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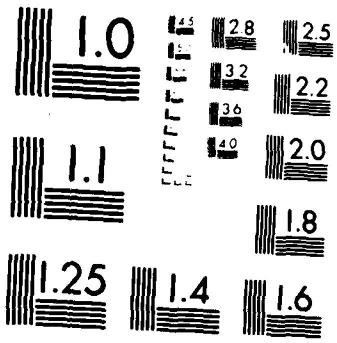

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Comparison of New Analog Device Technologies for Signal Processing*

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Introduction

In this paper I express my opinion regarding the relative merits of digital and analog signal processing technologies. My viewpoint is based primarily on my own experience within M.I.T. Lincoln Laboratory. It is influenced both by the relative effectiveness of a given technology to provide a wide range of signal processing functions, and by the attitudes of potential users to such "strange" technologies as SAW, CCD, optical and superconductive devices. I will try to convince you to share my view of the relative merits of the several technologies by (1) defining signal processing, (2) establishing criteria for the selection of competing technologies, (3) delineating the limits of conventional techniques, (4) discussing the goals of VHSIC, and the unique advantages of SAW, CCD, optical and superconductive technologies, and (5) drawing some general conclusions.

1. Definition of Signal Processing

The purpose behind the processing of signals is to improve the signal-to-noise or -interference ratio to an acceptable level. This is usually accomplished by linear processing techniques such as correlation, convolution, temporal or spatial summation or integration, spectral analysis such as Fourier transformation, matched or band-pass filtering, and so on. The ideal signal processing device transfers the signal to the output optimally while suppressing the noise or interference by a predictable amount. This improvement in signal-to-noise ratio, called signal processing gain, is typically in the range of 20 to 30 dB. Practical devices do not achieve the ideal signal transfer characteristics and often add noise and interference to the output as well. This results in a net signal-to-noise ratio reduction called implementation loss. Usually, implementation losses of no more than about 1 dB can be tolerated, and this in turn places stringent requirements on band-pass characteristics, dynamic range, and the suppression of self-generated noise and interference signals. Only those technologies will be discussed which have the capability of providing many different processing functions with signal-processing gain of 20 dB or more, and with minimal implementation loss. These criteria eliminate from discussion magnetostatic and optical fiber devices because the requisite performance has not, to my knowledge, been demonstrated.

2. Criteria for the Selection of Technology

We are engaged in developing new technologies partly because we enjoy working at the frontier of applied physics and device design. Therefore we welcome, we are delighted with new ideas, concepts and techniques, and we work very hard to realistically demonstrate the advantages of our creations to system designers. Most of the time our devices are summarily rejected in favor of older, more cumbersome and unexciting techniques, and it is rarely that our technology is selected. It is necessary to understand the reasons for this decision so that we can more effectively focus our energies on productive goals.

System designers are committed to delivering a product that meets specifications on time and within overall budget allowances. To such a designer, new, untried devices represent an unknown risk, especially if the devices are outside the training and experience of the design staff. Most systems requiring high-performance signal processing functions are large, primarily digital, and expensive. Therefore digital signal processing solutions are compatible with the rest of the system hardware and with the accummulated experience of the staff. Although higher-performance devices could provide substantial savings in the signal processor, these savings usually are a small fraction of the overall system cost, and these marginal savings do not compensate for the potential risk of missed deadlines and the associated expense. Thus the insertion of new technology into a system occurs only if there is a compelling reason to use it, and this happens only if there is no other, more conventional way for achieving the requisite performance. Once the new technology performs adequately, then resistance to its use vanishes within the system design group, and other, less compelling utilization would occur in subsequent systems, provided reliable suppliers of the new technology are available. Usually these new devices are produced within the research branch of the company developing the system. Such groups are ill-equipped to provide follow-on engineering and production services, and new sources must in consequence be established. The creation of a new design and production facility requires both entrepreneurial

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[illegible] a deep appreciation of the new tech- [illegible] generally large corporations are [illegible] to assign their best people to develop [illegible] of limited sales potential, and in [illegible] provide only limited resources to the [illegible]. It has been my experience that these [illegible] attempts result in needlessly expensive [illegible] efficient operations. This in turn pro- [illegible] competitive advantage to new, dedicated [illegible] that enter the field. Thus new tech- [illegible] becomes established only if there is [illegible] compelling need for it, there is [illegible] leverage on system sales to cause [illegible] corporations to create a modest production [illegible], and there is eventually a sufficient [illegible] to attract new companies.

