LOGIC AT MICROWAVE FREQUENCIES

COURTSHIP OR MARRIAGE?

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INTRODUCTION

The recent advent of logic and pseudo-logic devices operating at microwave frequencies poses many questions and the investigations to date provide some --but not all--of the answers. Perhaps the most frequently asked question is "why do we need logic at microwave frequencies and how will it be used." These questions are inevitably followed by "how do we fabricate gigabit logic devices and who is already in the business." This paper will address these questions, pose others, and attempt to assess the future of both the technology itself and its relationship to future microwave systems. Competing and overlapping base technologies such as silicon, gallium arsenide (GaAs), indium phosphide (InP), Josephson junction (JJ), and others will be compared and their state-of-the-art and future capabilities assessed. Also addressed are such issues as the "cross pollination" of microwave engineers and logic device designers as well as selected application examples.

WHY?

What can one do with gigabits of data per second? Aside from sitting back and looking with astonishment upon such large data rates, there is plenty that can be done. Of even more importance, there are developing several things that can NOT be readily accomplished without these high data rates!

Counters

The ability to divide an r.f. signal by an integer factor *and* to maintain a precise phase reference between that r.f. signal and its divided (counted down) result provides engineers with new capabilities in metrology and in larger system applications. The ability of these devices to operate directly at the microwave frequencies also eliminates sources of inaccuracy and additional complexity accruing from the use of a heterodyne offset oscillator. As early as 1972 tunnel diode circuits were used in hybrid integrated configuration to count at frequencies up to 2 GHz.[1] Silicon discrete bipolar devices have operated as frequency counters at frequencies as high as 9 GHz[2] and in monolithic form at frequencies up to 2 GHz.[3] Monolithic gallium arsenide FET devices have been demonstrated to count at frequencies up to 4.5 GHz[4] while GaAs TELD divider devices of extreme simplicity have been demonstrated to work at frequencies as high as 64 GHz[5,6] albeit with non-continuous spectrum coverage. These counters are essential for the comparatively simple measurement of time intervals, waveform periods, and signal frequencies of interest to the microwave engineer. The precision obtainable is ± ½ period of the clock frequency. Thus subnanosecond precision requires gigahertz clock frequencies. The use of the vernier technique can usually be implemented to provide an additional order of magnitude improvement.

*The views and positions herein expressed are not necessarily those of the Department of the Navy and shall not be so construed.

Frequency Synthesizers

Closely associated with and frequently derived from the counter is the frequency synthesizer. The use of multigigahertz GaAs baseband amplifiers[7] and dual gate GaAs FETs in the feedback circuits of frequency synthesizers represents a virtually unexplored area for the microwave engineer interested in generating coherent and extremely spread spectrum signals, signals using exotic waveforms/modulation techniques, and multiple simultaneous signals having a coherent phase reference. Certain direct (non-feedback) frequency synthesizers require high speed digital voltage references for control of the output if imaginative microwave signals are to be obtained from these devices.

Analog-To-Digital

In spite of the attractiveness of digital techniques for signal processing, digital signals do not propagate well through the "ether"!* Thus the microwave engineer will most assuredly require a means of converting from the analog to the digital (A/D) and back again. A fundamental relationship exists among the number of bits of resolution obtainable (N), the sampling frequency (F), and the effective aperture time (T). It is expressed as

$$T = 1/\pi F 2^{(N+1)} \tag{1}$$

and is, admittedly a worst case analysis. The use of a vernier technique has been proposed (but not demonstrated) to double the number of bits resolution.[8] The current state-of-the-art in A/D converters places an off-the-shelf silicon unit at 400 MHz with 5 bits (2 Gbits/sec)[9], a JJ unit at 200 MHz with 4 bits[10], and a monolithic hybrid FET-TELD unit at 8 GHz with one bit. The prospects for eventually doubling the sampling frequency of the silicon unit are good if electron beam lithography is used. A five bit, 5 GHz FET-TELD hybrid unit is currently under development and is based on state-of-the-art photolithography. Its d.c. power requirement will be about 2% of that of the currently existing 400 MHz 5 bit silicon device. The JJ device as of this writing has been tested at clock speeds up to 200 MHz and found to be monotonic (accurate). It is believed to be capable of operation in the gigahertz range. Dynamic range of the device is limited primarily by lithographic resolution. With electron beam technology, 8 bits is thought to be obtainable while 6 bits is almost certain. Such a device may well also operate at clock speeds exceeding 10 GHz.

