Origins of High-Power Diode Switching

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I. A QUIET BEGINNING

THE MOST REMARKABLE aspect of high-power semiconductor switching is the quiet way in which it slipped into the engineering art.

Low-power semiconductor switching began with the use of detector diodes, and can be traced, back to about 1955 [1], by an orderly progression of papers in the IEEE PROCEEDINGS and the TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES. In May 1961, Robert Garver wrote "Theory of TEM Diode Switching" [2], probably the most extensive paper in the contemporary literature about the use of semiconductor diodes to switch microwave energy. From it one could infer, due to the recommendation to use a reverse-bias voltage at least as large as the peak applied RF voltage, that the semiconductor diode might respond as rapidly to microwave signals as it would to dc signals, and that, therefore, the microwave behavior should be analyzed substantially by considering it to be a "small signal" superimposed on the dc *VI* curve, shown in Fig. 1. It was not obvious that, later, the microwave signal indeed would be found to be "small signal" on a p-i-n diode but not on the basis of voltage or current. More about this later.

In his paper, Garver analyzed the amount of power that could be switched, predicated on a 125-V breakdown voltage, at that time about as large as was obtained for simple p-n diffused diodes. He concluded that peak powers of 10, possibly 40 W could be sustained in the reverse-bias state, while thermal dissipations would limit average power handling to about 1 W in either state. No mention was made of how long a pulse could be sustained under "pulse conditions" before the diode's junction temperature would rise appreciably within that pulse in response to the heat generated. The notion of diode thermal time constant had not yet been proposed.

In 1961, I joined Microwave Associates, Inc. (now called M/A-COM, Inc.) to work on developing high-power (the goal was 100 kW peak!) p-i-n diode phase shifters. I obtained my design concepts and device data from the proposal written at that time for Navy research sponsorship[1] by Kenneth Mortenson, and from Henry Griffin, whose task was to assemble and operate the high-power setups needed to test circuits to the power objectives set for the program.

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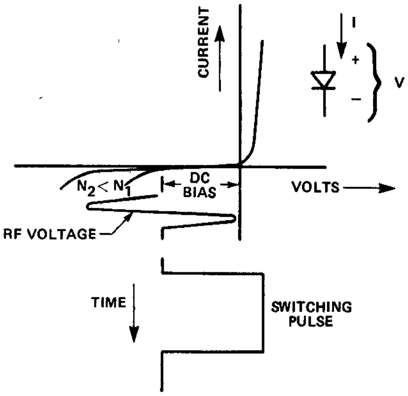

Fig. 1. Early (1957) reference to the presumed rapid response, within the RF cycle, of control diodes [6].

It was not clear in the early 1960's just what antenna would ever be built whose individual radiating elements each would require 100-kW peak power capability. But, this was the Sputnik Era, and at that time no goal was considered too high. In fact, we later met the 100-kW objective, but that's getting ahead of the story. Early in the circuit development, I was told that the bias on the p-i-n diode need not equal one half of the peak RF voltage or current; rather, relatively small forward current and reverse voltage biases were sufficient to establish the respective low- or high-impedance states of the diode, and that, once these states were so established, the diode's impedance remained the same. That is, the p-i-n was linear until such RF levels were applied which overheated or induced voltage breakdown in the diode. I distinguish this phenomenon from "small signal" behavior by the sketch in Fig. 2 [6].

Arguably, this operation could be inferred from the p-i-n's "conductivity modulation" description prevalent since the microwave p-i-n was described by Arthur Uhlir in 1958 [3]–[5], but if anyone did, he didn't publish the inference as clearly as Bob Ryder later described it. This remarkably small required bias, which we'll see shortly is easily explained, was something with which I worked for years before obtaining a clearly stated model to explain it, an early experience that convinced me that familiarity with a subject doesn't necessitate insightful understanding.

Moreover, the development of the p-i-n diode itself progressed slowly without an identifiable "breakthrough" in technology. Looking at Garver's *et al.* paper in the *Journal of Applied Physics* in 1957 [7], one sees from their figures the suggestion of what later was to evolve as the p-i-n diode. The two dc breakdown curves presented (Fig. 1 here) for the diodes represent decreasing selected values for *N*, the donor concentration in the active zone of the

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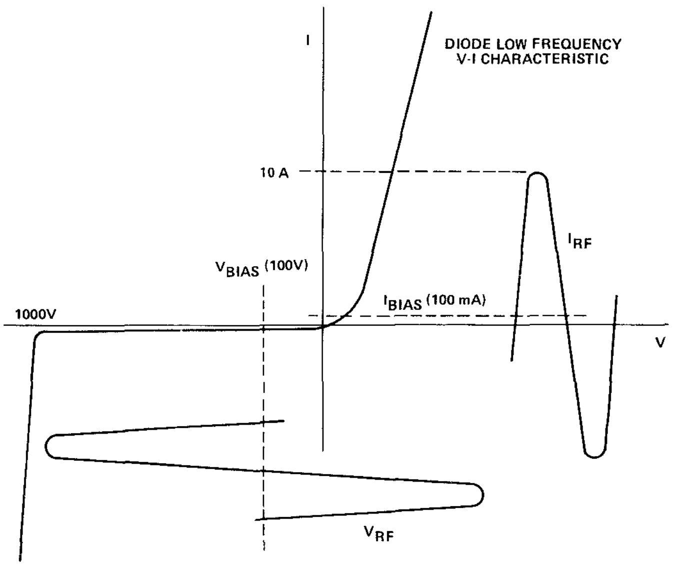


Fig. 2. Diode low-frequency characteristic with superimposed bias and RF excitations.

diode. As can be seen, the lower the donor concentration, or conversely, the higher the resistivity of the semiconductor material, the higher a dc breakdown is achieved. It remained as a simple step to conclude that no donor concentration at all, i.e., intrinsic or "*I*-type" material, is best for high breakdown. The resultant p-i-n structure from Mortenson's paper [8] is shown in Fig. 3.

I think that Bob Ryder [9] best explained the p-i-n when he called it a "charge control device." Lucidly, he pointed out that the microwave signal actually is the *small* signal and the bias signal is the *large* signal if these signals are viewed from the *charge* perspective rather than that of their respective voltage and current magnitudes.

Simply put, holes and electrons are injected (roughly equally to preserve charge neutrality) into the *I*-region by the forward-bias current, where they remain until they recombine with one another. The initial amount of charge Q_0 established by the dc forward-bias current I_b is given by

$$Q_0 = I_b \cdot \tau$$

where τ is the lifetime. The instantaneous remaining charge q, with time t, following a cessation of the bias current, is described by

$$q = Q_0 e^{-t/\tau}.$$

Thus, for example, with 100 mA of bias current and a lifetime of 10 μs, the stored charge is 1000 nC (which decays to 368 nC 10 μs after the forward bias is shut off).

Even at a microwave frequency as slow as 1000 MHz, the RF half period is only 0.5 ns. Thus, an RF pulse of 10-A peak current amplitude will move, on alternate RF half cycles, into and out of the junction, a charge no greater than 5 nC (actually less, considering its sinusoidal waveform). This is only 1/200th of the charge Q_0 stored in the *I*-region by the forward-bias current. The result is that the *I*-region behaves as if it were a linear ohmic conductor throughout both the positive and negative going cycles of

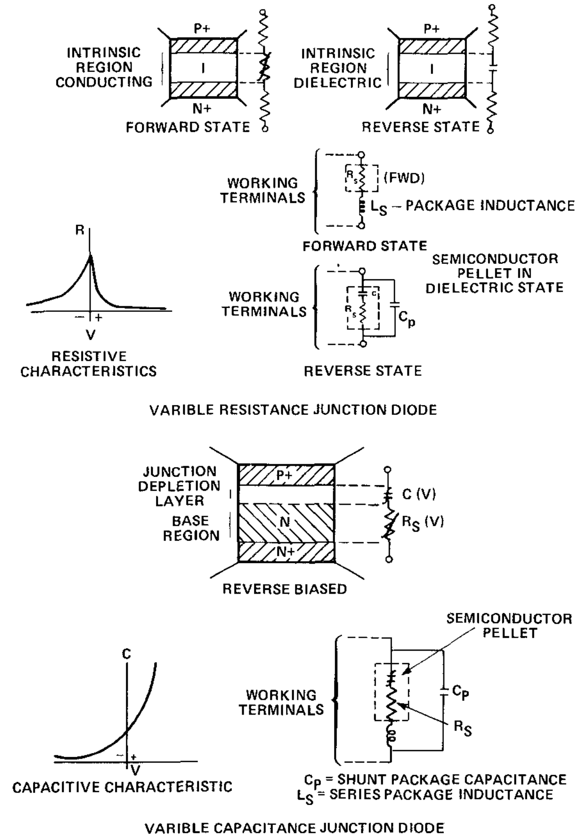


Fig. 3. Early (1964) description of the p-i-n (variable resistance) and varactor (variable capacitance) microwave diodes (after Mortensen [8]).

the RF signals. Thereby is an RF signal of 10 A controlled with a bias signal of 0.1 A, only 1 percent of the peak RF amplitude! Yet, considering charge, the RF is a *small* (charge movement) *signal* superimposed on the *large* (injected charge) *signal* established by the bias.

