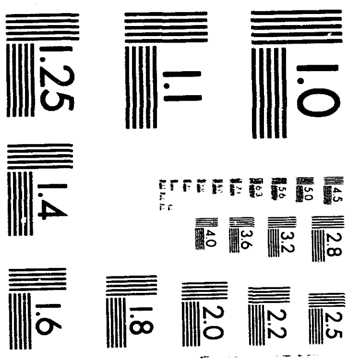

850,475 SUPERCONDUCTING ACTIVE IMPEDANCE CONVERTER

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SUPERCONDUCTING ACTIVE IMPEDANCE CONVERTER

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SUPERCONDUCTING ACTIVE IMPEDANCE CONVERTER

The United States Government has rights in this invention pursuant to Contract No. DE-AC04-76DP00789 between the Department of Energy and American Telephone & Telegraph Company.

BACKGROUND OF THE INVENTION

This invention relates generally to the field of superconducting electronics, and more particularly, to a transimpedance amplifier for a weak current source, which may originate from superconducting electronics, to interconnect with conventional semiconductor or other high impedance electronics.

Superconducting electronics yield important advantages such as the high speed, minimal noise, and low power not available with conventional semiconductor electronics. Semiconductor electronics, on the other hand, have the unparalleled advantages of memory capabilities and a well-developed technology base. A hybrid technology to exploit the advantages of both superconductors and semiconductors is developing. One of the most challenging aspects facing developers of this hybrid technology is the development of an interface circuit to convert signals from superconducting circuits to semiconductor technologies, such as CMOS. *See* Ghoshal et al., Spice Models and Applications of Superconducting FETS and Higher-Voltage Josephson Gates, 1991 IEDM Conference.

Such transimpedance amplifiers using conventional semiconductor technology requires exceedingly complicated circuits having a number of transistors and many passive components which perform within a limited temperature range and which are characterized by high noise. Typical pre-amplifiers used may consist of several MOSFET stages as discussed in Paik et al., "A Staring Monolithic FPA with High Speed Readout and Frame Averaging," Northrup Technical Report, p. 11 (December 1987). MOS devices, however, generally cannot operate at low superconducting temperatures, and performance is not uniform across the temperature ranges of interest. This limitation is in fact true for all semiconductor-based systems because of carrier freeze-out and other thermal effects. To date, there is no superconducting device which will transform a weak current from a superconducting source to a higher voltage for use in semiconductor circuits, and which allow for signal conversion from a low impedance circuit to a high impedance system.

It is thus an object of the invention to provide impedance conversion from a low impedance circuit, which may or may not include superconducting electronics, to a higher impedance circuit, typically conventional semiconductor electronics. This object is achieved through the use of the superconducting flux flow transistor (SFFT), and given that the impedance characteristics of the differential structure of the transimpedance amplifier of the invention is not significantly different from the impedance characteristics of the SFFT itself. An additional advantage of this particular feature of the invention results in low power dissipation.

It is another object of the invention to provide for amplification of a weak current to sufficient voltage suitable for semiconductor applications. This differential amplifier configuration of SFFTs increases the output voltage available. An advantage of this increased output voltage is increased compatibility with multiple forms of conventional electronics.

It is another object of the invention to provide for the reduction of noise which is achieved by the differential configuration of SFFTs which allows the circuit to be used in more electromagnetically sensitive environments.

It is another object of the invention to provide for wide bandwidth from GHz down to DC with adequate gain. Bandwidth of the amplifier itself is preserved by the differential configuration of the transimpedance amplifier.

These and other objects are achieved by the invention specified and claimed herein as a transimpedance amplifier which has at least a first and a second SFFT connected in parallel, each having a control line and means to apply a signal to the control lines of each SFFT, but the signal as applied to one SFFT being of opposite polarity than the signal as applied to the other SFFT, and a means to provide a current bias to each SFFT sufficient to drive each SFFT transistors into a flux flow state, wherein the signal applied to the control lines of each SFFT is converted to higher signal and higher impedance levels which is taken across the means to provide a current bias to said transistors. In addition, impedance elements having a resistive component can be connected between each SFFT and the means to provide a current bias to each SFFT wherein the impedance elements increase said output signal and impedance.

A double differential transimpedance amplifier then comprises a first and a second SFFT connected in parallel, each having a current bias applied, and a control line input of low impedance and weak current, wherein the input as applied to the first SFFT is of opposite polarity than that applied to the second SFFT, and an output of the first and second SFFTs taken across the bias wherein the output is an amplified signal of the low impedance, weak current input; and further comprising a third and a fourth SFFT connected in parallel, the third and fourth SFFT also having a current bias applied, and an ancillary impedance connected between the bias and each of the third and fourth SFFT, and having a second input which is the output of the first and second SFFT, wherein the input as applied to the fourth SFFT is of opposite polarity than that applied to the third SFFT, wherein the output of the third and fourth SFFT is an amplified signal of the second input, and the bias is sufficient to drive each SFFT into a flux flow state.

It is envisioned that the input to the transimpedance amplifier can be from any weak current source, and can be high temperature superconductor electronics, superconductor electronics, or conventional semiconductors. The invention is particularly useful when the input is provided by far-IR focal plane detectors or Josephson junctions because of the temperature and frequency range enabled by the invention.

The invention, moreover, comprises a differential amplifier stage wherein the input to the first amplifier stage is derived from the low impedance signal source, and the output of each stage is applied as input to the control lines of the next amplifier stage, with the final output differential amplifier stage having the resistive elements between the bias and the SFFTs for appropriate impedance matching to the processing electronics, usually of conventional semiconductor electronics.

The invention is described with reference to the following figures.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 illustrates a layout of the superconducting flux flow transistor (SFFT) used in the transimpedance amplifier of the invention.

Figure 2 illustrates a schematic of the invention using one pair of SFFTs arranged as a differential amplifier.

Figure 3 is another embodiment of the invention which is a doubly differential superconducting transimpedance amplifier, using, for example, an IR detector as a current source for the transimpedance amplifier.

Figures 4a and 4b are physical layouts of the single differential pair and the double differential pair, respectively, of SFFTs configured into the transimpedance amplifier of the invention.

Figures 5a and 5b is a plot of the composite transresistance and the input noise current of the transimpedance amplifier using a YBaCuO device, and the schematic of the circuit used to obtain the measurement.

Figure 6 illustrates a typical response of the superconducting transimpedance amplifier as a IR line driver.

Figure 7 is a schematic of a circuit using a Josephson junction as the weak current source that drives the transimpedance amplifier of the invention.

Figure 8 is a graph of the transient response of a single differential pair SFFT transimpedance amplifier to a Josephson junction switching event.

