Design of ISM-Band High Power and High Efficiency Solid-State VCOs for Use in Next Generation Microwave Oven

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SUMMARY Recently, intelligent heating, next generation microwave ovens that achieve uniform heating and spot heating using solid-state devices, has been actively studied. There are two types of microwave generators using solid-state devices. Since compactness is indispensable to accommodate in a limited space, the miniaturized oscillator type was selected. The authors proposed an imbalanced coupling resonator, a resonator-less feedback circuit, a high power frequency variable resonator, and injection-locked phase control in order to achieve high performance of the oscillator type microwave generator. In addition, we confirmed that the oscillator type can be used as the microwave generator for intelligent heating using a Wilkinson combiner. As a result, it was demonstrated that the oscillator type microwave generator, realized the same high efficiency (67%) as the amplifier type, and found the possibility of variable frequency (2.4 to 2.5GHz) and variable phase, and can be used as the microwave generator for intelligent heating.

key words: high power, high efficiency, feedback oscillator, VCO, intelligent heating

1. Introduction

Recently, microwave heating has become increasingly used in various fields and applications [1]. In particular chemical reaction applications [2], research on new chemical reactions by microwave heating is active at the Japan Electromagnetic Energy Application Society (JEMEA) [3], where chemical engineers and microwave engineers can discuss it across fields. Moreover, in the next generation microwave ovens instead of the conventional magnetron oscillators, intelligent heating that achieves uniform heating and spot heating using solid-state microwave generators has been actively studied [4]. Compared with magnetron oscillators, solid-state oscillators have low voltage operation, long life, and easy EMC countermeasures. In Europe, many semiconductor companies and microwave equipment companies have joined the RF Energy Alliance on microwave heating, and discuss the next generation microwave oven actively [5]. In order to realize intelligent heating, it is necessary to provide multiple microwave radiation antennas and radiate microwaves into the cavity at the same frequency. By varying frequency, relative phase and radiated power of the microwaves radiated from each antenna, it becomes possible to freely select the heating location in the cavity. In order

to replace the magnetron oscillator, the specifications of the solid-state oscillator are variable frequency 2.4 to 2.5GHz, output power 500W (space synthesis), efficiency is 60% or more, and magnetron size ($70 \times 100 \times 120\text{mm}^3$) or less.

There are two types of microwave generators using solid-state devices: an amplifier type and an oscillator type. Table 1 shows a comparison of the configurations and functions of the amplifier type and the oscillator type microwave generators. The amplifier type can control the frequency, phase, and output power, because the signal is oscillated by a small signal VCO (Voltage Controlled Oscillator) and the frequency is stabilized by PLL (Phase Locked Loop) control and then amplifies it to high output power through a phase adjustment circuit and an amplitude adjustment circuit. For this reason, the RF Energy Alliance has developed the amplifier type and has been adopted by microwave ovens [5]. Many high efficiency power amplifiers composing amplifier type microwave generators have been reported, such as class F [6], class J [7] and class E power amplifier [8]. As an alternative method, the oscillators have been studied more recently because of their potential for miniaturization and cost reduction as a microwave generator. The conventional 2.4GHz band oscillator type microwave generator reported an output of 48W and an efficiency of 58% with a GaN-HEMT amplifier with an efficiency of 70% and an external feedback circuit in 2011 [9]. LDMOS amplifiers were integrated with a feedback circuit using a ring resonator or DR resonator, and an output of 157W (efficiency 43%) and an output of 330W (efficiency 45%) were reported

Table 1 Comparison of the amplifier type and oscillator type microwave generators

Parameter	Amplifier type	Oscillator type
Configuration
Circuit	Complicated	Simple
Size	Large	Small
Efficiency	50-70% ¹⁾	40-60% ²⁾
Variable frequency	Easy	Difficult
Variable phase	Easy	Difficult
Variable Output power	Easy	Easy

1) Drain efficiency of final amplifier

2) Efficiency of oscillator

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in 2012 [10], [11]. The efficiency of these oscillators is 10 percentage points lower than the efficiency of the amplifiers used in these oscillators.

In this paper, we report methods to achieve high efficiency, variable frequency and variable phase for high power VCOs.

