NBSIR 74-377

PICOSECOND PULSE GENERATORS USING MICROMINIATURE MERCURY SWITCHES

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Final Report

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U.S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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PICOSECOND PULSE GENERATORS USING MICROMINIATURE MERCURY SWITCHES

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Pulse generators have been built using microminiature mercury switches. A commercial RF coaxial switch was also evaluated as a pulse generator. A superconducting delay line (t_r = 18 ps, t_d = 70 ns) and a sampling oscilloscope (t_r = 22 ps) were used to measure the generated pulse 10%-90% transition time. The best result obtained was a transition time of 39 ps. Pulse amplitudes were independently adjustable up to 50 volts. The microminiature mercury switches in general were found to give very unreliable operation.

Key words: Mercury switch; picosecond; pulse generator; pulse measurement; superconductivity.

I. INTRODUCTION

This is the final report on CCG project 72-66. The objective of this project was to construct a 7 mm reference waveform generator with a 50 picosecond (ps) or less 10%-90% transition time, one volt maximum amplitude with a known uncertainty and source impedance. The generator was to use a microminiature coaxial mercury switch as the pulse source.

Mercury wetted switches have been used for many years to generate subnanosecond transition time (risetime) pulses [1,2]. The fundamental mechanism of the mercury wetted contact is not fully understood as to just what the ultimate switching time limitation is. The switching times of present switches have been limited by parasitic reactances associated with the switch package rather than the mercury-wetted contact. Some mercury-wetted switches are also capable of generating voltage pulses of several kilovolts. The pulse amplitude is adjustable and independent of the pulse waveform. The major disadvantage of the mercury switch is its mechanical nature which inherently limits its switching repetition rate to a few hundred hertz at most. Also due to its mechanical inertia, friction, etc., it is not possible to trigger the switch closure with better than a few hundred microseconds precision.

In 1968, Elliott [3] was able to achieve a 70 ps, 10%-90% transition time with a classical mercury-wetted reed relay. In 1970 Meyer [4] reported a self-sampling pulse measurement system with system transition time of 18 ps. Meyer used a recently introduced microminiature mercury switch [5,6] as his pulse generator. He reported a 12 ps transition time for the mercury switch. Subsequently Meyer has reported more details of his work [7,8].

NBS Reference Waveform Generators use the band-limiting properties of a lossy uniform transmission line [9,10]. The line is driven by an abrupt step-like pulse. The pulse output of the line then closely approximates the step response of the line which may be mathematically predicted using the various physical and electrical parameters of the line. Deviations in the driving waveform from an ideal step cause corresponding deviations in the output from its ideal step response. The contribution of the driving source transition time is given approximately by the sum of the squares expression.

$$t^2_{r\ \text{total}} = \sum t^2_{ri}$$

$t_{r\ \text{total}}$ is the transition time of the total system, while t_{ri} is the transition time of an individual component.

The present NBS Reference Waveform Generators are lossy transmission lines with ideal step response transition times in the range of 200 ps to 500 ps. They are driven by a commercial tunnel diode pulse generator with a transition time of the order of 20 ps. Based upon the above equation this nonperfect driving function introduces an error of 0.5% in the output transition time for a line with a 200 ps transition time. If one had a line with a 50 ps transition time an error of 7% is introduced. Additional errors of even greater importance are caused by the further imperfections of the waveshape of the pulse from the commercial tunnel diode generator. When the tunnel diode switches from its low to high voltage state, it does produce a fast rising step-like transition (≃ 20 ps). However this transition is superimposed upon a slow (1 ns) triggering pulse that distorts the baseline and topline. In addition there are some multiple reflections and ringing on the topline that are excited by the fast transition. An additional problem with the commercial tunnel diode generator is a long term sag in the pulse topline. The sag amounts to 3% in the first 100 ns. These perturbations are not completely removed by the band-limiting properties of the lossy transmission line. They thus appear in the output and distort it from the ideal, perfectly smooth, theoretical step response.

Due to the limitations of the present tunnel diode driving source and the encouraging results reported by Meyer, this project was proposed to develop a reference waveform generator driven by a microminiature mercury wetted switch. The switch promised a 2:1 improvement in transition time, elimination of the problem of the superposition of the triggering pulse on the step transition, and elimination of the long term sag.

Another independent benefit of the development of a fast mercury switch pulse generator related to the CCG project 72-68, "Pulse Testing of RF and Microwave Devices" [11]. The objective of this project was to measure the attenuation versus frequency of coaxial attenuators using fast pulse techniques and the fast Fourier transform (FFT). The measurement system uses a sampling oscilloscope and a minicomputer. To maximize the signal to noise (S/N) ratio in the measurement, it is desirable to use a signal into the sampling head of amplitude slightly less than the dynamic range (± 1 V) of the instrument. Using a tunnel diode the pulse amplitude is fixed ($\sim$ 250 mV). This is adequate as a signal to apply directly to the sampler. However when this pulse is passed through a 40 dB attenuator the output pulse applied to the sampler is only 2.5 mV. The noise level of the sampler is of the order of 10 mV, thus a very poor signal to noise (S/N) ratio results. The output amplitude from a mercury switch generator may be independently adjusted by simply varying the power supply voltage. With this it is possible to maintain the same S/N ratio for both the attenuator input and output waveforms. The input waveform amplitude could be set up for say 500 mV and measured. The attenuator would then be inserted. The power supply dc voltage would then be increased precisely by the attenuator's nominal value. For example, for a 40 dB attenuator the dc voltage would be increased from 500 mV to 50 V. These dc voltages can be measured very accurately. The output from the attenuator would then still be approximately 500 mV; thus perserving the S/N ratio. The results of this measurement and the FFT would then give the attenuator's deviation from its nominal value.

Several different housings for the microminiature mercury switch were investigated. They included: (1) DIP integrated circuit packages; (2) 7 mm coaxial line; (3) 14 mm coaxial line; (4) microstrip; and (5) stripline. In most all instances, considerable difficulty was encountered in obtaining suitable magnetic circuits for proper functioning of the switch.

The microminiature mercury switches have in this investigation been found to give very unreliable performance. When this project was first conceived in 1970, switches were immediately purchased. At that time the manufacturer was selling a high reliability series of switches. Those switches gave uniformly good performance and reliability. On the basis of our initial tests at that time we made a proposal to the CCG to support this project. The initial batch of switches was soon exhausted due to repeated use and also breakage during development of various coaxial housings. The switch is very fragile. In the meantime the manufacturer discontinued the high reliability series. Subsequent purchases of switches have not performed well. They have given erratic behavior. Some have required rather strong magnetic fields to activate. Many have exhibited contact bounce indicating a dry metal contact and an apparent insufficiency of mercury. Many of the switches that did not bounce were plagued by a contact resistance R_{ON} that varied wildly from one closure to the next. Variations in R_{ON} from milliohms to 25 ohms were observed.

Several measurement techniques were used to measure the transition times of the generated pulses. They included: (1) an ordinary delay line and a sampling oscilloscope; (2) a random sampling oscilloscope; (3) a pulse autocorrelator; and (4) a superconducting delay line and a sampling oscilloscope. The superconducting delay line gave the best results.

A superconducting 70 ns delay line system was assembled. With this delay line and our 22 ps sampling oscilloscope we were able to observe the mercury switch electrical transition time. The 10%-90% transition time of the superconducting line and its associated input/output lines and various connectors and adapters was 18 ps. Thus the measurement system transition time was 28 ps.

The objective of this project was achieved in one instance. The best result obtained was a transition time of 39 ps. Pulse amplitudes up to 50 volts were possible and were independently adjustable.

II. FLAT PULSE GENERATOR CONCEPT

With conventional pulse generators it is difficult to obtain a pulse with a topline that is known to be absolutely flat. One of the common design defects is a varying load (pulse on-off) on the generator's power supply. Depending upon the power supply's dynamic regulation some aberrations may appear in the generated topline and/or baseline. Other possible sources of aberrations are parasitic reactances, charge storage times, etc. associated with the active devices used in the generator.

One technique used by the author [12] to obtain a flat pulse consisted of a simple diode switch, figure 2-1. Initially the switch S_1 (in reality a PNP transistor operated in saturation or cutoff) is open. The constant current I_o passes through the diode and R_1 producing the generator baseline voltage $-I_oR_1$. When the switch S_1 is closed, the diode becomes reverse-biased thus disconnecting I_o from R_1. The output voltage thus changes rapidly to its topline value of zero volts. The pulse generator system has a source resistance equal to R_1. A constant current I_o is always drawn from the independent power supply -V. Thus the topline and baseline determining elements are completely free from power supply dynamic regulation problems. The only uncertainty in this circuit is in the transition region due to the switching transients of S_1 and the charge storage time in the diode. By using a Schottky diode the charge storage time may be minimized. With this circuit very flat pulses are obtained 20 ns after the positive going transition.

To extend the flat pulse concept to the subnanosecond region the mercury wetted switch was attractive. Figure 2-2 proposes such a flat pulse generator. Again the power supply (+V) supplies a constant current I_o irregardless of the switch condition (open or closed). With the switch open, the baseline is zero volts. When the switch closes, the equivalent generator topline is I_oR_1. The equivalent generator source resistance is R_1.

III. PRELIMINARY WORK

When this project was first conceived in 1970, some microminiature mercury switches were initially purchased. Basic switches, figure 3-1, and switches packaged in a 14 pin DIP IC package along with their associated electromagnet coils were obtained. Only top-of-the-line, high reliability switches were purchased.

Immediately a simple generator was constructed using an IC packaged switch. The circuit diagram of the generator is shown in figure 3-2. The flat pulse concept of chapter II was utilized. The 1.5 KΩ resistor and the +15V supply function as the constant current source I_o. The IC switch is driven directly by TTL logic square waves which was similar to [13].

This generator performed very reliably. It was possible to operate this switch at repetition rates up to 350 Hz without drop-out, contact bounce, or intermittent closures.