DESCRIPTION OF THE INVENTION

The transimpedance amplifier of the invention utilizes the unique characteristics of the superconducting flux flow transistor (SFFT) more fully described in U. S. Patent No. 5,019,721, entitled "Active Superconducting Devices Formed of Thin Films," to Martens et al., herein incorporated by reference. Figure 1 illustrates a sample layout of the SFFT 10. The SFFT 10 is a device which can be made of a single film of most superconductors, and may utilize TlCaBaCuO films to maximize the operating temperature range. The SFFT 10 consists of a parallel array 20 of superconducting links 12, connecting the two output terminals, 16 and 18, biased such that flux quanta or vortices move across the links 12 at reasonably high speed. An adjacent superconducting control line 14 provides a local magnetic field to alter the flux state and hence the terminal voltage. Such a device can be characterized by a low input impedance wherein the control line 14 represents a near superconducting short which can be driven easily by a small current source; a transresistance element of approximately 15-25 Ω (not shown in Figure 1), a finite output resistance of approximately 3-6 Ω (also not shown in Figure 1), low cross talk and primarily inductive parasitics. The SFFT 10, moreover, has high power gain and impedance levels suitable for active impedance conversion because it has low input impedance and an output impedance that matches readily to conventional circuitry. Among the material parameters that affect device performance are pinning and critical fields. Weaker pinning leads to faster and more sensitive devices, and lower critical fields lead to more sensitive SFFTs. A current in the low impedance control line 14 modulates bundles of magnetic flux in the link system 20 to ultimately determine the output voltage.

Devices made from different superconducting materials will have different performance. YBaCuO films made by some processes are highly pinned, but even with processing modifications to make the links thinner which promote lower H_{c1} and easier flux flow, the flux still moves relatively slow. This results in smaller bandwidths and typically lower sensitivities than with devices made from TlCaBaCuO or the more weakly pinned YBaCuO. In TlCaBaCuO there is the added complication of a transition in the flux lattice in the 25-35 K range. Below that temperature the lattice nucleates resulting in somewhat slower flux speeds and reduced sensitivity. This behavior also occurs in BiSrCaCuO and may occur in some YBaCuO films.

The configuration used for the transimpedance amplifier 30 is shown in Figure 2 and is a differential pair of SFFTs 32 and 34. A bias current 36 is applied to the body of each SFFT 32 and 34, sufficient to drive each SFFT 32 and 34 into a flux flow state. A source 40 applies a weak current, I_o, to the control line (as seen in Figure 1 as 14) of SFFT 32, and a current of opposite polarity, $-I_0$, to the control line of SFFT 34. Thus, the current $A \cdot I_0 + \Delta$ flows through the body of SFFT 32, whereas the current $- A \cdot I_0 + \Delta$ flows through the body of the other SFFT 34. This weak current source 40 may be an array of Josephson junctions or IR detectors; alternatively, the weak current source 40 may be other superconducting sources, including HTS sources, or the current source may be of conventional semiconductors; so long as there is a weak current source into a low impedance network. The output of the differential amplifier 30 using one pair of SFFTs 32 and 34 is taken between the upper terminals 42 and 44 of the SFFTs 32 and 34, respectively. Resistive elements 46 and 48 may be connected between the bias 36 and the body of each SFFT 32 and 34, respectively, and the use of resistance is preferred because they facilitate extraction of voltage rather than a current output from the transimpedance amplifier 30. The use and values of these resistive elements 46 and 48 are dependent upon the actual application of the transimpedance amplifier 30. The resultant output from this differential pair 30 of SFFT 32 and 34 is essentially $2AI_0$; thus the current has been amplified, and the contribution from noise and bias, Δ, in each control line has been cancelled.

As shown in the schematic of Figure 3, two differential pairs of SFFTs, 52 and 54, are arranged as one differential amplifier, and 56 and 58 as a second differential amplifier. These two pairs of differential amplifiers are configured into a doubly differential amplifier 50 wherein the output 62 and 64 of the first differential pair 52 and 54 serves as the input to the control line of the second differential pair 56 and 58. A bias current 66 sufficient to drive each SFFT into a flux flow state is applied to each of the four SFFTs 52, 54, 56, and 58. Just as above in the case shown in Figure 2 of a single pair of SFFTs 32 and 34 arranged in a differential amplifier 30, the resultant output 62 from SFFT 52 shown in Figure 3 is $A \cdot I_0 + \Delta$, whereas the resultant output 64 from SFFT 54 is $- A \cdot I_0 + \Delta$; these outputs are applied to the control line of each individual SFFT 56 and 58, respectively of the second differential pair 50. The second differential amplifier pair 50 then amplifies the signals so that the signal through the body of SFFT 56 is $A^2 \cdot I_0 + \Delta'$, and the signal through the body of SFFT 58 is $- A^2 \cdot I_0 + \Delta'$. The resultant output voltage is taken across the upper terminals 76 and 78 of SFFTs 56 and 58, respectively and is proportional to $2A^2 \cdot I_0$. Impedance elements with resistive components 72 and 74 again may be used to enhance the output signal across terminals 72 and 74 for compatibility. This arrangement results in high gain, high speed, a wide bandwidth from DC to GHz, and good noise immunity.

The transimpedance differential amplifier may be configured into multiple stages of the amplifier described with respect to Figure 2, wherein the output of one differential stage is applied to the control line of the subsequent differential stage. Generally, the impedance elements with the resistive components, shown as 46 and 48 in Figure 2 and shown as 72 and 74 in Figure 3 need only be used at the output terminals of the final transimpedance differential amplification stage. Moreover, in general, as the stages of transimpedance differential amplifiers increase, the bandwidth of the device will decrease. Also, the more stages of differential pairs of SFFTs used in the transimpedance differential amplifier will enhance the gain characteristics, but will decrease the speed of the device 50.

Input 60 to the doubly differential amplifier 50 of Figure 3 may be, for example, an IR detector pixel which drives the control lines of devices 52 and 54 generating an amplified differential current 62 and 64 in the outer loop 68. This outer loop 68 forms the control lines for SFFTs 56 and 58. The output signal voltage is taken across the two resistive elements 72 and 74, of about 10 Ω each. The output equivalent circuit consists of a voltage source with an impedance of about 5 Ω and the input has very low impedance. The amplifier response time is limited to approximately 105 picoseconds by the L/R time constant in the outer loop 68. The actual circuit may encompass an area less than 30 μm by 30 μm which is smaller than a pixel of a typical currently available far-IR focal plane array. Thus, the doubly differential transimpedance amplifier of the invention may be mounted on the back of each pixel with no increase in area. With typical SFFTs and bias selected for maximum transresistance, power dissipation will generally not exceed 25 microwatts. Dynamic range with the invention has typically exceeded an equipment-limited 30 dB.

