ADVANCES AND BREAKTHROUGHS IN RADARs AND PHASED-ARRAYs

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ARRAY-2016, UPDATED FOR 1/11/17 BOSTON IEEE RELIABILITY AESS DISTINGUISHED LECTURE (DL)


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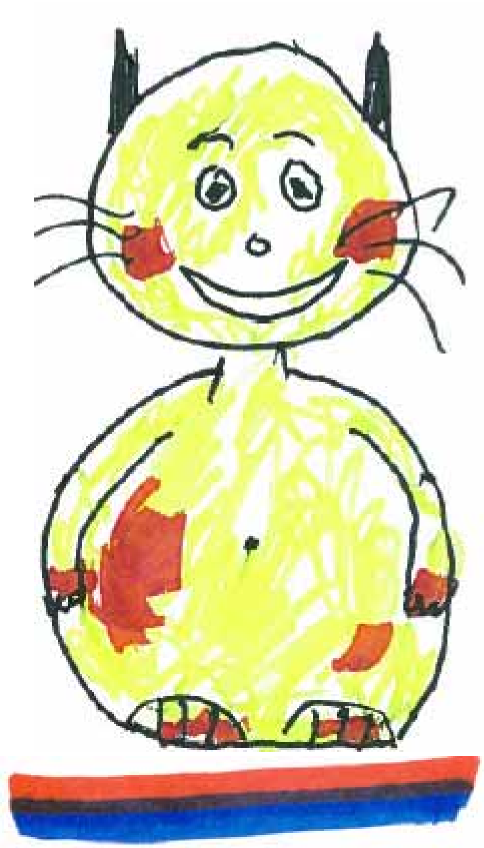

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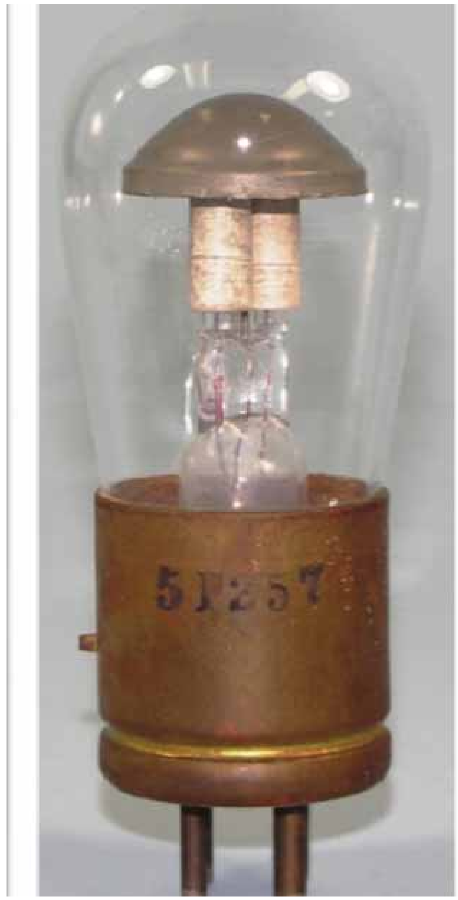
4050287

MOORE'S LAW

VACUUM TUBE

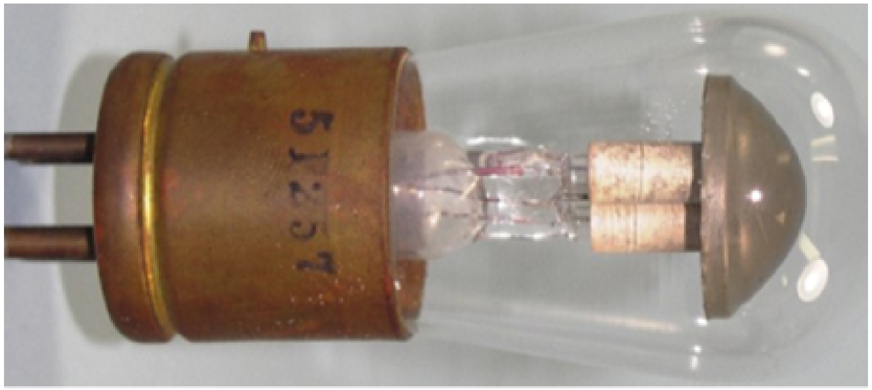


1X1X2 INCHES

128GB MEMORY STICK HAS 130 BILLION TRANSISTORS $\Leftrightarrow$ 130 BILLION TUBES

0.5″X0.8″X2″ FITS IN YOUR POCKET

\$35 128GB MEMORY STICK HAS
130 B TRANSISTORS ⇔
130B TUBES ⇔ 4B TUBES/1\$



1X1X2 INCHES

VACUUM TUBE

0.5X0.8X2
INCHES

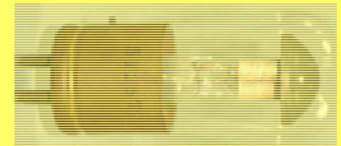
$35 128GB MEMORY STICK
HAS 130 B TRANSISTORS

USING TUBES $35 STICK WOULD:

- COST **$13OB ($1/TUBE)**
- REQUIRE **130 GW** (1W/TUBE)
  OR **130 NUCLEAR POWER PLANTS**
- WOULD STACK TO **9X DISTANCE TO THE MOON**

128GB MEMORY STICK 

130 BILLION TRANSISTORS ⇔

130 BILLION TUBES 

EARTH

MOON

130B TUBES COST $130B
VS $35 FOR STICK!!!

D

D=DISTANCE TO MOON

9D=HEIGHT OF STACK OF130B TUBES
= 9X DISTANCE TO MOON!!!

9D

STACK OF 130B TUBES (1X1X2 IN^3)

APPLE IPHONE 6 WITH 128 GB OF MEMORY

USING TUBES IPHONE WOULD:

- COST **$13OB**
- REQUIRE **130 GW** (1W/TUBE) OR **130 NUCLEAR POWER PLANTS**
- WOULD STACK TO **9X DISTANCE TO THE MOON**

NUMBER OF TRANSISTORS MADE IN 2014: $2.5X10^{20}$

USING VACUUM TUBES WOULD EXTEND TO 40 MILLION TIMES DISTANCE TO SUN

(1X1X2 IN^3 TUBES STACKED SIDEWAYS ON TOP OF EACH OTHER)

MOORE'S LAW IS NOT DEAD

13

MOORE LAW: DOUBLE # TRANSISTORS EVERY 2 YEARS

SLOW DOWN NOW EXPECTED BUT FACTOR OF ~50 DENSITY INCREASE EXPECTED IN NEXT 30 YEARS

(ROBERT COLWELL, FORMERLY DARPA MICROSYSTEM TECHNOLOGY OFFICE, BEFORE THAT INTEL'S CHIEF ARCHITECH, AVIATION WEEK, AUG. 11/18, 2014)

DARPA PLAN

REDUCE POWER CONSUMPTION BY FACTOR OF ~75 INDEPENDENT OF WHAT HAPPENS WITH MOORE'S LAW

(ROBERT COLWELL, FORMERLY DARPA MICROSYSTEM TECHNOLOGY OFFICE, BEFORE THAT INTEL'S CHIEF ARCHITECH, AVIATION WEEK, AUG. 11/18, 2014)

INTEL

- 14 NM: 2014
- 10 NM: 2017

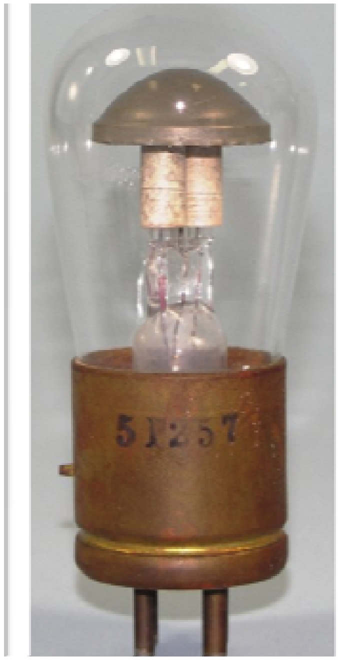
(WALL ST. J., PP. B1, B2, 7/17/1

STATUS OF FPGAs

YEAR	TYPE MULTLIER	NUMBER OF MULTILIERS PER CHIIP	CLOCK RATE	POWER
			MHz	W
1977	16X16	1	4.3	5
2013	18X18	4,000	600	8

IMPROVEMENT OF 350,000 IN 36 YEARS. AMAZING!

IN 60 YEARS



USING TUBES $35 STICK WOULD:

- COST **$13OB**
- REQUIRE **130 GW** (1W/TUBE) OR **130 NUCLEAR POWER PLANTS**
- WOULD STACK TO **9X DISTANCE TO THE MOON**

HUMAN BRAIN

2-3 LBS
~20W

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

SMALL CITY

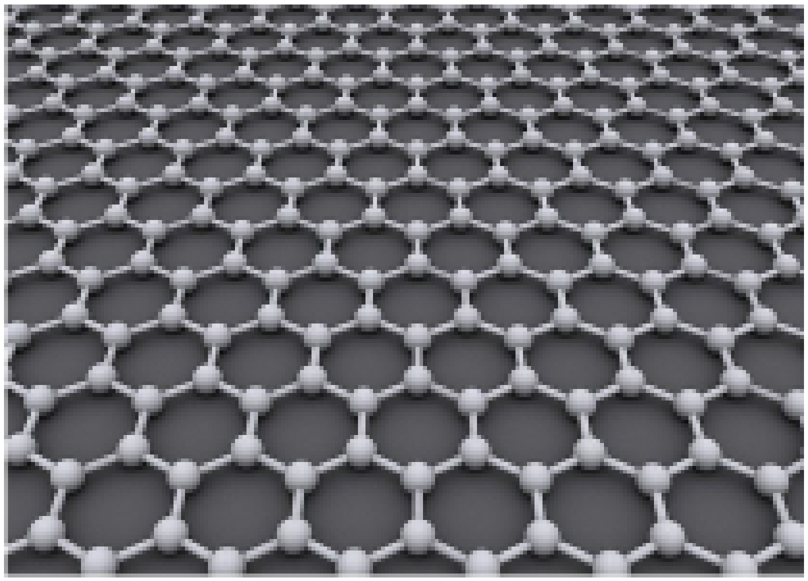
SEVERAL NUCLEAR PLANTS

WE ARE IN THE HORSE AND BUGGY DAYS

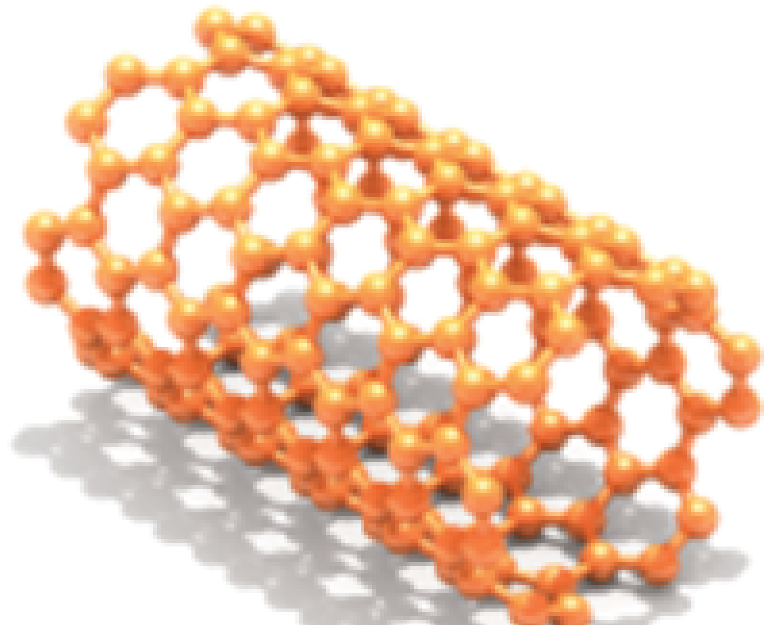
WE HAVE A LONG WAY TO GO

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

THZ CLOCK SPEED



GRAPHENE: 1 ATOM THICK CRYSTAL; STRONGEST MATERIAL

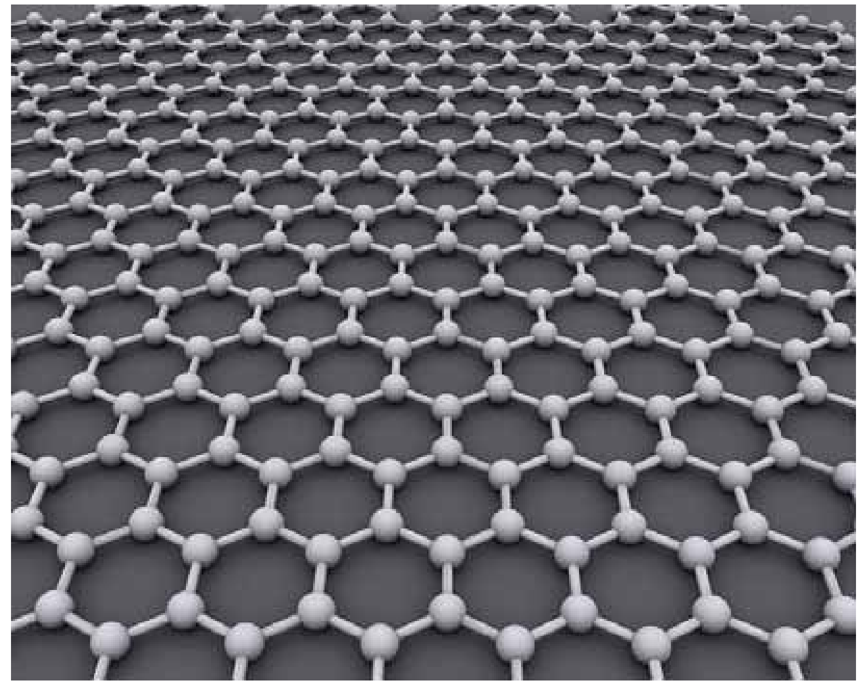


CNT: MANUFACTURE ON CMOS DEMO'D

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.

WHAT IS GRAPHENE?

- **2-DIMENSIONAL FORM OF CARBON CRYSTAL – ONE ATOM THICK SHEET**



GRAPHENE NOBEL PRIZE WINNER (2010 IN PHYSICS FOR DISCOVERY OF GRAPHENE, AGE 37) DR. KONSTANTIN NOVOSELOV WITH DR. ELI

GRAPHENE USED IN ARM OF HEAD $200 TENNIS RACQUET

SUPERMAN OF BULLET PROOF MATERIALS GRAPHENE 10X BETTER THAN STEEL

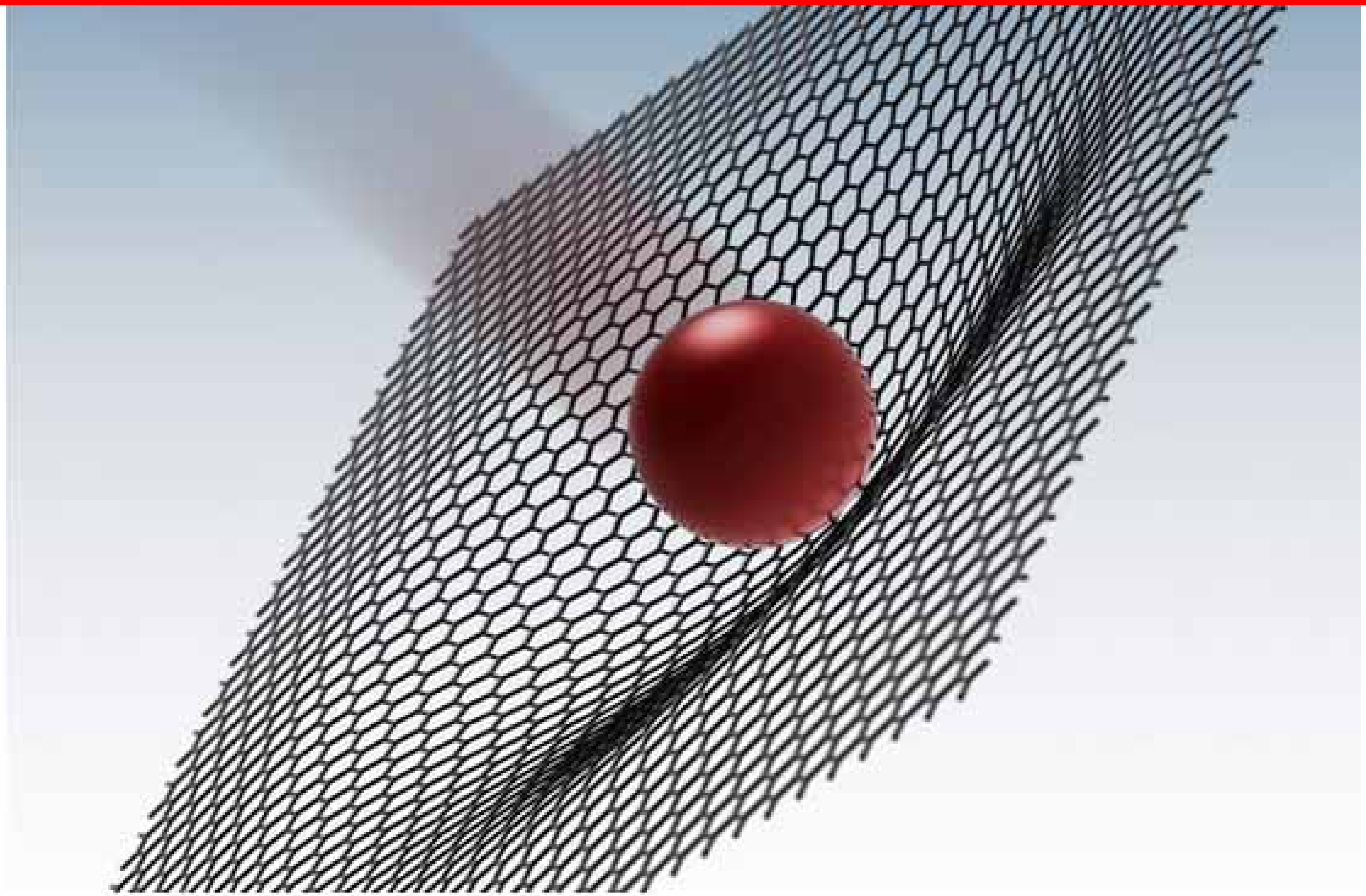
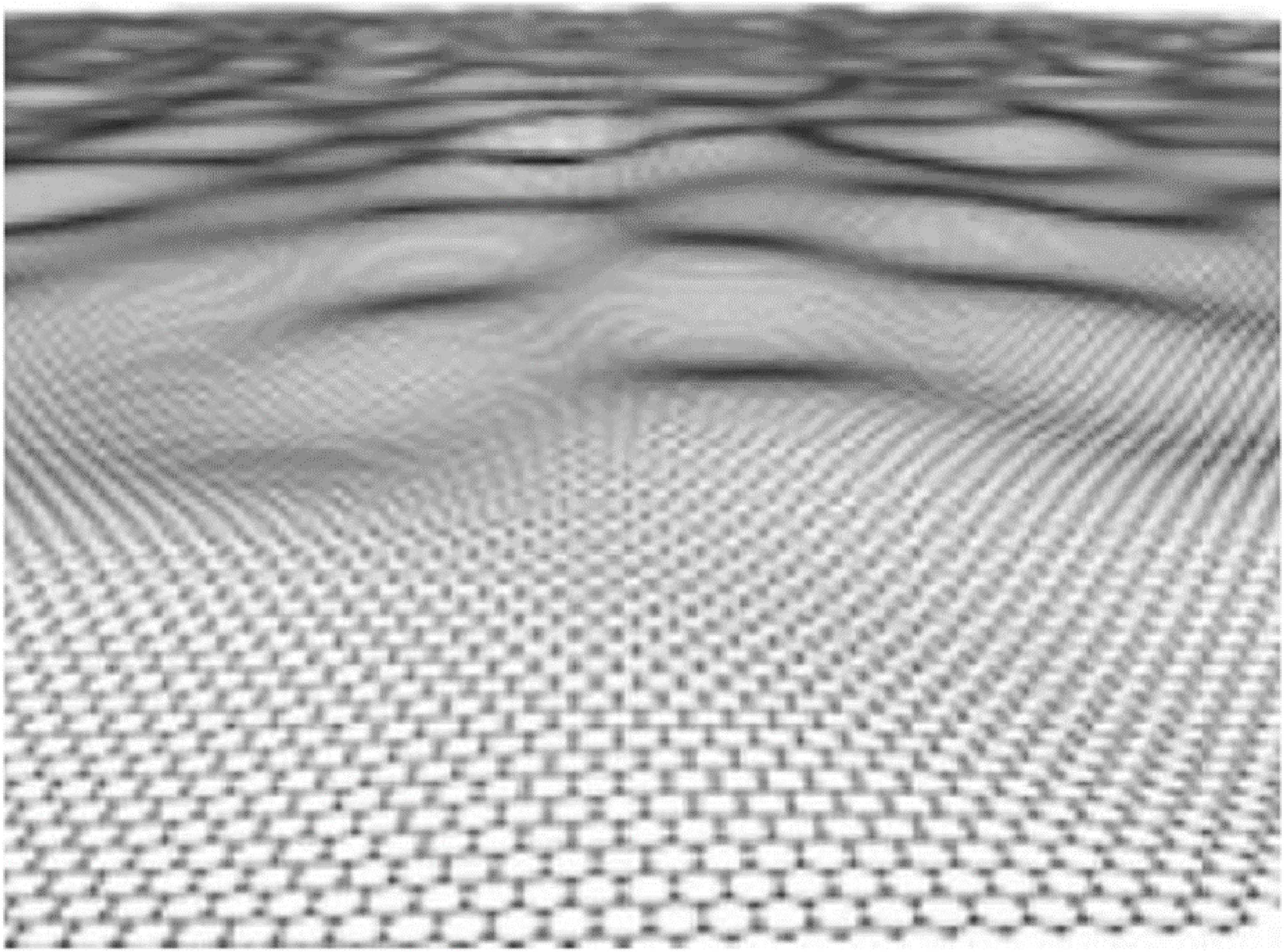


Image: Jae-Hwang Lee/Rice University

HTTP://SPECTRUM.IEEE.ORG/NANOCLAST/SEMICONDUCTORS/MATERIALS/GRAPHENE-PROVES-TO-BE-SUPERMAN-OF-BULLET-PROOF-MATERIALS/?UTM_SOURCE=TECHALERT&UTM_MEDIUM=EMAIL&UTM_CAMPAIGN=121114; SEE ALSO: M. SULTANA, "SPACE APPLICATIONS OF GRAPHENE" AND C. BASARAN, "PACKAGING" BOTH AT SABANCI UN. MICROELECTRONICS WORKSHOP, JUNE 15-17, 2015.)

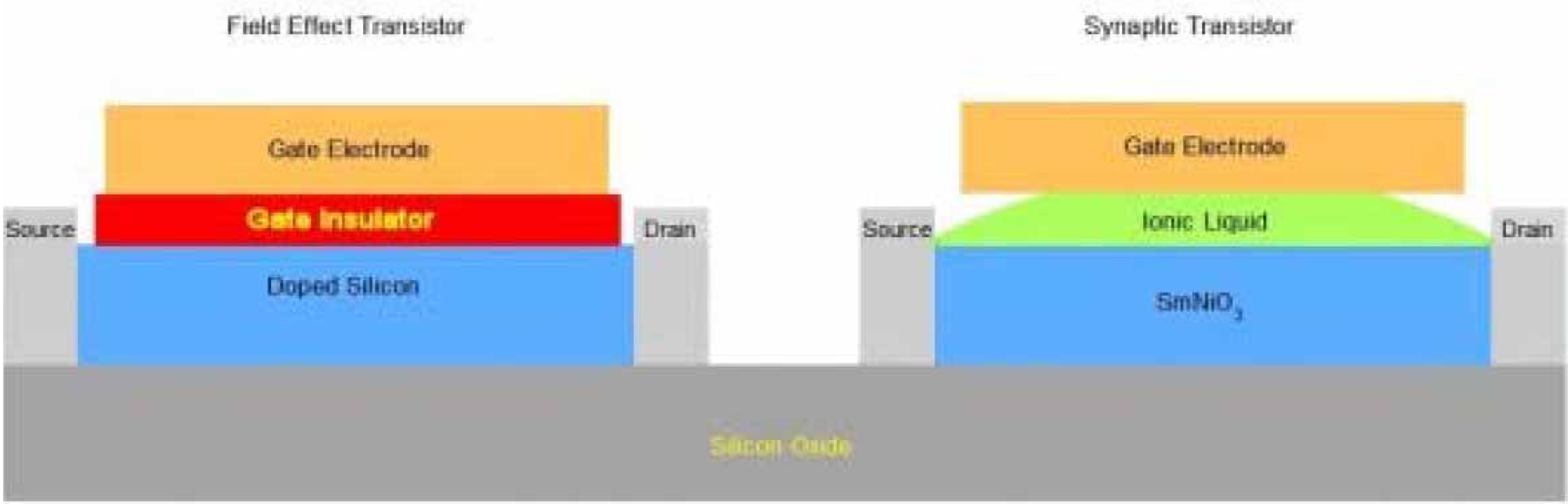
GRAPHENE BASED FUEL CELL MEMBRANE: EXTRACTS HYDROGEN FROM AIR



http://spectrum.ieee.org/nanoclast/green-tech/fuel-cells/graphenebased-fuel-cell-membrane-could-extract-hydrogen-directly-from-air/?utm_source=techalert&utm_medium=email&utm_campaign=120414

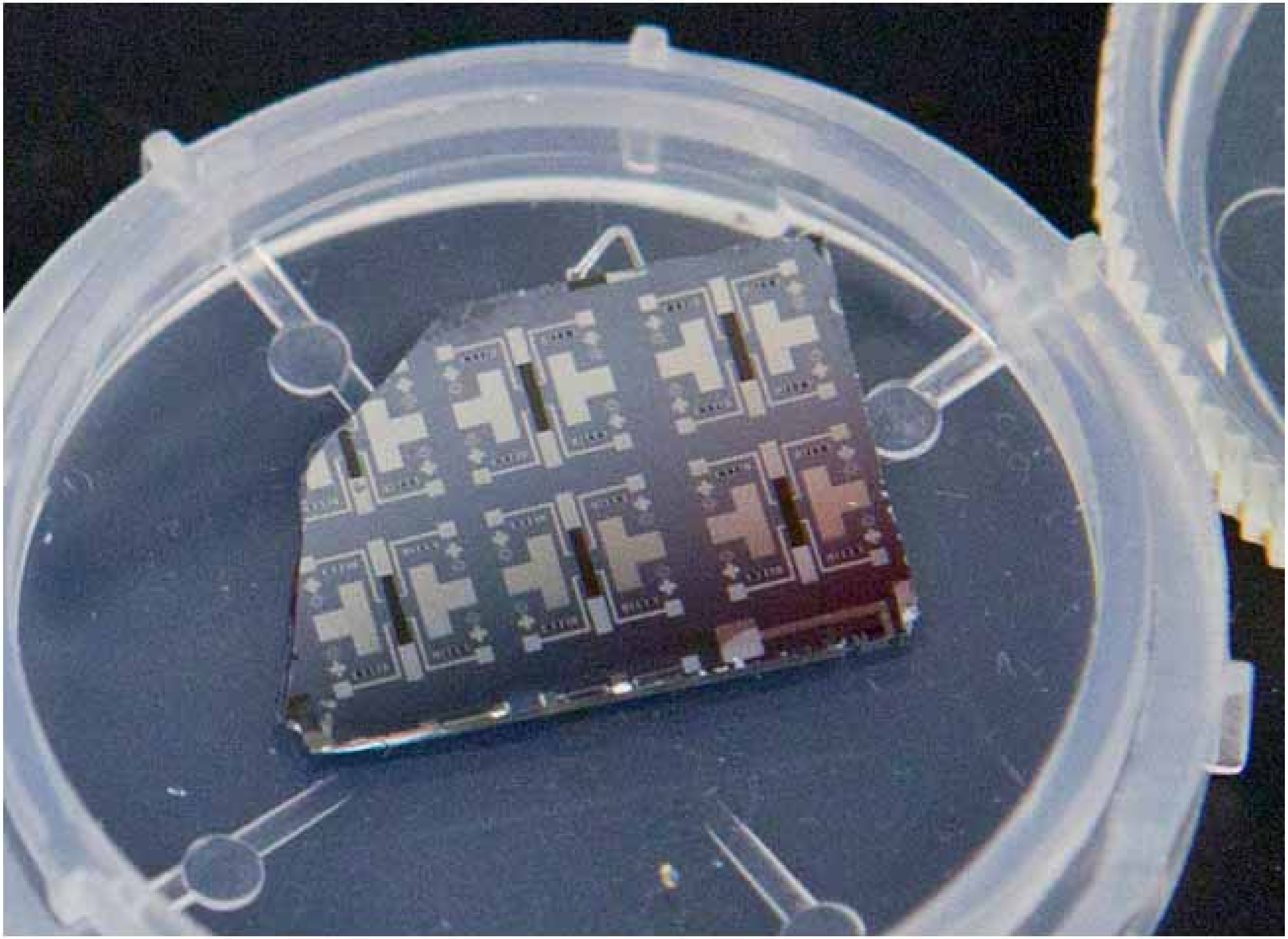
SYNAPTIC TRANSISTOR

- 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)

SYNAPTIC TRANSISTORS



Several prototypes of the synaptic transistor are visible on this silicon chip. (Photo by Eliza Grinnell, SEAS.

SPINTRONICS

- COULD REVOLUTIONIZE COMPUTER ARCHITECTURE AWAY FROM 1945 VON NEUMANN MODEL OF SEPARATE MEMORY & LOGIC
- PROVIDE HARD DRIVES WITH NO MOVING PARTS

(KHALILI, P. AND K. L. WANG, “THE COMPUTER CHIP THAT NEVER FORGETS”, IEEE SPECTRUM TECH ALERT, JUNE 26, 2015.)

