A Parametric Operational Amplifier

Varactor bridge circuit achieves 10^{-12} amps input current and 10^{-14} amps current noise . . . a tenfold improvement over the best FET operational amplifiers.

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The 301 operational amplifier was designed to amplify currents in the picoampere range. Logarithmic and integrating circuits and a wide range of transducers including p-h electrodes, ion detectors and photomultiplier tubes are typical applications. Measuring or detecting small currents requires offset and noise currents that are smaller than the signal.

The parametric technique[1] was chosen because it can provide offset currents approaching zero without degrading other parameters desired in an operational amplifier. Chopper amplifiers have considerable low frequency noise and generally sacrifice either bandwidth and overload response or differential operation. Although metal oxide silicon field effect transistors and electrometer tubes have offset currents well below 1 picoampere, they suffer from zero drift especially during warm up. Field effect transistors have offset currents that are 100 times those possible with the 301.

The parametric amplifier offers a current noise improvement of as much as 1000 to 1 over conventional circuits. The noise performance is especially good in the sub-audio range where conventional circuits suffer from 1/f noise[2].

High performance differential operation comes almost automatically. Common mode parameters are limited only by the insulation properties of the materials used to build the input stage.

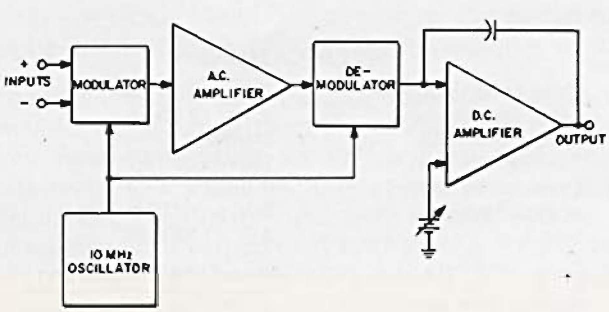


Figure 1. Block Diagram

A block diagram of the amplifier is shown in Figure 1. The parametric section is pumped by a low level 10MHz signal. The modulated output signal is amplified by a 3 stage AC amplifier. Negative feedback is used to stabilize the gain of the AC amplifier. The signal is then synchronously rectified by a diode ring demodulator. The signal is further amplified by a conventional differential transistor operational amplifier.

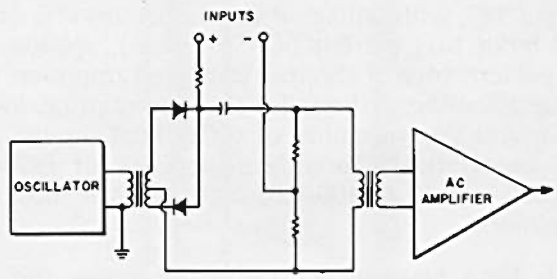
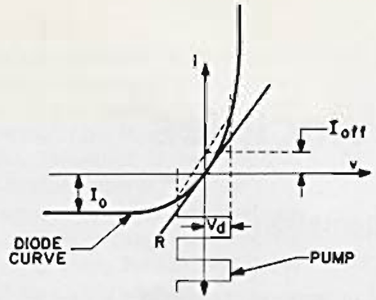


Figure 2. Parametric Section

Figure 2 shows the parametric section which is a balanced varactor diode capacitance bridge. The input signal unbalances the bridge, giving a suppressed carrier modulated output. The bridge has a power gain of 43 dB, resulting from the large ratio of DC input resistance to 10MHz output impedance.

As shown in Figure 3, offset current, I_{off}, is due to square law rectification in the varactors and can be made arbitrarily small by decreasing the pump amplitude, V_d. A compromise must be made between offset current and noise, since decreasing the pump amplitude reduces the parametric gain and increases the equivalent input noise voltage. One feature of this design is that only minor component value changes are needed to favor either offset current or noise performance. Normally the pump amplitude is fixed at a level which gives less than 2 picoampere offset current at 25°C. The offset current doubles for every 9.5°C increase in ambient temperature.



$$i = I_0\left(e^{\frac{V}{.026\eta}} - 1\right)$$

LET $\eta \approx 2$ AND EXPAND:

$$i \approx I_0\left[\frac{V}{.052} + \frac{1}{2}\frac{V^2}{(.052)^2} + + +\right]$$

$$R \approx \frac{.052}{I_0}$$

$\therefore$ FOR $R > 10^{+10}\Omega$ $I_0 < 5pA$

ASSUME SQUARE WAVE DRIVE:

$$I_{off} \approx \frac{I_0 V_d^2}{2(.052)^2} \approx \frac{V_d^2}{2 \times .052R}$$

