RADAR AND PHASED-ARRAYS: ADVANCES, BREAKTHROUGHS AND FUTURE

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IRSI-17, Dec.12-16, 2017, Bangalore, India

Keywords: **Radar, AESA, phased arrays, metamaterial, MIMO, Extreme MMIC, PATRIOT, JLENS, AMDR, SPY-3, graphene, car radar, signal processing, Moore's law. FPGA, Digital Beam Forming, carbon nanotubes, transistors, synaptic transistors, cloaking, stealth, COSMOS, ACT, DAHI.**

Abstract:

Moore's Law is slowing down but still has a way to go. Potential further major advances of Moore's Law via: Spintronics, Memristors , Graphene, and Quantum Computing. Advances made in metamaterials covered in area of low cost electronically scanned arrays, stealth, cloaking (invisibility), low profie VHF/UHF antennas, and focusing beyond λ/2 . PATRIOT has GaN active electronically scanned arrays (AESAs) which gives 360° coverage without mechanical rotation. The S-band AMDR handles >30 times more targets and has >30 times sensitivity of the SPY-1D(V). Can now put a 256 element 60 GHz transmit array on a chip. All the RF circuitry for mm-wave radars is put on a chip. Such radars and phased arrays could cost just a few dollars in future. Major advances made toward low cost printed flexible electronic circuits with diodes operating at 1.6 GHz. A low profile dual polarized tightly coupled dipole antenna (TCDA) has been developed which provides a 20:1 bandwidth and has λ/40 thickness. The latest type of phased array is the MIMO radar phased array which has been shown to provide orders of magnitude better accuracy and resolution as well as better GMTI performance than conventional arrays. However, as summarized here, more recently this author has shown that conventional arrays can do just as well if properly used without suffering MIMO's signal processing load and waveform design problems.

1. Radars Upgrades and New Developments

This paper is an update to previous papers written by the author on the significant developments, trends and breakthroughs in radar and phased-arrays [1-8, 56]. The big news relative to upgrades is the PATRIOT (Fig. 1) has a Gallium Nitride (GaN) active electronically scanned arrays (AESAs) which gives it a 360° coverage without mechanical rotation [57]. It uses a 9ft by 13ft main antenna that is bolted on and 2 quarter size rear antennas. It is a simple upgrade to apply to the 220 fielded systems. The back end of the PATRIOT had already been completed in 2012 with a $400 million investment. With these upgrades the PATRIOT is a 2015 state-of-the-art radar. The system is backwards compatible. Raytheon has spent over $150 million on the development of GaN. This upgrade reduces operation and maintenance cost by as much as 50%. The impressive performance of the Air and Missile Defense Radar (AMDR, Fig. 2) has recently been released [68]. It has a 4-faced S-band radar for air and missile defense, a 3-faced X-band radar for horizon search; adaptive digital beam forming; handles 30 times more targets and has more than 30 times sensitivity of SPY-1D(V).; uses GaN which is 34% less costly than GaAs; GaN has 10^8 hour MTBF; antenna composed of 2x2x2 ft^3 radar module assembly (RMA) building blocks; 4 line replaceable units (LRU) per RMA; each LRU replaced in less than 6 minutes; fully programmable, 37 RMAs produce a system that is equivalent to the SPY-1D(V)+15dB, back-end radar controller built out of commercial off-the-shelf (COTS) x86 processors which allows adapting to future threats and easy upgrading with future COTS processors eliminating obsolescence; S-band antenna is scalable. Another development is the Zumwalt DDG-1000 stealth ship (Fig. 3) launched Oct. 28, 2013 with two more under development. It has the 3 faced X-band SPY-3 radar [1]. Lockheed Martin's space fence radar uses digital beam forming (DBF) at the element level for their dual polarized 86K element receive array using 172K A/Ds; Fig. 3A [71]. The JLENS (Joint Land Attack Cruise Missile Defence Elevated Netted Sensor) blimp (airship) system [1] has been deployed over Washington DC. It is nominally tethered at 10,000 ft to give it a look down capability. Has 360° coverage. It can detect a low flying cruise missile (CM) at a range of 340 nmi, cues PATRIOT and TPY-2, has demonstrated detection and tracking of ballistic missiles and intercept of CMs.

The trend by Raytheon and MIT Lincoln Laboratory to use commercial technology such as printed circuit boards (PCBs) and non-hermetically sealed packaging to achieve low cost AESAs for ground radars was reported on in [1]. Rockwell Collins is continuing this trend with the development of an X-band airborne radar using PCBs for the array and low cost SiGe chips [46]. South Korea is also

PATRIOT UPGRADES

- 2012: $400M UPGRADE
- 2015: GaN AESA; 360^{O} COV.

