Performance of Acoustic Charge Transport Chirp Filters

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Abstract —The measured performance of acoustic charge transport (ACT) based linear FM dispersive delay line filters is presented and compared to modelled performance. The excellent agreement between the theoretically predicted device performance and the measured results shows clearly that apodization of the nondestructive sensing array is an effective means for achieving weighted ACT filter responses.

I. Introduction

THE OBJECTIVE of this work is to report the development of acoustic charge transport (ACT) based linear FM chirp filters. Acoustic charge transport delay lines have been employed to achieve a variety of signal processing functions. Devices demonstrated to date include fixed tap transversal filters, programmable tapped delay lines, convolvers, variable delay analog memory devices, and analog-to-digital converters [1], [2].

The following section provides a description of an ACT delay line and the principles of operation of an ACT linear FM chirp filter [1]–[8]. The third section of this paper presents the initial experimental results and performance evaluation of ACT chirp filters. This is followed by a section describing measured data from other ACT delay lines and filters.

II. Device Description and Operation

The ACT device [1]–[10] is a new type of high-frequency monolithic charge transfer device, and so is similar to CCD's and other transversal filter signal processors. In the ACT device illustrated in Fig. 1, a powerful, unidirectional, single-frequency surface acoustic wave (SAW) is generated by the combined operation of a transducer and a reflector, when an appropriate electrical excitation is provided. Typically, 27 dBm of electrical power is supplied to the transducer at its center frequency. The SAW travels from left to right as shown in Fig. 1 from the transducer, past the input contact, through the channel, and then past the output contact. The channel is composed of GaAs semiconductor material which has been depleted of mobile carriers by dc bias voltages. This is illustrated in Fig. 2, which depicts a cross section of the device along the direction of propagation of the SAW. In Fig. 2, dc bias voltages are shown applied to the (ohmic) input and (forward-biased Schottky barrier) output contacts relative to the (reverse-biased Schottky barrier) nondestructive sense array (NDSA). Fabrication details are discussed in [1]–[7]; [1] and [7] are particularly detailed descriptions. The ACT channel is electrically isolated from the rest of the device by proton bombardment [3] of the GaAs epitaxial layer outside of the channel area.

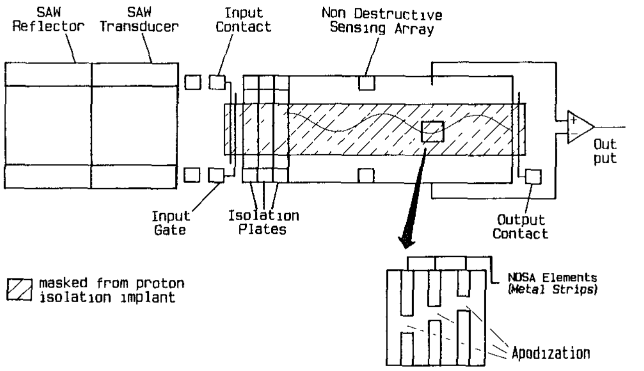

Fig 1. Overhead view of a proton isolated ACT delay line. Direction of SAW propagation is from left to right.

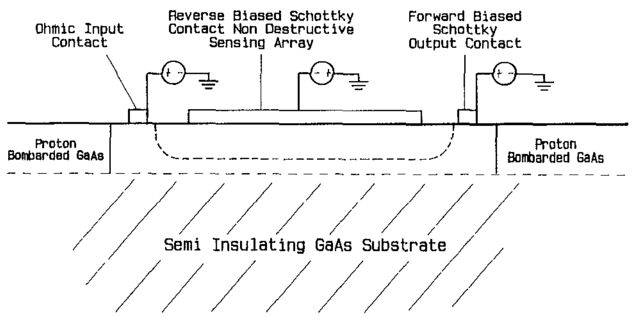

Fig. 2 Cross section of ACT delay line and typical bias voltage scenario. SAW propagation is from left to right.