Similar reasoning, as well as the consideration of space-charge effects, leads to the conclusion that even very large RF voltages applied across a reverse-biased diode have such a short duration that very little charge is injected by the RF into the *I*-region, and what charge is injected by a forward-going RF voltage is rapidly swept out by the combined effects of the subsequent reverse-going RF voltage and the reverse bias. Thus, the diode remains nonconducting even when the zero-to-peak RF applied voltage greatly exceeds the bias voltage, as implied by Fig. 2. With this simple operational advantage, we commenced to develop multikilowatt, even megawatt, control devices.

There are many interesting stories about the design of switches, operable to 120 kW [6], and megawatt duplexers (which handle high power in only one of the diode's bias states, the transmit condition) [4], [[5], [10], [11]. But the most extensive and interesting development has been that of the p-i-n high-power phase shifter, and so I have selected it to illustrate the evolution of high-power p-i-n switching.

II. High-Power Phase-Shifter Research

While the p-i-n diode's stored charge was very accommodating to the microwave switching function, there still

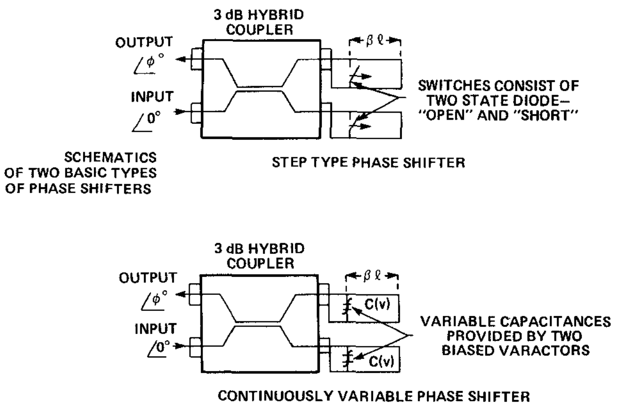
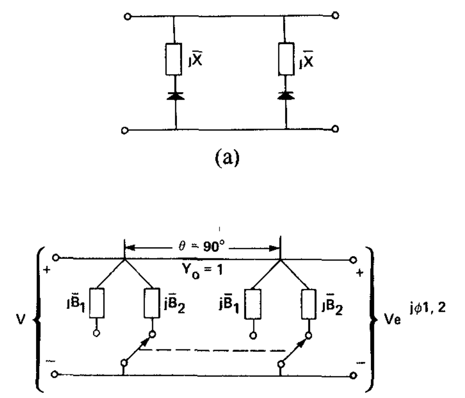


Fig. 4. Early schematic of the reflection (hybrid) phase shifter circuit using p-i-n's (open and short) for step phase shifting and varactors for continuous phase control (after Mortensen [8]).



(b)

Fig. 5. The first published diagram of the diode transmission phase shifter (from the *Nerem Record* [17]). (a) Prototype section schematic. (b) Equivalent circuit: $\Delta\phi \approx B_1 - B_2$.

remained a great deal to be done by way of the circuit design. My early supervisor and mentor, Ken Mortenson, already had assembled a team of diode experts, notably Carmen Genzabella, Charles Howell, and Larry Mesler, to design and make high-voltage p-i-n diodes and, since it was thought that continuous phase shift would also be needed at high power, high-voltage varactor diodes, as well. The p-i-n's and varactors would be used in pairs, symmetrically terminating a 3-dB hybrid coupler to give matched two-port transmission characteristics. The first step of the developmental plan was perceived to be the realization of the highest power capability practical in the two-diode, 50-Ω hybrid circuit, it then being considered by Mortenson and the other semiconductor physicists to be a straightforward exercise for microwave circuit engineers to use circuit transforming, power divisional, and other "well-known" techniques to obtain any higher power capability that might be desired. I was expected to be the circuit engineer skilled in the well-known techniques.

At 50-Ω characteristic impedance, a line carrying 100 kW has an RF voltage propagating along it toward a matched load of 2236-V RMS or 3162-V peak. At that time, a simple 180° phase-shifter bit (Fig. 4) was envisioned to have a short-circuit termination a quarter wavelength ($\beta l = 90°$ in Fig. 4) behind the diode. This gives, neglecting capacitive and inductive effects, the desired 180° phase shift as the diode is switched, but also produces a doubling of the voltage at the diode compared to the voltage which would be experienced if 50-Ω loads terminated the lines on either side of the diodes. Even allowing for the 3-dB power reduction of the hybrid coupler, the voltage stress on the diode would be over 4000-V peak. This would occur with a matched load on the phase shifter itself. However, if the output load is not a perfect match, the diode voltage stress is higher, up to 8000 V, with a totally reflecting antenna and a lossless phase shifter.

Clearly, the task was challenging. To this end, stacked p-i-n diodes were assembled. At that time, each p-i-n chip yielded about 200 V of breakdown, and so as many as 20 of them were fitted into the ceramic microwave detector diode package, common at that time, to produce p-i-n's with breakdown voltages as high as 4000 V. With these early diodes, pulsed peak powers of as much as 50 kW were sustained before burnout, with associated phase shift of 180°. But the RF pulse length had to be limited to one microsecond, lest the high thermal impedance of these multi-diode chip stacks cause them to overheat.

Also in 1964, Marion Hines, my M/A colleague, prepared a paper entitled, "Fundamental Limits of RF Switching" [12], the essence of which was that any power could be switched provided one used enough diodes to do it. Marion had a classical background, and doubtless his thinking followed that of Isaac Newton in his assertion that he could move the earth if given suitable fulcrum and lever. Marion's classic paper related the minimum RF voltage (under reverse bias) and minimum RF current (under forward bias) which the diode must sustain for phase shifting, switching, and duplexing to the RF power that was being controlled [12]. Given this advantageous perspective, the problem remaining was how to combine the many diodes that his analysis demanded without incurring high insertion loss.

I recalled a 1961 *Microwave Journal* paper by Dawirs and Swarner [13] describing a diode phase shifter that did not use a hybrid coupler. They half-wave-spaced two varactors along a transmission line and employed a third, independently biased diode to correct for the VSWR mismatch introduced by the first two. This yielded up to 180° of phase shift. In another paper by Al Simmons in the 1955 IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, a waveguide polarizer was described which achieved lengthening and shortening of orthogonal TE_{10}-mode paths in square waveguide using quarter-wave-spaced irises that were capacitive to one and inductive to the other TE_{10} mode in the polarizer [14], yielding about 20° phase shift.

The hybrid coupler had been employed in phase shifters to provide transmission match, but if, by necessity, one had to employ numerous diodes to control very high power, then the amount of phase shift per diode, and correspondingly the need for mismatch correcting, could be accommodated with a circuit of less complexity and insertion loss than that of the hybrid coupler. This suggested placing the

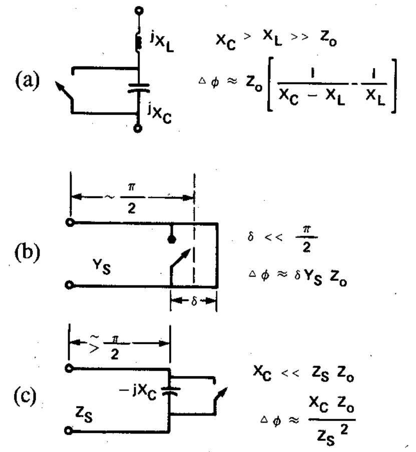


Fig. 6. Typical circuits used to implement the switchable susceptances $B_{1,2}$ required in the transmission phase shifter shown in Fig. 5. The approximate values of phase shift (in radians) are obtained when a pair of elements of small normalized susceptance are spaced about 90° apart on a Z_0 impedance line (after White [18]).

diodes a quarter-wavelength apart on the transmission line, and coupling them lightly to the line. In this way, their phase shifts add constructively but mismatches mutually cancel. The diode pair (in shunt with the line for good heat sinking) switch between capacitive and inductive susceptances. This process alternately lengthens and shortens the line's electrical length to produce phase shift with a minimum of circuit reactance and its undesirable insertion loss [15].

This approach further appealed to me personally, because it was subject to analysis using the *ABCD* matrix, something I had recently learned and which I wanted to use to describe the phase shifter in my first *MTT Transactions* paper [16]. The equivalent circuit [17] is shown in Fig. 5.

The approach did work very well. The simple, lightly loaded line elements offered a low-loss means of harnessing uniformly many diodes to the high-power job. Furthermore, there were many of ways of coupling to the transmission line to realize susceptance switching (Fig. 6). A 1300-MHz embodiment used shunt coaxial stubs whose length could be varied both mechanically and, about that mechanical length, electrically by switching the p-i-n diodes. This provided an excellent experimental device for demonstrating high-power potential. Up to 100 kW of peak power under matched-load conditions with 40° of phase shift was obtained with the 16-diode model, and since circuit losses were very low, a longer device with more diodes could yield up to the full 360° of phase control. Alternatively, 15 kW was controlled with 180° of phase shift by the same experimental unit with suitable adjustment of the critical lengths of the diode switched shunt stubs. Fig. 7 shows the front cover of the May, 1964 *Microwave Journal*, highlighting this model.