Electro-optic A/D converters are also under development[11,12]. Although comparitively little work has been done in E/O converters, 6 bit resolution at 1 GHz sampling frequency certainly appears within reason to expect. The hybrid vacuum tube/semiconductor or electron beam semiconductor (EBS) A/D converter[13] is currently being marketed and (with accelerated develop-

*Walsh function digital-like signals have been propagated; however it is not the intent of the author to advocate such work.

ment) may eventually be capable of up to 8 bits resolution and sampling frequencies of up to 4 GHz (but probably not associated). The EBS device, of course, is considerably more bulky than other approaches but may be less consumptive of power than silicon devices.

An excellent prospect exists for microwave engineers to be using 5 bit, 5 GHz A/D converters in microwave systems designs in the not too distant future.

Totally Digital Receiver

Using the A/D converter described by Hurrell and Pridmore-Brown[14], one can easily envision a totally digital r.f. receiver containing no analog components. Such a receiver would employ the superconducting quantum interference device (SQUID) as both (1) a sensitive detector and (2) a quantizer which uses the quantum steps of the device itself to create its own jitter-free effective aperture. An added feature of such a receiver is its virtual immunity to burn-out by transient inputs. The entire detector and quantizer is characterized by the ultimate in simplicity; it has but one active device!

Phased Arrays

The ability to selectively program a deep null in the radiation pattern of a phased array aperture is an area of more than casual interest to the microwave engineer. This frequently requires phase-matched receivers at the output ports of each antenna element. By using high speed A/D converters, Griffiths and Jim[15] show that one not only eliminates the need for a receiver for each element, but that a much simpler system results which retains the capability to maintain the spatial null in the direction of the moving target. Only 3 bit A/D resolution is required to obtain a 30 db null. Instantaneous bandwidths of 500 MHz are maintained with this technique.

The direction θ of the beam of a phased array antenna (from broadside) is usually given as

$$\sin\theta = \phi\lambda/2\pi d \qquad (2)$$

where ϕ is the phase difference between adjacent elements, d is the interelement separation, and λ is the wavelength. From first glance it would appear that phased array beam steering is a direct function of signal wavelength. A step back to the basics of phased array technology, however, soon recalls that

$$\sin\theta = \tau\ c/d \qquad (3)$$

where λ is the time delay between a signal fed to any element and the same signal fed to an adjacent element. Since the velocity c is a constant, the steering function is totally independent of frequency and there are no intrinsically dispersive factors. This does not help the microwave engineer *unless* one can provide a programmable time delay τ. This, of course, is precisely the function of a digital shift register! With such a device a single antenna array aperture can be envisioned which could simultaneously radiate (or receive) multiple beams of electromagnetic energy in such a manner that each beam is given independent control of its beamshape, its power level, its direction, and its frequency. As such, the same antenna could serve for surveillance, target tracking, target illumination, weapon control, and EW purposes.

Radar Systems

In addition to the radar applications noted above for phased arrays and A/D converters, an additional radar requirement is gaining in prominence. Traditionally range, bearing, frequency, amplitude, pulse width, and pulse repetition rate were the main parameters required from a radar signal. Now when 2-D or 3-D target details are required for identification or classification purposes, phase perturbation parameters ease this task considerably.[16,17,18] This is an area where gigabit logic can excell. In fact, there may be no cost effective alternative.

Phase shift keying modulation has long been used in communication systems. Half wavelength shorted waveguides do not, however, make for miniature systems. The recent advent of biphase shift key (BPSK) modulators and demodulators on a chip of GaAs, however, brings ultra-miniaturization to the BPSK area.[19,20] Even more attractive for the radar engineer is the extreme instantaneous bandwidths obtainable by these new devices. In theory, the new approach to BPSK technology should be capable of Nyquist bandwidths. Testing to date has been limited to data stream bandwidths of 1.6 GHz while the r.f. carrier could be varied from 4 GHz to 10 GHz without tuning. This functional capability contained in an integrated circuit on a chip thus provides the radar engineer with a signal capable of 9 cm range resolution and extreme frequency agility. The coherent nature of the BPSK modulation also provides the radar engineer with the basis for a "buried in the noise" signal.

Radar Signal Correlation/Characterization

The fast Fourier transform (FFT) is being used more and more for the correlation of radar echoes. As currently used, however, the FFT is frequently the bottleneck of the system as it operates at a comparitively slow speed. Currently under development are new non-silicon approaches which will alleviate this problem. The basis for the new approaches are monolithic hybrid FET-TELD high speed (2 GHz) adders and multipliers[21] which sould provide at least a 10 fold increase in the speed of the FFT process. Further improvement in signal correlation is expected to result from the new maximum entropy transform (MET) which is expected to provide a higher probability of recognizing a signal than does the FET.