[illegible] processors are usually imbedded [illegible] systems, and the compatibility of a [illegible] with digital devices is important, [illegible] additional costs of providing digital [illegible] and other special features can be the [illegible] its rejection. In addition, the new [illegible] should be readily manufacturable if it [illegible] gain wide acceptance. Therefore, devices [illegible] can be made with conventional microfabrica- [illegible] methods are preferred. Finally, technol- [illegible] that have been perfected to the point where [illegible] applications have occurred elsewhere are [illegible] over untried methods.

[illegible] selection criteria are applied to the [illegible] new technologies, and the results are [illegible], in decreasing order of preference, in [illegible] I. The weights in Table I are in accordance [illegible] impression of the inverse degree of [illegible] of each feature.

TABLE I
RELATIVE ACCEPTANCE OF
[illegible] PROCESSING TECHNOLOGIES

[illegible]	TECHNOLOGICAL [illegible]	MANUFACTURABILITY	INTERFACE COSTS	PERIPHERAL [illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	2	2	[illegible]
SAW	[illegible]	2	[illegible]	[illegible]
OPTICAL	[illegible]	4	4	3
SUPERCONDUCTIVE	4	[illegible]	4	5

[illegible] NUMBERS ARE INVERSELY RELATED TO PREFERENCE

Technological risk exists when there is little direct experience with a technology. The [illegible] experience with SAW devices makes them substantially less risky than untried superconductive devices. Silicon VHSIC devices are to be manufactured in upgraded production facilities, whereas CCD and SAW devices may require modified microfabrication equipment and procedures. Both optical and superconductive devices require new facilities for their manufacture. The digital outputs of VHSIC circuits can be made compatible with conventional digital circuits, and in consequence the interface costs are likely to be small. CCD and SAW inputs and outputs are analog, and they may therefore require digital-to-analog (D/A) and analog-to-digital (A/D) converters at their interfaces. The bandwidths of the inputs and outputs of both optical and superconductive devices are usually too wide for D/A and A/D converters. Thus these technologies are useful primarily for the processing of wideband analog signals. The output circuits of such devices usually include wideband detectors, comparators and integrators that extract the relatively narrower bandwidth data contained in the very wide bandwidth output signal. This data usually occurs at a rate that is compatible with conventional A/D converters. VHSIC circuits are likely to be compatible with conventional digital environments and power supplies, and in consequence require little additional peripheral equipment. However, CCDs require dedicated power supplies and drive circuits. SAW devices need special ovens or dedicated calibrating equipment in order to keep the SAW output signals aligned with the digital system clock. Optical systems may require both special power supplies and elaborate mechanical hardware for the stable mounting of optical components, and superconductive devices require the very substantial investment in cryogenic coolers and interfaces.

3. Limitations of Digital Signal Processors

Digital signal processing circuits are specialized computers that are designed to calculate the desired signal-processing function. An example of this is the fast-Fourier-transform (FFT) array processor which is a dedicated, efficient mathematical simulation of the process that occurs in a lens. (In a lens the image plane is the Fourier transform of the object plane.) Digital signal processing techniques are highly developed, and it is possible to quantify the magnitude of the process in terms of the number of arithmetic operations per second. Once this is known, then an estimate can be made of the number of transistors needed to perform the desired functions, and from this the size, cost and power requirements of the processor can be deduced. We at Lincoln Laboratory have extended this analysis to analog devices as well, by calculating the number of operations per second (OPS) that would be required by a conventional digital approach for the equivalent signal-processing function. This calculation provides a convenient means for comparing the effectiveness of analog signal processing techniques with respect to conventional digital methods.