To evaluate the transition time characteristics of the mercury switch pulse generators, the measurement setup of figure 3-3 was used. The delay line is necessary because the generators do not furnish a pretrigger. The oscilloscope must be triggered 70 ns prior to the event of interest with at most a few picoseconds of jitter. It is impossible to use the driving square wave as a trigger as the switches typically exhibit 200 μs of jitter relative to it. The transient step response of this measurement setup is shown in figure 3-4. This was obtained by pulsing the system with an ultrafast tunnel diode pulse generator (t_r < 23 ps). The system transition time (10%-90%) is 154 ps. The overshoot and ringing is due to the phase dispersion of the large diameter, semi-solid coaxial delay line [14].

Figure 3-5 is the measured leading edge of the pulse from the IC switch generator. The transition time is 0.7 ns. The reason for the relatively slow transition time is the unavoidable parasitic reactances associated with the IC package. The switch element is surrounded by the electromagnet coils which is a far cry from the ideal coaxial line or stripline geometry.

IV. ALTERNATE SWITCH CONFIGURATIONS STUDIED

After the very encouraging results obtained with the IC switch, efforts were then directed toward using the basic microminiature switch element in a coaxial holder. The objective was to eliminate the parasitic reactances that were limiting the transition time of the IC packaged switch. By putting the switch in a very clean, coaxial environment, we felt we might achieve the 12 ps transition time reported by Myers [15]. A suitable holder was fabricated using precision 7 mm coaxial air line. However extreme difficulty was encountered in developing a suitable magnetic circuit to reliably activate the switch. Numerous arrangements were tried without success.

After abandoning the 7 mm coaxial holder, efforts were directed toward obtaining a workable magnetic circuit. A workable solution was obtained by rotating a small bar magnet very near the microminiature switch. One configuration used a small motor with a magnet attached and mounted on a printed circuit board. The switch was soldered by its wire leads onto a 50 ohm microstrip on the board. Transition times of the order of 500 ps were obtained due to the non-optimum mounting of the switch. With selected switches, good switch closures were obtained. Due to mechanical considerations, vibrations, etc. the maximum repetition rate of this configuration was rather low, typically 20 Hz or less.

In an attempt to improve the electrical environment for the switch, a modified 14 mm, coaxial insertion unit was devised, figure 4-1. The insertion unit slide-on cover was removed. An eight pole disc magnet was mounted on the shaft of a small variable speed hand drill. The magnet was placed in close proximity (4-8 mm) to the switch. This arrangement worked. However, it was extremely critical in terms of magnet position and motor speed to obtain a good switch closure. It did not have any long term stability, i.e., it seldom functioned at one setting for longer than a minute.

Figure 4-2 shows the leading edge of the observed pulse. The observed transition time is 0.15 ns. The waveform and transition time are almost identical to that of the measurement system step response, figure 3-4. Thus this generator's transition time is considerably less than 150 ps but no exact value can be assigned.

While the 14 mm insertion unit was an improvement over the simple circuit board, it was still not the optimum as shown by TDR and pulse transmission tests. The necessity of removing the outer cover of the insertion unit raised the characteristic impedance of the unit to 65 ohms. In addition the very small diameter switch (O.D. ∿ 1 mm) inserted in the large diameter center conductor (6.35 mm) created a large inductive discontinuity. With the switch closed a pulse transmission step response (10%-90%) time of 59 ps was measured. Thus additional improvements were still called for both in the coaxial housing and in the magnetic circuit.

V. COMMERCIAL STRIPLINE SWITCH EVALUATION

In 1972 the manufacturer of the microminiature mercury switches introduced a coaxial switch product line using the microminiature switch elements [16]. Several of these coaxial switches were purchased for evaluation. Included was a SPDT coaxial switch, figure 5-1, which was the top-of-the-line product rated especially for the transmission of fast ($t_r < 100$ ps) pulses. This switch was also rather expensive (≃ $115).

Although the switches were advertised as being coaxial switches, they were not built in a true circular coaxial configuration. The microminiature switch element was mounted as the center conductor in a triplate stripline configuration. The input/output connections were made through 3 mm SMA coaxial connectors. The two electromagnet switching coils were mounted on the outside and adjacent to one of the two ground planes [17]. To complete the magnetic circuit a small ferrite toroid was slipped over the center of the microminiature switch element.

Pulse transmission and TDR tests were performed on this stripline switch. For the purposes of the remaining discussion port 2 is defined as the center wiper of the SPDT configuration. Port 1 is defined as the arm of the SPDT switch which has the above mentioned ferrite toroid slipped over it. The remaining arm is defined as port 3. Figure 5-2 shows the TDR characteristics of this switch. The TDR test instrument was looking into port 2. The switch was connected to either port 1 or port 3 with the connected port terminated in a 3 mm, 50 ohm termination. The presence of the ferrite toroid is definitely shown on the port 2 to 1 TDR trace by the large negative dip.

From the TDR information one would intuitively reason that the transmission bandwidth from port 2 to 1 would be less than from port 2 to 3. Figure 5-3 demonstrates that such is indeed the case. The same sampling oscilloscope and tunnel diode used in the TDR tests were used for the transmission tests. The input transition time (fig. 5-3a) was 30 ps. For port 2 to 1 the observed transition time (fig. 5-3b) was 57 ps. Removing the input transition time a value of 49 ps is obtained for this half of the switch. For port 2 to 3 the observed transition time was 52 ps giving a value of 43 ps for the switch.

Problems were encountered in obtaining reliable operation of this switch. The switch gave very erratic switch closures. It was plagued with contact bounce symptomatic of dry contacts. When the switch did close, its contact resistance many times varied wildly from a few milliohms to as much as 25 ohms. To obtain a good mercury wetted contact closure it was found necessary to adjust the electromagnet driving current square wave frequency to match a mechanical resonance of the switch. For this particular switch, this resonance was found to be in the vicinity of 140-150 Hz. However, even operating at this frequency did not assure continuously reliable closures as the switch was still prone to erratic behavior.

The output pulse waveform from this switch when it was operated as a pulse generator was measured with several different techniques. They were: (1) an ordinary delay line setup, figure 3-3; (2) a random sampling oscilloscope; (3) a pulse autocorrelator; and (4) a superconducting delay line and sampling oscilloscope.

Using the same delay line setup as mentioned earlier, figure 3-3, the result shown in figure 5-4 was obtained. The result is almost identical to that of the measurement system step response measured earlier, figure 3-4. The conclusion from this first test was that the mercury switch generator 10%-90% transition time was easily less than 50 ps.

The second transition time measurement method used a random sampling oscilloscope specifically constructed at NBS for this purpose [18,19]. Due to the random measurement process the probability P of obtaining a valid sampled data point is quite small.

$$P = t_w/T$$

T is the period of the pulse generator. t_w is the time window of interest. In this case the time window is positioned to include the fast rising, leading edge transition. Although the random sampling time base contained a trigger arrival time prediction circuit (i.e., a phase locked oscillator), this feature did not appreciably increase P due to the extreme pulse to pulse jitter (∿ 200 μs). This circuit did function properly with better behaved waveforms.

The random sampling time base was capable of sweep speeds as fast as 10 ps/div. Due to the inability of the trigger predictor circuit to increase P, considerations of data acquisition time forced us to use a wider than desired time window of 6 ns (i.e., 0.6 ns/div.). Figure 5-5 is the result of this measurement. The data acquisition time for this photograph was 120 minutes. The transition time is seen to be less than 50 ps. A 30 ps feedthrough sampler was used. The long term timing drift for this NBS time base was less than 15 ps/hr.

Measurements were attempted using the NBS pulse autocorrelator [20-23]. This instrument utilized a pyroelectric square law detector and a sliding short. Its theory, construction and operation are fully described in references [21,22]. It was not possible to obtain reliable, repeatable measurements of the generator transition time. This was due to the erratic performance of the switch. Fifty volt pulses were used. The pyroelectric detector electrical output was a very low level signal. Phase-lock signal detection amplifiers were required to recover the detector signal. The erratic switch behavior seriously degraded the phase-lock system's performance. From the data obtained, it did however appear that the transition time was less than 100 ps.

The results of the measurements using the ordinary delay line, random sampling, and the pulse autocorrelator were all inconclusive. They all indicated that the transition time was less than 50 ps but could not assign an exact value. The remaining alternative was to use a superconducting delay line and our fastest sampling oscilloscope.

In 1960 Nahman and Gooch [24] first proposed the use of superconductivity as a means of drastically reducing the metal losses in a coaxial delay line. In 1968 Elliott [25] used a Pb-Nb superconducting line. He obtained a 30 ps transition time with a 100 ns delay. The most recent progress in developing high quality, miniature, superconducting coaxial lines has been accomplished in Japan [26].

We have obtained a superconducting coaxial line similar to that reported by Nahman [26] in his figure 1, curve A. The inner and outer conductors are lead plated copper. The dielectric is fluorethylene propylene (FEP) with a diameter of 1.6 mm. A 15 meter length is used to give a nominal delay of 70 ns. The line was wrapped into a 10 cm diameter coil for immersion into a liquid helium bath. The line was fitted with slightly modified 3 mm SMA connectors. The 50 ohm input and output air lines for the cryostat were 7 mm O.D., 50 cm long with precision 7 mm connectors at each end. Silver plated, rhodium flashed, brass tubing was used to minimize the ohmic losses and provide the maximum bandwidth. To minimize the heat leak into the liquid helium, very thin wall (0.5 mm) tubing was used. Precision 7 mm to 3 mm SMA adapters were used to connect the superconducting line and the input/output air lines.

This delay line gave excellent performance as shown by the pulse transmission test, figure 5-6. For these measurements a tunnel diode pulse generator and sampling oscilloscope having 10%-90% transition times of 15 ps and 20 ps respectively were used. The observed system transition time is 31 ps. Thus the transition time of the total delay line package is 18 ps. The two input/output air lines and the two 7 mm/3 mm adapters together had a transition time of 14 ps. TDR measurements of the two 3 mm connectors showed series inductive discontinuities of 0.3 nH. These inductive discontinuities yielded a transition time of 9.3 ps. Thus, the transition time of the superconducting line itself is deduced to be of the order of 8 ps or less.

