ADVANCES AND BREAKTHROUGHS IN RADAR AND PHASED ARRAYS

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BRIEF ABSTRACT: 3, 4, 6 face "Aegis" systems. Patriot now has GaN AESA; S/X-band AMDR provides 30 times the sensitivity and number of tracks as SPY-1D(V); ***Low Cost Packaging:*** *Using COTS, PCBs;* ***Extreme MMIC:*** *32 element 60 GHz T/R array on chip;* ***Digital Beam Forming (DBF):*** *A/D for every element;* ***Materials:*** *GaN can now put 5X to 10X the power of GaAs in same footprint, 38% less costly, 100 million hr MTBF;* ***MIMO (Multiple Input Multiple Output):*** *Where it makes sense;* ***Metamaterial Antennas:*** *$1K 20 GHz and 30 GHz AESAs;* ***Very Low Cost Systems:*** *Cars radar costing < $100, future few $'s:* ***MEMS:*** *Phase shifters;* ***MEMS Piezoelectric Material = piezoMEMS:*** *For flying insect robots;* ***Printed Electronics:*** *Low cost 1.6 GHz (goal 2.4 GHz) diodes printed;* ***Electrical and Optical Signals on Same Chip;*** *IR transparent in silicon;* ***Graphene and Carbon Nanotube (CNT)****: Potential for Terahertz transistor clock speeds;* ***Revolutionary 3-D Micromachining****;* ***Superconductivity; Biodegradable Arrays of Transistors or LEDs:*** *Imbedded for detecting cancer or low glucose;* ***Quantum Radar:*** *See stealth targets;*

DETAILED ABSTRACT: **Systems:** Patriot now has GaN active electronically scanned array (AESA) providing 360^o coverage, now a 2015 state-of-the-art AESA radar system; S/X-band AMDR provides 30 times the sensitivity and number of tracks as SPY-1D(V); JLENS aerostat radar system now deployed over Washington DC; 3, 4, 6 faced "Aegis" radar systems developed by China, Japan, Australia, Netherlands, USA; **Low Cost, Low Power Extreme MMIC (Moore's law at Microwave ane mm-waves):** 4 T/R modules on single chip at X-band costing ~$10 per T/R module ; Intel single chip 32-Element 60 GHz Tx/Rx Phased Array, full phased array on wafer at 110 GHz; on-chip built-in-self-test (BIST), will be used in the internet-of-things and in cell phones which by 2020 is expected to number 50 billion, expect such single chip arrays to cost only few dollars in future; All the RF circuitry for mm-wave automobile radars at 25 GHz and 77 GHz are being put on a chip with some believing that such arrays and radars will soon be produced for just a few dollars; Valeo Raytheon (now Valeo Radar) developed low cost, $100s, car 25 GHz 7 beam phased array radar; about 2 million sold already, more than all the radars ever built up to a very few years ago; DARPA had goal to build 28,000 element 94 GHz array costing $1/element, 50W total RF peak power. **Digital Beam Forming (DBF):** Israel, Thales and Australia AESAs under development have an A/D for every element channel; Raytheon developing mixer-less direct RF A/D having >400 MHz instantaneous bandwidth, reconfigurable between S and X-band; Radio Astronomers looking at using arrays with DBF. **Materials:** GaN can now put 5X to 10X the power of GaAs in same footprint, 38% less costly, 100 million hr MTBF, Raytheon invested $150 million to develop GaN; SiGe for backend, GaN for front end of T/R module. **MIMO (Multiple Input Multiple Output):** Where it makes sense; contrary to what is claimed MIMO array radars do not provide 1, 2 or 3 orders of magnitude better resolution and accuracy than conventional array radars; MIMO does not provide better barrage-noise-jammer, repeater-jammer or hot-clutter rejection than conventional array radars; contrary to claims MIMO should not provide better minimum detectable velocity for airborne radars; **Metamaterials:** Material custom made (not found in nature): using 20 and 30 GHz metamaterial electronically steered antennas about the size of a laptop developed for transmission to satellites and back was demonstrated December 2013, goal is $1K per antenna, remains to prove low cost and reliability; 2-20GHz stealthing by absorption simulated using <1 mm coating; target made invisible over 50% bandwidth at L-band; Focus 6X beyond diffraction limit at 0.38 μm; 40X diffraction limit, λ/80, at 375 MHz; In cell phones provides antennas 5X smaller (1/10th λ) having 700 MHz-2.7 GHz bandwidth; The Army Research Laboratory in Adelphi MD has funded the development of a low profile metamaterial 250-505 MHZ antenna having a λ/20 thickness; Provides isolation