Our digital reference is the RADIX II FFT (Ref. 1), which requires a computational rate

$$R = 5\gamma BN \log_2(\gamma N) \quad \text{OPS}, \tag{1}$$

where N is the size (or number of points) of the Fourier transform, γ the Nyquist factor, and B the bandwidth of the signal. Notice that the size of the processor is directly proportional to the bandwidth. This is a major limitation of digital techniques because wideband continuous signals require a huge amount of computation. This approach is valid for the processing of relatively large transforms, where $N > 32$. In this situation the size of the FFT is the greater part of the signal processor. However, if $N < 32$, the peripheral electronics of the FFT dominates, and more direct methods, such as the discrete Fourier transform, can be more efficient. The equivalent rate of an analog Fourier transformer can be computed by direct substitution in Eq. (1). The digital equivalent of a fixed matched filter function requires that the Fourier transform of the signal be obtained. The transform is mutiplied with a set of stored weights, and the inverse Fourier transform provides the desired output. Thus the size of a fixed matched filter is estimated by setting $N = TB$, where TB is the time-bandwidth product of the filter, and $\gamma > 2$; the number of operations per second are then somewhat greater than 2R. (In continuous real-time applications two interlaced inverse transforms are required, and the equivalent size of the process would be greater than 3R.) The convolution or correlation of arbitrary, continuously changing waveforms require the Fourier transform of the reference as well as the signal, and the size of an equivalent Radix II processor is greater than 3R. We have plotted the computational rates of several digital and analog devices in Fig. 1. The entries on the left are digital, those on the right are analog. The array processor providing 10^8 OPS is a state-of-art device. One of the

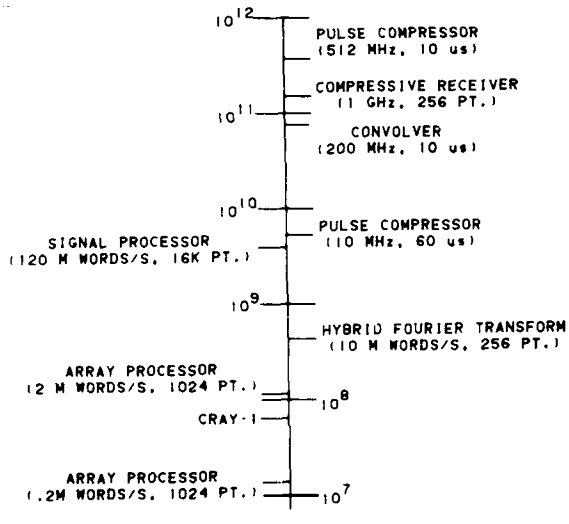

Figure 1. Computational speed of several representative signal processing devices. Entries on the left are digital, on the right analog.

largest digital radar signal processors built in the past decade provides 3×10^{10} OPS. It is housed in five 7-ft-high cabinets and requires 48 kW. By contrast, a SAW fixed matched filter, with a 512-MHz bandwidth, is housed with its peripheral circuits in a drawer, requires a few watts, and performs an equivalent processing rate of 3×10^{11} OPS.

Clearly currently available analog devices can provide substantial savings in hardware and power in relation to state-of-art digital approaches, especially when the bandwidth is wide and $TB > 10$. Indeed, analog approaches are generally used whenever the size, weight and power consumption is of primary concern to the system designer. However, in systems where these are not overiding issues, digital approaches continue to be used, for the reasons outlined in the previous section.