Swept frequency measurements were made of the insertion loss of the delay line. At 1 GHz an insertion loss of 0.21 dB was obtained. Extrapolated to 1 km this yielded an attenuation coefficient of 14 dB/km. At 10 GHz a minimum insertion loss of 0.8 dB was noted with a 0.8 dB ripple.

The measurement setup shown in figure 5-7 was used. To avoid degrading the generated pulse by a trigger pickoff at the input to the delay line, as is normally done, the trigger pickoff was placed in the charge line 1 ns away from the switch. When the switch closed (2-3), a positive pulse was generated at terminal 3 and propagated into the superconducting line. A negative pulse propagated away from the switch back down the charge line. This negative pulse was used to trigger the sampling oscilloscope.

Using the commercial stripline mercury switch the result shown in figure 5-8 was obtained. The observed transition time is 48 ps. After removing the transition times of the delay line and the sampling oscilloscope, a value of 39 ps was obtained for the mercury switch. This compares closely with the 43 ps value obtained for pulse transmission through the switch, figure 5-2.

The close correlation between the transition times obtained for pulse transmission through the closed switch and operation as a pulse generator lead to a significant conclusion. The basic physical mechanism of a mercury wetted contact closure is thus shown to be considerably faster than 40 ps. The factor limiting the transition time of this particular switch is the parasitic reactances associated with the switch and its housing.

Considerable difficulty was encountered in the above measurement due to the erratic behavior of the switch. The switch would not operate continuously long enough to obtain an X-Y recorder trace of the waveform. A decision was then made to replace the switch element with a new one. The new switch element was mounted exactly as the old one. This switch was also erratic but not as bad as the original one. However when this switch was operated as a pulse generator, the output waveform, figure 5-9, was deteriorated. The initial transition is comparable in speed (∿ 50 ps) to figure 5-8 but the pulse top has a very long dribble-up.

VI. NBS STRIPLINE SWITCH

The transition time achieved with the commercial stripline switch discussed in chapter V was encouraging. It was felt that we could improve upon the stripline housing for the microminiature switch and thus obtain a faster transition time.

The design of the commercial stripline housing had several shortcomings:

1. The SPDT configuration necessitated an abrupt right angle bend in the signal path.

2. The unconnected portion of the center of the switch element appeared as a short open-circuited transmission line connected to the signal path.
3. The presence of the ferrite toroid in the signal path.
4. The switch element was soldered to the input/output 50 ohm striplines by wire leads welded to the switch. These wires introduced additional series inductance.

To meet these shortcomings several steps were taken. For items 1 and 2 a SPST in-line configuration was chosen. The center contact and one end terminal were shorted together by coating half of the switch with conducting silver paint, figure 6-1.

For item 3, the ferrite toroid was eliminated. To replace the toroid in the magnetic circuit, a small bias magnet was mounted on the opposite side of the board from the driving electromagnetic coils. It was necessary to adjust the position of this magnet to obtain proper operation with each particular microminiature switch element.

For item 4, the wire leads were removed. The microminiature switch was held in place by two small sockets originally designed as printed circuit sockets for individual transistor leads.

Figure 6-2 shows the NBS in-line stripline housing for the modified microminiature mercury switch in both assembled and disassembled views. The switch is mounted in the large opening in the two circuit boards. The voids are then refilled with pieces of FEP and small strips of brass to reestablish a uniform 50 Ω characteristic impedance throughout the switch housing. A 30 ps TDR instrument was used for this purpose.

Pulse transmission and TDR measurement results are shown in figures 6-3 and 6-4. After removing the input transition time, a 10%-90% transition time of 34 ps was obtained for this switch housing. This is 9 ps faster than the value obtained for the commercial housing. Even faster housings would be possible to obtain with further effort. The attenuation seen between the input and output waveforms, figure 6-4, is due to the 8 ohms series resistance introduced by the imperfectly conducting silver paint on the switch.

Many problems were encountered in obtaining a good microminiature mercury switch to use in this housing. The original stock of high reliability switches had been depleted by the time this housing was developed. This was due to their fragile nature and consequent breakage in the design phases of this project. When a new stock of switches were ordered, the manufacturer no longer sold a high reliability version. This new batch of switches without exception gave very erratic behavior. The manufacturer was contacted concerning the problem. He offered to sell us a quantity of nonadvertised, specially selected switches that they normally reserve for their products requiring their highest quality switches. Some of these were purchased. They worked somewhat better than the previous batch. They were still plagued by dry contacts and the necessity to operate at a mechanical resonance.

The best switch available was assembled into the NBS stripline switch housing. The output pulse waveform from this switch when it was operated as a pulse generator was measured using the superconducting delay line technique described in chapter V, figure 5-6. The results are shown in figure 6-5. The 10%-90% transition time is 80 ps.

The best results obtained with the commercial switch, figure 5-7, showed that for a properly functioning mercury wetted contact there was a close correlation between the transition times obtained for pulse transmission through the closed switch and operation as a pulse generator. The transmission results obtained with the NBS stripline indicate the potential for obtaining generated pulse transition times of 34 ps or faster. The actual value obtained of 80 ps clearly indicates that the mercury wetted contact was not functioning properly. This was also apparent from the erratic function of the switch.

An interesting effect was observed on the opening of the switch. The pulse trailing edge transition exhibited a long slow (∿ 4 ns) sag, figure 6-6. This can be explained physically. As the solid metal sliding contact starts to move away from the fixed contact, a steadily lengthening filament of mercury maintains electrical contact. As time progresses, the filament becomes longer and narrower thus increasing its resistance. This resistance acts to steadily decrease the output voltage. Ultimately the filament breaks completely interrupting the output voltage.

VII. CLASSICAL MERCURY SWITCH PULSE GENERATOR

The major goal of this project was to construct an extremely fast pulse generator using the radically different microminiature mercury switch element, figure 3-1. As a comparison, a pulse generator was also built using a mercury switch of classical construction.

A classical reed mercury switch is shown in figure 7-1. It consists of a fixed and a movable flat reed sealed in a glass envelope. A pool of mercury is also sealed in the envelope. The mercury wets all of the metal surfaces. The large pool serves to constantly replenish the mercury on the contacts.

A simple 3 mm coaxial housing for this switch was built, figure 7-2. Individual transistor lead sockets were soldered to the long center pins of the 3mm SMA jacks. The mercury switch was held in place by its wire leads in the sockets. The outer conductor was a 6.35 cm length of 3.4 mm I.D. brass tubing. The mercury switch made a slip fit inside this tubing. A 5 volt relay coil was then slipped over the outer conductor. This switch could then be driven directly by a TTL power buffer (7440).

The switch housing was designed to provide a 50 ohm impedance up to the switch package itself. It was impossible to maintain a 50 ohm impedance through the glass enclosed portion of the switch. The minimum outer conductor diameter was fixed by the glass envelope diameter. In the flat moving reed region, the reed dimensions are such as to cause a higher characteristic impedance ($> 50\ \Omega$). The mercury pool has a much larger equivalent diameter and thus has a characteristic impedance considerably less than 50 ohms. That such is the case is shown by the TDR measurement, figure 7-3.

The large capacitive dip due to the mercury pool is seen to be the major reactive discontinuity. It would be possible to reduce the magnitude of this dip by carefully tailoring the outer conductor diameter to follow the geometry of the mercury pool. However the shape of the mercury pool varies with each individual switch and is also dependent upon the physical orientation of the switch. Thus to optimize this a special housing would have to be designed for each individual switch. B. Elliot [27] has done this and was able to obtain a generated pulse transition time of 70 ps.

With the non-optimized 3 mm switch housing, figure 7-2, pulse transmission and pulse generation tests were performed. For pulse transmission a 10%-90% transition time of 0.10 ns was obtained, figure 7-4. The output pulse waveform, figure 7-5, from this switch when it was operated as a pulse generator was measured using the superconducting delay line technique. The 10%-90% transition time is 0.21 ns.

No problems were encountered with this classical switch. It functioned very reliably. It would switch at frequencies up to 180 Hz. It has been used to generate 150 ns pulses of up to 25 volts without degradation.

VIII. CONCLUSIONS

Several conclusions can be drawn from this work:

1. The basic physical mechanism of a mercury wetted contact is exceedingly fast (<< 40 ps).
2. Generated pulse transition times of 39 ps may be obtained from a commercial switch using a microminiature mercury switch element.
3. The reliability of the microminiature mercury switch element is very poor.
4. The microminiature mercury switch element is totally unsuitable for use by NBS in any standards such as the reference waveform generator due to the poor reliability and erratic behavior.
5. For times greater than 500 ps the classical reed mercury switch should be used.

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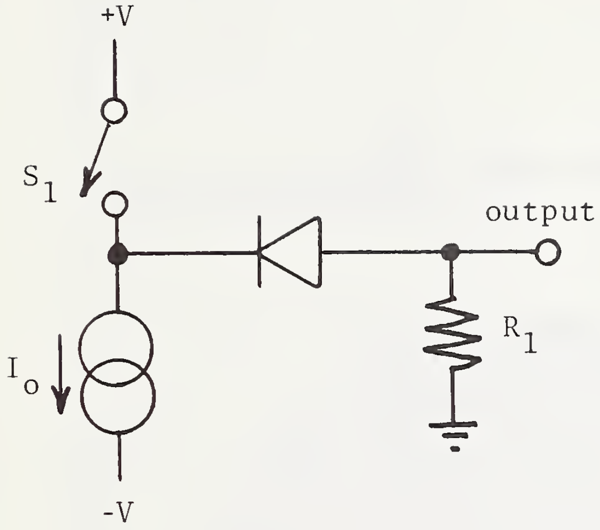
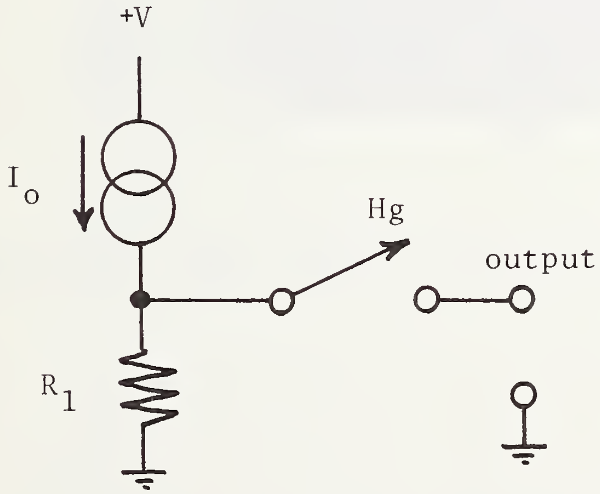


$V_{baseline} = -I_oR_1$

$V_{topline} = 0$

$R_{gen} = R_1$

Fig. 2-1. Diode switch flat pulse generator.



