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Development of a High efficiency HF power amplifier

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***Abstract*-- This paper describes development of a High efficiency HF power amplifier. We fabricated a new wideband power amplifier operating at short wave band (3MHz-26MHz) using class-E amplifier and obtained a high output power efficiency of 74% at 25.5MHz that is a target performance by controlling the shunt capacity for wideband operation. In addition, the low loss characteristic of about 0.4dB and under and wideband characteristics was obtained by employing the balun using the transformer with coaxial cables and output circuit combiner tuned including stray capacitance and inductance.**

***Index Terms*--Short-wave, High-efficiency, class-E, Power amplifier, Transmitter**

1. Introduction

Medium-frequency (0.5 MHz to 1.6 MHz) AM transmitters have already been made more efficient and reliable by converting completely to semiconductors up to outputs of 500 kW[1] to [3], and the complete conversion to semiconductors of international broadcast shortwave (3 MHz to 26 MHz) high-power transmitters is also being investigated[4]. The use of D-class power amplifiers (PAs) with a SEPP configuration has made it possible to achieve a drain efficiency of about 73% (output power: 120 W) at 13 MHz, but at higher frequencies switching loss increases due to FET output capacity and transition loss, making efficiency improvements unfeasible at present[4]. This paper reports the achievement of output power efficiency (output power/DC input power) of about 74% at 25.5 MHz by using a correction circuit providing the optimum switching parameters for E-class operation, in order to achieve an E-class PA that is both has a broad frequency range and is highly efficient. The authors were also able to predict that this circuit will provide high efficiency over a broad frequency range (3 MHz to 26 MHz).

2. Basic Design Policy

Table 1 shows the target specifications. In order to meet the specifications, the authors selected a RFMOS-FET, the performance of which is shown in Table 2. The most important issues for the design of the PA and output combiner were as follows.

2.1 Making a Highly Efficient PA

In order to operate efficiently at high frequencies like shortwave broadcasts (maximum frequency: 26 MHz), it is necessary to reduce switching loss and improve drain efficiency. The authors thus used an E-class push-pull PA, whose FET output capacitance makes it possible to ignore switching loss at high frequencies, and which is able to reduce the second harmonic.

Table.1 Design specifications.

Output power	100W
Frequency range	3MHz～26MHz
Circuit mode	Class-E push-pull
Load impedance	50Ω
Output power efficiency	70% and above at 25.5MHz
Power supply voltage	45V
Number of MOS-FET	2
Cooling method	Air-cooling without blowers
Size	100mm(W)×100mm(H)×50mm(D)

2.2 Increasing the Bandwidth of the PA

In order to make an E-class PA operate efficiently, it must be made to meet the E-class switching requirements ($V_s = 0$, $dV_s / dt = 0$, Vs: drain voltage). This means that a voltage resonance circuit is needed for the output circuit[6] to [8], but this would cause a deterioration in the frequency characteristics when high bandwidth is required.

Meanwhile, the PA's circuit constant, device output capacitance, and the like are fixed values. This causes the necessary shunt capacitance to be lower than the device's output capacitance (at high frequencies in particular), thus making it unfeasible to meet the E-class switching requirements. The authors thus improved the output-circuit bandwidth characteristics (including shunt capacitance), through such means as injecting inductance[7]; this improved the drain efficiency at the target frequency band (3 MHz to 26 MHz).

Table.2 Performance of the RF MOS-FET.

Drain to Source breakdown Voltage	500V
Drain current	16A
Gate to Source voltage	±20V
Allowable power dissipation	590W
Thermal resistance between junction and case	0.25℃/W
Max Junction Temperature	175℃
Drain to Source ON-resistance	0.4Ω
Input capacitance	1800pF
Output capacitance	150pF(at Vgs=0V, Vds=400V 1MHz)
Reverse transfer capacitance	40pF
Drain to Source cut-off current	1mA (at Vds=400V)