1/4TH SIZE AESAs IN REAR ⇒
2015 STATE-OF-THE-ART SYSTEM

US ARMY
FIELDING TO 2048

- >200 BUILT, 13 NATIONS
- 5000 EL PER/FACE, C-BAND

(FEB. 19, 2015/PRNEWSWIR1520E/;
MICROWAVE&RF, AUG 2015, P. 24;
RAYTHEON WEBSITE) (PHOTO: BROOKNER, E., MJ,2/15)

Figure 1. C-Band PATRIOT now 2015 State-of-the-Art GaN AESA Radar System.

developing a low cost X-band array [58]. DARPA has an aggressive revolutionary effort called Arrays at Commercial Timescales (ACT) program whose goal is to lower the procurement cost of new AESAs and ESAs by at least 80% [59]. The ACT program is focused on shorter design cycles and creating a commercial market approach to developing antenna arrays. This program aims to make AESAs and ESAs more affordable by offering common building block components. The common building block modules can be used for diverse AESA and ESA programs and applications – radar, signals intelligence (SIGINT), electronic warfare (EW) and communication. The building blocks would be easily upgradable so as to avoid obsolescence. They would allow flexibility in system parameters by being reconfigurable which also reduces obsolescence. The building blocks would be for the antenna, called reconfigurable electromagnetic interface blocks, and for the circuitry following the antenna building blocks, called the common module (see Fig. 4), which are digitally connected. The program is also looking at cohering AESAs and ESAs on different platforms. DARPA is investing $100 million for the ACT program with contracts having been given out to the leading AESA and ESA companies and research organizations: Raytheon, Northrop Grumman, Lockheed Martin, Boeing, Rockwell Collins, HRL Laboratories, and Georgia Tech Applied Research.

2. New Technology and Advances

2.1.Extreme MMIC and Moore’s Law

Extreme MMIC has gone from 4 T/R modules with its control circuitry on a chip at X-band [1, 2] with each T/R costing about $10 to a whole 256 element arrays on a chip at 60 GHz; see Fig. 5 and [9, 10]. These phased array chips will have built in test circuits for calibration. What is driving this technology is the cell phone and WiFi business. From 2010 to 2020 the bandwidth demand is predicted to increase

AIR & MISSILE DEFENSE RADAR (AMDR)

S-BAND: AIR & MISSILE DEFENSE:

- ADAPTIVE DIGITAL BEAM FORMING
- 30X > TARGETS THAN SPY-1D(V)
- 30X > SENSITIVE THAN SPY-1D(V)
- RADAR MODULAR ASSEMBLIES (RAMs) ARE BUIDING BLOCKS
- LRU IN RAM REPLACED <6MIN, EASY, ONLY 2 TOOLS NEEDED
- 37 RAMs = SPY-1D(V)+15DB = ~14’x14’ ≈ SIZE OF SPY-1D(V)
- GaN ARRAY, 4 FACED
- GaN 34% < $ THAN GaAs
- GaN HAS 10^8 HR MTBF
- RAYTHEON INVESTED $150M IN GaN
- SCALABLE

ARLEIGH BURKE
DESTROYER

X-BAND: HORIZON SEARCH

(WIKIPEDIA PHOTO)

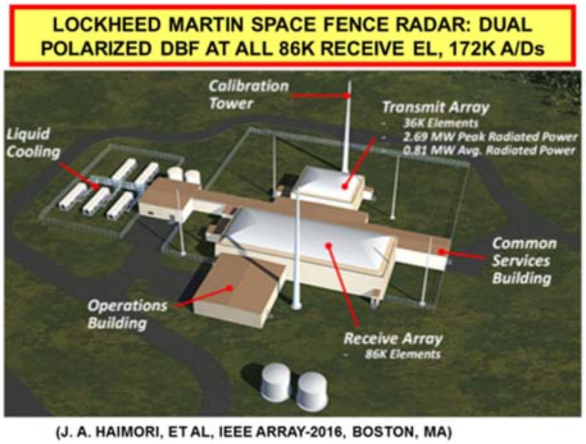
Figure 2. Air and Missile Defense Radar (AMDR).