$V_{baseline} = 0$

$V_{topline} = I_oR_1$

$R_{gen} = R_1$

Fig. 2-2. Mercury switch flat pulse generator.

Fig. 3-1. Basic SPDT microminiature mercury wetted switch.

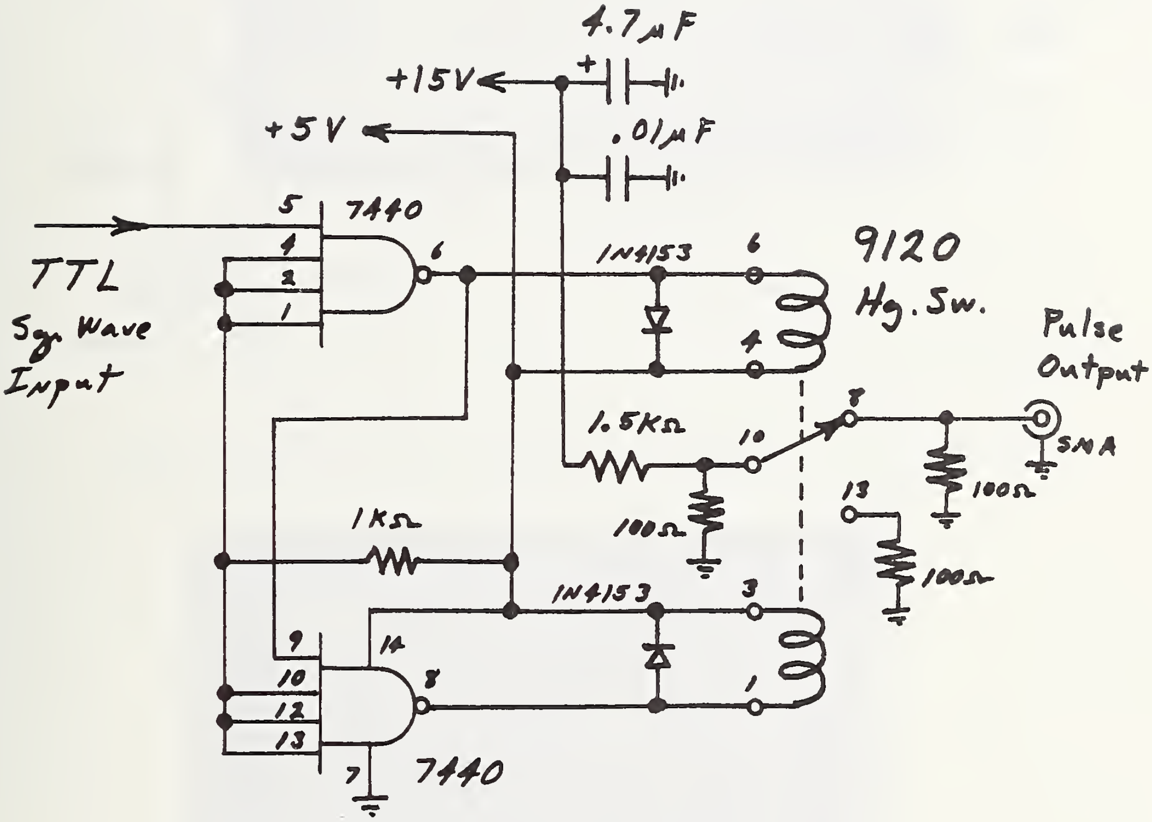


Fig. 3-2. DIP IC mercury switch pulse generator.

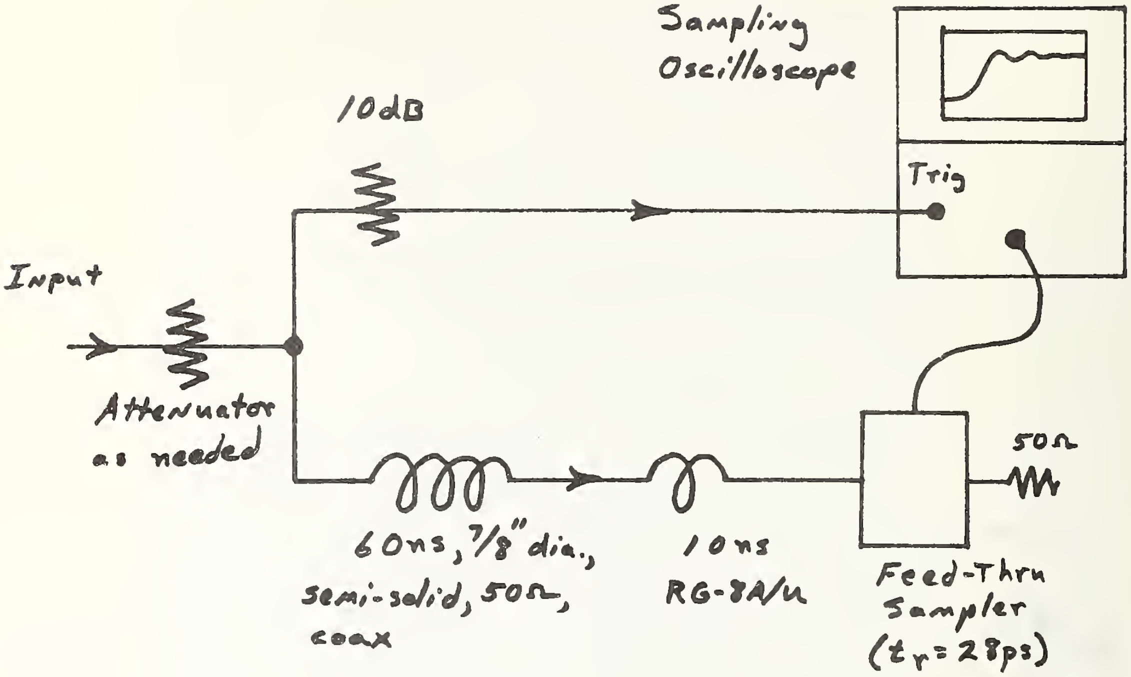


Fig. 3-3. Transition time measurement set-up

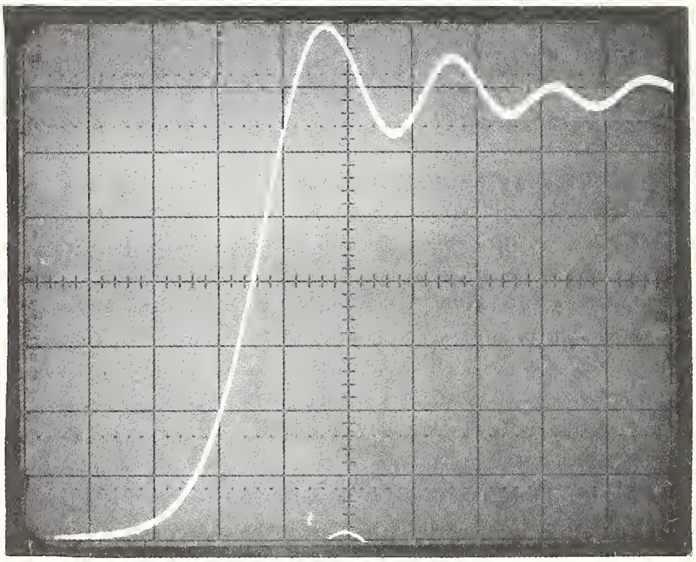


Fig. 3-4. Transient step response of measurement set-up. Horizontal scale is 100 ps/div.

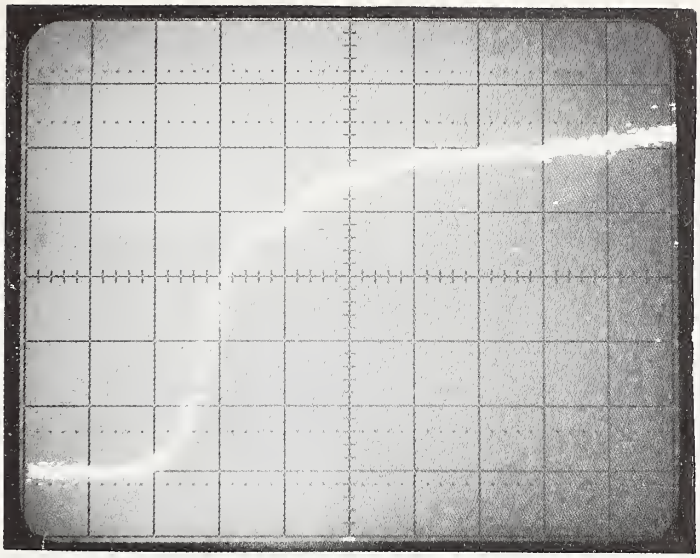


Fig. 3-5. Pulse output from DIP IC mercury switch pulse generator. Horizontal scale is 200 ps/div.

