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Acoustic Charge Transport Technology Investigation for Advanced Development Transponder

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Acoustic charge transport (ACT) technology has provided a basis for a new family of analog signal processors, including a programmable transversal filter (PTF). Through monolithic integration of ACT delay lines with GaAs metal semiconductor field effect transistor (MESFET) digital memory and controllers, these devices significantly extend the performance of PTFs. This article introduces the basic operation of these devices and summarizes their present and future specifications. The production and testing of these devices indicate that this new technology is a promising one for future space applications.

I. Introduction

The acoustic charge transport (ACT) processor is a new class of signal-processing devices that enables the user to sample a time signal (digital) without quantizing the sample amplitudes (analog) [1]. A comparison of signal-processing architectures using conventional digital processors and ACT processors is shown in Fig. 1. The ACT processor, which eliminates the use of analog-to-digital (A/D) and digital-to-analog (D/A) converters, offers a capability that can be advantageous in a wide variety of applications, such as equalizers, programmable IF filters, and numerically controlled oscillators.

Two programmable transversal filter (PTF) modules, which use ACT technology, and data acquisition and analysis software (WAVE) were procured from Electronic Decisions Incorporated (EDI). This article summarizes the investigation and the testing performed on the ACT PTF module, and considers possible functions that can be implemented at different stages in the advanced development transponder (ADT).

II. Significance of ACT in the Advanced Development Transponder Design

The PTF uses an ACT processor that enables the user to process analog signals without quantizing them. A benefit of using this device in the ADT is the ability to control independently the center frequency, bandwidth, amplitude, and phase of the PTF. A filter with variable center frequency allows the designer to use an optimum IF frequency or, if needed, a variable IF frequency to minimize the effects of mixing products and other unwanted signals. By varying the bandwidth of the ACT PTF filter, the receiver bandwidth may be matched closely to the information bandwidth of the desired signal, thus minimizing the channel noise. Figure 2 shows a block diagram of the ADT with the shaded blocks indicating the possible usage of the ACT processor. Included among these blocks are the bandpass filters (BPFs), downconverters, and voltage-controlled oscillators (VCOs). At present, the ACT PTF filter realizations are limited in that these filters do not have high Q factors that are needed in the transponder. Thus, the most likely application of ACT PTF in the ADT design is the ranging channel bandpass filter.

III. ACT Principles of Operation

The acoustic charge transport technique of the ACT processor is drawn from a technology mix of surface acoustic waves (SAWs), charge-coupled devices (CCDs), and GaAs [2]. The ACT device comprises a single GaAs integrated circuit (IC) that requires minimal support circuitry and uses an on-chip delay line that can be tapped at several points without distorting the signal.

Rather than converting signals to SAWs, the ACT devices use acoustic waves to transport sampled signals in a bucket-brigade fashion, much like CCDs. Unlike CCDs, however, ACT channels transport charge packets using SAW-induced electric fields, and signals can be sensed nondestructively at several points.

An input signal, shown as $x(t)$ in Fig. 3, is applied to an ohmic input contact (IC) on a depleted n-type epitaxial layer on a semi-insulating GaAs substrate. At one end of the channel, acoustic waves are generated by a high-Q piezoelectric transducer in a proton-isolated region. These waves propagate across the device at the speed of sound (2,864 m/sec). Since GaAs is a piezoelectric material, the propagating surface wave induces within the epitaxial layer a series of electric fields that may be thought of as traveling potential wells. As each well passes under the input contact, a number of electrons proportional to the input voltage at that instant are injected into the well. Through this process the analog input signal has been converted into a discrete-time signal. The signal is thus sampled in time, but not quantized in amplitude. This key feature of the ACT device is also indicated in Fig. 1.

Because the amount of charge is proportional to the input electrode's voltage, each packet represents a sample of the input signal. The fields associated with the surface wave then transport these samples through the ACT channel. The inherently smooth and continuous nature of the traveling wave transport accounts for the processor's high efficiency and low noise.

The sampling rate of an ACT channel, which is equal to the frequency of the acoustic waves, typically ranges from 300 to 600 MHz. High device speeds are possible because of the high electron mobility of GaAs. Acoustically transported charge packets are sensed by one or more output electrodes placed on the surface of the delay line. Charge packets in the channel induce image charges on the sensing electrodes, creating a voltage at each electrode that is proportional to the amount of charge in its vicinity. Electrode voltages are created without affecting the charge packets by the nondestructive sensing (NDS) circuitry. At the end of the ACT channel, an ohmic extraction contact (EX) is used to remove the charge from the wells.

A standard ACT chip, shown in Fig. 7, consists of a delay line, a SAW drive, and tap-weight and tap-address registers.

IV. The EDI Programmable Transversal Filter

The ACT tapped delay line has been used to implement a complete and compact PTF through the addition of on-chip tap-weighting and memory circuits, as shown in Fig. 4 [3,4]. The tap weights are used to set the magnitude of the coefficients of the desired impulse response. The accumulation function required by the transversal filter is performed by two summing buses and an operational amplifier.

