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Amplifying High-Frequency Acoustic Signals

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Abstract

Amplifying High Frequency Acoustic Signals. CARMEN R. KUNZ (San Jose State University, San Jose **CA,** 95192) J. FRISCH (Stanford Linear Accelerator Center **(SLAC),** Menlo **Park,** California, 94025)

In search of the hypothetical Higgs boson, a prototype electron accelerator structure has been developed for use in the Next Linear Collider (NLC), SLAC's proposed version of the machine necessary to create the predicted particle. The Next Linear Test Accelerator (NLCTA), designed to provide 0.5GeV - 1TeV center-of-mass collision energy, generates electromagnetic breakdowns inside its copper structure while the beam is running. The sparks vaporize the surface of the copper, and will eventually ruin the accelerator. They also create high-frequency (hf) acoustic signals (100 kHz - 1 MHz). Acoustic sensors have been placed on the structure, however current knowledge regarding sound propagation in copper limits spark location to within one centimeter. **A** system was needed that simulates the **sparks** so further study of acoustic propagation can be pursued; the goal is locate them to within one millimeter. Various tests were done in order to identify an appropriate hf signal source, and to identify appropriate acoustic sensors to use. **A** high-voltage spark generator and the same sensors used on the actual structure proved most useful for the system. Two high-pass filters were also fabricated in order to measure signals that might be created above 2MHz. The 11-gain filter was used on the acoustic simulation system that was developed, **and** the 100-gain filter will be used on the NLCTA.

Introduction

A common method for probing nature to answer the question, "What are the smallest pieces of matter that make up the universe?" is the use of high-energy particle accelerators. When particles collide with other high-energy particles traveling in the opposite direction, their energies combine to form new fundamental particles, whose existence can be recorded, studied and classified. These high-energy experiments are done all over the world, seeking to unlock nature's secrets of fundamental matter.

When accelerating electrons, "linear" machines are used, since the electrons would radiate most of their energy if moving in a circular fashion. The electrons are concentrated in the form of a beam in order to increase collision probability. High collision energy directly correlates to seeing smaller details about the particles that arise as a result of the collision. Since a goal for particle physicists is to identify all of the possible constituents of matter, an accelerator that can produce extremely high energies is both desirable and necessary.

Stanford Linear Accelerator Center (SLAC) is home to the world's highest energy linear accelerator, the Linac, which first began operation in 1966. Using microwaves for acceleration, the SLAC Linac accelerates an electron beam to 100 GeV center of mass (CM) and has allowed physicists to receive three Noble Prizes for: identifying the charm quark, revealing the internal structure of quarks, and the discovery of the tau lepton. Recently, attention has been drawn to the Higgs boson, an "as yet hypothetical particle invoked to explain why the carriers of the electroweak force (the W and Z bosons) have mass" (Gribbin, 1998). Unfortunately, the energy required to create the Higgs particle is beyond the limits of any facility in the world; a new accelerator must be built that achieves higher energies than ever before.

SLAC has been developing their version of the new machine, the Next Linear Collider (NLC) which is built in the image of the SLAC Linac, and uses copper as its structural material. The NLC will be 10 times longer than the 2-mile SLAC Linac. It has a higher energy gradient and is designed to achieve peak CM energy in the range of 0.5-1TeV, five times the CM energy currently attained at SLAC. The prototype for the accelerator structure, the Next Linear Collider Test Accelerator (NLCTA), operates at a frequency of 11.424 Hz, which is four times that of the SLAC Linac. As a result, the cavities inside the NLCTA structure are four times smaller than those in Stanford's pioneering machine.

When the NLCTA is operating, unwelcome electromagnetic breakdowns are occurring inside the structure. The sparks vaporize the surface of the copper, and over time will ruin the accelerator. The breakdowns generate acoustic signals at ultrasonic frequencies in the range of 100 kHz – 1 MHz. Acoustic sensors have been placed on the test accelerator in order to detect the signals. However, as of today, few studies have been done on sound propagation through copper. Current knowledge, coupled with the data generated by the sensors, has allowed the sparks to be located to within one centimeter. A new system is needed in order to more accurately locate the sparks; the current goal is to locate them to within one millimeter.