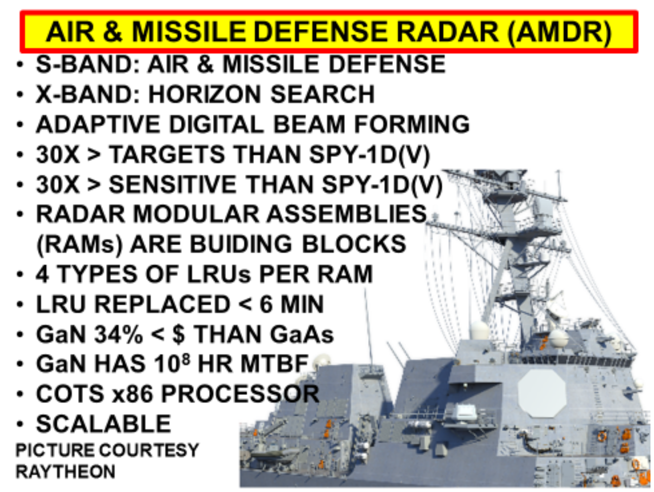
between antennas with 2.5 cm separation equivalent to 1 m separation; used for phased array WAIM; n-doped graphene has negative index of refraction, first such material found in nature; **Digital Processing and Moore's Law:** Not dead yet; Slowed down but has much more to go; Expect increase in transistors density by about a factor of ~50 in the next 30 years and reduction in signal processing power consumption by factor of ~75; and then there is graphene which has potential for terahertz transistor clock speeds, manufacture on CMOS demonstrated, could allow Moore's law to march forward using present day manufacturing techniques; there is also spintronics which could revolutionize the computer architecture away from the John von Neumann model; and there is finally doing computation the way the brain efficiently and amazingly does perhaps by using synaptic transistors and/or memristors, remember the brain only weighs about 2-3 pounds and uses only ~20 W, we have a long way to go; **Low Cost Packaging:** Raytheon funding development of low cost flat panel X-band AESA using COTS type printed circuit boards (PCBs)**;** Rockwell Collins doing it for airborne AESA; Lincoln-Lab./MA-COM developing low cost S-band flat panel array using PCBs, overlapped subarrays and a T/R switch instead of a circulator; **SAR/ISAR:** Principal Components of matrix formed from prominent scatterers track history used to determine target unknown motion and thus compensate for it to provide focused ISAR image. **Technology and Algorithms:** A dual polarized, low profile, (λ/40), wideband (1:20) antenna can be built using tightly coupled dipole antennas (TCDA); Lincoln Lab increases spurious free dynamic range of receiver plus A/D by 40 dB; **MEMS:** reliability reaches 300 billion cycles without failure; Has potential to reduce the T/R module count in an array by a factor of 2 to 4; Provides microwave filters like 200 MHz wide tunable from 8-12 GH**z; MEMS Piezoelectric Material = piezoMEMS:** Enables flying insect robots; **Printed Electronics:** Low cost 1.6 GHz (goal 2.4 GHz) diodes printed with Si and $NbSi_2$ particles; **Electrical and Optical Signals on Same Chip:** IR beams could be used for transporting on computer chips digital information at the speed of light; **COSMOS:** DARPA revolutionary MMIC program: Allows integration of III-V, CMOS and opto-electronics on one chip without bonded wires leading to higher performance, lower power, smaller size, components; **Graphene and Carbon Nanotube (CNT**): potential also for non-volatile memory, flexible displays and camouflage clothing, self-cooling, IBM producing 200 mm wafers with RF devices; **Superconductivity:** We may still achieve superconductivity at room temperature; Superconductivity recently obtained for first time with iron compounds; **Biodegradable Array** of Transistors or LEDs: Imbedded for detecting cancer or low glucose; can then dispense chemotherapy or insulin**; Quantum Radar:** See stealth targets**; New polarizations: OAMs, (Orbital Angular Momentum)** unlimited data rate over finite band using new polarizations??