The data in Fig. 1. represent the accomplishments of the past, but current research efforts should compare favorably with VHSIC technology in the near term, and with digital GaAs technology in the 1990's. The goals of VHSIC are summarized in Fig. 2. This figure is reproduced from an

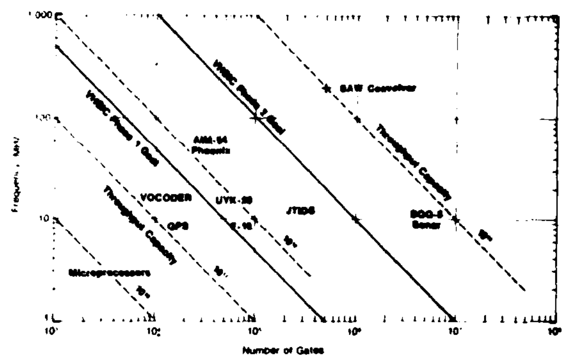

Figure 2 - Computational rate as function of gate density in integrated circuits. The dotted diagonal lines represent constant gate-Hz/cm^2. The entries are requirements for systems. The solid diagonal lines are VHSIC Phase 1 and Phase 2 goals.

article that appeared in Aviation Week (Ref. 2) about two years ago. It shows the needs of various military systems for advances in digital signal processing technology. These entries are consistent with system needs for signal and data processors of acceptable size, weight, and power requirements. These needs are expressed in terms of the bandwidth and the number of gates/cm^2 in digital integrated circuits. For example, microprocessors contain Si chips with a few thousand gates/cm^2 and they operate at a few megahertz. The dotted diagonal lines are constant gate-Hz/cm^2, which is equivalent to the processing rate per unit area. Note that system requirements exceed 10^{13} gate-Hz/cm^2. The goals of VHSIC Phase 2, a technology which is to be demonstrated by 1986 and to be realized by 1990, is targeted to provide this processing rate. The SAW convolver, with an equivalent processing capability of 10^{14} gate-Hz/cm^2, was perfected in 1980.

As in any one-dimensional comparison, the relative position of a given technology in Fig. 2 can be misleading. For example, analog CCD devices with modest equivalent gate densities nevertheless can have exceptional advantages over VHSIC Phase 2 technology. This will be discussed in the next section. Finally, VHSIC devices provide a much greater range of signal and data-processing functions than is possible with analog methods. Thus the subsequent conclusions are meaningful only in the narrow sense of the linear signal processing functions discussed in this paper. Data processing functions and nonlinear or conditional processes are provided only by digital means.

4. Advantages of Analog Signal Processing

The crucial advantage that compels a designer to specifiy a particular technology is very much a function of intended application, and it is therefore not possible to assign preference, in a broad general way, to a technology for a given signal processing function. I intend to share with you our own parochial reasons for exploring certain devices. The message that I wish to communicate is that it is possible to develop a rationale for a research program within a given organization. Our particular conclusions are useful only to those laboratories that serve the needs of advanced radar and communications systems; they are not necessarily applicable to other situations.

We are developing analog CCDs with conventional silicon MOS technology. Thus the bandwidth limitations of that technology apply to both analog and digital devices. We are pursuing this technology despite its performance overlap with digital circuits because it has about an order-of-magnitude advantage in processing capability per unit area with respect to digital approaches. The key to that advantage is the multiplying digital-to-analog converter (MDAC) is shown in Fig. 3 (Ref.3). The figure is a schematic top view of an array of ohmic sources and transfer gates. The width of the gates are increased in binary fashion as shown. The binary digital input turns the source gate either fully on or off, and the adjacent holding well is either fully filled or held empty of charge. The amount of charge transferred to the output well is proportional to the analog potential on the intervening gate. Thus the sum of the output charges is the product of the digital and analog inputs. The chip in Fig. 4 contains 32 MDACs, each capable of multiplying an 8-bit word with an analog signal at a 10-MHz clock rate (Ref. 4). By contrast, an equivalent digital multiplier of one MDAC would require a substantial portion of this total chip area. In addition to the MDACs the chip includes input and output shift registers, and the output of each MDAC is connected to 32 holding wells. One application of this chip is to perform the complete doppler processing for 32 range cells, including the buffering and staging of the data. There are 32 doppler cells provided for each range cell. The equivalent performance with a conventional digital approach could be achieved only with a ten-fold increase in component count and silicon area.