3. PA Design

3.1 Basic Design of E-class PA

3.1.1 Basic Operation

Fig. 1 shows the basic circuit architecture and operating waveform of the E-class PA. As with class C, the circuit is driven via a square wave or sinusoidal wave, and FET (FET) is operated in complete switching mode. Only the fundamental wave components are supplied to load resistance (R_L). The output current (Io) is supplied by the series resonance circuit (Co, L), via FET (FET) when the FET is on, and shunt capacitance (C_1) when the FET is off. With E-class switching, it is necessary to meet the following conditions: the drain voltage (Vs (ω t): ω is the angular frequency) when switching is turned on, and the Vs tilt during switching (at ω t = π in Fig. 1) are 0[5]. In this case, Vs (ω t) is shown in the following formula[6].

$$Vs(\omega t) = \frac{1}{C_1}\int_0^t \left[I_{DD} - I_m \sin(\omega t + \phi)\right]dt \qquad (1)$$

Where I_{DD} is power current; Im is max output current; and C_1 is shunt capacitance (including FET output capacitance).

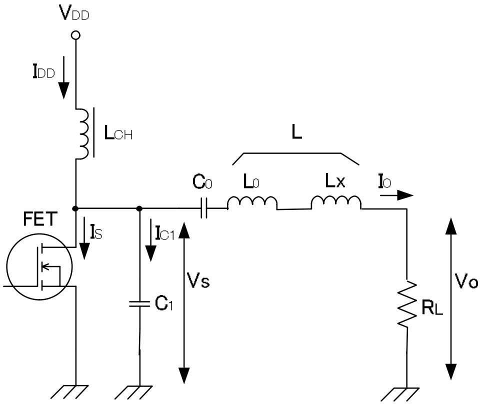
3.1.2 Calculating Drain Efficiency

If one ignores charge loss due to FET output capacitance, possible causes of FET drain loss are loss (P_R) due to on loss (R_{on}), and loss (P_θ) due to drain voltage and drain current overlapping phase angle (θo)[5].

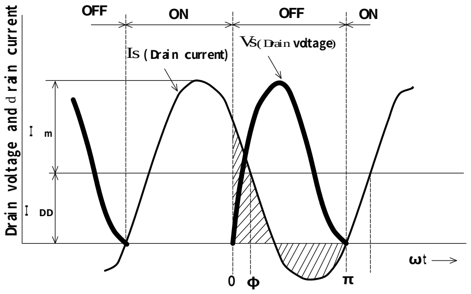
As shown by the operating waveform in Fig. 2, turn-on loss is small with E-class switching because drain current flows after drain voltage Vs (ω t) starts. There is a large loss upon turn-on, however, because drain current overlaps with drain voltage during the drain current's startup process. Here, drain loss (P_D) is as follows: $P_D = P_R + P_\theta$. Substituting $P_R = 1.3652 P_o \cdot R_{on}/R_L$ and $P_\theta = P_o \cdot \theta_o^{\,2}/12$ from the literature[5] for the drain efficiency (η_D) in the formula above, we get the following formula:

$$\eta_D = \frac{1}{1 + \frac{1.3652 \cdot R_{on}}{R_L} + \frac{\theta_o^{\,2}}{12}} \qquad (2)$$

Here, Po is the output power, and R_L is the load resistance.



(Circuit configuration)



(Drain current and drain voltage waveforms)

Fig 1 Basic circuit configuration and operation waveforms of the class-E amplifier.

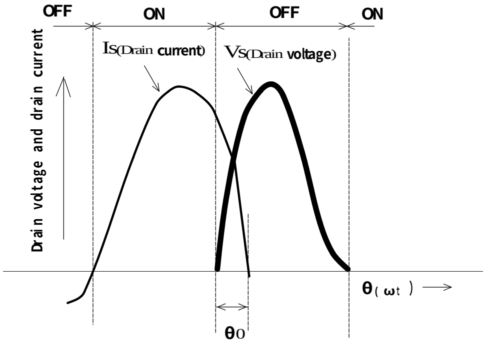


Fig.2 Waveforms of the drain voltage(Vs) and drain current(Is) of class E power amplifier at the turn-off time.