This project was to design and construct a system that simulates breakdowns in the NLCTA in order to allow further study of high-frequency acoustic propagation in accelerator-grade copper; spark location and elimination is crucial to the development of the NLC.

Materials and Methods

The system contains both hardware and software components: high -frequency acoustic sensors, a repeatable high-frequency acoustic signal source, an oscilloscope, function generators, and computer programs for data analysis were all necessary. Electronic amplifiers able to filter out frequencies below 100 kHz were also critical for signal isolation and analysis. Work was done in collaboration with Greenwood, E. on the sensor calibration and signal generation.

The Pacific Acoustics Company Microdot 100 (PAC) acoustic sensors were tested on the Network Analyzer to determine if they were all functioning at the same frequency range, and to weed out potentially malfunctioning sensors. The faces of two sensors were clamped together in a vice so that one transmitted while the other received. The sensors were then connected to the Network Analyzer, which drives the input with a swept frequency and measures the output amplitude. Five other types of sensors were tested in this manner. The two best sensors were determined to be the PAC sensors and the International Transducer Co. 9020 1 N57 (ITC) sensors, which both provided sensitivity up to 3-4 MHz. The PAC sensors were used for the research described in this paper.

The impact on a 4x4x2 inch piece of accelerator-grade copper was tested by: tossing three different size ball-bearings by hand, rolling the same ball-bearings down an inclined ramp 2 feet high at a 45 degree angle, and from other various heights, tapping three different Dremel grinding bits rotating at maximum speed setting, and a UV-laser pulse. A BB gun, and a high-voltage spark generator were also tested. The acoustic waveforms from each source were then analyzed using a MATLAB program (Greenwood, 2002), designed to provide Fourier analysis of the generated signals. Although the laser provided the best results, the spark-generator was the method chosen for the final system.

Amplifier Design and Fabrication

An amplifier's performance is expressed in terms of its "gain," the ratio of the output voltage to the input voltage (Dorf and Svoboda, 2001). These days it is convenient to use integrated-circuit (IC) operational amplifiers (op amps) to provide gain in a circuit. The schematic symbol for an op amp has two input signals, and one output signal. A closed loop op amp with the output lead connected to the negative input lead (Figure 1) creates feedback. Feedback is when part of the output is used to control the performance of the amp. (Oxford, 2000) When it has no feedback loop, the gain of the op amp itself is referred to as its open loop gain, and is determined by the design of the chip.

An "ideal" op amp has infinite open-loop gain, infinite input impedance, and zero output impedance (Horowitz and Hill, 1989). Although no op amps are ideal, they are designed to adhere to these criteria as strictly as physically possible. In a properly designed and operating amplifier circuit, the two input voltages are equal to each other. If they were not, the output signal would go to infinity.

Current feedback (CF) and voltage feedback(VF) are the two different ways op amps attempt to behave in the ideal manner. The VF amp measures the difference between the two input voltages, called error voltage. VF output is the product of the error voltage and the open loop gain. When using negative feedback, the VF op amp attempts to make the error voltage zero. The CF amp measures the current between the two input voltages, called error current. CF output is the product of the error current and the open loop transimpedance gain. Similar to the VF amp in a negative feedback loop, the CF amp attempts at making the error current zero (Karki, 1998). The advantage of the CF is that it provides less distortion due to a higher slew rate (rate of amplitude increase in Volts/s) than the VF, and results in a faster chip (Intersil, 1999). The other major difference, in comparison of the ideal models, is that ideally, the CF bandwidth (frequency range of amplification) is independent of its closed loop gain, while gain and bandwidth for the VF are interdependent (Karki, 1998).