III. The MSR Program

While a 100-kW burnout-rated phase shifter did not fit into any phased-array plans then, it did dispel the notion that microwave semiconductors were relegated to low-

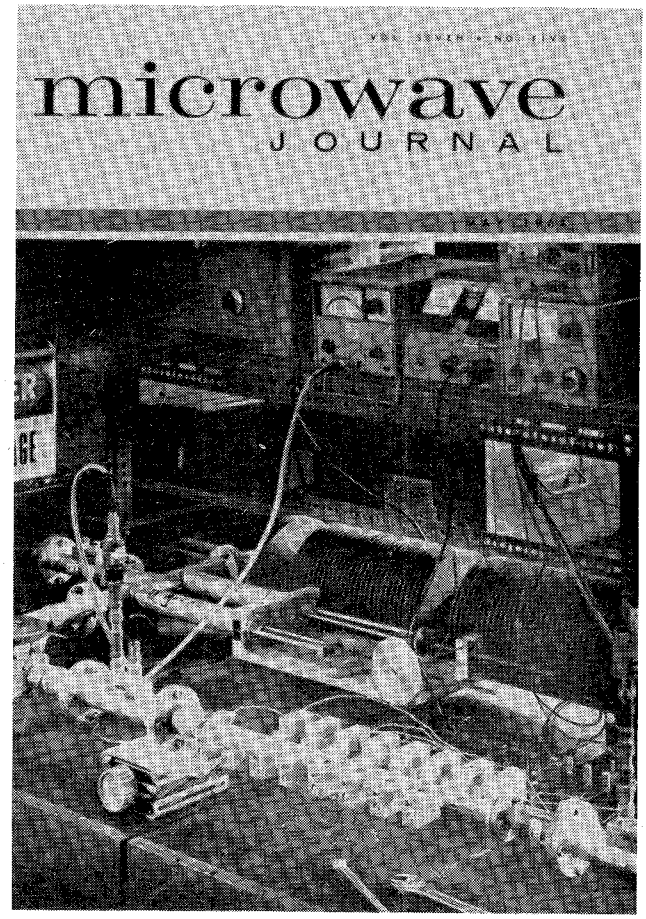


Fig. 7. Front cover of the *Microwave Journal*, May 1964, showing the 100-kW diode phase shifter.

power activities. In fact, at that time, the Bell Telephone Laboratory (BTL) at Whippany, NJ, was evaluating high-speed antenna steering techniques suitable for the *S*-band radar guidance of an antiballistic missile, later to be called the Missile Site Radar (MSR). Phillip Sproul and Gerald DiPiazza visited M/A in 1964, having heard of the high-power diode phase-shifting results. The question was, "Could a suitable *S*-band phase shifter be built for MSR?" Fortuitously, the Navy program's objective had been to develop both *L*- and *S*-band devices. The 3000-MHz unit (Fig. 8) had demonstrated 15-kW burnout capability, and its data was reviewed on their visit.

At the time, I remember believing that things couldn't be falling into place any better. The Navy program's experimental model comfortably afforded a 10–15-percent operational bandwidth. For MSR, a relatively minor scaling to 3.3 GHz was needed. I thought that we would have the design ready for production in six months, but I had not anticipated the thoroughness with which BTL approached such design projects.

Instead of using switched stubs, the *S*-band model achieved the required diode decoupling by transforming the 50-Ω line to 4 Ω in the first model later designed for BTL. In this environment, a miniature ceramic packaged diode (packages had come along since the early detector packages) with a little extra lead length could be made to

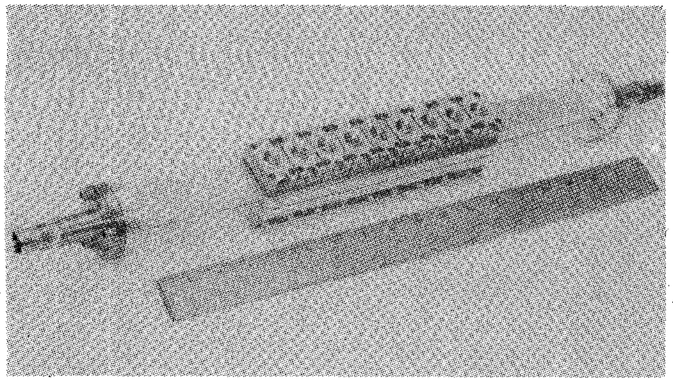


Fig. 8. A 6-Ω line impedance was used in the prototype, 15-kW burnout 0–180° 3-GHz transmission phase shifter developed under Navy contract, which led to the 4-Ω line model, Missile Site Radar (MSR) diode phase shifter.

switch between $\pm j\ 20\ \Omega$, resulting in normalized susceptances of $\pm j0.2$ (Fig. 6(a)). Pairs of such susceptances give a phase shift which is numerically equal in radians to the normalized susceptance switched (± 0.2 rad, $\pm 11.25°$, perturbation to the 90° line length which separated them), yielding 22.5° phase-shift per diode pair, the smallest of 4 bits of control. Moreover, at a given power level, the low main line impedance has reduced propagating RF voltage.

My first experience with the BTL rigor occurred after M/A received a pilot study program to build 30 representative phase shifters to the provisional MSR specifications. Gerry DiPiazza called and asked me *what* slotted line (not what slotted line impedance) we planned to use. BTL had a goal of a 1.1 maximum VSWR for 6 bits of phase control. Since no more than 22.5° would be obtained per diode pair, a 34-diode circuit was planned. This yields all values 0 to 354.375° in 5.625° steps (since 0° and 360° are equivalent, the last 5.625° step is omitted).

In addition, transformers at each end of the phase shifter, a dc return between center conductor and outer conductor, and an RF connector at each end of the phase shifter also would contribute to mismatches. At the time, I did not consider the 1.1 VSWR goal realistic. Gerry insisted that we buy new coax slotted lines made to the same outer conductor diameter as planned for the phase shifter, 0.56 in, and carefully designed to have residual VSWR of 1.01 or less. Most manufacturers would have nothing to do with such an esoteric special order, but in due course we were able to order a pair of such lines designed by Andrew Alford, of the Alford Manufacturing Company in Boston.

Network analyzers, even those without computer control, were not available then. To measure the phase-shifter engineering models, we used a phase bridge, which contained a mechanical line stretcher and an attenuator as phase and loss standards. Separate slotted-line measurements provided VSWR data. The 6-bit device (64 possible bias states) with measurements of VSWR, insertion loss, and transmission phase made at five frequencies required 960 separate RF measurements, testing that required the labor of two technicians working continuously for two days.

Once measurements were completed in Burlington, the ever emerging prototype devices would be sent to Bell Labs, where the same measurements were duplicated to see whether "Burlington and Whippany degrees and decibels correlated." Gerry called me, on finishing the first check, and said that the VSWR measurements differed typically by a reflection magnitude error equivalent to a 1.03 VSWR. I recall thinking that this was splendid agreement, but he insisted that the correlation should be much better, given the precision of our identical, custom-made slotted lines. Possibly, he suggested, I was using the slotted line backwards. I told him that I wouldn't fall for such a foolish joke, that either end of a slotted line could be used. But he was right. I later learned that the special slotted lines achieved their low VSWR by virtue of an extremely fragile center conductor support at the load end, the support which my technician and I had inadvertently located on the generator end, leaving the more durable but higher reflection support nearer to the phase shifter under test. Two years of such exacting detail were to follow. The device which was ultimately developed, despite all its complexity, typically delivered in production below 1.2 VSWR over all bias states throughout the 3.1–3.5-GHz band, a credit to the BTL persistence that Gerry exhibited.

But before production could begin, a much larger hurdle presented itself. On further evaluation, the system designers concluded that more array power was needed. The phase shifters must handle much more than the initial rated power of 2 kW. Instead, they should sustain 8 kW. This was the burnout level of the current 4-Ω line design. Moreover, the 4 to 1 margin between burnout and rated power was necessary, since, neglecting losses, the line voltage could double if the load were even temporarily totally reflecting, precipitating immediate failure of any diodes[2] lacking this 4 to 1 safety factor.

The new design problem, requiring an equivalent 32-kW burnout capability, seemed especially intractable. The obvious power scaling would have required transforming the 50-Ω line to 1.0-Ω characteristic impedance, instead of 4 Ω. Already, at 4 Ω, the space between center conductor and outer conductor was only 0.02 in. The requisite tolerances, and the associated ohmic insertion loss at 1 Ω, made this scaling unthinkable. So, too, were diodes having double the breakdown voltage, except as a stacked pair of junctions within the package. But this posed switching problems, since series junctions do not continue to be switched off by the reverse bias once one of them depletes its charge; accordingly, series junctions have switching speed uncertainty.

At this time, Gerry DiPiazza rescued the program, but his solution required a new design. Rather than transform the main line impedance to a low level, he proposed that the diodes themselves be transformed, each one having a small quarter-wave stub embedded in the outer conductor

[2] Technically, only diodes at standing-wave maxima would be so stressed, but these would short, causing the maxima to "walk" through the phase shifts toward the generator, causing more failures.

