

Note: Single-polarity high-voltage amplifier to drive coarse-approach slip-stick piezoelectric motors

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Scanning probe microscopies typically rely on coarse-approach slip-stick piezoelectric motors that work by exciting piezoelectric stacks with sawtooth signals of hundreds of V and some kHz. For this application, we introduce a single-polarity high-voltage amplifier based on discrete MOSFET-technology components with improved output current desirable for low-temperature actuation. The amplifier has an output signal of 600 V, 100 mA output current, noise level below $2 \mu\text{V}/\sqrt{\text{Hz}}$, 4 kHz high-voltage bandwidth, $2 \text{ V}/\mu\text{s}$ slew-rate, and rise and fall times of $80 \mu\text{s}$ (when loaded with 30 nF). The circuit was successfully applied to drive a home-made scanning tunnelling microscope.

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Tailoring the physical properties of nano-scale devices based on novel materials interesting for applications requires access to local electronic and magnetic properties at different temperatures. This problem can be investigated in research laboratories by means of scanning tunnelling,¹ near-field,² atomic,³ and magnetic force⁴ microscopies. These techniques allow characterizing the physical properties of metals, semiconductors, and superconductors with atomic resolution and in an extended range of temperatures. Most of scanning probe microscopes base their scan method in coarse and fine piezoelectric motors. When cooling the microscopes down to low temperatures, the performance and reliability of the coarse positioning system are particularly critical.

A typical solution to the problem of approaching the microscope sensor to the sample down to millimeter distances is the use of slip-stick piezoelectric motors^{5–7} profiting from the reverse piezoelectric effect. Slip-stick motors are based on piezoelectric legs that are put in contact with the mobile sensor-holder and driven by asymmetric signals, typically sawtooth⁵ or cycloid-like.⁸ During the slow part of the driving signal the sensor-holder remains stuck to the piezoelectric legs since the applied force does not exceed the static friction. During the fast part, this friction is overcome and the sensor-holder slides in a motion governed by the dynamic-friction coefficient.

A reliable actuation of such motors requires low-noise and high-voltage amplifiers, with output signal amplitudes in the 200–600 V range, as well as a broad bandwidth. In addition, providing a high output-current is crucial since slip-stick piezoelectric motors present a highly-capacitive impedance in the range of 10–40 nF.⁹ Therefore, in order to produce one step with the motor, the driving electronics has to charge and discharge this capacitance with hundreds of Volts in microsecond times. The high-voltage amplifier required for this application has to possess two basic properties that are not trivial to meet at the same time, namely high output currents and high slew-rate. Many commercial electronics to drive piezoelec-

tric motors are available in the market though most of them are relatively expensive.^{10,11} In this paper we introduce an inexpensive single-polarity high-voltage amplifier for the discussed application.

High-voltage amplifiers face important limitations when applied to drive piezoelectric motors: significant bandwidth reduction, appearance of phase-lag in the feedback path, and impractically high power-dissipation at high-frequencies.¹² These reasons make difficult to develop a high-voltage amplifier for 10–40 nF loads with bandwidths exceeding 10 kHz. Having this in mind, we focused our efforts in developing an amplifier circuit with some kHz bandwidth but improved output current, slew-rate, and rise and fall times. The amplifier presented here is based in MOSFET-technology components and has therefore a much lower cost than those based in integrated high-voltage operational amplifiers.¹³ One important characteristic of our amplifier is its single-polarity that avoids the reversal of polarization that can occur when applying significant negative voltages.