The presently available ACT PTFs have 128 taps that may be set to any of 31 values between +1 and −1 (5-bit tap weighting). The input sampling rate is 360 MHz, and the tap spacing is 5.6 nsec. This gives a single-tap bandwidth of 180 MHz and a filter Nyquist interval of 90 MHz. A single tap may be programmed in 1 μsec, and the entire device may be programmed in under 100 μsec.

Table 1 shows a comparison between the EDI's current design and projected future designs of the ACT PTF.

V. The EDI PTF Module

The EDI PTF module, shown in Fig. 8, consists of an ACT processor, digital control and interface circuits, and a chassis with connectors for an external RF signal, DC power supplies, and a digital I/O port.

The ACT processor, shown in Fig. 9, is the physical and functional center of the module. It contains the ACT PTF device, I/O RF interface amplifiers, a hybrid SAW drive amplifier, bias and decoupling circuitry, and digital connections. The ACT PTF device includes a 128-tap ACT delay line, 128 5-bit (4-bit magnitude and sign) attenuators, a 128 × 5 RAM architecture, and address decoding circuitry. This chip provides a complete PTF in a monolithic form. An input amplifier and a differential output amplifier are added to reduce insertion loss and to provide matching to a 50-Ω system. The hybrid SAW drive amplifier is used in conjunction with SAW transducers on the PTF chip to form a delay-line oscillator which supplies the 1-W, 360-MHz signal needed to transport the charge.

VI. ACT Testing and Applications

A. Space Qualification

EDI has performed some preliminary radiation and temperature tests on the ACT device. The neutron radiation hardness tests were conducted using four neutron doses of 5×10^{11}, 2×10^{12}, 1×10^{13}, and 1×10^{14} per cm^2. These tests indicate that in spite of relatively large losses in the sheet conductance of the epitaxial layer which forms the transport channel, the key operational parameters of the ACT device—namely charge injection transconductance, charge capacity, and Nyquist bandwidth frequency response loss—are barely affected. This performance is attributed to the advanced architecture of the ACT channel structure which uses a graded doping profile to maintain an extremely narrow charge packet cross section. Thus the ACT device exhibits excellent neutron radiation hardness. The total dose gamma radiation hardness test has not yet been conducted, but it is believed that this type of radiation is expected to present less risk than neutron radiation effects because the ACT device is implemented using GaAs technology—GaAs devices are inherently radiation hard.

The ACT device has also been tested by EDI at temperatures 0, 25, and 50 deg C, with limited testing at −20 deg C. It has performed satisfactorily at all temperatures. The Missile Division of the Hughes Technology Center at Carlsbad, California, is currently working towards the space qualification of the ACT chips.

B. ACT Foundry

EDI is transferring the ACT technology to Hughes for a large-scale production of the standard ACT PTF. One of the immediate applications of this standard ACT PTF will be as matched filters in commercial disk drives. Three-inch GaAs wafers are being used for the fabrication process. Hughes is implementing qualified GaAs processes for the fabrication of ACT chips. The current processes are qualified for level 3. They need to be brought up to level 5 for space qualification. Hughes is maintaining 3-sigma performance up to the end-product, including the fabrication processes.

C. Performance Verification

The ACT PTF module test setup (Fig. 5) was configured in the Transponder Development Laboratory by using an IBM computer and WAVE data acquisition and analysis software. An IEEE-488 data acquisition card was installed in the IBM computer to have the capability of observing, storing, and analyzing the I/O RF signals.

The WAVE software allows the user to specify the desired response, to program the PTF modules, and to access an extensive set of tools for analyzing, manipulating, and displaying waveforms. Some of the prominent features of WAVE software are: built-in signal-processing functions and an editor, built-in interface functions for an IEEE-488 card, a finite-impulse-response (FIR) filter-design function, PTF tap-weights loading utility, individual/group PTF tap control, and interactive graphics.

D. Filtering Application

A series of tests were performed at JPL to verify the operating characteristics of the ACT PTF module when it is used as a filter. The test equipment was configured as shown in Fig. 5.

Figure 10 shows the frequency response of the ACT PTF when a single tap is turned on (i.e., set for a tap weight of +1) with all other taps turned off in a manner to balance the capacitive loading equally between the positive and negative bus bars. The frequency response is quite flat, with the exception of the slope caused by the ACT element factor. The small peak at 89 MHz is due to the summation of the off (but not exactly zero) taps.

Figure 11 shows the frequency response when the taps are set alternatively to +1 and −1. The highest peak is centered at about 89 MHz, with tapering peaks on both sides.

Figure 12 shows multiple traces of a Hanning-weighted bandpass filter having a 2-MHz passband with center frequencies at 41, 46, 51, and 56 MHz. The roll-off in the passband gain is due to the ACT element factor. The passband gain can be adjusted to compensate for the element factor or other system gain variations.

