Using MEMS in Class D Amplifiers for Standard GSM Carrier

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Abstract

The equivalent circuit of MEMS capacitive switches can be used to analyze a class D power amplifier, operated by a power supply of 3.7V. The system is intended for GSM audio frequency to produce an output power of (0.5-1.0) mW at a load output impedance of (8-10) Ω. The system gain must be greater than 33dBm and the estimated loss (0.5-1) dB.

A model for the power amplifier using MEMS passive devices has been developed. The model helps to determine the design parameters that affect the performance and reliability of the system that operate an RF transceiver. The optimization of the amplifier and the MEMS capacitor switching devices and how to integrate the system, will also be discussed. The design and the equivalent circuit were simulated using a PSpice model.

I. INTRODUCTION

There are many industrial applications, where it is necessary to develop a model for an amplifier, in which MEMS capacitive switches are used. The present task should satisfy the specifications required by Global System for Mobile Telecommunication (GSM) and identify the important parameters for the design and implementation of such circuits. Other objectives include developing standard design procedures and ways to examine the various parameters viz. efficiency, gain, and noise figure by using suitable software and simulation techniques. The development includes mathematical formulation and suggests appropriate manufacturing methods. Further more, it should indicate how to integrate the separate parts into a single system down to a blueprint proposal. Using a PSpice simulation, the model has been analyzed and discussed.

II. MEMS SWITCHES

Fig.1 shows one possible layout for a capacitive shunt switch [1]. This is similar to a standard air bridge used in integrated circuits. If voltage is applied between the center conductor and ground, the bridge starts to curve towards the signal line. This means that the capacitance between the signal line and ground is changed. At a certain voltage the bridge collapses to the down-state "pull-down". Pull-down occurs, when the distance between the bridge and the signal line is reduced to 2/3 of its original distance. The pull-down voltage is given by:

$$V_P = \sqrt{\frac{8k\delta^3}{27\varepsilon_0 A}} \quad \ldots\ldots \quad \ldots\ldots \qquad (1)$$

Where; k is spring constant of the bridge, ε_0 is permittivity of vacuum, A is over lap area of electrodes, and δ is the gap between electrodes.

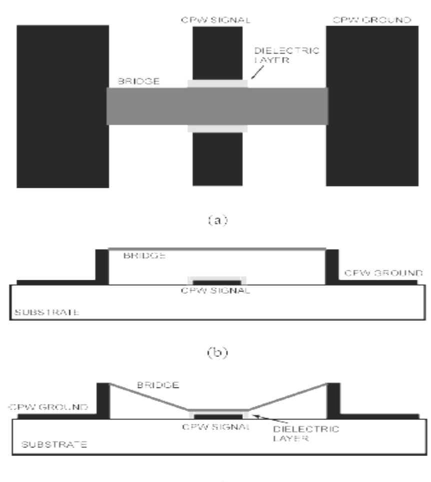

Figure 1. Shunt switches in a Co-Planar Waveguide configuration: a) Top view, b) Side-view in the up-state, and c) Side-view in the down-state.

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The capacitance of a MEMS switch varactor is calculated using the parallel-plate equation

$$C_{TOT} = \frac{C_{MEMS} C_{FIXED}}{C_{MEMS} + C_{FIXED}} \quad \ldots\ldots \;\; \ldots. \;\; .. \qquad (2)$$

Eq.(2) can be used for both the up and down-state capacitances. In practice, the actual up-state capacitance is (20-40) % higher than the calculated value due to fringing. The capacitance ratio between the up and down states is typically 20-100 depending on the gap δ, the thickness of dielectric layer, smoothness of all layers, and contact force in the down-state [2].

Equivalent circuits for a MEMS switch are shown in Figs. 2 and 3, where R_{MEMS} and L_{MEMS} are the resistance and inductance of the MEMS component, and Z_0, β, and l are the transmission line impedance, propagation constant, and length, respectively.

The bridge can be used also as an analog varactor because the gap can be changed by about 1/3 before the bridge pulls down. This method has been applied successfully in many tunable circuits like phase shifters and filters [3].

