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A Comparison of Phase-Shift Self-Oscillating and Carrier-based PWM Modulation for Embedded Audio Amplifiers

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ABSTRACT

This paper compares two modulation schemes for Class-D amplifiers: Phase-Shift Self-Oscillating (PSSO) and Carrier-Based Pulse Width Modulation (PWM). Theoretical analysis (modulation, frequency of oscillation, bandwidth...), design procedure, and IC silicon evaluation will be shown for mono and stereo operation (on the same silicon die) on both structures. The design of both architectures will use as many identical building blocks as possible, to provide a fair, “all else being equal”, comparison. THD+N performance and idle consumption went from 0.02% and 5.6mA in PWM to 0.007% and 5.2mA in Self-Oscillating. Other advantages and drawbacks of the Self-Oscillating structure will be explained and compared to the classical Carrier-Based PWM one, with a focus on battery-powered applications.

1. INTRODUCTION

The wide use of switching amplifiers for mobile applications is greatly influenced by their lower current consumption and higher efficiency [1]. They however have linearity limitations, some linked to the widely used carrier-based PWM modulation. A newer modulation scheme, Phase-Shift Self-Oscillating, is presented here and compared to standard PWM.

The principle of operation will be detailed for Carrier-Based PWM and Phase-Shift Self-Oscillating in Section 2 and Section 3 respectively. Section 4 will detail the design and IC implementation of both structures. Their simulated and measured performances will be shown in Section 5 and 6 respectively, to show the advantages brought by the new solution with a focus on audio performance. Finally, conclusions will be drawn in Section 7.

2. CARRIER-BASED PWM

Carrier-Based PWM modulation [2] relies on the comparison of an input signal (or error signal in closed loop configurations) with a high frequency reference (sawtooth or triangle wave). The result of the comparison is a square wave which duty cycle is modulated by the input signal's amplitude. A low output impedance buffer amplifies this signal to form the output PWM signal. After low passing of the output PWM signal, the high frequency content is removed and the amplified input signal is recovered. The switching frequency is constant, at the frequency of the reference signal. Figure 1 shows the block diagram of such an amplifier, the modulation's behavior is illustrated in Figure 2.

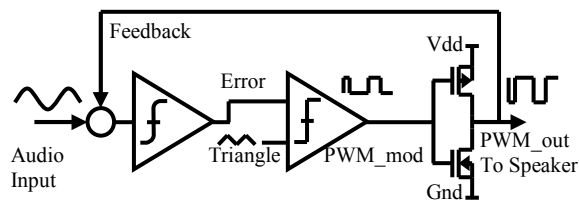


Figure 1: PWM Amplifier Structure

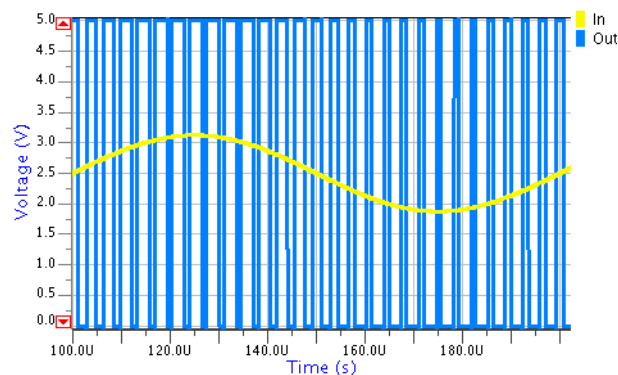


Figure 2: PWM Modulation

The errors introduced in the signal path (output stage non linearities, supply noise, etc) increase the distortion on the output signal. In order to obtain low THD figures, a feedback loop is required to correct these errors.

In a feedback configuration, the loop bandwidth of a Carrier-Based PWM amplifier is limited for large-signal stability reasons [3]. The error signal's slope has to be

lower than the slope of the reference signal it is compared with, otherwise overmodulation will occur. To prevent this behavior, the loop bandwidth is limited to f_s/π (usually $f_s/4$ in practice, to keep a safety margin). This instability is shown in Figure 3.