As shown in Figure 2, the physical op amps used have 8 pins: 2 for input, 1 for output, 2 connected to power supplies, and 3 that are not connected. The specific resistor arrangement around the op amp determines the gain of the circuit. A wide range of common mathematical functions are available by simple resistor configurations. The non-inverting op amp (Figure 3) was the design chosen for the amplifier, deemed "non-inverting" because the polarity of the output is the same as the polarity of the input. Whenever this op amp circuit is configured, the gain of the circuit is $(1 + R_{feedback}/R_1)$. (Calculation 1). Two amplifiers were designed in this manner: one with a gain of 11, and one with a gain of 100.

Three different op amps were located and tested in the circiut, Analog Devices: 9631, 8055, and 8001. The 9631 is a VF amp; it claims ultra low distortion, high speed, and wide bandwidth capabilities. The 8055 is also a VF amp. It claims a bandwidth and slew rate comparable to a CF amp. The 8001 is the only CF amp used, claiming: a fast speed, bandwidth, and low distortion. Resistors and capacitors were also purchased. The circuits were fabricated by use of soldering the components onto a circuit board. An 8-pin IC socket was soldered where the op amp sits so that the chips could easily be interchanged. Three additional capacitors were placed in parallel with the amp's power supply delivery to the chip when needed. A 50-ohm resistor in parallel with the input signal terminates the reflection the signal generates.

Amplifying ability was tested on an oscilloscope, sampling at 250 Msa/s. (Figure 4). A signal of known amplitude was put into the amplifier and compared to the amplitude of the output signal. The 11-gain amplifier worked as designed from the start. The 100-gain amplifier did not. Troubleshooting methods were taken to fix the amp by means of: replacing specific resistors and capacitors, resoldering joints, fabricating different input and output leads, and providing extra ground leads for the circuit. After these measures were taken, it performed with a gain of 100 (Figure 5).

The speed of each op amp was tested by measuring the rise time. The 8001 was fastest, and the 9631 proved to be the slowest.

Filter implementation

In order to better suit our needs of mostly amplifying signals greater than 100 kHz, a capacitor was added in series with the R_1 resistor (Figure 4). Current through a capacitor (I_c) = $C*dV_c/dt$. High-frequency signals mean a large dV_c/dt, which equates to a large current through the capacitor. As the frequency approaches infinity, so does the current in the capacitor; it acts just like a short circuit, a wire. The short-circuit behavior causes the gain of the circuit to be the same as when the capacitor is not there: $(1 + R_f/R_1)$. However, at low frequencies, the opposite is true; dV_c/dt is small and the current through the capacitor is small. As the frequency approaches zero, the current also approaches zero; the capacitor behaves like an open circuit, not allowing any current to flow in the R_1 leg of the circuit and can be thought of as having infinite resistance. The R_f/R_1 term goes to zero and the gain of the circuit becomes 1.

The amplifiers were designed for gain above 2 MHz. Capacitor values were determined by the relationship omega = (2*pi*f) = 1/RC; the frequency equating to the inverse of tau (the time constant for an RC circuit). Solving the equation for C , with R as the resistor value in series with the capacitor, and the frequency set to be 2 MHz, gave a value of 800 Pico Farads for the 11-gain amp; a 1000 Pico Farad capacitor was soldered into the actual circuit. Using the same technique to solve for C of the 100-gain amplifier gave a value of 7950 Pico Farads, however 10,000 Pico Farads was the value actually used. Figure 6 shows the complete circuit diagram of the 11-gain amp. Figure 7 shows the 100-gain amplifier.

The bandwidth of each amplifier was determined by placing it on the Network Analyzer. The two frequencies at which the signal was 3dB down from the maximum amplification were recorded. 3 dB down corresponds to one half the maximum power of the signal, and 70% of the maximum voltage level; it is the common determinant of bandwidth. Larger bandwidths were achieved by the faster op amps (Table 1).

Results

Although the PAC sensors were the ones used to gather the data, ITC sensors proved slightly more sensitive up to 3-4 MHz (Greenwood, 2002).