2. Study on High Efficiency VCOs

2.1 Basic Design of High Power VCO

The oscillator efficiency is very important because it is related to power consumption and heat dissipation. In this section, the efficiency of the feedback oscillator is studied. S. Kim et al's paper [9] and T. Shi et al's papers [10] and [11] on the conventional oscillator type microwave generators do not discuss the coupling capacitances of the resonator of the feedback circuit. Therefore, the authors examined the coupling capacitances.

The configuration of the feedback oscillator is shown in Fig. 1 [12]–[15]. It consists of (A) feedback circuit and (B) power amplifier. The feedback circuit (A) picks up a part of the output signal and then takes back to the input of the power amplifier (B) via the imbalanced coupling resonator. The feedback characteristic is defined as $\beta(s)$. The power amplifier uses the high efficiency amplifier [6]–[8] described above, and the amplification characteristic is defined as $A(s)$.

In order to realize a high efficiency oscillator, it is necessary to increase the efficiency of the power amplifier and minimize the signal flowing to the feedback circuit. The power amplifier device uses LD-MOSFET that does not require negative bias or GaN-HFET with higher efficiency and higher gain. Since GaN-HFET has higher gain than LD-MOSFET, the signal flowing into the feedback circuit can be reduced.

Fig. 1 Schematic diagram of the feedback oscillator

2.2 Feedback Circuit of High Power VCO

We focus on the coupling capacitors of the resonator in the feedback circuit [13], [14]. There are a coupling capacitor (C_{1a}) that picks up a part of the output signal of the amplifier, the filter that composed of coupling capacitors (C_{1b}) and (C_2) at both ends of the resonator that passes only the oscillation frequency, and the transmission line that adjust the feedback phase in the feedback circuit. C_1 in Fig. 1 is the capacitance of C_{1a} and C_{1b} connected in series. In other words, C_1 is a coupling capacitance with the power amplifier, and C_2 is a coupling capacitance with the feedback circuit. In this case, since the capacitance of C_1 and C_2 are different values, they are expressed as an imbalanced coupling resonator. By reducing the capacitance of C_1 coupled to the main transmission line at the resonance frequency of the imbalanced coupling resonator and weak coupling factor, the input impedance is increased and the effect on the load impedance of the power amplifier is reduced. In this time, the transmission line T_1 is made as short as possible. Furthermore, by increasing the other coupling capacitance C_2 and lowering the impedance, more energy stored in the resonator is supplied to the input of the power amplifier. In other words, the output loss of the oscillator and the influence on the output matching circuit of the power amplifier can be reduced, and at the same time, the amount of feedback can be increased. By optimizing the coupling capacitances C_1 and C_2 , the high efficiency of the oscillator can be realized.

Oscillation conditions are expressed by Eq. (1) and Eq. (2) from Barkhausen Criteria [16].

$$|A(s) \cdot \beta(s)| \geq 1 \quad (1)$$

$$\sum \Phi = 2\pi \times n \quad (n = 1, 2, \dots) \quad (2)$$

The amplitude condition is shown in Eq. (1), and the total amplitude of the power amplifier and the feedback circuit must be 1 or more. The phase condition is shown in Eq. (2), and the total transmission phase of the power amplifier and the feedback circuit is $2\pi \times n$ (n is a natural number). That is positive feedback.

2.3 Comparison of LD-MOSFET and GaN-HFET

Next, the coupling capacitance of the imbalanced coupling resonator in the feedback circuit is calculated by numerical analysis and is determined by the gain (Gain_{osc}) during the oscillation operation of the power amplifier. In the case of a 200W LD-MOSFET [12], the gain obtained by subtracting 3dB from the linear gain is defined as Gain_{osc} because the efficiency is high at P3dB (3dB gain compression). In the case of a 50W GaN-HFET [14], the gain obtained by subtracting 2dB from the linear gain is defined as Gain_{osc} because the efficiency is high at P2dB (2dB gain compression). Since Gain_{osc} differs depending on the device used, the optimal C_1 and C_2 were determined by analysis. As a