During operation of the ACT device, mobile carriers are injected into the semiconductor channel by the RF voltage applied to the input contact. Here, they are gathered and transported within the electrical potential extrema of the powerful SAW. The high-frequency SAW is thus the sampling clock for an ACT device. The injected charge samples are then transported, at the SAW velocity, through the channel and past the NDSA, and finally they are removed from the channel by means of a positive dc bias voltage on

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the output contact. The NDSA structure is capacitively coupled to the charge samples in the channel, forming the basis for a transversal filter. The desired filter response can be embedded in the NDSA structure by apodization of the electrode lengths over the channel. Other means for weighting the NDS element responses are available as well.

The objective of this work is to develop techniques for designing and constructing linear FM dispersive delay lines, or chirp filters, utilizing ACT technology. The devices discussed here are the result of the initial ACT chirp filter device efforts. The filters shown here are examples of monolithic GaAs signal processors having bandwidths of 45 MHz, center frequencies of 90 MHz, clock frequencies of 360 MHz, and a dispersive delay of 0.5 μs, providing a time–bandwidth product of 22.5. The weighting technique employed to achieve the desired frequency response and to compensate for the frequency dependence of the ACT NDS output signal [10] relies on apodization of the NDSA structure (a grid of one eight an acoustic wavelength, or 1-μm electrodes connected to summing buses at either end, and extending across the channel as shown in Fig. 1). The apodization of the charge-sensing structure is similar to that employed in SAW and CCD filters.

III. Experimental Results/Performance Evaluation

The measured ACT chirp filter frequency response is compared to the predicted response in Fig. 3, and excellent agreement is obtained. A tap weight error of the order of −43.9 dB was obtained by computing the root-mean-squared value of the difference in linear amplitude between the ideal and experimental normalized frequency responses. Apodization relies on a uniform (or at least a known) distribution of signal strength along the length of the sensing element which extends across the channel. A calculation of the expected weight of a sensing element is possible when the spatial distribution of signal energy is well known. It is for this reason that SAW filters employing two apodized transducers use a multistrip coupler.

The success of apodization in faithfully reproducing the desired response is not immediately obvious when one examines the amplitude of the SAW as a function of position across the channel width. The amplitude of the SAW is measured using a knife edge laser probe [11]. The channel is 400 μm wide (or 50 SAW wavelengths), centered in the SAW profile shown in Fig. 4. The SAW electrical potential is directly proportional to the surface corrugation measured by the laser probe. The measured nonuniformity of the SAW amplitude across the channel suggests that the charge in the channel will not be uniformly distributed across the channel width, as is required for the NDS element weights to be proportional to the electrode length. If the charge distribution which represents the input signal were proportional to the measured SAW amplitude, then the NDS element weights, set by the apodization of the NDS elements, would be distorted.

In practice, however, the degree of modulation of the channel charge by the input signal is such that the nonuniformity of the SAW across the channel is not significant to device performance. At maximum input amplitude for distortion-free operation, the peaks in the SAW potential are smoothed by the small fraction of the channel quiescent current which is not modulated by the input signal. This excess quiescent current slightly reduces the headroom available for input signal storage, but the reduction in device dynamic range is less than 3 dB. Smaller input signal levels result in charge variations from