Figures 4a and 4b show the physical layout of the transimpedance differential amplifier; Figure 4a is a single differential pair 80, schematically shown in Figure 2, of the transimpedance amplifier. The weak current input 86 is connected to two upper pads 82 and 84. The bias is supplied in the middle lower pad 88, and pad 90 is connected to ground. The output voltage is taken across the two lower pads 92 and 94. All the components, including the SFFTs and the wiring, etc. is shown in the inner region 96 of the Figure 4a; resistive elements 98 and 100 may also be implemented.

Figure 4b illustrates the physical layout of the double differential transimpedance amplifier 120, shown as 50 in Figure 3. The double differential transimpedance amplifier has two differential pairs of SFFTs in the inner region 122. The pad configuration is the same as in Figure 4a with the exception of an added bias 124 and ground pad 126, which perform the same function as the other bias pad 88 and ground pad 90. A weak current source shown as a far-IR focal plane detector is located between pads 128 and 130. The output is taken across pads 92 and 94.

Far-infrared focal plane arrays are becoming increasingly important for terrestrial and space-based imaging applications. For noise reasons, it is desirable to have transresistance pre-amplifiers at the focal plane and therefore they need to operate over wide temperature ranges. The invention described herein, then, provides high temperature superconducting amplifiers characterized by high gain, relatively low noise, and response times less than 200 picoseconds over at least a 10-80 K temperature range.

For this application with far-infrared focal plane arrays of the transimpedance amplifier, the critical amplifier performance needs are transresistance gain, temperature stability, and minimal noise. Composite transresistance, r_m, and effective input noise current, I_n, of the amplifier alone were measured as a function of temperature and the results are shown in Figure 5a for a YBaCuO device using relatively highly pinned films. For both types of measurements, the input drive was a current source of impedance greater than 100 KΩ driving the amplifier input whose impedance is less than 0.5 Ω. The transresistance, a DC value that was essentially constant through at least 500 MHz, stays fairly constant near 400 Ω over the range 10-80 K which was measured with a 50 Ω oscilloscope impedance. Typical transresistances for TlCaBaCuO and weakly-pinned YBaCuO amplifiers between 40 K and 77 K are 500 Ω and 490 Ω respectively. The equivalent input noise current, I_n, was measured using a follower low-noise amplifier and power spectral computations; the values at 10 Hz are plotted in Figure 5a, along with an outline of the measurement arrangement shown in Figure 5b. System noise was measured without the amplifier in place and was found to be about 1 $nV/(Hz)^{1/2}$ at the output. This was subtracted from the measured total output noise with the amplifier in place before referring it to the input. Over this temperature range I_n does not change much but there is considerable uncertainty of $\pm$ 0.5 $pA/(Hz)^{1/2}$ in these noise values because of equipment limitations. Typical broadband, down to $\approx$100 Hz, noise current of far-IR detectors are on the order of 1 $pA/(Hz)^{1/2}$ depending on pixel area so there may be some system noise concerns. Typical noise values for amplifiers made from TlCaBaCuO or weakly pinned YBaCuO are about 0.5 $pA/(Hz)^{1/2}$.

TlCaBaCuO devices have more variation in both r_m and I_n below about 40 K; about 10% changes in composite transresistance, $r_{m\ composite}$, and about 20-25% changes in equivalent input noise current. This probably happens because of the flux lattice change discussed earlier. TlCaBaCuO amplifier performance is, however, stable up to about 95 K.

Speed is not as much of a concern as the above parameters because the detectors are relatively slow. The rise times were measured using time domain transmission techniques on a high speed sampling oscilloscope, a 50 Ω system. Over the range 10-80 K, amplifier rise time has been less than a fixture-limited 180 picoseconds for all circuits tested. The amplifier rise time did not show up clearly in these measurements because of apparatus limitations, but in more careful single device measurements, devices made with highly pinned YBaCuO have been shown to be somewhat slower than those made of the other two material types.

A practical test was undertaken to couple the amplifier to an actual IR detector and measure the response to light changes. The IR detector used was grown using molecular beam epitaxy and consists of an InSb-based PIN photodiode embedded in an In $As_{0.17}Sb_{0.83}$/InSb of 15 nm/15 nm thick layers strained layer superlattice. The peak photoresponse for this detector occurred at a wavelength of about 5μm with a detectivity of 10^{10} cm $Hz^{1/2}$/W. The photodiode spanned both mid and long wavelength infrared spectral regions with usable photoresponse extending out to 12 μm. A SiC IR source with a mechanical chopper in front was used as the excitation. A swing of over 2 mV was delivered to the 50 Ω load, or any load greater than 10 Ω, for that matter. The time response of the detector alone and the detector plus the amplifier are shown in Figure 6. The amplifier was easily responsive to the detector and qualitatively did not add noise. This measurement was done at 77 K and while the detector's response changed at lower temperatures, the amplifier remained very stable. Similar response curves with increase of up to 20-30% gain and output voltage levels were obtained with amplifiers made from TlCaBaCuO or weakly pinned YBaCuO.

Thus, this relatively simple, small area circuit provides adequate, broad temperature range transresistance gain for a far-IR detector allowing it to easily drive processing electronics. Bandwidth will be limited only by the detector and the noise added by the amplifier will be minimal compared to that of the detector. For YBaCuO devices, stable performance is available over at least 10-80 K, while for TlCaBaCuO devices the range is 10-95 K with up to 10% variation in $r_{m,\ composite}$.

Another application of the transimpedance amplifier of the invention is with Josephson junctions. Josephson junctions can typically drive a current on the order of milliamps into a low impedance. In contrast to the far-IR detectors, however, the junctions will most likely be used at high speed, hence the single differential pair shown in Figure 2 may be more appropriate. In a typical circuit shown in Figure 7, the junction will switch causing a current to be driven into the control lines of the amplifier. The output of the transimpedance amplifier of the invention is at a suitable signal and impedance level to drive conventional high speed electronics such as MESFETs or HEMTs. A transient response of the amplifier output to a junction switching event is shown in Figure 8. In practice, moreover, entire junction-based circuits, rather than a single junction, may drive the amplifier. These circuits include Josephson logic, parametric amplifier, SIS mixers and waveform shapers. In all of these applications, the signals from the Josephson circuits are in the form of small currents and must be amplified and transferred to a higher impedance to communicate with conventional circuitry.

While the invention has been described with respect to several embodiments, and to several applications, it is intended that the invention not be limited to the specifics disclosed therein; rather, the invention is presented as broadly claimed.