Figure 13 shows the filter at 56 MHz with its bandwidth adjusted to 2, 4, 6, and 8 MHz. The increase in gain as the bandwidth decreases is expected since a processing gain is realized for narrower passbands which have longer impulse responses and thus make use of a large number of taps.

Passband phase control is also easily achieved as shown in Fig. 14. Here the phase is adjusted in steps of 45 deg, from −180 to 180 deg. The passband shape remains undisturbed by the phase adjustments as shown in Fig. 15.

E. Oscillator Application

A few tests were performed to verify the operating characteristics of the ACT PTF module when it is used as an oscillator. The digitally controlled oscillator (DCO) configured with the ACT PTF is shown in Fig. 6. The output of the PTF is fed back to the input, such that the loop gain is approximately 1, causing the circuit to oscillate. The loop gain is greater than 1 only near the center of the passband, giving coarse selection of frequency. The frequency that causes the loop phase shift of 0 deg is the frequency of oscillation.

The ACT DCO has a programmable range from 15 to 80 MHz. It can shift relative frequencies by steps as small as 1 kHz for use in frequency tracking applications. It can be set to an absolute frequency with a precision of ±2.5 kHz if module temperature is considered in the tap settings. Figure 16 shows a 1-kHz-per-division superposition of the DCO output when it was programmed to 56.010 and 56.011 MHz. The verification of phase noise and stability of the ACT DCO is included as part of the future plan.

F. Items Remaining

The following tasks need to be performed to more fully characterize the ACT PTF module for possible inclusion and implementation in the ADT:

1. Verification of the phase noise and stability characteristics of the ACT DCO.
2. Verification of whether the ACT PTF module can be used as a downconverter.
3. Replacement of the second IF bandpass filter in the breadboard transponder and verification of its operation in terms of: I/O impedance, I/O signal levels, insertion loss, power consumption, temperature stability, roll-off factors, passband gain, and out-of-band rejection.
4. Replacement of one of the reference oscillators used in the breadboard transponder and verification of its operation in terms of: I/O impedance, I/O signal levels, insertion loss, power consumption, temperature stability, and frequency stability.
5. In cooperation with the Electronic Decisions Division of Comlinear Corporation, assessment of the viability of implementing the functions of the ACT processor discussed above for the ADT. It may be possible to custom design an ACT processor which meets the requirements stated in Table 1, specifically a filter with a narrower bandwidth, either by cascading two ACT filters to extend the channel length or by using heterojunction ACT (HACT) devices.

VII. Conclusion

In this article the principal characteristics and the unique features of the Acoustic Charge Transport Programmable Transversal Filter have been reviewed. Tests have been performed to characterize some of the applications, and this filter's possible use in the Advanced Development Transponder has been considered. The principal advantages of using such a device are its size, weight, power consumption, and programmability. In addition, it offers digital signal-processing techniques without A/D and D/A conversions.

References

[1] A. Laundrie, "ACT Technology bestows accelerated signal processing," *Microwaves and RF*, vol. 28, no. 8, pp. 147–150, August 1989.

[2] M. J. Hoskins, J. Morkoc, and B. J. Hunsinger, "Charge transport by surface acoustic waves in GaAs," *Applied Physics Letters*, vol. 41, no. 4, pp. 332–334, August 1982.

[3] D. A. Fleish and G. C. Pieters, "The ACT Programmable Transversal Filter," *Microwave Journal*, vol. 34, pp. 284, 289–292, May 1991.

[4] F. M. Fliegel, R. L. Martin, and F. Guediri, "Performance of acoustic charge transport filters," *IEEE Trans. on Microwave Theory and Techniques*, vol. 35, no. 12, pp. 1164–1168, December 1987.

Table 1. Programmable transversal filter specifications.

Specification	EDI Present design	EDI Future design	Transponder design
Sampling rate, MHz	360	1000	360–2000
Number of taps	128	1024	128–1024
Tap spacing, nsec	5.6	<3	0.5–5.6
Tap weights, bits (bipolar)	5	8	5–10
Programming time	<1 μsec per tap	—	—
Dynamic range			
Spurious free, dB	40	50–60	40–70
Blocking, dB	55	>60	>60
Max. input level, dBm	−10	−10	−10
Insertion loss, dB	20	0	0
I/O impedance, Ω	50	50	50
Temperature range, deg C	0–70	0–70	−30 to +85
Power dissipation, W	<3	<1	<1
Radiation hardness, kilorads	—	—	100
Package size, cm×cm	3×3	3×3	3×3

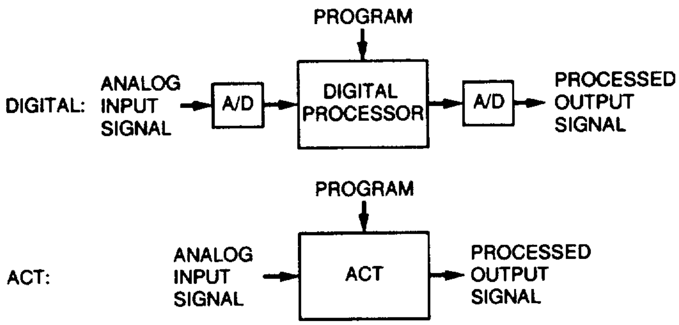


Fig. 1. Digital processing versus ACT processing.