3.1.3 Operation of Push Pull Circuit

The push-pull circuit that was actually used (Fig. 3) performed E-class switching on two PAs with phases 180 degrees apart, and provide combined output via the output circuit. Comparing the push-pull circuit with the basic circuit in Fig. 1, the output voltage appearing in RL is the fundamental wave component (Vf) of the drain voltage calculated. In the basic circuit, this is $V_f = {9 \cdot \pi \cdot V_{DD}}/{16}$. In the push-pull circuit, this is doubled because of switching between FETs, as expressed by the following formula:

$$V_f = {9 \cdot \pi \cdot V_{DD}}/{8} \qquad (3)$$

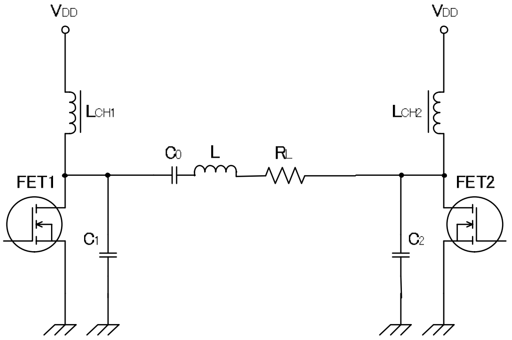


Fig.3 Circuit configuration of the Class-E Push-pull PA.

3.2 Making a Highly Efficient Push Pull PA

3.2.1 PA Circuit Architecture

Fig. 4 shows the actual circuit architecture of the PA. A distributor was used to convert the input excitation voltage to a 180-degree out-of-phase signal, and apply it between the RFMOS-FET (FET_1/FET_2) gate and source. As shown in Table 2, the FET input capacitance is extremely high. As a result, the input impedance is remarkably lower at shortwave frequencies. A large amount of excitation voltage is thus required, reducing the total efficiency (output power/dc input power). The authors tweaked the PA to enable it to be driven with low excitation voltage by charging the input capacitance via DC bias resistance (R_1/R_2 and R_3/R_4) as long as the FET is not on. Additionally, at high frequencies like the shortwave band, reverse transfer capacitance between the drain and gate could cause oscillation as the drain voltage returns to the gate input. A neutralizing circuit (T_1 and R_5/R_6) was thus built, taking advantage of the 180-degree phase difference between FET_1 and FET_2 in the drain voltage. This prevented oscillation. These measures are vital, because shortwave transmitters are susceptible to oscillation due to changes in the circuit constants from switching frequencies, and fluctuations in the load impedance due to snow adhering to the antenna, lighting damage, or other factors.

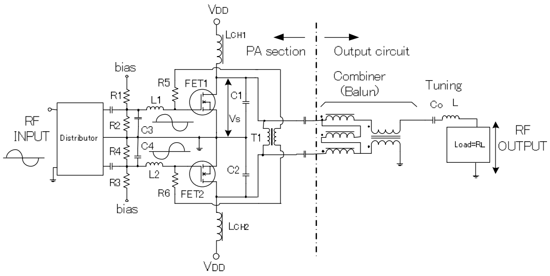


Fig.4 Circuit of the PA(Class-E push-pull).

3.2.2 Selecting Circuit Constants

Circuit constants must be selected to put the PA circuit into E-class operation. As shown in Fig. 3, the key frequency-dependent components of an E-class PA are L_{CH1} and L_{CH2} (choke inductance), C_1 and C_2 (shunt capacitance), and L and Co (voltage resonator). Although L and Co must be modified in accordance with the frequency, it is necessary to verify efficiency impact of choke inductance (L_{CH}) and shunt capacitance (C_1) in order to ensure high efficiency over a broad frequency range. For the design of the PA, the authors thus calculated L_{CH} and C_1 in the shortwave band (min 3 MHz to max 30 MHz) , and calculated the correspondence between frequency and drain efficiency when these are