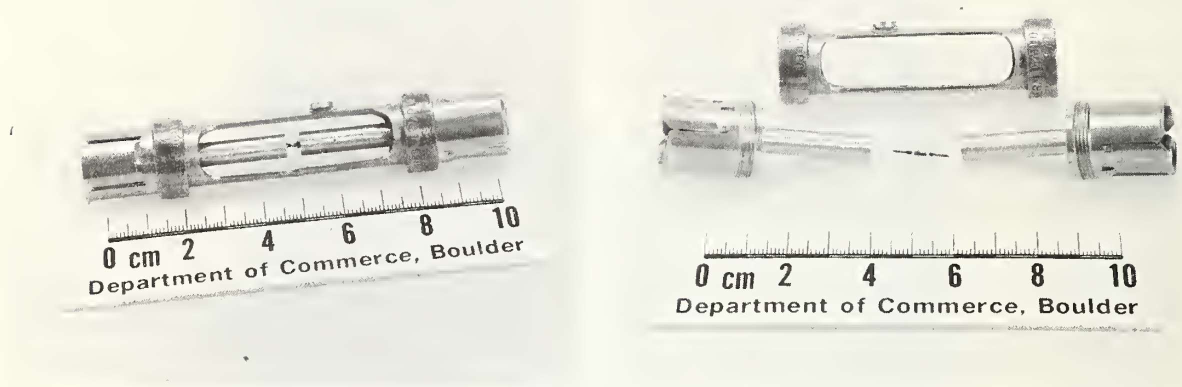


Fig. 4-1. Microminiature mercury switched mounted in a 14 mm insertion unit.

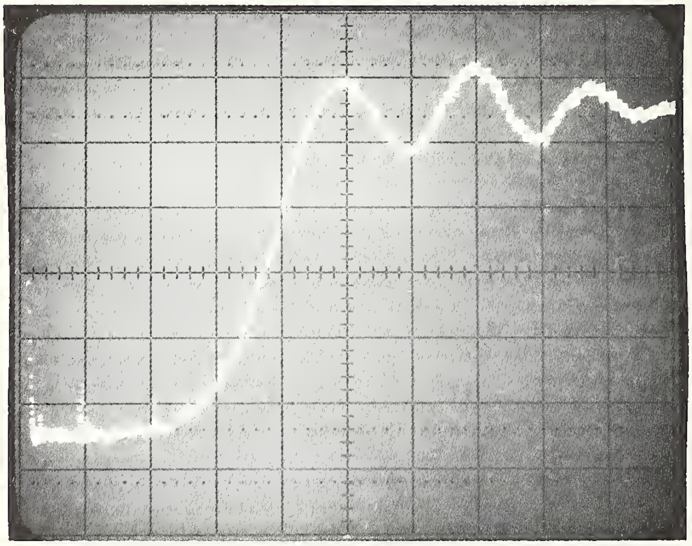


Fig. 4-2. Pulse output of a microminiature switch mounted in a 14 mm insertion unit. Horizontal scale is 100 ps/div.

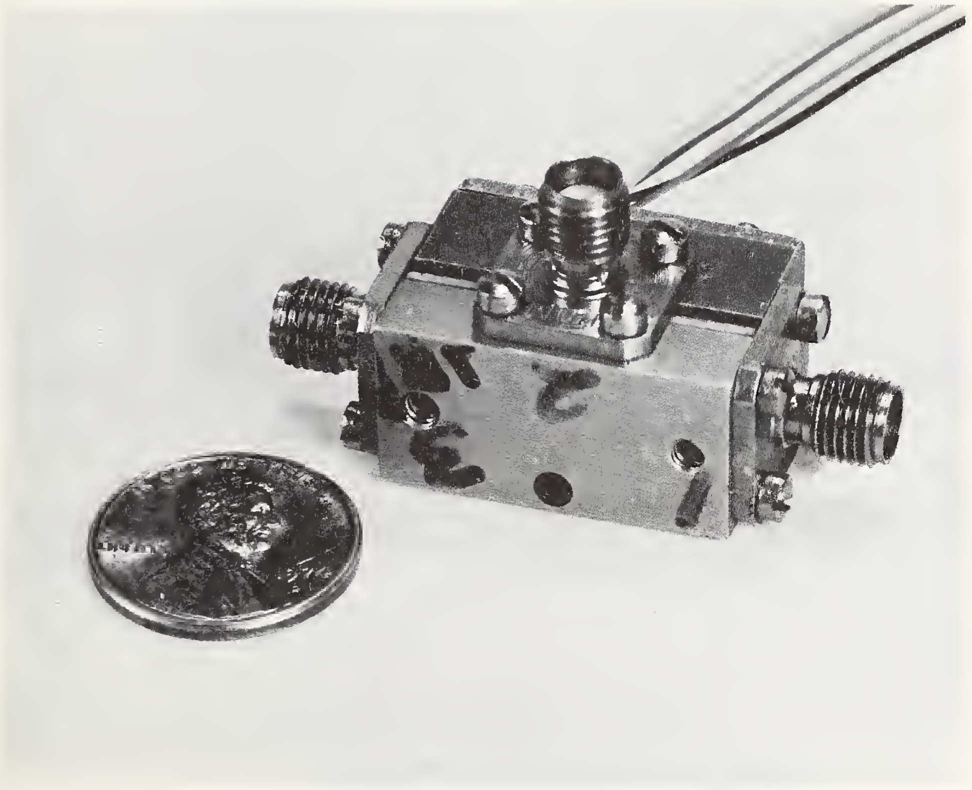


Fig. 5-1. Microminiature mercury switch in commercial strip line package.

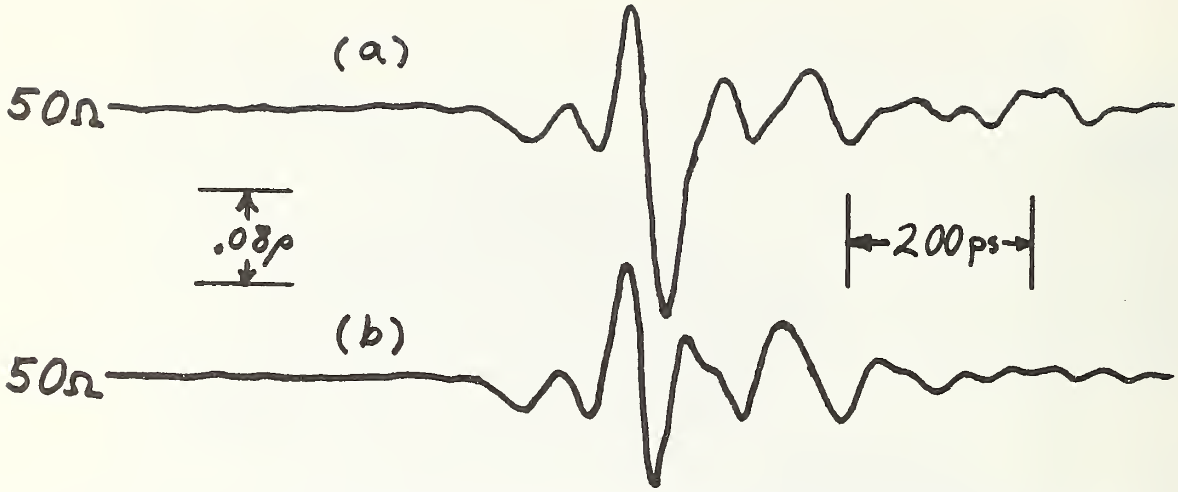


Fig. 5-2. TDR characteristics of commercial stripline microminiature mercury switch. (a) Port 2 to Port 1. (b) Port 2 to Port 3.

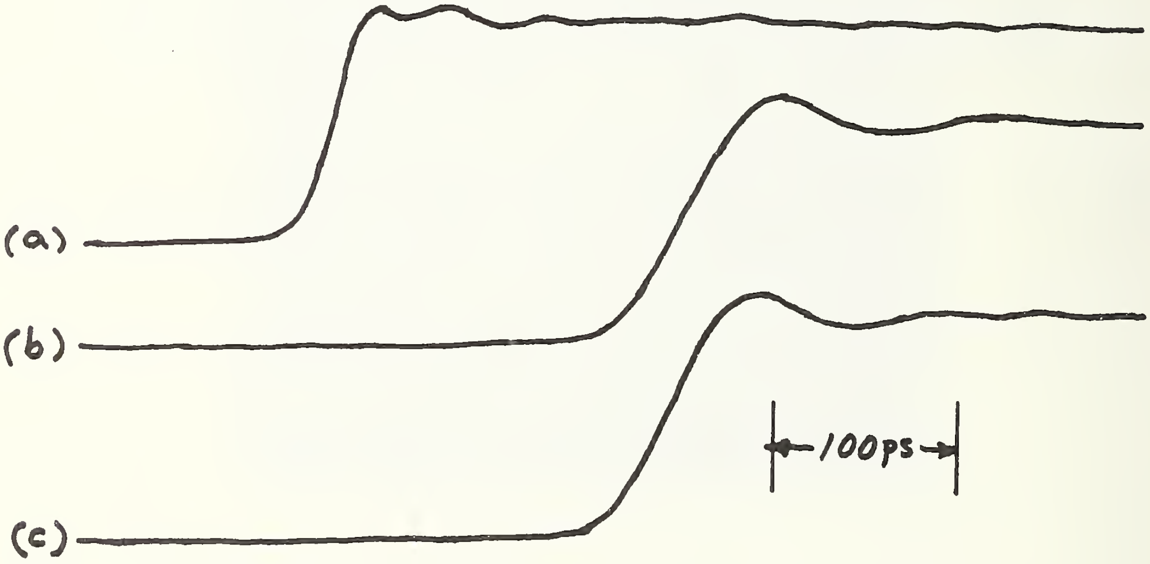


Fig. 5-3. Fast pulse transmission characteristics of commercial stripline microminiature mercury switch. (a) Input. (b) Port 2 to Port 1. (c) Port 2 to Port 3.