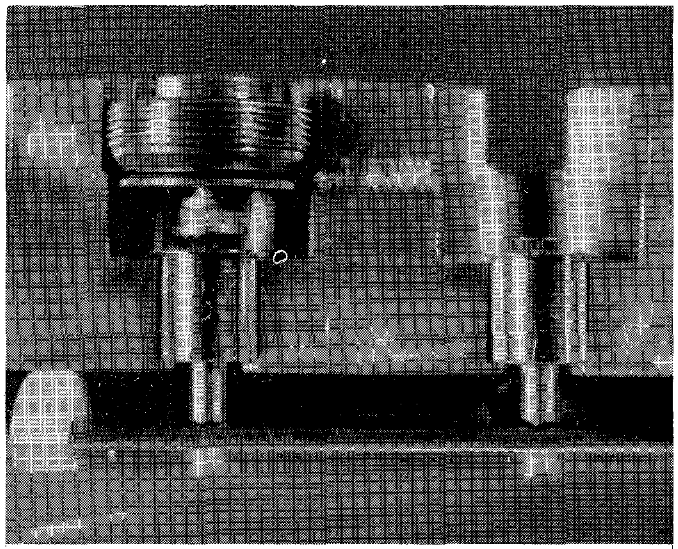


Fig. 9. Cutaway photo of the final MSR phase-shifter configuration utilizing a 50-Ω main line with shunt diode transforming stub ("can" insert). "Daisy" above stub connects ceramic packaged diode which, in turn, is heat sunk to outer-conductor, but dc isolated, by mica disc filter assembly.

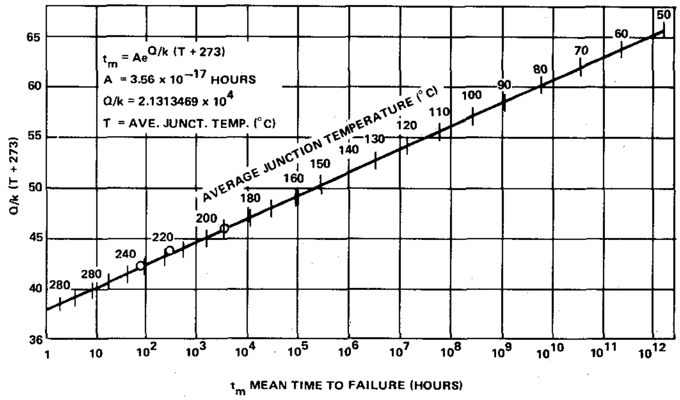


Fig. 10. Accelerated temperature life testing under RF power used to estimate that an MSR diode operated at 150°C would enjoy a mean-time-to-failure of 300 000 hours, over 30 years of continuous operation [6].

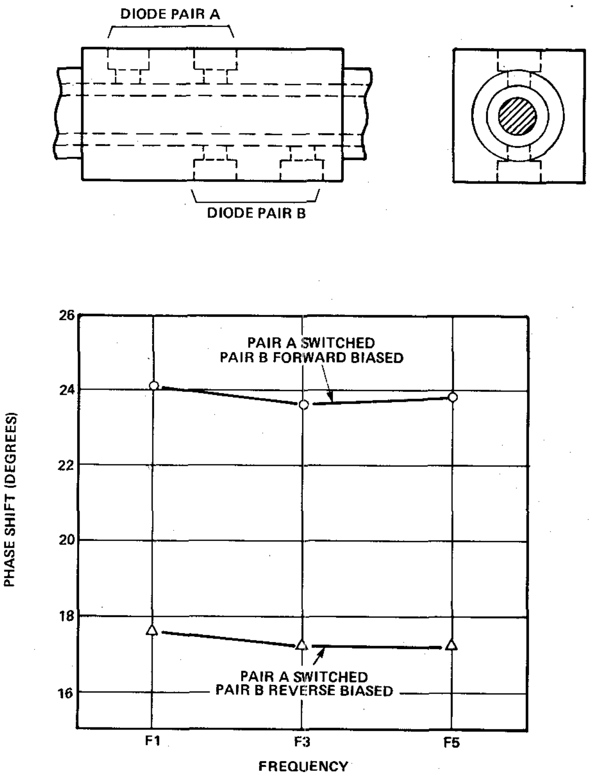


Fig. 11. The phase-shift interaction, probably caused by higher order modes, observed for diametrically opposite diode pairs.

assembly which would transform (more precisely, invert) the diode's impedance to an appropriate loading on the 50-Ω main line. The equivalent circuit of this approach is shown in Fig. 6(c). This design has the advantage that the larger the diode's capacitance, the smaller is the susceptance loading it produces on the main line.

Initial calculations indicated that if, instead of the 1-pF diode in use then, a 3-pF diode were used, then the requisite transforming stub, as well as the main line, would have about 50-Ω characteristic impedance. Time was running short, and we were expected to have working models within six months. A new diode (and more significantly, a newer and larger diode package) would have to be designed and realized quickly. The goal was met with a diode having 2.2 pF of junction capacity and a package with nearly 1 pF. Its 4.3 mil *I*-region gave a bulk breakdown voltage in excess of 1200 V. Fig. 9 shows a cutaway view of the new circuit, packaged diode, and bias bypass filter.

New transistors also were needed for the driver, having 400-V breakdown, so that they could operate safely at 200 V of reverse bias; this bias needed to minimize nonlinear RF loss. Accelerated reliability testing was conducted to establish that the operating life of these phase shifters would be long enough to provide an acceptable rate of repair in a phased-array antenna that would be employing 5000 phase shifters with 30 diodes in each shifter (the number of bits BTL and Raytheon engineers required had been revised from 6 to 4) for a total of 150000 p-i-n diodes per antenna face, or 600000 diodes per four-antenna radar site! A special phase-shifter circuit made of stainless steel and teflon was used for these tests, for which the ambient temperature reached 230°C. The results extrapolated, from actual high-power data, to a diode mean-time-to-failure at 150°C operation of 300000 h, over 30 years of continuous operation (Fig. 10)!

Meeting after monthly meeting occurred. The written reports eventually became a stack five feet high, for which no one then or since wrote an index. During this time, countless details were considered. A special filter capacitor was found to be necessary behind the diode which would pass the bias signal and yet provide both a heat-conducting path, as well as *S*-band RF isolation greater than 30 dB. Less isolation resulted in a radiative loss (the diode bias leads represented a small phased array themselves) of about 0.2 dB, intolerable with the insertion loss goal of 1 dB. Eventually, a two-section mica disc filter resulted, having over 500-V breakdown and more than 40-dB isolation at *S*-band. All of this fit within a quarter-inch of

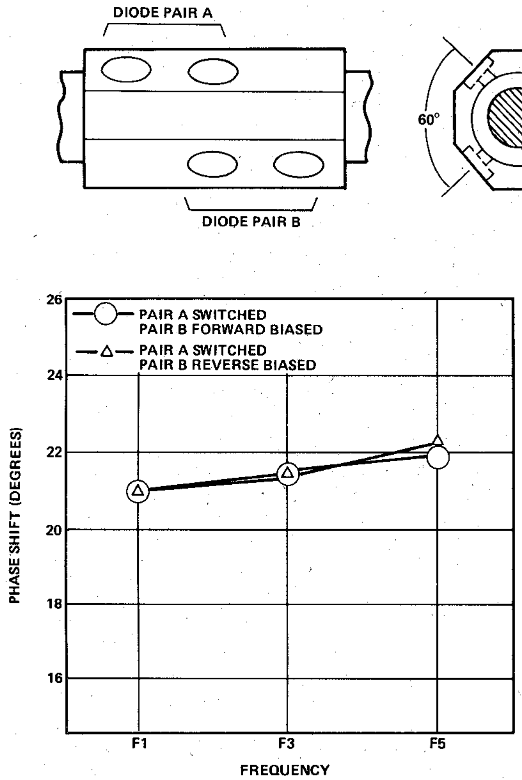


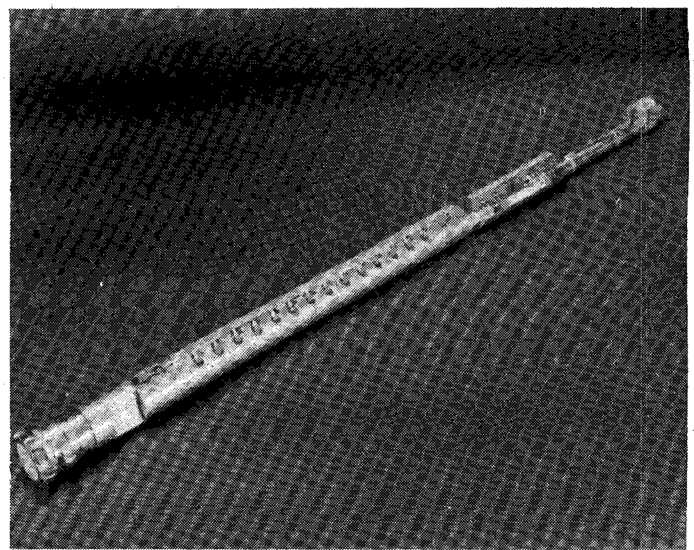
Fig. 12. A 60° vee mounting for diodes was found empirically which practically eliminated phase-shift interaction.

length and a half-inch diameter. This is the threaded part in the cutaway photo shown in Fig. 9.

