VCO is considered +4.5 dBm in simulations and other components are modeled by their measured scattering parameters. The power supply of the Doherty RF transistor is 30 V and some optimization techniques were performed in PCB layout to achieve maximum power and better output return loss.

Figure 5 shows the measured scattering parameters of the utilized hybrid coupler. The isolated port has 35 dB isolation at the center frequency of 2.45 GHz. Also, the coupled ports have 3 dB attenuation and have a 90-degree phase difference.

Table 1: Comparison of the proposed power source with other solid-state based works.

Document	Frequency (GHz)	Power (dBm)	Type	Efficiency (%)	Year
(Wen et al., 2018)	2.45	< 53	-	-	2018
(Fatkullin et al., 2018)	2.4 - 2.5	<50	-	-	2018
(Latrasse et al., 2017)	2.4 - 2.5	0 - 53	-	<80	2017
(Yang et al., 2015)	1.7 - 2.7	52.7 - 54.3	Doherty	<50	2015
(Chen et al., 2017)	2.7 - 3.1	<44	B	<44	2017
(Belaïd et al., 2020)	2.7 - 2.9	< 45	AB	<48	2020
(Nakatani and Ishizaki, 2015)	2.4 - 2.5	50	F	<68	2015
(Bogomolov et al., 2019)	2.4 - 2.5	< 50	-	-	2019
(Rahimpour et al., 2022)	2.4 - 2.5	25 - 55	AB	<70	2022
Present study	2.3 - 2.5	25 - 57	Doherty	<45	

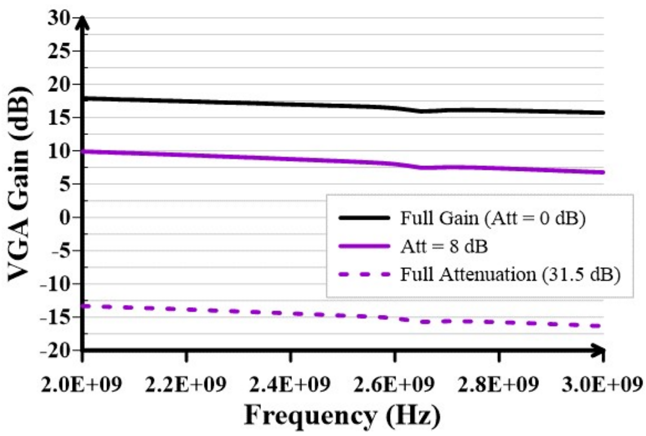

Figure 6: Small signal gain of the variable gain amplifier.

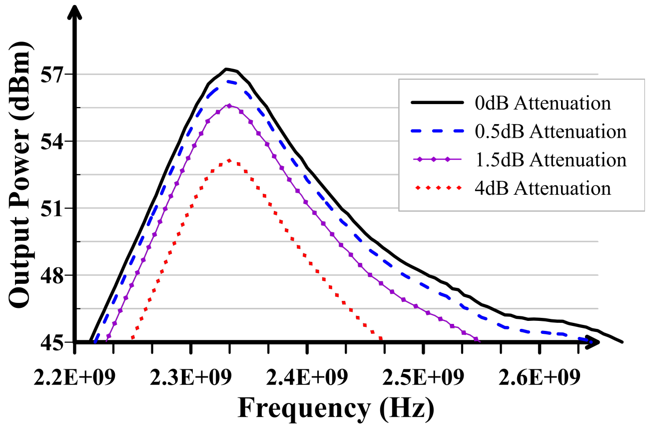

Figure 8: Output power of the proposed RF sourc for differe attenuation values.