The amplifier has a gain of 100, a maximum output voltage of 600 V, input signal between 0 and 10 V, input impedance of 1 k Ω , output current of 100 mA rms, and output power of 60 W. Figure 1 shows a detailed diagram of the amplifier circuit that basically consists in three stages. In the first one, a TL081 operational amplifier with relatively high input impedance linearizes the circuit. The second stage consists on a high-voltage n-MOSFET transistor (Q3 in Fig. 1) and associated components. This configuration works as a common source, provides high-voltage gain, and drives the gate of the transistor of the following stage. This third stage has the same n-MOSFET transistor (Q1 in Fig. 1) that works both as a common drain when the input signal increases and as a push-pull circuit when the input signal decreases. This performance is due to the presence of the diode D2 connected between the gate and the source of Q1. The remaining components of the circuit provide the feedback path (R15, R17, R18, R19, R20, and R21), protection (D6, D5, D3, D4, and Q2), and compensation (R10, R11, C10, C11, and C5). The feedback path resistances limit the gain of the amplifier at low frequencies. The circuit includes an auxiliary low-voltage output in order to monitor the high-voltage output.

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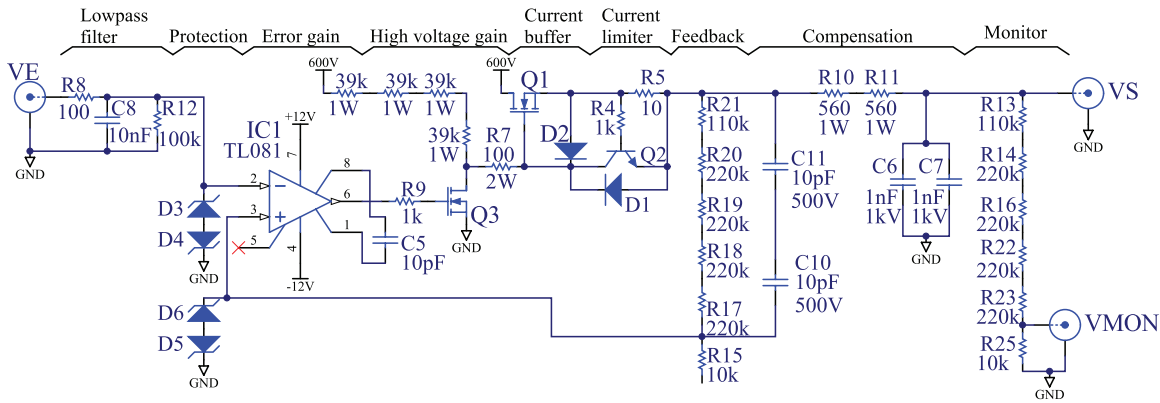


FIG. 1. Detailed circuit for up to 600 V high-voltage amplifier. The MOSFET transistors are Q1, Q3:BUZ80A; Q2, Q4, Q5:BC548C. The diodes are D1, D2:UF4007; D3, D4, D5, D6:DZ 12V. Resistances are given in Ohms and are of 0.5 W except indicated otherwise. Capacitances are given in Farads and have a voltage limit of 50 V, except C10 and C11 with 500 V and C6 and C7 with 1 kV.

The appearance of instabilities when using amplifier circuits to drive highly-capacitive loads is quite common, mainly due to the reaction of the load to the output impedance of the circuit. We have therefore compensated the gain of the Texas Instruments TL081 with C5, added C10 and C11 to the feedback path, and included the output resistances R10 and R11. By properly choosing the values of these five components we have obtained an amplifier that is stable for loads of up to 30 nF. However, this gain in stability entails a reduction on bandwidth and slew-rate.

The linearity and stability of the amplifier was tested with resistive and capacitive impedances but the performance discussed in what follows was measured using a 30 nF load mimicking that of a piezoelectric motor. Figure 2 presents data on the gain and phase-shift of the amplifier for input signals $V_{in} = 1$ and 5 V. The -3 dB criterium for bandwidth is reached at 6 kHz for the low-input signal and decreases to 3 kHz for the higher input. Nevertheless, Fig. 2 indicates that this amplifier is suitable to drive piezoelectric motors up to 600 V in the 4 kHz range.

Figure 3 shows the amplifier response to a square pulse of 500 μ s with input signals amplitude ranging from 1 to 6 V.