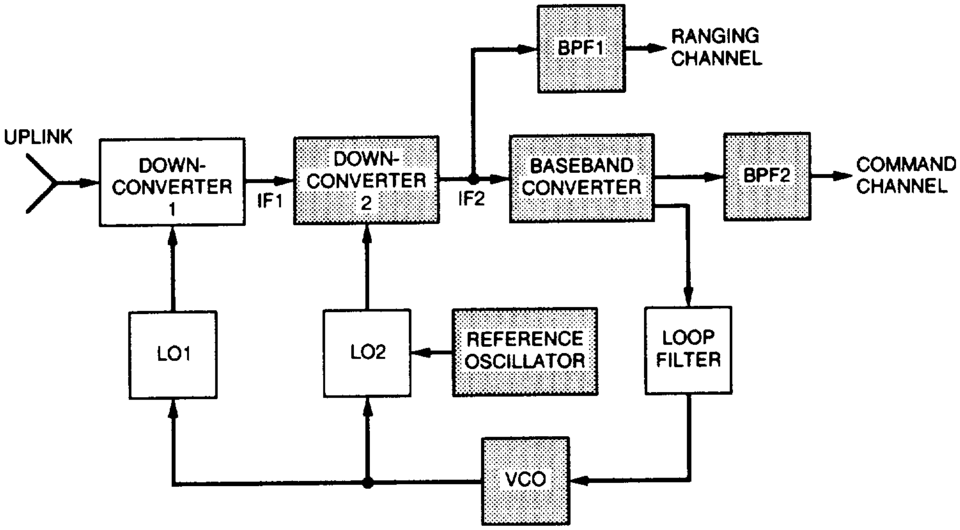


Fig. 2. Possible ACT applications in the advanced development transponder.

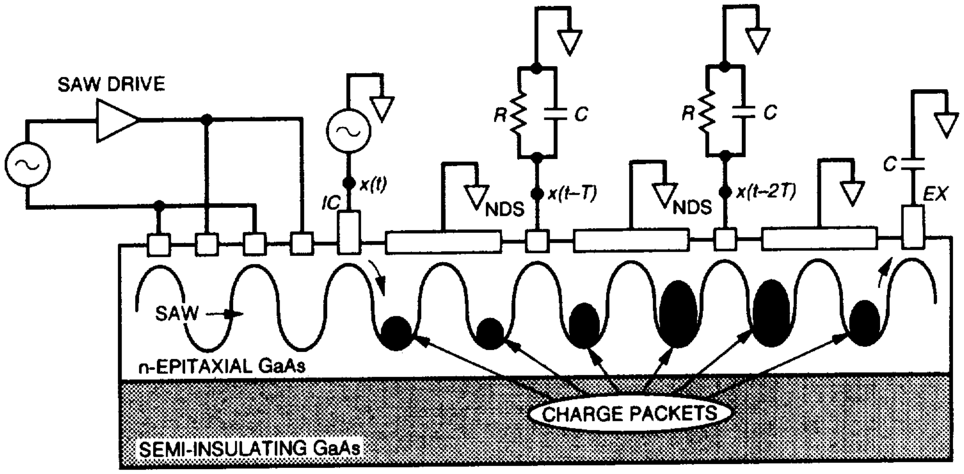
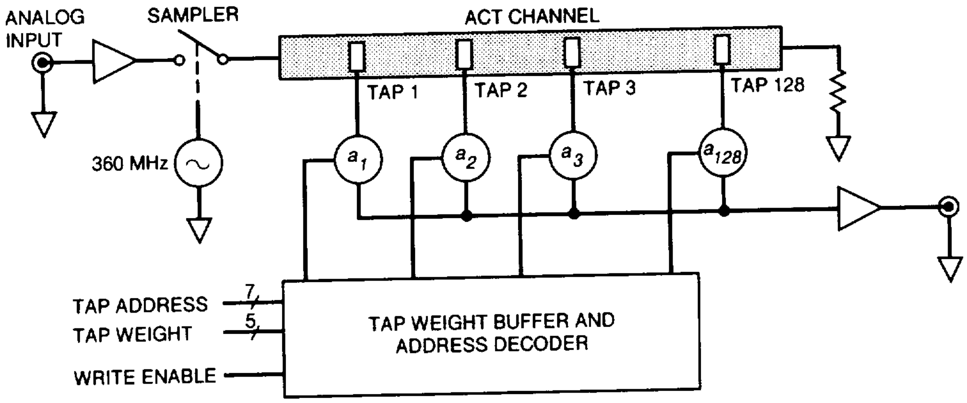


Fig. 3. ACT delay-line structure.