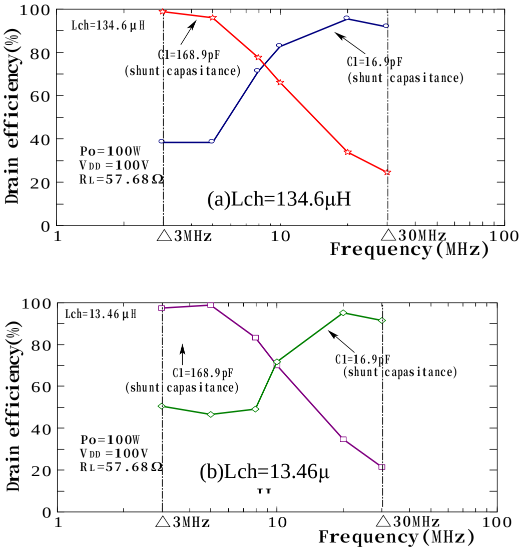
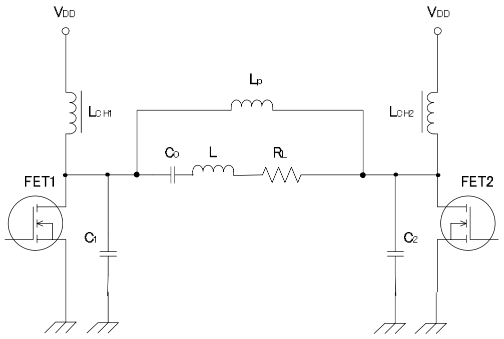


Fig.5 Drain efficiency in terms of the frequency with the circuit parameters changed.

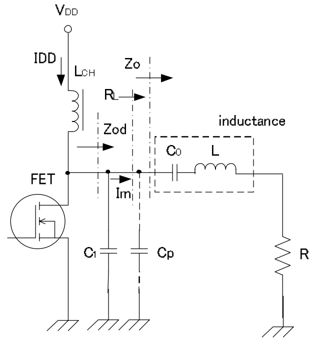
varied as parameters via simulation (SPICE). These calculations are shown in Fig. 5. The results of the simulation showed that regardless of the L_{CH} value, if a capacitor with maximum C_1 is used, then drain efficiency is much lower at 30 MHz than it is at 3 MHz (about 24% versus about 98%). Conversely, if a capacitor with the minimum C_1 is used, then the drain efficiency at 3 MHz is much lower than at 30 MHz. In Fig. 5, (a) and (b) show that L_{CH} has little impact on drain efficiency, with C_1 the dominating factor. This is because the resonant frequency of the filter consisting of L, Co, and C_1 in the voltage resonator is different when the FET is on and when it is off, thus creating a large ratio between the resonant frequency and the operating frequency. The selection of a C_1 suited to the frequency used is thus a key point for optimization.

3.3 Increasing the Bandwidth of the PA

A shortwave-broadcast transmitter requires stable high performance (high efficiency and linearity) over a broad frequency range (3 MHz to 26 MHz). As described in §3.2.2, however, it is necessary to switch C_1 in accordance with the frequency in order to ensure broadband performance in an E-class PA. It is not practical to use the C_1-switching method, however, because doing so would increase the sizes of the circuit and package. It is also not practical from a reliability standpoint. As shown in Fig. 6 (a), we thus connected inductance (Lp) serially to C_1 and C_2, architecting a band-pass filter (BPF) between C_1/C_2 and the output circuit. A shortwave-broadcast transmitter, however, must be used while switching between many different frequencies, and the Lp must be similarly switched. This increases the number of switches, reducing reliability. As shown in Fig. 6 (b), the authors thus considered a method to control the PA load's output circuit impedance (not including $C_1 + C_p$), in order to make the FET's drain output impedance (Z_{od}) (including $C_1 + C_p$ and PA load output circuit impedance (Z_o)) the same as the drain output impedance when Lp is introduced. This satisfies formula (1), while satisfying the condition that the Vs tilt during drain voltage and switching ($dVs(\omega t) / dt$) be 0 during turn-on, which is a condition of E-class switching. Here, C_1 is value of the FET's output capacitance reduced by C_p, and I_m in the figure is the maximum output current flowing in the PA load impedance R_L including C_p. Specifically, letting the PA load's output circuit impedance be inductance, it has the same effect as introducing Lp.