Fig. 2 Photograph of the prototype feedback 50W oscillator

Table 2 Results of the prototype oscillators and the conventional oscillators

Parameter		200W LD-MOSFET [12]	150W LD-MOSFET [10]	50W GaN-HFET [14]	50W GaN-HFET [9]
Amplifier Fabrication	Linear Gain	15dB	-	18dB	16dB
	Output Power	53.9dBm (P3dB)	-	47.5dBm (P2dB)	47.9dBm (P4dB)
	Efficiency	52%	-	70%	67%
OSC Simulation	Output Power	54.4dBm	-	47.6dBm	-
	Efficiency	50.9%	-	66%	-
OSC Fabrication	Output Power	53.3dBm	52.0dBm	47.1dBm	46.8dBm
	Efficiency	51%	43%	67%	58%

result, $C_1 = 0.1\text{pF}$ and $C_2 = 0.3\text{pF}$ were obtained for the 200W LD-MOSFET [12], and $C_1 = 0.05\text{pF}$ and $C_2 = 0.3\text{pF}$ were obtained for the 50W GaN-HFET [14].

Using the obtained values of C_1 and C_2 , the oscillator circuit was designed, and after the oscillation operation was confirmed by simulation, the prototype oscillator was manufactured and verified. The photograph of the prototype feedback oscillator using the 50W GaN-HFET is shown in Fig. 2. The short-circuited $\lambda/4$ coaxial resonator using ceramics with a dielectric constant of 44 was mounted on a Rogers 4350B board ($90 \times 40 \times 0.76 \text{ mm}^3$) with solder. The output signal (V_o) of the oscillator passes through the circulator to stabilize the load and is output from the output (Mo) of the module. The results of the prototype oscillators and the conventional oscillators are shown in Table 2. The output power and efficiency of the power amplifier draw out the performance of the power device. Since the characteristics of the oscillator reproduce the characteristics of the amplifier, it was demonstrated that by optimizing C_1 and C_2 of the feedback circuit, almost the same output power and efficiency as those of the power amplifier could be obtained. It can be seen that the efficiency of the GaN-HFET oscillator is more than 10% better than the LD-MOSFET one. In this case, the efficiency was improved by 10% compared to the conventional oscillators.

3. Study on Broadband VCOS

To be adopted for the microwave generator that can be used for intelligent heating, variable frequency and variable phase are required. It is necessary to simultaneously satisfy the

Fig. 3 Configuration of novel resonator-less VCO

Fig. 4 Loop characteristics of the oscillators (simulation)

oscillation conditions Eq. (1) and Eq. (2) at the desired frequency to vary the frequency of the feedback oscillator. However, the resonance frequency cannot be adjusted by the conventional low-voltage and low-power varactor diode because the large-signal passes through the feedback circuit. Therefore, how to vary the frequency that satisfies the large-signal oscillation condition is the challenge. Thus, we proposed three methods of varying the frequency {3.1}: determine the oscillation frequency by varying only the phase condition of Eq. (2), {3.2}: determine it by varying only the amplitude condition of Eq. (1), {3.3}: determine it by varying the conditions of both Eq. (1) and Eq. (2) and verify them. Finally, {3.4}: the oscillation frequency stability and phase control are verified by injection locking.

3.1 Resonator-Less VCO

We proposed a feedback circuit without the resonator, that was determined the oscillation frequency by changing the phase condition by adding the phase shifter to the feedback circuit [17]. The configuration of the conventional oscillator is shown in Fig. 3 (a). The configuration of the resonator-less VCO is shown in Fig. 3 (b). The VCO in Fig. 3 (b) is not limited to the amplitude condition of the feedback circuit, and the phase shifter is inserted. The loop characteristics (Simulation) of the two types of oscillators in Fig. 3 are shown in Fig. 4. The frequency band satisfying the amplitude condition (Loop gain > 0dB) in Fig. 4 (a) is narrow, but the resonator-less VCO proposed in Fig. 4 (b) is wide and the oscillation frequency is determined by the phase condition.