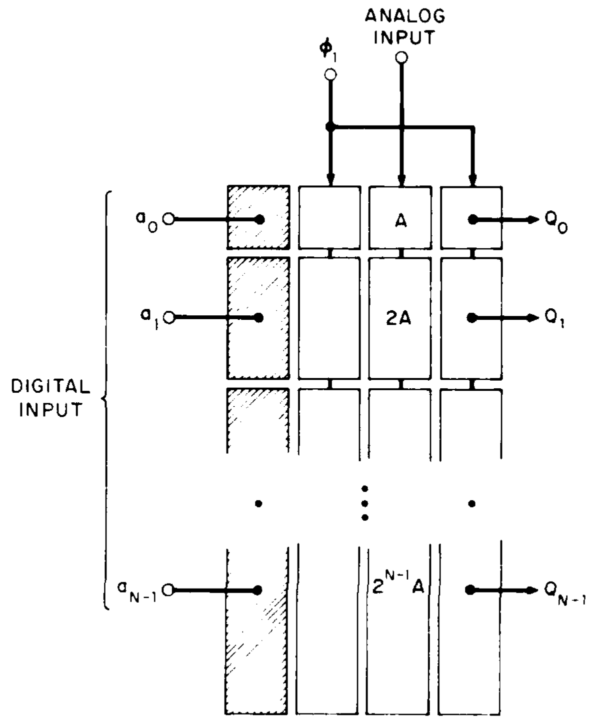

Figure 3 - Schematic diagram of multiplying digital-to-analog converter (MDAC). The digital input on the left turns on (or off) the ohmic cross-hatched source. The first well is either fully filled or empty of charge. The amount of charge transferred to the output gates is proportional to the analog signal. The combined output charge from all the gates is proportional to the product of the digital and analog signal.

A schematic of a reflective-array compressor (RAC) is in Fig. 5 (Ref. 5). It consists of metallic input and output transducers and two mirror-image etched gratings. The grating period increases with distance from the input, and strong Bragg reflection from input to output occurs when the wavelength matches the grating periodicity. This device is designed to provide a linear frequency-modulated impulse response. Key to the utility of this device is the phase-compensating film that is inserted between gratings. The pattern corrects phase errors inherent in the

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grating and crystal, and phase errors of no more than several parts per million are customarily achieved in devices with bandwidths of several hundred megahertz and time-bandwidth (TB) products of several thousand. The precision is needed in chirp-Fourier-transform applications, and the power-spectrum analyzer in Fig. 6 performs its function with about an order-of-magnitude less power, weight, and volume than its digital counterpart. A device with similar advantages is the elastic convolver (Ref. 6), in which the convolution of two arbitrary signals with bandwidths of several hundred megahertz and TB of more than 1000 can be obtained.

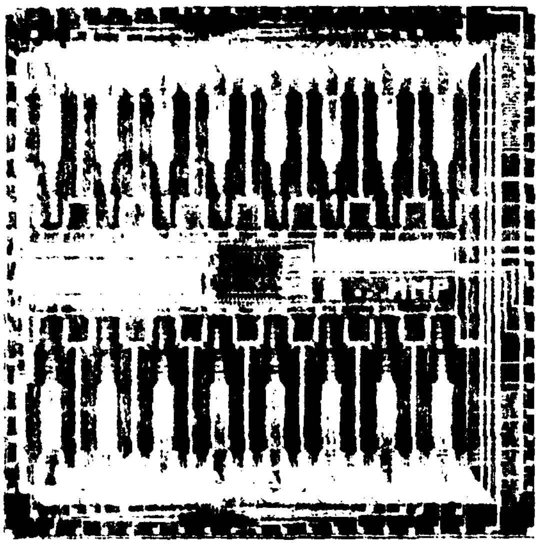

Figure 4 - Micrograph of 32-stage matrix-matrix product charge-coupled device.

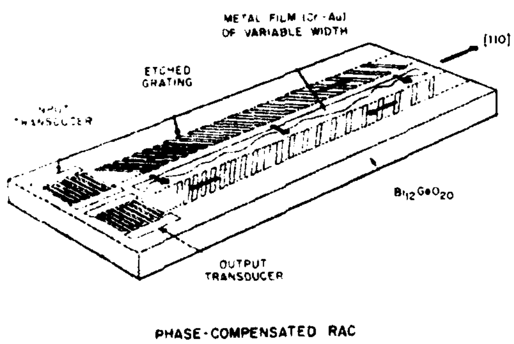

Figure 5 - Schematic of phase-compensated reflective-array compressor.