MEMRISTOR

CAN DO WHAT THE MOUSE BRAIN DOES IN SHOEBOX INSTEAD OF COMPUTER SIZE OF CITY REQUIRING NUCLEAR PLANT

(R. S. WILLIAMS, IEEE SPECTRUM, 12/08;
E. BROOKNER, ARRAY-2010)

MEMRISTOR

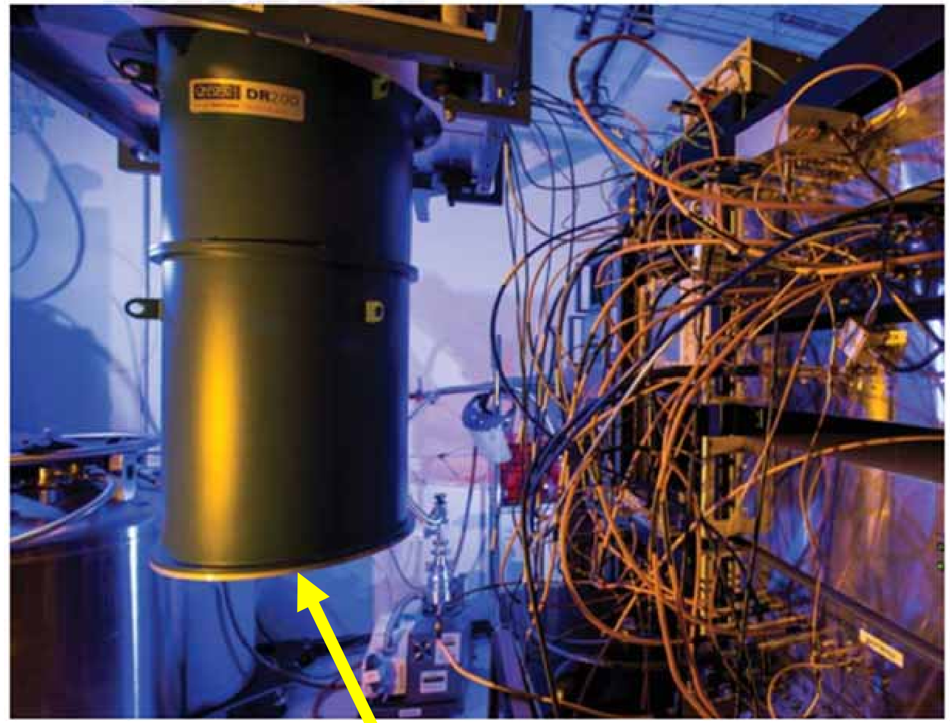
SMALL CITY

NUCLEAR PLANTS

SHOE BOX

QUANTUM COMPUTING

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



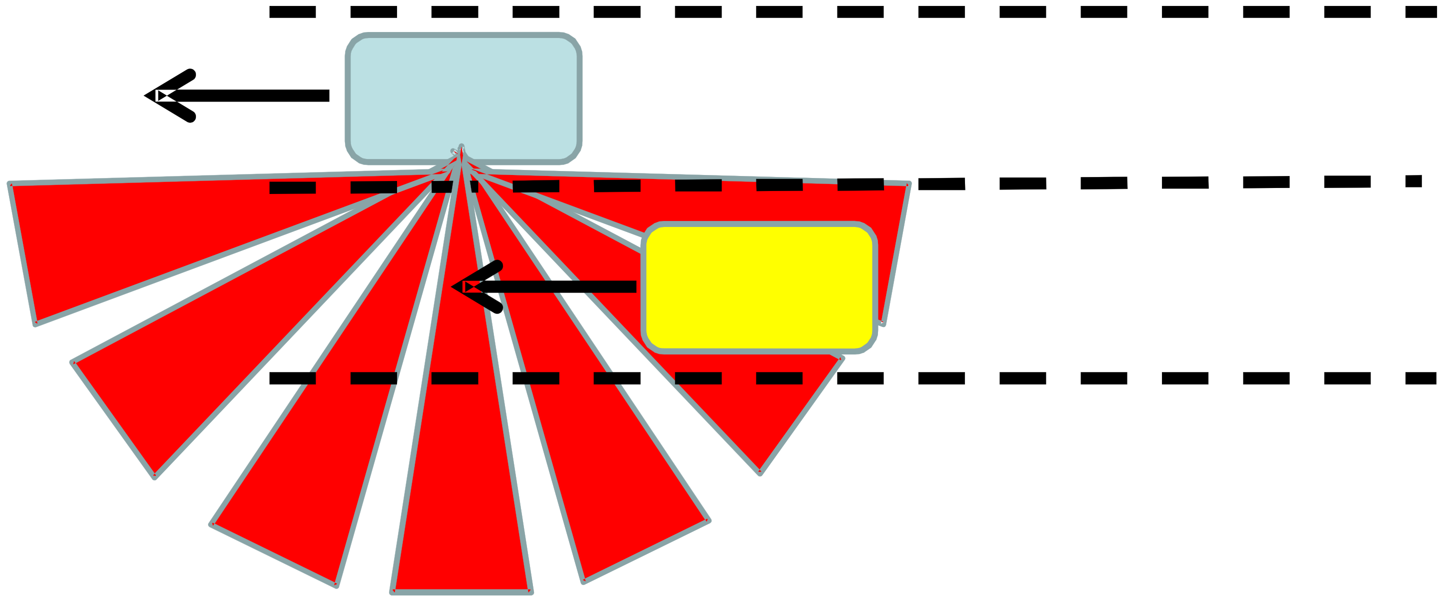
TEMPERATURE <50 MILLI-K

(*VERN BROWNELL, GIGAOM STRUCTURE DATA CONF., 2014)

(PHOTO FROM TECHNOLOGY TODAY, 2014, ISSUE 1)

WHAT ABOUT MICROWAVES

VALEO RAYTHEON SYSTEMS* DEVELOPED BLIND SPOT RADAR



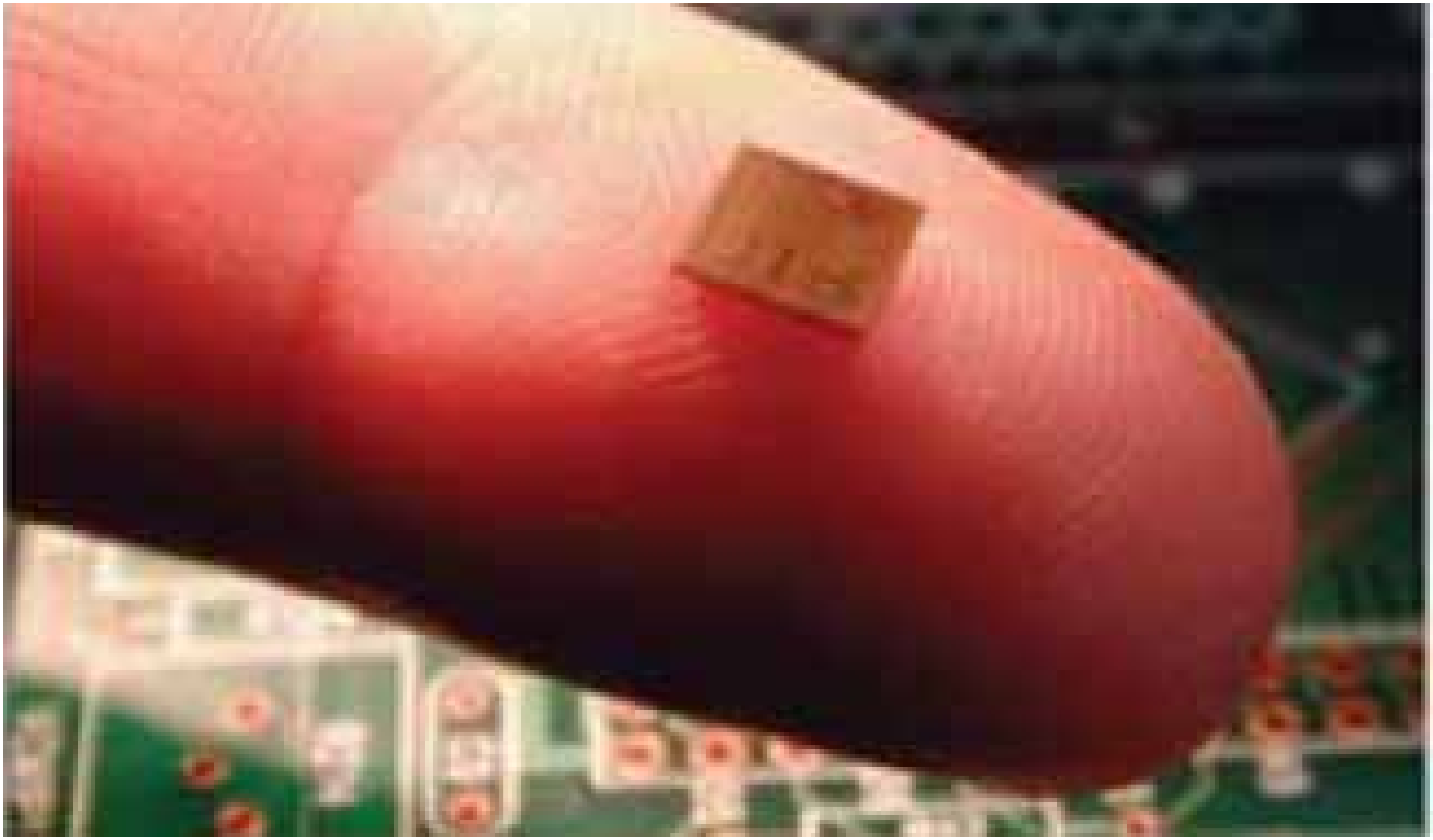
~ 2 MILLION SOLD

IT ALERTS YOU TO CARS YOU MAY NOT SEE

BLIND SPOT CAR PHASED-ARRAY RADAR -- ONLY $100's

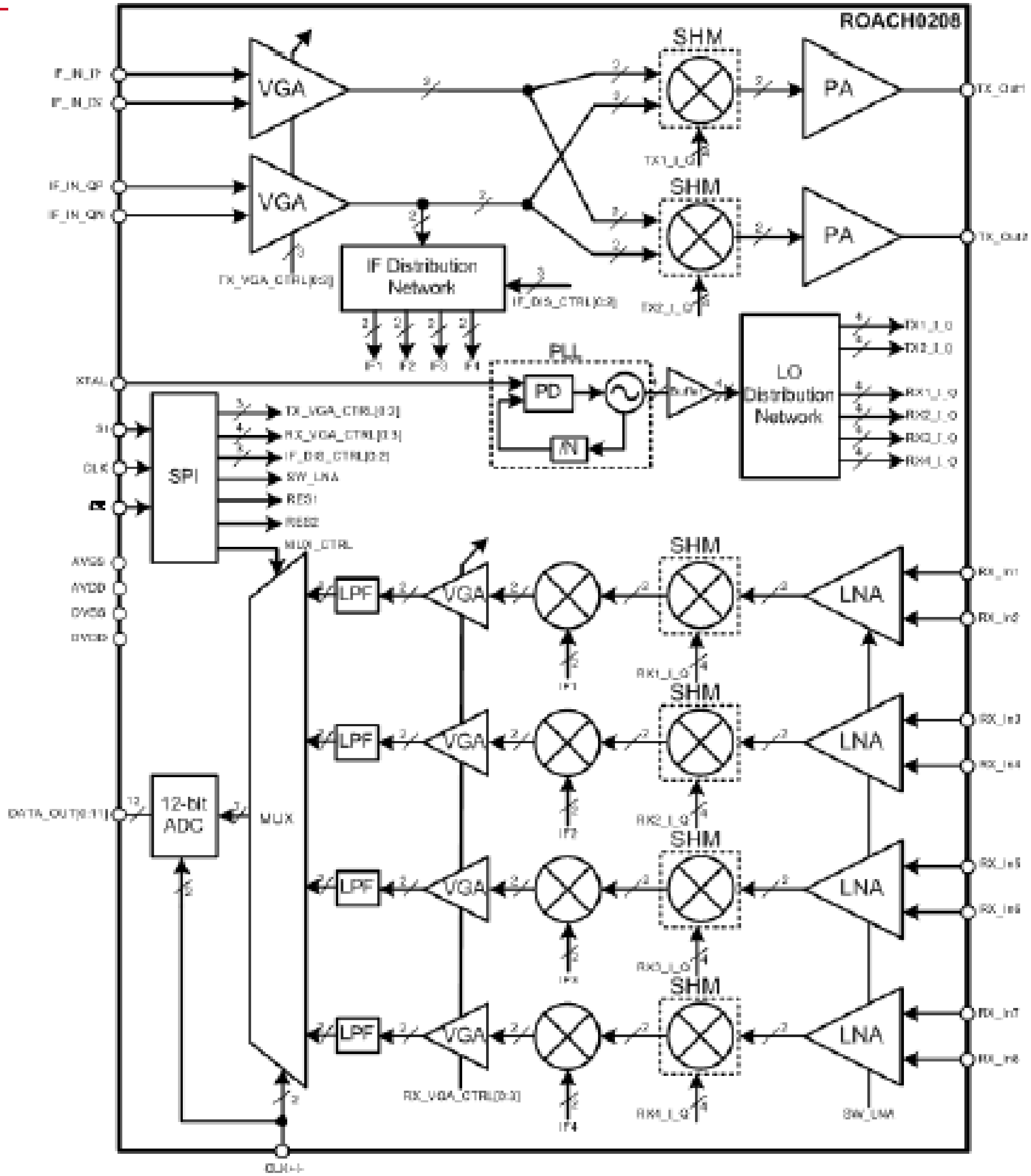
*NOW: VALEO RADAR SYSTEMS, INC.

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)

77GHz RADAR CHIP: 2 TRANSMITTERS, 4 RECEIVERS & LO



EXTREME MMIC

FUTURE CAR RADAR FOR FEW $

GOOGLE RADAR IN SMART WRIST WATCH

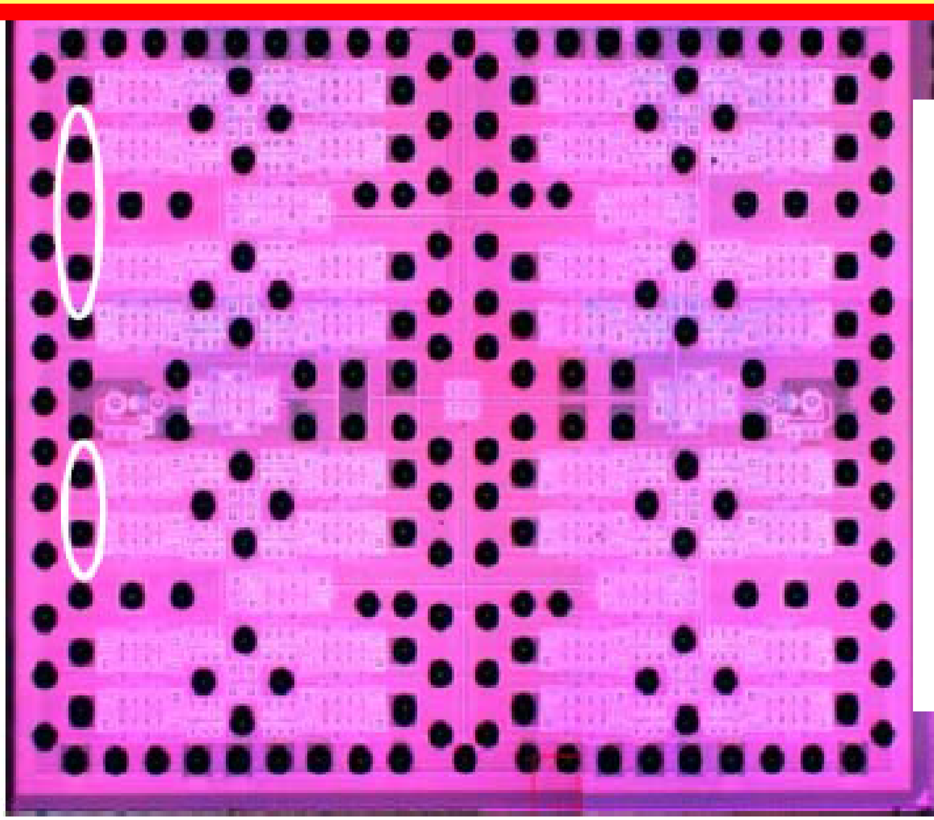
FITS ON PINKY TOE NAIL
4 ANTENNAS; 0.05W DC POWER

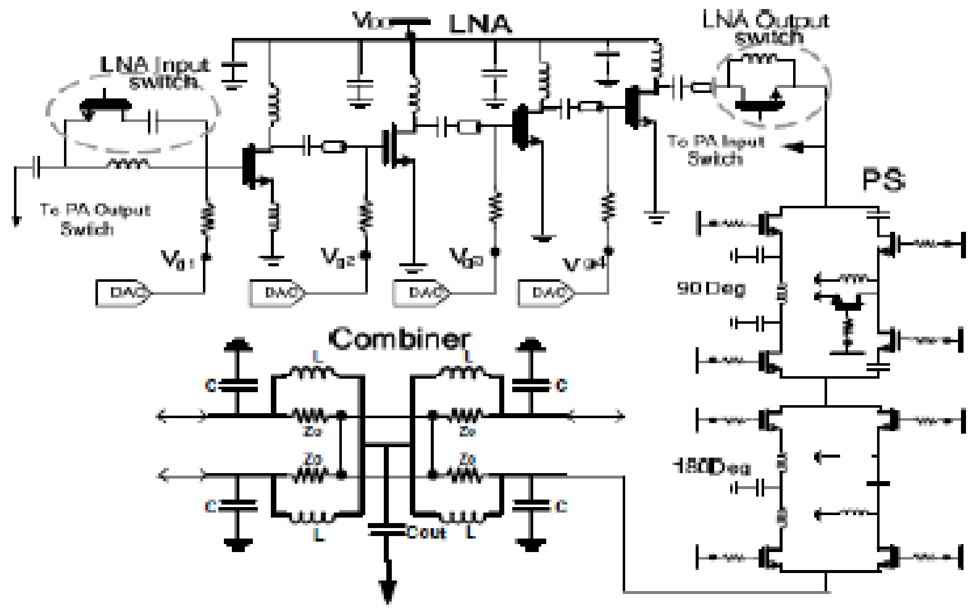
http://spendergast.blogspot.com/2016/05/googles-project-soli-demos-mmw-micro.html

http://www.theverge.com/2016/5/20/11720876/google-soli-smart-watch-radar-atap-io-2016

DICK TRACY

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

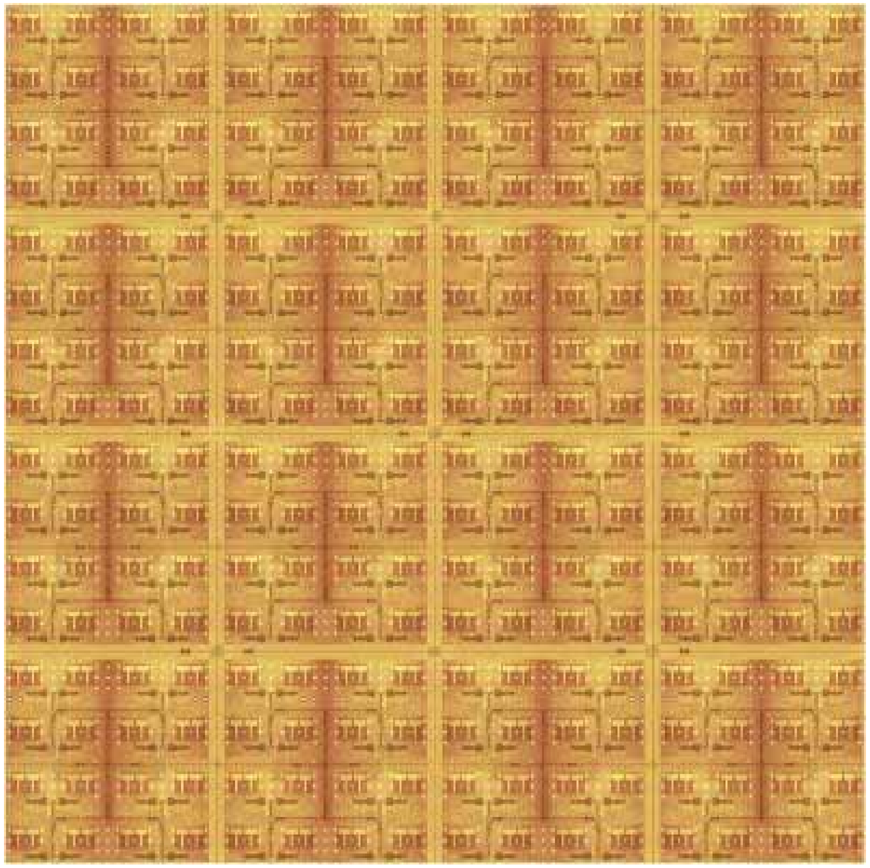


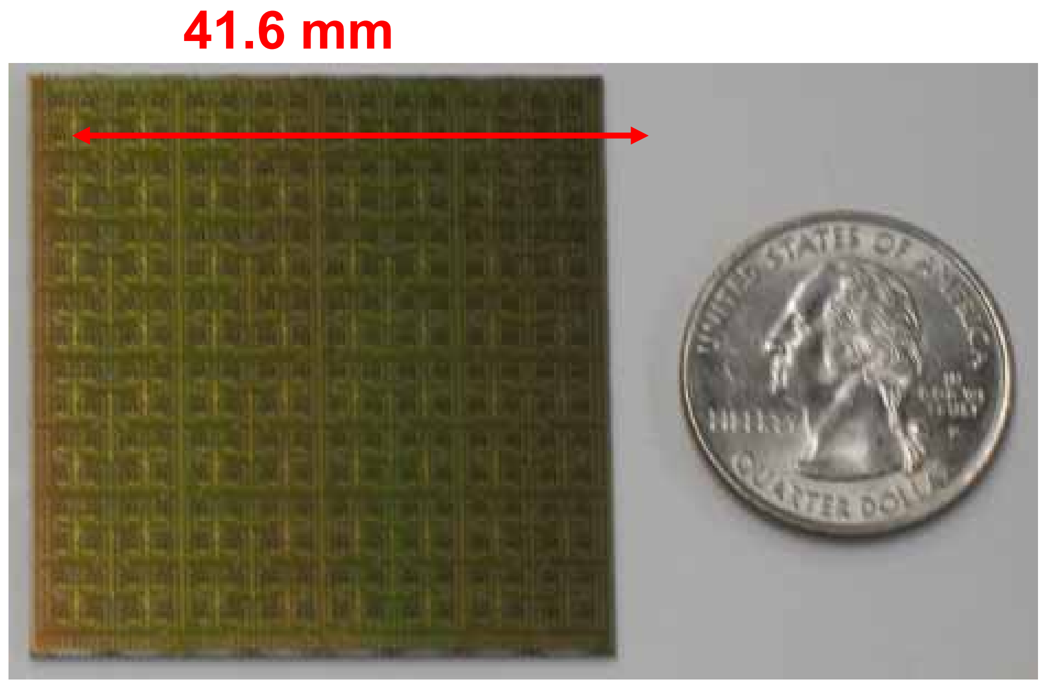


EXTREME MMIC

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

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





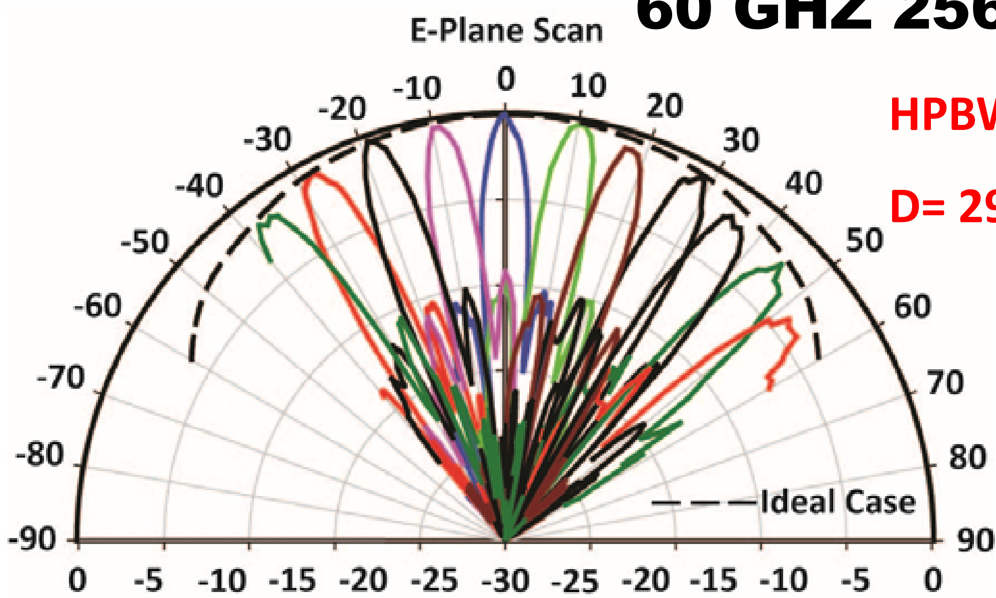
1740mm^2, largest RF chip ever produced

6,000 RF TRANSISTORS
100K FOR BIAS/CONTROL

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

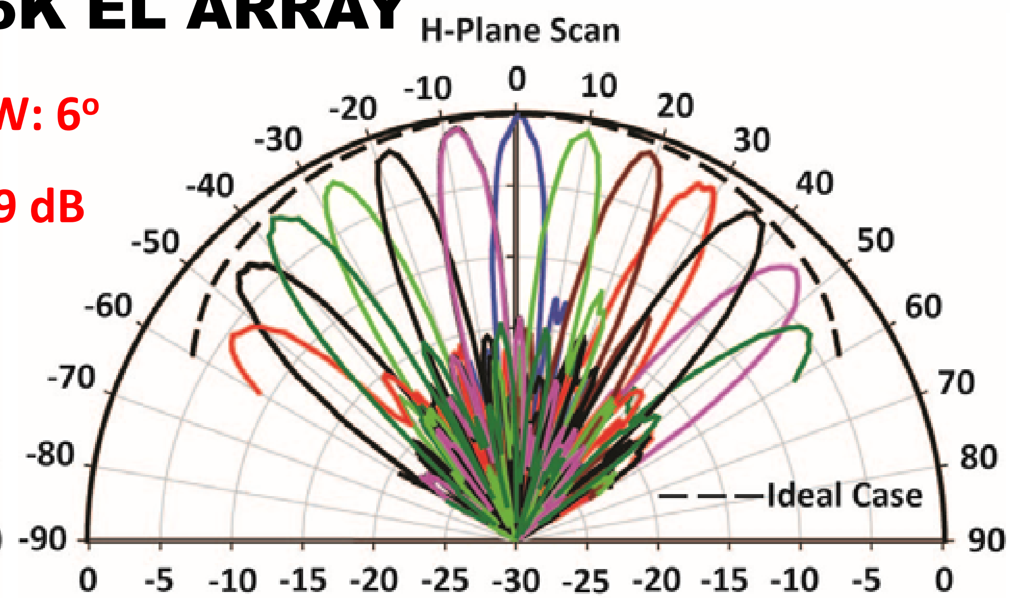
Measured Patterns and EIRP

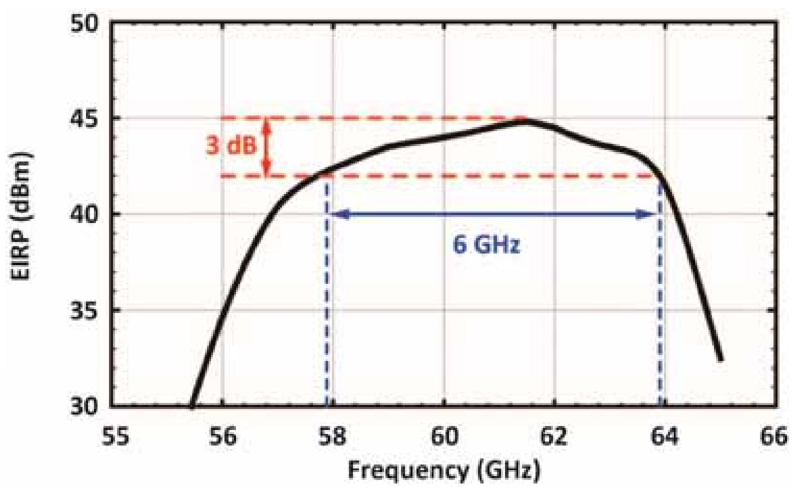
60 GHZ 256K EL ARRAY



HPBW: 6°

D= 29 dB





- Largest phased arrays at 60 GHz
- Simple packaging used
- Full-2D scan to +/-60 deg.
- Gbps links possible at 1 km

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

FUTURE
THESE
ARRAYS
FOR FEW $

Raytheon

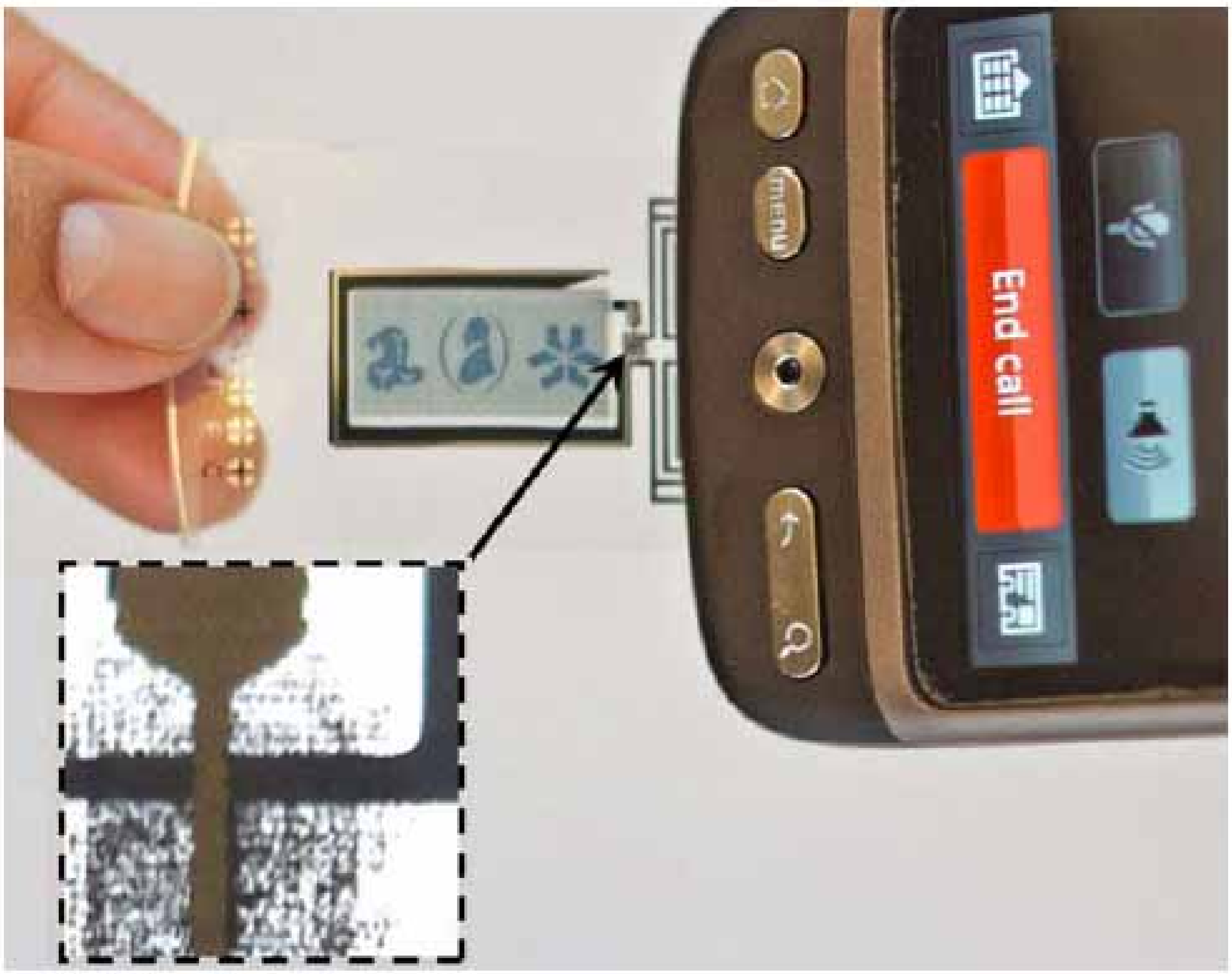
FUTURE USED IN CELL PHONES & INTERNET OF THINGS

SMART GLASSES

http://spectrum.ieee.org/tech-talk/biomedical/devices/displays-of-subliminal-cues-boost-athletic-performance/?utm_source=techalert&utm_medium=email&utm_campaign=121114

PRINTED DIODES AT 1.6 GHZ

- TALKS TO CELL PHONE
- HARVESTS CELL PHONE SIGNAL FOR POWER
- MAKES PRINTED ELECTRONIC LABELS
- FUTURE **GOAL 2.4 GHZ**



(M. PEPLOW, IEEE SPECTRUM 7/7/14)

WEARABLE ELECTRONICS

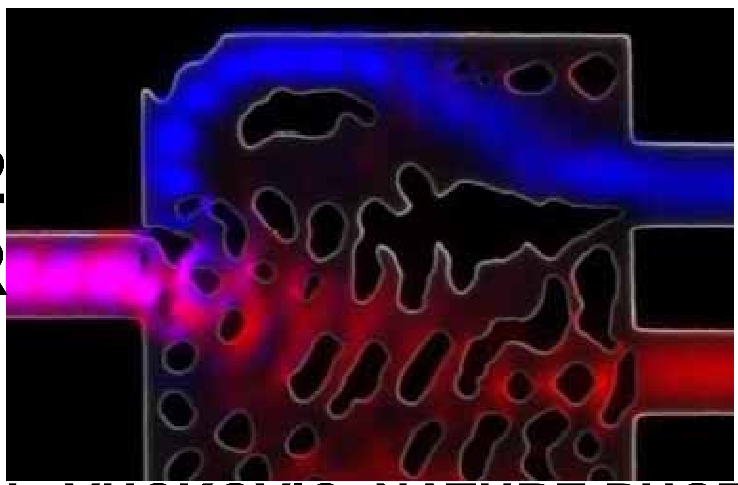
MONITOR FOR INFANT SUDDEN DEATH SYDROME

TIME MAG. 9/11/13, 6-11-13, P 18

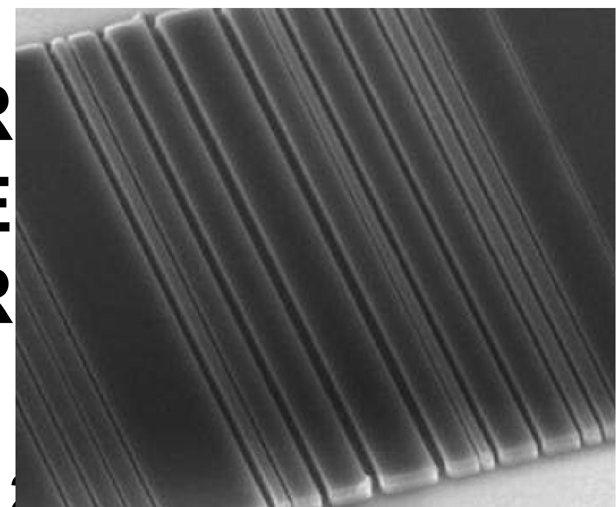
FUTURE: IR FOR DATA TRANSFER IN CHIPS & BETWEEN SYSTEMS

- 80% OF POWER IN CHIP DUE TO DATA OVERS WIRES
- CAN SEND 20X AS MUCH DATA OPTICALLY
- 20 CHANNELS IN DIAMETER OF HUMAN HAIR
- 1000’S SUCH LINKS IN CHIP
- SILICON TRANPARENT TO IR
- SOFTWARE DESIGNS LINKS