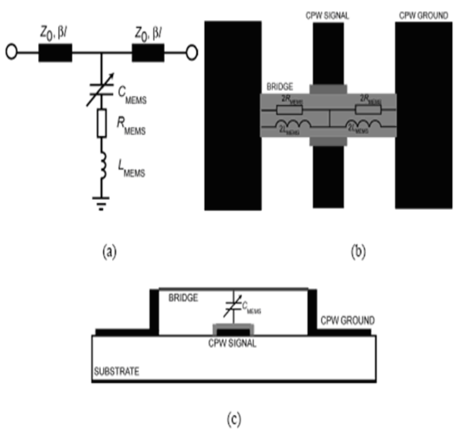

Figure 2. a) Equivalent circuit of capacitive shunt switch or varactor. Schematic drawing of a shunt switch showing the physical meaning of the equivalent circuit. b) Top view and c) side view.

MEMS capacitive switches are fabricated with a metal, dielectric, air gap, and metal cross section as shown in Fig.4. The upper metal plate known as bridge can be actuated from an up state to a downstate. In the upstate, the plate is relaxed. In the downstate, an electrostatic force is applied by an external control voltage causing it to collapse and eliminating the air gap. Capacitance ratios between the two states of 600:1 are attainable although 30–40:1 is more typical [4].

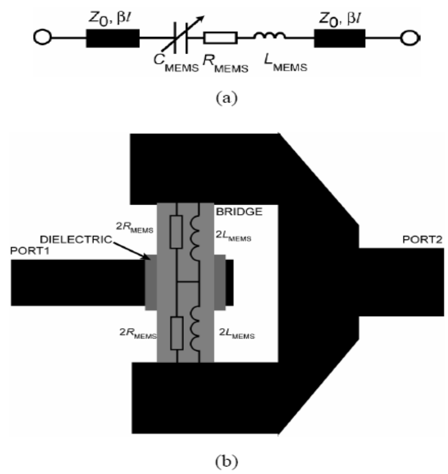

Figure 3. a) Equivalent circuit of a capacitive series switch and b) its possible layout.

Due to the mechanical nature of the switches, the frequency response of the bridge follows a low pass characteristic with a mechanical resonance in the range of 10–200 kHz. Although the switching speed of MEMS is relatively low, they offer the advantage of very low static power dissipation. MEMS switches still face challenges in the areas of reliability and packaging to be, however their wide tuning range allows for new circuit topologies.

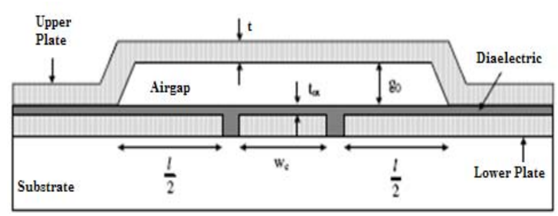

Figure 4. MEMS capacitive switch cross section

The actuation voltage of a MEMS switch is determined by equating the electrostatic force of the applied voltage to the mechanical restoring force of the beam. This depends on the spring constant k, for a fixed-fixed bridge, which can be determined by:

$$k = \frac{32 E t^3 w}{l^3} \quad \ldots.. \;\; \ldots. \;\; \ldots\ldots.. \qquad (3)$$

Where: *E* is Young's modulus, *t* bridge thickness, w bridge width, and bridge length.

For the case shown in Fig. 4, the force is applied to the two ground plate. The actuation voltage is given by:

$$V_{sw} = \sqrt{\frac{2k}{\varepsilon_0 A} g^2 (g_0 - g)} \quad \ldots.. \quad (4)$$

Where: g_0 is bridge height in the up state (at 0V), g is the current beam height, and $A= wl$ is the bridge area that overlaps the lower-ground plate.

Instability may occur when the electrostatic force exceeds the restoring force. At this point, the bridge pulls down. This instability occurs at a bridge height of

$$g = \frac{2}{3} g_0 \quad \ldots. \quad (5)$$

Knowing the bridge height, and substituting for k and A, the pull-down voltage can be determined:

$$V_p = V_{sw|(2/3)g_0} = \sqrt{\frac{256 E g_0^3 t^3}{27 \varepsilon_0 l^4}} \quad \ldots\ldots \quad (6)$$

The pull-down voltage must not exceed the breakdown voltage of the dielectric, therefore limiting the thickness. The pull-down voltage determines the maximum practical capacitance. The potential nonlinearity is another concern. Two RF tones separated by a frequency below the resonant frequency of the switch create an envelope effect that modulates the air gap in the switch, hence changing the capacitance. Careful design to increase the bridge spring constant can mitigate this problem. It should be noted that MEMS switches are still more linear than diode or FET based devices [5].