The laser was most effective at generating high-frequency acoustic signals in the copper block (Greenwood, 2002). Both it and the high-voltage spark generator proved to be more effective than any kind of mechanical impact from a ball bearing or BBgun (Greenwood, 2002). The electrical noise from the Dremel's motor was triggering the oscilloscope without having impacted the block yet.

The 11-gain amp performed as designed the first time tested, while the 100-gain amp proved to be more finicky and needed to have some components replaced, and more ground paths inserted before performing as designed. Out of the three op amps purchased and tested, the AD8001 proved to be the fastest chip and provided the largest bandwidth. The AD9631 proved to be the slowest chip with the smallest bandwidth. The effect of placing a capacitor in the negative input leg of the non-inverting op amp circuit created a high-pass filter. Network analysis revealed that gain value and chip speed affect the bandwidth of the filter; (Table 1) the combination of smallest gain and fastest chip speed provide the largest bandwidth.

Discussion and conclusions

Although the PAC sensors were determined to be slightly less sensitive than the ITC sensors, they were used to collect all data. Since they were the ones being used before the sensor calibration began, they provided a reference by which to compare data. The ITCs were the sensors chosen for the final system, not only because they are slightly more sensitive, but because they are the actual sensors used on the NLCTA.

Electromagnetic (EM) sources are more effective than mechanical sources at generating high-frequency acoustic signals in accelerator-grade copper (Greenwood, 2002). Although the UV-laser is the superior EM source of the two (Greenwood, 2002), the sparker is more practical; the laser is expensive to run and can only be operated by specially trained personnel. Also, sparking is more akin to the actual problem in the NLCTA. In conjunction with the 11-gain amplifier, the sparker will be as effective as the laser (Greenwood, 2002).

The three different op amps and two different amplifier circuits offer a total of 6 different bandwidth options (Table 1, Table 2). The higher speed chips and lower-gain amplifier might prove most useful in these first stages of the overall system design, since the high bandwidth this combination provides might identify. alternate means of high-frequency signal generation. If amplification over smaller ranges is desired, say the NLCTA discovers a higher probability of 1-2 MHz signals than 2-10 MHz signals, the higher gain amplifier can then be used in conjunction with the slower chips, providing a more narrow bandwidth.

Overall, the research presented in this paper will provide a strong foundation for future research to be conducted regarding the propagation of high-frequency acoustic signals in accelerator-grade copper.

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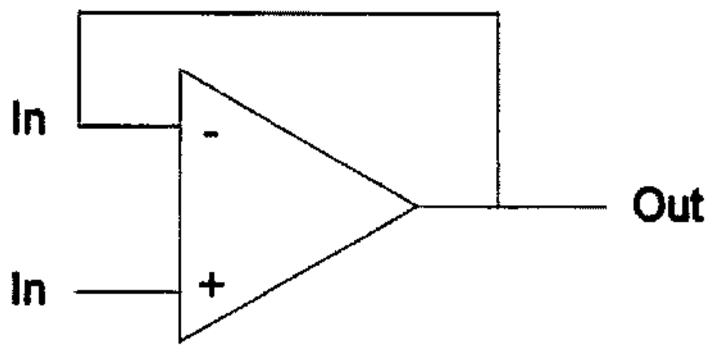

Figure 1. Schematic Symbol for an Op Amp with Negative Feedback

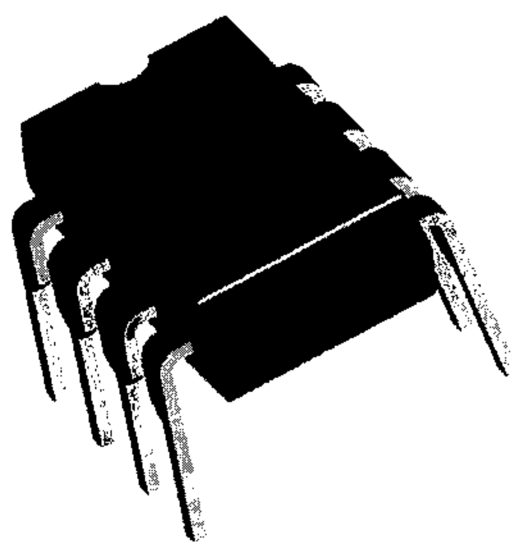

Figure 2. Model of an Actual 8-pin Operational Amplifier.