IMPULSE RESPONSE: $h(t) = \sum_{n=1}^{128} a_n \delta(t - nT)$ TRANSFER FUNCTION: $H(\omega) = \sum_{n=1}^{128} a_n e^{-jn\omega T}$

Fig. 4. EDI ACT programmable transversal filter (PTF).

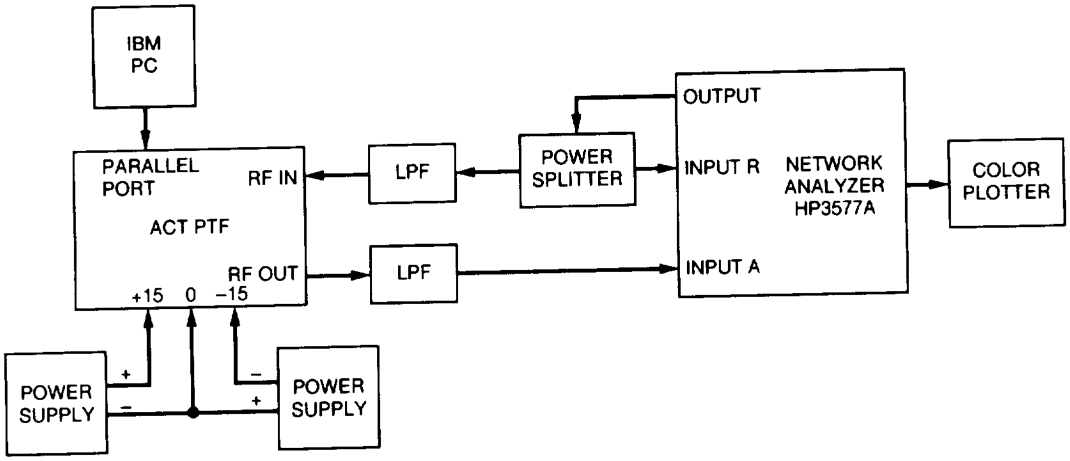


Fig. 5. Test configuration for the ACT PTF.

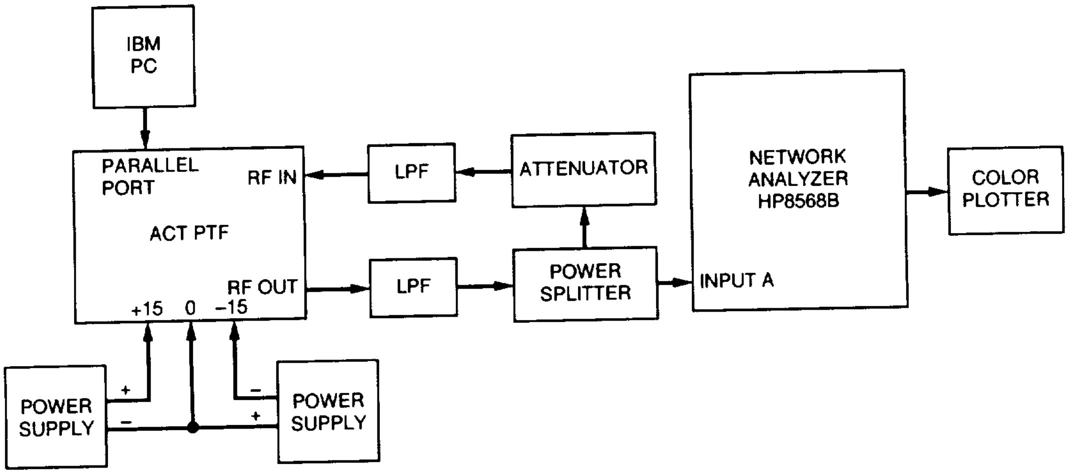


Fig. 6. Test configuration for the digitally controlled oscillator.