Optical signal-processing devices at Lincoln Laboratory have not been reduced to practice to the same degree as other technologies. However, we are pursuing this technology assiduously because it has two inherent key advantages. The first is the immense parallelism associated with optical devices. Energy converging to a point in an image-plane of a lens is the coherent sum of energy emitted from every point in the object plane. By interposing the appropriate amplitude and phase modulation between object and image plane it is possible to perform a large variety of signal processing functions in parallel, where each pixel in either the input or output plane can become an independent input or output. Key to gaining access to this potential processing capability are high speed, two-dimensional input and output planes. We have demonstrated the use of GaAs for this purpose (Ref. 7), and a development effort is just beginning. The second advantage is the high speed response of optoelectronic devices. Fig. 7 is a schematic diagram of an optoelectronic switch. It consists of a microstrip transmission line interupted by an interdigital capacitor on a block of semi-insulating InP. When the interdigitated region is illuminated with a diode laser, photocarriers are generated which connect input to output with a low resistance. When the light is turned off the connection is broken. The response of the switch to a short impulse of light is shown in Fig. 8 (Ref. 8). Note that rise and fall times of about 10 psec have been obtained, and the resultant signal sample at the output is without the switching noise that limits the speed of conventional sampling devices to a few nanoseconds. This unique switch together with similar optoelectronic components is likely to provide, in the low gigahertz range, the functions of sampling, mixing, modulation and A/D conversion.

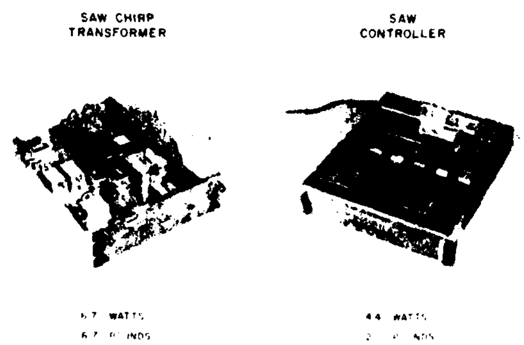

Figure 6 - Photograph of SAW chirp transformer and its associated controller.

Analog superconductive devices are being developed at Lincoln Laboratory for signal processing bandwidths in the 2-20 GHz range. Key to the utility of this technology is a low-loss superconductive transmission line on a silicon substrate. The loss per wavelength is plotted in Fig. 9 as a function of frequency. In this instance the line is 2000-A thick and about 10-μm wide. The losses associated with normal conductors lie outside this figure and are therefore unacceptable for signal-processing functions in the gigahertz range. Superconductive transmission lines are photolithographically defined, and

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InP OPTOELECTRONIC SWITCH

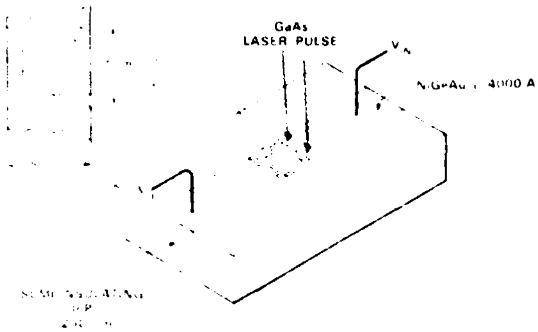
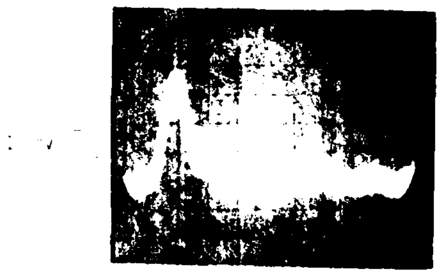


Figure 7 - Schematic diagrams of optoelectronic switch. The switch is normally off, except when flooded with light from diode laser.