Short Bio of Dr. Eli Brookner: BEE: The City College of the City of New York, '53, MEE and DrSc: Columbia University '55 and '62. worked at Raytheon Company from 1962 until 2014 when he retired. There he was a Principal Engineering Fellow and worked on ASDE-X airport radar, ASTOR Air Surveillance Radar, RADARSAT II, Affordable Ground Based Radar (AGBR), major Space Based Radar programs, NAVSPASUR S-Band upgrade, COBRA DANE, PAVE PAWS, Missile Site Radar (MSR), COBRA JUDY Replacement, THAAD, Brazilian SIVAM, SPY-3, Patriot, BMEWS, UEWR, Surveillance Radar Program (SRP), Pathfinder marine radar, Long Range Radar (upgrade for >70 ATC ARSRs), COBRA DANE Upgrade, AMDR, Space Fence, 3DELRR, FAA NexGen ATC radar program. Prior to Raytheon he worked on radar at Columbia Un. Electronics Research Lab. (now RRI), Nicolet and Rome AF Lab.

Received IEEE 2006 Dennis J. Picard Medal for Radar Technology & Application "For Pioneering Contributions to Phased Array Radar System Designs, to Radar Signal Processing Designs, and to Continuing Education Programs for Radar Engineers"; IEEE '03 Warren White Award; Journal of the Franklin Institute Premium Award for best paper award for 1966; IEEE Wheeler Prize for Best Applications Paper for 1998. Fellow of IEEE, AIAA, MSS. Member of the National Academies Panel on Sensors & Electron Devices for Review of Army Research Lab. Sensors & Electron Devices Directorate (SEDD).

Published four books: Tracking and Kalman Filtering Made Easy, John Wiley and Sons, Inc., 1998; Practical Phased Array Antenna Systems (1991), Aspects of Modern Radar (1988), and Radar Technology (1977), Artech House. Gives tutorial courses on Radar, Phased Arrays and Tracking around the world (25 countries). Over 10,000 attended these tutorial courses. Gave over 150 tutorial courses. Banquet/keynote speaker twelve times. >230 papers, talks and correspondences, >100 invited. 6 paper reprinted in Books of Reprints (one in 2 books). Contributed chapters to three books. 9 patents.

Very Short Bio of Dr. Eli Brookner: BachSc City College of New York, DrSc from Columbia University '62.
Worked on marine, Air Traffic Control, ballistic missile defense, space radars and phased arrays at Raytheon 1962-2015 (retired). 1952-1962 at: Columbia University, Nicolet, Rome AF Lab.
IEEE 2006 Dennis Picard Medal for Radar Technology & Application; IEEE '03 Warren White Award; 1966 Journal of Franklin Institute Premium Best Paper Award; 1998 Best Applications Paper IEEE Wheeler Prize. Fellow: IEEE, AIAA, MSS. 4 popular books on radar, arrays, tracking. Gave courses to >10,000 in 25 countries. Banquet/keynote speaker 12 times. >230 papers, talks, correspondences of which >100 invited. 6 papers in Books of Reprints. Contributed chapters to three books. 9 patents.