1ST ZUMWALT DDG-1000 STEALTH
SHIP LAUNCHED OCT. 28, 2013

X-BAND SPY-3 THREE FACED ARRAY

(US NAVY PHOTO)

Figure 3. Zumwalt DDG-1000 Stealth ship. (Photo by Kevin Baron)



LOCKHEED MARTIN SPACE FENCE RADAR: DUAL
POLARIZED DBF AT ALL 86K RECEIVE EL, 172K A/Ds

(J. A. HAIMORI, ET AL, IEEE ARRAY-2016, BOSTON, MA)

Figure 3A. Lockheed Marin Space Fence Radar [71].

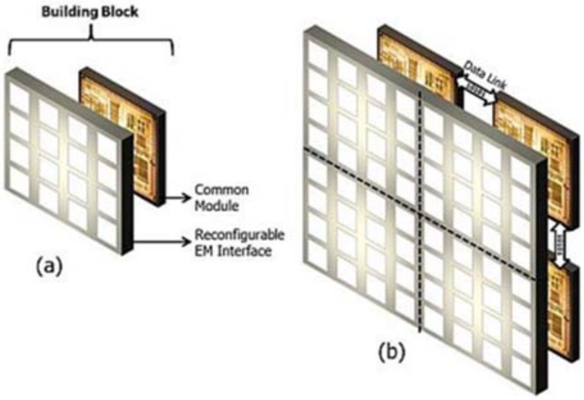
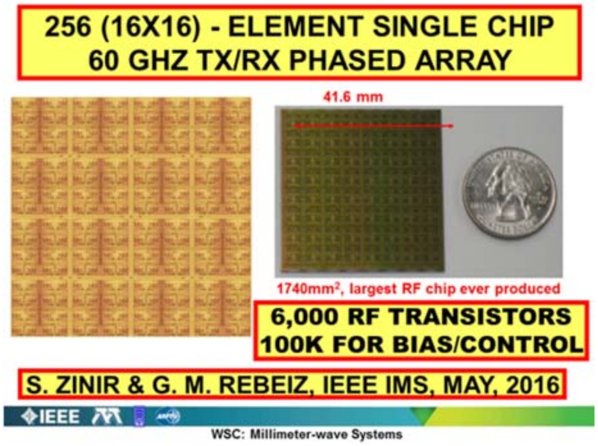


Figure 4. ACT antenna building blocks [59].


256 (16X16) - ELEMENT SINGLE CHIP
60 GHZ TX/RX PHASED ARRAY

41.6 mm

1740mm^2, largest RF chip ever produced

6,000 RF TRANSISTORS
100K FOR BIAS/CONTROL

S. ZINIR & G. M. REBEIZ, IEEE IMS, MAY, 2016

Figure 5. 256-Element 60 GHz Transmit Phased Array [9].

1000 fold and the number of mobile connected devices from 5 to 50 billon [10]. These array chips are expected to find in the next decade wide use for garage door openers, videos players and computers [10]. They will all talk to each other via high BW Wi-Fi. In the future compact, ultra-low cost MIMO mm-wave multi-beam AESAs will be in everyday devices [10]. Car radars are also benefiting from extreme MMIC [11-13]. The 77 GHz car radar chip of Fig. 6 has all the RF circuitry needed: 2 transmitters, 4 receivers and LOs. Some feel in the future such car radar will cost only a few dollars. Ref.13 gives a commercial 24 GHz multi user a single chip radar. Autoliv has a car radar on a 3.5"x2.25" board which includes a radar chip and a Texas Instruments signal processing chip that does Kalman Filter tracking [14]. They have manufactured over 2 million of them with the cost of the board being less than $100 [14]. Valeo Raytheon has developed a 25 GHz blind spot 7 beam phased array radar costing only $100s of dollars from the car dealer in purchases of one [1,15,16]. So who said phased arrays are expensive! Over 2 million of these have also been produced [16]. The car radars market is large. Over 70 million cars were built in 2014. Assuming 4 radars per car we get a total of over 210 million. Google has developed a radar for a smartwatch; see Fig. 7.


UN. MELBOURNE SINGLE
CHIP 77GHz RADAR T/R

Figure 6. Un. Melbourne single chip 77 GHz Radar T/R. From G.Klari, et al, Microwave J., 1-14-15 [11].

