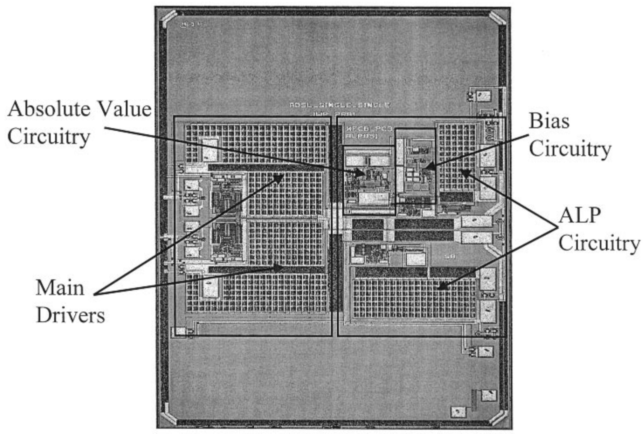

Fig. 12. Die photo.

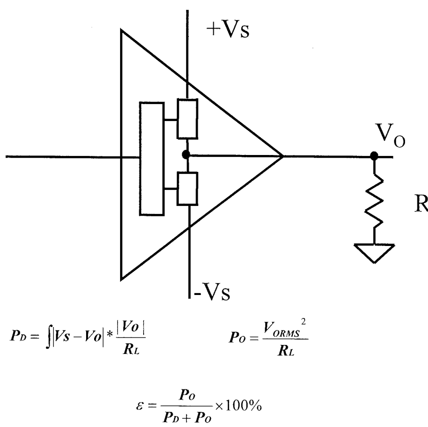

Fig. 13. Ideal class A/B efficiency.

The chip was fabricated in a high-voltage, trench-isolated, complementary bipolar process utilizing SOI bonded wafers. The IC was packaged in both a 28TSSOP EPAD and 32LFCSP for evaluation.

Appendix

It is useful as a starting point to derive the maximum possible efficiency of a class AB amplifier driving a resistive load. If efficiency is defined as the power out divided by the power out plus the power dissipated in the amplifier (assuming zero quiescent power), the efficiency can be derived knowing just the output Voltage (Vo) and the supply voltage (Vs). Fig. 13 presents this condition. Some definitions are as follows.

Total power consumptions is defined as

$$P_D = \int |Vs - Vo| \cdot \frac{|Vo|}{R_L}. \tag{A1}$$

Power delivered to the load is defined as

$$P_O = \frac{V_{O\mathrm{rms}}^2}{R_L} \tag{A2}$$

and the efficiency of the system as

$$\varepsilon = \frac{P_O}{P_D + P_O} \times 100\%. \tag{A3}$$

Substituting (A1) and (A2) into (A3) and recognizing that the integral of Vo squared is the mean squared and the integral of the absolute value is just the mean average deviation (MAD), the following results for efficiency:

$$\varepsilon = \frac{V_{O\mathrm{rms}}^2}{V_S \times V_{O\mathrm{MAD}}} \times 100\%. \tag{A4}$$

It is worth noting that the denominator in (A4) is only proportional to the average dc current drawn from the supplies, since the negative term in (A1) always cancels the positive Po term in the denominator of (A3). This fact will simplify later computations. For a perfect amplifier, Vs is equal to the peak output voltage V_P. Taking the expression in (A4), efficiencies for the amplifier system in Fig. 12 processing sinewaves and squarewaves yield the familiar results

$$\varepsilon(\sin) = \frac{V_P^2/2}{V_P \cdot (2V_P)/\pi} = \frac{\pi}{4} = 78.54\% \tag{A5}$$

$$\varepsilon(sqr) = \frac{V_P^2}{V_P \cdot V_P} = 100\%. \tag{A6}$$

The DMT waveform is modeled as Gaussian-like noise with a standard deviation of sigma (the rms value). The mean average deviation of the waveform is computed as follows:

$$V_{O\mathrm{MAD}} = 2\int_0^{\infty} \frac{x}{\sigma\sqrt{2\pi}}\, e^{-x^2/2\sigma^2} \tag{A7}$$

$$= \sqrt{\frac{2}{\pi}}\,\sigma. \tag{A8}$$

Substituting (A8) into (A4) and remembering that Vs is the CF times sigma (the rms level), the efficiency of the above Class AB systems processing a noise like waveform is

$$\varepsilon(noise\text{-}like) = \frac{V_{\mathrm{rms}}^2}{V_{\mathrm{rms}} \cdot CF \cdot V_{\mathrm{rms}} \cdot \sqrt{\frac{2}{\pi}}} \tag{A9}$$

$$= \sqrt{\frac{\pi}{2}}\,\frac{1}{CF} \times 100\%. \tag{A10}$$

The expression in (A10) is interesting as it directly relates the efficiency of a Class AB system driving a DMT noise-like Gaussian waveform to the CF of that waveform. For example, an ideal amplifier (no quiescent current, Iq) with a CF of 5.3 (the minimum for ADSL) has a maximum theoretical efficiency of only 23.6%.

There are practical limits to this efficiency. Practical line drivers must include provisions for back-termination of the line impedance and coupling losses, each consuming power. In general, the power supplies are some factor ($A > CF$) times the rms output voltage to include headroom. Quiescent power P_Q must be included also. Equation (A10) then modifies to

$$\varepsilon = \frac{1}{A\sqrt{\frac{2}{\pi}} + \frac{P_Q}{P_O}} \times 100\%. \tag{A11}$$

With (A11), a Class AB amplifier with a quiescent power P_Q of 120 mW (24 V $*$ 5 mA), driving 20.4 dBm, with a CF (A) of 5.3, into 100 Ω on ±12-V supplies, has an efficiency of 18.4%.