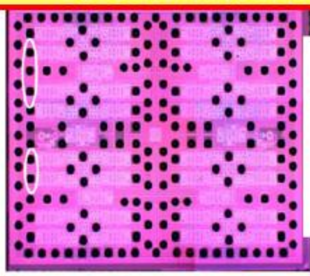


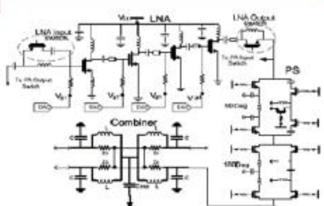
X-BAND 25K ELEMENT AESA AN/TPY-2

8 DELIVERED, 3 MORE ON ORDER.

PHOTO COURTESY RAYTHEON

INTEL 32-ELEMENT SINGLE CHIP 60 GHZ TX/RX PHASED ARRAY





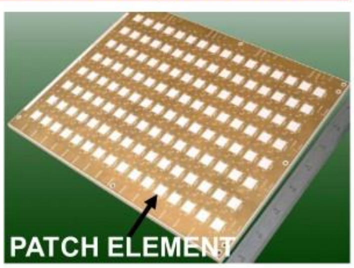
EXTREME MMIC

- Based on work with UCSD (we helped them a lot)
- Flip-chip packaging – CMOS from TSMC.
- Does not contain baseband circuitry for Gbps communications

UCSD PROF. GABRIEL M. REBEIZ
IEEE Phased Array Symposium Short Course, October 2013 – © UCSD and IEEE 19

Raytheon Low Cost X-Band Array PCB Building Block

- 128 T/Rs & Elements
- 2.2 lbs
- 7.4x10.1x0.21 Inches



(PUZELLA, ALM, RADARCON-2007)

10/6/2014 | 111

METAMATERIAL ANTENNA; SCANS BEAM ELECTRONICALLY WITHOUT PHASE SHIFTERS

DEMO'D DEC. 2013

http://www.kymetacorp.com/products/portable-satellite-terminal/

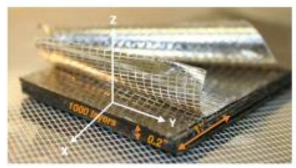
SEE ALSO: E. BROOKNER, "RECENT ACHIEVEMENTS", IEEE ARRAY-2013

UNCLASSIFIED//APPROVED FOR PUBLIC RELEASE

U.S. ARMY RDECOM — ARL

Extremely Low Profile Magnetic Metamaterial Antenna

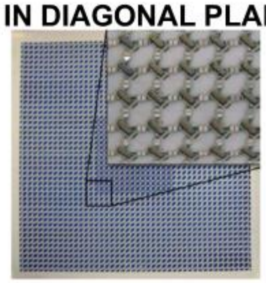
Gregory Mitchell RDRL-SER-M
gregory.a.mitchell1.civ@mail.mil ph: 301-394-2322



- 3.3" THICK
- 250 TO 505 MHZ
- ~2500 LAYERS
- MAGNETIC METAMATERIAL ANTENNA
- REPLACE LARGE VERY VISIBLE WHIP ANTENNA USED ON ARMY VEHICLES
- DEVELOPED UNDER ARL CONTRACT WITH METAMETERIALS INC.

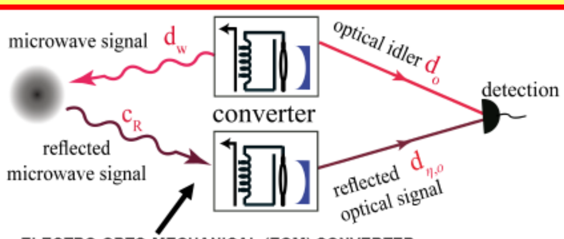
TIGHTLY COUPLED DIPOLE ARRAY (TCDA)

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



(RAYTHEON TECHNOLOGY TODAY, 2014, ISSUE 1)

QUANTUM RADAR

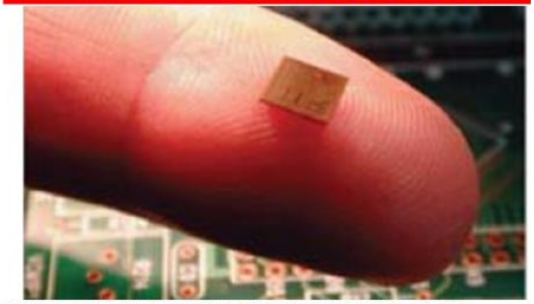


ELECTRO-OPTO-MECHANICAL (EOM) CONVERTER

- GENERATES MICROWAVE-OPTICAL ENTANGLEMENT
- USES QUANTUM CORRELATION BETWEEN MICROWAVE AND OPTICAL BEAMS
- USES QUANTUM CORRELATION OF MICROWAVE & OPTICAL BEAMS TO DETECT LOW REFLECTIVITY CANCER CELLS OR STEALTH AIRCRAFT