Abstract

A transimpedance amplifier for use with high temperature superconducting, other superconducting, and conventional semiconductor allows for appropriate signal amplification and impedance matching to processing electronics. The amplifier incorporates the superconducting flux flow transistor into a differential amplifier configuration which allows for operation over a wide temperature range, and is characterized by high gain, relatively low noise, and response times less than 200 picoseconds over at least a 10-80 K temperature range. The invention is particularly useful when a signal derived from either far-IR focal plane detectors or from Josephson junctions is to be processed by higher signal/higher impedance electronics, such as conventional semiconductor technology.

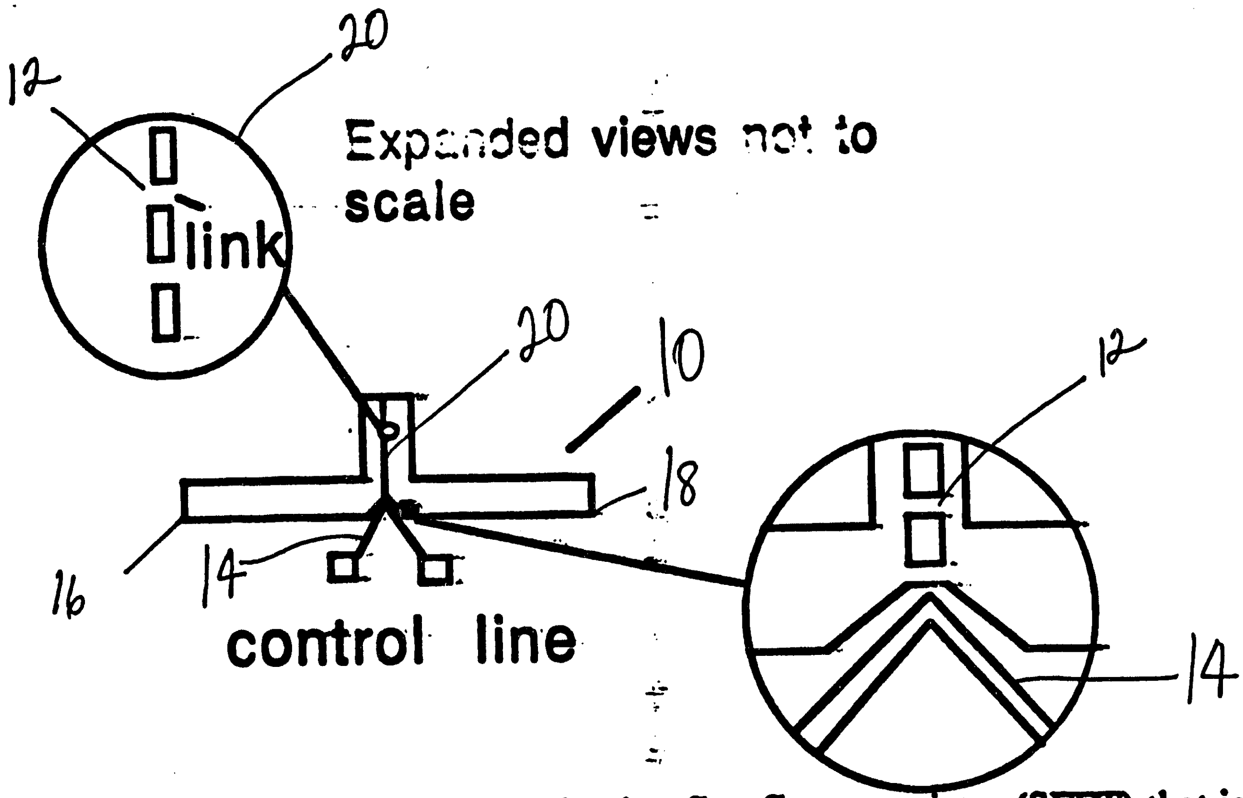


Figure 1. A sample layout of the superconducting flux flow transistor (SFFT) that is discussed in more detail in the references [1] and [2].

