EARLY WORK ON MILLIMETER WAVE SYSTEMS AND PHASED ARRAY RADARS (IN THE BALTIMORE-WASHINGTON AREA)

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ABSTRACT

Early development (1950s-1960s) of millimeter wave systems and phased array radars in the Baltimore/Washington area is recalled. Although, many of the components and instruments of the period have been superseded by more modern technology, many accomplishments became milestones or seeded later work. Some notable examples include: radiometers up to 600 GHz (0.5-millimeter wavelength), the first modern phased array radar- the FPS-85, self-focused imaging radars, and sea scattering measurements in the 10 to 50-GHz region.

PRESENTATION

Millimeter wave technology was given coherent life (after a few "sparks") by the availability to universities of war surplus (WWII) K-band reflex klystrons that had been produced by Raytheon. By a stroke of "bad/good" luck an anticipated K-band radar lay astride the atmosphere water vapor resonant absorption region and was doomed to failure- hence the large surplus of K-band tubes. Water was not the only molecule that absorbs in the microwave region, and hence, the field of microwave spectroscopy was born. Many light weight molecules, such as O_2, CO and NO, have their first resonant absorptions in the millimeter wave region and the push to develop a means of coherent microwave radiation at millimeter wavelengths become a major goal. Crystal harmonic generators driven by the surplus centimeter klystrons provided the answer.

This technology born from the needs of spectroscopists was translated to The Johns Hopkins University Radiation Laboratory nearly 50 years ago. Our first engineering application was in a millimeter wave range for modeling off-angle scattering from aircraft. Obviously, digital computer modeling was in a primitive state, and we had to resort to a five-foot searchlight dish fed by our millimeter-wave transmitter, an aluminized model aircraft in the collimated beam and a moveable millimeter wave antenna/receiver. The amount of millimeter wave power that we could generate at 100 GHz (3mm) was limited[1] and the detectivity of the crystal video receiver used was low. Consequently, the system could not satisfactorily measure the diffraction scattering intensity between the high level specular scatterers.

As increased millimeter wave power became available both via improved harmonic generators and higher frequency, more reliable klystrons, more things could be done. People began to think of possible millimeter wave applications, such as weapon seekers and fuzes. Clutter background measurements had not been measured at this time, and to fill this void we proposed to our Navy sponsors to make backscattering measurements from the sea at several frequencies up to 50 GHz (5 mm) simultaneously. It just happened that the ship on which we proposed to make the measurement, was sailing from Baltimore to Puerto Rico in December. In addition to having a good time in Puerto Rico we did get some good measurements that have proven useful for many years.[2] Once we had measured background clutter it was obvious that we should also make target backscattering measurements over similar frequency bands. This we did by convincing the Maryland National Guard to fly some of their 1950s jets low overhead of our apparatus. Fortunately stealth aircraft had not yet been invented.

As analytical and experimental work began on low loss transmission lines for millimeter waves, in particular dieletric image lines [3,4]. Also, in addition to improved harmonic generators and detectors, a technique we called harmonic mixing[5] was devised, which pointed the way to heterodyne detection with much improved sensitivity over the video detectors in use at the time. The harmonic mixer was a variant on a harmonic generator- the difference being principally in usage. This harmonic mixer was used to generate local oscillator power at, for example, 200 Mhz in the mixer directly from a klystron at 50 GHz. The device proved quite useful later in millimeter wave radiometry.

In the mid to late 1950s people doing millimeter wave work at the Johns Hopkins Radiation Laboratory gradually moved out to the Research Division of Electronic Communications, Inc. (ECI), located in Timonium, MD (as we said in those days "Rare Earth" Maryland). They continued work in millimeter-wave applications and started some of the very early phased array radar work.

The focus of the millimeter wave work shifted to component improvements, low loss propagation media and eventually radiometers. Determined work[6] on improving harmonic generators for transmitter sources and harmonic mixers for receivers provided the basic parts for systems, such as radiometers, in the millimeter and sub-millimeter region. Also, various organizations were improving the fundamental sources- both electron tubes and solid state osillators- and extending their operating frequencies well into the millimeter wave region. Conversion losses, repeatability and reliability improved by orders of magnitude.

Correspondingly, a strong, creative effort[7] to find and characterize low-loss transmission media for millimeter waves had high pay-off. Analytical and experimental studies were conducted in the 100-300-GHz region of many candidates: waveguide, single mode and overmoded; dielectric image lines; single conductor transmission lines, Gaubau wave and Sommerfeld wave; coax with circular and elliptical cross section and quasi-optical components such as Fresnel zone plates for transmission and filtering. The level of detail is illustrated by their finding that dielectric image lines with a thin tape of rectangular or elliptical cross section were used rather than the usual semicircular shape.

High sensitivity Dicke-type radiometers were built to operate in the millimeter and sub-millimeter regions.[8] These radiometers used of harmonic mixing and circumvention of local oscillator noise by use of microwave intermediate frequencies. High thermal sensitivity was achieved through use of large IF bandwidth. Minimum detectable temperature differences of a few tenths of degree were obtained with 10 second integration time. Antenna temperatures and atmospheric absorption measurements were made with these radiometers. The highest frequency radiometer[9] built during this period at ECI was 600 GHz. Other work on millimeter wave radiometers in the Baltimore-Washington area was pursued during about the same time period at the Naval Research Laboratory.[10]

Another application area which was pursued at the component level[11] was point-to-point communications. Real progress in this area was severely limited by lack of suitable transmitters.