1:2 SPLITTER

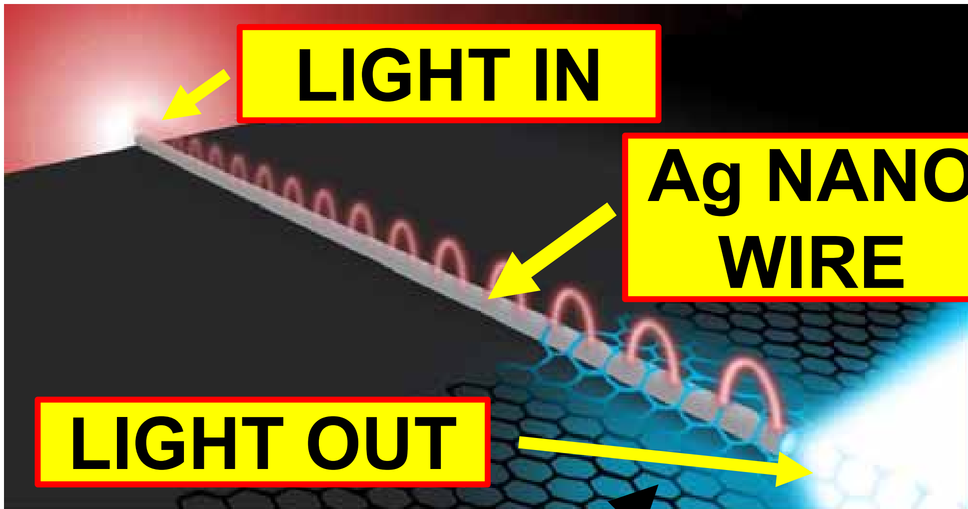


BAR CODE SPLITTER



(A. PIGGOTT, J . VUCKOVIC, NATURE PHOTONICS, 10 1038 2

OPTICAL & ELECTRICAL SIGNALS PROPAGATED OVER SAME WIRE



SINGLE LAYER MoS_2

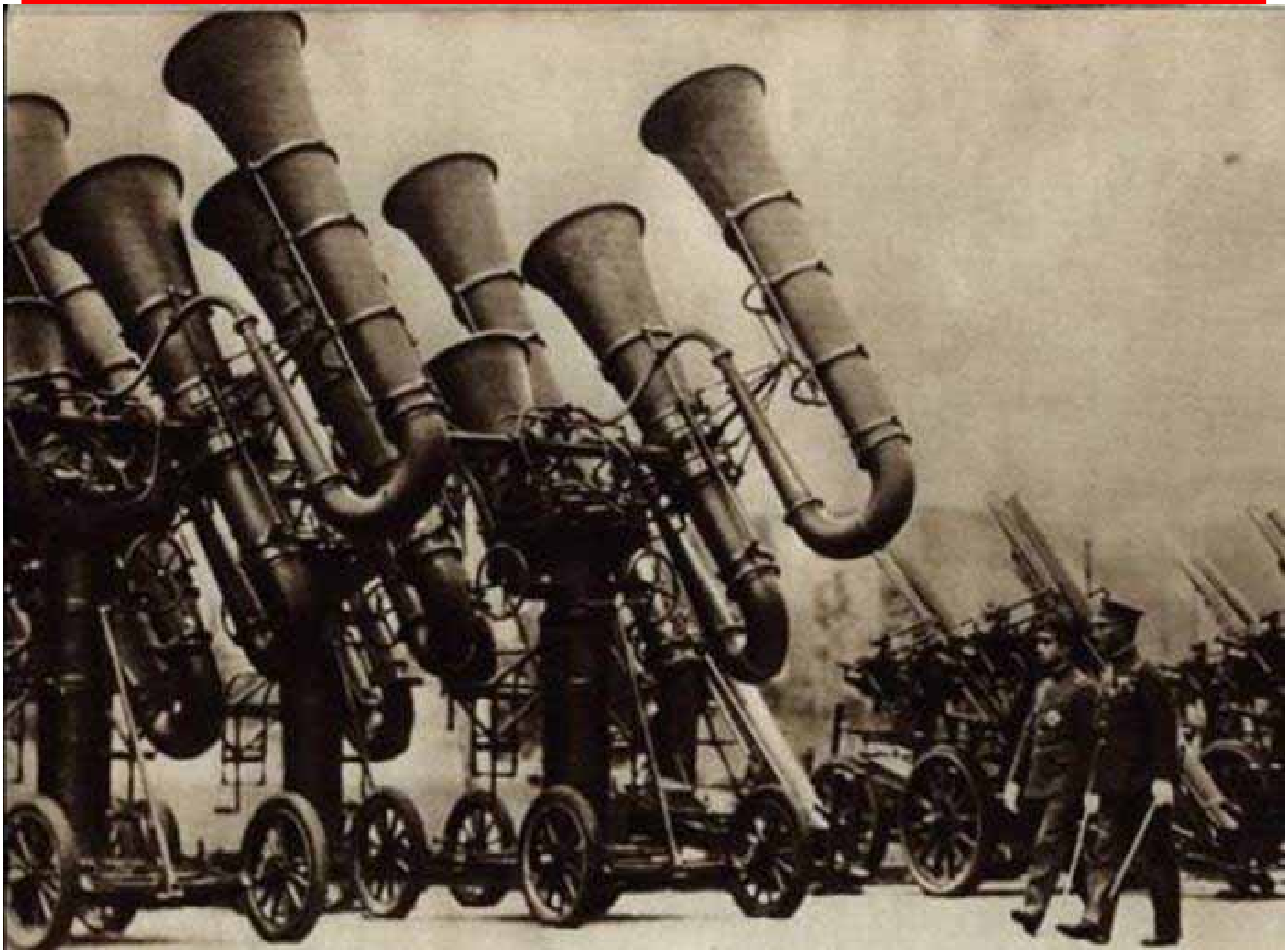
- ALLOWS ELECTRICAL SIGNALS TO GO AT SPEED OF LIGHT ON CHIP
- ALLOWS PHOTONICS & ELECTRONICS ON SAME CHIP

(K. GOODFELLOW, ET AL OPTICA VOL. 1, ISSUE 3, PP.149-152 [2014])

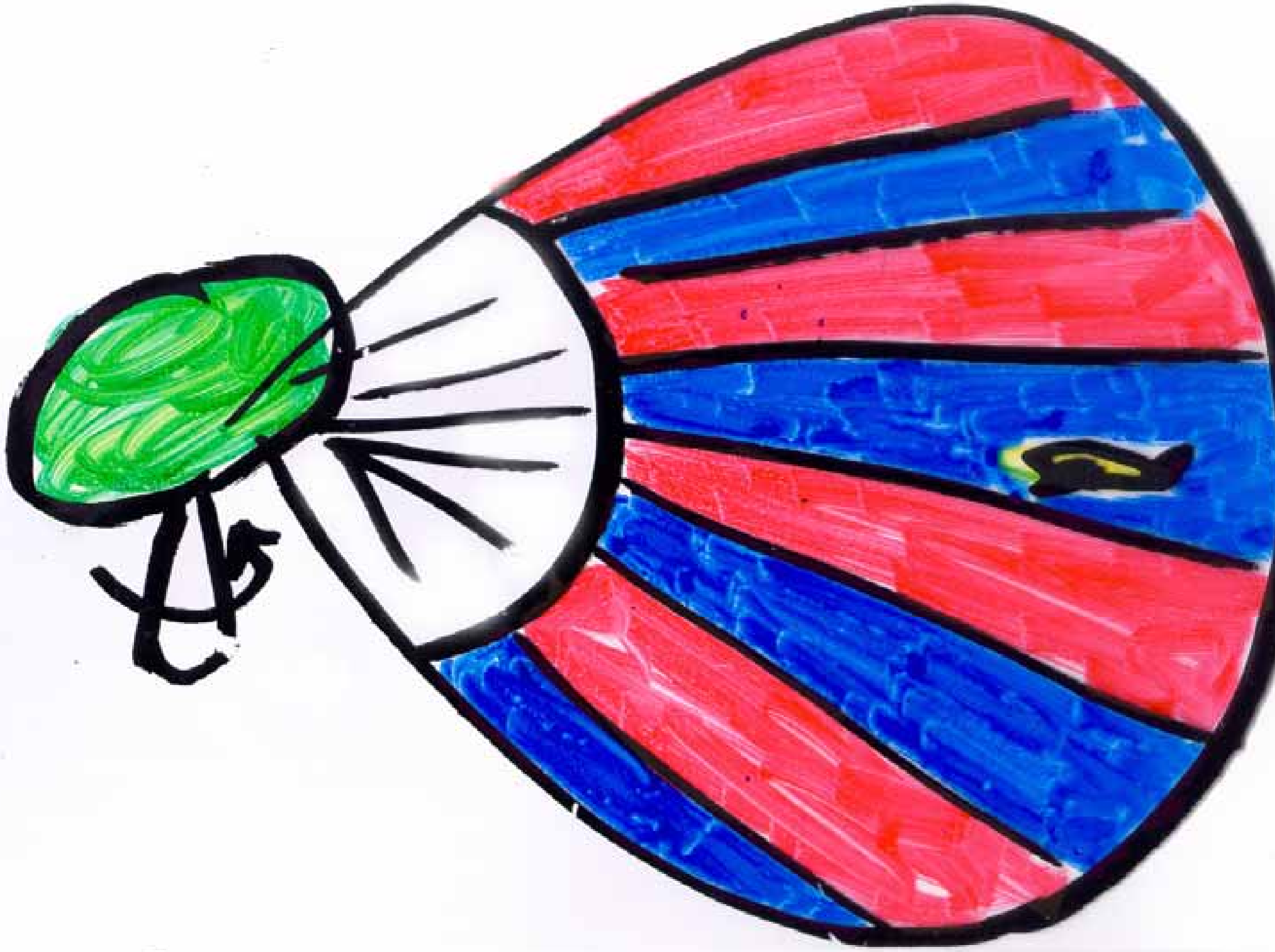
WORLD WAR I

WW I ACOUSTIC SENSOR

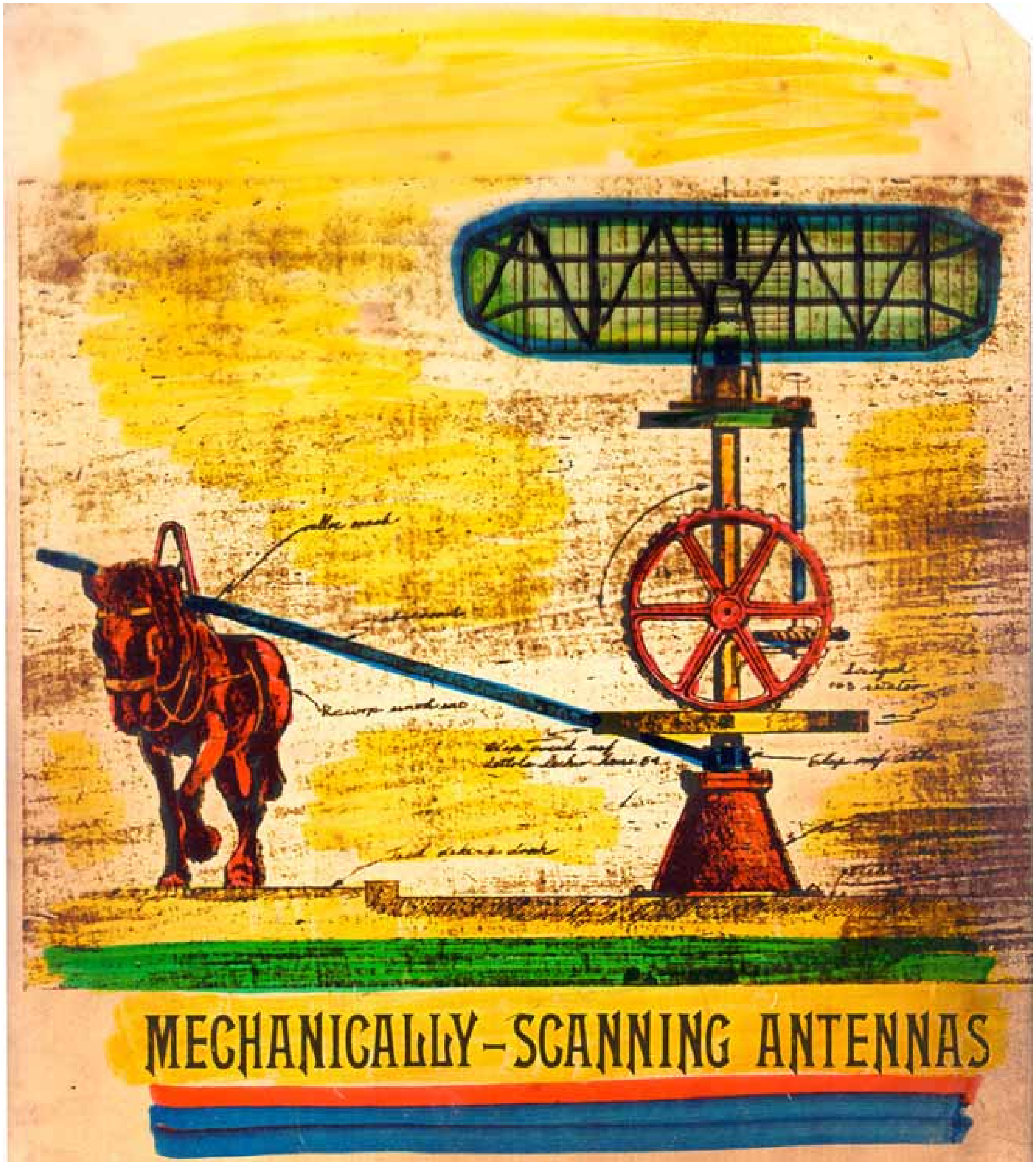
WW I ACOUSTIC ARRAY



WORLD WAR 2



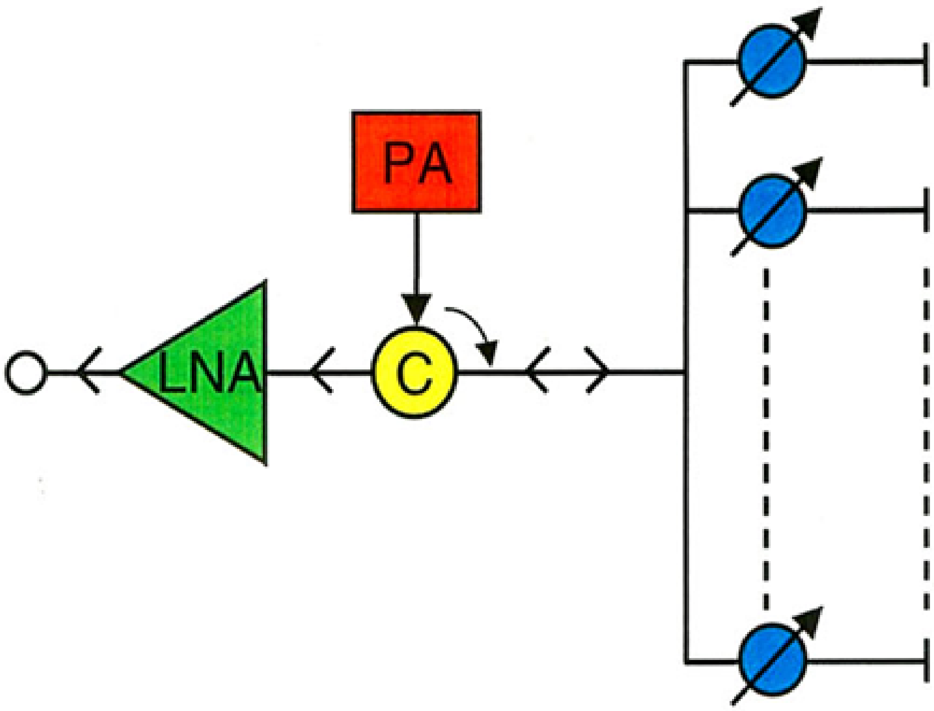
FAN BEAM
RADAR


MECHANICALLY-SCANNING ANTENNAS

PAT ARENA

PHASED ARRAYS HAVE SEEN AMAZING ADVANCES

1^{ST} GENERATION ARRAYS
PASSIVE ARRAYS



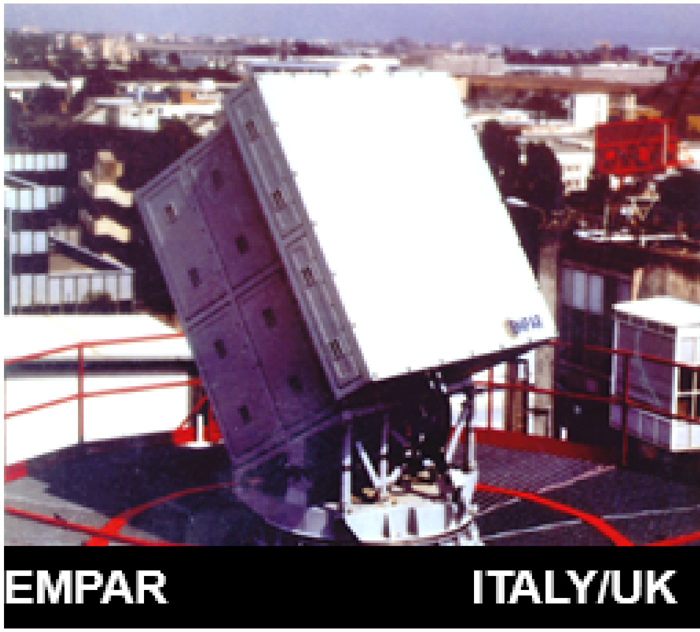
PA = Power Amplifier
LNA = Low Noise Amplifier
S = Switch

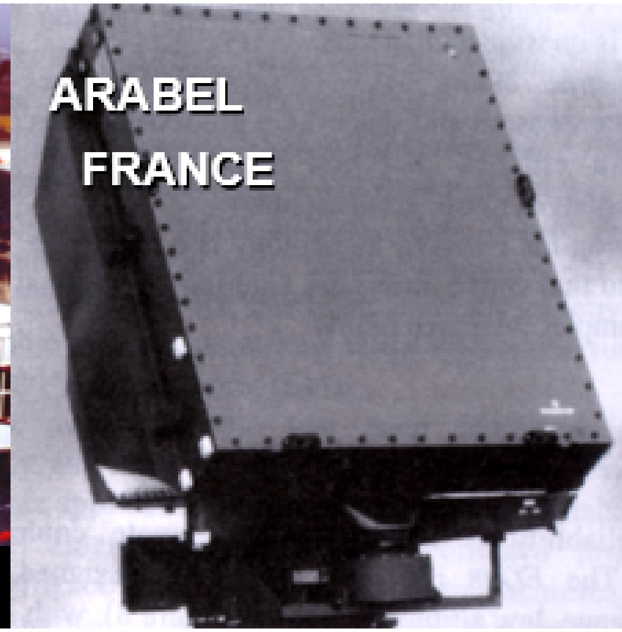
PASSIVE ARRAY

TUBE TRANSMITTER SYSTEM

Example U.S.A. Passive Phased Arrays Having Large Productions

PASSIVE PHASED ARRAYS FROM AROUND THE WORLD





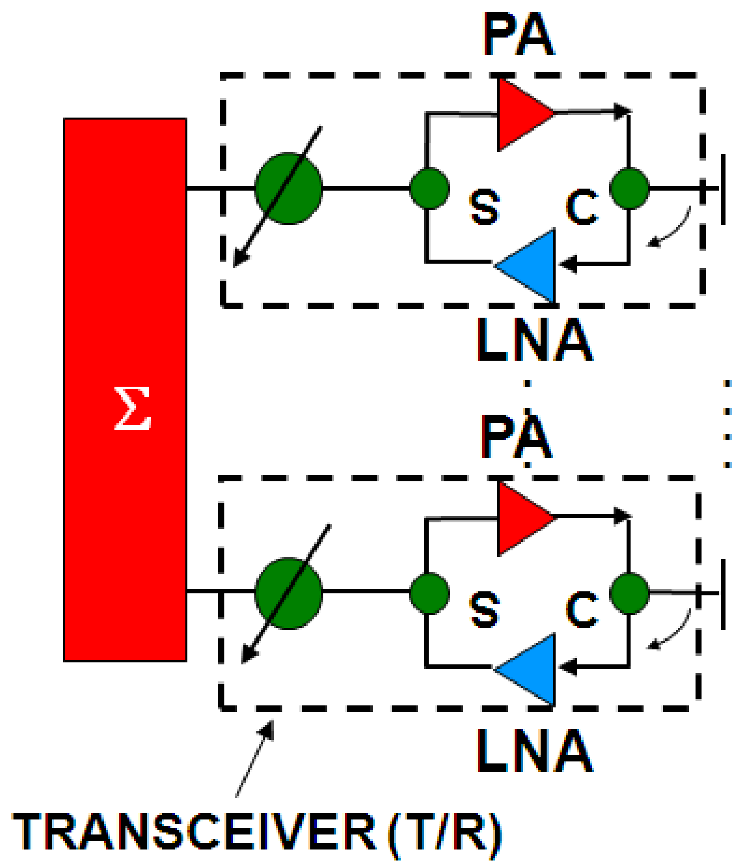
(BROOKNER, MJ,1/08)

2ND GENERATION ARRAYS
ACTIVE ARRAYS


TRAVELING
WAVE
TUBE

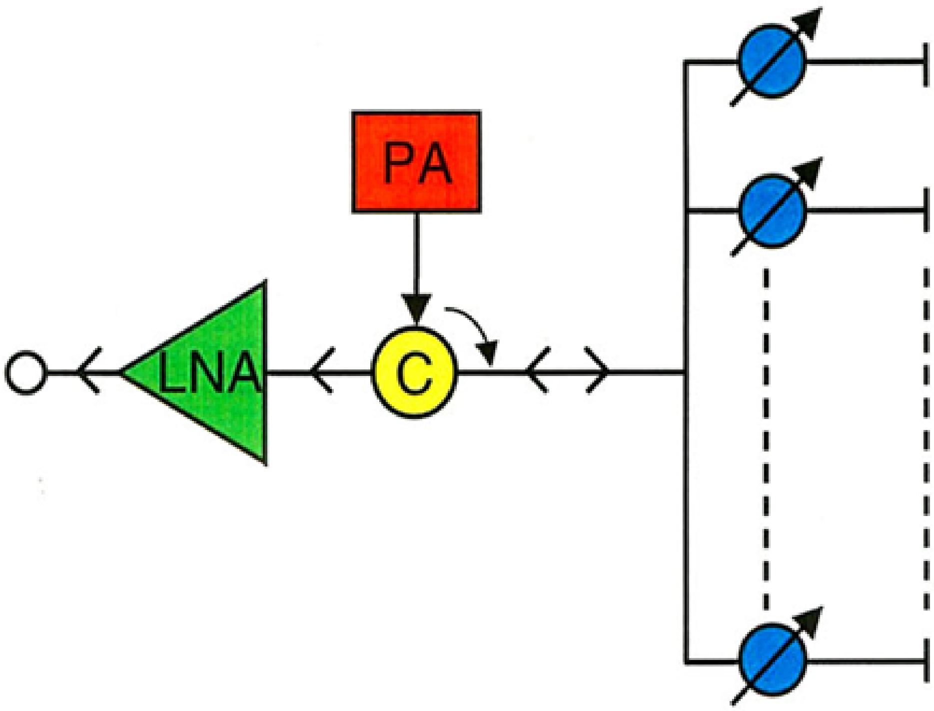
2ND GENERATION: ACTIVE ELECTRONICALLY SCANNED ARRAYS (AESAs)

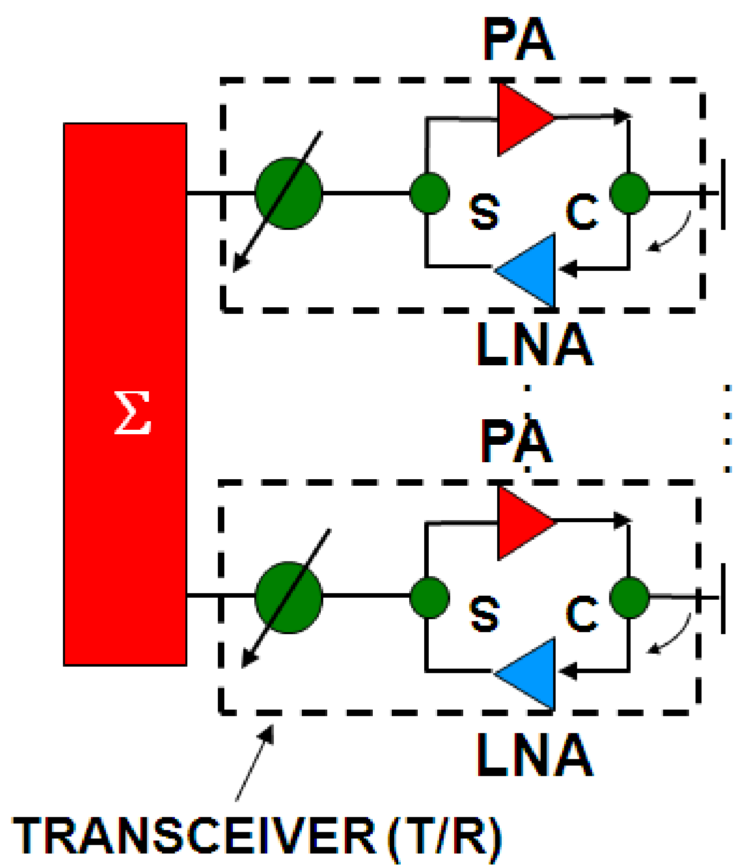
TRANSISTOR TRANSMITTER, NO MICROWAVE INTEGRATED CIRCUITS



ACTIVE ARRAY

PASSIVE VS ACTIVE ARRAY



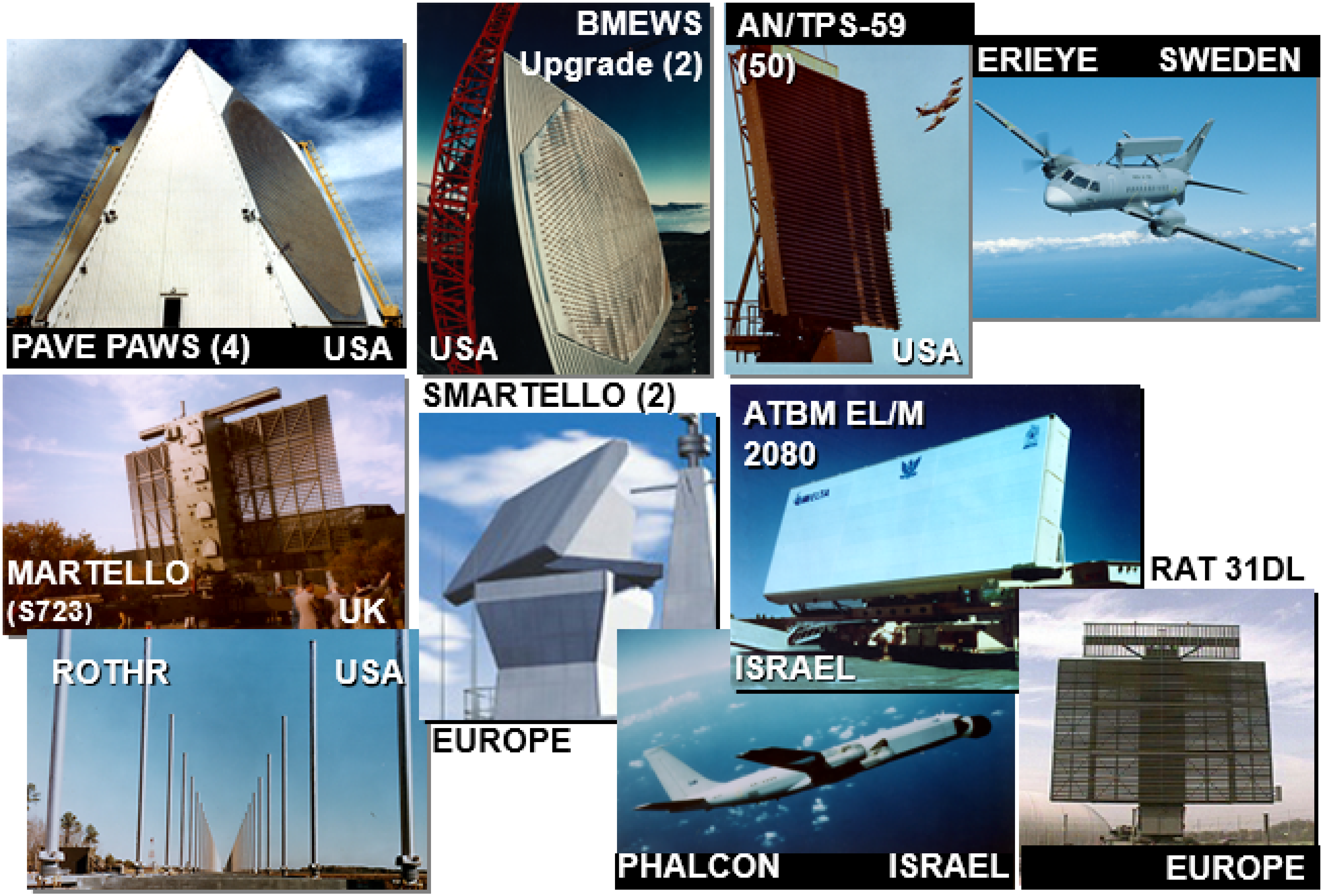


PA = Power Amplifier
LNA = Low Noise Amplifier
S = Switch

PASSIVE ARRAY

ACTIVE ARRAY

2ND GENERATION ACTIVE ARRAYS

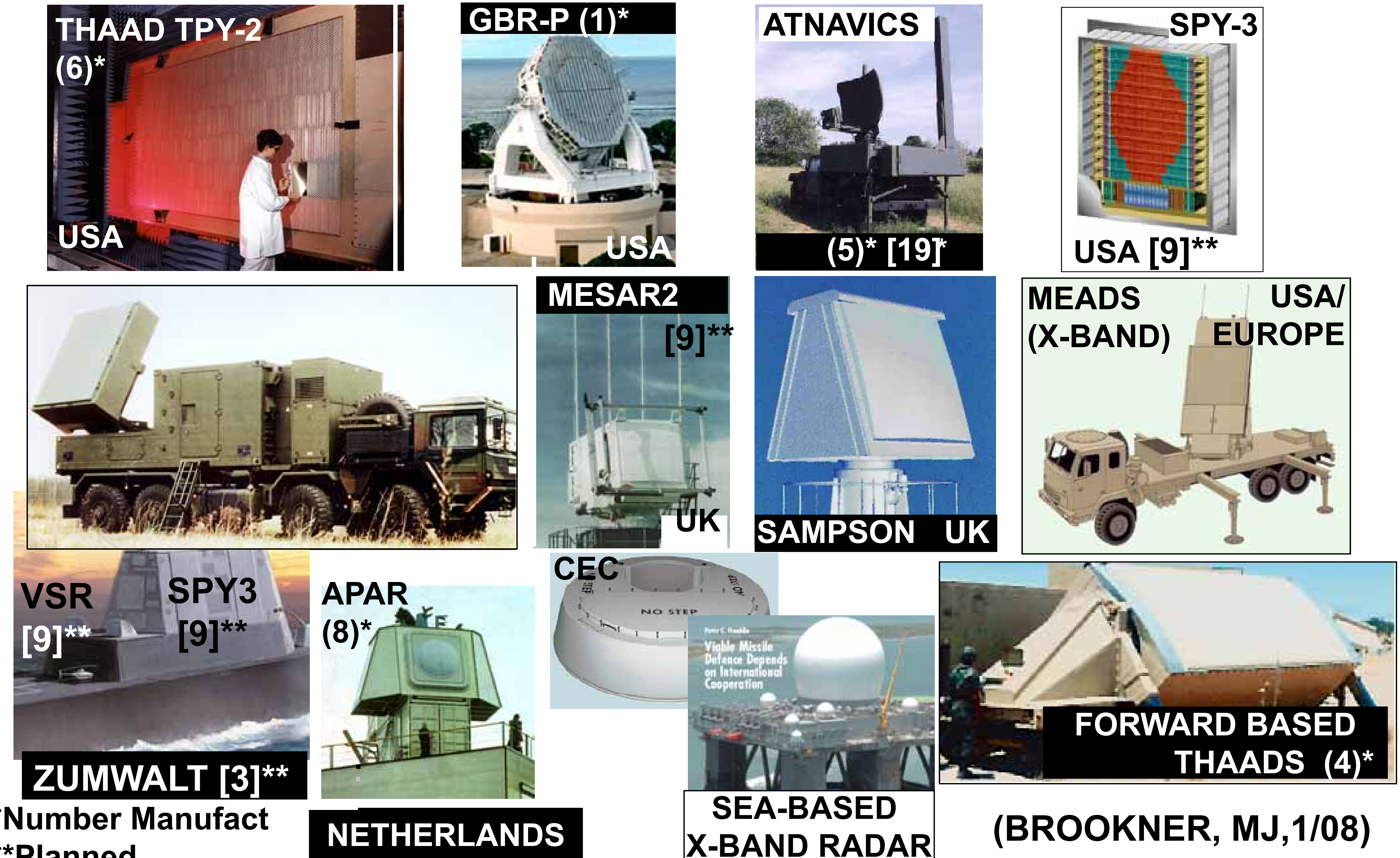


(BROOKNER, MJ,1/08)

3RD GENERATION: ANALOG MICROWAVE INTEGRATED CIRCUIT (MMIC*) ASEAs

*MONOLITHIC MICROWAVE INTEGRATED CIRCUITS

Ground/Sea Active Arrays Using Integrated Circuit (MMIC) Solid-State Transmitters



*Number Manufact
**Planned

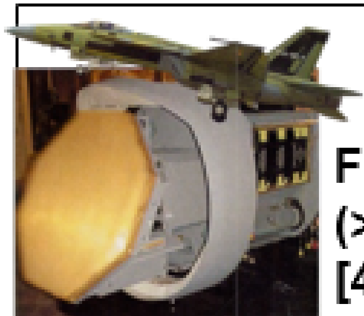
(BROOKNER, MJ,1/08)