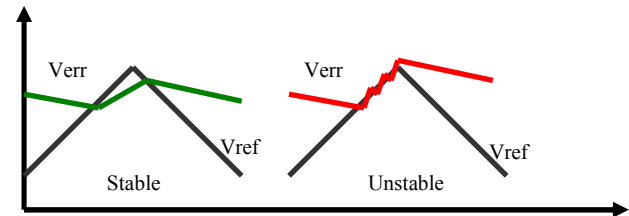


Figure 3: Instability in Feedback PWM Amplifiers

The output frequency spectrum resembles the one of a square wave at the switching frequency, plus sidebands around every switching frequency harmonic due to the modulation of the input signal (defined by Bessel functions) [4]. At audio frequencies, the spectrum of the input signal is present. No harmonics of the input signal are present in theory, if just the modulation is considered, with linear blocks. Figure 4 shows the theoretical spectrum of a PWM signal, with a sinusoidal input signal at -6dB FS.

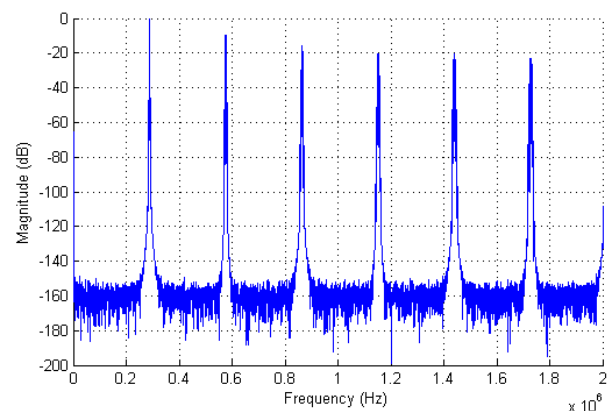


Figure 4: PWM Modulation Frequency Spectrum

3. PHASE-SHIFT SELF-OSCILLATING

This newer structure is based on a self-oscillating loop, as in oscillators' theory [5]. The modulator, output stage and feedback filter form gains, poles, possibly zeros and delays. Figure 5 shows its electrical structure. The block diagram is in Figure 6 showing the integrating error amplifier ($C(s)$), the comparator and output stage ($K(s)$) and the feedback filter ($H(s)$).

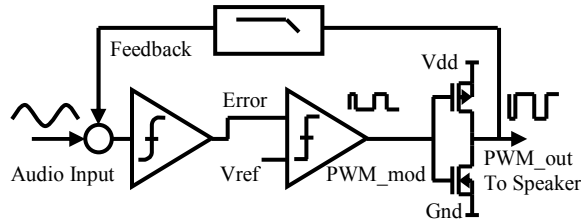


Figure 5: PSSO Oscillating Amplifier Structure

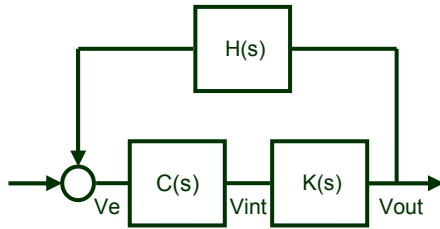


Figure 6: PSSO Amplifier Block Diagram

Barkhausen's criterion defines the oscillation of a closed-loop system. If its phase equals 360° at a frequency where the loop gain is unity, oscillations will occur. The PSSO loop from Figure 6 has a loop gain and phase as defined by (1) and (2) respectively.

$$|G(f)| = |H(f) \cdot C(f) \cdot K(f)| = \left| \frac{V_e(f)}{V_{out}(f)} \cdot \frac{V_{int}(f)}{V_e(f)} \cdot \frac{V_{dd}}{V_{int}(f)} \right| \quad (1)$$

$$\angle G(f) = 90 + \angle \left(\frac{1}{1 + j \cdot f / f_c} \right) + 360 \cdot f \cdot t_d \quad (2)$$

The output stage generates a rail to rail square wave at the switching frequency, the output amplitude of $K(f)$ equals then V_{dd} there. This makes the loop gain $G(s)$ unity at the switching frequency. The oscillation criterion is then only defined by the loop phase, by the poles and zeros placement. The loop bandwidth is four

times higher than with PWM modulation. At the same signal frequency, more error correction is applied and a fourfold decrease in THD can be expected.

A low frequency signal input is added to the loop, which is able to modulate the duty cycle of the output waveform as in Carrier-Based PWM. However, self-oscillating modulation does not operate at a constant switching frequency: the higher the modulation index the lower the switching frequency, as shows Figure 7. There is no low-frequency limit, when the amplifier clips the switching frequency goes down to zero.