BASE TECHNOLOGIES

Silicon

The technology first considered for frequency upgrading is silicon because of its well established technology base. Unfortunately, silicon based technology has two intrinsic limitations which limit its usefulness for logic at microwave frequencies. The first such limitation is that silicon, unlike GaAs, is not a good insulator in its highest purity form. Thus monolithic structures of silicon experience large parasitic losses at the microwave frequencies. (Microwave frequency logic requires microstrip and/or coplanar transmission lines on the monolithic circuits). This limitation can be overcome to some extent by heteroepitaxially growing silicon on sapphire (SOS). With the current state-of-the-art, however, this approach creates another problem; electron mobility in silicon--already low--becomes even lower in SOS technology owing to crystalline lattice constant mismatched induced strain. Research efforts are currently underway at several facilities to overcome this problem, but prospects for obtaining the equal of homoepitaxial silicon mobilities are anything but certain. The second major limitation of silicon is its electron mobility compared to that of competing semiconductor technologies. It is 1/7 that of GaAs. While this mobility limitation is not overly critical in a room temperature technology based on 2 micrometer lithographic resolution* it becomes a rather severe limitation for extremely short channel lengths and for cooled operation where mobility becomes a predominent factor. Improvements in the speed of silicon devices will, however, continue to be made. Even then, the most optimistic operating frequencies for silicon monolithic circuitry is 4.5 GHz. Within the decade it is probable that a family of silicon logic gates and registers will be available which will exhibit clock frequencies in excess of 1 GHz. A secondary limitation of silicon technology is its bandgap. At 1.1 electron volts, it is 23% less than that of GaAs and even poorer when compared to other semiconductors of interest. This limitation is chiefly encountered in terms of ambient temperature. The problem is compounded by the high current (power dissipation) requirements of silicon logic at frequencies exceeding several hundred MHz. Silicon will, however, continue to be the technology most used in virtually all electromagnetic systems in the foreseeable future. Serial to parallel converters and front end processing in other technologies will bring the logic speed down to speeds compatible with silicon devices.

III-V Semiconductors

Gallium arsenide (GaAs) and indium phosphide (InP) semiconductors and their structural alloy ternary and quaternary analogs are the most promising semiconductors for signal processing logic at clock frequencies exceeding 2 GHz. These materials have three intrinsic benefits over elemental semiconductors such as germanium and silicon. First, they are direct bandgap high mobility materials. Even when doped to the levels required for practical devices they typically exhibit mobilities exceeding 4000. This advantage is particularly relevant for short channel (e.g., < 2μm) devices and for cooled (i.e., 77°K) devices. The second intrinsic advantage of this class of semiconductors is that they can be obtained in semi-insulating form (i.e., $10^8\Omega$-cm). Indeed, a GaℓAs buffer layer capability may soon exist wherein resistivity is $10^{10}\Omega$-cm. This greatly reduces parasitic loss and deleterious phase shifting effects confronting the gigabit logic designer. The last primary intrinsic advantage is that these materials exhibit a transferred electron effect wherein the electrons have a dual nature. That is, at a given energy level they can be either light and fast or heavy and slow. This effect is exploited in transferred electron logic devices (TELDs) and results in much less complicated circuitry to achieve a given function. The generally higher bandgap of these devices holds the potential for operation at higher ambient temperatures than would be permitted for silicon. Monolithic GaAs FET-TELD circuits have already been demonstrated to operate at frequencies up to 10 GHz and several developments have been reported in the vicinity of 4 GHz.[19,20] It is safe to assume that many if not most of the microwave logic functions required for next generation systems will be available well within the next decade. Logic operation above 10 GHz by any semiconductor technology should not be expected with any degree of confidence within the next decade.

Josephson Junctions

The Josephson junction (JJ) tunnel diode was first predicted in 1962 and demonstrated soon thereafter. It consists of two superconductors separated by a very thin (e.g., 10-40 A°) gap across which Cooper-pairs and quasi particles (i.e., for illustrative purposes, electrons) tunnel. In practice, the gap is typically an oxide of a superconducting metal or alloy. Departures from the true tunnel junction (but still loosely referred to as Josephson junctions) are proximity bridges and Dayem bridges. The latter is simply a constriction in the superconducting line. JJs made of lead must operate at liquid helium temperatures while those of niobium (Nb) operate at 8K. Compounds such as Nb_3Ge are superconducting at 23K and, as such, may be used in closed cycle refrigerators using hydrogen (B.P 15K) as the working fluid. Since the power dissipated by a JJ is typically less than one microwatt, a liquid helium Dewar "ice box" needs refilling on a monthly basis.