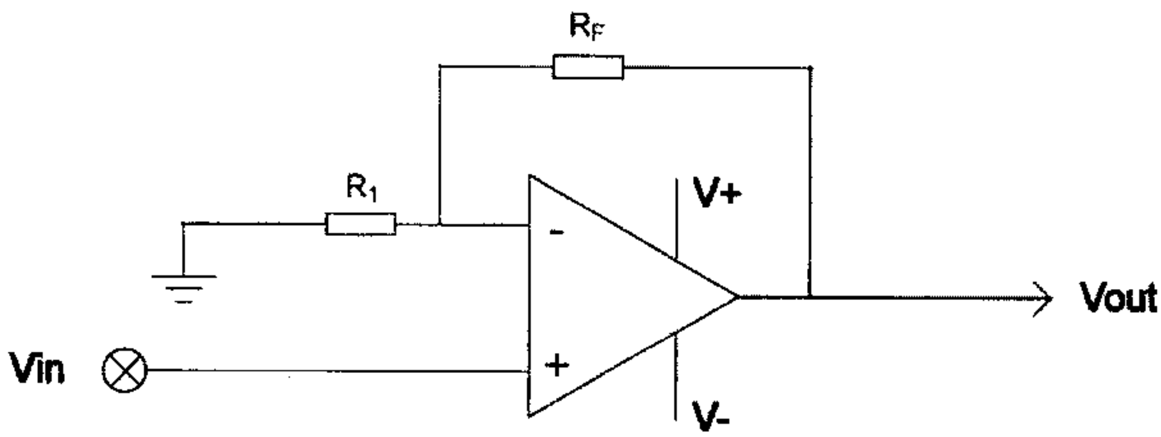

Figure 3. Non-Inverting Op Amp

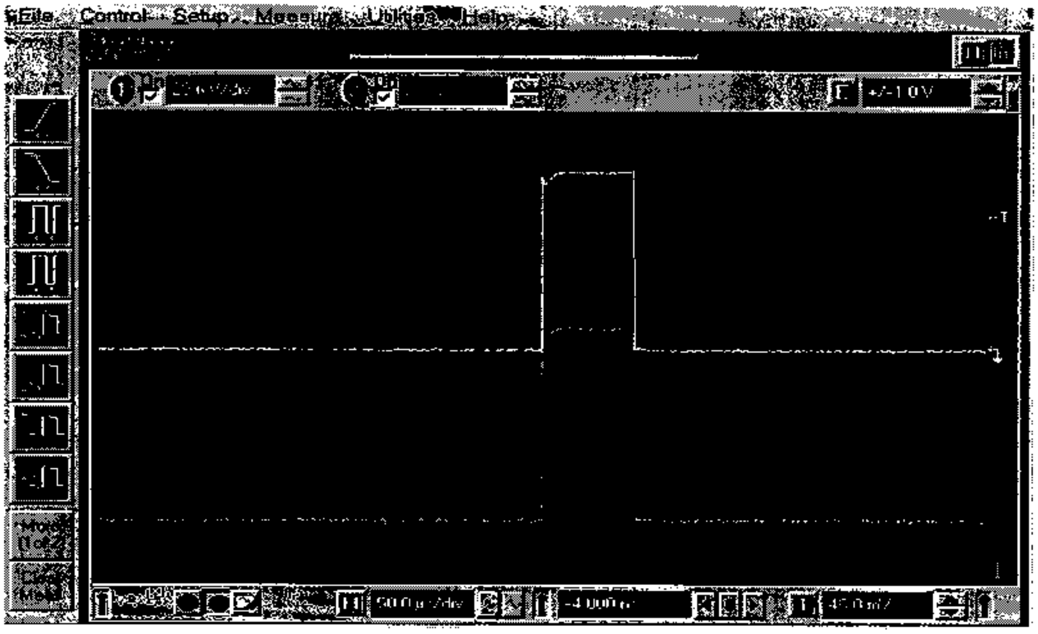

Figure 4. 11-Gain Amplifier.
Top is input signal and bottom, attenuated at 20dB, is output