To extend this analysis to a multisupply system, the power must be computed in two regions: from the origin to the value of the first supply (switching point) and from this point to the value of the second (higher) supply. The power dissipation is related to the sum of the contribution from the two regions

$$P_D \propto \left(V_{S1}V_{\text{OMAD1}} - V_{\text{Orms1}}^2\right) + \left(V_{S2}V_{\text{OMAD2}} - V_{\text{Orms2}}^2\right). \tag{A12}$$

As mentioned before, only the MAD component need be evaluated

$$V_{\text{OMAD}} = 2\int_0^\infty \frac{x}{\sigma\sqrt{2\pi}}\, e^{-x^2/2\sigma^2}. \tag{A13}$$

Evaluating the integral for the two regions yields

$$V_{\text{OMAD}}|_0^x = \sqrt{\frac{2}{\pi}}\,\sigma\left(1 - e^{-x^2/2\sigma^2}\right) \tag{A14}$$

$$V_{\text{OMAD}}|_x^\infty = \sqrt{\frac{2}{\pi}}\,\sigma e^{-x^2/2\sigma^2}. \tag{A15}$$

For a final result, several substitutions will be made and simplification done to obtain an efficiency equation for these amplifiers. First, V_{S1} (the lower supply) will be set to some number A of standard deviations and the higher supply V_{S2} to some factor B, the maximum number of standard deviations needed, again the minimum that B can be is equal to the crest factor, CF. The end result is as follows:

$$\varepsilon = \frac{P_O}{P_D + P_O + P_Q} * 100\%. \tag{A16}$$

Finalizing into the same form as (11) yields

$$\varepsilon = \frac{100\%}{A\sqrt{\frac{2}{\pi}}\,\left(1 - e^{-A^2/2}\right) + B\sqrt{\frac{2}{\pi}}\,e^{-A^2/2} + \frac{P_Q}{P_O}}. \tag{A17}$$

This equation is plotted in Fig. 3 for a P_Q of zero and B equal to CF.

The maximum efficiency, in this ideal case, is ~51% at A~2.02. This represents a lower supply voltage of only $\pm$3.33 V, which in most cases is impractically low. So again, headroom constraints and quiescent power will limit maximum achievable efficiency.

To compare the multisupply case to the ALP™ amplifier, first note that the first term in the denominator represents the power supplied by the main supplies and is the same for both cases. It dominates even at the maximum efficiency point and exponentially dominates as the main supply is increased. The second term represents the power from the second supplies in the case of Class G and the power supplied by the pumps in the case of the ALP™ circuit.

From Fig. 7, it can be seen that in equilibrium the integrated charge supplied by the pump capacitor C_1 must be equal to the recharge current I_1. There must also be an equal current for each pump and both currents flow across the total supply voltage so the supplied power is $2*Vs*I_1$. In the case of Class G, the same current (in both cases we are assuming no overhead current for the moment) flows across the total secondary supply for a power supplied of $Vs * I_1$. So if the secondary voltage in the Class G circuit is twice the supply voltage of the ALP™ circuit and the primary supplies are equal, the two efficiencies would be equivalent. At the maximum efficiency, $A = 2.02$, the ALP™ has a slight advantage as shown in Fig. 3.

The final form of the efficiency equation, to include headroom and quiescent power for Class G is

$$\varepsilon = \frac{100\%}{A_1\sqrt{\frac{2}{\pi}}\,\left(1 - e^{-A^2/2}\right) + A_2\sqrt{\frac{2}{\pi}}e^{-A^2/2} + \frac{P_Q}{P_O}} \tag{A18}$$

where $A1$ is primary voltage in standard deviations, $A2$ is the secondary voltage, and A is now the point where the output current commutates between the two supplies.

For the ALP™ case we have

$$\varepsilon = \frac{100\%}{A_1\sqrt{\frac{2}{\pi}}\left(1 - e^{-A^2/2}\right) + 2A_1\sqrt{\frac{2}{\pi}}\,e^{-A^2/2} + \frac{P_Q}{P_O}} \tag{A19}$$

where $A1$ is the supply voltage and A is again the switching point, in standard deviations.

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REFERENCES

[1] M. Corsi, R. Hester, K. Maclean, M. Agah, J. Quarfoot, C. Kozok, N. Gibson, and T. Hagen, "An ADSL central office analog front-end integrating actively-terminated line driver, receiver and filters," in *Proc. ISSCC 2001*, vol. 44, Paper 19.4, pp. 304–305.

[2] F. Sabouri and R. Shariatdoust, "A 740 mW ADSL line driver for central office with 75dB MTPR," in *Proc. ISSCC 2002*, vol. 45, Paper 19.2, pp. 322–323.

[3] R. Benton, R. Apfel, B. Webb, J. Wenske, W. Schopfer, and F. Thiel, "A high-voltage line driver (HVLDR) for combined voice and data services," in *Proc. ISSCC 2001*, vol. 44, Paper 19.3, pp. 302–303.

[4] D. Whitney, "Circuit adapts differential input to drive coax," EDN, May 8, 1997.

[5] Tripath Data Sheet, , TLD401x, 2001.

[6] SoundCraftsman MA5002, , 1978.

[7] Philips TDA8574 & TDA1562Q, , 1998.

[8] J. Quarfoot, "Managing ADSL signals and contending with noise," *CDS Mag.*, vol. 4, pp. 19–22, Dec. 1998.

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