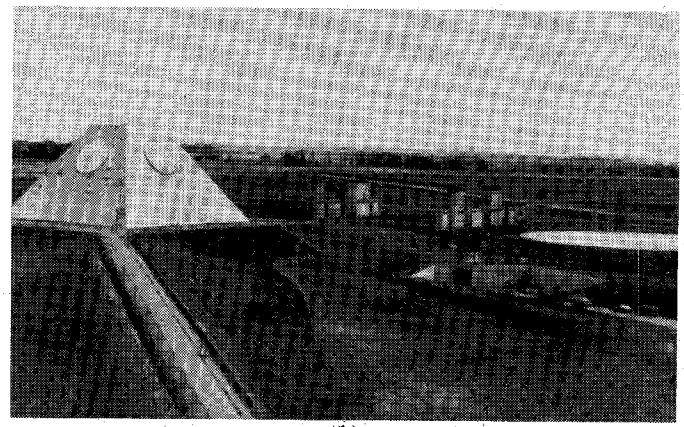
Then, an especially vexing problem surfaced. When stubs were mounted on opposite sides of the main 50-Ω line, each pair was found to have a phase shift which depended upon the bias condition of the adjacent pair (Fig. 11). This was an unanticipated and totally unacceptable interaction that had not been experienced in the 4-Ω main line impedance developmental unit. The interaction was finally eliminated by trying various angular orientations for the stubs in the outer conductor of the main line. The solution was a 60° separation, found empirically and laboriously by machining different models. This reduced the interaction to less than 1 percent of the section's phase shift (Fig. 12).

The complete phase-shifter cartridge, designed by Raytheon, Bedford, complete with a radiating circularly polarized element, had a blast-hardened ceramic end cap, as shown in Fig. 13(a). As long as it was, requiring special gun-drilling techniques to produce the precision-bored aluminum housing, even more length was needed for it to pass through the blast-hardened, water-cooled plenum, antenna-face structure. So a 1-ft, 50-Ω extender was added, producing the "piccolo" format seen in the photograph.

In production, an early network analyzer was designed by Seymour Cohn and built by the Rantec Corporation, Calabasas, CA. The impetus for this development was stimulated by his then recent article in the *Microwave Journal* [19]. Kept in an air-conditioned room because of its germanium transistorized computer, it performed all 240 production measurements on each phase shifter within



(a)



(b)

Fig. 13. (a) Photograph of the 30-diode, 8-kW peak operating (32-kW burnout) MSR phase-shifter cartridge, now a part of the MTT Historical Exhibit. Duty cycle of 0.06 with 120-μs pulses gave 480 W of average rated power. (Photo courtesy of Geoge Fraizer, Raytheon Co., Bedford, MA.) (b) The MSR radar at the North Dakota site. The active "bulls eye" of the antenna is 28 feet in diameter. (Photo courtesy of E. Weinberg, Raytheon Co., Bedford, MA.)

5 min, and even printed the data, highlighting out-of-specification values, on a paper tape. Then, as today, all visitors' tours included a stop at the "modern, computer automated test facility," which eliminated what would have been hours of test labor for each phase shifter.

To conserve space within the antenna itself, which was densely packed with phase shifters, mechanical supports, and liquid cooling, the drivers had to be located quite a distance away, in the lower level of the radar building. The diodes were coupled to these drivers through coaxial cables, as much as 150 ft in length. However, diodes present a very nonlinear load to a cable, and the resultant "ringing," due to multiple reflections of the 200-V reverse-bias pulses on the cables, had a tendency to cause voltage build up at the switching transistors, burning them out. This problem was solved by adding resistors to the wiring at the phase shifter, damping reflections on the cables. Details such as this, which surfaced with dismaying frequency, had to be resolved quickly as we moved toward production.

The MSR Program was terminated by Congress after one operational site was built in North Dakota (Fig. 13(b)). This site had four antenna faces each containing 5000 phase shifters, for a total of 20000. By the time it was built, additional p-i-n breakdown voltage was achieved which, together with some circuit changes, permitted up to 45° to be obtained per diode pair, and thereby reduced the number of diodes in a phase shifter from 30 to 16. Even so, over 320000 diodes were employed in a site.

While this system set a measurable milestone for phased arrays, it had a "good news and bad news" aspect. The good news was that it worked and worked very well, but the bad news was that it was extremely expensive. Both the development and production were performed on a cost plus fixed-fee basis. Numerous sites were envisioned, justifying the high development investment. It was difficult to assess later exactly what the cost of the phase shifter had been in the quantities needed for one system, but it was likely in excess of $1000, particularly when the cost of the high-voltage driver was included.

IV. The Cobra Dane Radar

It was not until 10 years later, in 1975, that this MSR experience could be applied to a lower cost phase-shifter execution. A requirement developed for an even higher pulse energy application; yet, to reduce cost, only 6 diodes would be used in each phase shifter. The U.S. Air Force was planning construction of an *L*-band surveillance radar to be located at the end of the Aleutian Islands chain on Shemya Island. The system would be called the *Cobra Dane*.

The task could have been performed with a mechanically steered antenna, but a premium was placed both by the application requirements, as well as by the Air Force's desire to advance the technology, on an electronic phased array. A low-cost device was necessary; each phase shifter was to be furnished for about $150, including the driver. Only 3 bits of control were necessary, but the phase shifter must sustain a peak input power of 1 kW with RF pulse lengths of 2000 μs. The combined technical and cost challenge of implementing a design which used a minimum of diodes, 2 per bit, while sustaining the very long RF pulse and embodying a high-voltage driver was considerable.

In the years following the MSR, a variety of approaches had been examined to reduce the phase-shifter cost. Alumina–ceramic (Al_2O_3) hybrid integrated circuits using chip diodes received considerate attention. One such circuit, sponsored by the Advanced Ballistic Missile Defense Agency (ABMDA), is shown in Fig. 14. This circuit had reduced RF power capability (about 7-kW burnout), but the expectation was to build a larger diameter antenna, called IMSR (for improved MSR), yielding higher gain. Unfortunately, the alumina model also had higher insertion loss, about 1.5 dB. In any event, the project was dead-ended when Congress cancelled the ballistic missile defense.

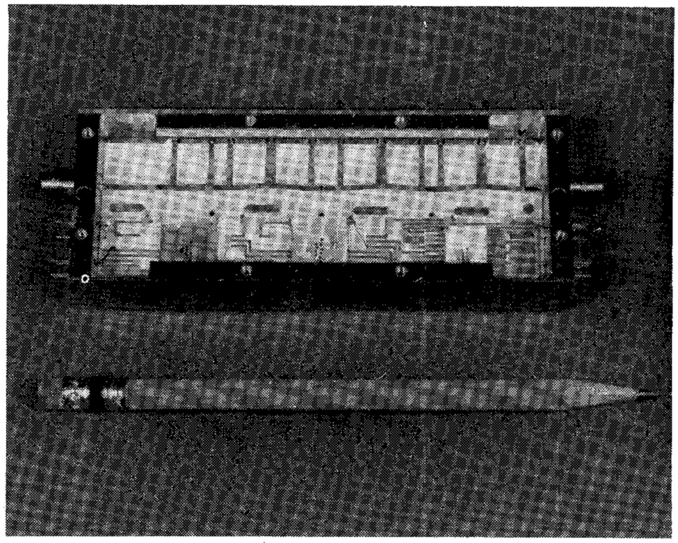


Fig. 14. *S*-band, 3-bit diode hybrid integrated phase shifter designed for 2-kW peak power operation. Drivers and memory logic for phased-array antennas are included in the 4×1.8×0.5-in package.

Meanwhile, a very good low-cost and low-loss approach was advanced by Ray Tang and Dick Burns at Hughes Aircraft in Culver City, CA. They used teflon fiberglass (TFG) dielectric stripline with two "center conduction" patterns. Using only two diodes per bit, the backward wave, 90° hybrid coupler was resurrected with low cost (previously, the coupler had been a separate coaxial or waveguide device). This development, too, had been sponsored by ABMDA, and later, an *X*-band stripline embodiment also was supported by the Air Force at Wright Patterson AFB in Dayton, OH [20].

Ultimately, the design for *Cobra Dane* was realized using stripline made up of a self-jigging package. This was formed by parallel plates large enough to hold four phase shifters in one housing [21]. To reduce costs further, no diode package would be used. The diode was passivated using glass which could be fired directly onto the silicon[3] to protect the exposed area of the *I*-region (Fig. 15). A 6-mil *I*-region, 1800-bulk breakdown diode, with 3-pF junction capacitance was employed for this application. With only 0.2 Ω of RF resistance at *L*-band when biased at 200 mA, it regularly sustained in production testing RF peak sinusoids as large as 16 A and, when reverse biased with 200 V, peak RF voltages of 1000 V. At the rated 1-kW power, RF voltages and currents of one-half these values were applied.

The 200-V reverse-bias voltage posed a problem if a diode shorted (the usual failure mode), for it then could pull down the reverse-bias supply, depriving up to 160 phase shifters of reverse bias. How to disconnect the short quickly was the question. Conventional lead fuses were not reliable enough and would be expected to open more often than diodes, thereby inducing diode failures. I had proposed the use of a 1/2 W carbon resistor as a fuze. The

[3]A M/A-COM process with the Trademark, CERMACHIP.