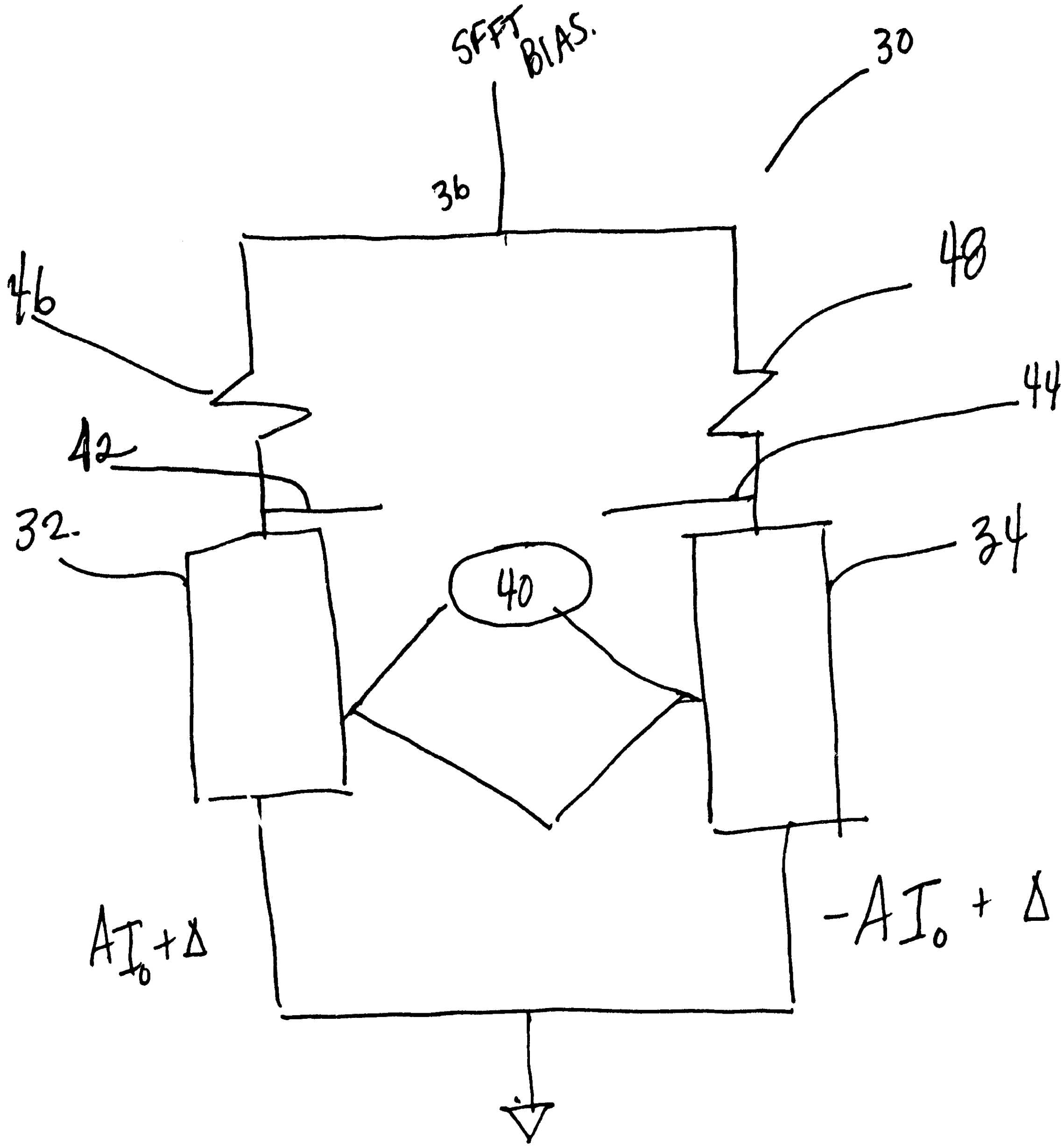


Figure 2

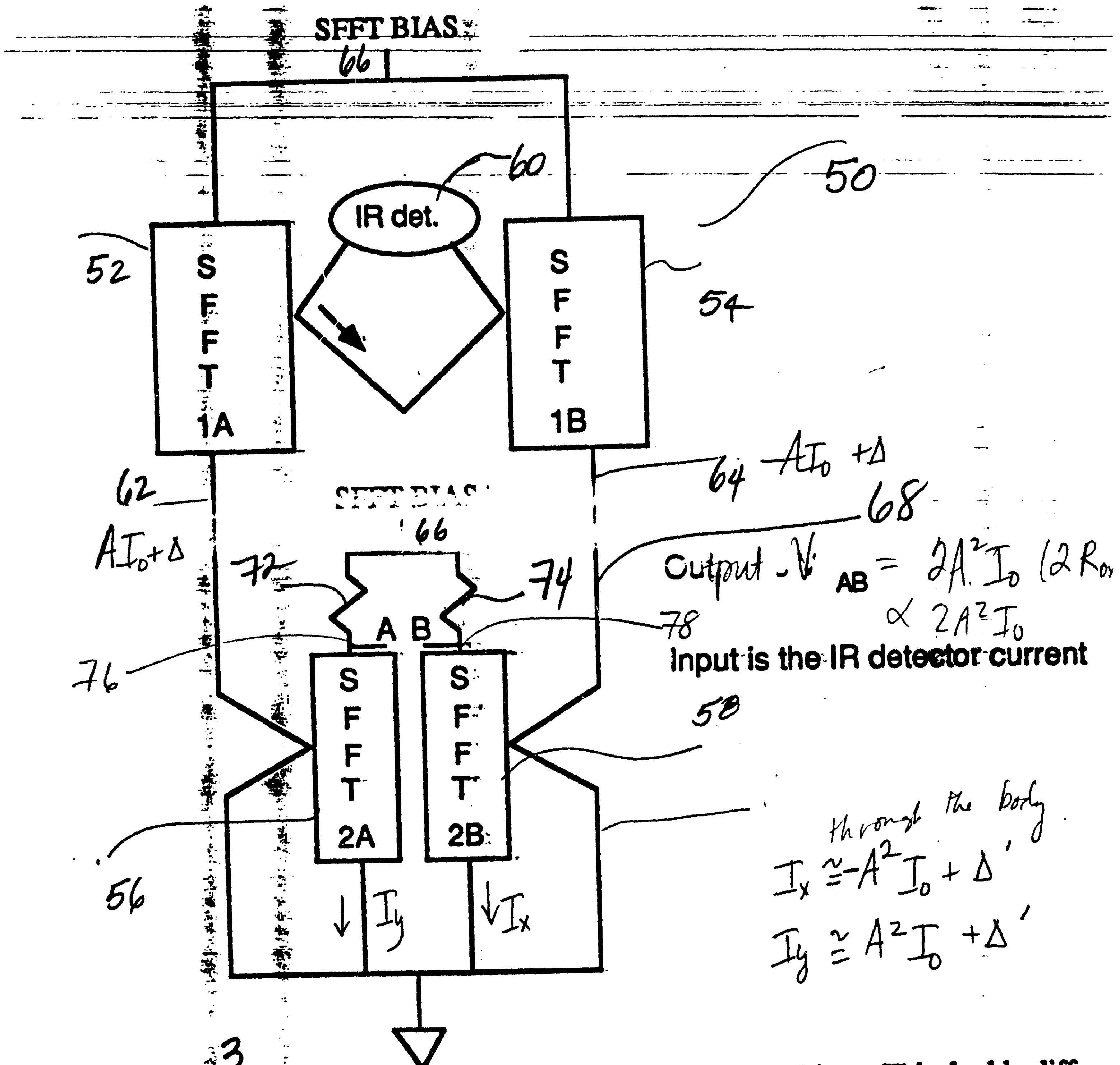


Figure 3 The schematic of a superconducting IR line driver. This doubly differe configuration of SFFTs allows good noise performance, high gain and large bandv Although not clear from this simplified schematic, the input signal to SFFT 1A is I while that to SFFT 1B is $-I_{IR\ detector}$. The input currents to SFFT 2A and 2B are respectively the currents in outer branch A and outer branch B. The SFFT is biase current source.