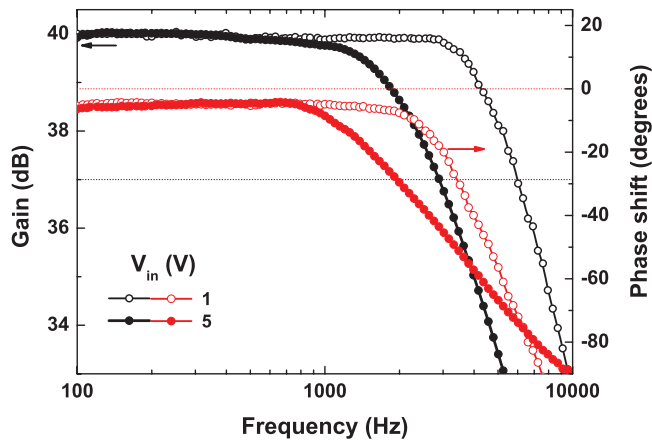


FIG. 2. Gain (black points) and phase (red points) of the high-voltage amplifier loaded with 30 nF for input signals $V_{in} = 1$ (open symbols) and 5 V (full symbols). The upper red-dotted-line shows the zero-degree phase whereas the lower black one indicates the -3 dB criteria for the gain.

On increasing V_{in} within this range the rise time enhances between (80 ± 3) to (213 ± 3) μ s; on the contrary, the fall time does not evolve too much varying between (80 ± 3) and (77 ± 3) μ s. The settling time increases between (190 ± 2) and (500 ± 2) μ s for V_{in} between 1 and 5 V. For the larger input signal of 6 V the settling time is larger than 500 μ s. Overshooting decreases from 50% to 8% on increasing V_{in} between 1 and 5 V. The slew-rate does not change significantly on increasing the input signal. This slew-rate for a piezoelectric load of 30 nF is given by the 100 mA output current limit of the amplifier circuit plus the limiting resistances R10 and R11.

Figure 4 (a) shows the typical output drift over a 400 ms time-window. In the absence of input signal the mean peak-to-peak drift is below 10 μ V. The amplitude of the drift signal increases roughly two orders of magnitude for $V_{in} = 1$ V. The output noise level in a large frequency range up to 100 kHz is below 2μ V/ $\sqrt{\text{Hz}}$, see Fig. 4 (b). The spectrum presents two appreciable peaks at 75 and 250 Hz, well below the typical operation frequencies. Above 700 Hz the noise decreases linearly with frequency in a logarithmic scale and no significant features appear in the 1–5 kHz range in which the amplifier is meant to be applied.

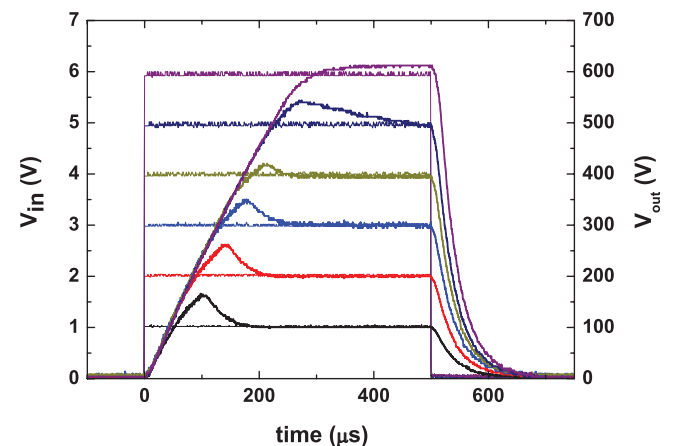


FIG. 3. Response of the high-voltage amplifier, V_{out} , to square pulses V_{in} of 500 μ s and amplitudes ranging 1–6 V. The amplifier is loaded with a 30 nF capacitance.