Gordon Moore predicted the above application of MMIC to radar and phased arrays. The last sentence in his now famous Moore's Law paper [17] is: "The successful realization of such items as phased-array antennas, for example, using a multiplicity of integrated microwave power sources, could completely revolutionize radar." DARPA is funding the development of commercial FPGAs at microwave frequencies [1]. Commercial FPGAs now have clock speeds of 1 GHz

When I built my radio and oscilloscope for my high school laboratory class in the 1940's I used vacuum tubes. They were about 1x1x2 in^3. Now 130 billion transistors go on a 128 GB memory stick 0.5X0.8X2 in^3, smaller than one of my vacuum tubes. The memory stick fits in my pants back pocket. If you used the tubes I used in high school for this memory stick then when stacked sideways one on top of the other they would extend to a height 9 times the distance to the moon or equivalently about 90 times synchronous altitude and have a 1X2 in^2 footprint!!! This certainly would not fit in my back pocket. My 128 GB memory stick containing 130 billion transistors cost me only $35. Using tubes it would cost $130 billion at $1 per tube. The power needed to run these tubes would be 130 GW each tube needing about one watt. This is equivalent to 130 nuclear power plants. This comparison between what we get using transistors and what it would take using tubes is summarized in Fig. 8. This puts in perspective the amazing achievement made with integrated circuits for memory storage over the last 70 years. This same comparison applies to our smart phones that have 128 GB of memory. We talk about inflation. Because of inflation what used to cost $1 in the mid-forties now typically cost ten times as much or $10. But this is not true for electronics. With that dollar we can today buy 4 billion transistors, the equivalence of 4 billion tubes!!! What inflation? When it comes to electronics we have here extreme deflation. The number of transistors produced worldwide in 2014 was 250 billion billion (2.5X10^{20}). Using vacuum tubes stacked one on top of each other sideways this would extend to 40 million times the distance to sun!!! See Fig. 9. The above advance in integrated circuits is due to Moore's Law which states that the density of transistors will increase a factor of two every two years. This has been going on for several decades. Some have said it is dead but indications are that it is slowed down and we still have a way to go. Specifically it is predicted that the density of transistors will increase by about a factor of 50 over the next 30 years with the power per transistor going down by about a factor of 75. Still impressive.

Figure 7. Google Smartwatch with radar [66].

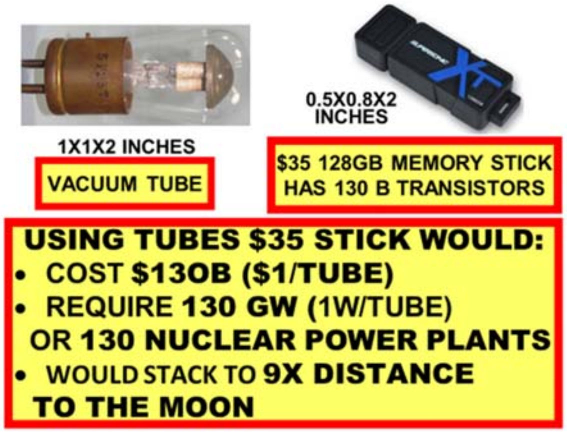


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Figure 8.

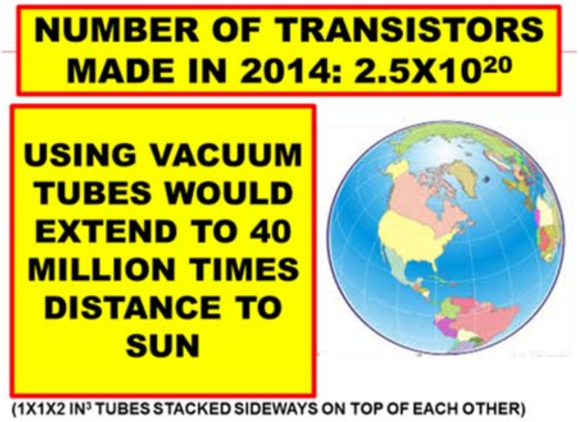


Figure 9.