III. SIMULATION

The chosen model is a class D amplifier with MEMS switching devices to replace FETs or transistors. The amplifier design is required to provide an output power of 1mW to an 8Ω load. The amplifier is for the audio bandwidth (20Hz - 20 kHz). At these frequencies, the gain should be constant with a total harmonic distortion less than 1% and a priority consideration for efficiency and distortion. The LM 324 with a negative feedback of 100kΩ is chosen as the power amplification stage. MEMS with a shunt configuration switch the output up and down. A simple LC filter converts the Pulse Width Modulation (PWM) signal back to its analog form with some added distortion. An 8Ω load resistor is connected to the filter and the measurement is carried out at the load. The amplifier consists of 4 stages: input switching stage, power amplification stage, switching stage of MEMS and output filter stage. The PWM is used for switch mode operated amplifiers. The audio signal is compared to a high frequency triangular waveform using a comparator. When the voltage at the inverting input is higher than the non-inverting input, the output voltage is low, and when it is smaller, the output voltage is high.

The power amplification stage is operational amplifier, LM 324 with negative feedback. The model excludes bipolar and FET transistors and uses op-amp as another amplifying device. The LM324 consist of four independent operational amplifiers of high gain, internally frequency compensated for unity gain, which are designed to operate from a single power supply, although a split power supplies is possible. The voltage Gain is approximately 100dB, and the power drain is suitable for battery operation.

A shunt MEMS switch is modeled as shown in Fig.6. It operates in up and down states, depending on the applied voltage. For a low frequency analysis, the values of the equivalent circuit are given in Table 1 below.

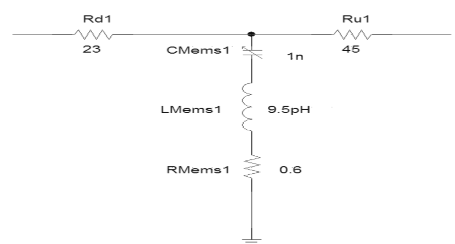

Figure 5. Equivalent circuit for MEMS Shunt capacitive switching used on this work

TABLE 1 PARAMETER VALUES FOR UP AND DOWN STATE CONDITIONS

Components	Values
Upstate impedance, Zu (Ω)	23 Ω
Downstate impedance, Zd (Ω)	45 Ω
CMEMS up (F)	91 fF
CMEMS down (F)	750 fF
LMEMS (H)	9.5 pH
RMEMS (Ω)	0.6 Ω

The output stage is an LC filter with a cutoff frequency (*fc*), as given by Eq. (7), which should be set above the audio bandwidth. Since the filter is used to convert the PWM to its original form, *fc* is determined with respect to the switching frequency of the amplifier, which is equal to the frequency of the triangular wave (f_T). Therefore, *fc* and f_T are related and both values will affect the amount of harmonics present in the output.

The cut-off frequency of the LC filter is ω_c.

$$w_c = \frac{1}{\sqrt{LC}} = 2\pi f_c \quad \ldots\ldots \quad \ldots.. \quad \ldots \qquad (7)$$

For an input signal frequency (*fs*), the lowest harmonic is f_T - 2 *fs*. Since *fs* is 20kHz, and in order to minimize distortion, it is required that f_T - 2 *fs* >> *fs*, therefore f_T should ideally be 600 kHz. However, due to magnetic interference, a more practical value for f_T would be 300 kHz. Once f_T has been determined, only *fc* remains. In order to minimize the amount of ripple in the output, *fc* has to be smaller than f_T. Therefore, *fc* should ideally be 20 kHz. Furthermore, *fc* affects the amount of phase shift at the output. A high *fc* will decrease the phase shift, and vice versa. For the LC filter, the phase shift usually appears at frequencies above 10 kHz and brings delay in the µs range. The designer has to make a choice between phase shift and ripple. In this design, phase shift was considered. The LC filter is shown in Fig. 7 with its characteristics in Table 2. Higher inductance increases the phase, but the amount of ripple is reduced and a higher capacitance also reduces the ripple with less added phase shift.

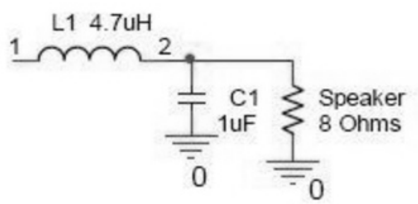

Figure 6. LC Filter

TABLE 2 CHARACTERISTICS OF THE LC FILTER

Magnitude	0 – 0.6dB
Phase Shift	0 - 5°
Group Delay	0 – 720 ns
ω_C	73 kHz

The noise figure (NF) in telecommunication is a measure of degradation of the signal to noise ratio (SNR), caused by components in the RF signal chain. The noise figure is the ratio of the output noise power of a device to the portion thereof attributable to thermal noise in the input termination at standard noise temperature, T_O is usually 290 K. The noise figure is thus the ratio of actual output noise to that which would remain if the device itself did not introduce noise. It is a number by which the performance of a radio receiver can be specified.