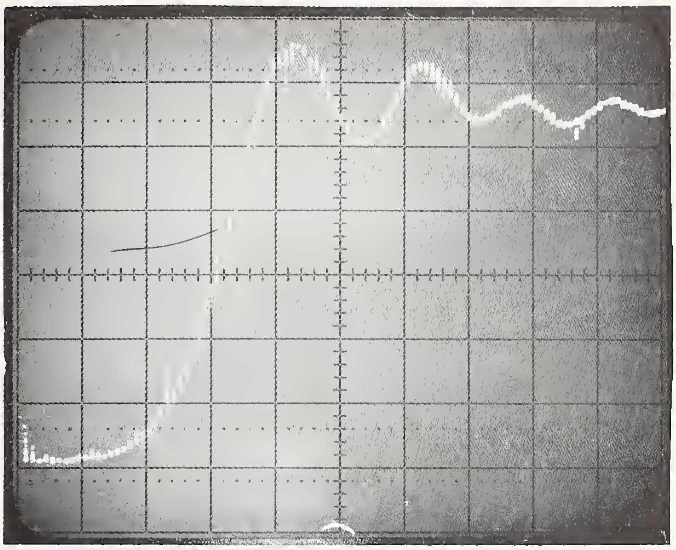


Fig. 5-4. Pulse output from commercial stripline microminiature mercury switch. Ordinary delay line measurement set-up, Fig. 3-3. Horizontal scale is 100 ps/cm.

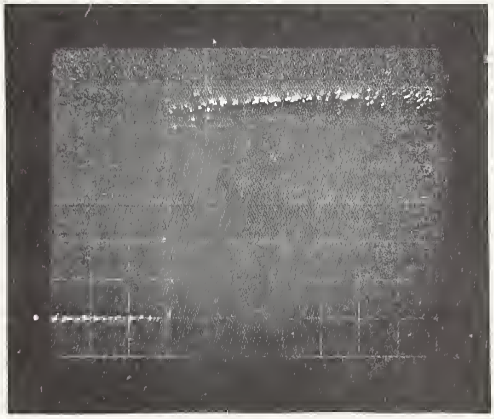


Fig. 5-5. Pulse output from commercial stripline microminiature mercury switch. Random sampling measurement. Horizontal scale is 0.6 ns/div. Data acquisition time of 120 min.

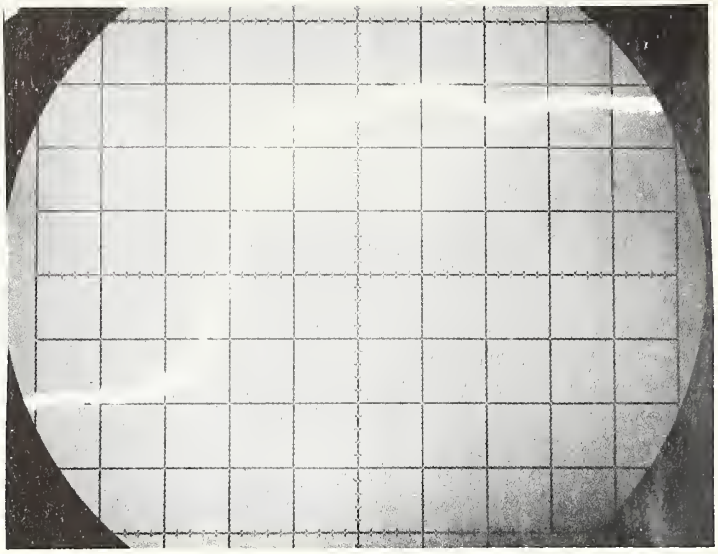


Fig. 5-6. Transient step response of 70 ns superconducting delay line. Horizontal scale is 20 ps/div.

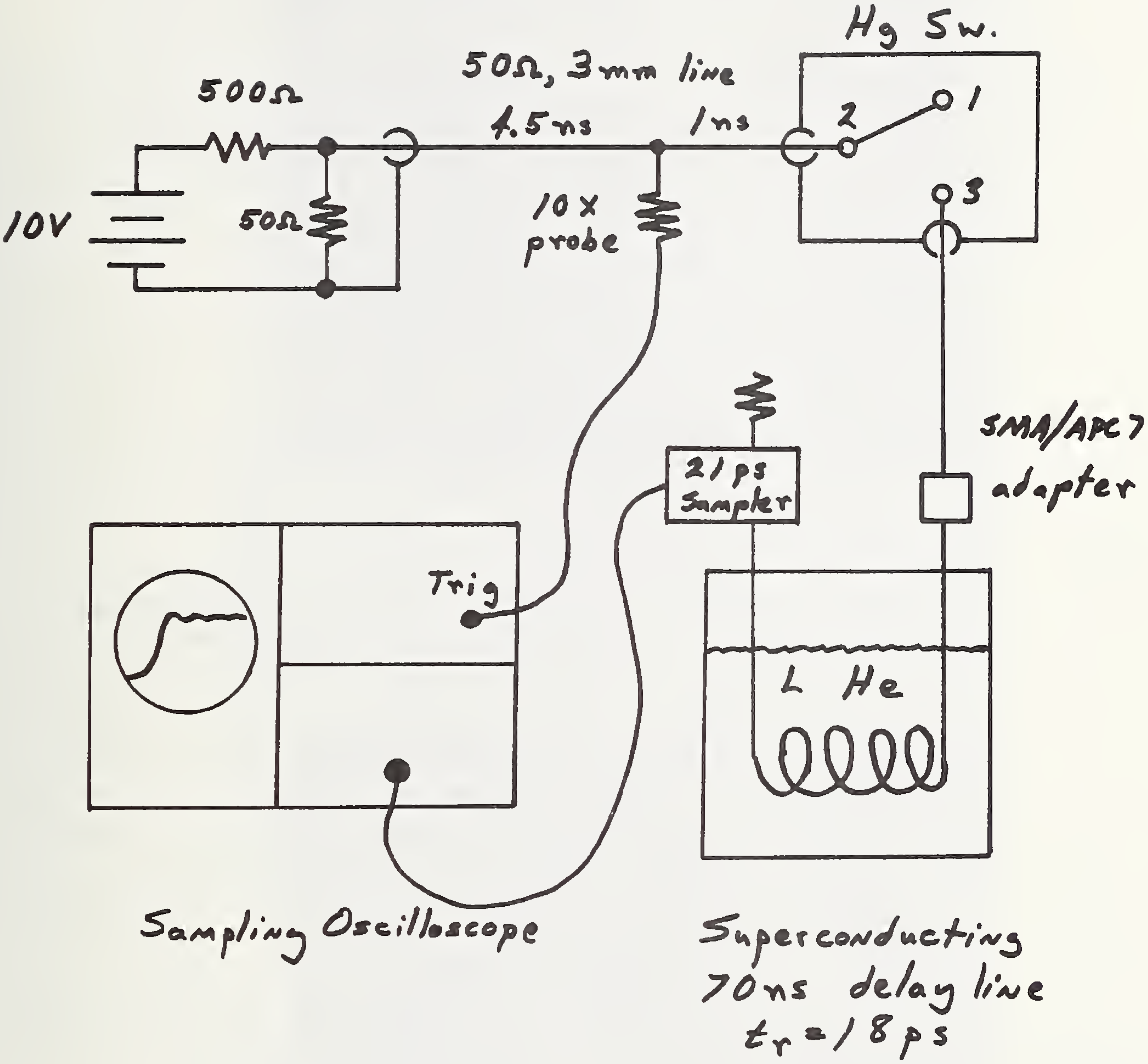


Fig. 5-7. Mercury switch transition time measurement setup using a superconducting delay line.

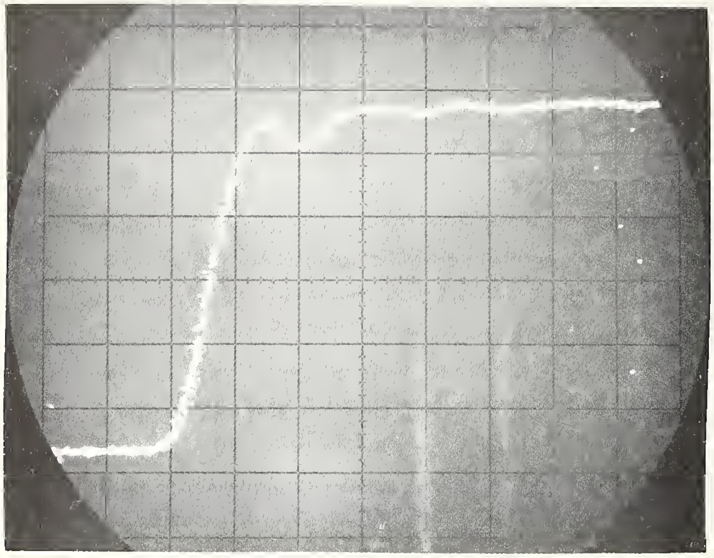


Fig. 5-8. Pulse output from commercial stripline microminiature mercury switch. Superconducting delay line measurement setup, Fig. 5-7. Horizontal scale is 50 ps/div.

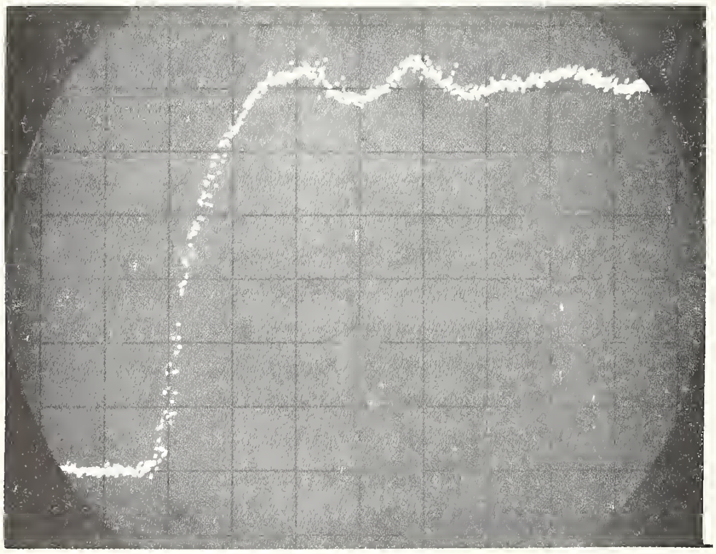


Fig. 5-9. Same as Fig. 5-8 except with replacement switch element. Horizontal scale is 100 ps/div.