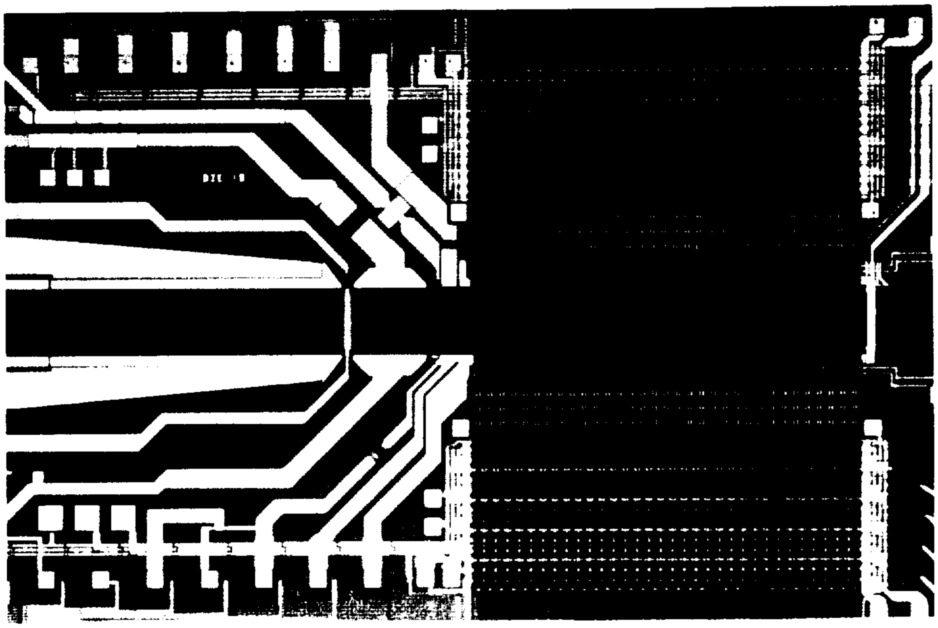


Fig. 7. ACT chip.

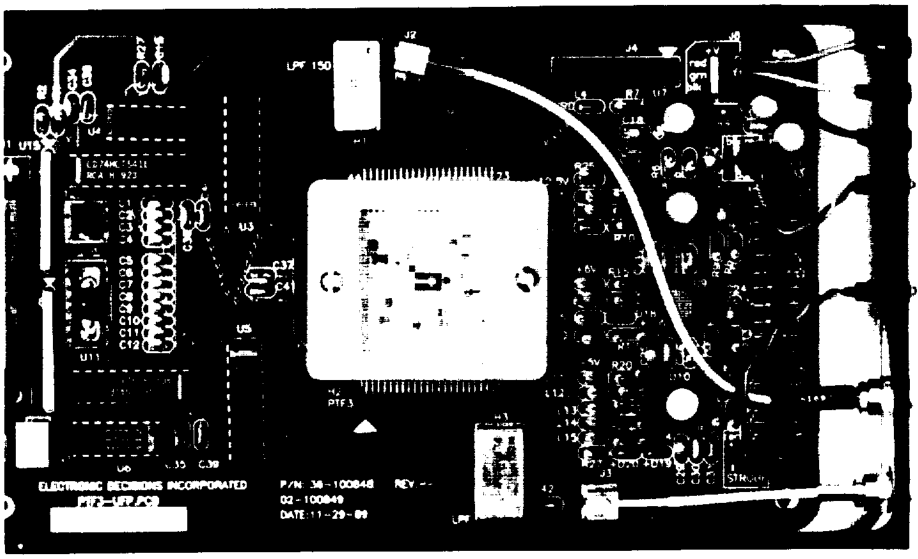


Fig. 8. ACT PTF module.

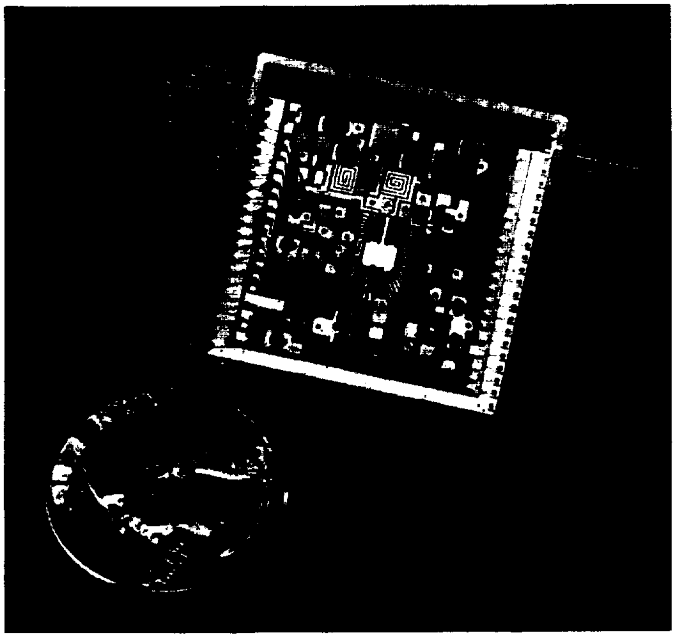


Fig. 9. ACT processor.