In heterodyne systems, output noise power includes spurious contributions from image-frequency transformation. Essentially, the noise figure is the difference in decibels between the noise output of the actual receiver to the noise output of an "ideal" receiver. The noise power from a simple load is kTB, where B is the measurement bandwidth. Noise figure is NF;

$$NF = SNRin - SNRout \quad \ldots\ldots\ldots \quad (8)$$

The formula is only valid if the input termination is at standard noise temperature, T_O. Sometimes the noise factor F is specified. NF is the decibel equivalent of F. The following formula is only valid when the input termination is at standard noise temperature T_0:

$$F = 1 + \frac{T_e}{T_0} \quad \ldots\ldots \quad \ldots\ldots \ldots.. \quad \ldots.. \quad (9)$$

$$F = 10^{NF/10},\ F = 10\log(F) \quad \ldots\ldots.. \quad .. \quad (10)$$

The noise factor of a device is related to its noise temperature via

$$F = 1 + \frac{T_e}{T_0} \quad \ldots\ldots \quad \ldots.. \quad \ldots.. \quad (11)$$

IV. RESULTS AND ANALYSIS

The amplifier analysis is based on the model shown in Fig.7, which was simulated and built using PSpice. The power supplies were set to 5V for V_{cc} and +5V and -5V for V_{ee} respectively. To facilitate the simulation with an audio frequency input, a second order LC filter was used. Since phase difference appears at 10 kHz, a detailed analysis was carried out at that frequency.

The PWM and the input signal are compared to each other. A sinusoidal signal used in the simulation as the signal to be amplified by the system. The input signal frequency is *fs* and the lowest harmonic present is f_T - 2*fs*. Since *fs* is 20 kHz, it is required that f_T - 2*fs* >> *fs*, therefore f_T should ideally be 600kHz and in order to minimize distortion. However, due to magnetic interference, a more practical value for f_T would be 300 kHz. The PWM has 3.7V DC voltage amplitude creating15 triangular waves for a single period of input. The input waveform to the operational amplifier is shown in Fig.9. The voltage waveform produced by each input switching stage was found from transient to a step index of 50 ms.

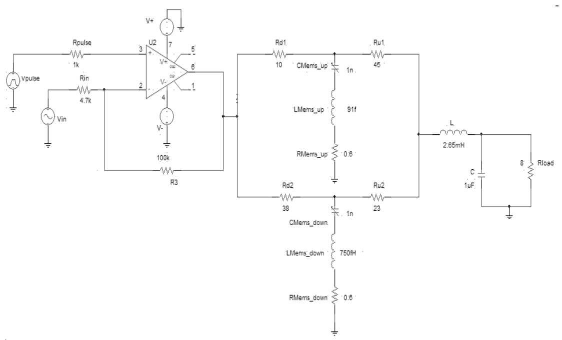

Figure 7. Amplifier using MEMS capacitive switching model

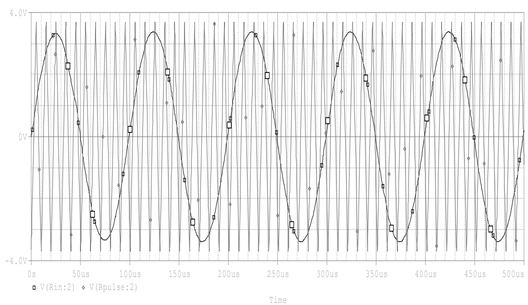

Figure 8. Pulse Width Modulation waveform and input signal waveform.

The gain of the amplifier is calculated by the ratio of the output of the operational amplifier voltage to the input voltage. The values of gain can be seen in a Fig.10. The gain exhibits values of -20000 to 20000. The value of the transient gain increases until it reaches a constant value limited by the capability of the operational amplifier.