(a) PA using the parallel inductance



(b) Inductive PA output circuit

Fig.6 Output circuit of the PA.

Fig. 7 shows the results of a circuit simulation (SPICE) of the changes in PA drain efficiency consequent to frequency with Lp connected, using the constants calculated in accordance. With conventional design methods[5],[6], shunt capacitance (C_1) is fixed, which causes drain efficiency to degrade notably at high frequencies (see Fig. 5).

In Fig. 7 as well, without Lp the drain efficiency is about 66% at a frequency (f) of 25.5 MHz. When Lp is introduced, however, the efficiency improves by about 20%, promising a drain efficiency of about 85%.

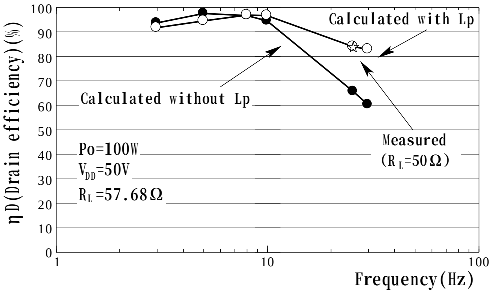


Fig.7 PA drain efficiency change in terms of the frequency.

4. Performance

4.1 Output Power Efficiency Characteristics

Fig. 8 shows a comparison of the actual measurements of output power efficiency for the PA's power voltage with the results of the circuit simulation. The efficiency is highest when power voltage (V_{DD}) is 45 V, with an output power efficiency of about 74% achieved. This fully meets the output power efficiency specification indicated in Table 1 (at least 70% at 25.5 MHz). Additionally, the actual measurements match well with the simulation results, showing the effectiveness of the present design.

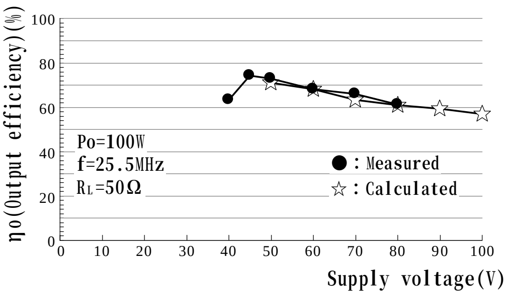


Fig.8 Output efficiency of the PA in terms of the Power supply voltage.

4.2 Linearity

Fig. 9 shows the linearity with respect to power voltage. The output voltage varies linearly with respect to power voltage, and the linearity characteristics were equivalent to those of commercial transmitters.

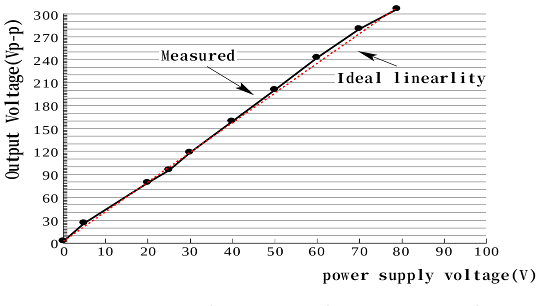


Fig.9 Linearity of the amplifier in terms of the power supply voltage.

5. Conclusions

Shortwave PAs must operate efficiently over a broad frequency range (3 MHz to 26 MHz). For this reason, it has not been feasible to utilize conventional E-class switching circuits as-is in broadband applications. The authors have thus proposed a method capable of using FET output capacitance (which is a fixed value) as shunt capacitance, achieving an output power efficiency of about 74% at 25.5 MHz. The present PAs, however, were designed for output power of 100 W. In order to switch to high-power PAs, their tolerance and stability at high output must be ensured. Specifically, switching to high-power versions requires an investigation of switching to high power voltage and the number of FET's to use in series, which consequently leaves the issues of how to prevent oscillation and tolerance to load fluctuation (tolerance to increases in power loss). The authors are committed to the development of complete semiconductor high-efficiency shortwave AM transmitters, and will continue their development and assessment efforts to achieve high-power versions.

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