Fig. 6-1. Modified microminiature mercury switch. Center contact and end terminal shorted with silver paint.

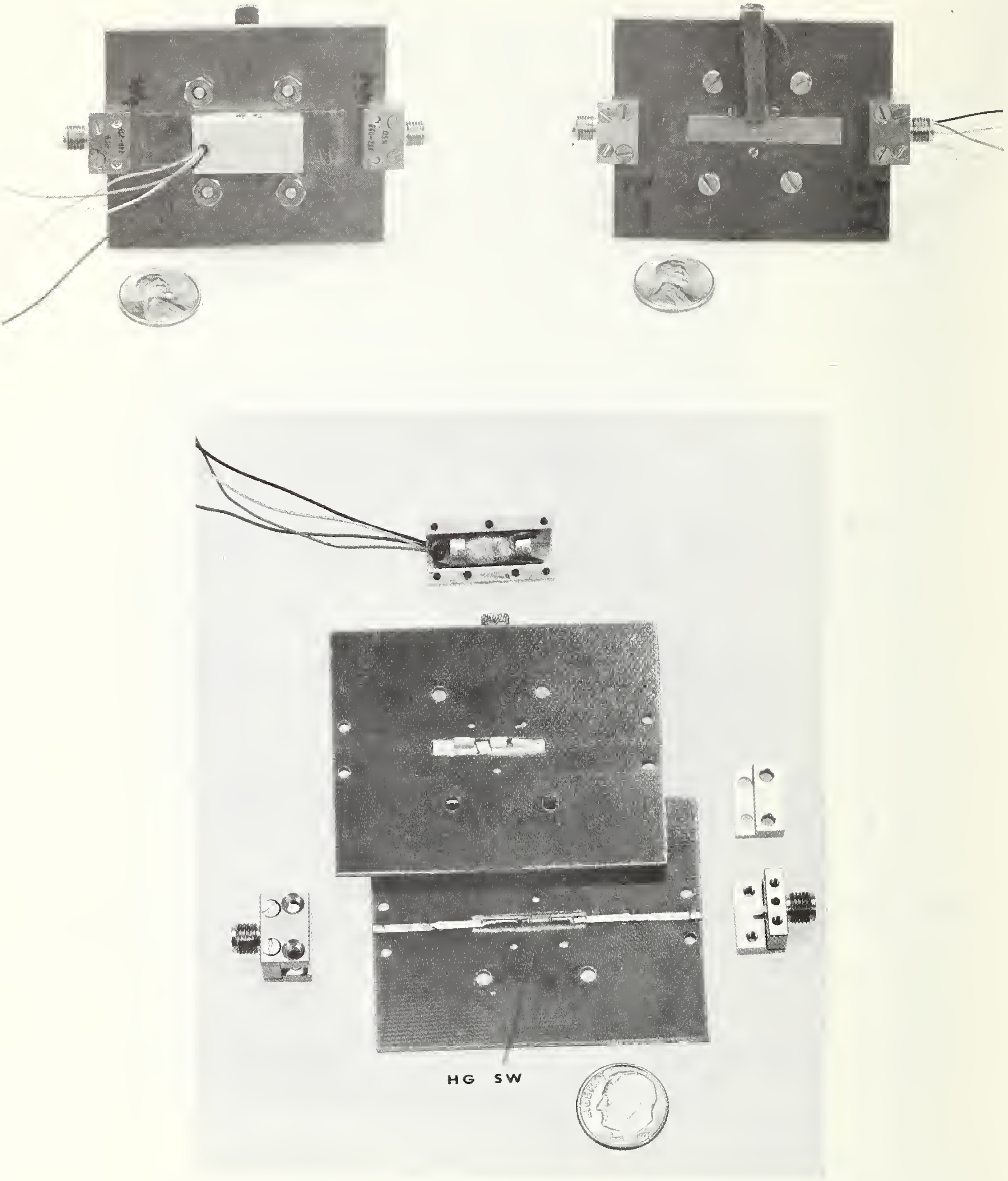


Fig. 6-2. NBS in-line stripline housing for a modified microminiature mercury switch.

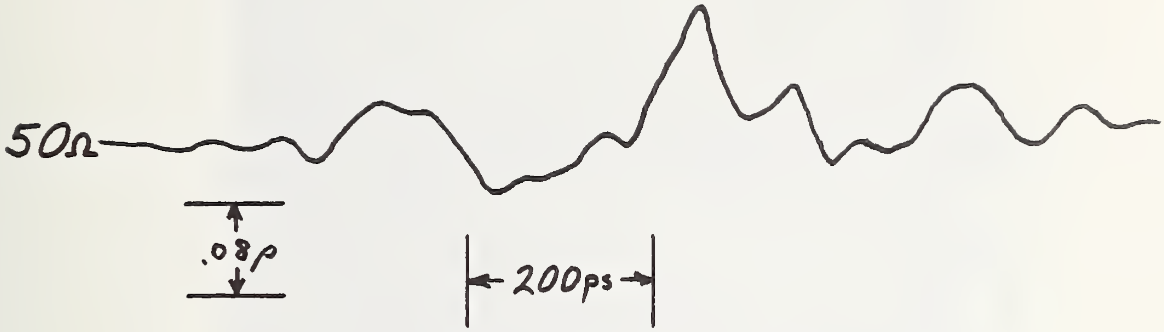


Fig. 6-3. TDR characteristic of NBS stripline mercury switch housing.

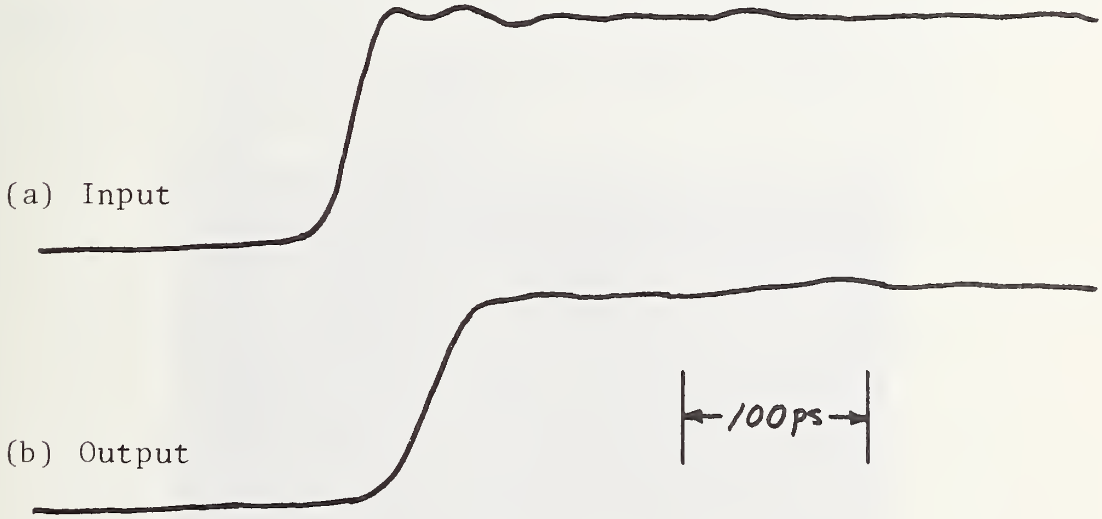


Fig. 6-4. Fast pulse transmission characteristic of NBS stripline mercury switch housing.

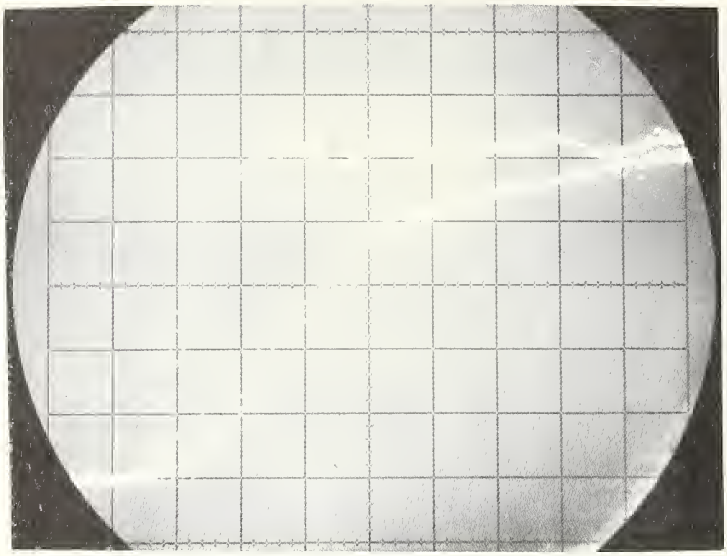


Fig. 6-5. Pulse output from the NBS stripline mercury switch pulse generator. Superconducting delay line measurement setup, Fig. 5-7. Horizontal scale is 100 ps/div. and 20 ps/div.

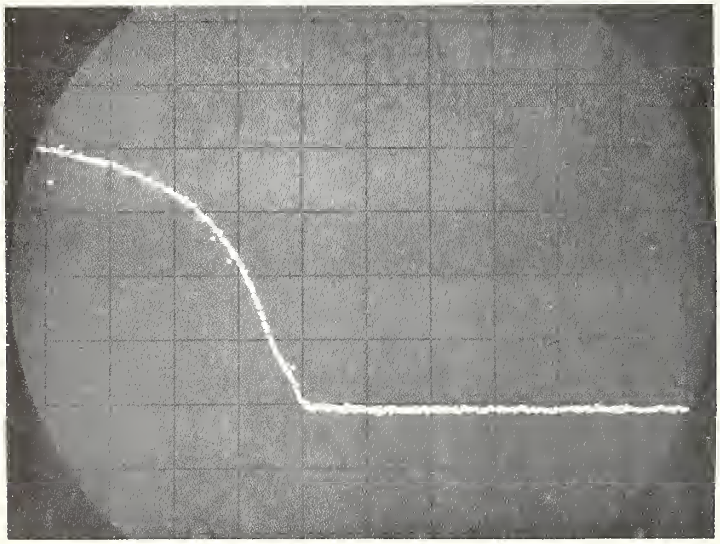


Fig. 6-6. Mercury switch trailing edge transition observed on the opening of the switch. Horizontal scale is 1 ns/div.