Somewhat later research and development on millimeter wave components and systems were started at Harry Diamond Laboratory and Aberdeen Proving Ground.

Notable was HDL work on millimeter wave diode switches.[12]

Research and development on phased array radars and their critical components, in particular phased shifters and antenna arrays, began at ECI in the mid 1950s - in pre "Sputnik" days. Emphasis was on development of low-loss ferrite phase shifters at C and, S-bands and at UHF. Likewise, emphasis was on analysis of mutual coupling between radiating elements in two dimensional arrays and on element thinning in large arrays. Early on UHF seemed the ideal frequency for a large phased array. The technology of efficient transmitter tubes and reasonably low-noise receivers was well in hand. A low-loss phase shifter appeared to be the missing link. So we developed a compact, low-loss, ferrite, folded strip line model.[13] These phase shifters never found use in a phased array radar, but did find application in a direction-finding system.

Our sponsor brought back some critical findings from the atomspheric nuclear bomb test in the Pacific at that time and asked us to switch our phase shifter work to S and C band. As a consequence, we shifted our effort to ferrite phase shifters and switches[14,15] in these bands and to precise control[16] of these devices. Small phased arrays were built and tested. At that time we thought that ferrite phase shifters would always have the advantage of handling more power than diode phase shifters. Of course, we were still solidly in the pre digital age.

Once there was relatively high interest in radar phased array radars for defense, the next question asked was could acres of phased radiating elements make a useful beam weapon against the emerging ICBM threat. ECI people thought about the problem and analyzed approaches to achieving self-focused arrays. However, they soon realized that such a weapon was impractical for several reasons - the radiation wavelength was too long to achieve a diffraction spot small enough to produce lethal power density on the target and the target itself was already superhand to allow it to reenter the atmosphere.

A more practical endeavor came when Bendix Corp. in Baltimore won the contract to develop an experimental phased array called ESAR (Electronically Steerable Array Radar) for DARPA/RADC. ECI was asked to help with design of the radiating elements and the thinned array. In ESAR phase shifting was accomplished by a complex frequency steering scheme. But from this work Bendix won the contract to develop what became the FPS-85 radar located at Eglin, FL. Bendix built this UHF phased array radar with diode phase shifters. After two starts - one burned down - this radar became part of the US/NORAD Early Warning System. It operated with high reliability in this role for many years. Once space satellite systems took over much of the early warning functions, the FPS-85 became part of the satellite track network, a role it continues in today. I believe it is the world's oldest large phased array radar in operation today.

At ECI work on radiating elemements continued, both on individual elements and on large arrays of elements. By analysis and experiments elements were developed for radiation efficiency and minimum mutual coupling.[17]

Considerable work was done to try to achieve predictable performance from thinned arrays and from unequally spaced arrays.[18]

Later (circa 1968), the ECI group developed an experimental imaging X-band phased array.[19] This group developed an electronic scanning technique which was used to record target images at a high rate. Reliable IF processing and display techniques were developed, capable of scanning an array beam through 40 beamwidths in each dimension at a rate of 100 complete scans per second.

The ECI Research Division underwent several name changes before finally closing its door in 1969.

The early work at The Johns Hopkins Radiation Laboratory and at the ECI Research

Division acted as the seed for millimeter wave and phased array radar work elsewhere as key people left for other organizations: Marv Cohn to Westinghouse; Don King to Aerospace and Phillips Laboratories; Bob Roush to Westinghouse; Bert Sichelstiel to Westinghouse; Merrill Skolnik to Naval Research Laboratory; Bill Waters to Applied Physics Laboratory and Naval Research Laboratory; Jim Wiltse to Martin and Georgia Tech.

Today millimeter wave systems are used extensively for missile seekers, satellite communications, diagnostics and radiometry. The most famous application, of course, is the measurement of the ubiquitous cosmic background radiation - for which Penzias and Wilson were awarded the Nobel Prize in 1978. Just think of what the 1960 ECI radiometer builders missed by not having a large antenna to go with their receiver. Penzias and Wilson had only a 7.5 centimeter wave radiometer and were really only trying to get rid of the pesky background noise.

The microwave background is currently being assessed via the COBE satellite (Cosmic Microwave Background Explorer). Its Differential Microwave Radiometer has measured temperature variations of 36 micro Kelvin degrees in the microwave cosmic background, confirming the Big Bang theory.

Phased array radars have become the norm for nearly all early warning and air and missile defense systems. Technology has advanced greatly since the 1950-60s. The transmit/receive modules in the newer radars are integrated packages containing all microwave components- phase-shifter, circular, switches, and amplifiers. Only low-power synching and receiver processing tie the array together.

Quite amazingly, back in the late 1950s when we first seriously envisioned a practical electronically scanned array, we estimated the price per radiating element as 1000 dollars. People still estimate the price per element as 1000 to 2000 dollars per element. Of course, the technology has changed enormously in 40 years, but it is still very difficult to determine if the cost estimate actually refers to the element module alone or to the cost of the radar divided by the number of elements.

Its been a fun 40 years for many of us.

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