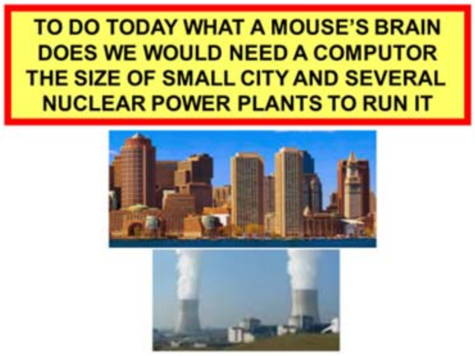
Helping with advance in extreme MMIC will be the revolutionary DARPA Compound Semiconductor Materials on Silicon (COSMOS) program [1, 20] and its follow on Diverse Accessible Heterogeneous Integration (DAHI) program [21]. The COSMOS program has demonstrated for the first time the integration of GaN and CMOS on the same Si substrate without bonded wires [20, 21]. Helping with the advance of signal processing capability are the technologies of nanotechnology, spintronics [54], graphene and carbon nanotubes [1, 22], memristors [2], synaptic transistors [23], quantum computing and the possibility in the future of the transmission of data optically on the chip. The ability to transmit electrical and optical signals over the same wire has been demonstrated [24]. Ref. 25 indicates the alternate possibility of the use of IR beams in a Si chip (which is transparent to IR) for transmission of signals without ohmic loss and at the speed of light. Graphene and carbon nanotubes (CNT) have the potential for terahertz transistor clock speeds instead of a few gigaherz, nearly 3 orders of magnitude faster. The manufacture of graphene transistors on CMOS has been demonstrated. Could allow Moore's law to march forward using present day manufacturing techniques. Spintronics could revolutionize the computer architecture away from the 1945 John von Neumann model of separate logic and memory units. Instead could be one and the same for some parts with logic being low cost nonvolatle memory. Spintronics has the potential to replace hard drive with low cost, low power, more reliable memory having no moving parts and faster access time for the data. And then there is potential of doing computations the way the brain efficiently and amazingly does, going analog by perhaps using synaptic transistors and/or memristors.

We are very proud with our accomplishments in signal processing and memory. Remember though that the brain only weighs about 2-3 pounds and uses only ~20 W; see Fig. 10. It has been estimated that to do even what a mouse's brain does would require a computer the size of a small city and require several nuclear power plants to run it [55]. See Fig. 11. We have a long way to go yet. We are still in the horse and buggy days when it comes to computer capability. See Fig. 12. The future should bring us to a capability closer to what our brain can do. As mentioned above technologies that potentially will help in this direction are memristors, quantum computing, graphene transistors operating at terahertz clock speeds and synaptic transistors that mimic our brain [1, 55]. It took man 70 years to go from a single tube to a memory stick with the equivalent of 130 billion tubes. It took nature 4 billion years of evolution to create our brain. Memristors can be made very small. They function like our brain synapses. They could possibly enable us to build analog electronic circuits that solve the astronomical number of coupled partial differential equations that our brain does and that could fit in a shoebox and function according to the same physical principles as a brain [55]. Quantum computing also offers the potential of an orders of magnitude increase in computer power every generation instead of a factor of two that Moore's law provided [53, 64]; Fig. 14.

HUMAN BRAIN

2-3 LBS
~20W

Figure 10.

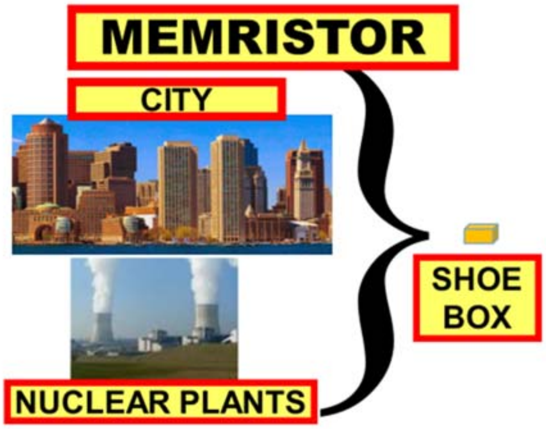


TO DO TODAY WHAT A MOUSE'S BRAIN DOES WE WOULD NEED A COMPUTOR THE SIZE OF SMALL CITY AND SEVERAL NUCLEAR POWER PLANTS TO RUN IT

Figure 11.

WE ARE IN THE HORSE AND BUGGY DAYS

Figure 12.



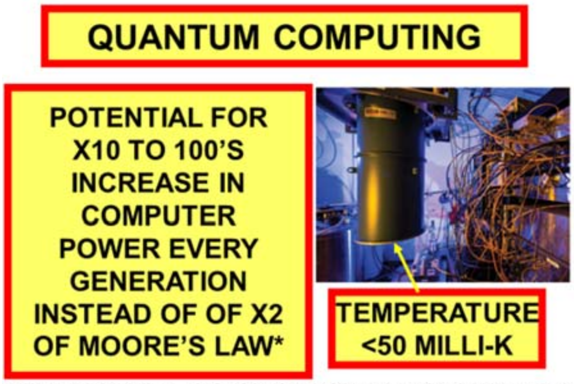
MEMRISTOR

CITY

NUCLEAR PLANTS

SHOE BOX

Figure 13.