$\therefore$ FOR $I_{off} < 1pA$ AND $R = 10^{+10}\Omega$

$$V_d < \sqrt{2 \times .052 \times 10^{+10} \times 10^{-12}}$$

$$V_d < 30\text{ mV.}$$

Figure 3. Offset Current (I_{off}) vs Pump Amplitude (V_d)

The silicon varactor diodes are selected for high DC resistance at zero bias. This is important for obtaining low offset currents and high input resistance. The input resistance is typically 10^{10} at 25°C. The input resistance halves for every 9.5°C temperature rise.

The varactor diodes are matched to obtain less than 50µV/°C voltage offset temperature drift. Sufficient gain stabilization is provided in the carrier portion of the amplifier to allow trimming of the voltage offset to be performed after demodulation. Since the zero adjustment operates at DC instead of 10MHz the control may be placed at any convenient location.

The equivalent input current noise is due to Johnson noise arising from the zero biased diode resistance. At frequencies under 4Hz the current noise is approximately 0.0012pA/$\sqrt{Hz}$. Above 4Hz the current noise rises at a 6dB/octave rate due to the equivalent input noise voltage appearing across the input capacitance. The equivalent input noise voltage results from the noise of the first transistor in the AC stage. This amounts to 0.07µV/$\sqrt{Hz}$, above 1Hz. 1/f noise dominates below 1Hz. At sub-audio frequencies the amplifier has a 0.1dB noise figure at an optimum source impedance of 50M. This is a marked improvement over the 10 to 40dB sub-audio noise figure of more conventional circuits.

Since a 10MHz pump was used it has been possible to couple the varactor bridge with miniature ferrite transformers. The isolation thus obtained results in common mode rejection ratios of at least 160dB and common mode voltage capability of up to 300 volts. The transformer cores and much of the input circuitry is insulated with teflon so that the common mode resistance typically measures 6 x $10^{13}\Omega$. Thus when connected with series feedback the closed loop input impedance will generally be well above 10^{12}.

Other characteristics include: gain of greater than 5 x 10^5, gain bandwidth of 500kHz, and an output of ±10 volts at ±20mA. The amplifier is packaged as a fully encapsulated 3 cubic inch module, which can be mounted directly to a printed circuit board or inserted in a socket.

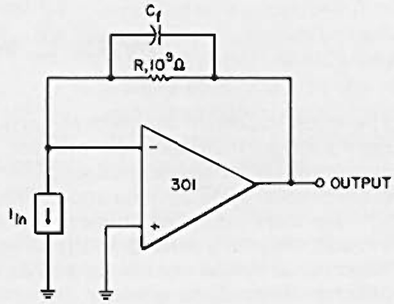


Figure 4. Current to Voltage Converter

Figure 4 shows a typical application of the amplifier. A current source transducer feeds a current to voltage converter. The output is one millivolt per picoampere of input. A feedback capacitor, C_f, is required to eliminate a phase lag due to the 500pF input capacitance of the amplifier and the 10^9 megohm feedback resistor. A 5 to 50 pF value, depending on overshoot requirements, will usually be sufficient. Shielding is usually required to eliminate 60Hz pickup and the effect of a moving charged body (such as a vibrating b+ lead). Graphite coated low noise coaxial cable has proven effective in reducing cable triboelectric effects.

The DC parametric amplifier described extends the performance of operational amplifiers down to the picoampere level. With further development of varactor diodes with higher gap potentials, such as gallium arsenide[3], offset currents of several femtoamperes should be possible. The low sub-audio noise of the 301 operational amplifier can be further improved if higher offset currents can be tolerated.

[1] Hoge, R. R. "A Sensitive Parametric Modulator For DC Measurements," IRE International Conventional Record, Vol. 8, Part 9, p. 34, 1960.
[2] J. R. Biard, "Low Frequency Reactance Amplifier," IEEE, February, 1960.
[3] J. Halpern, R. H. Rediker, "Low Reverse Leakage Gallium-Arsenide Diodes," Proceedings of the IRE, Vol. 48, No. 10, pp. 1780-1781, October, 1960.

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