The JJ is an extremely nonlinear device. When inserted in an otherwise continuous superconducting loop, a superconducting quantum interference device (SQUID) is formed. The SQUID is extremely sensitive to changes in applied magnetic as electromagnetic field. The first useful phenomenon of the JJ was that of an extremely low noise detector of electromagnetic signals. Unfortunately, the JJ E/M detector was mostly used in analog type circuits and the intermodulation products produced by the extreme nonlinearity of the device made the use of such a detector a very frustrating experience. The procedure is reminescent of the early days of transistor technology when many a head was scratched when a transistor did not perform well in circuits originally designed for vacuum tubes! Recently the JJ has become increasingly exploited for its nonlinear properties by applying it to digital circuitry. The first session of the First Speciality Conference on Gigabit Logic (immediately following this Symposium) is devoted exclusively to the newly emerging digital aspects of JJ technology. Although digital JJ technology is expected to make an enormous impact on high speed, high capacity computer (data processing) technology, it may well represent the ultimate in digital processing of microwave signals. This latter aspect is being addressed first in two rather significant efforts in A/D converter development. One feature of interest to the microwave engineer is that a superconducting microstrip transmission line is both lossless and dispersionless. This feature greatly facilitates circuit layout at K band and above.

The reliability and reproducibility of the lead oxide oriented JJ technology has now been established at both IBM and NBS/Boulder. In many respects, the fabrication process is simpler than that of semiconductor technology. NBS/Boulder has recently demonstrated a closed Stirling cycle liquid helium refrigerator requiring but a few tens of watts of external power. As such, the future of JJ technology seems assured.

PUTTING IT ALL TOGETHER

Multifunctional electromagnetic suites as well as other sophisticated sensing and communications systems are already nearing the gigabit/second information rate. Soon they will require multigigabits/second. To accomplish this, a new breed of systems design team is envisioned. Traditional Logicians (designers of logic circuits) typically communicate in the language of the time domain. As logic speeds increase, logicians will become more dependent upon the microwave engineer who typically communicates in the language of the frequency domain. This will force a greater use/understanding of such common links as the Fourier

*High field saturated velocity is an equally important criterion at room temperature on for electron transport lengths of several micrometers.

and LaPlace transforms. Characteristic impedance, standing waves, and propagation dispersion which can be virtually ignored at traditional logic frequencies now become problems of equal magnitude with switching speed, power dissipation density, and submicrometer lithography. The solid state physicist will be more in demand. As device size shrinks to reduce parasitic capacitance and improve switching speeds, electrons are forced to pass through channels so small that quantum size effects begin to dominate device performance. A symbionic relationship among these three professional groups will materialize.

Who?

The traditional silicon logic houses are not in the position of the blacksmith at the advent of the automobile. The new technologies necessary for gigabit logic will not replace silicon as the dominant logic vehicle. The incentive for gigabit logic will certainly originate with the systems houses and their customers. To remain competitive, they must either develop their own gigabit logic technology or team with other interested groups. The cost is anything but trivial. Those organizations which already have installed a III-V materials/device capability for solid state analog (linear) microwave circuits have a decided advantage if they exploit it now. Those few organizations who have initiated JJ development have found it not as formidable as first envisioned. Those systems houses who wait for the traditional logic houses to supply them with a family of gigabit logic devices will be most disappointed.

CONCLUSIONS

Gigabit logic is emerging as a new branch of technology which must, by necessity, bring together the traditional microwave community, the logician, and the solid state physicist. The need for coherently organized electromagnetic suites to replace collages of electronic subsystems, improved signal to noise ratios, reduced interference, and simplified overall circuit design will force the use of gigabit logic microwave systems. There are two major aspects which will set the pace for gigabit logic implementation. They are the development time and cost (currently under active pursuit) and the re-education of the microwave systems designer (just beginning). Many gigabit logic devices generic to totally new systems concepts have already been demonstrated. The feasibility of others has yet to be established.

The technology is new. A small number of organizations are already married to gigabit logic, while many others are still courting. A promising statistic: there have been no known divorces!

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