Example Airborne MMIC Active Arrays Deployed and Under Development

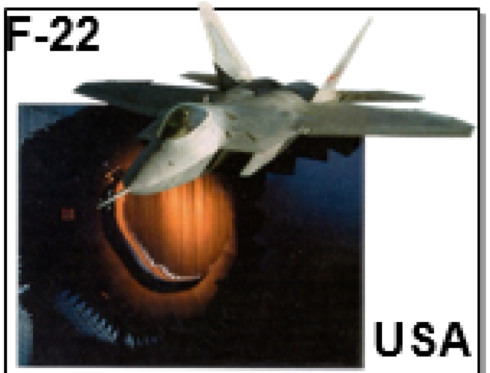
MP-RTIP on E-10A USA

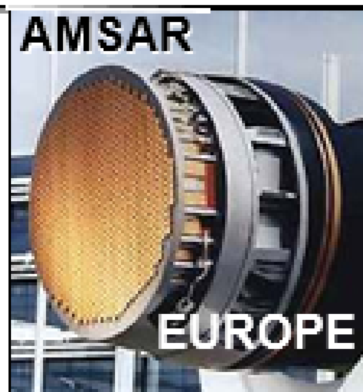
APG-63(V)2 ON F-15 (18)* [200]**

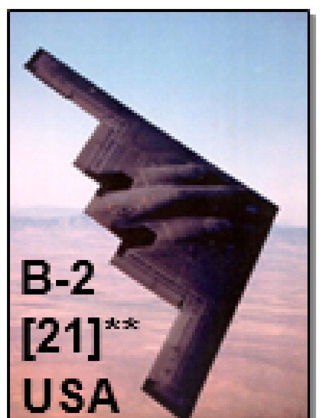
MP-RTIP on GLOBAL HAWK

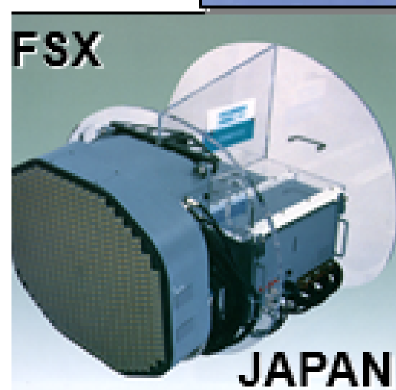


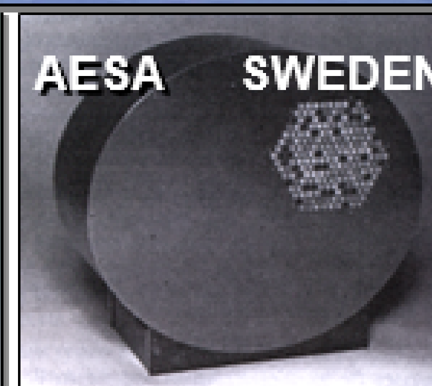
F-18 (>40)* [411]** USA











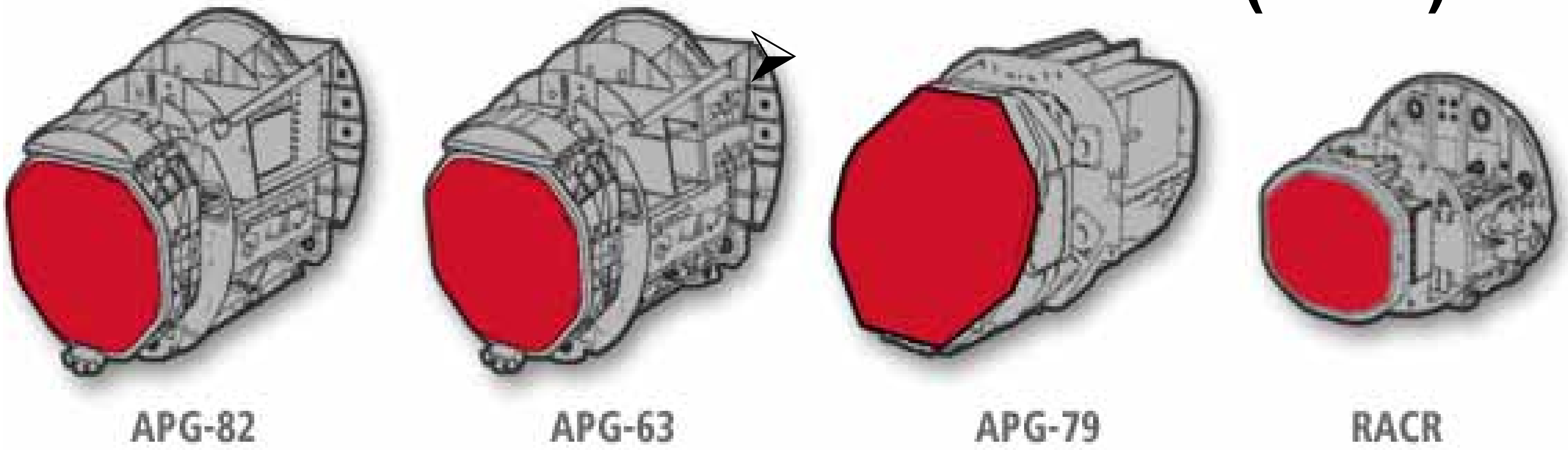
*Number Manufact.

**Planned

(BROOKNER, MJ,1/06)

FIGHTER MMIC AESA RADARS

USED ON F/A-18, F-15, EA-18G AND F-16
>500 AESAs PRODUCED BY RAYTHEON
>1.8 MILLION AESA T/R MODULES (2013)



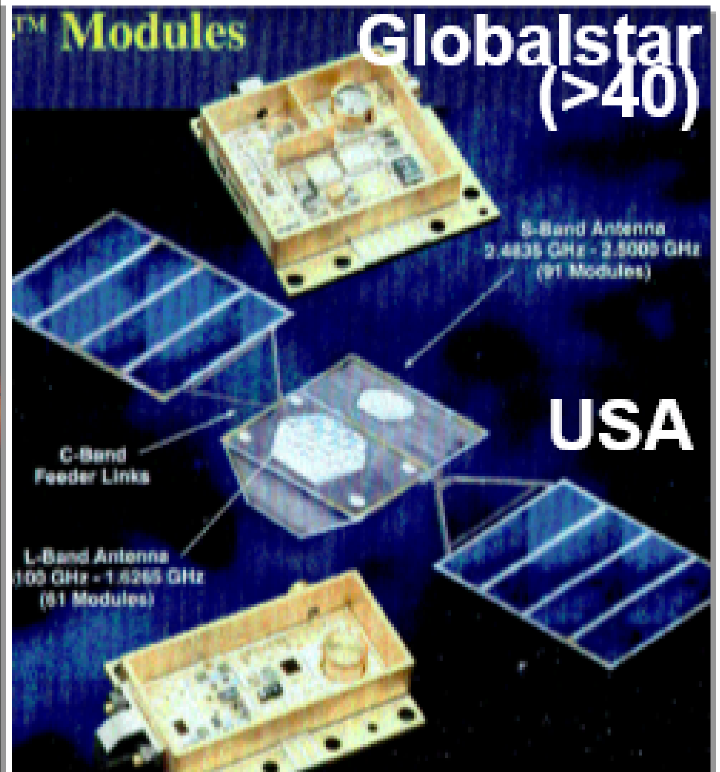
F-15

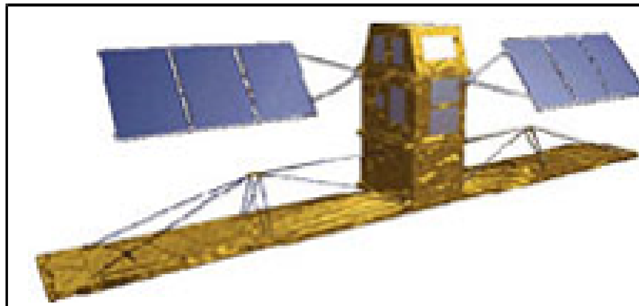
F/A-18

F-16

(BROOKNER, ARRAY IEEE, “PHASED ARRAYS”, 10-2013)

Space-Based-Radars (SBR)

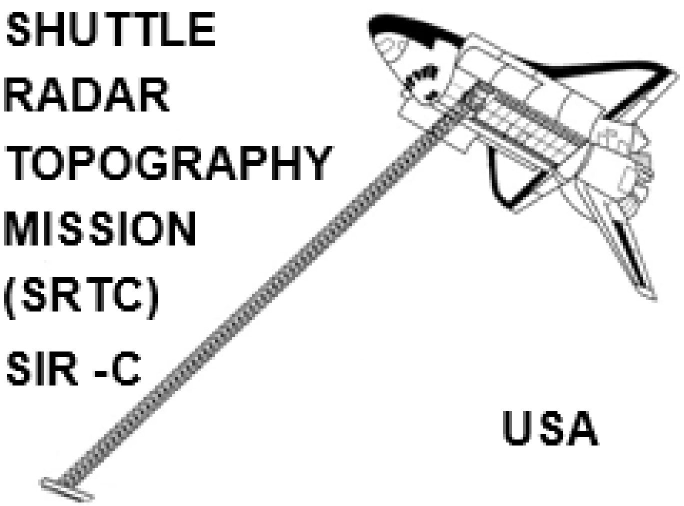




RADARSAT 2

CANADA

SHUTTLE
RADAR
TOPOGRAPHY
MISSION
(SRTC)
SIR -C



USA

(BROOKNER, MJ,1/06)

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

X-BAND SPY-3 THREE FACED ARRAY

(US NAVY PHOTO)

1ST ZUMWALT DDG-1000

(US NAVY PHOTO)

ZUMWALT DDG-1000 LAUNCH DAY

(US NAVY PHOTO)

JLENS* BLIMP (AIRSHIP) MMIC AESA RADAR

NOW DEPLOYED OVER WASH.D.C.

- SEE CRUISE MISSILES (CM) OUT TO 340 MILES
- 360° COVERAGE
- CUES PATRIOT AND THAAD (AN/TPY-2):
  - DEMONSTRATED:
    - INTERCEPT OF CMs
    - DETECTION & TRACKING OF BALLISTIC MISSILES (BMs)

*JOINT LAND ATTACK CRUISE MISSILE DEFENSE ELEVATED NETTED SENSOR

(WIKIPEDIA PHOTO)

AIR & MISSILE DEFENSE RADAR (AMDR)

S-BAND: AIR & MISSILE DEFENSE:

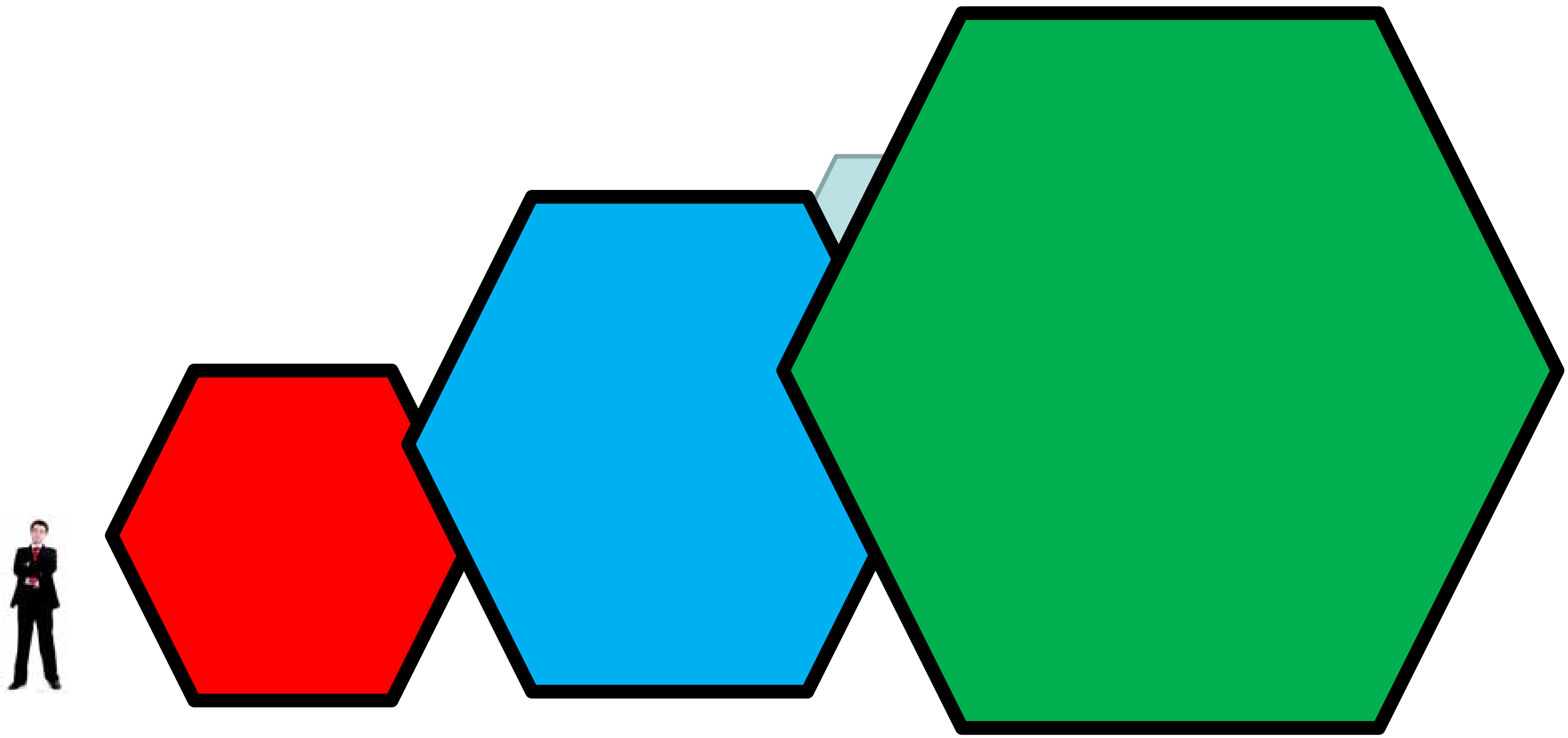
- ADAPTIVE DIGITAL BEAM FORMING
- 30X > TARGETS THAN SPY-1D(V)
- 30X > SENSITIVE THAN SPY-1D(V)
- RADAR MODULAR ASSEMBLIES (RAMs) ARE BUIDING BLOCKS
- LRU IN RAM REPLACED <6MIN, EASY, ONLY 2 TOOLS NEEDED
- 37 RAMs = SPY-1D(V)+15DB = ~14’x14’ ≈ SIZE OF SPY-1D(V)
- GaN ARRAY, 4 FACED
- GaN 34% < $ THAN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

ARLEIGH BURKE DESTROYER

X-BAND: HORIZON SEARCH

(WIKIPEDIA PHOTO)

AMDR FULLY SCALABLE



PATRIOT UPGRADES

- 2012: $400M UPGRADE
- 2015: GaN AESA; 360º 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)

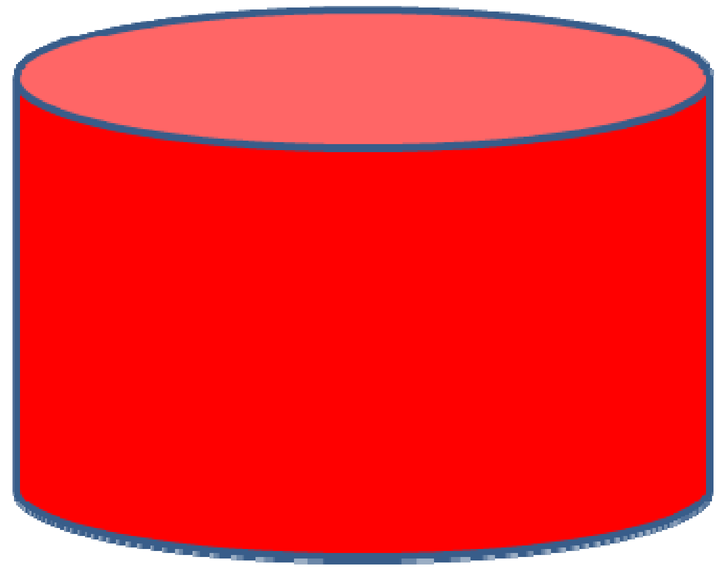
(PHOTO: BROOKNER, E., MJ,2/15)

NEXGEN: USA ATC & WEATHER RADARS → AESAs

- NEXGEN: REPLACE ALL MECHANICALLY STEERED ATC (EN-ROUTE & TERMINAL) & WEATHER (NEXRAD & TDWR) RADARS IN USA WITH COMMON TECHNOLOGY AESAs
- ABOUT 350 AESA RADARS
- VALUE: ~ $4 BILLION

CANDIDATES AESAs

4 FACED



CYLINDER

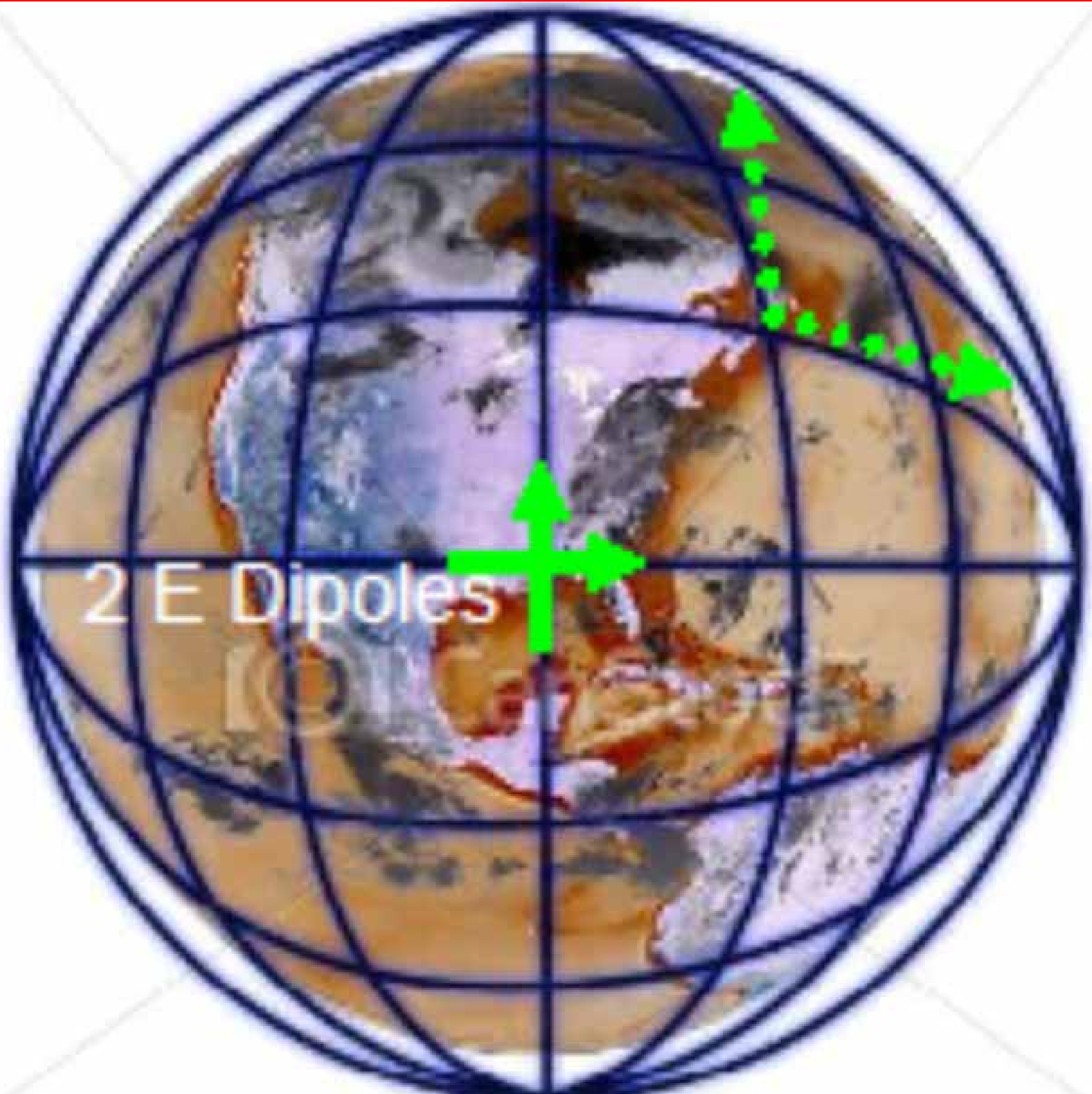
WEATHER RADARS A CHALLENGE

- NEED DUAL POLARIZATION
- WHEN TRANSMITTING SIMULTANEOUS
  H & V NEED CROSS POL TO BE:

≥ 40 DB DOWN

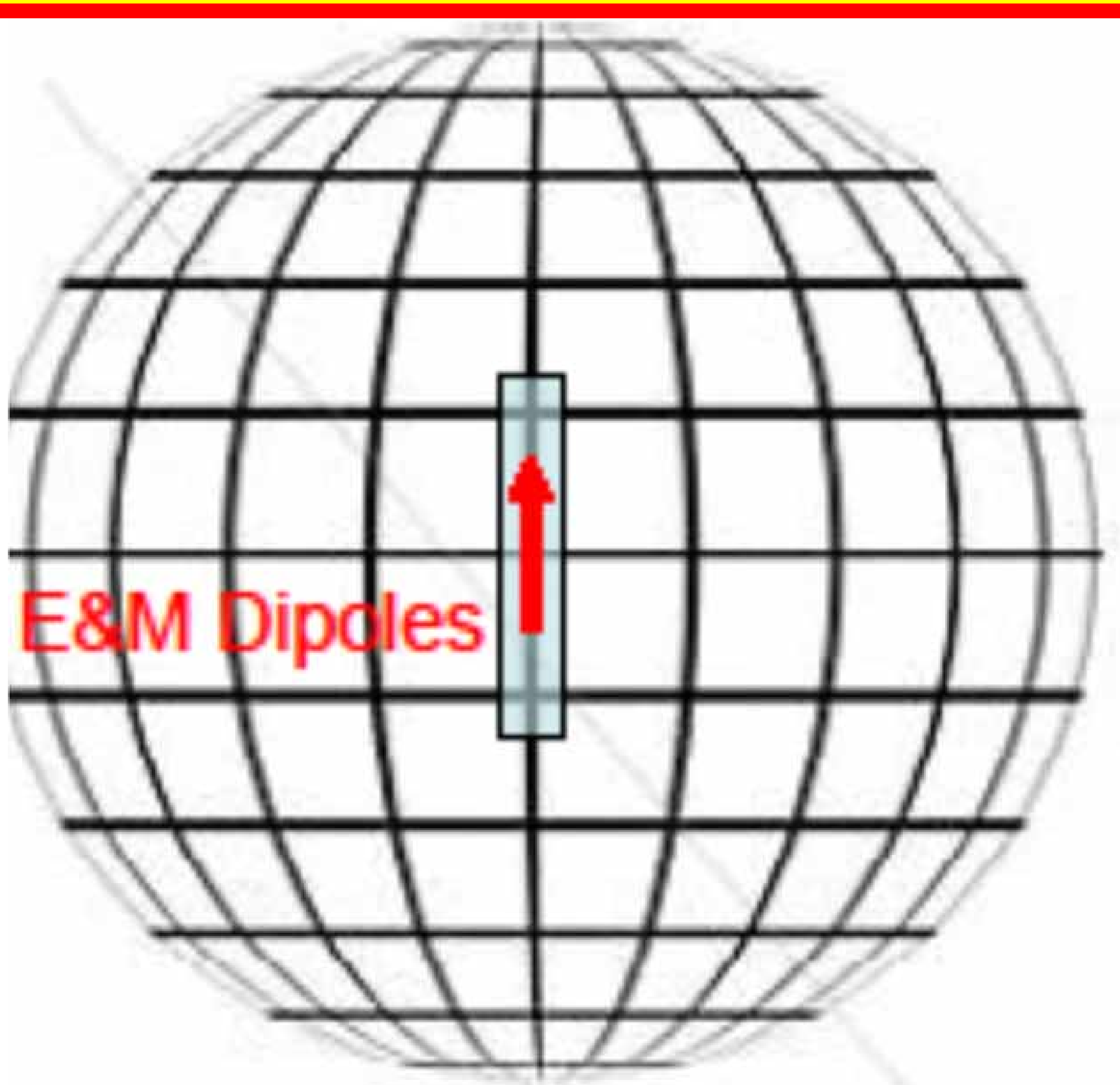
- CUSTOMER HAS COME UP WITH
  INNOVATIVE SOLUTIONS

CROSSED EELECTRIC DIPOLES V & H E-FIELDS



ZRNIC, D. S., ET AL, POLARIMETRIC CHALLENGES, 2013, NOAA

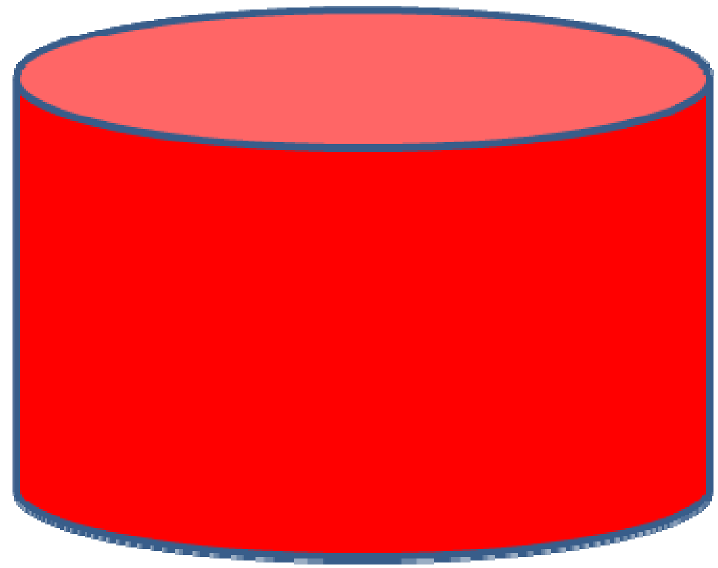
CROSSED ELECTRIC & MAGNETIC DIPOLES V & H E-FIELDS



ZRNIC, D. S., ET AL, POLARIMETRIC CHALLENGES, 2013, NOAA

CANDIDATES AESAs

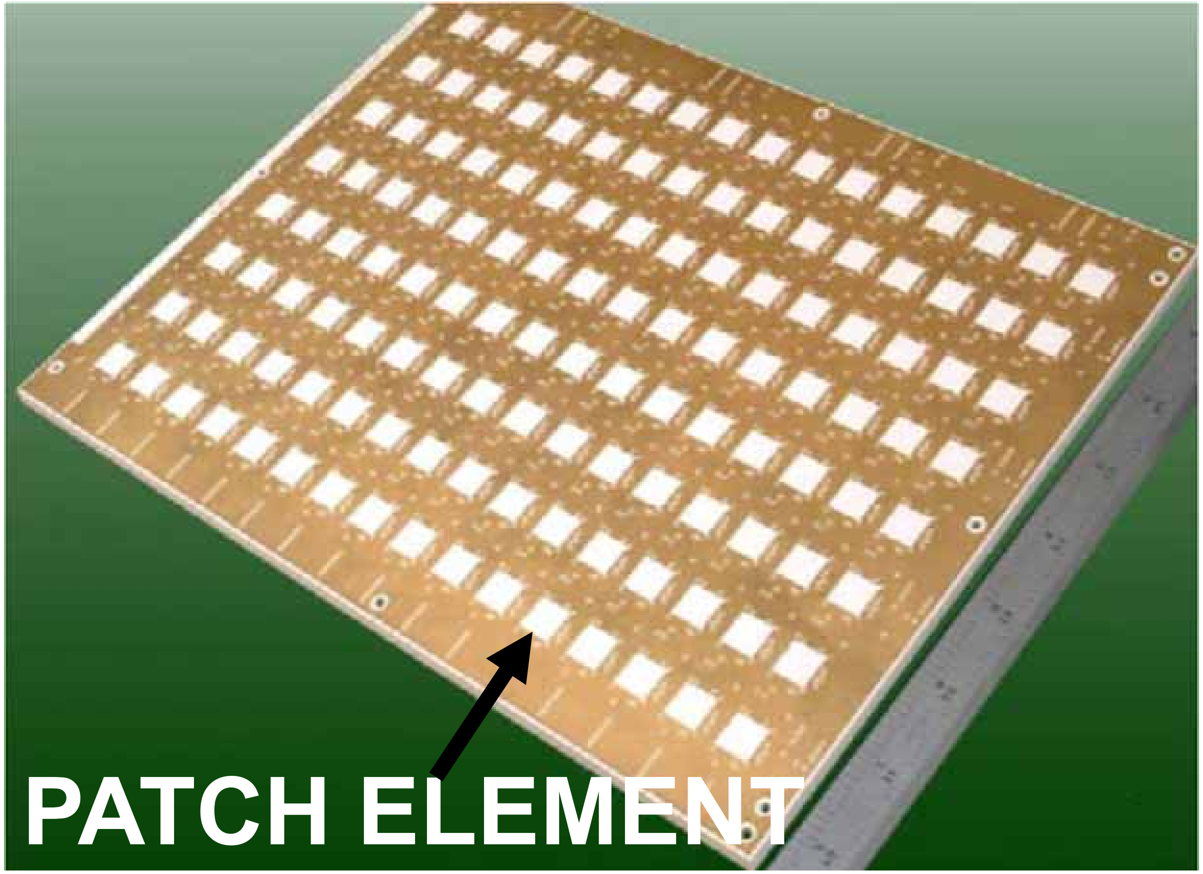
4 FACED



CYLINDER

Raytheon Low Cost X-Band Array PCB Building Block

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

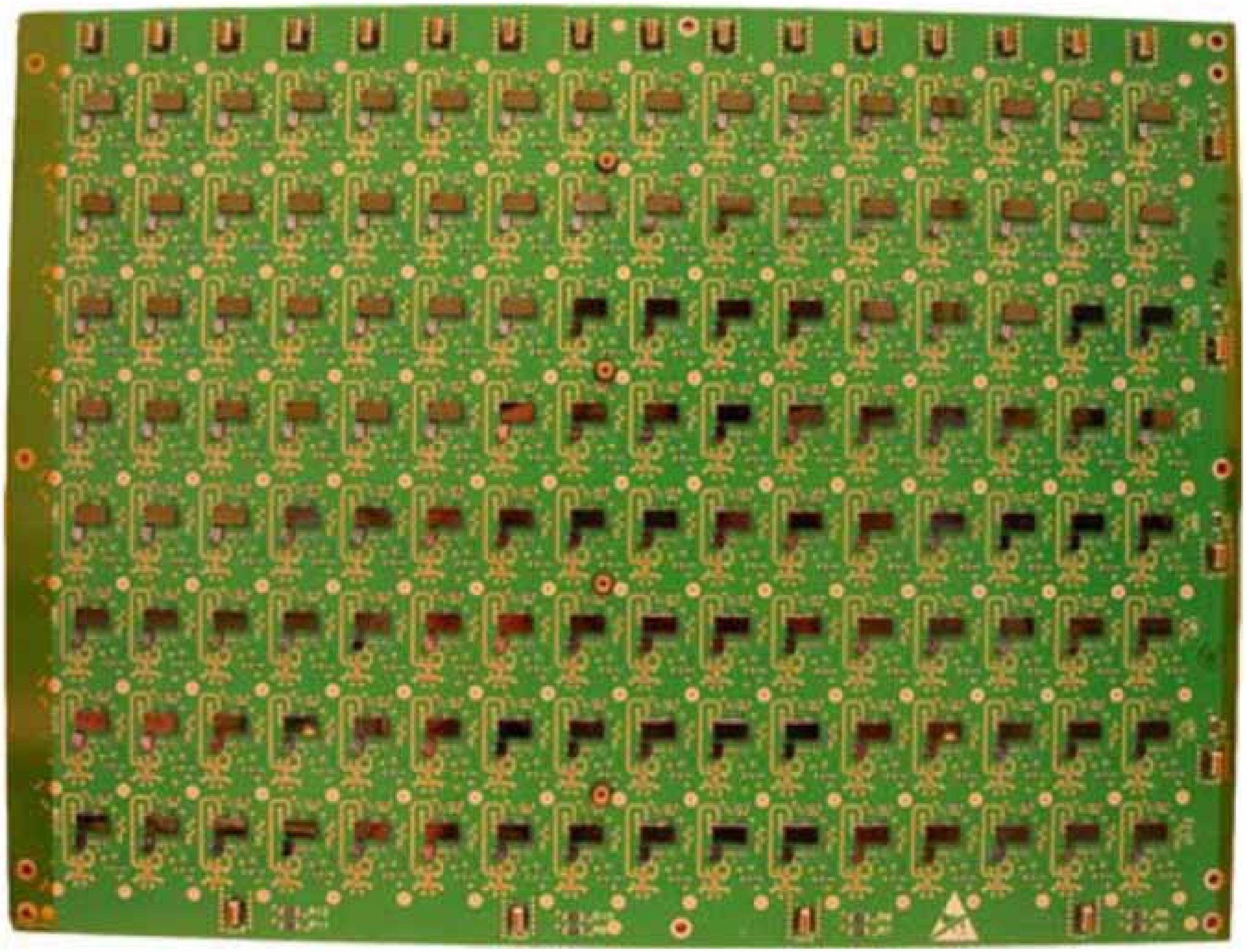


(PUZELLA, ALM, RADARCON-2007)