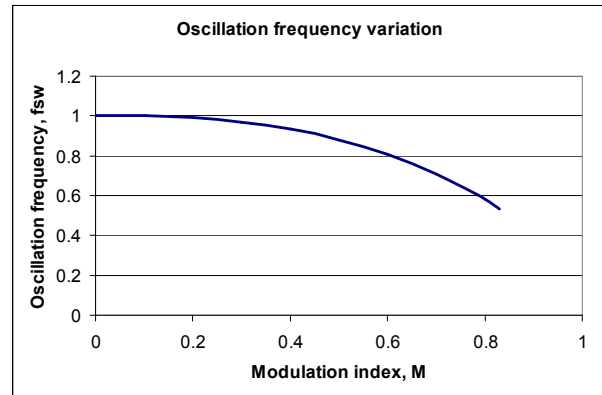


Figure 7: Oscillation Frequency vs. Modulation Index

The output frequency spectrum is the one of a square wave which frequency varies with time, modulated by the amplitude of the audio input signal. At low frequencies, the audio signal can be found. The peak amplitude of the HF components is lower than with PWM. This is an advantage when EMI is a concern.

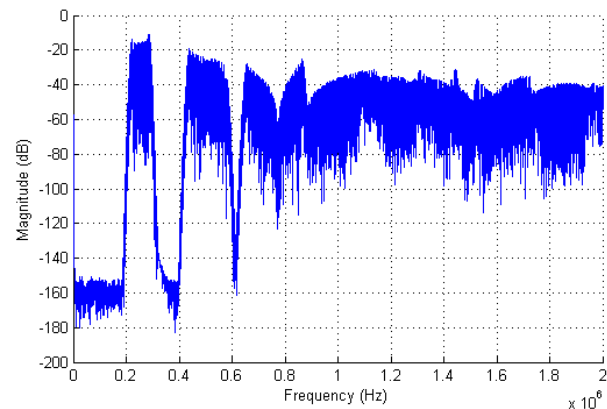


Figure 8: PSSO Modulation Frequency Spectrum

4. IC IMPLEMENTATION

Both ICs are implemented in a STMicroelectronics 0.25 μ m CMOS IC process with thick oxide transistors, capable of running up to 5.5V. The building blocks (error amplifier, comparator, MOS drivers and output stage) are the same for both configurations to make the comparison as fair as possible.

4.1. Preamplifier

In addition to the Class-D loop, both amplifiers (PSSO and PWM) are used with a linear (Class-AB) preamplifier. This fully differential amplifier serves multiple functions like setting the input impedance, improving the Common Mode Rejection Ratio (CMRR) and setting the voltage gain [6].

Components mismatch in this stage, especially on the input and feedback resistors, limits its Power Supply Rejection Ratio (PSRR) to about 65dB at low frequencies. This stage is then the limiting factor for the complete amplifier's PSRR, meaning that it will unfortunately not be possible to compare the PSRR performance of PWM and PSSO architectures here.

4.2. Differential Operation

The single supply rail available in battery powered applications leads to two possibilities for the load connection. A single ended output can be used, but would require a large coupling capacitor to provide a DC-free output voltage. A bridge configuration is then preferred, having no DC voltage on its output. Also, its voltage swing is doubled compared to a single ended configuration, allowing four times more output power.

This differential configuration allows the use of a slightly different modulation on the output: instead of

driving both switching legs in opposite phase, they can be controlled by a 3-level modulation [4]. This reduces the high frequency content on the output and permits the use of a smaller output filter, or no filter at all if the speaker load is inductive enough to provide filtering on its own. Figure 9 illustrates this 3-level modulation.

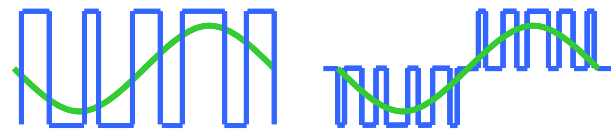


Figure 9: 2-level (left) and 3-Level (right) Modulation

While the implementation of a 3-level PWM modulation is straightforward [4], a PSSO amplifier requires a synchronization between both polarities to maintain them in frequency and phase. Due to components mismatch between both polarities, they will not oscillate at the exact same frequencies and the high frequency content will not be ideally reduced. [7] and [8] propose a synchronization scheme that does not increase the system complexity and that functions here with good results, with a coupling factor K of about 0.1.

4.3. Carrier-Based PWM Amplifier

The amplifier is made of an integrating error amplifier (comparing input and feedback signals), a comparator fed by the error signal and the triangle wave, followed by the MOS drivers and the output stage. Two signal paths are used, fed by input signals in opposite phase, to generate a 3-level PWM modulation. The linear preamplifier is placed in front of the Class-D path, and an oscillator is required here to provide the sawtooth reference signal. The signal path for one channel is illustrated in Figure 10.