QUANTUM COMPUTING

POTENTIAL FOR X10 TO 100'S INCREASE IN COMPUTER POWER EVERY GENERATION INSTEAD OF OF X2 OF MOORE'S LAW*

TEMPERATURE <50 MILLI-K

*VERN BROWNELL, GIGAOM STRUCTURE DATA CONF., 2014)
PHOTO FROM TECHNOLOGY TODAY, 2014, ISSUE 1)

Figure 14.

2.2 Metamaterials

Metamaterials are man-made materials consisting of an array of repeated structures having a size less than a wavelength. These materials have properties not found in nature, like a negative index of refraction. Kymeta is developing a low cost electronically steered metamaterial antenna for communications via satellites. They are commercializing a product that operates in the Ku band (10-15 GHz). Overall data rates for the antennas depends on a number of factors like the size and operating frequency of the antenna. The RF radiated power is on the order of a few watts. Transmission from the ground to the satellites and back has been demonstrated. Kymeta originally received about $65 million in funding, mostly from Intellectual Ventures, about $10 million of which is from Bill Gates. They have received more funding since then. For further details on the Kymeta's collaborations see their website.

Explanations of how the antenna could do its scanning based on the published material is now given. The array is formed from several rows of travelling wave feeds which could be a leaky wave guide over which a metal cover is placed which has slots [26, 63]. Think of it as a slotted waveguides. The antenna consists of rows of these slotted waveguides which are end fed. Assume one wants to radiate in a specified direction. One then determines at which slots the signals have the desired phase shift to form a beam in that direction. Then only from those slots is the signal allowed to radiate. The signals from the other slots are blocked. The switch is a resonator placed over each slot which controls whether the signal is radiated from the slot or not. When the resonator center frequency is at the frequency of the signal coming out of the slot it lets the signal pass through to radiate. If it is shifted away from the signal frequency the signal from that slot will not be radiated. The resonators use a liquid crystals whose dielectric constant can be controlled by a bias voltage to shift the resonator frequency, allowing the signal to radiate or not [26].

The traveling wave feed is end fed. One way to scan the beam for an end fed slotted wave guide is to use frequency scanning [72, 73]. This is not a desirable approach for the communication application intended here. An alternative way to scan in the row direction is the use a metamaterial surface for the traveling guide as done in [74]. Another alternate way is to use a high dielectric constant material in the guide whose dielectric constant can be controlled as done for the resonator. This slows down the speed of propagation down the feed. Doing this would allow the beam to be scanned in the row direction by changing the dielectric constant. This would allow the slotted wave guide antenna to operate like an end fed slotted array with a serpentine feed to achieve large scan angles using small changes in frequency except here we would use changes in the dielectric constant [73]. To scan in the direction perpendicular to the rows a different set of slots are used from row-to-row-to achieve a phase gradient in the direction perpendicular to the rows. The spacing between the slots in each row is much less than the conventional $\sim\lambda/2$. This can facilitate scanning orthogonal to the rows. It is also possible to scan in the direction perpendicular to the rows by having the signals feeding each row have a different phase shift, but this does not appear to be their choice.

For this antenna each resonator is used independently to act as an on-off switch. It is a novel and clever concept wherein one achieves phase shifting without the use of an active phase shifter at every element. It is a new type of electronically scanning array (ESA). The resonators were developed in the metamaterial world to create a negative permittivity metamaterial [62]. Because there are no active components the cost of building this antenna with many slots or elements should be low. Instead of the covered leaky waveguide the signal can propagated down a microstrip, coplanar waveguide, parallel plate waveguide, dielectric slab or lossy waveguide [63].

In addition to using orbiting satellites for internet access these antennas could be used for access over a limited area through the use a constellation of high flying (65,000 ft) drones [67]. A potential competing technology to the Kymeta approach is to use a conventional AESA built using low cost extreme MMIC like shown in Fig. 5 and 6 [10, 56, 65].

Echodyne is developing metamaterial antennas and radars for facility protection and UAVs for collision avoidance. [30]. The radar application requires faster switching times for the beam. Metawave, a spinoff from PARC a Xerox Co., is developing metamaterial electronically steered antennas for self-driving cars using AI and for cell towers.