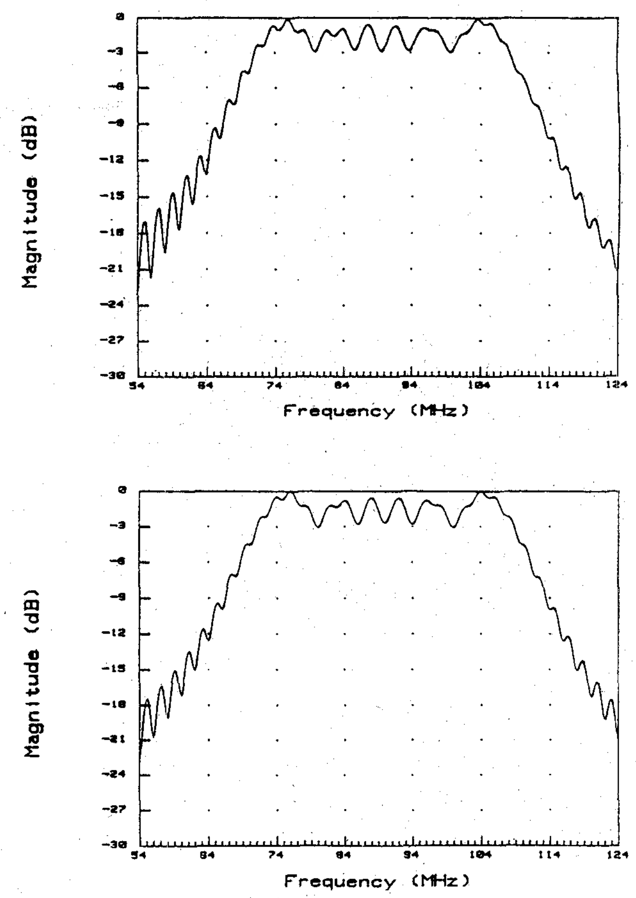

Fig. 3. Measured performance of ACT chirp filter (upper) and modeled performance (lower).

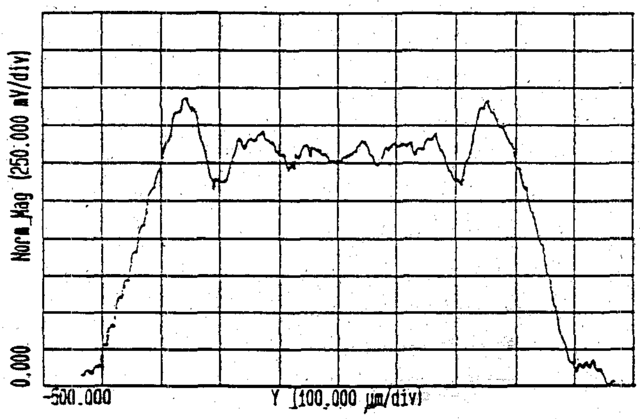

Fig. 4. Amplitude of SAW clock across channel width as measured by a laser probe. Vertical scale is amplitude (arbitrary units); horizontal scale is 100 μm per division. The ACT channel extends across the middle 400 μm of the figure.

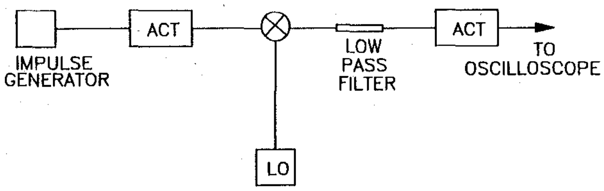

Fig. 5. Test setup used to convolve impulse responses of two upchirp filters.

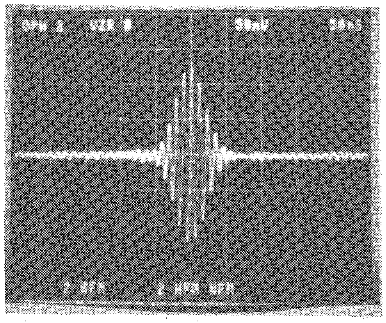

Fig. 6. Measured time-domain device response for two chirp filters (one with Hamming weighting, one as in Fig. 3) in setup depicted in Fig. 5.

packet to packet which are uniform across the width of the channel (along the NDS element length), resulting in high-fidelity realization of NDS tap weighting by apodization.

The smoothing effect of the excess quiescent channel current on the electrical potential of the SAW is analogous to the smoothing effect of a body of water. An example might be a stream with an irregular bottom and vertical sides. An initial amount of water covers the irregular bottom and results in a flat surface. Additional water added to the stream is then directly proportional to additional stream depth, across the entire stream. In the ACT device, the total charge distribution is not uniform across the channel width, but the variations in charge which represent the stored signal are. This is the reason for the success of the NDS element apodization in faithfully reproducing the desired tap weights.