93

Backside Showing SiGe & GaAs Flip-Chips

4 RF AND 24 DC/LOGIC CONNECTORS

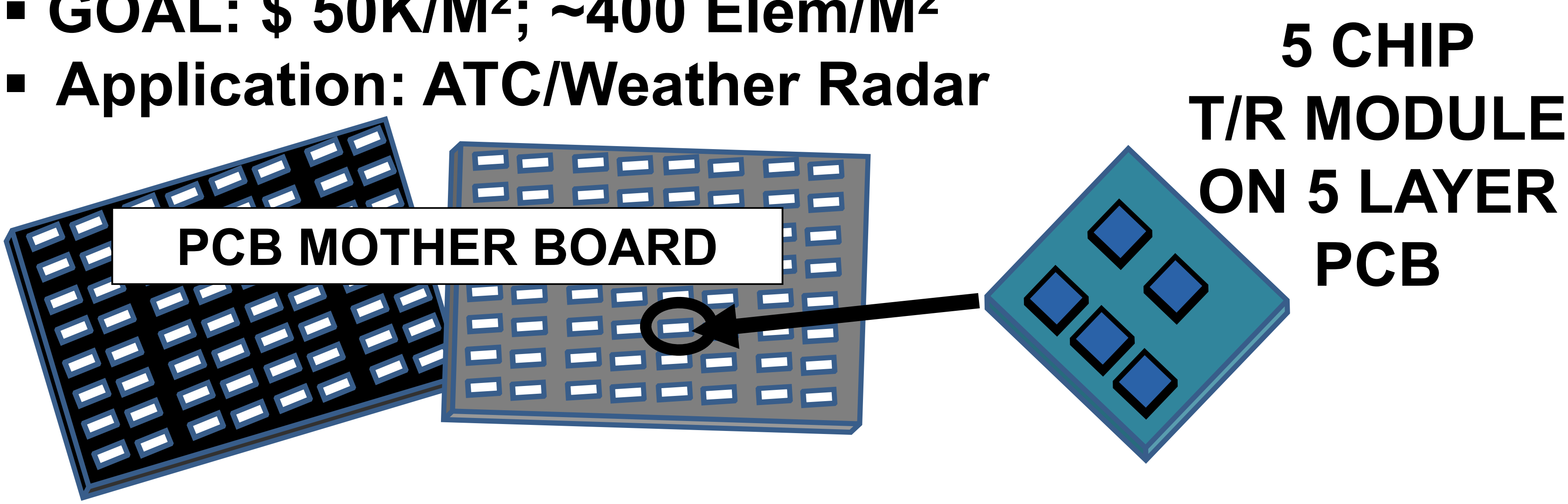


(PUZELLA, ALM, RADARCON-2007)

94

Lincoln-Lab/M/A-Com S-Band Low $ Array

- 16 Layer PCB Mother Board
- 5 Chip T/R Module On 5 Layer PCB
- Switch T/R, No Circulator
- Dual POL Patch Element
- 8 W/POL Peak
- Up To 24 Simultaneous Beams
- Overlapped Subarrays
- GOAL: $ 50K/M²; ~400 Elem/M²
- Application: ATC/Weather Radar



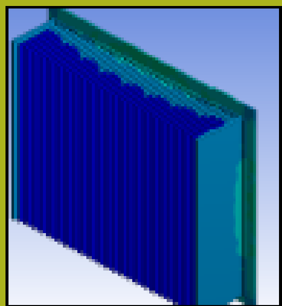
(J. HERD, ET AL, IEEE RADAR 2010, WASHINGTON DC)

X-BAND AIRBORNE ARRAY; 512 ELEMENTS, 2W/ EL

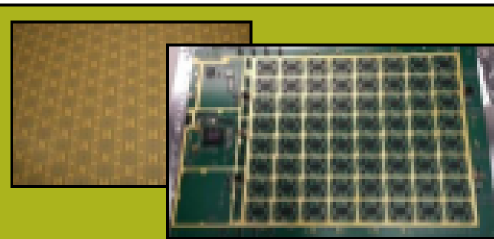
Affordable ASEA Cost Partitioning

50X COST REDUCTION

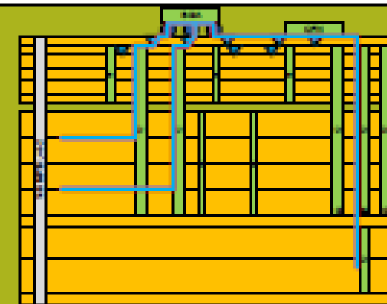
1:2 BANDWIDTH



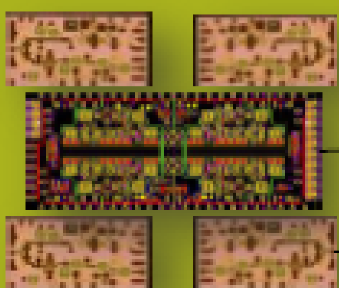
Simple Forced Air Cooling



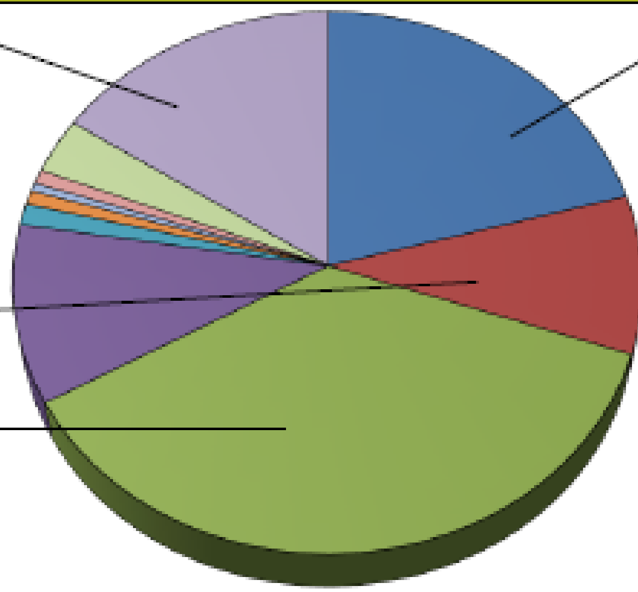
RC Affordable AESA



Low cost FR4 Printed Circuit Board



Low-cost SiGe & Minimal GaAs



Relative Recurring Cost Breakdown

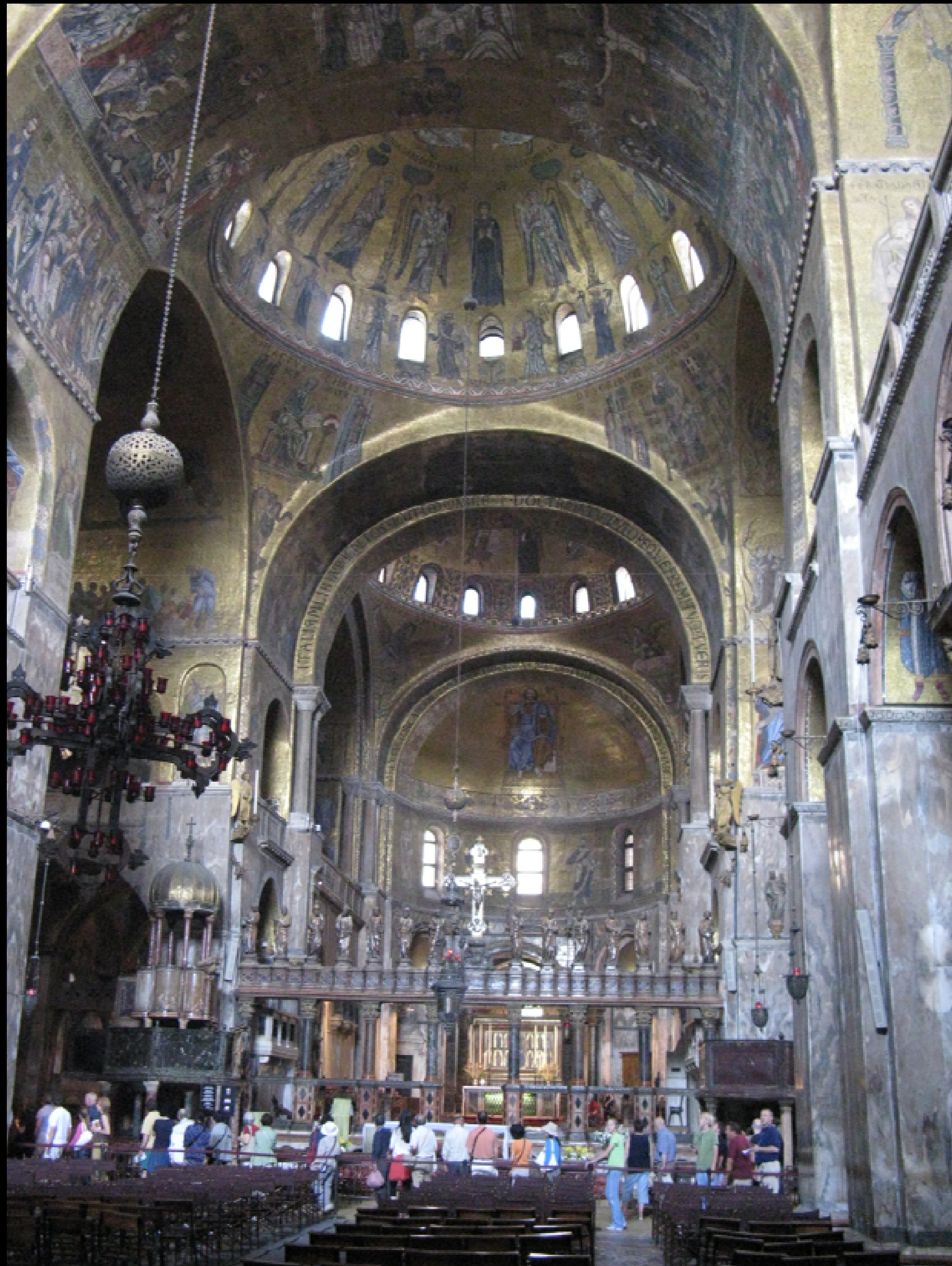
Affordable AESA Cost Strategy

- Minimize GaAs die size and complexity - the pacing cost driver
- Maximize low cost SiGe circuit density
- Inexpensive, high performance FR4 RF printed wiring board

(WANG, ET AL, MILITARY RADAR SUMMIT, 2/24-26/15, ARLINGTON, VA)

VENICE


VENICE

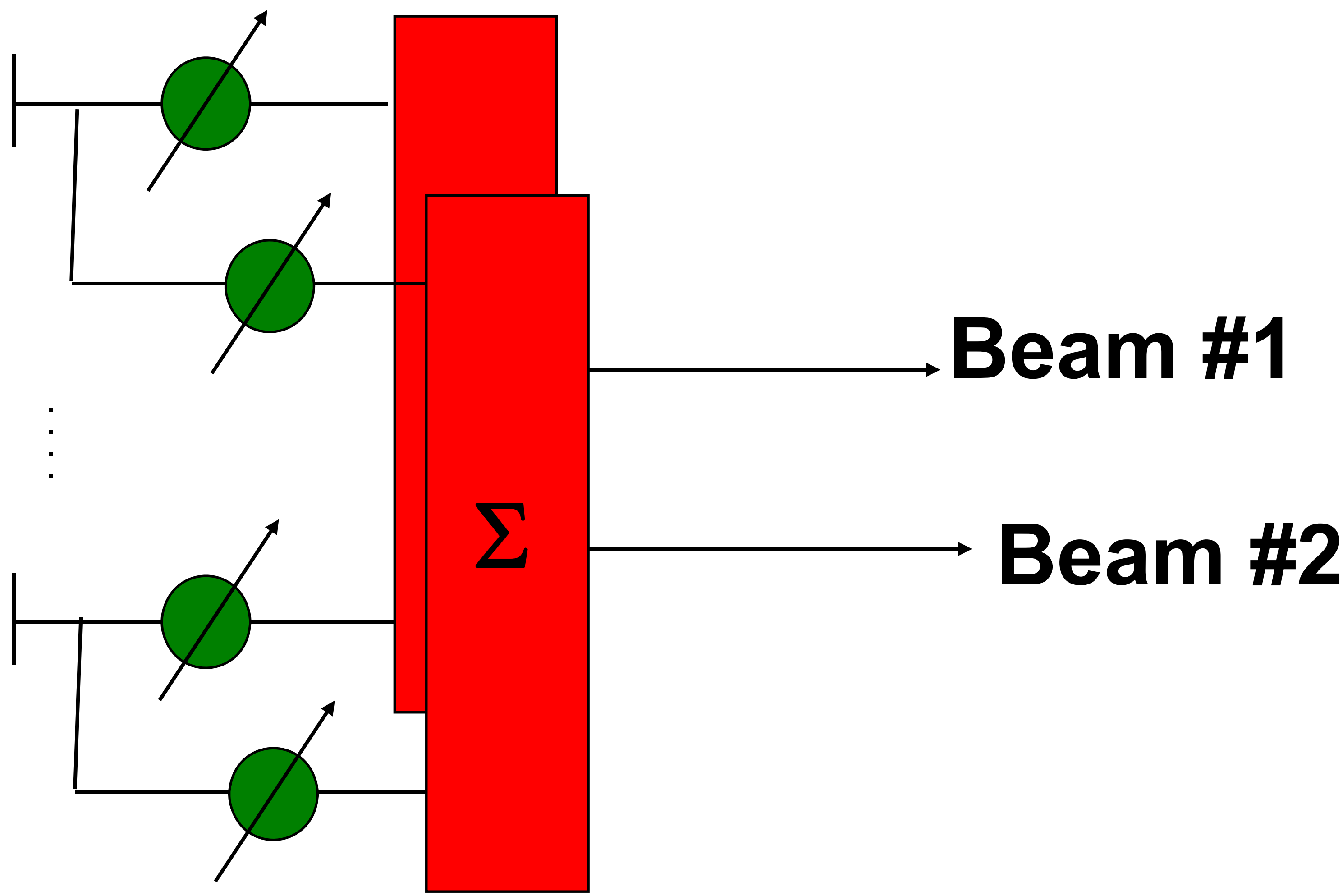



THE NORTH FACE

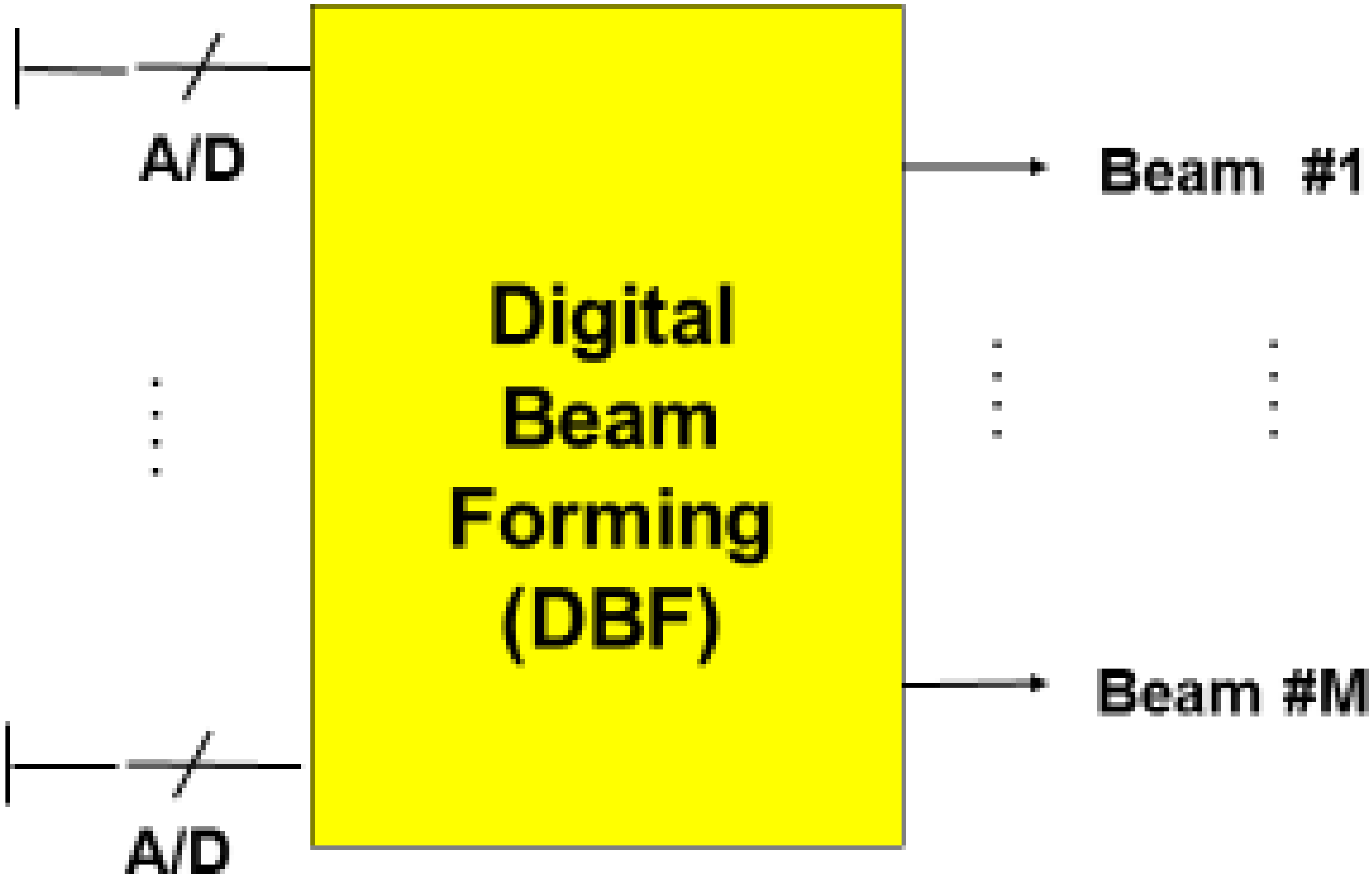

SOUZHOU

DIGITAL BEAM FORMING

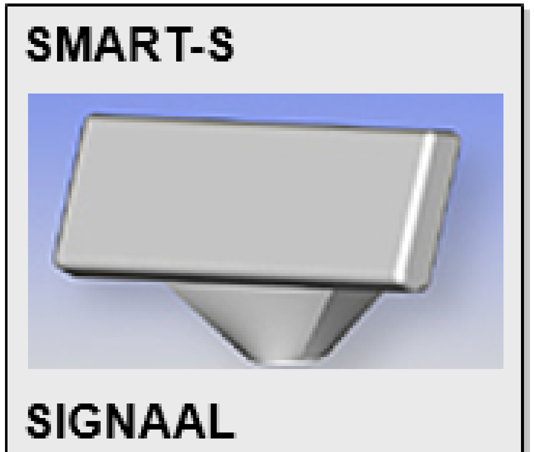
ANALOG MULTIPLE BEAM FORMING

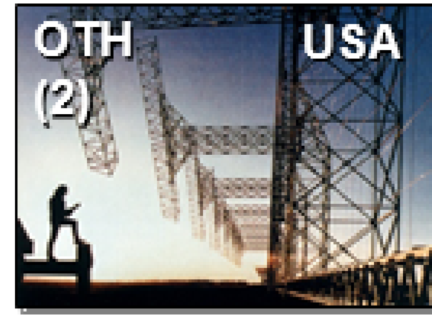


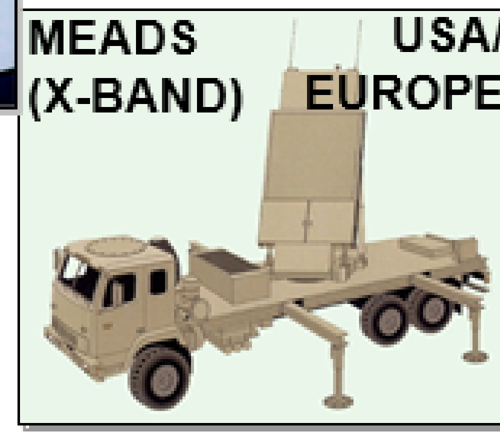
DIGITAL BEAM FORMING

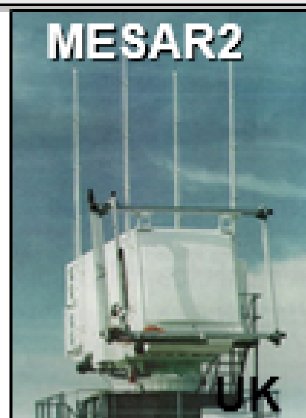


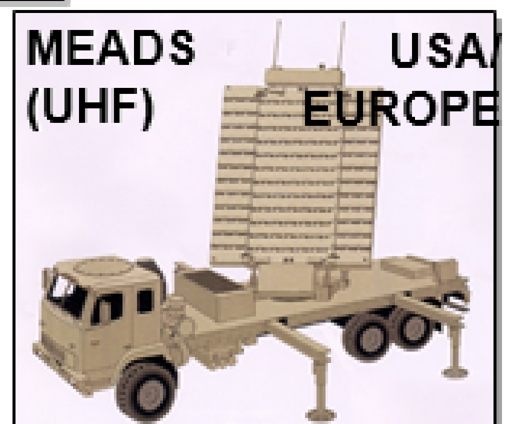
PHASED ARRAYS THAT USE DIGITAL BEAM FORMING











ELTA EL/M-2248

AMSAR

DIGITAL BEAM FORMING AT ELEMENT

ELTA EL/M-2248 MF-STAR (MULTI-FUNCTION SURVEILLANCE, TRACK & GUIDANCE RADAR)

(SEE I. LUPA, IRIS-2007 BANGALORE , INDIA)

AESA, 4-FACES, S-BAND, 2,500-ELEMENTS/FACE DBF WITH A/D PER ELEMENT

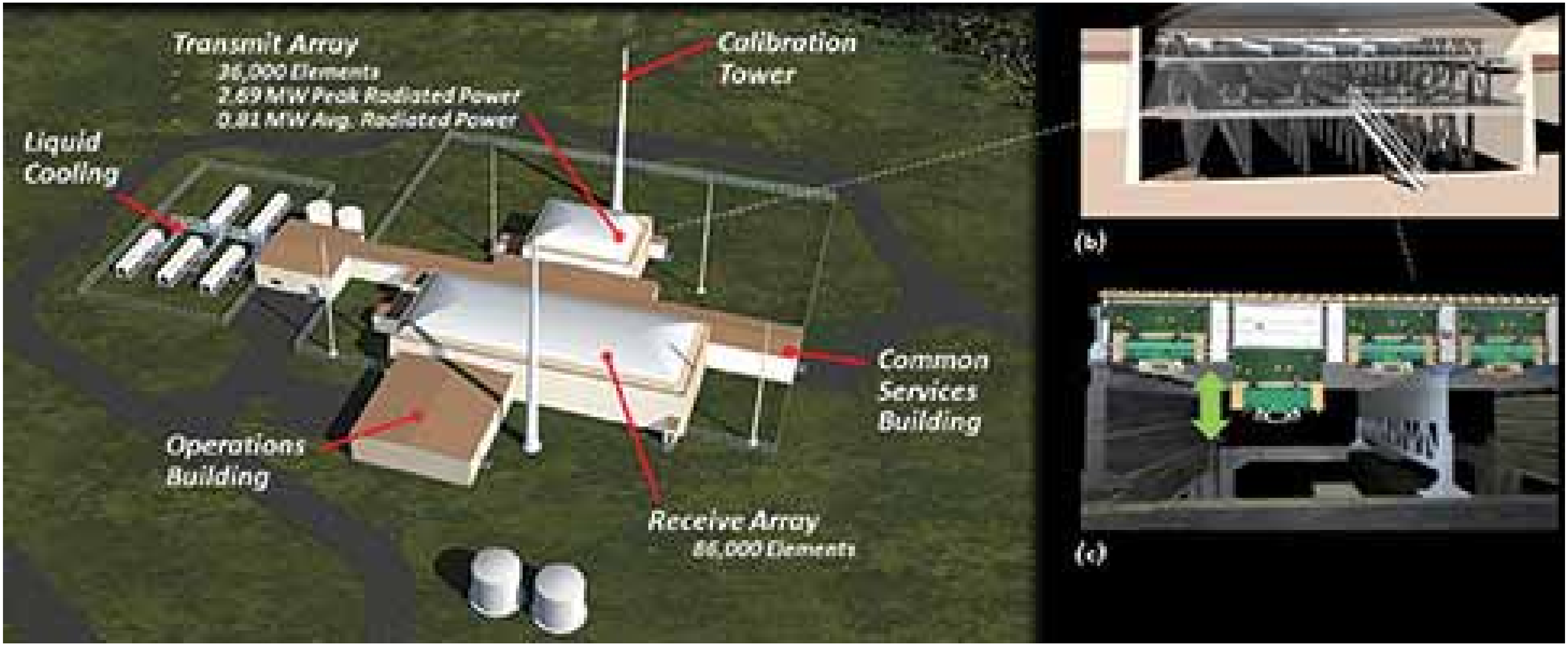
AUSTRLIA CEAFAR S-BAND 6 FACE RADAR AT SEA TRIALS IN 2011

(Courtesy of CEA Technologies Pty. Limited; used with permission.)

THALES NETHERLANDS

HAS 1000 ELEMENT S-BAND ARRAY WITH A/D PER CHANNEL

LM USES DBF AT ELEMENT ON RECEIVE FOR SPACE FENCE RADAR: 172K A/Ds

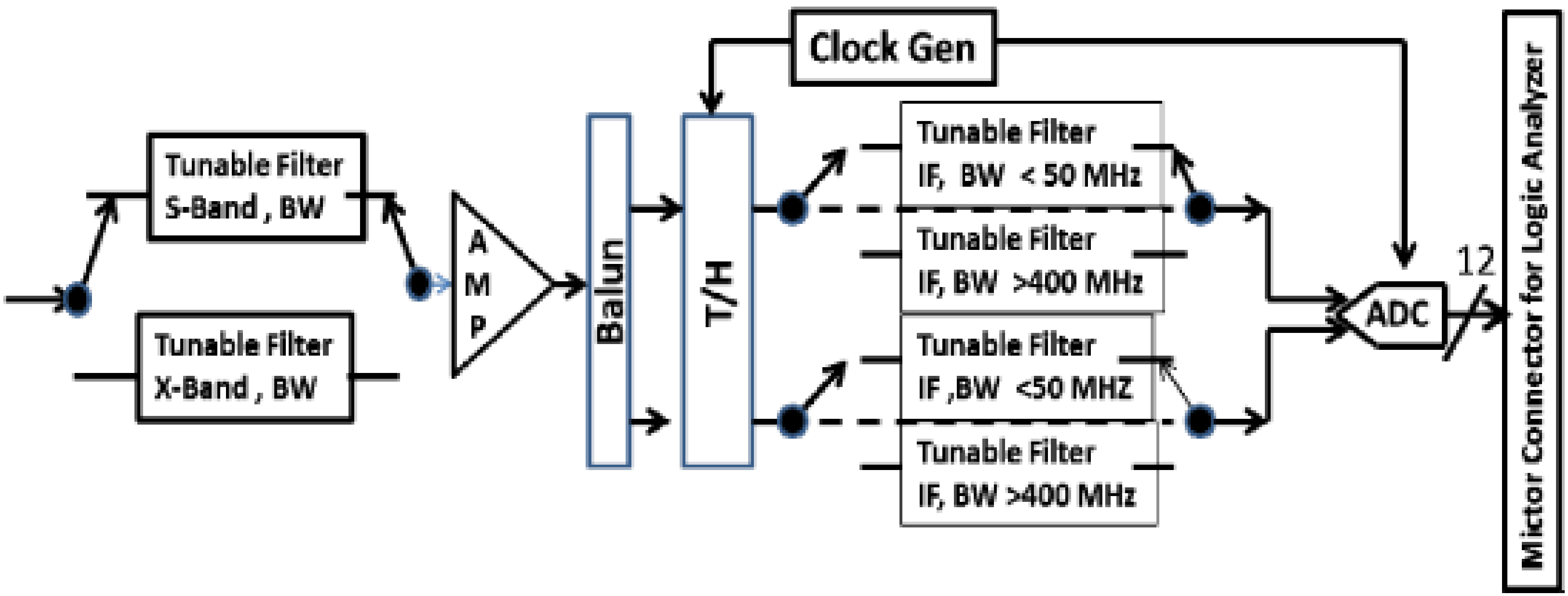


a.) LOCKHEAD MARTIN (LM) SPACE FENCE RADAR SITE, b.) CUTAWAY OF TRANSMIT ARRAY, c.) CROSS-SECTION OF RADAR-ON-A-BOARD TRANSMIT LRUs

(MICROWAVE J. SEPT-2016: HTTP://WWW.MICROWAVEJOURNAL.COM/ARTICLES/26872V)

MIXER-LESS DIRECT RF CONVERSION AT S- & X-BAND: UP TO 400 MHZ BW

Frequency Plan					
RF Input Frequency Band	RF Input Frequency Bandwidth	T/H Clock Frequency (MHz)	IF Bandwidth (MHz)	IF Filter Bandwidth (MHz)	A/D Clock (MHz)
S-Band	> 400 MHz	960/1280/2560	0-480	< 50	960/1280/2560
				> 400	
X-Band		960/1280/2560	0-480	< 50	
				> 400	

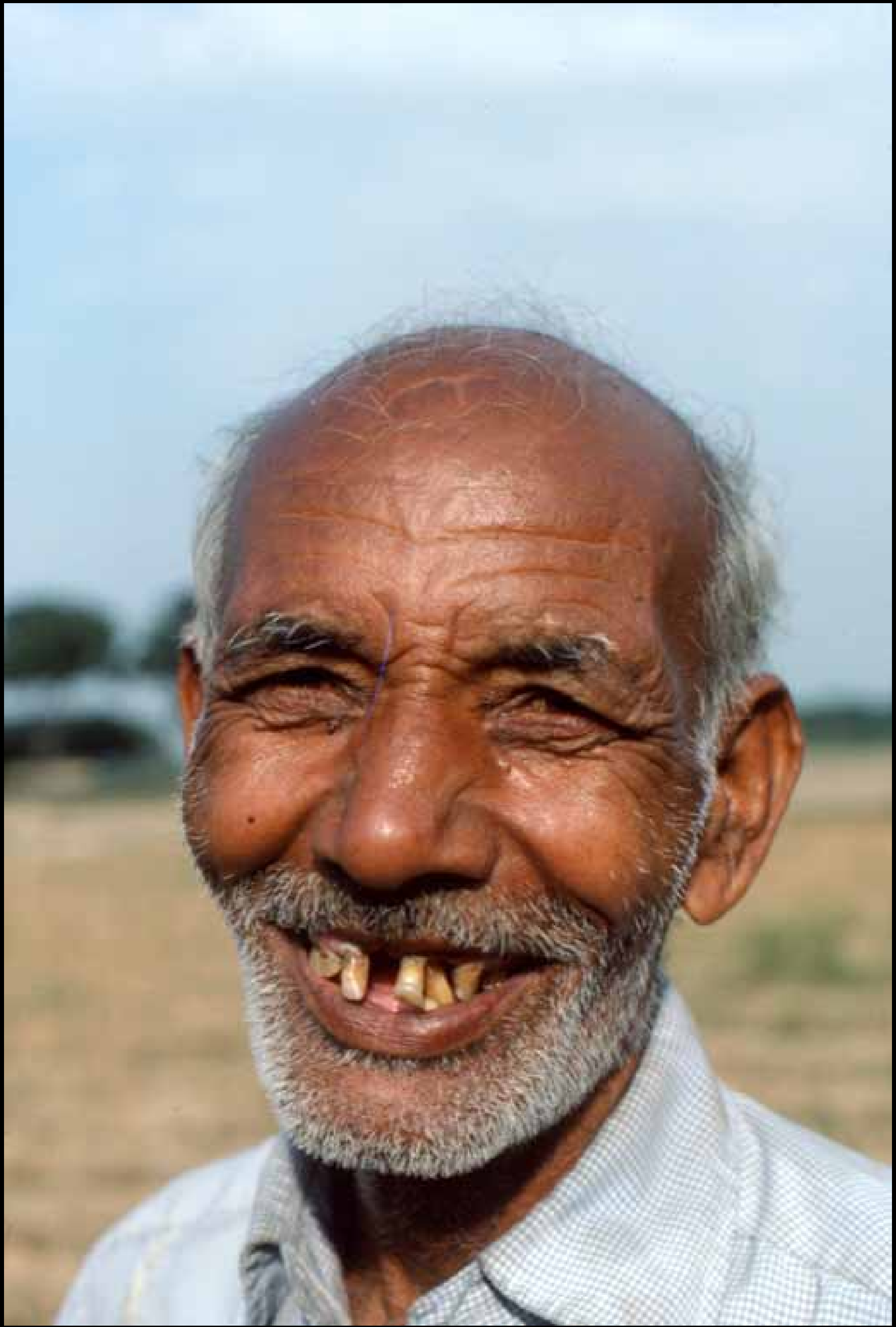


(S. MAZUMBER, D. UPTON, S. KUNASANI, IEEE ARRAY-2014, BOSTON, MA, PP 456-458)