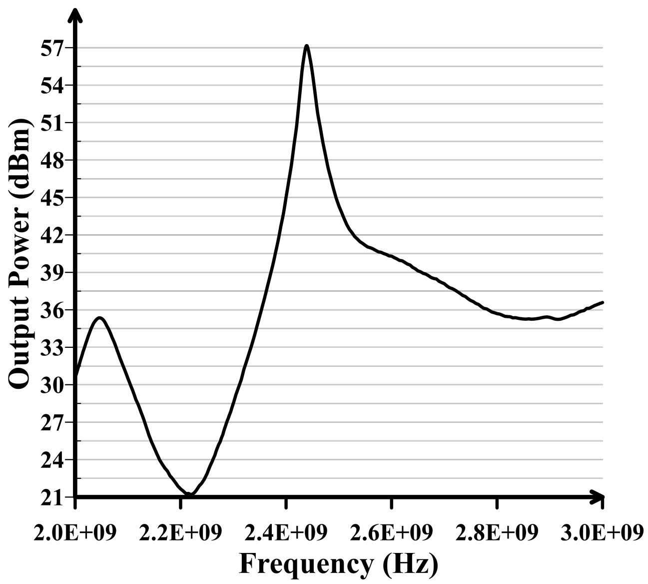

Figure 7: The simulated output power of the proposed RF source.

Figure 6 shows the small-signal gain of the variable gain amplifier which is obtained by its scattering parameters matrix. According to this figure, the maximum and minimum gain of the first amplifier can change from 17 dB to -14 dB. As it was explained, the resolution of attenuation is 0.5 dB.

Figure 7 shows the output power of the proposed RF source in dBm where 53 dBm and 56 dBm stand for 200 W and 400 W, respectively. The output frequency can be easily adjusted by changing the VCO voltage level which can be tuned from 2.1 to 2.5 GHz. The output power of the designed RF source is adjustable by the VGA 6-bit control bits which can be fined tune from 25 to 57 dBm.

The output power of the proposed source for different attenuation values is shown in Fig. 8. The maximum output power is obtained when all six control bits of VGA be pulled down. This state is shown in Fig. 8 by the black line. So other levels of the output power are easily obtainable by changing the value of control bits.

The output return loss frequency response of the proposed RF source is shown in Fig. 9. the bandwidth of the output matching can be optimized by adding a stub to the output side of the Doherty power amplifier. Also, the frequency location of the peak power can be tuned by changing the VCO voltage. The power efficiency of the proposed structure is sufficient because of using a Doherty-type amplifier.

A comprehensive comparison of the proposed structure with other related works is performed and the results are brought in Table 1. 'AB', 'B', and 'F' in Table 1 are different types of power amplifier working classes. The main difference between the proposed structure and our previous work (Rahimpour et al., 2022) is that the main high power transistor is internally matched at both input and output sides which eliminates designing a matching network. On the other hand, the gate voltage of the power transistor needs positive voltage and there is no need to use a bias sequence circuit.

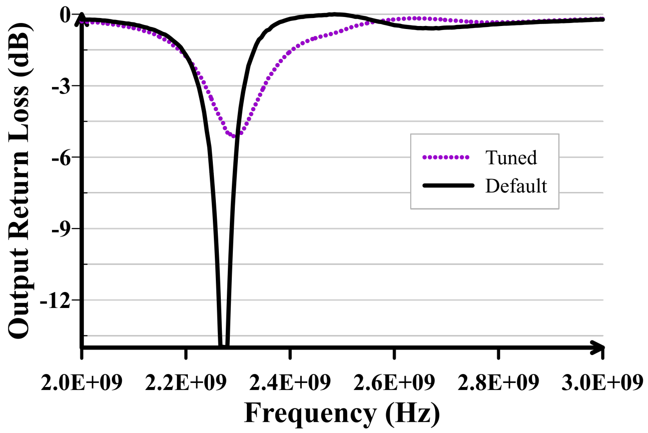

Figure 9: The simulated output return loss of the proposed RF source.

5 Conclusions

A single transistor-based solid-state power source for ion source application is presented in this paper with the ability of fine-tunable output power and center frequency. The proposed structure can deliver more than 400 W to the miniature ion chamber. The designed RF source has a good power efficiency and is reliable because there is no need to use an external matching network. As the main power transistor is enhancement-type MOSFET, the gate-source voltage should be positive to turn it on and there is no need to use a bias sequence controller. We would try to implement the proposed structure in future works.

Conflict of Interest

The authors declare no potential conflict of interest regarding the publication of this work.

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