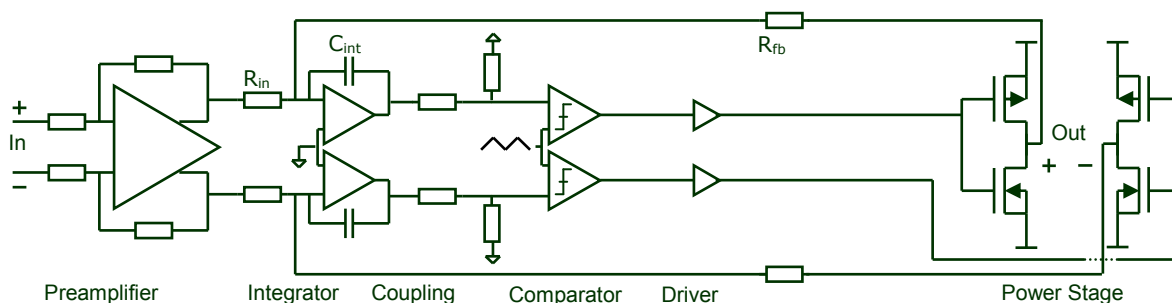


Figure 10: PWM Amplifier Schematic (one channel shown)

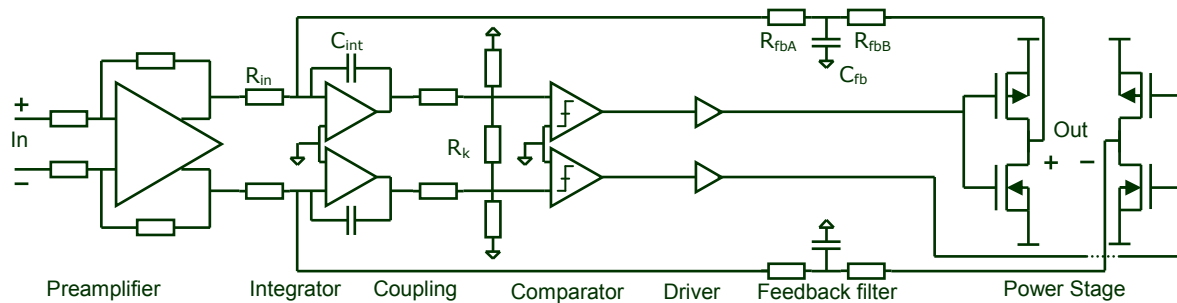


Figure 11: PSSO Amplifier Schematic (one channel shown)

4.4. Self-Oscillating Amplifier

To form an oscillating loop, the sawtooth signal is removed and the comparators are connected to a DC common-mode voltage instead. A pole is added to the feedback path to increase the phase. With this pole, the integrator and propagation delays, the required 180° are achieved at the switching frequency to start oscillations.

Figure 11 shows this implementation. R_{fbA} , R_{fbB} and C_{fb} form the feedback loop's pole. R_{fbA} , R_{fbB} and C_{int} around the opamp form the integrator and its time constant. The resistor R_k creates the coupling between the positive and negative polarities.

With this implementation, only the feedback pole's location and the loop delay influence the oscillation frequency. The integrator's phase is 90° at all the time so its time constant has no effect. For performance reasons it is best to keep the loop delay small, so the oscillation frequency adjustment is best made with the feedback pole.

With a stereo amplifier on the same silicon die, a coupling (via power supply rails, substrate, capacitive...) between the two channels is inevitable and intermodulation will occur at $f_{sw_{left}} - f_{sw_{right}}$. This intermodulation product will fall down in the audio band and will be audible. In order to prevent this, the left channel and right channel oscillation frequencies have been offset by 30kHz by using different feedback pole frequencies.

5. SIMULATED PERFORMANCE

The schematics from Figure 10 and Figure 11 have been simulated and the results are presented in this section. For the PWM amplifier, Figure 12 shows the behavior of the modulation. It operates as expected, with a fixed frequency and a duty cycle controlled by the input signal.