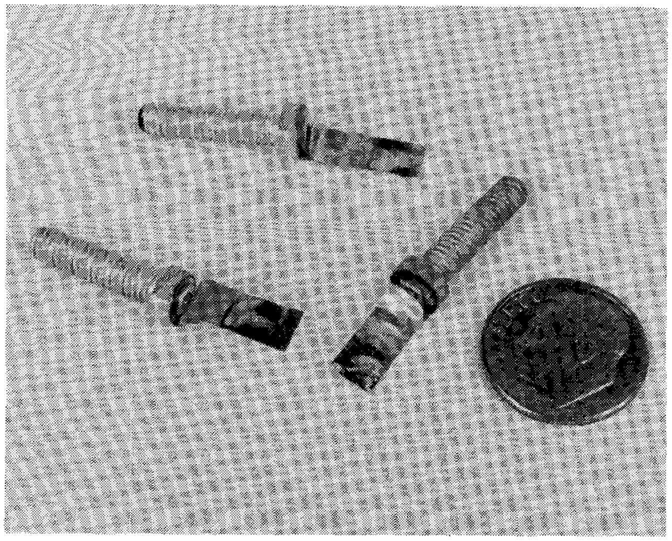


Fig. 15. High-voltage glass (the white area surrounding the strap contact) passivated diodes used in the *Cobra Dane*.

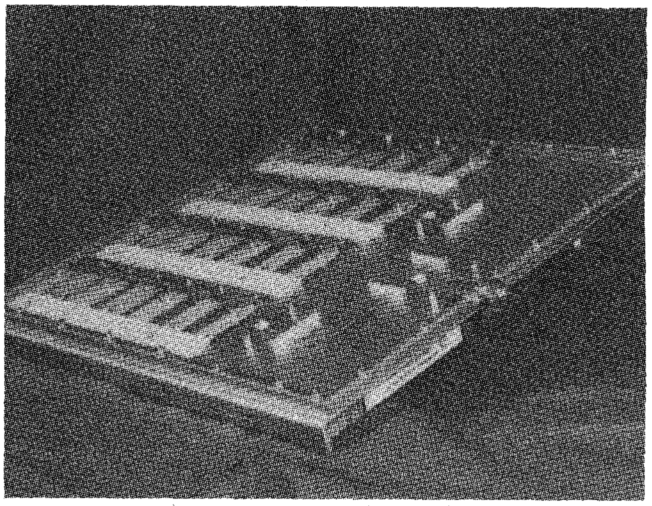


Fig. 16. Photograph of *Cobra Dane* driver and 4 to 1 high-power phase-shifter assembly.

"breadboard model," having the resistor's leads soldered into holes in the PC board, tested well and uneventfully. The resistor would fracture with the high bias current resulting from a diode short. Tension in its bent leads caused the parts to separate quickly, disconnecting the short circuit rapidly from the 200-V supply.

But the production model was "improved" with professional-looking, standoff terminals between which the resistor was soldered. On the day of the demonstration before our customers, the resistor snapped in half under a simulated diode short as planned but, supported by the new terminals, the remains of the resistor remained in close proximity, producing a dazzling carbon arc pyrotechnic display, complete with spattering hot particles, that caused everybody to jump back, including me. Ultimately, Dale Reis, of Raytheon, found a special wirewound resistor designed to act as a fuse. Such engineering misadventures seem to be an inevitable enlivenment of new high-power phase-shifter developments.

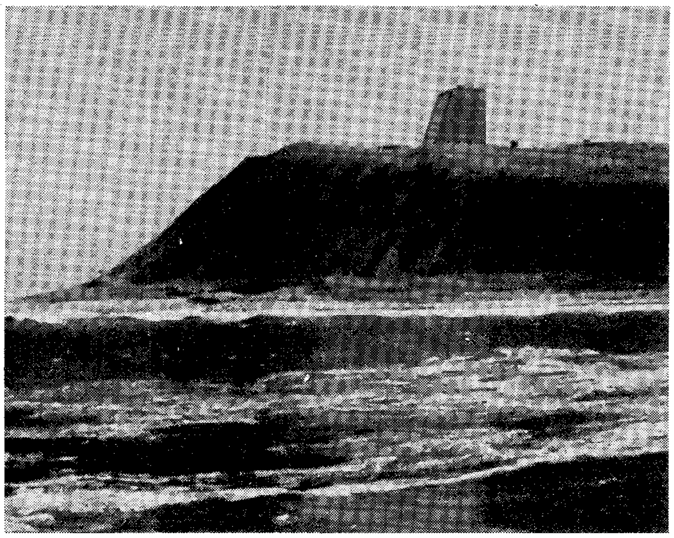
Four phase shifters were put into each housing with a 4 to 1 Wilkinson-type absorptive power divider (Fig. 16). This eliminated a connector interface, yielding savings both in cost and insertion loss. The output connectors had removable barrels into which could be inserted varying lengths of dielectric with an appropriate diameter center conductor, allowing us to phase-trim each channel $\pm 10°$ after package assembly. Ceramic thin-film loads had to be developed form the Wilkinson dividers which could sustain the entire reflected power of the array, a reflective condition which all phased arrays approach during severe ($\pm 60°$) off-axis scanning. The ceramic loads, measuring only a quarter of an inch square, absorbed up to a kilowatt of peak power at 6-percent duty cycle. The 2000-μs-long pulse length was equally critical for them, since such thin-film devices have no more thermal heat-sinking capability than do diodes (in fact, they have less).

The location of the *Cobra Dane* radar must qualify as one of the most desolate spots in the world. Shemya Island is about 1400 miles west of Anchorage, Alaska. I had occasion to visit this site because a problem developed in the phase-shifter circuit boards once they began to accumulate RF high-power hours.

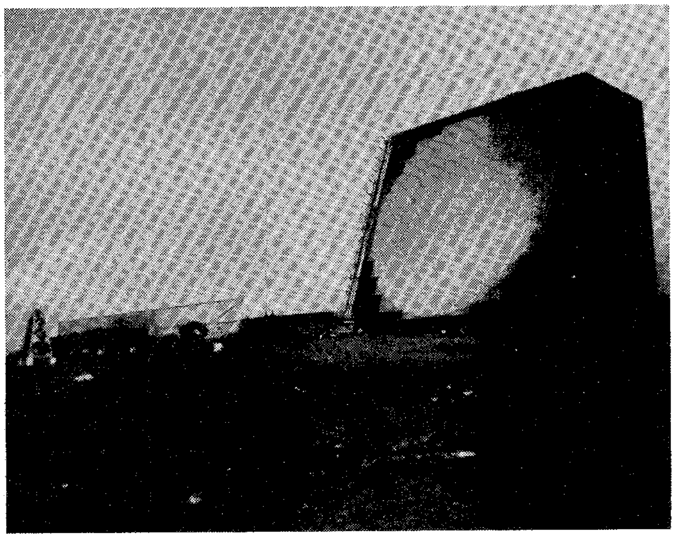
The RF board design required that connections be made from one side to the other. To be conservative, I had employed a brass rivet to provide this ohmic connection between the board's sides, eschewing the use of plated-through-holes because they could not be inspected, except through destructive sectioning. The rivet, in turn, was flow soldered on both sides of the board, a "belt and suspenders" approach to the problem. However, stresses in the boards, which showed up only after the phase shifters were installed in the array, caused some of the rivet connections to crack, which, with the attendant large RF currents following on the board, induced arcing and further deterioration of the circuit. The smell of burning components, which is very pervasive even with a limited number of failures, elicits an appeal for correction well beyond any peril it may portend. This occasioned site rework of the boards, consisting of the installation of jumper straps to parallel the rivets.

Such problems highlight the special nature of componentry made for one-of-a-kind systems, thus far an inevitable description of phased arrays. With most manufacture of large quantities of pieces, the production takes place gradually and over a sustained time period. Accordingly, there is an opportunity to discover design or manufacturing weaknesses before the entire production run of parts has been made and put into operation. With most phased-array projects, however, no such learning period is available. The entire array is usually assembled and operated, all of the phase shifters built and installed, before any operating life experience is obtained.

Notwithstanding this "brass rivet" problem, however, the phase shifters in the *Cobra Dane* proved to be extrao-



(a)



(b)

Fig. 17. (a) The Shema Island (240 foot high) bluff site. (b) Photograph of the *Cobra Dane* radar.

dinarily reliable. After a few months of operation, an average failure rate of less than one diode per day was experienced. The entire system is operated around the clock. Since individual subarrays can be shut down for servicing without disrupting the radar's operation, at least 20 high-power operation antenna hours for the array's nearly 100000 diodes are obtained each day. This produces a daily demonstration of a diode mean-time-to-failure in excess of 2000000 h, and it has performed this well or better (in one month only four failures were experienced) since it was turned on in 1978.