50 psec

Figure - Response of InP optoelectronic switch to a short optical impulse.

length consistent with time-bandwidth products of several hundred can be incorporated on a single substrate. The loss experienced with SAW on $LiNbO_3$ is presented as well in the figure. Note that the miniature microstrip loss is an order of magnitude less than $LiNbO_3$, and time-bandwidth products of 1000 at 10-GHz bandwidth can be achieved only with microstrip. A disassembled dispersive delay line with a bandwidth of 2.3 GHz and a TB-product of 86 is shown in Fig. 10 (Ref. 9). Two devices were used, one to provide an expanded pulse and the other to compress it. The output compressed pulse and sidelobe level is within a decibel or two of the theoretically expected result.

The relative merits of the various technologies are summarized in Fig. 11. The ordinate of the figure is the bandwidth in gigahertz and the abscissa the time-duration in nanoseconds of the signal to be processed. The diagonal line is a constant TB product of 1000. All four technologies are expected to provide a full range of signal processing functions consistent with low implementation loss. The technologies are stacked in the same order as in Table 1. Thus, if all other considerations are

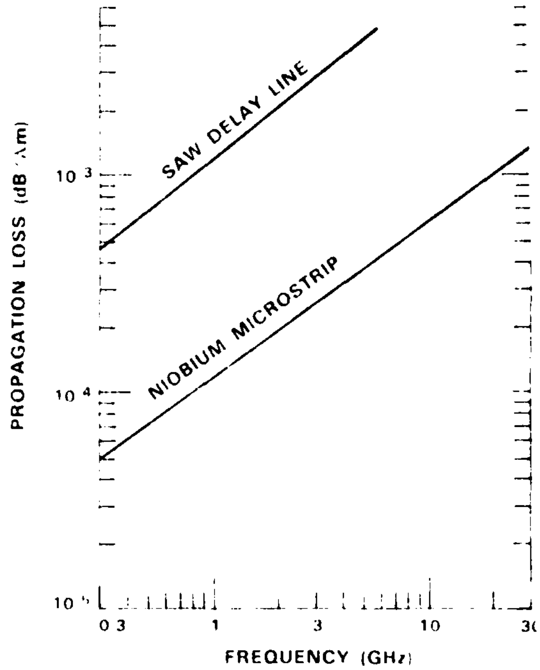


Figure 9 - Propagation loss in dB per wavelength for 10-μm-wide superconductive Nb microstrip and for $LiNbO_3$ SAW delay line.

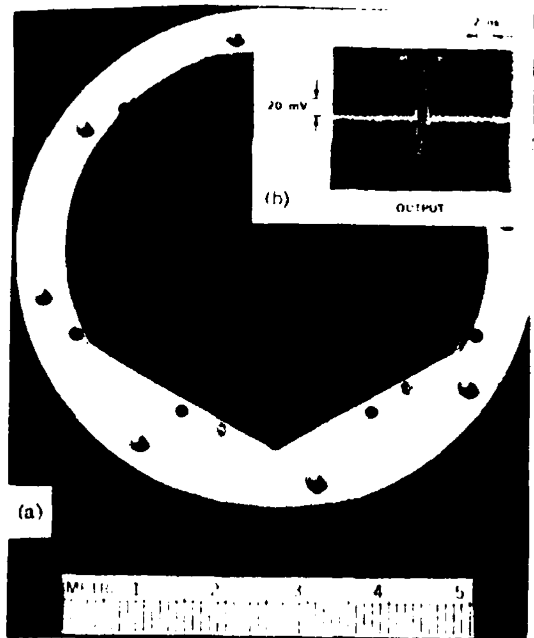


Figure 10 - Photograph of (a) superconductive dispersive delay line and of (b) output compressed pulse. The output is produced by a Hamming-weighted expander and compressor.

equal, CCD would be the preferred technology in the 10-MHz range even though SAW technology could provide the same function. The dotted lines show the approximate bandwidth limit to which a variety of devices can readily be made with time-bandwidth products of 1000. Thus, CCDs are likely to function to 20 MHz bandwidths, SAW devices to 200 MHz, optical devices to 2 GHz and superconductive devices to 10 GHz.