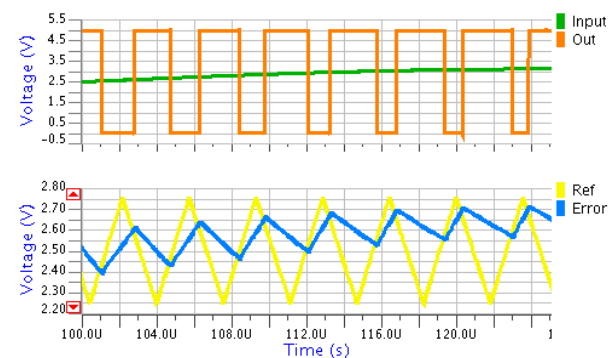


Figure 12: Simulated PWM Modulation

The simulation results for the PSSO modulation are illustrated in Figure 13. The system oscillates as predicted, and there is a frequency variation. The larger the signal is, the lower the switching frequency becomes.

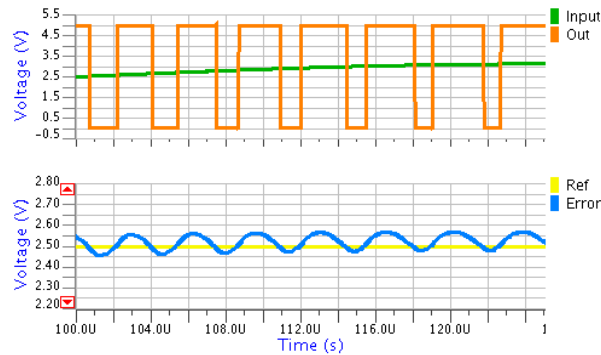


Figure 13: Simulated PWM Modulation

One important observation is that the error signal has lower slopes than with PWM modulation. This is due to the low pass filter in the feedback network. The requirements on the error amplifier can then be relaxed with the PSSO topology, especially on its slew-rate.

With the bridge tied load, the modulation is made 3-level as explained in section 4.2. Figure 14 and Figure 15 show the simulated output signals.

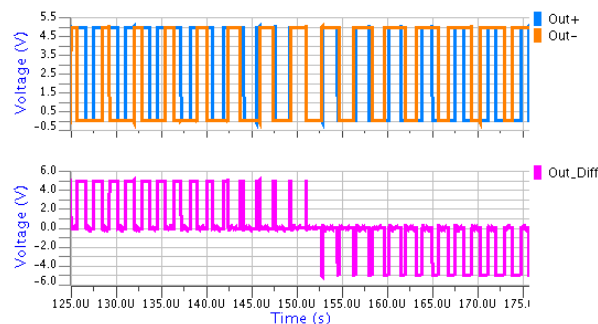


Figure 14: Simulated PWM 3-level Modulation

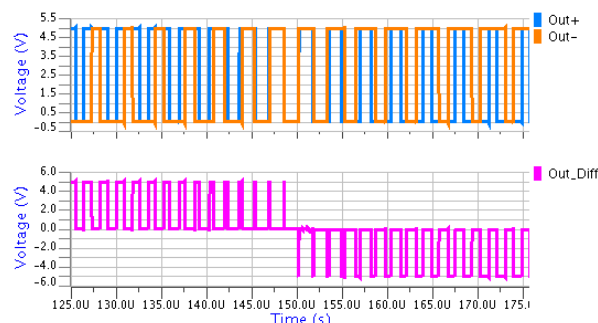


Figure 15: Simulated PSSO 3-level Modulation

Both versions have a correct 3-level modulation, thanks to the clocked PWM and the coupling in the PSSO. Without coupling, the results in Figure 16 are obtained.

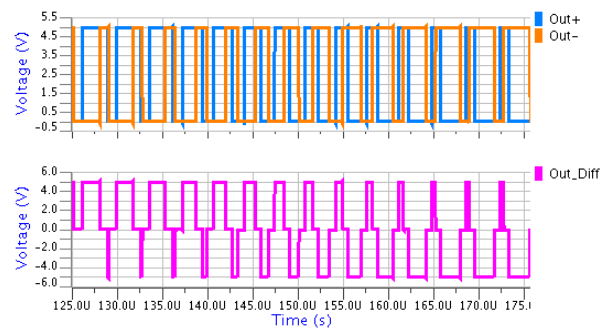


Figure 16: PSSO without coupling between polarities

The THD performance of both amplifiers have been simulated and with $V_{dd}=3.6V$, a load of 8Ω and a 1kHz signal at -6dB the THD is 0.02% for the PWM amplifier and 0.006% for the PSSO. The PSSO amplifier has a better THD performance, as predicted.