DBF MULTIPLE BEAM SYSTEM

BORNEO ORANGUTAN REHAB FACILITY

MACAQUE
MONKEY
BORNEO
PARK

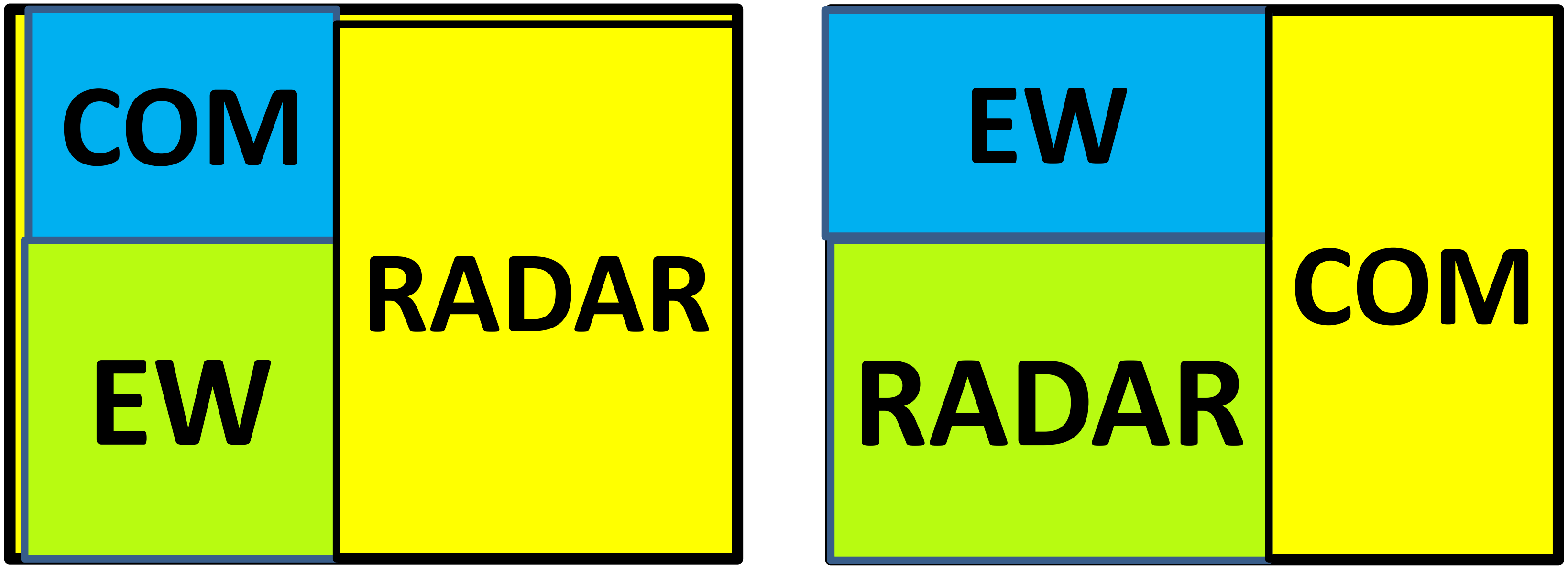


VARANASI
INDIA

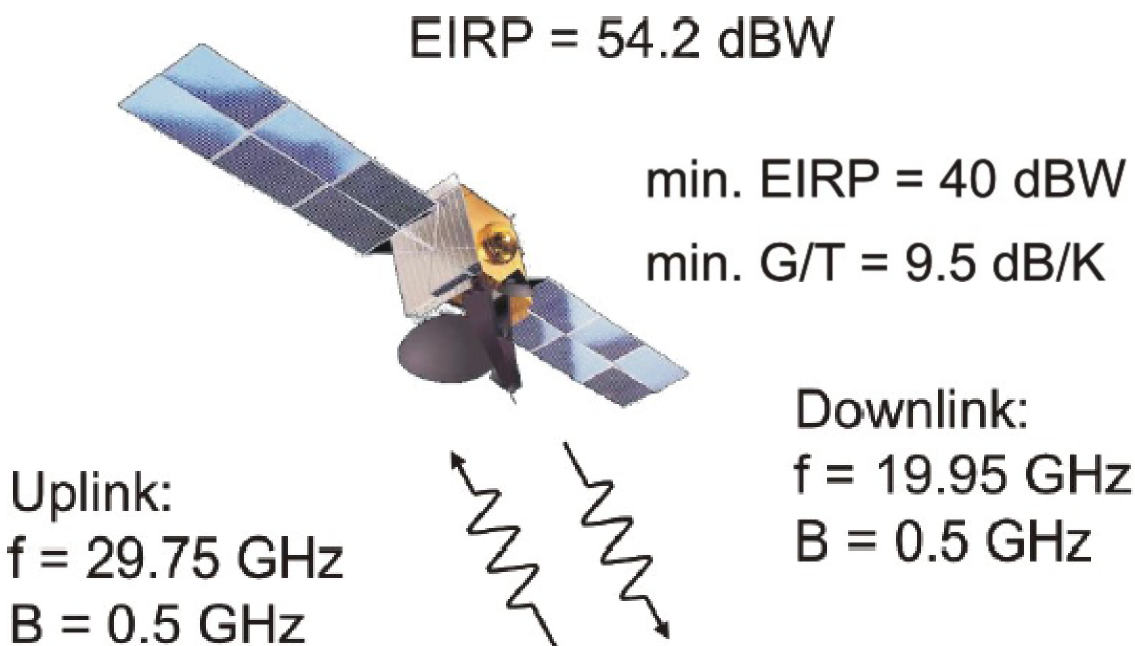
GAMELAN PLAYER AT CREMATION BALI

DBF ALLOWS INDEPENDENT RECONFIGUABLE SUB-APERTURES

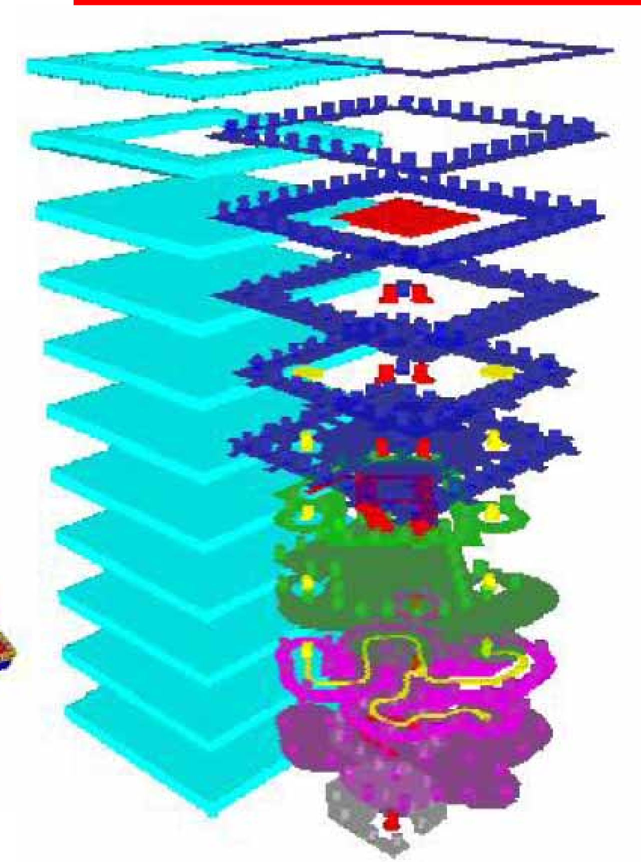
- DIFFERENT PARTS OF THE ARRAY HAVING INDEPENDENT FUNCTIONS THAT ARE RECONFIGURABLE



INTERNET ON THE MOVE –
IN AIRPLANE, RAILROAD TRAIN, CAR



ONE ELEMENT LTCC 11 LAYER STACKUP



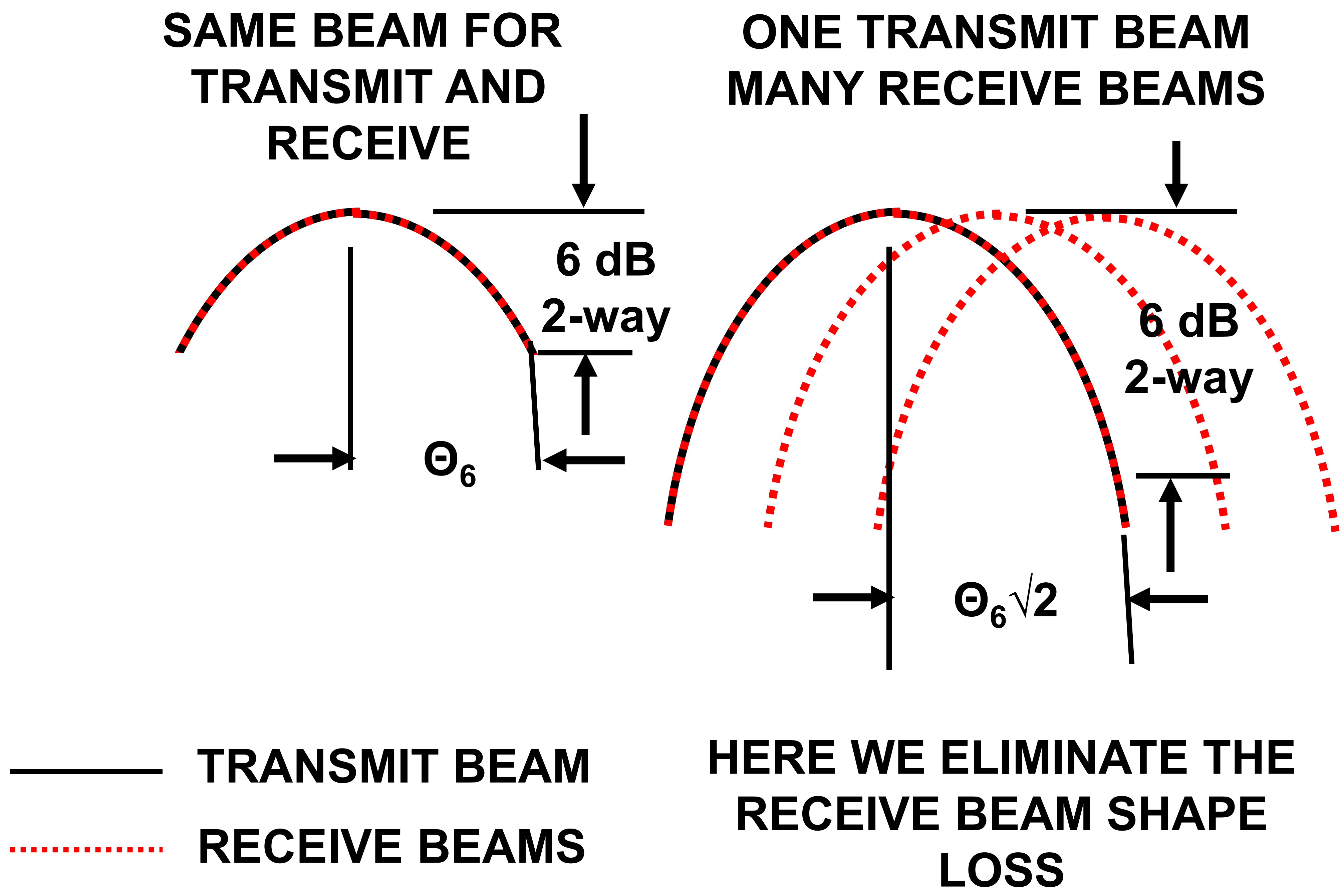
IMST SANTANA AESA USING DIGITAL BEAM FORMING (DBF) AT ELEMENT LEVEL ON TRANS & REC

(COURTESY OF IMST, USED WITH PERMISSION; SEE HOLZWARTH, ET AL, EUCAP-07; &: STARK, ET AL, KA-BAND SANTANA. EUCAP-09)

DBF CAN PROVIDE SEARCH WITH

- ~ 3 DB LESS POWER
- ~ HALF THE OCCUPANCY
- BETTER ANGLE ACCURACY

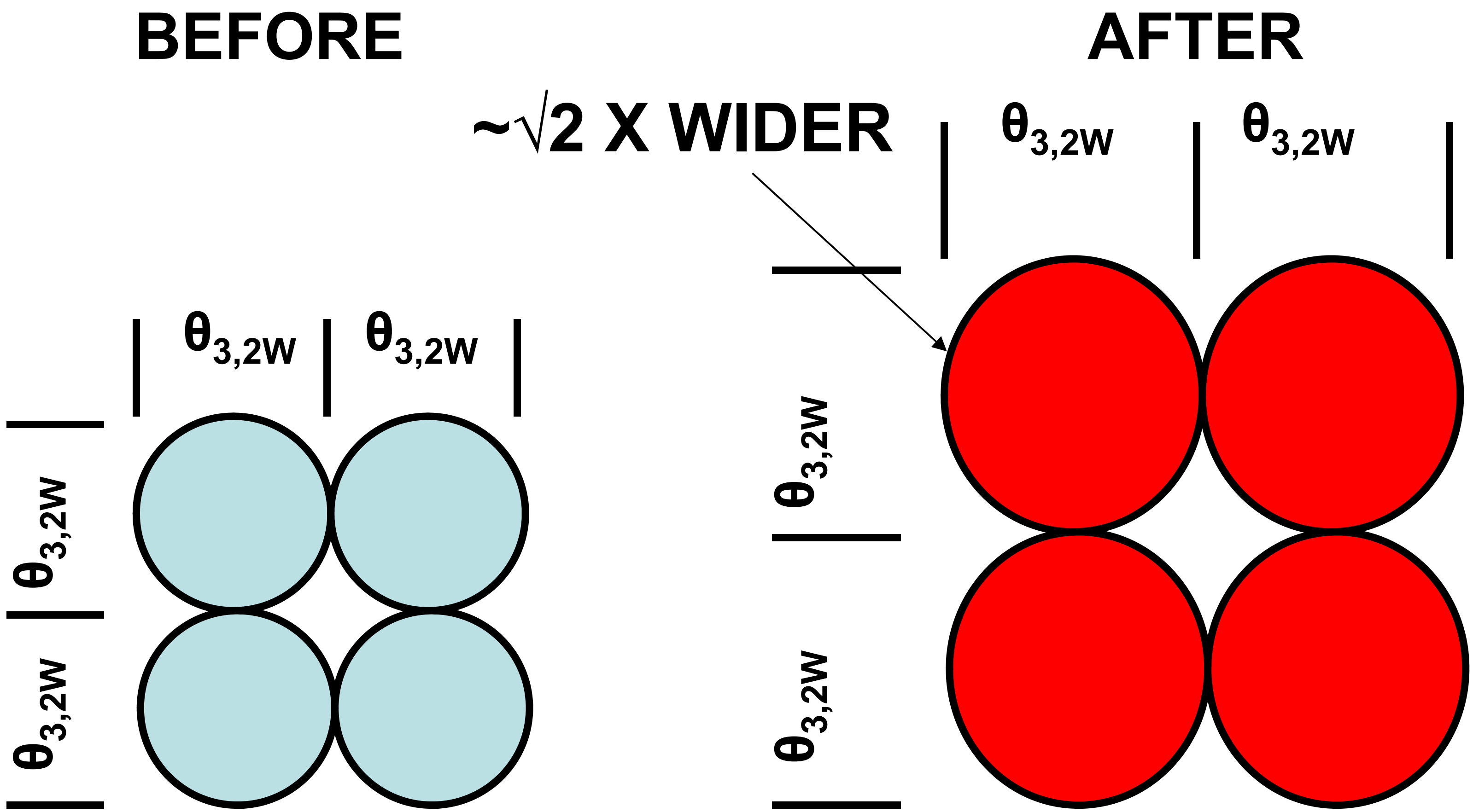
(SEE DAVIS AND FANTE, IEEE AP TRANS., JULY 2001, PP. 1043-53)



SAME BEAM FOR TRANSMIT AND RECEIVE
ONE TRANSMIT BEAM MANY RECEIVE BEAMS
6 dB 2-way
Θ6
6 dB 2-way
Θ6√2
TRANSMIT BEAM
RECEIVE BEAMS
HERE WE ELIMINATE THE RECEIVE BEAM SHAPE LOSS

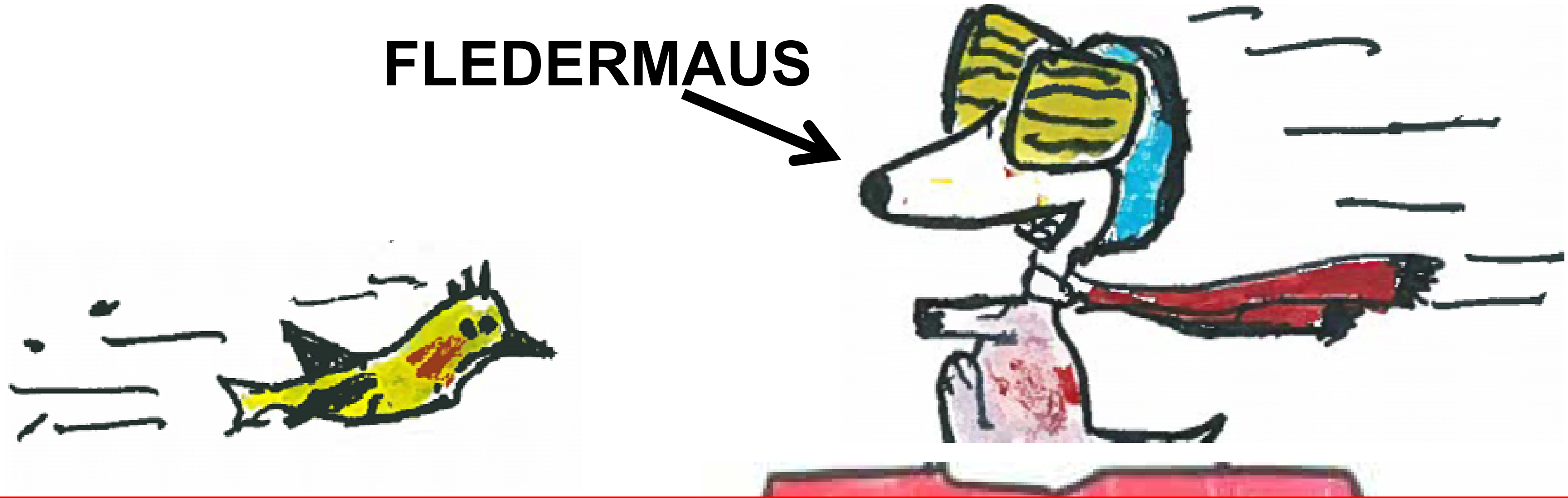
BY REMOVING RECEIVE BEAM SHAPE LOSS* CAN

- ~ HALVE THE NUMBER OF BEAMS TO SEARCH A GIVEN VOLUME OF SPACE
- ~ HALVE THE OCCUPANCY



*DONE USING DBF & MULTIPLE RECEIVE - ONLY BEAMS FOR EACH XTRM BEAM

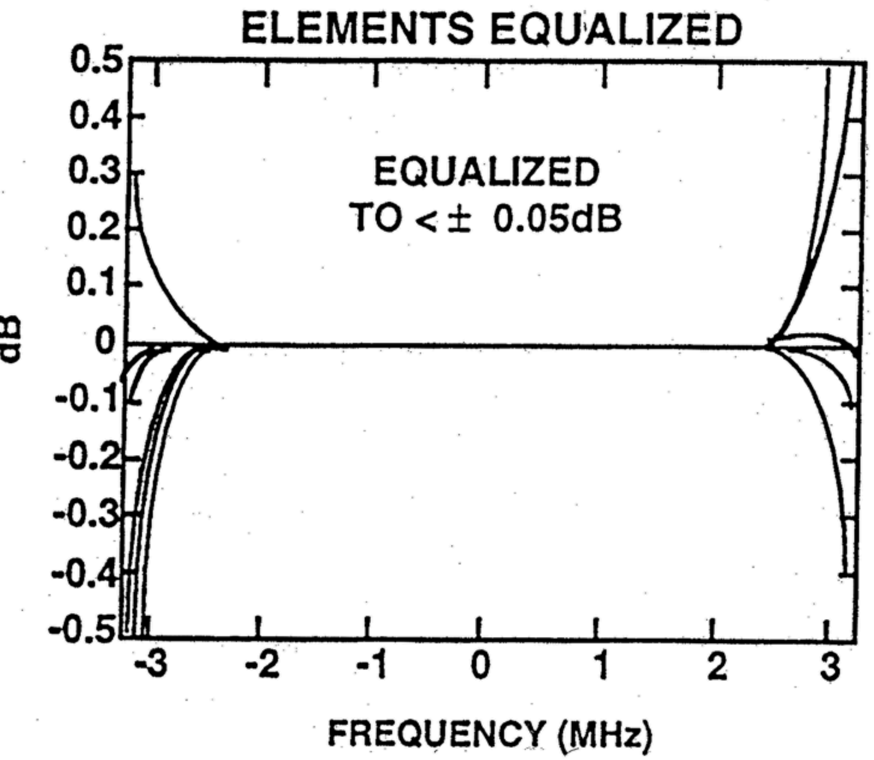
USE ALL INFO AVAILABLE



TO FULLY ADAPT TO SITUATION

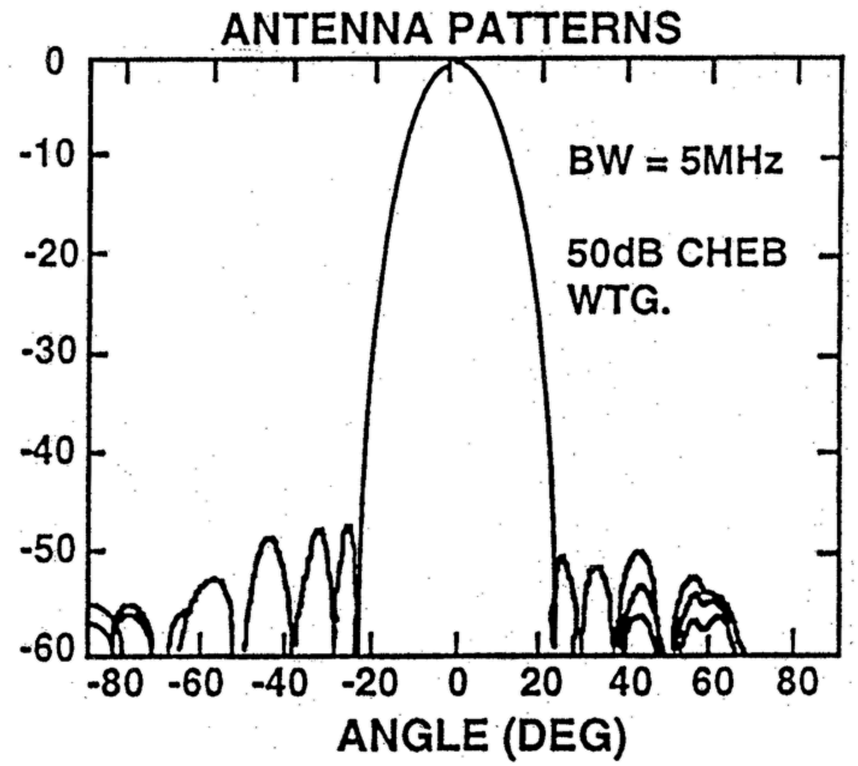
E. BROOKNER, J. HOWELL, RAYTHEON US PATENT 4,720,712

ULTRA-LOW SIDELOBES FOR S-BAND DBF ACTIVE PHASED ARRAY



a.

EQUALIZED ELEMENT PATTERNS FOR SWEDISH EXPERIMENTAL S-BAND ANTENNA



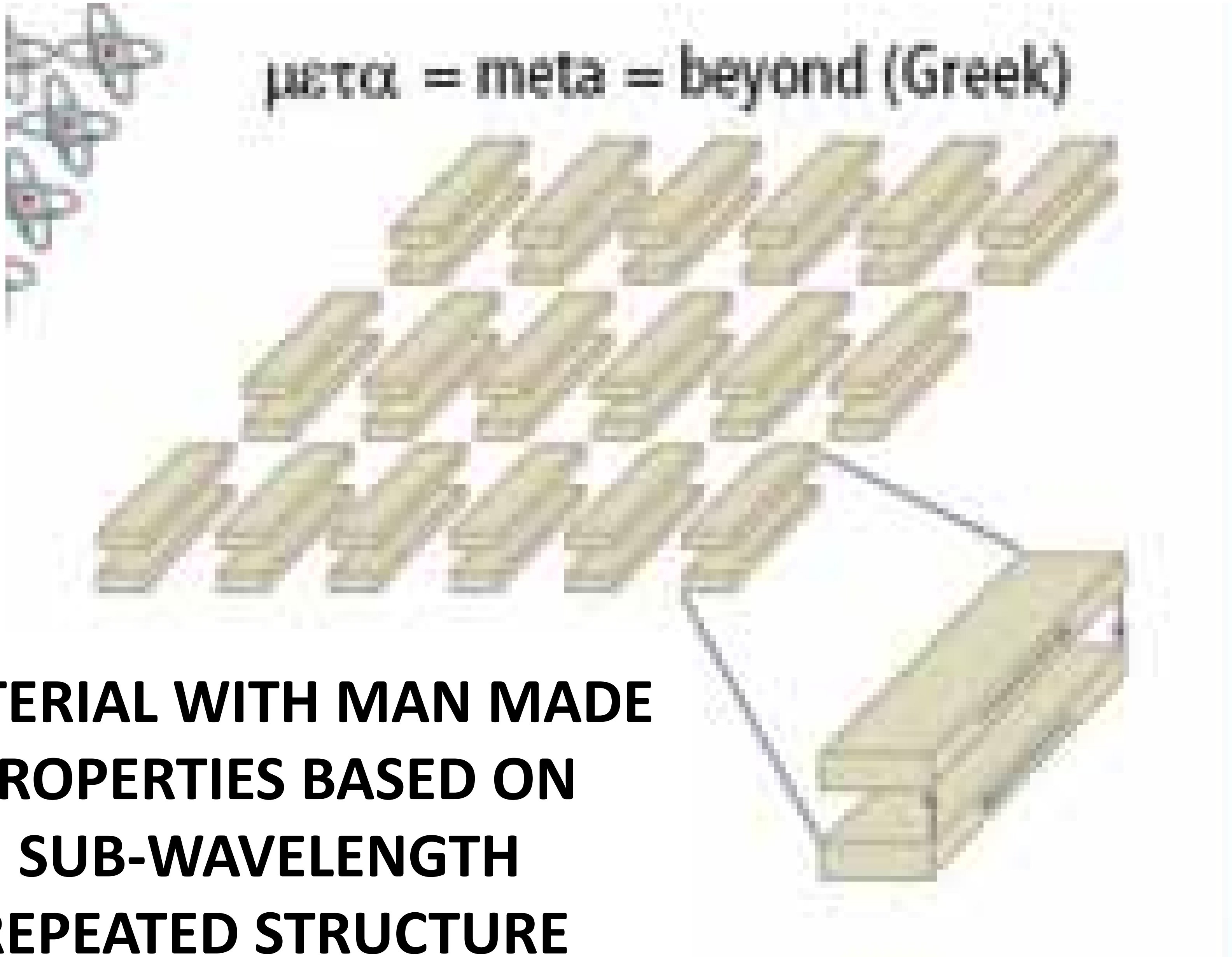
b.

ANTENNA PATTERNS FOR SWEDISH EXPERIMENTAL S-BAND ANTENNA USING DBF

(PETTERSSON, et al, ARRAY-96)

METAMATERIALS

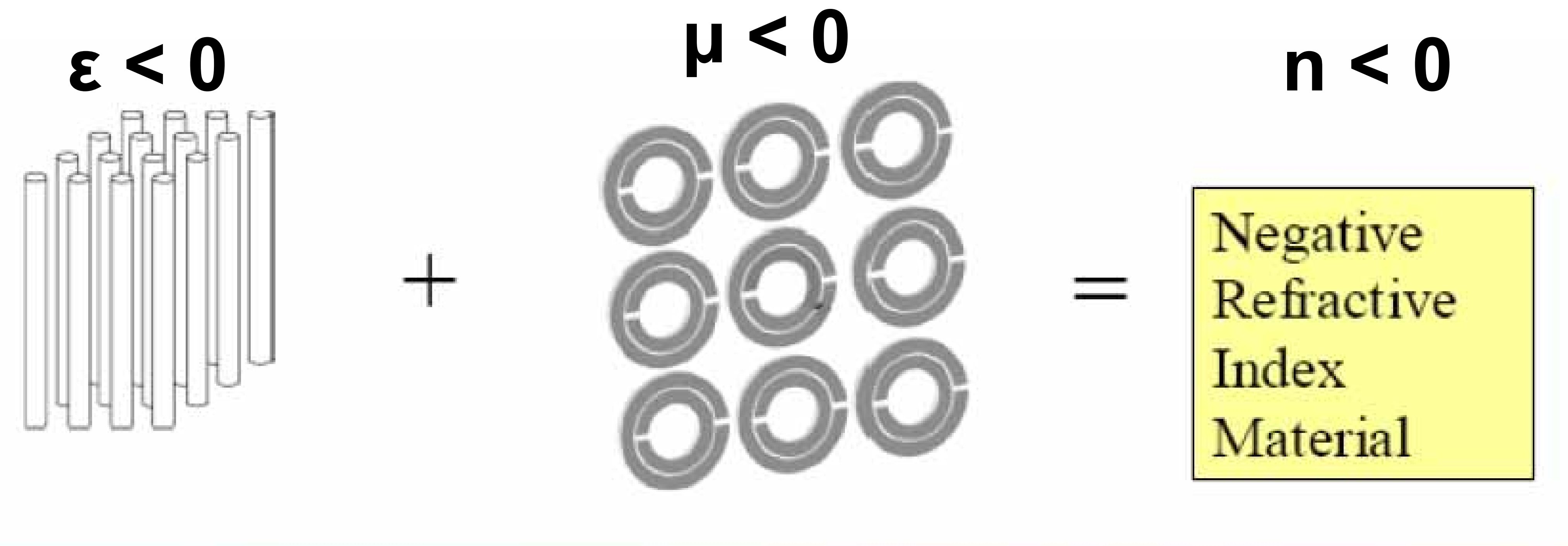
METAMATERIALS



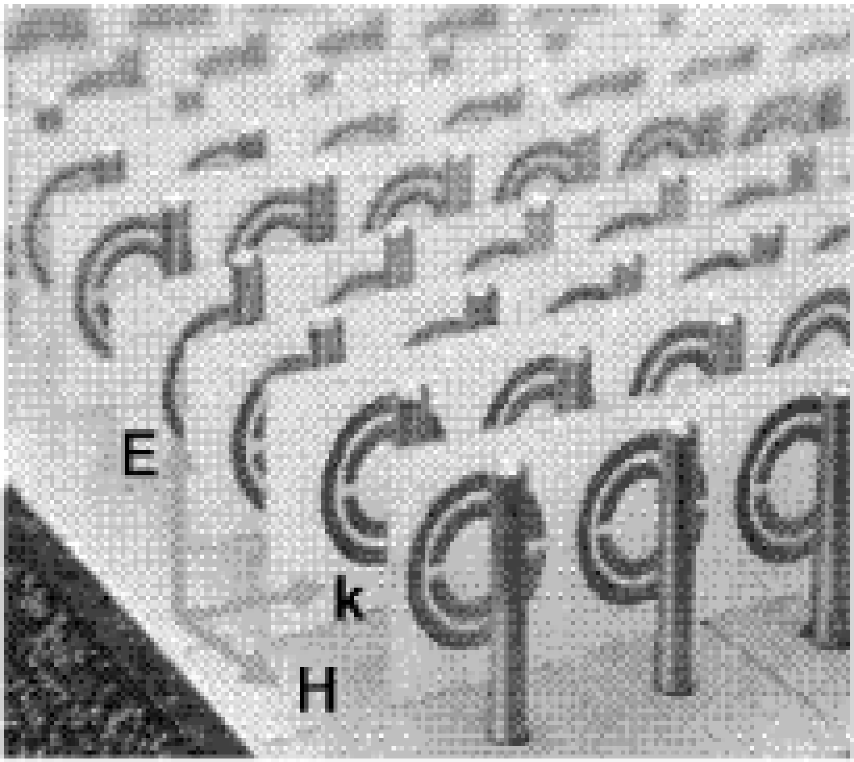
MATERIAL WITH MAN MADE PROPERTIES BASED ON SUB-WAVELENGTH REPEATED STRUCTURE

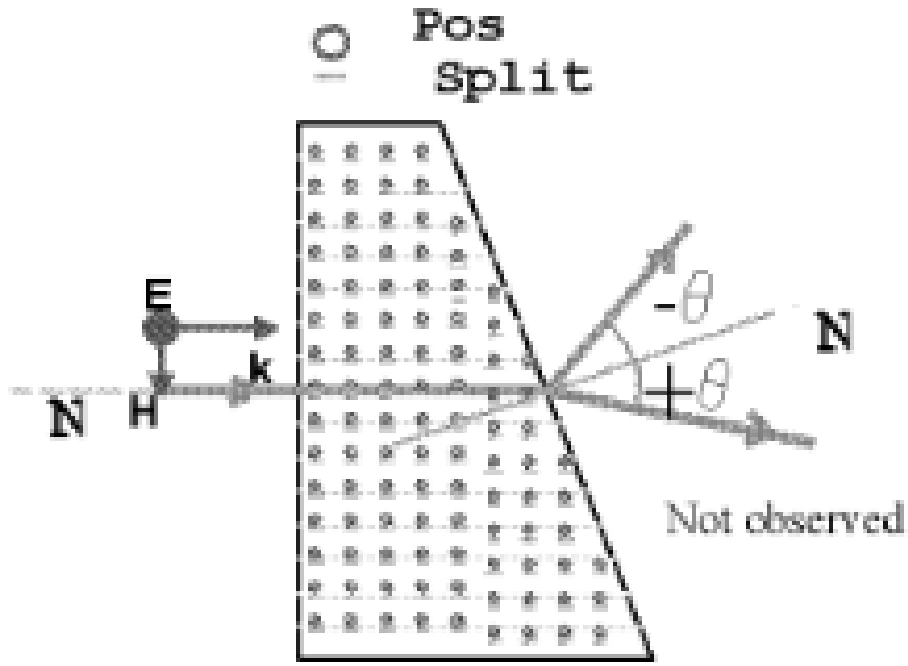
(TECHNOLOGY TODAY, 2012, ISSUE 1)