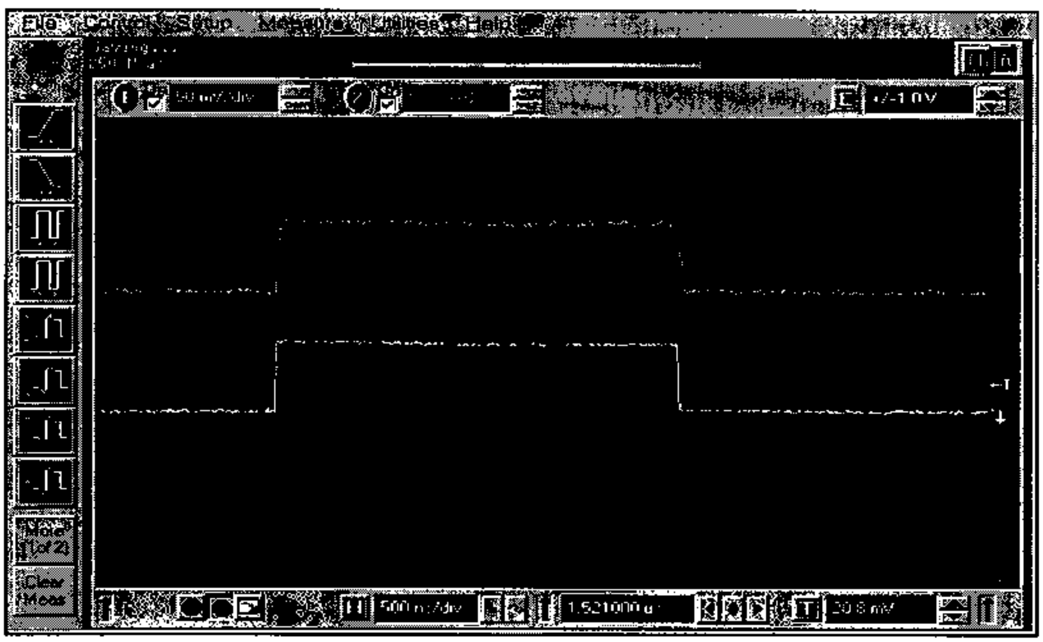

Figure 5. 100-Gain Amplifier.
Top is output signal and bottom, attenuated at 40 dB, is output.