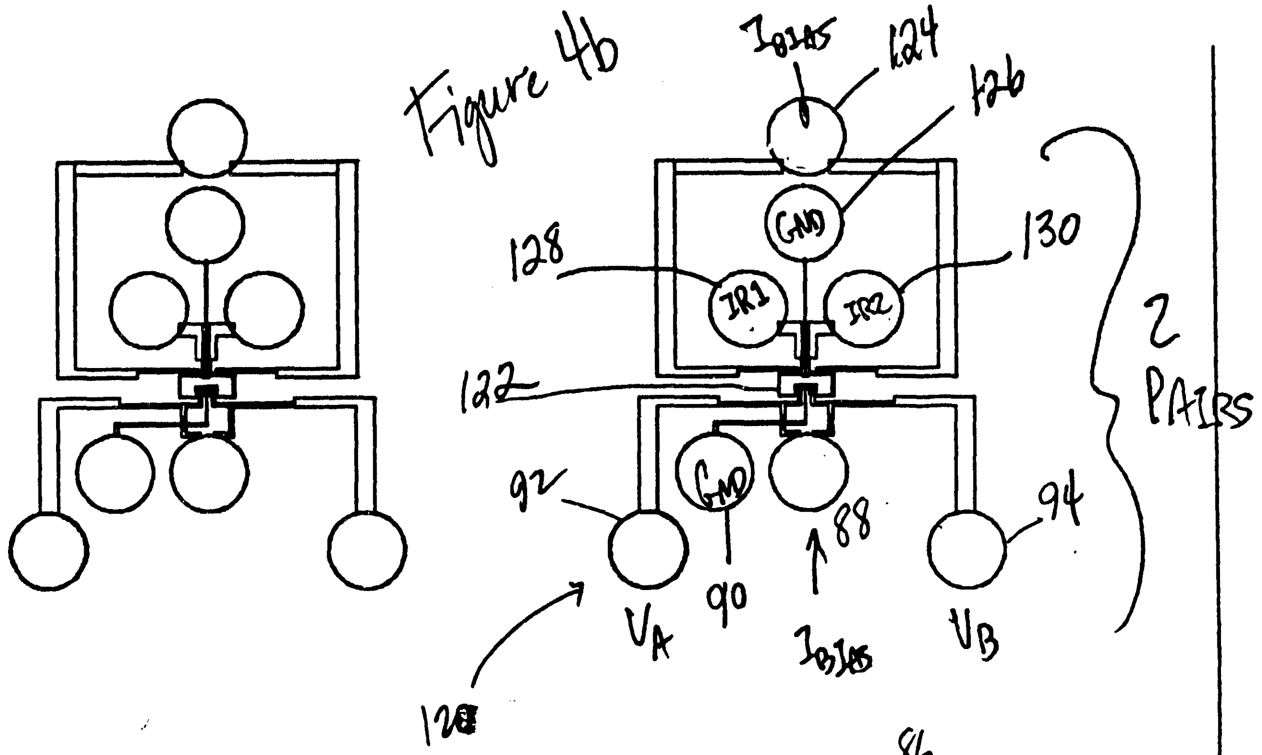


Figure 4b

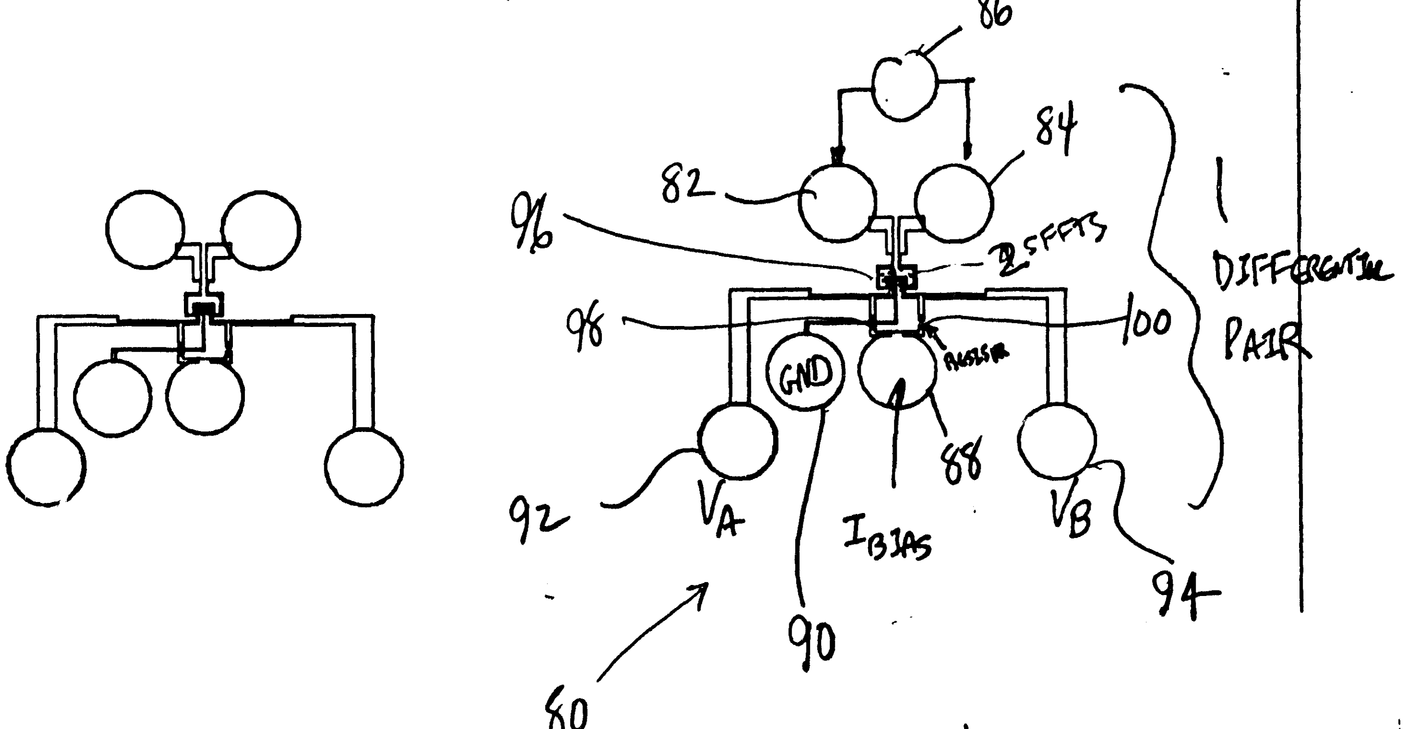


Figure 4a

Figure 4

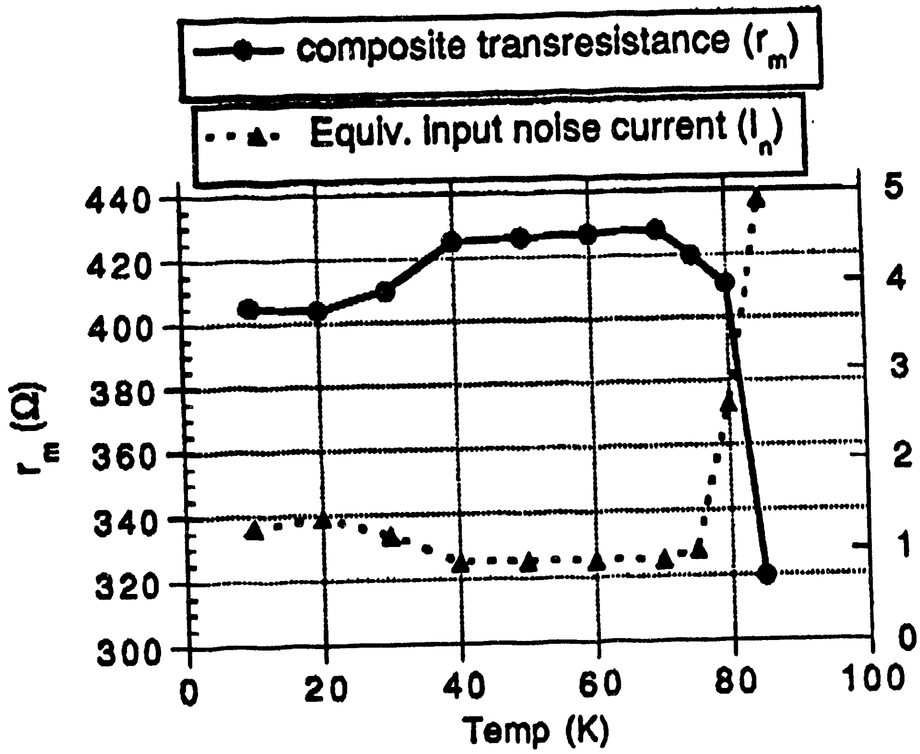
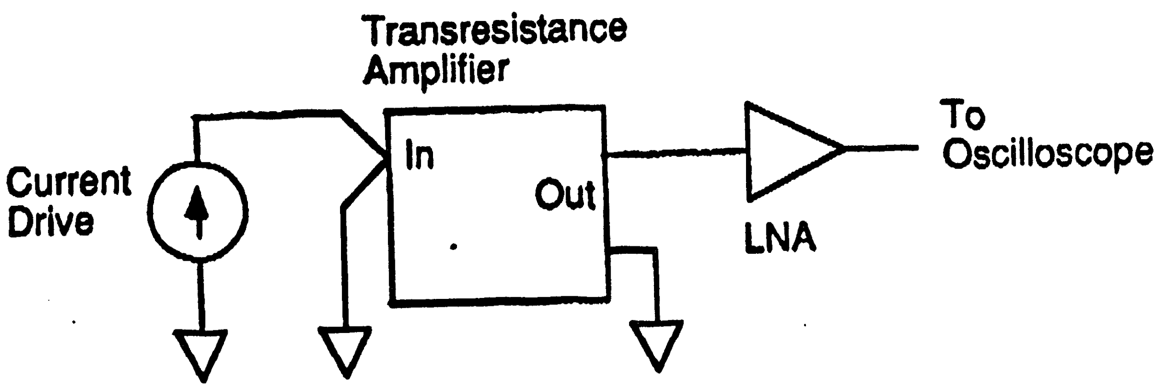


Figure 5a

(a)



(b)

Figure ~~Figure 2~~ 5b