The configuration of the prototype resonator less VCO is shown in Fig. 5. It consists of an attenuator for adjusting the input level of the phase shifter, the reflection type phase shifter, and the transmission line. The power amplifier cir-

Fig. 5 Configuration of the prototype resonator less VCO

Fig. 6 Results of the prototype resonator less VCO

cuit employed a two-stage amplifier in consideration of the loss of the feedback circuit. The circulator was attached to the output end of the VCO to reduce the load dependence on the oscillation frequency and output power [13]. The results of the prototype resonator-less VCO using the MAGE-102425-300S GaN-HFET (made by MACOM) as the final device is shown in Fig. 6. The VCO with an oscillation frequency of 2.42 to 2.46 GHz, an output power of 250 W or more, and an efficiency of 60% or more was realized by adjusting the feedback phase with the phase shifter [17].

3.2 VCO with High Power Frequency Tunable Resonator

In case of where a large-signal exceeding 1W is input to the feedback circuit, the resonance frequency of the resonator cannot be changed using the conventional small-signal varactor diode. Addressing this problem, we proposed the high power variable frequency resonator and confirmed its effectiveness by applying it to the high power VCO. The high power frequency tunable resonator proposed in this paper realizes high withstand voltage and wide frequency tunable characteristics by connecting multi-stage varactor diodes to the fixed frequency high power resonator in parallel.

The configuration of a novel VCO with a high power frequency variable resonator is shown in Fig. 7 [18]. The configuration of the VCO using the variable frequency resonator is shown in Fig. 7 (a). The configuration of the high

Fig. 7 Configuration of novel VCO with high power frequency tunable resonator

power frequency tunable resonator proposed in the resonator section in Fig. 7 (a) is shown in Fig. 7 (b). C_D is the varactor diode, C_1 and C_2 are coupling capacitors, C_{3a} is the DC-cut capacitor, and V_{CC} is the control voltage of the varactor diode in Fig. 7 (b). The resonance frequency of the resonator can be varied by the coupling capacitance of C_1 and C_2 , but the passing phase and amplitude also change. Therefore, the variation of the resonance frequency of the resonator is realized by changing only C_3 . In this case, when the coupling capacitances C_1 and C_2 are fixed and C_3 has varied the resonance frequency changes, but the loop phase at the resonance frequency does not change except for the power amplifier and the transmission line of the feedback circuit. Further, as the number of stages of the varactor diode in Fig. 7 (b) increases, it becomes easier to handle large power, but the variable capacitance is reduced and the frequency adjustable range is narrowed.

To achieve variable frequency range of 2.4 to 2.5GHz, which is the ISM (Industrial Science and Medical) band, when using a short-circuited $\lambda/4$ coaxial resonator using ceramics with a dielectric constant of 38 (characteristic impedance $Z_0 = 12.5\Omega$, unloaded $Q_u = 600$), the capacitance C_3 must be changed from 0.15 to 0.3pF [18]. If C_{3a} is smaller than C_D , the voltage applied to C_D can be reduced. In order to achieve the frequency variable range of 100 MHz, a 2.4GHz-band 20W VCO that a GaN-HFET power amplifier combined with the high power frequency tunable resonator that has two varactor diodes connected in series with $C_{3a} = 0.3\text{pF}$ and $C_D = 1$ to 16pF (32V to 0V) was prototyped. The Measured oscillation frequencies of the VCO are shown in Fig. 8 [18]. The oscillation frequency was able to be changed by 71MHz at the output power of 20W and the efficiency of 55%. However, the resonance frequency can be varied by 100MHz. This difference is considered to be due to the phase change of the power amplifier and the transmission line. Furthermore, the reason why the resonance frequency and the oscillation frequency match at the low frequency are because the device operates in the saturation region during oscillation and is different from the passing phase at the time of the small signal.

3.3 VCO with Both Tunable Resonator and Phase Shifter

In the VCO studied in (B), the resonance frequency of the

Fig. 8 Measured oscillation frequency of the VCO

Fig. 10 Measured oscillation frequency of the VCO

Fig. 9 Configuration of proposed VCO with both tunable resonator and phase shifter