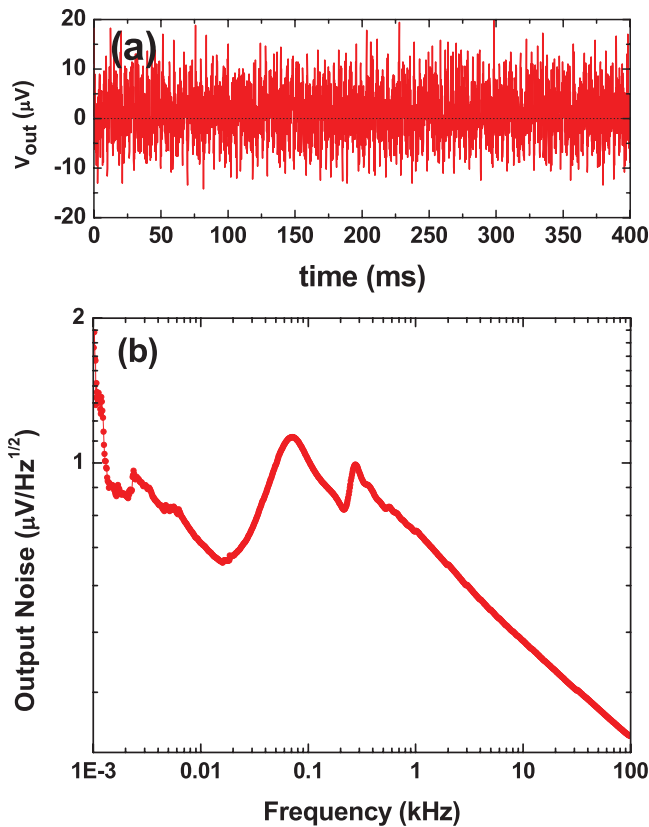


FIG. 4. Noise in the amplifier output signal for zero input. (a) Drift during a 400 ms time-window. (b) Output noise spectrum in a large frequency window. All data were acquired by means of a lock-in amplifier.

The finite slew-rate of the amplifier has an important effect on the performance of the system to follow the sawtooth signals typically used to drive piezoelectric motors. We found that the amplifier presented here can be reliably used to drive piezoelectric motors with sawtooth signals of up to 4 kHz and high-voltages between 400 and 600 V. The amplifier reasonably follows the input signal with falling times between 40 and 70 μs and a maximum signal decrease of up to 4% with respect to the theoretical value (100 times the input). Finally, we stress that this amplifier was successfully applied to drive a coarse-approach piezoelectric motor of a home-built scanning tunnelling microscope head of the Pan-design type.⁹ The amplifier was used to reliably drive this motor with sawtooth signals up to 600 V and 5 kHz.

Some works on high-voltage amplifiers applied to drive piezoelectric motors are available in the literature. A bi-polar dc-coupled low-cost amplifier¹⁴ with a similar topol-

ogy than the one presented here is useful up to 100 kHz, provides a maximum current of 340 mA, and has a slew-rate of 300 V/ μs . However, these performances were measured with a resistive load and this amplifier provides ± 200 V at best. In the same range of output voltages, a dual electronics comprising a standard high-voltage and a fast low-voltage amplifiers¹² probed to improve the bandwidth up to 2 MHz for small signals. Another bipolar amplifier with similar configuration to our design was previously proposed¹⁵ providing ± 800 V but no much data on its figures of merit is provided besides a claim on a 100 kHz bandwidth for 2 nF loads. One main drawback of this amplifier is its important overshoot. Three other works^{16–18} propose amplifier circuits based on discrete MOSFET technology providing maximum voltages between ± 500 V, however output currents are below 20 mA.

The high-voltage amplifier introduced here has several comparative advantages with respect to the previously discussed circuits in order to drive coarse-approach piezoelectric motors, particularly in terms of its single-polarity, maximum output of 600 V, 100 mA output current, and state-of-the-art noise level. In addition, the amplifier is based in MOSFET technology components available in any local market. Therefore, this design is an easy-accessible solution to the problem of providing sufficiently high transient currents and output voltages to drive piezoelectric coarse-approach motors for scanning probe microscopes.

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