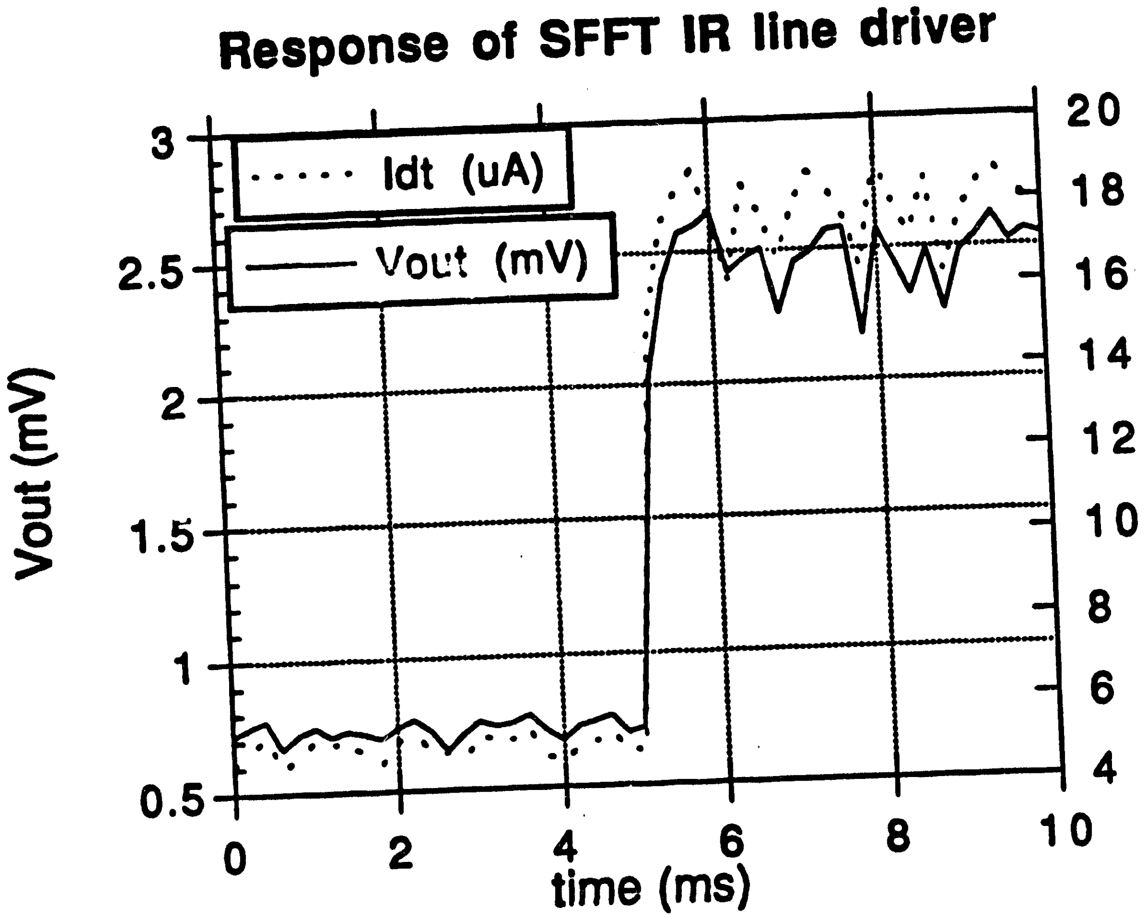


Figure 6 A typical response of the superconducting IR line driver. The IR detect current is Idt and the output voltage is $V_{out} = V_{AB}$ from Fig. 3 (from the SFFT to a 5 load).