Target cloaking wherein the target is made invisible has been demonstrated using metamaterials. With cloaking the object to be made invisible is surrounded by the metamaterial with the result that the electromagnetic wave signal transmitted by a radar goes around the target making it invisible. This has been demonstrated at microwaves by Duke Un. using metamaterials; see Fig. 15. Here the object to be made invisible is placed inside a 5 cm diameter cylinder surrounded by a metamaterial composed of split ring resonators. This has also been demonstrated by the company Fractal Antenna Systems located in the Boston area using fractal patterns to surround the cylinder [31, 32]. They made an engineer effectively invisible by placing him in a cylinder covered with a fractal metamaterial. Fig. 16 compares the metamaterial consisting of split ring resonators with the fractal material. With the fractal approach the engineer at the company was placed first in the path between the transmitter and receiver with the result that the signal was blocked being reduced by 6 to 15 dB over the band from 750 to 1250 MHz. Next the engineer was placed inside a cylinder with the fractal metamaterial coating and placed again in the path between the transmitter and receiver with result that the signal was no longer blocked, only being attenuated by a fraction of a dB over the same 50% bandwidth at L-band.

Figure 15.

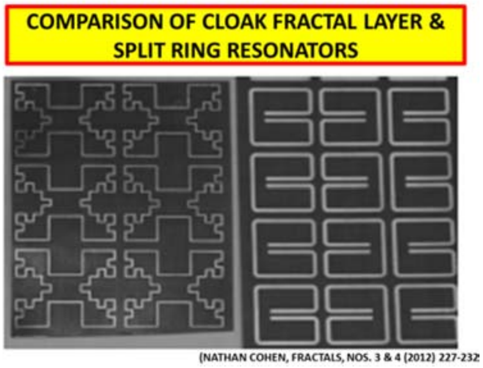
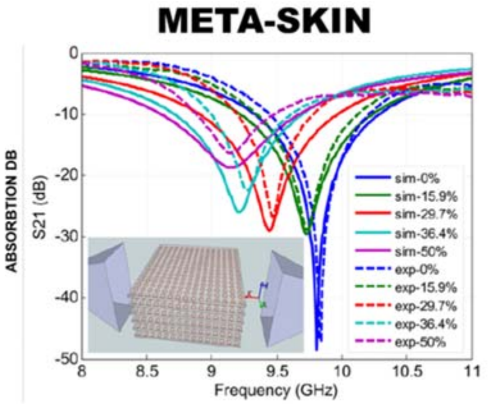


Figure 16.

Another way to hide a target is to have the target absorb the incident radar signal. Such stealthing has been demonstrated recently Iowa State Un. using a stretchable, flexible metamaterial sheet consisting of silicon with split ring resonators embedded in it that provided a 6 dB target cross section reduction from 8-10 GHz and larger reductions over narrower bandwidths; see Figs. 17 and 18. It should be possible to apply this material conformally over the object to be stealthed.

*EMBEDS INSIDE SILICONE SHEET ROWS OF SPLIT-RING RESONATORS CONTAINING LIQUID METAL ALLOY GALINSTAN MADE OF GALLIUM, INDIUM, TI
(PROF. JIMING SONG & ASSOC. PROF. LIANG DONG OF IOWA STATE UN.)

Figure 17.



(SIMING YANG, ET AL, *SCIENTIFIC REPORTS* 6, ARTICLE NUMBER: 21921, 2/23/16)

Figure 18.

Stealthing has also been simulated using a fractal coating that is < 1 mm thick [33]. Absorption of 90% was achieved from 2 to 20 GHz and about 99% from about 9-15 GHz. Good absorption was achieved for all incident angles and polarizations.

With metamaterials it is now possible to replace the tall highly visible Army jeep antennas with a flush mounted antenna [34]. Other capabilities of metamaterial like ability to achieve focusing beyond λ/2 diffraction limit, provide higher isolation and increased scan angle for arrays are covered in [1, 2].

For a more complete discussion of the recent advances in metamaterials see [69].