Two ACT chirp filters were used to measure the convolution of their impulse responses when connected in cascade. This is performed experimentally by impulsing the first device and then mixing the device impulse response with a single at twice the filter center frequency. The signal resulting from the difference between the LO and device response frequencies has the opposite chirp slope of the device impulse response, and has the same center frequency. This signal is the equivalent of the time-reversed device impulse response. After low-pass filtering to obtain only the opposite chirp direction, the time-inverted impulse response of the first device is recompressed by filtering it with the second device. The experimental arrangement is shown in Fig. 5. This arrangement was required as only upchirp filters were available at the time that this work was done. Time-domain sidelobe levels for the expander and a Hamming weighted compressor connected in cascade as in Fig. 5 are measured to be 21.5 dB and are theoretically computed to be 22.7 dB. The measured result is illustrated in Fig. 6.

IV. Conclusions/Other ACT Devices

The absence of second-order effects, which are particularly troublesome in SAW filters, results in simplified design procedures for ACT filters. If present, such effects would result in discrepancies between the measured and the predicted filter responses. The excellent agreement between the theoretically predicted device performance and the measured device performance shows clearly that apodization of the NDS array is an effective means for achieving weighted transversal filter responses. In the time since the initial chirp filter work was done, several extensions of the work have been accomplished.

ACT devices designed as delay lines using a SAW clock frequency of 600 MHz and a delay of 1 μs have been fabricated and tested. These devices have demonstrated charge transfer efficiencies in excess of 0.99998, measured by the frequency response method [12]. Other 600-MHz devices have been built as transversal filters. Fig. 7 shows the experimental frequency response of an ACT chirp filter having a bandwidth of 217 MHz, a center frequency of 147 MHz, a SAW clock frequency of 600 MHz, and a dispersive delay of 1.4 μs, providing a time–bandwidth product of 303.8. While these devices are still under investigation, they have provided blocking dynamic range measurements of the order of 82 dB. In these blocking dynamic range measurements, the NDS output signals due to a large and a small amplitude input signal are measured on a spectrum analyzer. In the absence of the large signal, the level of the small signal is adjusted to achieve a signal-to-noise ratio of 3 dB. The large signal is increased in amplitude until the output due to the weak input signal is compressed in amplitude by 1 dB.

Recent work using ACT devices employing 127-bit maximal sequence codes rather than a linear FM apodization has provided measured time-domain peak to RMS sidelobe level ratio of 53 dB. This measurement was obtained by measuring the peak value then gating out the peak to measure the RMS sidelobe level without saturating the measurement system. This measurement indicates also the deviation from the ideal device response of an infinite ac peak to sidelobe ratio. The physical origins of the deviations from the ideal are still under investigation. A correlation response from such a device is illustrated in Fig. 8. Additionally, a group of four such devices has been connected such that the delay lines are in cascade, while their NDS outputs were connected in parallel. The delay line output is obtained from this forward-biased output contact at the far right in Figs. 1 and 2. This resulted in the demonstration of an extension of the time–bandwidth product for the group of devices by a factor of four over that of an individual device.

The cascading results are made possible by two properties of the ACT devices which are unique in the frequency range being considered here. The first of these properties is that the delay line output has no frequency

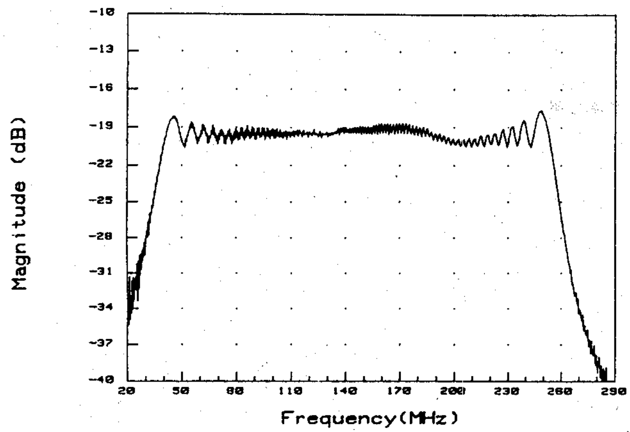

Fig. 7. Measured frequency response of an ACT chirp filter featuring a SAW clock frequency of 600 MHz.