This radar is remarkable for its huge size, the antenna aperture being 95 ft in diameter (Fig. 17). All phase shifters operate at the same 1-kW peak. The required amplitude taper for the array is achieved by random thinning of the density of phase-shifter control elements as a function of radial distance from the array's center. With 1-kW peak per active element, the more than 15000 phase shifters

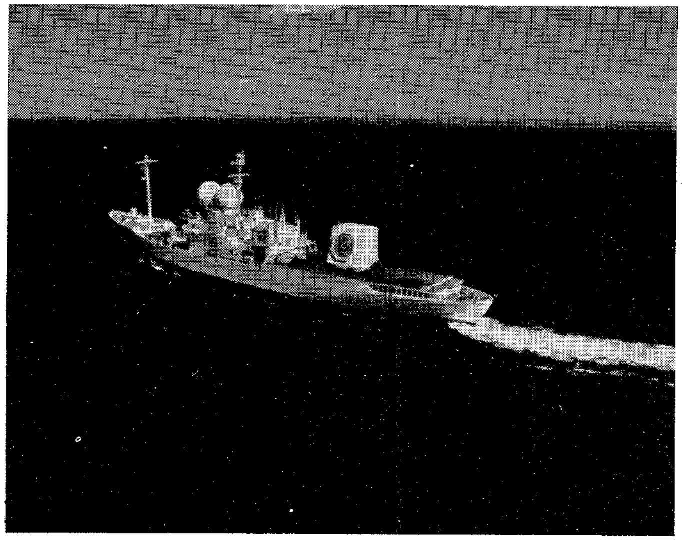


Fig. 18. The S-band *Cobra Judy* phased-array radar (large rotatable box structure near stern) on the ship, Observation Island. The system was built by the Raytheon Co., Wayland, MA, for the Air Force, Electronic Systems Division, at Hanscom AFB, Bedford, MA. (Photo courtesy of M. Carney, Raytheon Co., Lexington, MA.)

radiate over 15 MW of peak power, and, at a 6-percent duty cycle, over 1 MW of average power, equivalent mechanically to 1340 continuous horsepower.

This is controlled by 100000 diodes, each having a diameter of 90 mils and an I-region thickness of 6 mils, corresponding to a total active volume of silicon for all 100000 diodes of only 4 in^3. The dc power controlling the diodes (200 mils forward-bias delivered at 4.5 V from the power supply to the driver) results in an average control power (statistically only half of the diodes in the array are forward biased at one time and the reverse-biased diodes draw negligible power) of 45 kW for the array. This is only 5 percent of the average power and less than 0.3 percent of the peak RF power controlled, vividly demonstrating the impact of the charge control phenomenon of p-i-n diodes in this giant radar system. Mechanical alternatives to the movement of an antenna with a 95-ft diameter—even recognizing that such alternatives could not begin to match the microsecond region, random beam pointing capability accommodated by diode phase shifters—would require much more steering control power.

V. An S-Band Dual Polarization Phased-Array Module

In 1980, another large phased-array need evolved at S-band, the ship-based *Cobra Judy* radar (Fig. 18). For this we used similar techniques, but this time incorporating an additional 180° bit in the output of each phase-shifter channel to permit not only the 3-bit phase control, but the option of changing the output polarization of the radiated wave (Fig. 19). Special modified Wilkinson dividers were employed which use grounded 50-Ω loads. The dividers have low insertion loss, because when the outputs are symmetrically terminated, the loads are at voltage nulls.

By then, the hookup problem experienced with connecting the outputs from so many phase shifters to the array

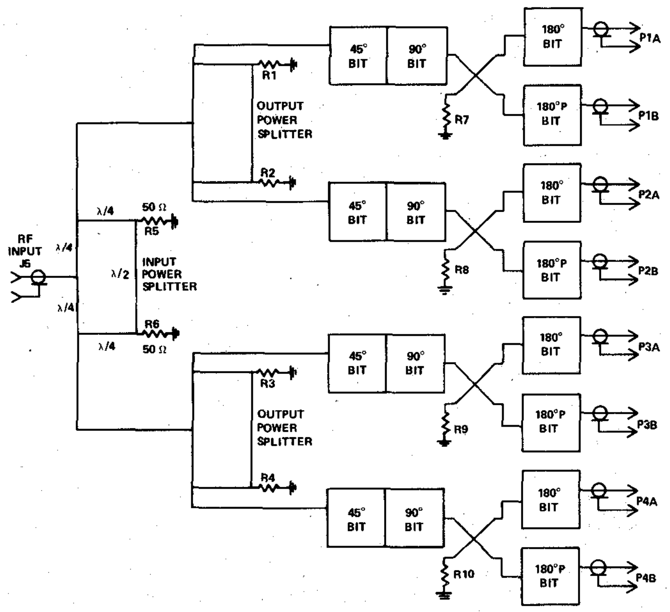


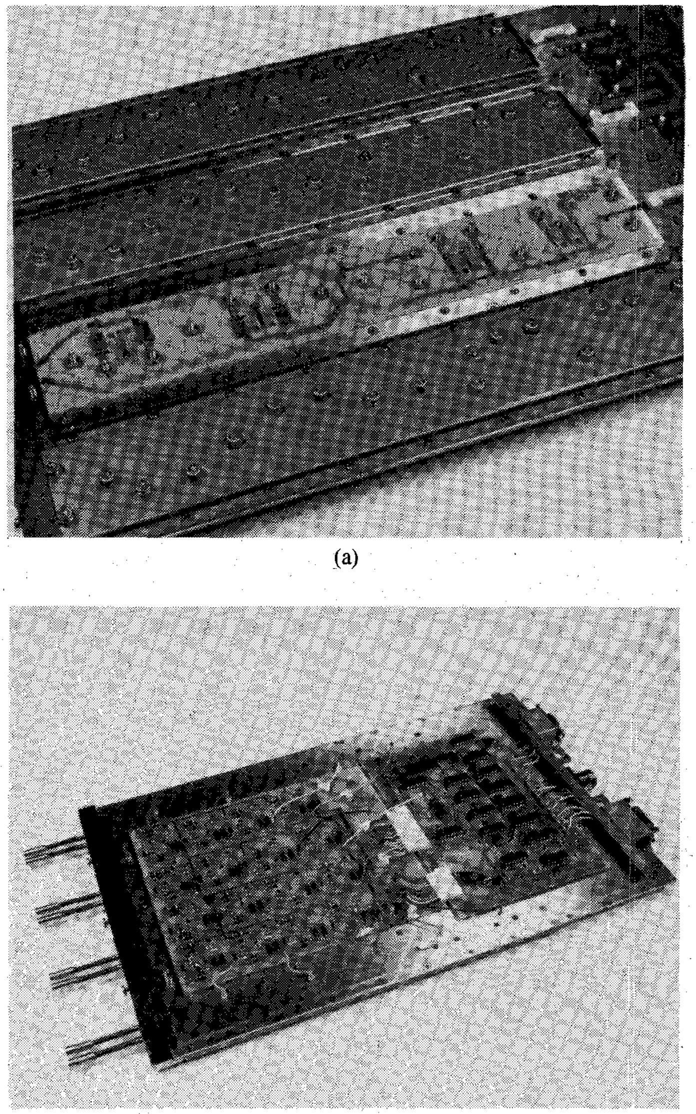
Fig. 19. *Cobra Judy* RF circuit layout.

antenna was given added attention. An output "rail" of the assembly would use eight push-on RF connectors, each machined to a length tolerance of ± 5 mils to permit a low-loss, low-VSWR simultaneous connection of the module to the radiating elements of the array antenna plate simply by pushing the assembly into place [22] (Fig. 20). Each such connection requires about a 10-lb force and, while connectors separately can be readily pushed together by hand, the 80-lb force required by eight of them combined is more than a man standing on a ladder can apply reliably. Insertion levers were needed to make this module installation.

Another phased-array complexity is the requirement to provide bias control signals to all of the individual bits of the phase shifters. The magnitude of the problem can be appreciated by considering that the 12000 phase shifters, each having four bits, would required 48000 such control wires if simultaneous and independent access were to be made to all bits in the array. An ingenious solution to this problem is the use of "row and column steering."

A phased array, by its nature, requires that a linear phase delay be applied in the plane formed by the vectors which describe the directions in which the beam is steered. For example, to steer 45° in azimuth off the boresight axis of a 30 wavelength diameter array, a delay of zero degrees for the vertical column of elements at one periphery of the aperture and 21.21 wavelengths of delay ($30 \times 360° \times$ sine 45°) is needed at the diametrically opposite element column of the aperture.

Quantization of the phase shift, rather than time delay, allows dropping the initial 21 wavelengths and applying the residual 0.21 wavelengths (77 degrees of phase shift). With 3-bit quantization level (45° steps), the nearest phase state is 90°, and this would be command applied to the phase shifters in that column. In a like manner, all of the azimuth steering commands for the remaining vertical columns of phase shifters can be calculated. For random two-dimensional scanning, the beam is steered both in azimuth and elevation, thus, the "residual phase shift command" is determined from the sum of the delays needed for both azimuth and elevation scanning axes.



(a)

(b)

Fig. 20. The *Cobra Judy* four-channel *S*-band phased-array module using 8 simultaneous push-on RF connections. (a) Dual polarized, four-channel phase-shifter assembly. (b) Logic and driver side of the assembly.

If all phase shifters in the array are identified according to a two-dimensional column and row (XY grid), then azimuth scanning commands can be applied to all columns and elevation commands to all rows. Each phase shifter, having built-in arithmetic logic, adds these two commands at its own particular "azimuth-elevation" command site, deriving a control signal unique to its particular XY, or column and row, location. In this way, a portion of the beam steering computer has been integrated into the array. More importantly, wiring need only be run for rows and columns. In a 100×100 array, this can reduce the signal paths from 10000 to only 200!