2.3 MIMO

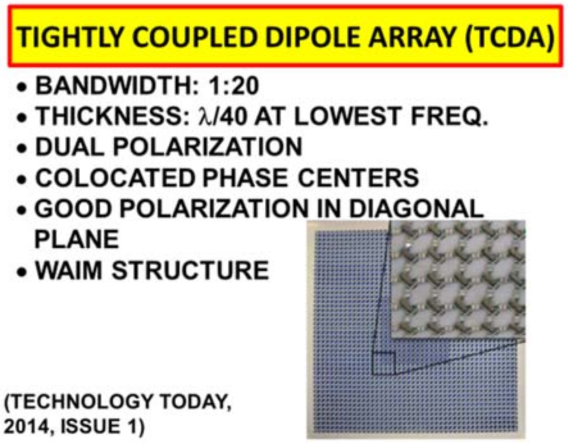
It had originally been shown in the literature that a MIMO full/thin array radar system consisting of a full transmit linear array of N elements having λ/2 spacing and a collocated, parallel, linear thinned receive array having Nλ/2 spacing is equivalent to a full array of N^2 elements having λ/2 spacing and thus achieves N times the accuracy and resolution as a conventional full array of N elements, 10 times or 100 times or 1000 times better than a conventional array depending on N [35, 36]. It has since been shown [37, 38] that a conventional array radar can do as well as a MIMO full/thin array radar. Specifically, a conventional full/thin array radar was shown to provide the same resolution and accuracy as the MIMO array. The conventional full/thin array had some disadvantages relative to grating lobes that had to be dealt with but in some situations it could provide better energy search efficiency than its MIMO equivalent [38, 70]. More recently another conventional array was presented which also has the same resolution and about the same angle accuracy as the MIMO full/thin array radar and has no grating lobes [39, 40, 70]. Also it uses the same search time and about the same power-aperture product to do volume search as the MIMO radar. The new conventional array consists of the same full and thin arrays but with their roles reversed with the thin array transmitting and the full array receiving. The new conventional array is called a thin/full array to distinguish it from the former full/thin array. The properties of the full/thin, thin/full and full/full MIMO array radars and their conventional equivalent array radars are elaborated on in [39, 40, 70] relative to waveforms and matched filter signal processing loads. The matched filter processing load for MIMO full/thin and thin/full arrays are dependent on whether the transmit or receive beam forming is done first. It was also pointed out that MIMO radar systems do not have any advantages relative to barrage jammer, hot clutter jammer or repeater jammer suppression [38-40]. Most recently it was shown how the conventional thin/full array can be used for GMTI so that it should provide the same minimum detectable velocity as does the MIMO thin/full array [40, 70].

2.4 Digital Beam Forming (DBF)

Besides the DBF at every element S-band shipboard AESAs of Elta in Israel and CEA Technologies in Australia mentioned in [2], Thales now has an S-band ~1000 element one [41]. LM's s[ace fence array having 172K channels and A/Ds was covered in Sect. 1.1. Raytheon is developing mixer-less direct RF A/D having >400 MHz instantaneous bandwidth and is reconfigurable being able to switch between S and X-band [42]. Instead of using down converters followed by a low frequency A/D it uses a sample and hold chip followed by a low frequency A/D. IMST has developed for the on the move SANTANA internet communication system AESAs for 30 MHz uplink and 20 MHz down links between satellites and airplanes, railroad trains and cars that utilize an A/D and D/A for every element channel [43]. Instead of PCBs they use LTCC stackups.

2.5 Additional Advances

It was shown recently that a low thickness wideband antenna can be built using tightly coupled dipole antennas (TCDA) [44, 45]; see Fig. 19. The high power microwave tubes used for active denial systems may soon be replaced by solid state power devices. The magnetrons in microwave ovens are being replaced by transistors. MIT Lincoln Laboratories increases receiver spurious free dynamic range as limited by intermods due to receiver and A/D nonlinearities by 40 dB, a 40 year advance because advance in A/Ds is 1 bit per 6 years [47]. Printable electronics is making great strides and should make major advances soon because of the large market for wearable, flexible electronics. Several approaches are being investigated: 1. Use of metal-insulator-metal (MIM) diodes [48]. 2. 2D MoS_2 ink [49]. 3. Si and $NbSi_2$ particles which have produced diodes operating at 1.6 GHz with the goal being 2.4 GHz, the Wi-Fi band [50]. Research is going on with a quantum radar that uses microwave-optical entanglement and is claimed to provide better false alarm rate and SNR than a conventional radar [51]. It also could detect stealth targets and small tumors in the body.



TIGHTLY COUPLED DIPOLE ARRAY (TCDA)

- BANDWIDTH: 1:20
- THICKNESS: $\lambda/40$ AT LOWEST FREQ.
- DUAL POLARIZATION
- COLOCATED PHASE CENTERS
- GOOD POLARIZATION IN DIAGONAL PLANE
- WAIM STRUCTURE

(TECHNOLOGY TODAY, 2014, ISSUE 1)

Figure 19. Extremely low thickness wideband antenna using tightly coupled dipole antennas (TCDA) [44, 45].

Aknowledgment: Update of paper published in Microwave J. (MJ) November 2015 [65]. They give permission to publish this updated version here.

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