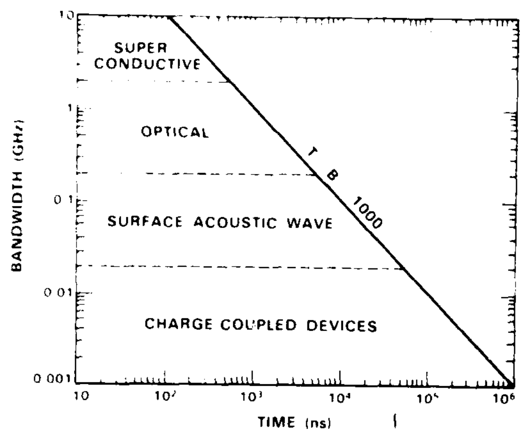


Figure 11 - Bandwidth limits of several signal processing technologies for a variety of devices with a time-bandwidth (TB) of 1000.

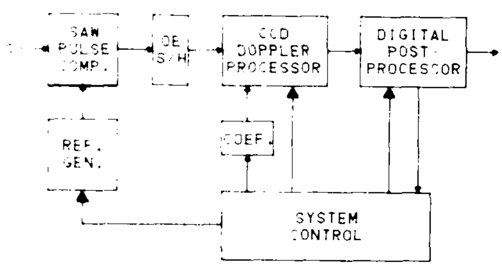


Figure 12 - Hybrid signal processor for doppler radar comprising SAW, CCD, opto-electronic and MOS digital devices.

The ideal arrangement for the processing of wideband signals would be a hybrid system in which the signal is processed by the technology appropriate to the bandwidth. Suitable interfaces would be used to lower the signal bandwidth in order to make the output compatible with digital A/D converters. A hybrid processor is currently being developed (Fig. 12) in which a wideband SAW convolver with a bandwidth of 200 MHz is interfaced with a 10-MHz analog CCD doppler processor with optoelectronic sample-and-hold circuits. The output of the CCD array is fully compatible with off-the-shelf digital post-processing circuits.

Conclusions

New signal-processing technologies are fully developed and used only if a needed capability cannot be provided by available digital means. Research and development of digital devices is progressing along a broad front, and it is therefore important to select goals for analog devices that exceed projected digital capabilities for signal processing by an order of magnitude or more. Once a new technology is successfully demonstrated in a system, a window in time occurs during which the technology may be used for a wide range of system applications. However, the actual use of a new technology is dependent on its general availability to potential users. That availability is related to its manufacturability, the leverage the new technology has on system performance, and the size of the potential market.

The acceptance of a new technology is also related to its compatibility with digital circuits. For these reasons potential users are likely to select, in decreasing order of preference, CCD, SAW, optical and superconductive devices. Optical and superconductive devices currently enjoy a major advantage of wider input bandwidth than competing technologies. However, their use is limited to applications where the output bandwidth can be decreased to the point where A/D converters are available. Therefore these wideband devices must include suitable detectors, comparators and integrators for the extraction of narrower bandwidth data from the wideband output signal before the data is transferred to A/D converters. Finally, these conclusions are parochial in the sense that they apply only to the needs of advanced radar and communication systems. Conclusions similar in kind but substantially different in detail could be drawn for other applications.

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Linear processing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In this paper I express my opinion regarding the relative merits of digital and analog signal processing technologies. My viewpoint is based primarily on my own experience within M.I.T. Lincoln Laboratory. It is influenced both by the relative effectiveness of a given technology to provide a wide range of signal processing functions, and on the attitudes of potential users to such "strange" technologies as SAW, CCD, optical and superconductive devices. I will try to convince you to share my view of the relative merits of the several technologies by (1) defining signal processing, (2) establishing criteria for the selection of competing technologies, (3) describing the limits of conventional techniques, (4) discussing the goals of VHSIC, and the unique advantages of SAW, CCD, optical and superconductive technologies, and (5) drawing some general conclusions.

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