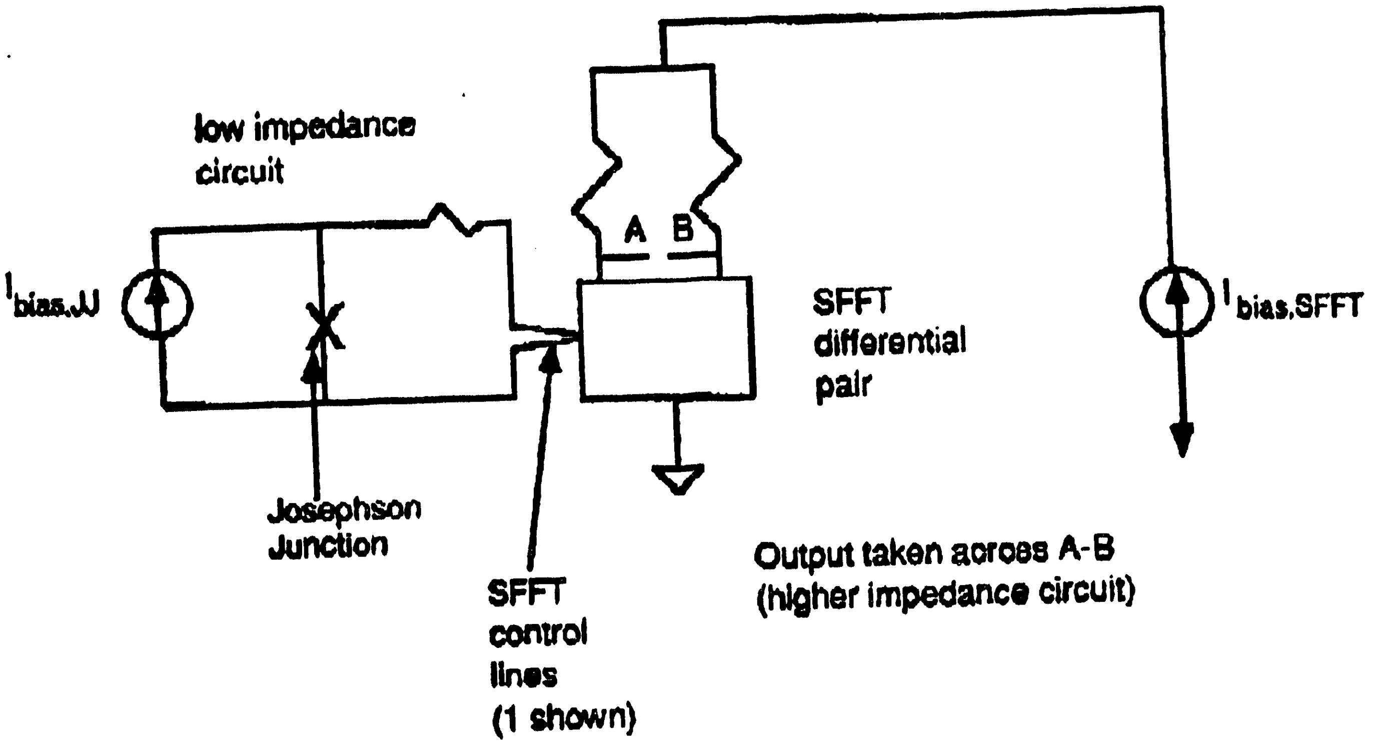


Figure 7. A circuit where a Josephson junction is the weak current source that drives the transimpedance amplifier.

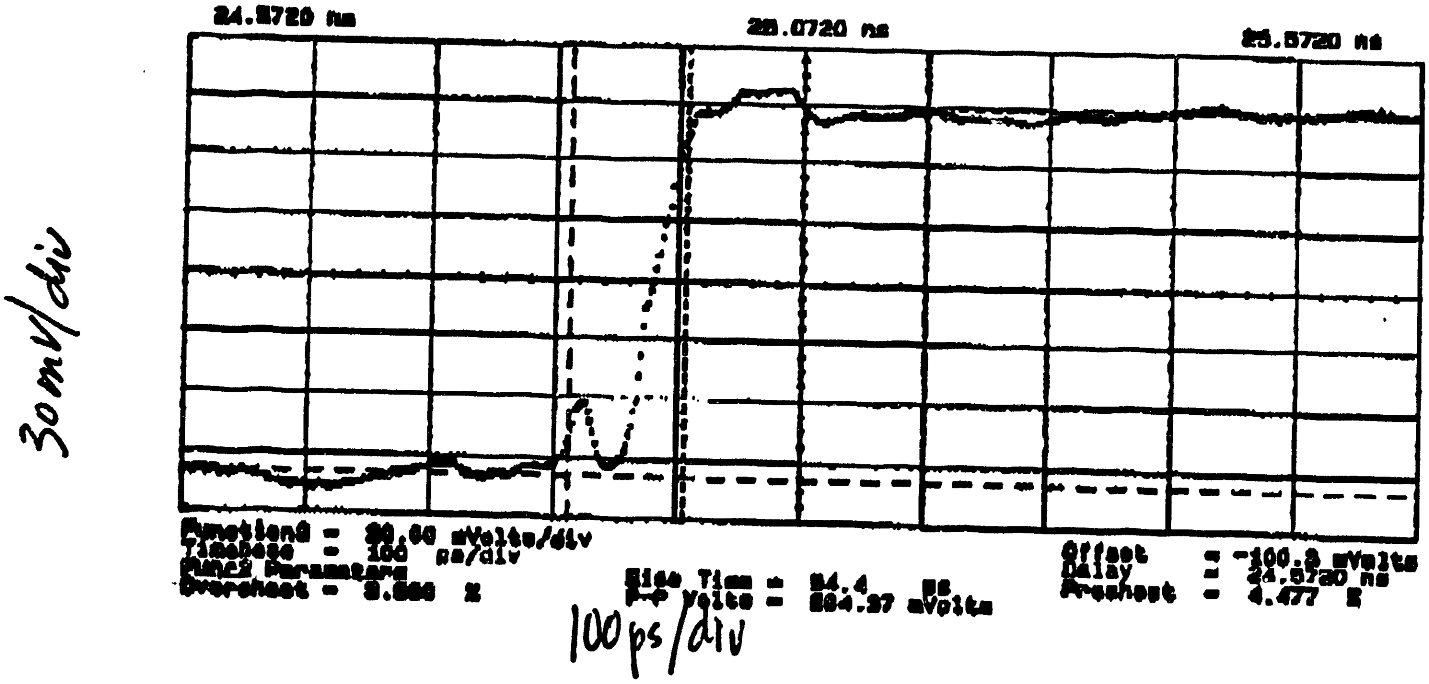


Figure 8. Transient response of a single differential pair SFFT transimpedance amplifier to a Josephson junction switching event. The horizontal scale is 100 ps/div and the vertical scale is 30 mV/div. The junction switched at the small blip shown in the trace. The response time is fixture limited.