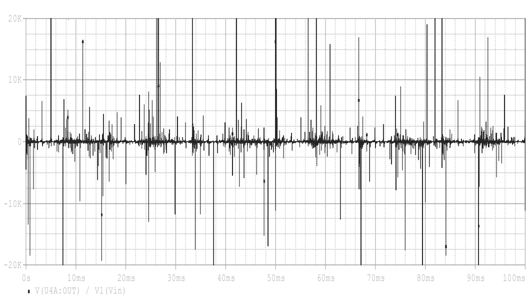

Figure 9. Operational Amplifier Gain

Gain (amplifier) = Vo (op-amp) / Vin
Gain (system) = Vo/Vin
Resonance frequency:

$\omega_c = 2\pi f_c = 1/\sqrt{LC}$ = 73.412 kHz

Quality factor:

$Q_c = 1/(\omega_c R_L C)$ = 1702.7

The fundamental frequency is 10 kHz with frequency range up to 360 kHz. The frequency domain analysis of the circuit was performed using FFT. For *fc* is 73 kHz and *fs* is 20 kHz, the significant harmonics are *fT* (300 kHz), *fT*-2*fs* (280 kHz), and *fT*+2*fs* (320 kHz). Harmonics are also present near *fc* (73 kHz) since resonance occurs at that point as shown in Fig.11 below. Using PSpice, total harmonic distortion was calculated to be 0.71%, which satisfies the design requirements. Furthermore, *fc* affects the amount of phase shift present at the output. A high *fc* will decrease the phase shift, while a low *fc* will increase it. For an LC filter, phase shift usually appears at frequencies above 10 kHz and brings delay in the microsecond range.

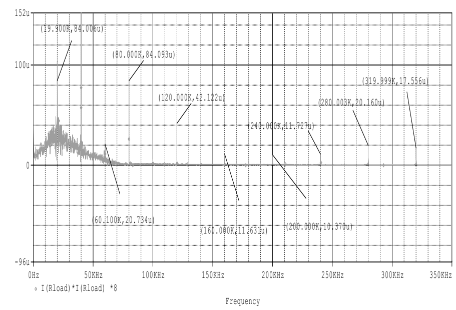

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Figure 10. Output Power in Frequency Domain

The power output in watt is found by using, $P = I_{Load}^2 R_{Load}$ .The average power delivered to the load is 0.7mW which is less than expected, due to the total power dissipation of 1.07×10^{-2} watt. However, this value is reasonable for audio applications. The average output power delivered to the load is 98.981dB or 39.519 in dBm.

The system efficiency can be calculated using

$$\gamma = \frac{I^2 R_L}{I^2 R_L + I^2 R_{in}} \quad \ldots.. \quad \ldots. \quad \ldots \qquad (12)$$

Following the switching signal produced by the operational amplifier, the power alternates form 0W to 0.7mW. This system has an average value of 1 which means the system has 100% efficiency.

V. DISCUSSION AND RECOMMENDATIONS

Although good results are obtained with this technique, there are still some problems. The 8Ω load resistance being an integral part of the filter affects the frequency response. To develop the design further, inductors can be used.

For high frequency applications that range (4-18)GHz a different kind of amplifier [6] switch is used. It employs a fixed Metal Air Metal (MAM) capacitor in series with a fixed capacitor. Fig.16 shows the equivalent circuit of a switched capacitor used as a tuning element [7].

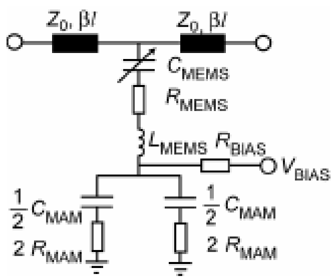

Figure 11. The equivalent circuit used for the switched capacitors 4-18GHz.

Another improvement can be made by using a higher order filter, which will reduce the amount of harmonics without introducing a large phase shift. A fourth order filter is shown in Fig 17, with its characteristics shown in Table 4

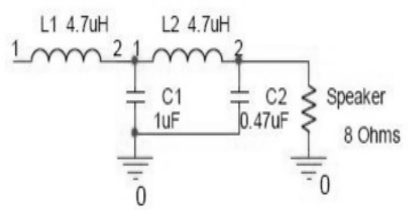

Figure 12. Fourth order LC filter

TABLE 3: FOURTH ORDER LC FILTER CHARACTERISTICS

Magnitude	0 - 1.2dB
Phase Shift	0 - 10°
Group Delay	0 – 1582 ns
ω_C	56 kHz

VI. CONCLUSION

Amplifiers integrated with MEMS switching devices can be highly efficient in terms of miniaturization and portability. Low power consumption is an attractive feature for many modern mobile applications. It is anticipated that further development will result in a technology that may prevail in the market.

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