It takes some time to load the signals into the array, during which time it is desirable that the phase-shifter settings corresponding to the previous beam position continue to be applied, lest RF power be radiated randomly by the antenna during the control signal loading. Accordingly, the old command for each phase shifter coninutes to be applied while the new one is loaded in. This, in turn, requires that a memory element, such as a shift register, be included within the driver and logic circuitry.

Summarizing, row and column signals must be summed, deleting even numbers of wavelengths (multiples of 360°), and the result stored while the old command continues to activate the phase shifter. A further requirement derives from the fact that to minimize further the number of control wires, the logic signals arrive as a time series bit sequence. Thus, wavelengths of delay arrive as four- or five-bit, time sequential, digital pulses. The phase-shifter's logic must convert serial-in-time signals to a simultaneous parallel output voltages and currents, real-time commands for use when the array is to change its beam pointing direction.

I include this description to show that microwave engineers, who previously were very rarely required to understand logic circuitry, now find themselves enmeshed in it as they build microwave phase shifters (and other modern control circuits). Moreover, the complexity of the driver and logic circuits, if they are to be efficient, reliable, and low cost, pose design disciplines equally demanding as those required for the microwave circuitry.

For systems such as the *Cobra Dane* and *Cobra Judy*, the phase-shifter development program required the full-time effort of two engineers and their technicians for a year in order to refine a single-channel prototype phase-shifter design, available at the program onset, to the stage at which it became a fully useable and producible element in the final array antenna. During that time, such special needs as high-power loads, drivers, logic, push-on connectors, *in situ* phase-trimming devices, tolerance studies, reliability estimates, thermal-cooling design and verification, temperature cycling, and computer-controlled RF measurements had to be accomplished.

VI. Summary Observations

When I began my work with phase shifters in 1961, most engineers in the radar field felt that it would be only a matter of time before the mechanically steered antenna would be relegated to museums. Phased arrays would appear on all scanning radar systems, even microwave communication systems. Phased arrays would be conformal, figuratively "painted on the exterior surfaces of aircraft, ships, motor vehicles, and even buildings."

Certainly, this has not happened in the 20-year period over which phase shifters and phase arrays evolved. Why not? First, the cost of a phased-array antenna is much more than that of its mechanically steered counterpart. For it to be considered on attractive alternative, its special features, such as very rapid scanning, or lack of mechanical movement, must be essential. Because of the limited instances of radars having such requirements, few phased arrays have been built.

In contrast, for those industries in which rapid growth and low-cost availability of a product has been experienced, such as television sets, calculators, personal computers, and so forth, the expansion is made possible by the identification of a continuing need over a number of years for a product of substantially unchanging primary characteristics. Year to year, television sets receive the same number of channels, use the same raster pattern, and so forth. But in radars, few such standard rules apply. Each radar application is designed as a stand alone system and is generally optimized for that function. Whether this is so of necessity or because it is a penchant of microwave engineers to custom tailor their creations, is a consideration beyond that scope of this paper. The fact remains that none of the phase shifters for the array antennas that these radars require are common to one another. The same two man–year customizing of each design seems to apply to any major phased-array application, and only one or two systems typically are built. Accordingly, the evolution of array antennas and their phase shifters seems destined to this radar-by-radar development process.

This paper is about the evolution of high-power p-i-n diode switching, of which the phase shifter is most illustrative. However, the specific system nature of high-power diode control devices is not limited to phase shifters. In fact, high-power p-i-n switches and duplexers are equally specific to the systems of use, and, since there are fewer of them per system, even less opportunity exists to evolve mature (low-cost) designs.

Accordingly, I believe that our expectations in this high-power p-i-n switching field should be in keeping with those of other custom-design applications. That is to say, rather than wait for phase shifters and other control devices to become inexpensively and commonly available as "standard off-the-shelf parts," which likely will never occur, we should recognize that the application itself should be sized to low cost, that once enough copies of a given system are planned—the future microwave landing system (MLS) is an example—the prices of these components will drop to practical levels.

Acknowledgment

Many people contributed to these programs beyond those identified in the text. The Raytheon Company was the prime contractor for all three array programs, the Bedford Division for the MSR, and the Wayland Division for the *Cobra Dane* and *Cobra Judy* radars. George Fraizer was the program leader for the MSR, Dennis Picard for the *Cobra Dane,* and Walter Stowell for the *Cobra Judy*. Within M/A, Richard Moser was the Program Manager for the MSR. He, Dana Atchley, Frank Brand, and Richard DiBona provided managerial support that only can be appreciated by those who were close to the efforts.

Between the testing of a first model and the delivery of a production design, a year or more of detailed engineering must be performed. Prominent in this effort was Ray

Forest for the MSR and Dave Fryklund for the *Cobra Dane* and *Cobra Judy*.

Special contributions were madey by Mike Ferrantino, Dan Fox, George Garas, George Fraizer, Chris Georgopoulos, John Gottlander, Henry Griffin, Ron Gutmann, Bill Hoelzer, Dave Kinzel, Peter Ledger, Tom Ligon, Henry Munsey, Dick O'Shea, Vern Philbrook, Ken Puglia, Bill Rushforth, Gordon Simpson, Dave Stikeman, Charles Ward, Dick Ziller, and Demir Zoroglu.

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References

[1] F. S. Coale, "A switch detector circuit," *IRE Trans. Microwave Theory Tech.*, vol. MTT-3, pp. 59–61, Dec. 1955.

[2] R. V. Garver, "Theory of TEM diode switching," *IRE Trans. Microwave Theory Tech.*, pp. 224–238, May 1961.

[3] A. Uhlir, Jr., "The potential of semiconductor diodes in high frequency communications," *IRE Proc.*, pp. 1099–1115, June 1958.

[4] D. Leenov, J. H. Forster, and N. G. Cranna, "PIN diodes for protective limiter applications," in *ISSCC Dig. Papers*, Feb. 16, 1961, pp. 84–85.

[5] D. Leenov, "The silicon PIN diode as a microwave radar protector at megawatt levels," *IEEE Trans. Electronic Devices*, pp. 53–61, Feb. 1964.

[6] J. F. White, *Microwave Semiconductor Engineering.* Van Nostrand Reinhold Co., New York, 1982; previously published by Artech House in 1977 under the title *Microwave Semiconductor Control.*

[7] R. V. Garver, E. G. Spencer, and R. C. LeCaw, "High speed switching of semiconductors," *J. Appl. Phys.*, pp. 1336–1338, Nov. 1957.

[8] K. E. Mortenson, "Microwave semiconductor control devices," *Microwave J.*, pp. 49–57, May 1964.

[9] R. Ryder in a talk at the IEEE NEREM show in Boston, MA, circa 1965.

[10] J. F. White, "High power solid-state switching," in *1964 ISSCC Dig.*, p. 30.

[11] R. V. Garver, *Microwave Diode Control Devices.* Dedham, MA: Artech House, 1976.

[12] M. E. Hines, "Fundamental limitations in RF switching and phase shifting using semiconductor diodes," *Proc. IEEE*, pp. 697–708, June 1964.

[13] H. N. Dawirs and W. G. Swarner, "A very fast voltage controlled microwave phase shifter," *Microwave J.*, pp. 99–106, June 1962.

[14] A. J. Simmons, "Phase shift by periodic loading of waveguide and its applications to broad-band circular polarization," *IRE Trans. Microwave Theory Tech.*, pp. 18–21, Dec. 1955.

[15] J. F. White, "Phase shifter having means to simultaneously switch first and second reactive means between a state of capacitive and inductive reactance," U.S. Patent 3491314, Jan. 20, 1970, United Kingdom 1101843, and France 1476448.

[16] J. F. White, "High power, pin diode controlled, microwave transmission phase shifters," *IEEE Trans. Microwave Theory Tech.*, pp. 233–242, Mar. 1965.

[17] J. F. White, "Semiconductor microwave phase control," in *Nerem REC.*, Nov. 5, 1963.

[18] J. F. White, "Review of semiconductor microwave phase shifters (Invited Paper)," *Proc. IEEE*, pp. 1924–1931, Nov. 1968.

[19] S. B. Cohn and N. P. Weinhouse, "An automatic microwave phase-measurement system," *Microwave J.*, pp. 49–56, Feb. 1964.

[20] R. W. Burns and L. Stark, "PIN diodes advance high power phase shifting," *Microwaves*, pp. 38–48, Nov. 1965.

[21] J. F. White, "Microwave device assemblies," U.S. Patent 3974465, Aug. 10, 1976.

[22] J. F. White and D. J. Fryklund, "Dual polarization phased array diode phase shifter module," in *1982 IEEE MTT Symp. Dig.*, pp. 182–184.

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In addition to numerous IEEE papers for Conferences, Proceedings, and Transactions, he has presented lectures and talks both in the United States and Europe. He is a member of Eta Kappa Nu, and Sigma Xi, Reviewer for the IEEE Transactions on Microwave Theory and Techniques, and author of *Microwave Semiconductor Engineering*, a text on microwave control circuits and semiconductors. He is the Consulting Editor for the *Microwave Journal* Magazine, an editorial activity he has continued since 1978.

The MTT Group awarded Dr. White its Application Award for "The development of practical high-power p-i-n diode phase shifters utilized in various phased array radars."