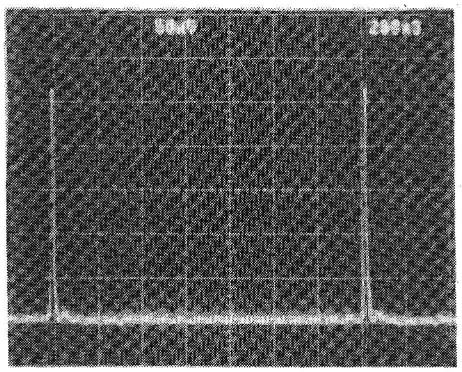

Fig. 8. Compressed pulse from 127-bit pseudonoise correlator device when the input signal is derived from an ECL code generator.

dependence over the Nyquist bandwidth of the delay lines (the delay line frequency response is flat to 0.1 dB). Cascading of devices without band-limiting due to a frequency dependence of the delay lines is thus possible in practice. The second property is that the output of a time-domain sampled device has a stability which is set by the clock stability, rather than by the stability of the device delay. These unique properties of the ACT delay lines allow them to be cascaded without suffering the limitations present for other technologies, such as SAW. This pseudonoise correlator device provides a signal-to-noise dynamic range of 92 dB when the compressed pulse amplitude is monitored. This was measured by varying the input signal amplitude from a level just below that large enough to result in increased sidelobe levels in the NDS output signal, to a small input signal level which provided an NDS output pulse which was 3 dB above the noise level.

The basic operational principles and performance of ACT chirp filters are summarized and experimental results are given along with a brief summary of the performance of other ACT devices, which together demonstrate the impact of ACT technology in the field of high-speed analog signal processing. The excellent agreement between the theoretically predicted device performance and the measured results demonstrates clearly the accuracy with which ACT devices can perform a variety of signal processing functions.

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References

[1] R. J. Kansy, M. J. Hoskins, and B. J. Hunsinger, "Analog–digital interface," Tech. Rep. No. RADC-TR-86-112, 1986 (available from DTIC).

[2] F. M. Fliegel, "An analysis of traveling-wave mixer structures," Ph.D. dissertation, University of Illinois at Urbana-Champaign, 1987 (available from University Microfilms International).

[3] M. J. Hoskins *et al.*, "Acoustic charge transport principles and performance," in *Proc. 1986 Freq. Cont. Symp.*

[4] M. J. Hoskins, H. Morkoc, and B. J. Hunsinger, "Charge transport by surface acoustic waves in GaAs," *Appl. Phys. Lett.*, vol. 41, pp. 332–334, Aug. 1982.

[5] M. J. Hoskins and B. J. Hunsinger, "Buried channel acoustic charge transport in GaAs," in *1983 GaAs I.C. Symp. Tech. Dig.*

[6] M. J. Hoskins, E. G. Bogus, and B. J. Hunsinger, "Experimental performance of the buried channel acoustic charge transport device," *IEEE Electron Device Lett.*, vol. EDL-4, pp. 396–399, Nov. 1983.

[7] M. J. Hoskins, "Acoustic charge transport in gallium arsenide," Ph.D. dissertation, University of Illinois at Urbana-Champaign, 1983.

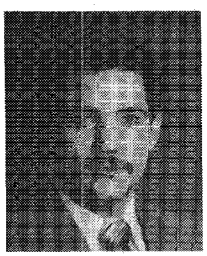
[8] M. J. Hoskins and B. J. Hunsinger, "Simple theory of buried channel acoustic charge transport in GaAs," *J. Appl. Phys.*, vol. 55, pp. 413–426, Jan. 1984.

[9] M. J. Hoskins and B. J. Hunsinger, "Recent developments in acoustic charge transport devices," in *1986 IEEE Son. Ultrason. Sym. Proc.*

[10] C. E. Warren, "Nondestructive sensing in buried channel traveling wave charge transfer devices," Master's Thesis, University of Illinois, 1985.

[11] R. Adler, A. Korpel, and P. Desmares, "An instrument for making surface waves visible," *IEEE Trans. Sonics Ultrason.*, vol. SU-15, no. 3, July 1968.

[12] C. N. Berglund, "Analog performance limitations of charge-transfer devices for delaying analog signals," *IEEE J. Solid-State Circuits*, vol. SC-8, no. 2, Apr. 1973.



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