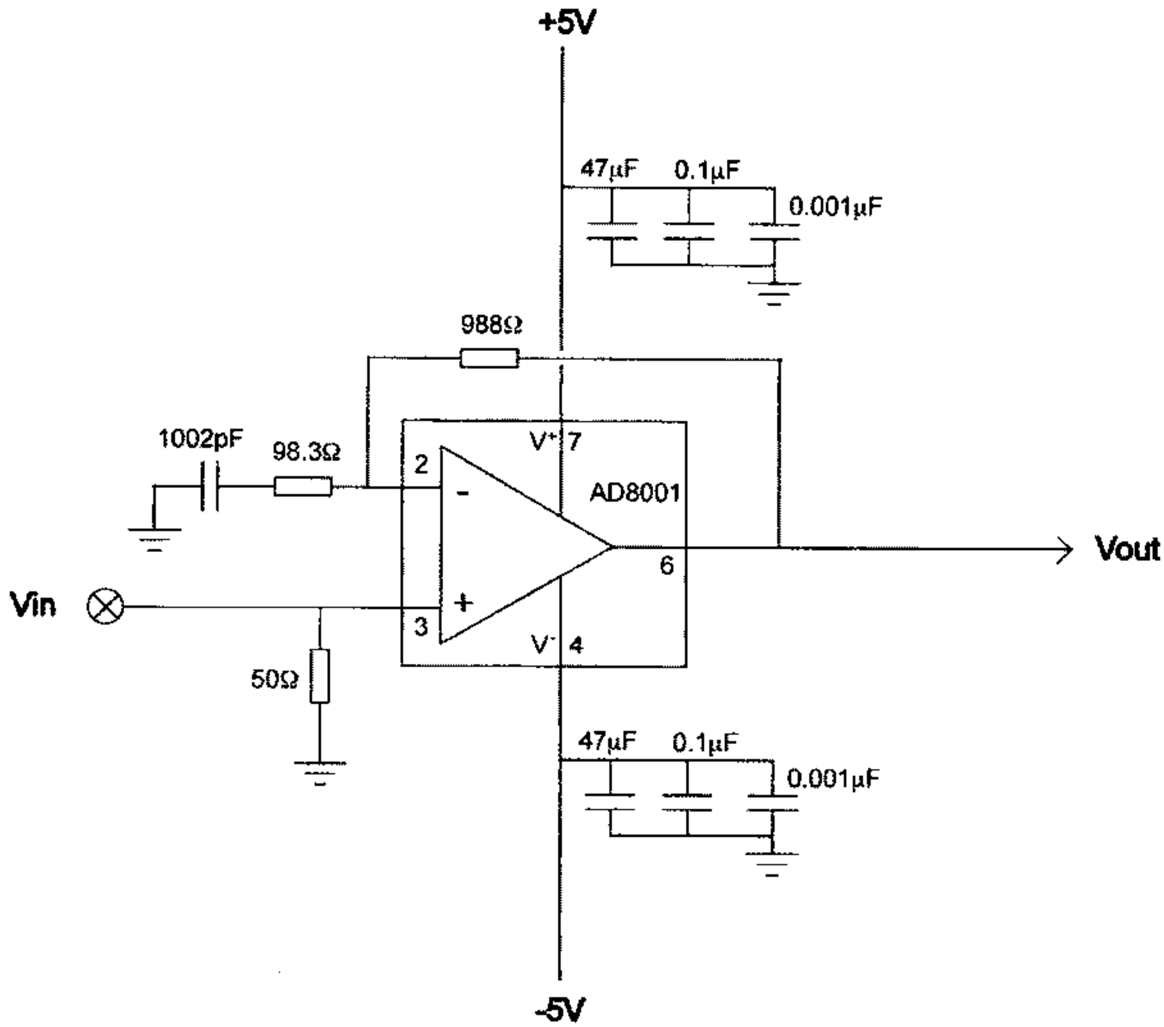

Figure 6. Circuit Diagram for 11-Gain High Pass Filter

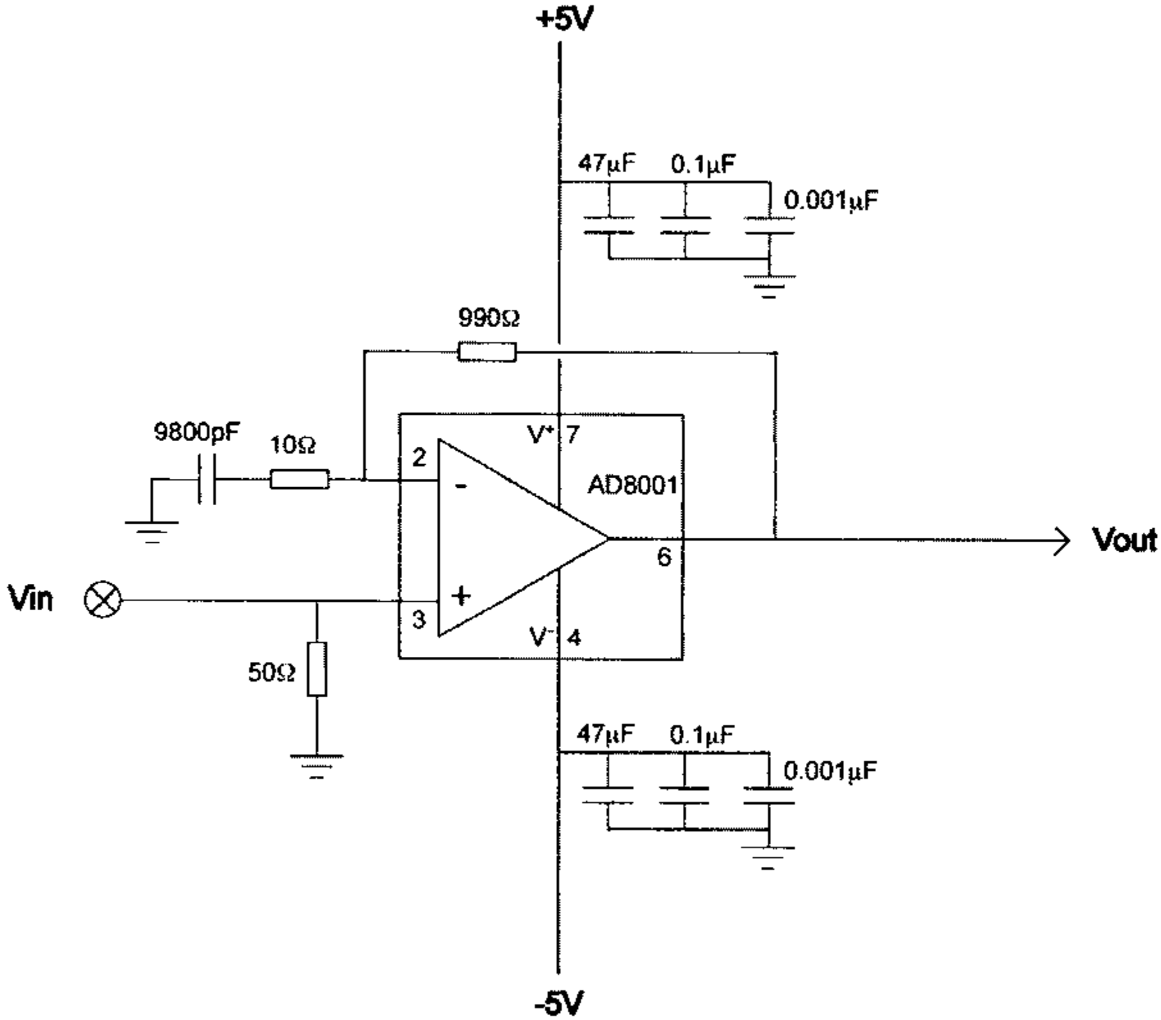

Figure 7. Circuit Diagram for 100-Gain High Pass Filter

Ideal op amp conditions

- $V_{pos\ input} = V_{neg\ input}$
- $I_{input\ 1} = I_{input\ 2} = 0$
- $Z_{output} = 0$

$$(V_{out} - V_{neg\ input}) / R_{feedback} = I_{feedback};$$

$$I_{feedback} = V_{neg\ input} / R_1; \text{ (condition 2)}$$

$$\text{Therefore } (V_{out} - V_{neg\ input}) / R_{feedback} = V_{neg\ input} / R_1;$$

$$\text{Substitute } V_{pos\ input} = V_{neg\ input}; \text{ (condition1)}$$

$$\text{Solving for } V_{out} / V_{pos\ input}\text{, yields:}$$

$$V_{out} / V_{pos\ input} = (1 + R_{feedback} / R_1).$$

Calculation 1. Solving Gain in a Non-Inverting Op Amp.

OP AMP	11-GAIN BANDWIDTH (MHz)	100-GAIN BANDWIDTH (MHz)
8001	2 - 47	1.5 - 14.5
8055	2 - 15	1 - 2.5
8631	2 - 12	1 - 2

Table 1. Op Amp Bandwidth