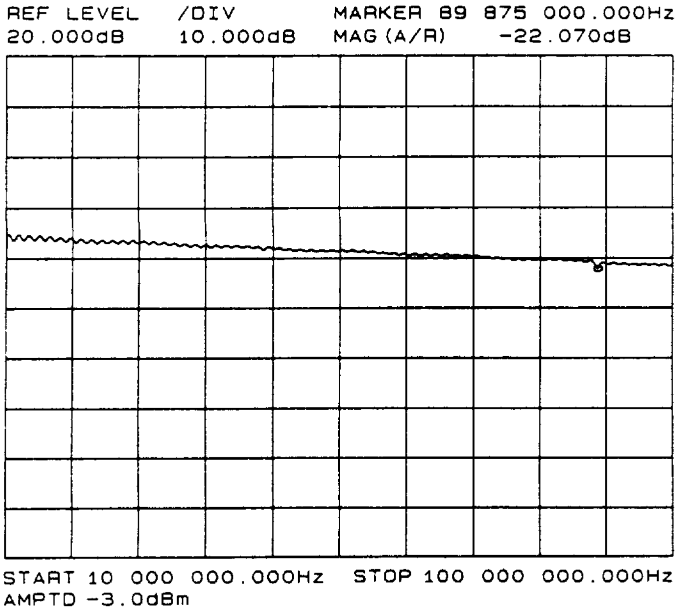


Fig. 10. ACT PTF single-tap frequency response.

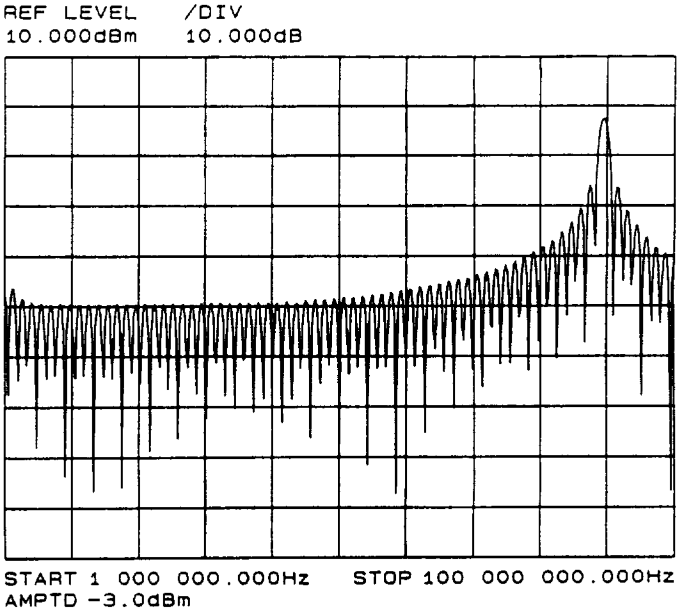


Fig. 11. ACT PTF frequency response with alternating +1 and −1 taps.

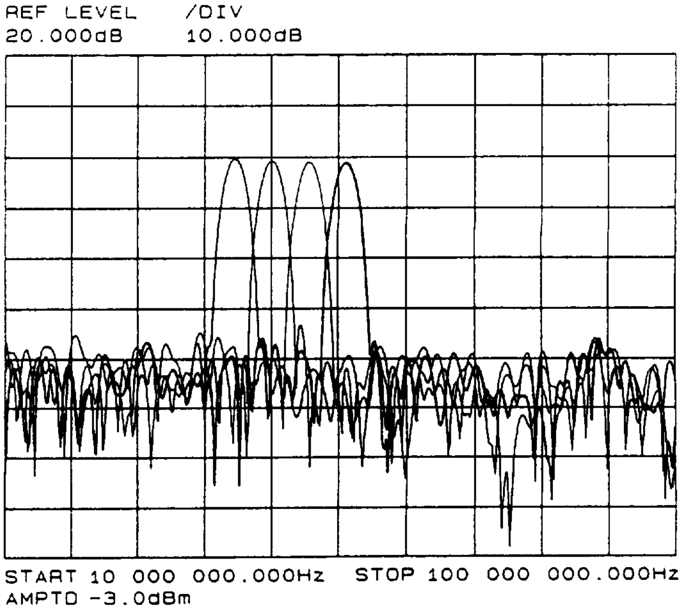


Fig. 12. ACT PTF center frequency control.

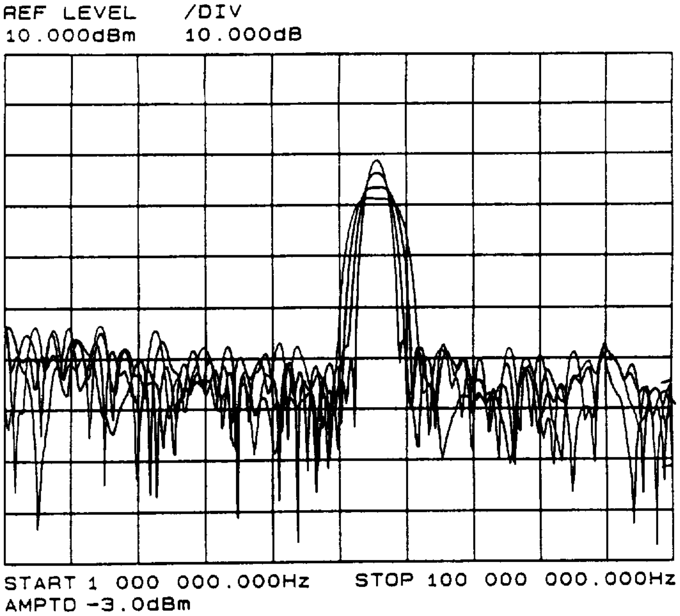


Fig. 13. ACT PTF bandwidth control.