resonator was varied, but it was found that the desired oscillation frequency could not be varied because the loop phase changed at the same time. Therefore, it is verified that the variable range of the oscillation frequency can be expanded by changing both the resonance frequency and the loop phase. The configuration of the proposed VCO with both tunable resonator and phase shifter is shown in Fig. 9 [19]. V_{cc1} varies the resonance frequency of the feedback circuit, and V_{cc2} varies the loop phase in Fig. 9. Since the purpose is to verify the expansion of the variable frequency range, an amplifier with a small-signal HBT connected in two stages is used so that commercially available varactors diode can be used. The value of the attenuator was determined so as to satisfy the amplitude condition of the oscillator. The proposed VCO was mounted on the FR-4 board ($18 \times 30 \times 1.2 \text{ mm}^3$). The oscillation frequency of the VCO when V_{cc2} is varied with V_{cc1} as the parameter is shown in Fig. 10. The frequency range exceeded 100MHz. The circle marks in Fig. 10 indicate the oscillation frequency when $V_{cc1} = V_{cc2}$. Thus, it was confirmed that the oscillation frequency of the feedback oscillator can be varied over the wide range by independently varying the amplitude and the phase conditions of the feedback circuit [19]. In the future, we plan to consider further broadband high power VCOS.

Fig. 11 Configuration of injection-locked oscillator

Fig. 12 Spectra of the oscillator

3.4 Injection-Locked Oscillator

To realize intelligent heating, it is necessary to control the frequency and phase of microwaves radiated from each antenna at the same frequency from multiple antennas. Since conventional oscillators oscillate free-running, their oscillation frequencies are different. Therefore, we study injection locking as a method of changing the relative phase with the same frequency. The configuration of an injection-locked oscillator is shown in Fig. 11 [12], [13]. The injection locking circuit in Fig. 11 consists of a reference signal generator, a phase shifter, and a coupling capacitor C_{in} . The larger the coupling factor of C_{in} , the larger the power of the injected signal. However, since the large signal of the feedback circuit breaks when it enters the phase shifter or reference signal generator, so that C_{in} has to be reduced. The injection

locking is verified using the 200W oscillator in Sect. 2. The capacitance of the coupling capacitor C_{in} was set to 0.1pF so as not to affect the design of the feedback circuit. The spectra of the oscillator are shown in Fig. 12 [13]. It can be seen that the oscillation frequency is stabilized by inserting the injection signal, and the phase noise is improved by increasing the injection power. Of course, the phase of the oscillator can be varied by synchronizing. In addition, since the output power of the oscillator can be synchronized with the output power of 200W and the efficiency of 51% with the injection power of 1mW, the control circuit can be integrated into an IC.

4. Intelligent Heating

As a result of the study up to the previous section, it was found that the oscillator type microwave generator can realize the same function as the amplifier type. In this section, we verify that two signals, the amplifier type microwave generator and the oscillator type, can be combined. The block diagram of verification using a Wilkinson combiner is shown in Fig. 13. The amplifier type and the oscillator type microwave generators are connected to the inputs of the Wilkinson combiner, and the output power of the combiner is verified [20]. Here, it is necessary to match the frequency and amplitude in order to perform energy synthesis. Since the locking frequency range of injection locking of the oscillator type microwave generator is narrow, the frequency of the amplifier type microwave generator was adjusted to the

Fig. 13 Block diagram of verification using the Wilkinson combiner

Fig. 14 Output power characteristics of the Wilkinson combiner which input two signals with different phases

oscillator type. Further, the amplitude of the amplifier type microwave generator was adjusted to the amplitude of the oscillator type. The output power of the Wilkinson combiner when two signals with different phases are input is shown in Fig. 14 [20]. The output power characteristics when controlling the phase of the amplifier type microwave generator with the other phase fixed and controlling the phase of the reference signal of the injection-locked oscillator type with the other phase fixed were in good agreement with the simulation result. From these results, it was confirmed that the phase control of the injection-locked oscillator type microwave generator was effective. By combining injection locking and variable frequency of the oscillator type microwave generator, the same function as the conventional amplifier type can be realized.

5. Conclusion

Microwave heating is expected to be applied to various applications by using solid-state device oscillators instead of magnetron oscillators. Many amplifier type solid-state device oscillators have been studied. In this paper, we studied the miniaturized oscillator type microwave generator, realized high efficiency (67%), and found the possibility of variable frequency (2.4 to 2.5GHz) and variable phase. The results showed that the miniaturized oscillator type microwave generator with a small number of components can be used for intelligent heating, the next generation of microwave ovens. The oscillator type microwave generator can be expected to spread as low-cost microwave generators. And, we plan to study broadband and high power VCOs.

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