6. MEASURED PERFORMANCE

THD+N performance has been measured with an Audio Precision System2. In mono operation the carrier-based system achieves a minimum of 0.02% as plotted in Figure 17 (with $V_{dd}=3.6V$, a 1kHz signal and a 8Ω load) while the self oscillating goes as low as 0.007%. The improvement is close to the 4:1 ratio expected from the bandwidth increase and matches the simulations.

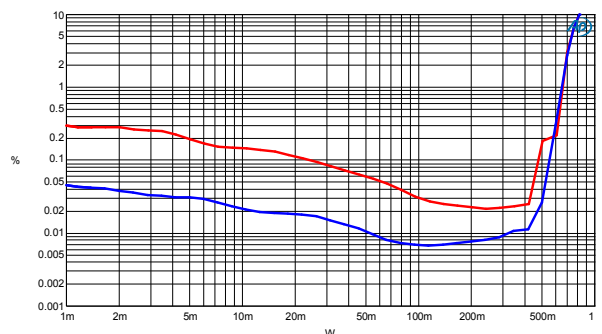


Figure 17: THD+N Performance, Mono Operation

In stereo, the performance of the PWM amplifier remains identical but the THD+N increases on the

PSSO amplifier as shown in Figure 18. Simulations did not predict this phenomenon, so its source is quite likely a parasitic coupling between the two channels when the output current increases, like a coupling through the substrate or the bonding wires. Further investigation with a different layout is required to precisely determine the origin of this effect.

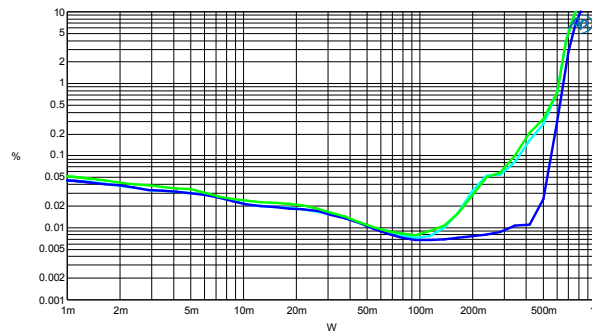


Figure 18: THD+N Performance, Mono vs. Stereo

An interesting discrete implementation of a self-oscillating Class-D amplifier [9] shows a solution by locking the modulator to a reference frequency for idle and low modulation indexes. However, a clock generator is required again and the THD+N performance is degraded.

The proper behavior of the coupling between both polarities, in the PSSO amplifier, is illustrated in Figure 19. The positive and negative outputs are plotted during idle. Both signals have the same frequency and phase, the differential signal seen by the load is then zero.

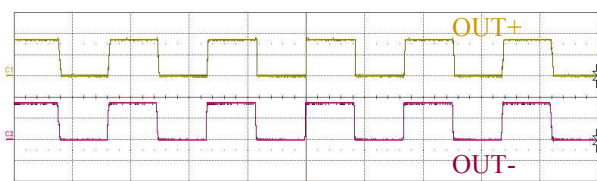


Figure 19: PSSO Outputs at Idle

Other performances are given Table 1, comparing Carrier-Based PWM (left column) to Phase-Shift Self-Oscillating (right column). Measurements have been performed at $V_{dd}=5V$ with a 1kHz input signal, an 8Ω and a gain of 6dB unless otherwise mentioned.

Parameter	PWM	PSSO
Output Noise, μV	27	27
PSRR 217Hz, dB	65	65
Icc 5V, mA	5.6	5.2
Fsw, kHz	280	275 (Left) 310 (Right)

Table 1: Measured Performance

Noise performance is identical, showing that it is determined by the thermal (white) and flicker (1/f) noise of the analog circuits as opamps and the like. The type of modulation used has no visible effect on the output noise.

The gain in current consumption, 8%, is due to the oscillator block that has been removed.

7. CONCLUSION

The evaluation of both modulation schemes showed that the newer self-oscillating one brings a series of advantages compared to fixed-frequency PWM. Theoretical analysis and measurement results showed THD+N improvements and idle current reduction, which is especially interesting in battery-powered audio systems. In terms of output frequency spectrum, the variable switching frequency of the self oscillating has the advantage of spreading the energy over a frequency range, but could complicate the integration with other switching devices when each of them should occupy a specific frequency band. Specific considerations to obtain a correct 3-level modulations have been shown, as well as the sensitivity of this topology to the use of multiple channels on the same silicon IC.

8. ACKNOWLEDGEMENTS

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