METAMATERIALS CONSTRUCTION



(Koray Aydin, Bilkent University, Turkey Sep 6 , 2004)





Linearly Polarized TEM Wave

***Figure 12**. photograph of the split-ring-resonator (SRR) and post NIM of the type used by Shelby et al. The incident microwave beam was TEM polarized, as shown (diagram at right) with the E-field parallel to the posts and the M-field threading the rings.*

(DEROV, J.S., ET AL, AFRL, CAMBRIDGE, ALLERTON, 2008)

LOW $ ELECTRONICALLY STEERED METAMATERIAL PASSIVE PHASED ARRAY

GROUPS:

1ST INTELLECTUAL VENTURES

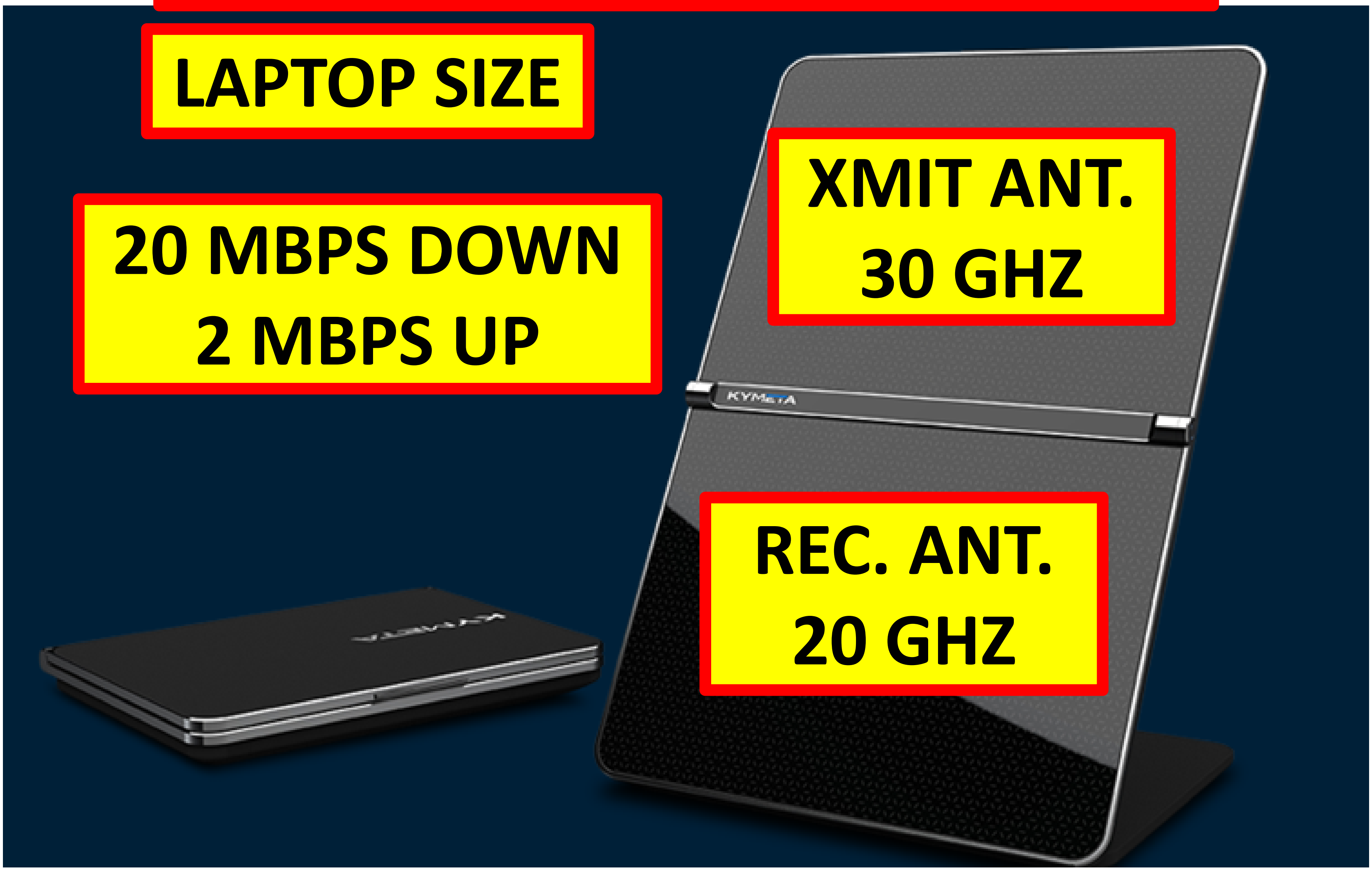
- APPLICATION: INTERNET-ON-THE-MOVE
- USES VOLTAGE CONTROL OF EITHER:
  - FERRO-ELECTRIC MATERIAL
  - MEMS
  - LIQUID CRYSTALS
- **DEMODED JUNE 2011; PRODUCTION: LATE 2014**
- EFFICIENCY AN ISSUE

2ND GROUP: UN. SIENA, ITALY

(K. M. PALMER, METAMATERIAL BREAKTHROUGH, IEEE SPECTRUM, 1/12, PP 13.14)

KYMETA MSA*-T; DEMO'D

GOAL- $1,000 PER ARRAY

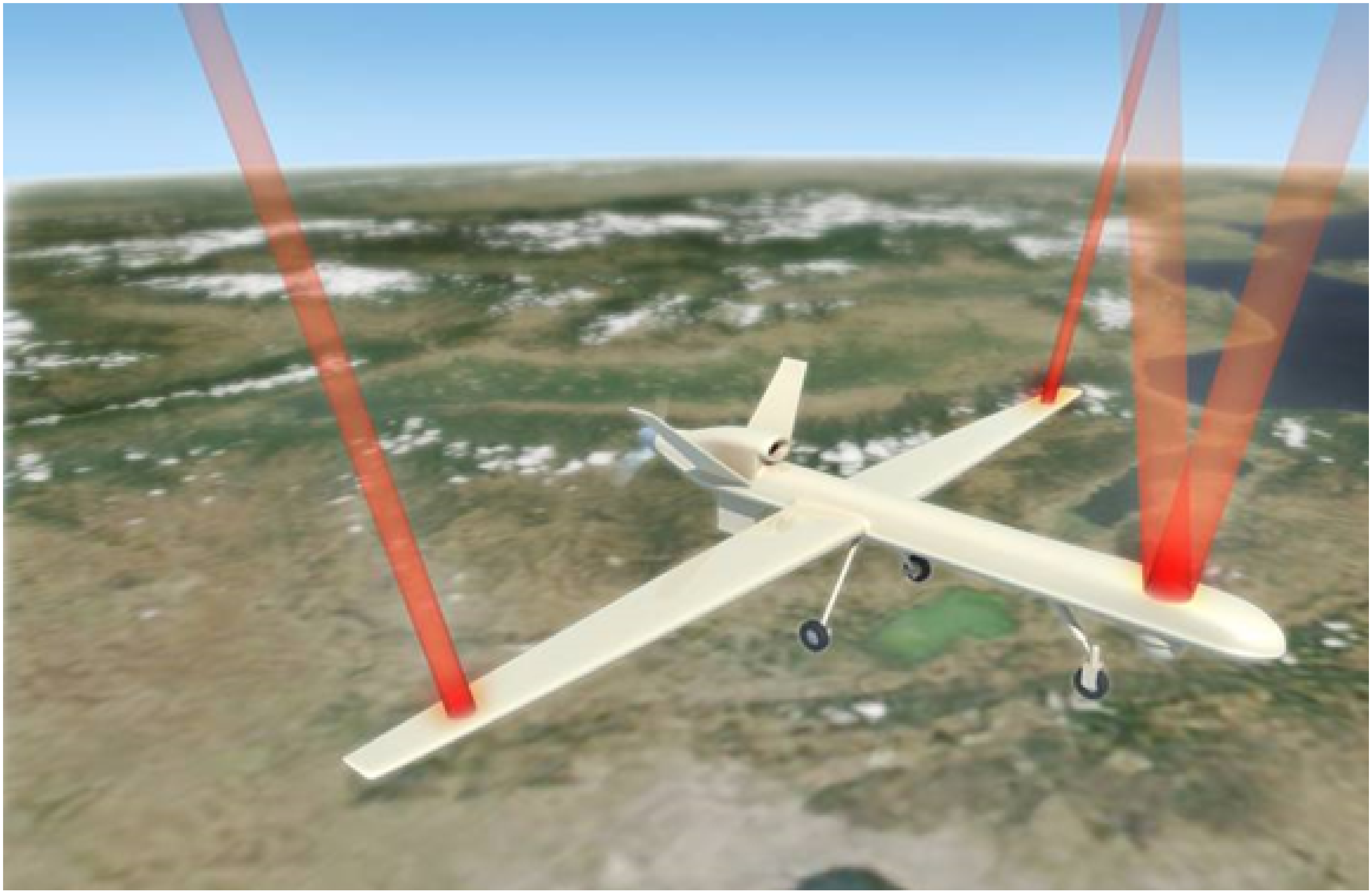


*METAMATERIAL SURFACE ANTENNA TECHNOLOGY

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

INTELECTUAL VENTURES

MSA-T *



*METAMATERIAL SURFACE ANTENNA TECHNOLOGY

METAMATERIAL SURFACE ANTENNA TECHNOLOGY (MSA-T)

- Ka BAND
- LAPTOP SIZE, LOW-COST, 1-3 KGM
- INSTANTANEOUS BW = 100 MHZ (HIGH DATA RATE)
- OPERATING BW = 1 GHZ
- 1-4 W RF
- ELECTRONIC SCAN = ± 65° (NO PHASE SHIFTERS)
- POLARIZATION: CIRCULAR, RIGHT OR LEFT
- APPLICATIONS: SATELLITE TO: A/C, RAIL, CAR, HOME
- COMPANIES: **INTELLECTUAL VENTURES & KYMETA**
- **COMMERCIAL DEVELOPMENT BY 2015**

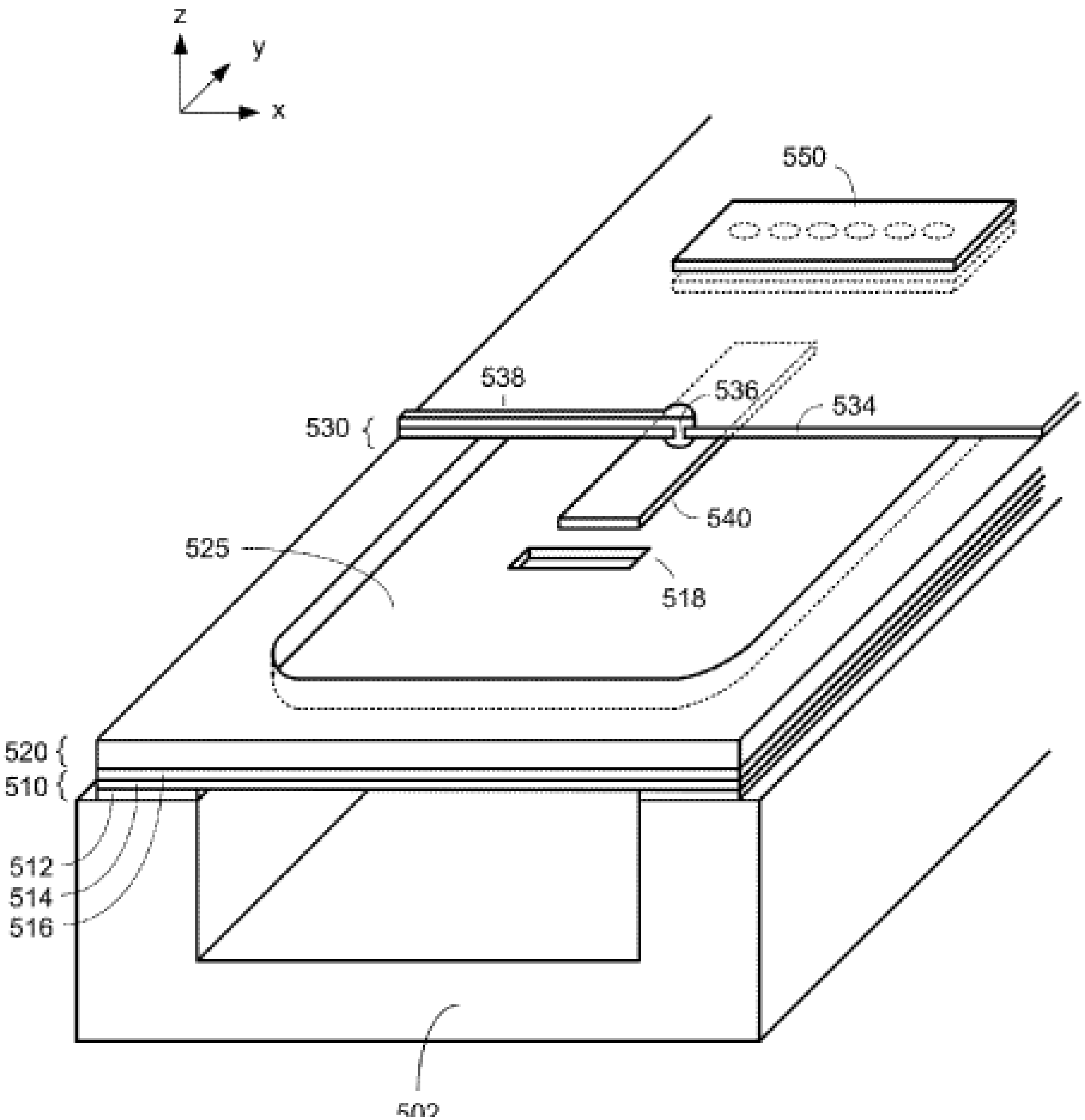
(http://www.intellectualventures.com/index.php/inventions-patents/our-inventions/msa-t; click on: download fact sheet)

MSA-T PARAMETERS

Technical Specifications

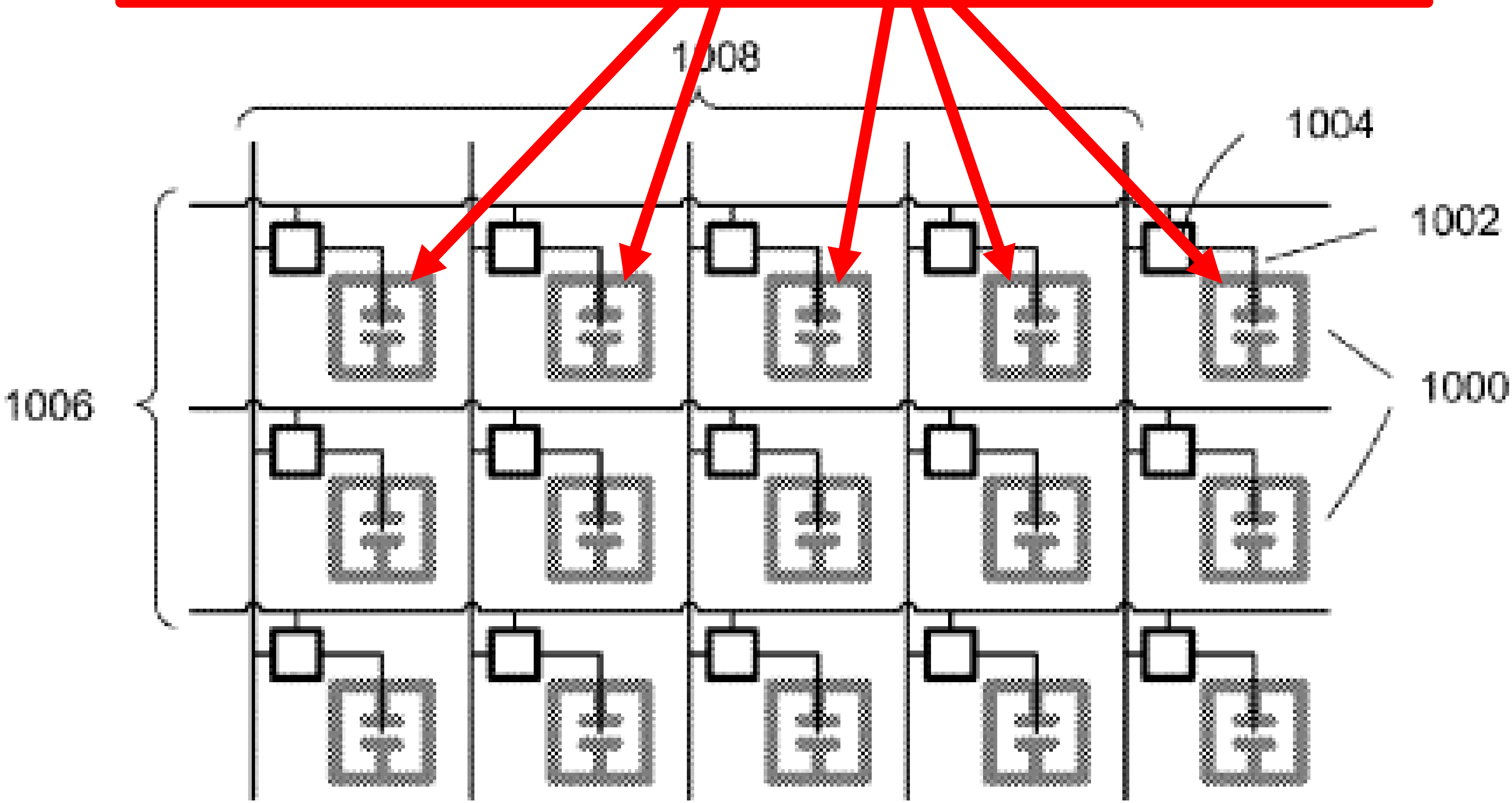
Parameter	Preliminary specifications
Single panel dimensions	Transmit: 30 x 30 x 2-3 cm Receive: 30-50 x 30-50 x 2-3 cm Panels can be tiled for required performance
Mass	1-3 kg Excludes modem, power handling, interfaces etc.
Packaging efficiency	90% Aperture area divided by the package footprint.
Total bandwidth	1 GHz @ Ka-band
Instantaneous bandwidth	100 MHz
Radiation efficiency	50% (3dB)
Polarization	Circular, left-handed or right-handed User selectable.
EIRP	37.5 dBW for 1 W RF 43.5 dBW for 4 W RF
G/T	8.3 dB/K for a 30 cm receive panel 12.7 dB/K for a 50 cm receive panel
Scan range	+/-65 deg from broadside, all azimuth
Beam steering rate	30 deg/sec, elevation and azimuth Expected to meet FCC pointing requirements.
Operating temp range	-54 to 85 deg C

ANTENNA LEAKY WAVE FEED



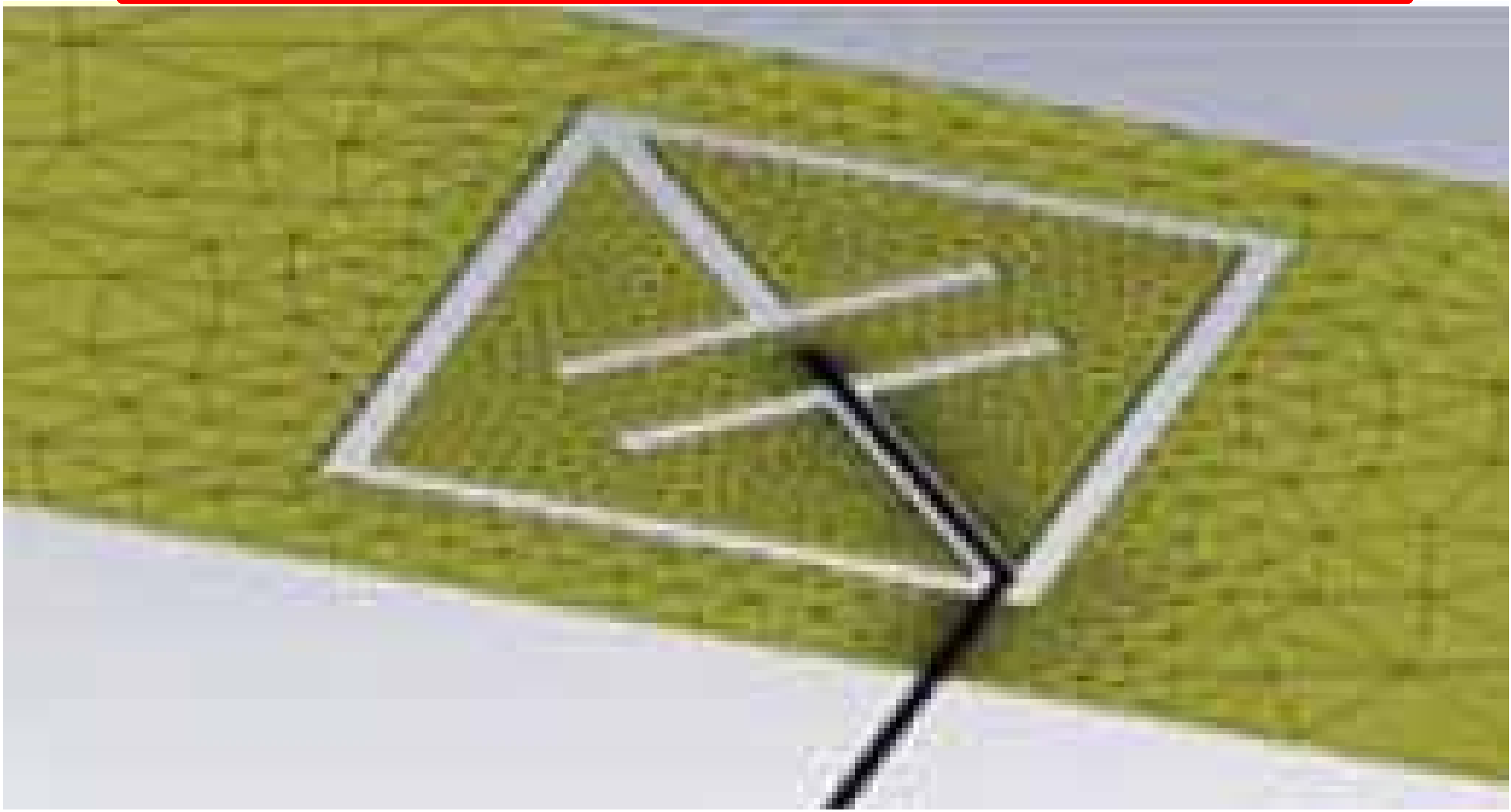
(US PATENT 2014/0266946 A1, SEPT. 8, 2014)

ANTENNA METAMATERIAL RESONATORS

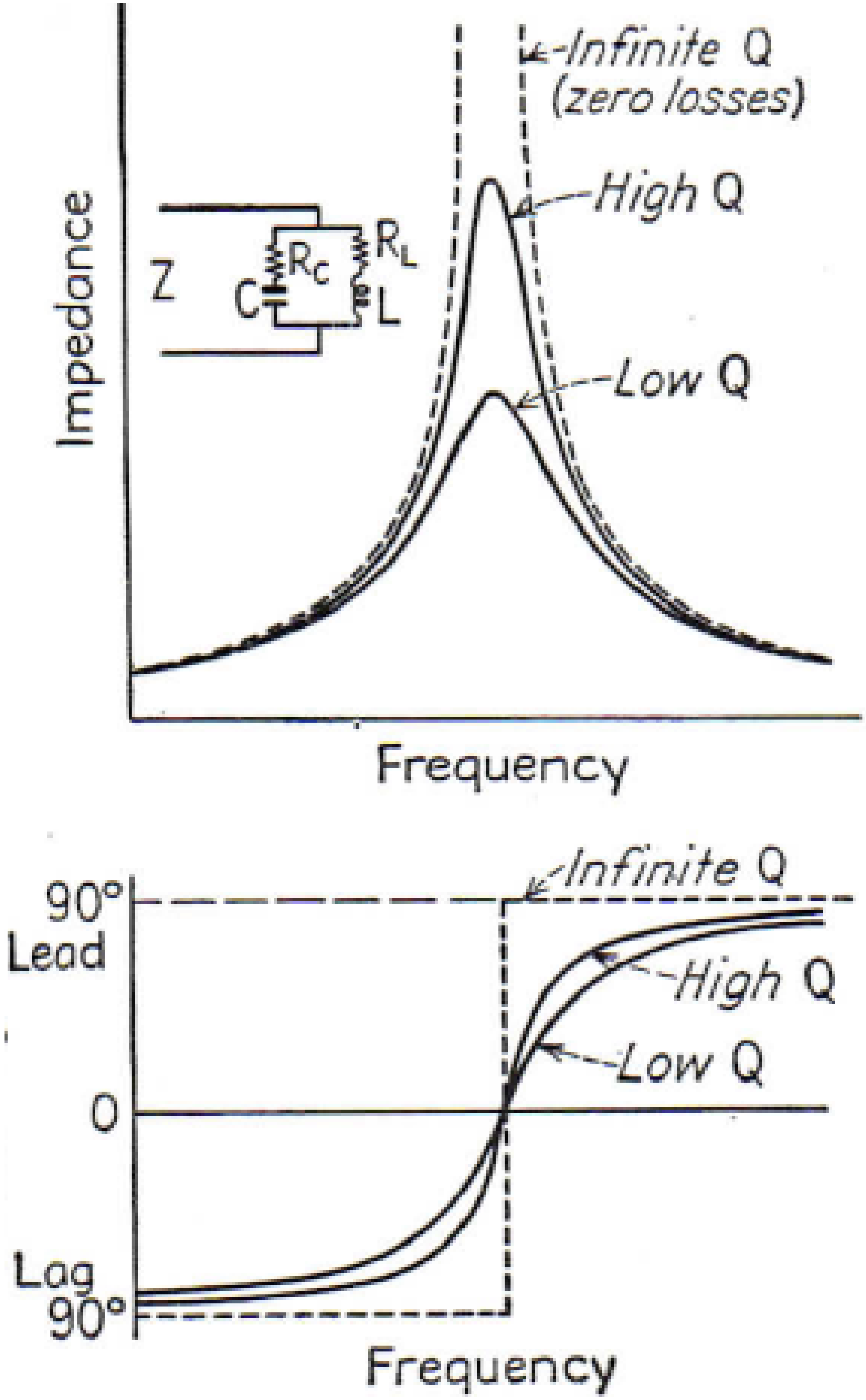


(US PATENT 2014/0266946 A1, SEPT. 8, 2014)

METAMATERIAL RESONATOR PHASE SHIFTER



NATHAN KUNDTZ, MJ, AUGUST, 2014



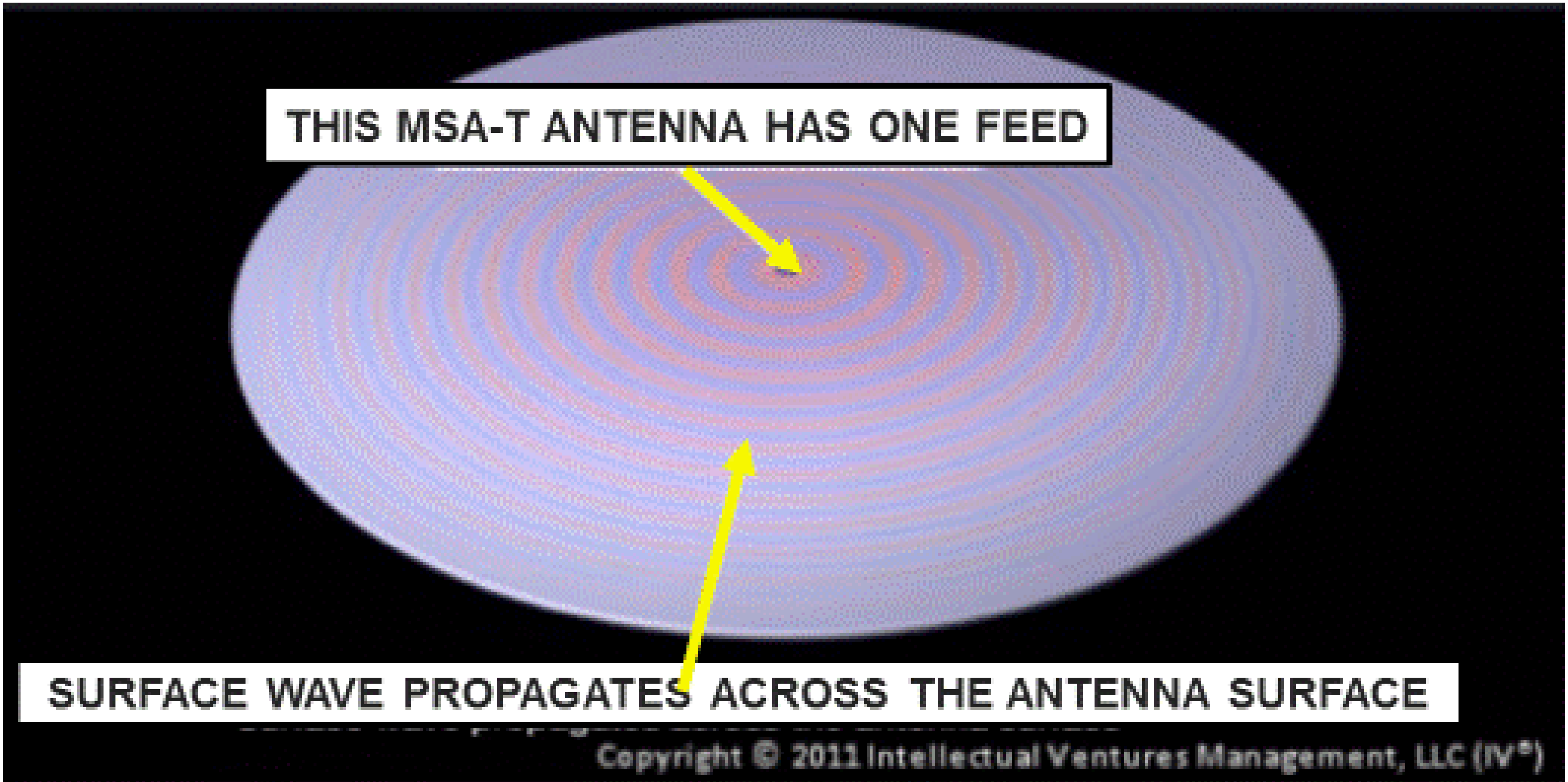
PARALLEL L/C MAGNITUDE & PHASE

(F. TERMAN, RADIO ENGINEERING, MCGRAW HILL, 1947)

CLOSE UP OF KYMETA ANTENNA

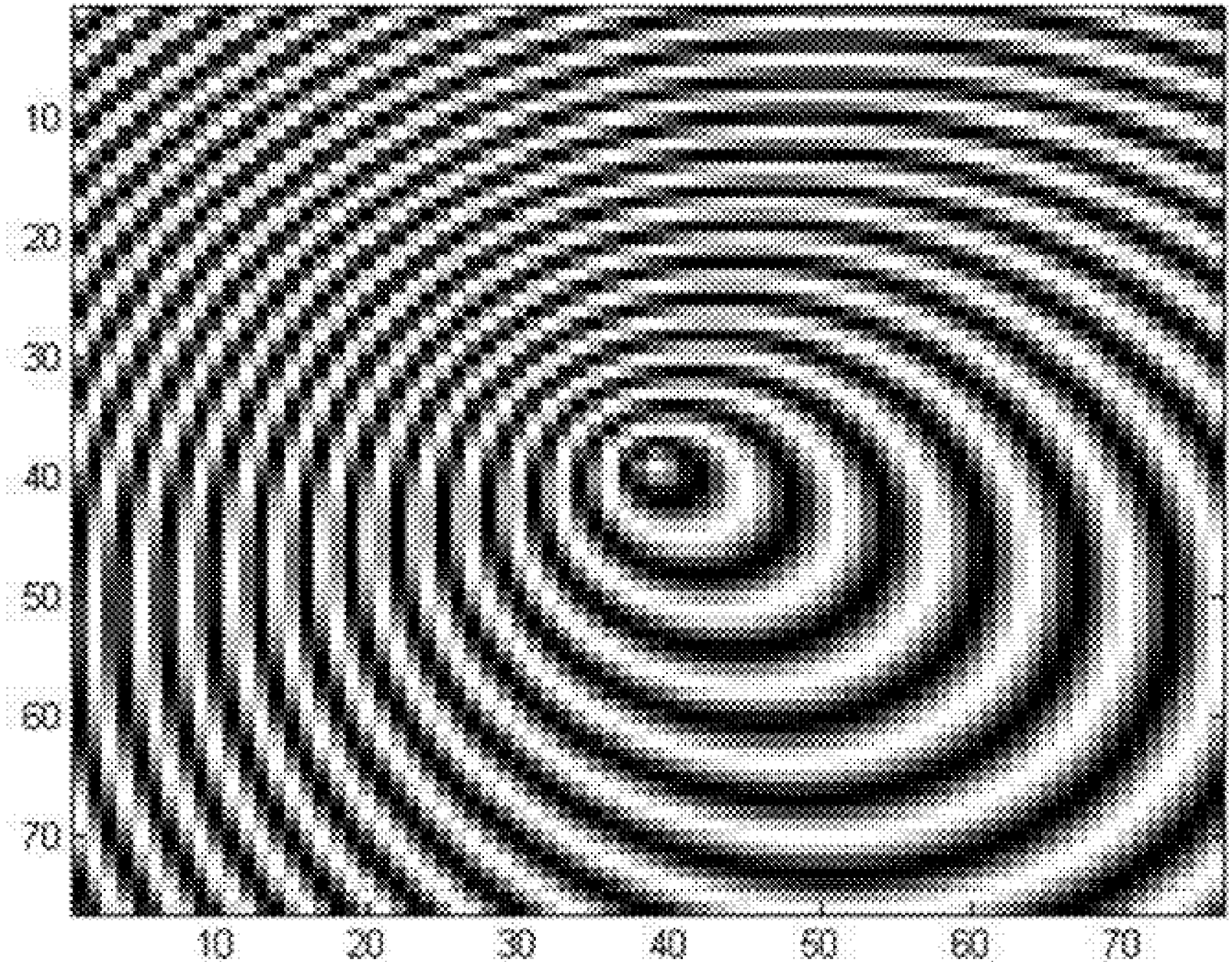
(http://www.kymetacorp.com/technology/product-stack/)