Fig. 7-1. Classical reed mercury switch.

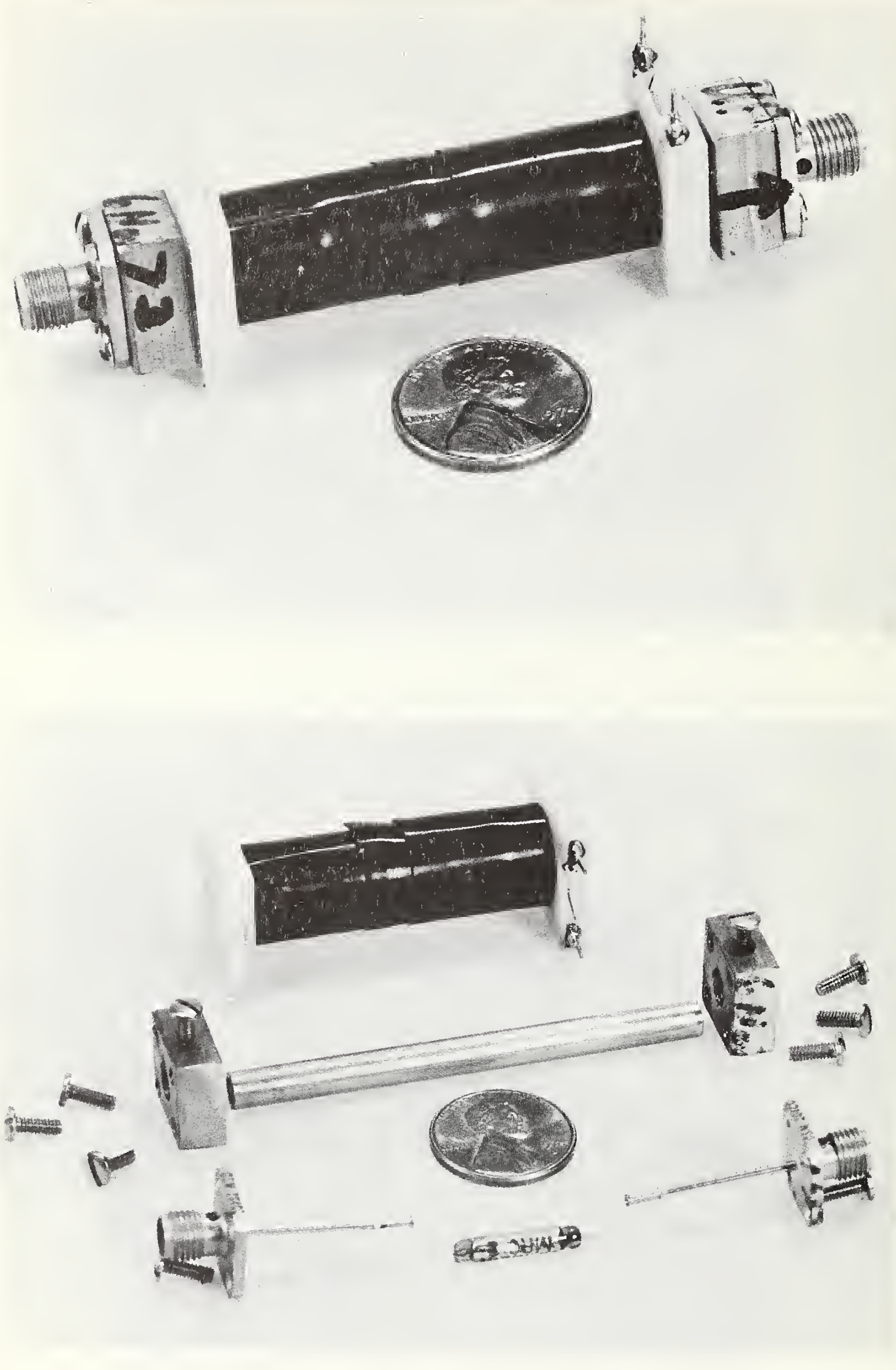


Fig. 7-2. 3 mm coaxial housing for a classical reed mercury switch.

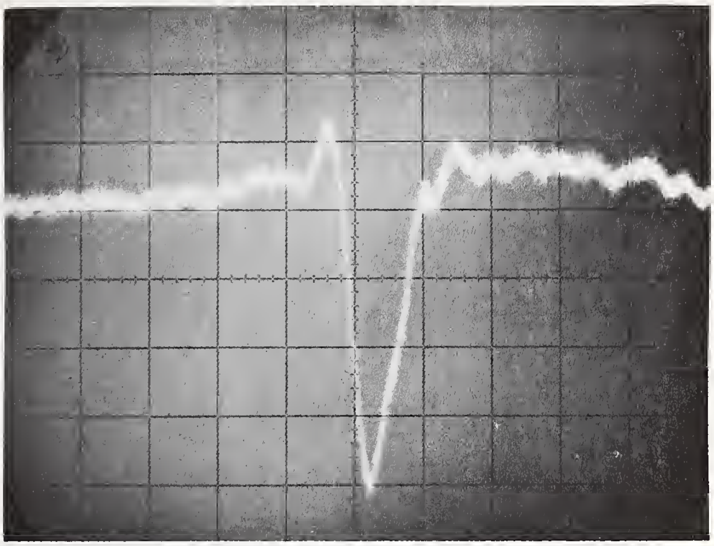


Fig. 7-3. TDR characteristic of classical reed mercury switch in 3 mm coaxial housing. Vertical scale is 0.1 ρ/div. Horizontal scale is 100 ps/div.

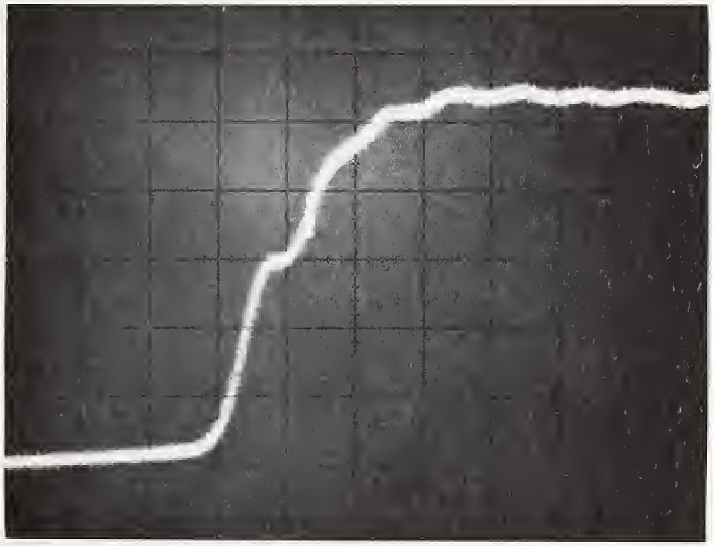


Fig. 7-4. Fast pulse transmission through a classical reed mercury switch in a 3 mm coaxial housing. Horizontal scale is 50 ps/div.

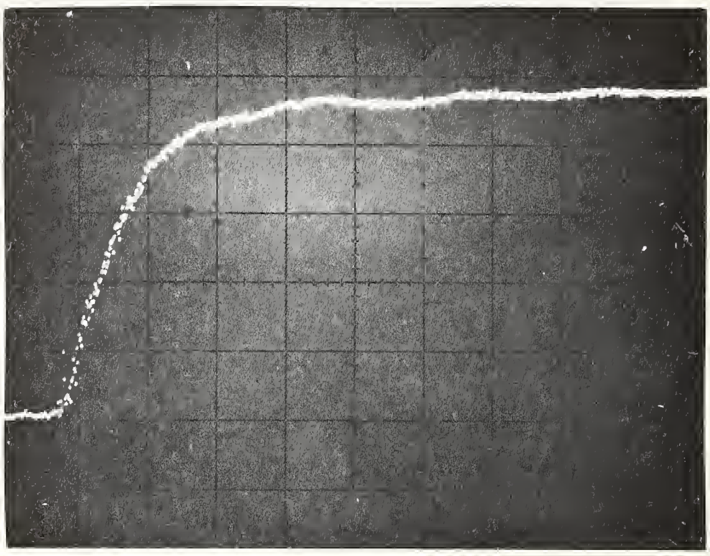


Fig. 7-5. Pulse output from classical reed mercury switch pulse generator. Superconducting delay line measurement set-up, Fig. 5-7. Horizontal scale is 100 ps/cm.

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET**	1. PUBLICATION OR REPORT NO. NBSIR 74-377	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE
Picosecond Pulse Generators Using Microminiature Mercury Switches

5. Publication Date
March 1974

6. Performing Organization Code
272.20 (FY'73)
272.50 (FY'74)

7. AUTHOR(S)
James R. Andrews

8. Performing Organ. Report No.
NBSIR 74-377

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
Washington, D.C. 20234

10. Project/Task/Work Unit No.
FY'73 2725390
FY'74 2725390

11. Contract/Grant No.
DoD CCG 72-66

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*
Dept. of Defense/Calibration Coordination Group
c/o Mr. M.L. Fruechtenicht AMSMI-M, Bldg. 5435
U.S. Army Metrology & Calibration Center
Redstone Arsenal, Alabama 35809

13. Type of Report & Period Covered
Final Report FY'73

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Pulse generators have been built using microminiature mercury switches. A commercial RF coaxial switch was also evaluated as a pulse generator. A superconducting delay line (t_r = 18 ps, t_d = 70 ns) and a sampling oscilloscope (t_r = 22 ps) were used to measure the generated pulse 10%-90% transition time. The best result obtained was a transition time of 39 ps. Pulse amplitudes were independently adjustable up to 50 volts. The microminiature mercury switches in general were found to give very unreliable operation.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Mercury switch; picosecond; pulse generator; pulse measurement; superconductivity

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21. NO. OF PAGES

22. Price