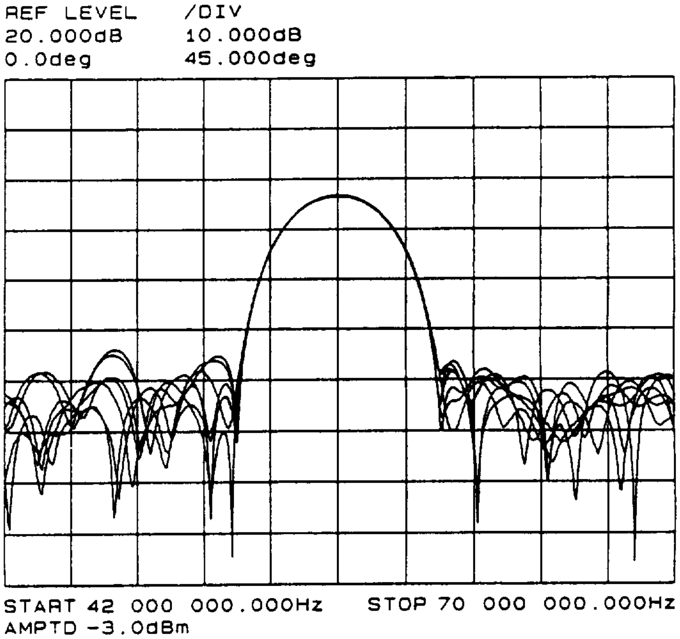


Fig. 15. ACT PTF passband constant amplitude during phase control.

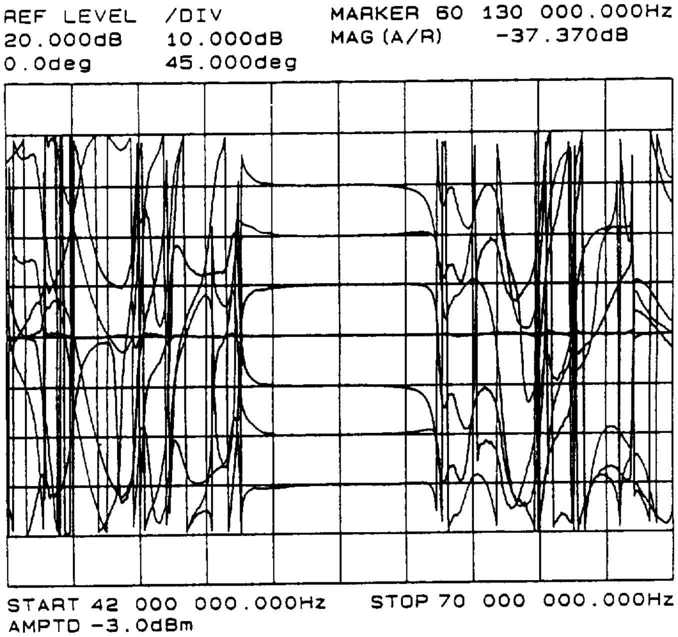


Fig. 14. ACT PTF passband phase control.

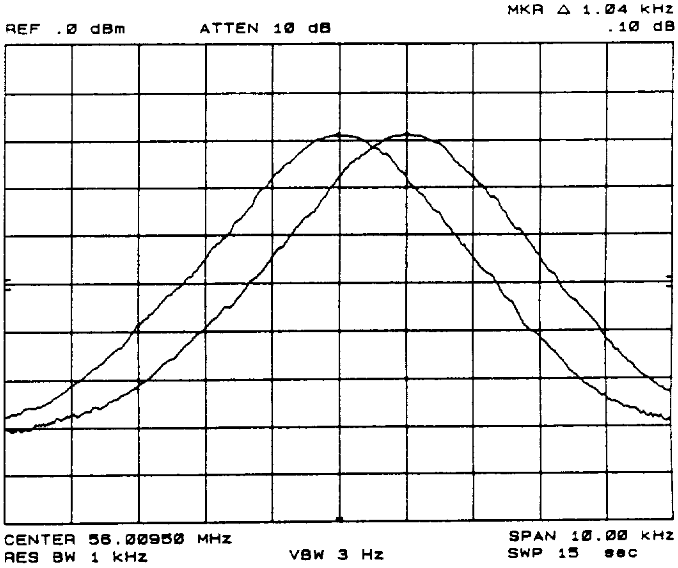


Fig. 16. ACT PTF oscillator relative frequency setability.