(S. BARZANJEH, "QUANTUM ILLUMINATION AT THE MICROWAVE WAVELENGTHS", FEB. 6, 2015, PHYSICAL REVIEW LETTERS)

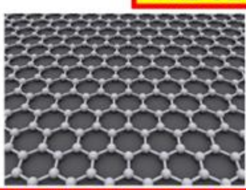
UN. MELBOURNE SINGLE CHIP 77GHz RADAR T/R

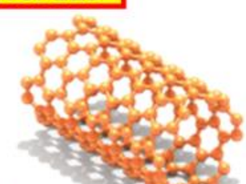


(G.KLARI,, ET AL, "SINGLE CHIP MM RADAR", MICROWAVE J., 1-14-15;
R. J. Evans et al., "Consumer Radar," *Int. Radar Conf.*,Adelaide, 9/2013, pp. 21–26)

GRAPHENE & CARBON (C) NANOTUBES (CNT): HOPE FOR MOORE'S LAW CONTINUATION

THZ CLOCK SPEED





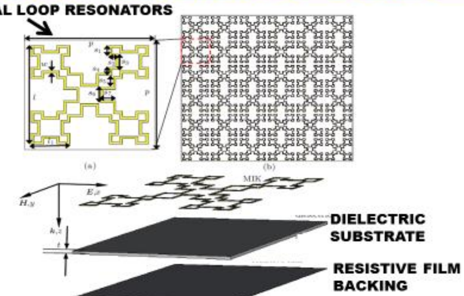
GRAPHENE: 1 ATOM THICK CRYSTAL; STRONGEST MATERIAL

CNT: MANUFACTURED ON COMOS DEMO'D

T. SIMONITE, MIT TECHNOLOGY REVIEW, SEPT-OCT, 2014, p. 17; ALSO E. BROOKNER, "RECENT ACHIEVEMENTS", IEEE ARRAY-2013; E. BROOKNER, "BREAKTHROUGHS IN PHASED ARRAYS & RADAR", IEEE ARRAY-2010.

FRACTAL STEALTH: 90% ABSORBSION 2-20 GHZ 99% ABSORBSION 10-15 GHZ

FRACTAL LOOP RESONATORS



(F. YUE-NONG, ET AL, CHINA PHYS. B VOL. 22, NO. 6, 2013, 067801)

SYNAPTIC TRANSISTOR

- LEARNS LIKE HUMAN BRAIN SYNAPS
- BRAIN HAS 86 BILLION NUERONS CONNECTED BY SYNAPSES
- HUMAN BRAIN USES ONLY ~20W
- LEADS TO ANALOG NOT BINARY COMPUTOR

(SHI, JIAM, ET AL, A CORRELATED NICKELATE SYNAPTIC TRANSISTOR", NATURE COMMUNICATION OCT 31, 2013)

CHINESE UHF JY-26 SKYWATCH DIGITAL AESA 3D LONG RANGE AIR SURVEILLANCE & TACTICAL MISSILE DEFENCE (TMD) RADAR

- Long range air surveillance and ground-control intercept
- TBM detection, launch and impact points estimation
- Stealth target detection
- Target recognition/classification and IFF
- Multi–radar tracking
- Various data report modes

- Operating frequency: UHF band
- Detection coverage
  - Instrumented range:
    - 600km (all azimuthal surveillance)
    - 700km (critical azimuthal sector surveillance)
    - 800km (TMD)
  - Azimuth: 360° (mechanical rotation) ± 45° (electronic scanning)
  - Elevation: 25° (against air breathing target) 70° (TBD)
- Data processing capacity: 500 tracks/scan
- Sub–clutter visibility: 50dB
- Reliability
  - MTBCF: ≥1000 hours
  - MTTR: ≤0.5 hour
- Power consumption: ≤175kW
- Teardown/Setup time: 1 hour by 10 men
- Transportation units: 5
- Transportability: by road, rail, sea and air