CENTER FED CIRCULAR ARRAY ARCHITECTURE



(FROM INTELLECTUAL VENTURES WEB SITE)

ANTENNA PATTERN FOR SINGLE BEAM



(US PATENT 2014/0266946 A1, SEPT. 8, 2014)

O3b & Kymeta Agree to Develop Flat Panel Antenna

(http://www.kymetacorp.com/technology/product-stack/)

GOOGLE INVESTING $1B IN $10B INTERNET SATELLITE SYSTEM

TELEDESIC SYSTEM

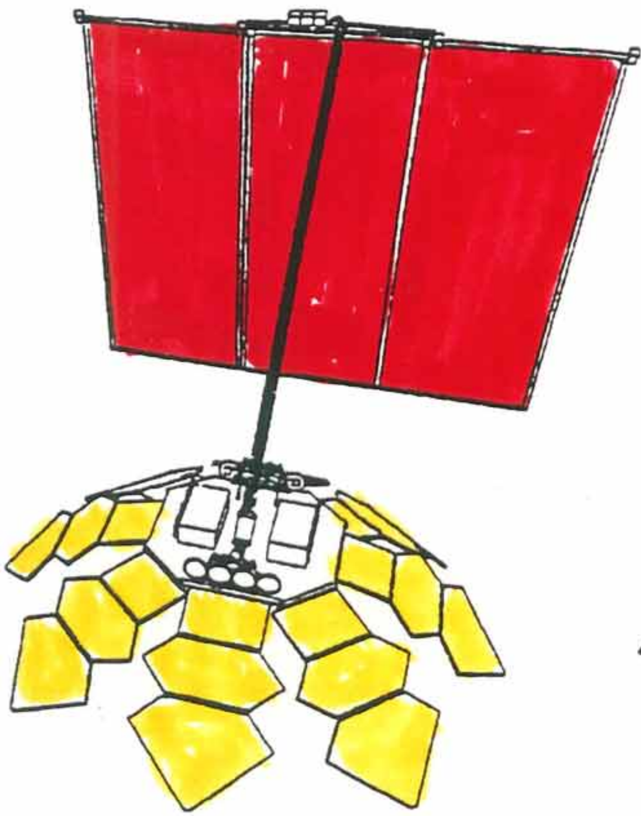
120 ARRAYS/SATELLITE

X ~400 ELEMENTS & MMIC MODULES/ARRAY

48000 ELEMENTS & MMIC
LES/SATELLITE

TES/CONSTELLATION

~40,000,000 ELEMENTS & MMIC MODULES/CONSTELLATION



TELEDESIC SATELLITE

SEED MONEY FROM: W. GATES & C. McCAW

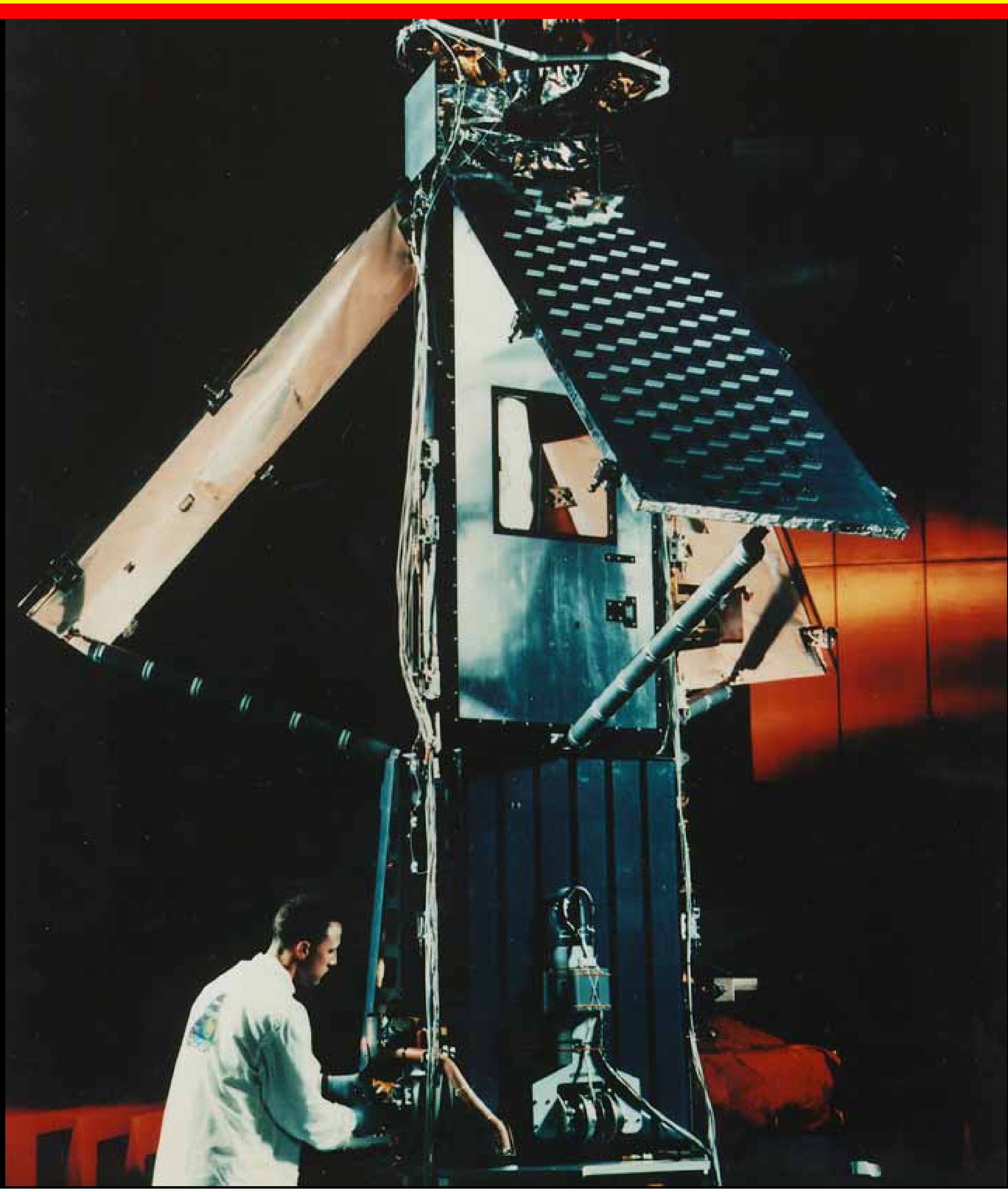
AIRBUS ZEPHYR 7 DRONES (PSEUDO-SATELLITES)

FLY AT 65,000 FT, 14 DAYS WITHOUT REFUELING, 44 LB PAYLOAD, 108 FT WINGSPAN

- SMALLER VERSION IN PRODUCTION ALREADY
- GOOGLE, NASA, FACEBOOK ALSO PERSUING USE OF DRONES

https://www.wired.com/2016/06/airbus-new-drones-actually-high-flying-pseudo-satellites/

IRIDIUM 66 SATELLITE TELEPHONE SYSTEM



(IEEE AESS Magazine)

IRIDUM Phone

AN ARRAY ANTENNA THAT HAS IT ALL — ACTIVE, MMIC, MULTIBEAMS, MICROSTRIP-PATCH ELEMENTS, SPACEBORNE, COMMERCIAL, LARGE PRODUCTION

IRIDIUM®: THREE L-BAND MMIC ARRAY PANELS DEPLOYED ON BUS

- REVOLUTIONARY COMMERCIAL GLOBAL SATELLITE PERSONAL COMMUNICATION SYSTEM
- NO. T/Rs: >100/ANT.
- NO. ANT. /SAT.: 3
- NO. SATS.: 66
- TOTAL NO. T/Rs/ CONST. : >19,800
- NO. BEAMS/ANT.: 16

PHOTO COURTESY OF RAYTHEON

ECHODYNE RADARS USING METAMATERIAL ARRAYS

MESA-D-DEV K-BAND RADAR:

MESA-DAA K-BAND RADAR:

ECHODYNE WEB PAGE)

MESA-D-DEV K-BAND RADAR

- WIDE FIELD OF VIEW – ±60° in azimuth and ±40° in elevation
- Beam switching speed <1 microsecond
- RANGE – +0dBSm objects at >500 m
- SIZE – 22 x 7.5 x 2.5 cm including packaging
- WEIGHT – 820 grams including packaging
- FREQUENCY – K-band
- POLARIZATION – horizontal
- PLUG AND PLAY – no calibration required
- SINGLE DC POWER SUPPLY – +7 to +28V DC
- SIMPLE CONTROL INTERFACE – USB Type C
- RADAR MODES – short and long range FMCW

(ECHODYNE WEB PAGE)

Table 2;

MESA-DAA K-BAND RADAR (Tentative Specs)

- **APPLICATION: Airborne Detect and Avoid (DAA) for small UAS***
- **RANGE: >3KM**
- **FIELD OF VIEW (FOV): ±60° in azimuth (120° total) and ±40° in elevation.**
  Multiple units combined for greater field of view.
- **SCANNING SPEED: 1Hz for FOV; To 10Hz for updating locations of previously detected objects.**

*** Unmanned Aircraft Systems**

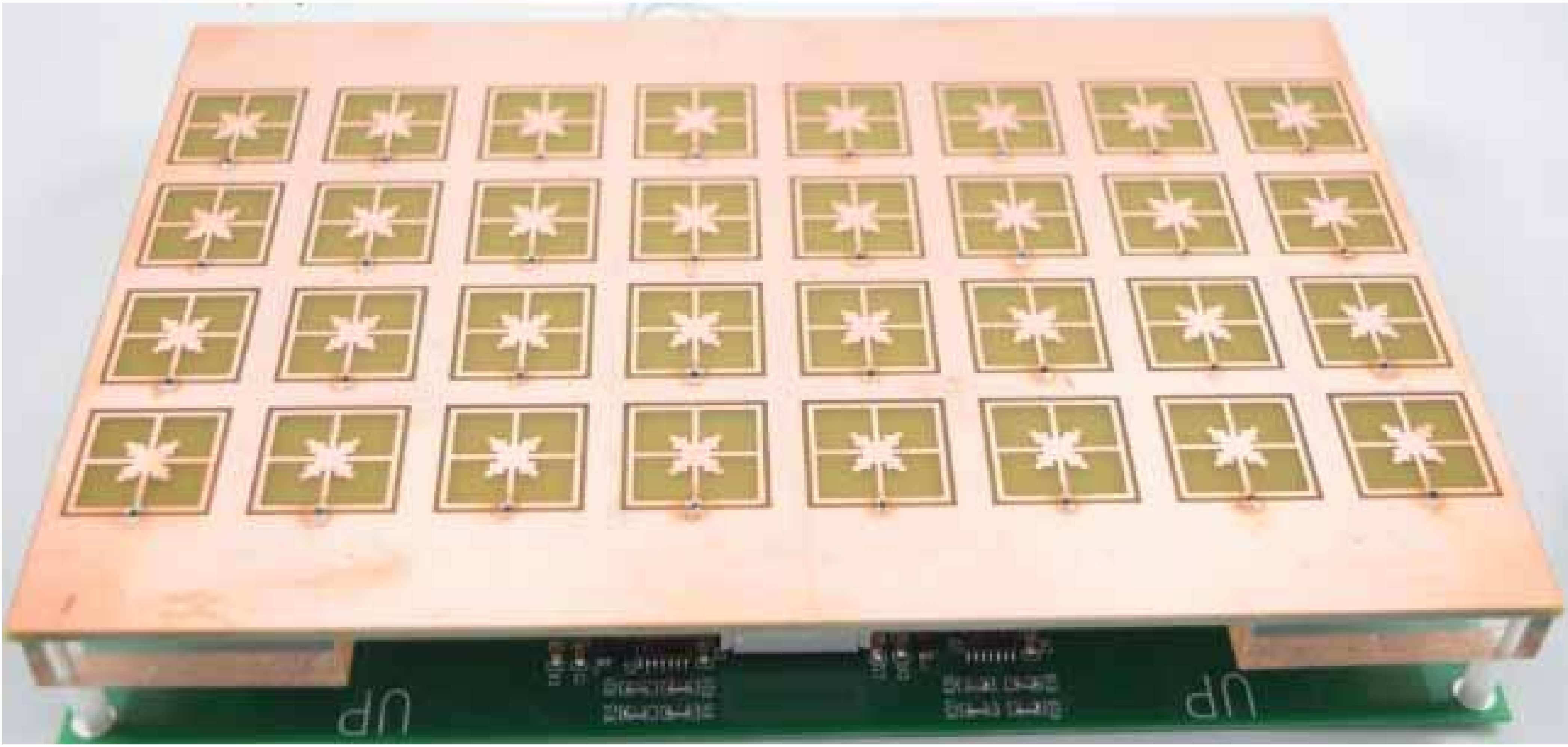
(ECHODYNE WEB PAGE)

MESA-X-EUV X-BAND PASSIVE ARRAY:

- FIELD OF VIEW – ±50° in azimuth and ±45° in elevation
- Beam Switching Speed: <1 microsecond
- SIZE – 2.5 cm (1 in) thick (excl. packaging)
- WEIGHT – <1.4 kg (3.1 lb) (excl. packaging)
- BROADSIDE GAIN – 19 dBi at 10.15 GHz
- POLARIZATION – horizontal
- PLUG AND PLAY – no calibration required
- SINGLE DC POWER SUPPLY – 12V DC
- INTERFACE – serial USB 2.0
- RF IN / RF OUT – SMA coax port to user transceiver
- PULSED AND CW COMPATIBLE

(ECHODYNE WEB PAGE)

PARC* METAMATERIAL CAR ARRAY



HTTP://BLOGS.PARC.COM/2015/10/SELF-DRIVING-CARS-NEED-BETTER-DIGITAL-EYES-TO-DETECT-PEDESTRIANS/

*A XEROX COMPANY

METAMATERIALS STEALTHING OR CLOAKING

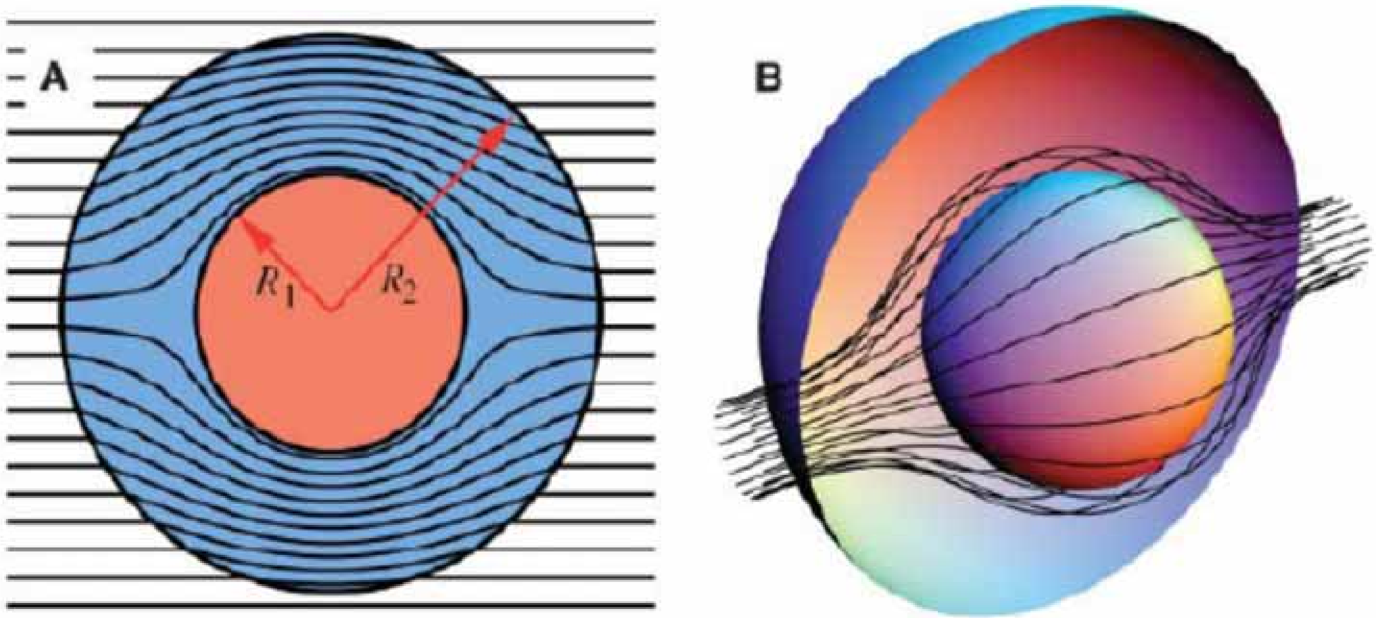


Fig. 2. A ray-tracing program has been used to calculate ray trajectories in the cloak, assuming that $R_2 \gg \lambda$. The rays essentially following the Poynting vector. **(A)** A two-dimensional (2D) cross section of rays striking our system, diverted within the annulus of cloaking material contained within $R_1 < r < R_2$ to emerge on the far side undeviated from their original course. **(B)** A 3D view of the same process.

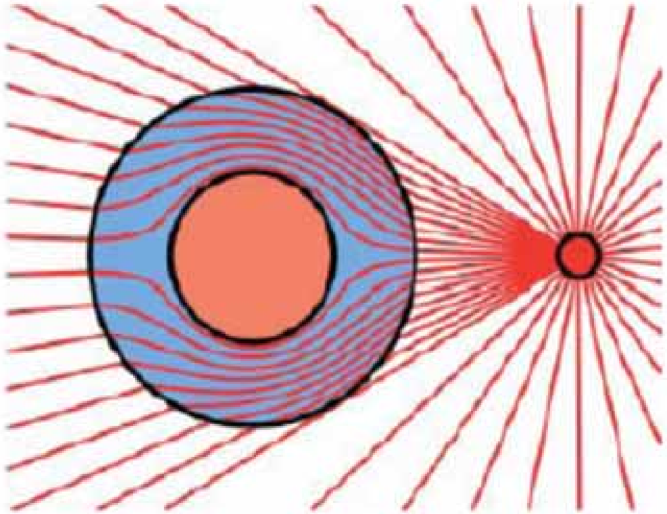
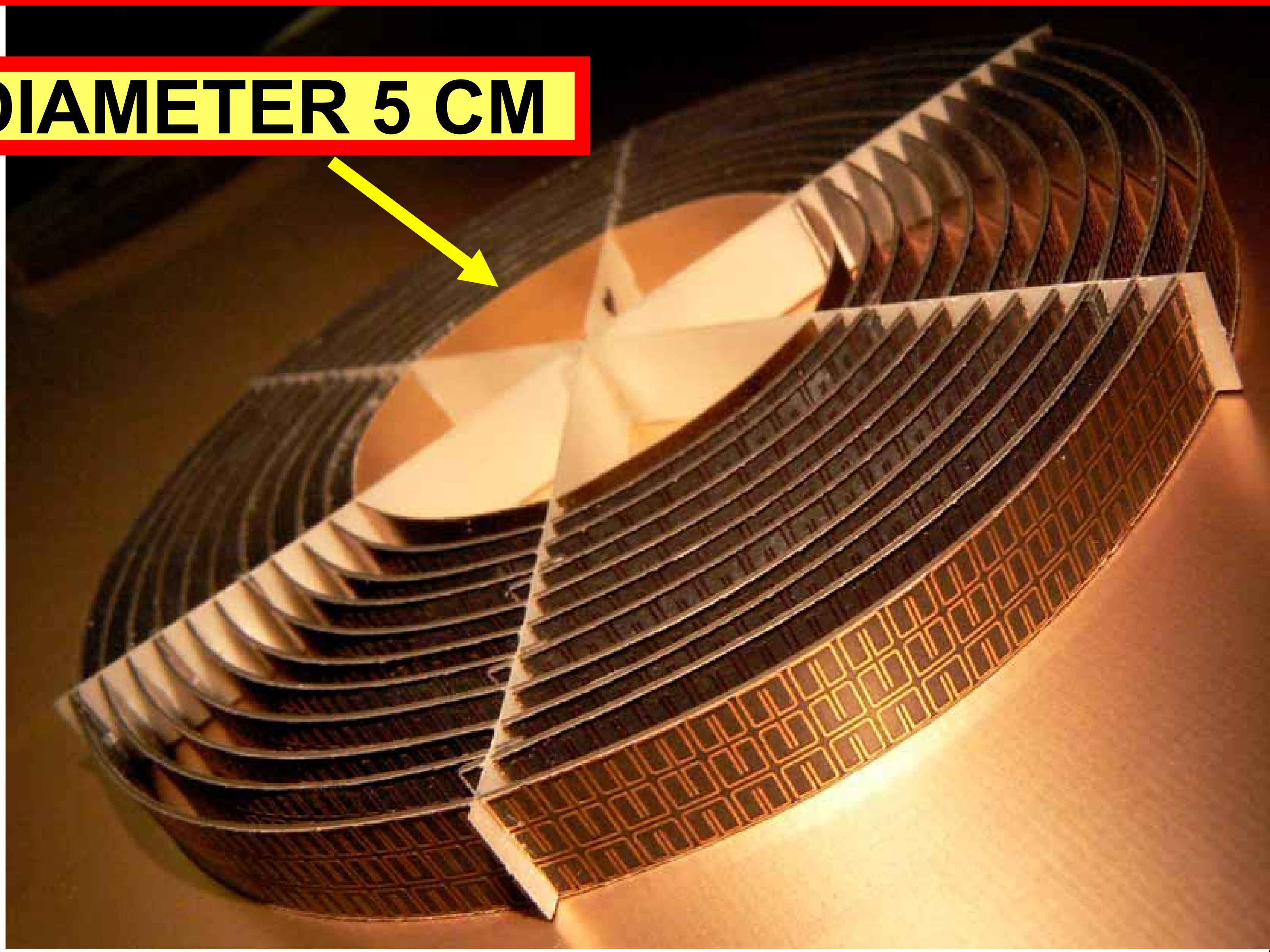


Fig. 3. A point charge located near the cloaked sphere. We assume that $R_2 \ll \lambda$, the near-field limit, and plot the electric displacement field. The field is excluded from the cloaked region, but emerges from the cloaking sphere undisturbed. We plot field lines closer together near the sphere to emphasize the screening effect.

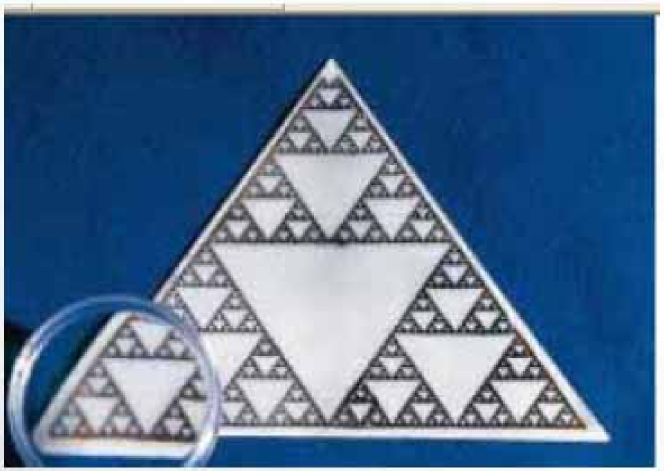
CLOAKING AT MICROWAVES USING SPLIT RINGS



DUKE UN.

Fractal Antenna and Fractal Antenna Modification to Traditional Broadband Antennas

A leaf is an example of a fractal pattern in nature



Sierpinski triangles fractal design typically used in fractal antennas (Ref. 3)

1/4 TH SIZE OF TRADITIONAL ANTENNA

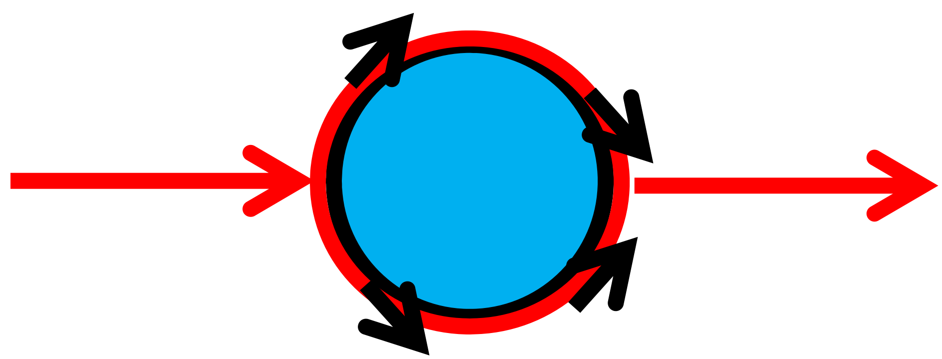
BANDWIDTH 25X LOWEST FREQUENCY CLAIMED

- Fractal Antenna Vendors include:
  - Fractus, S.A.Barcelona, Spain
  - Fractal antenna Systems Inc., Bedford, MA USA

(From: R, Mangra, Mil. Antennas 2009)

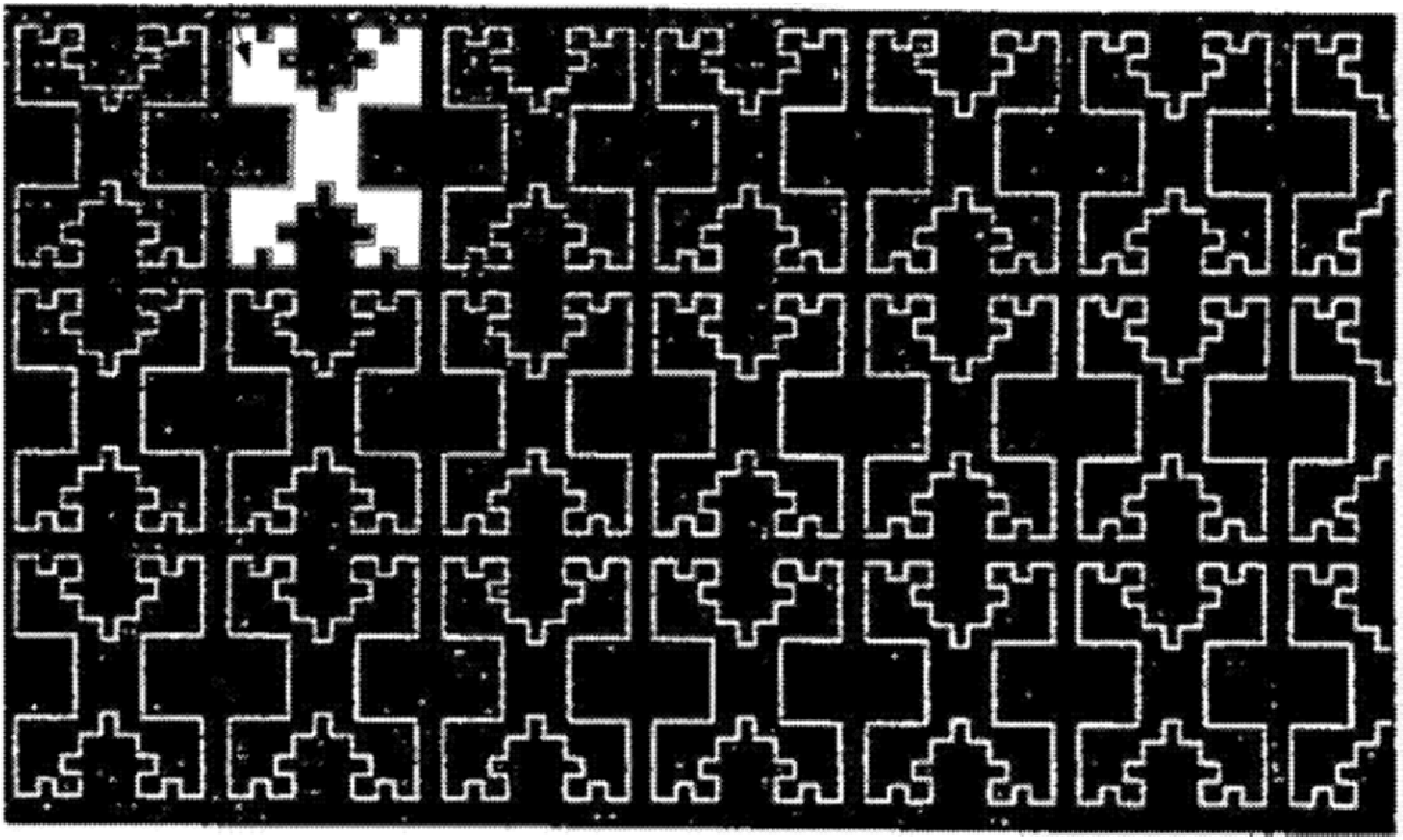
INVISIBILITY CLOAK

- CLOAKING OF A MAN HAS BEEN DEMONSTRATED BY DR. NATHAN COHEN OF FRACTAL ANTENNA SYSTEMS, INC. (HTTP://WWW.FRACTENNA.COM)
- DONE OVER **50% BANDWIDTH AT 1 GHz**.
- USED **FRACTAL METAMATERIALS**.
- METAMATERIALS NOT NEW – GO BACK ALMOST A CENTURY TO MARCONI AND FRANKLIN



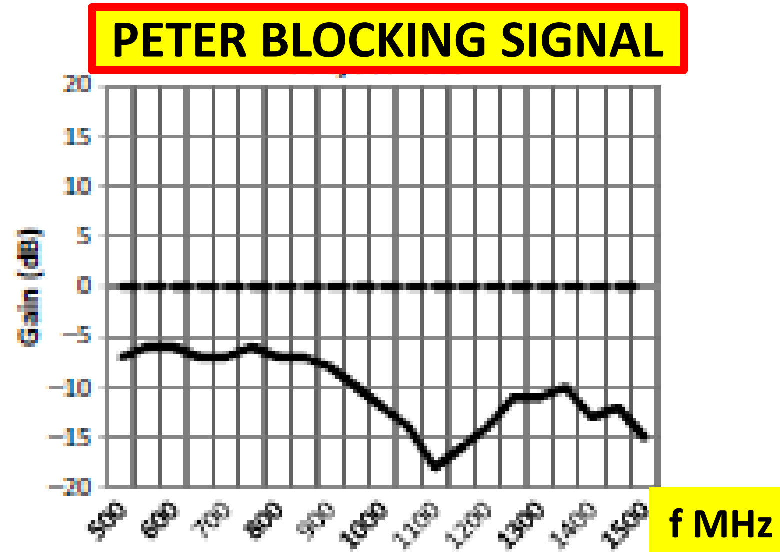
(N. COHEN, FRACTALS, VOL. 20, NOS. 3 & 4 2012, 227-232)

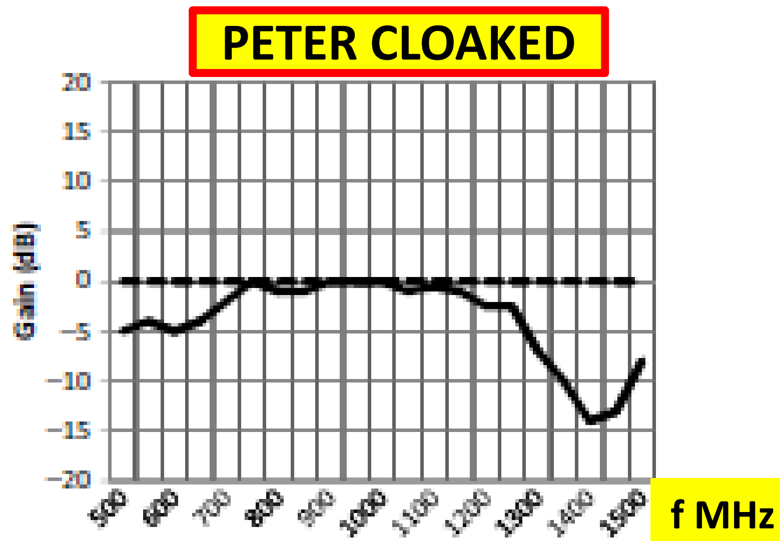
FRACTAL METAMATERIAL



(NATHAN COHEN, "WIDEBAND CLOAKING SYSTEM",
US PATENT 8,253,639, 8/28/12

WORLD'S FIRST HUMAN INVISIBILITY CLOAK





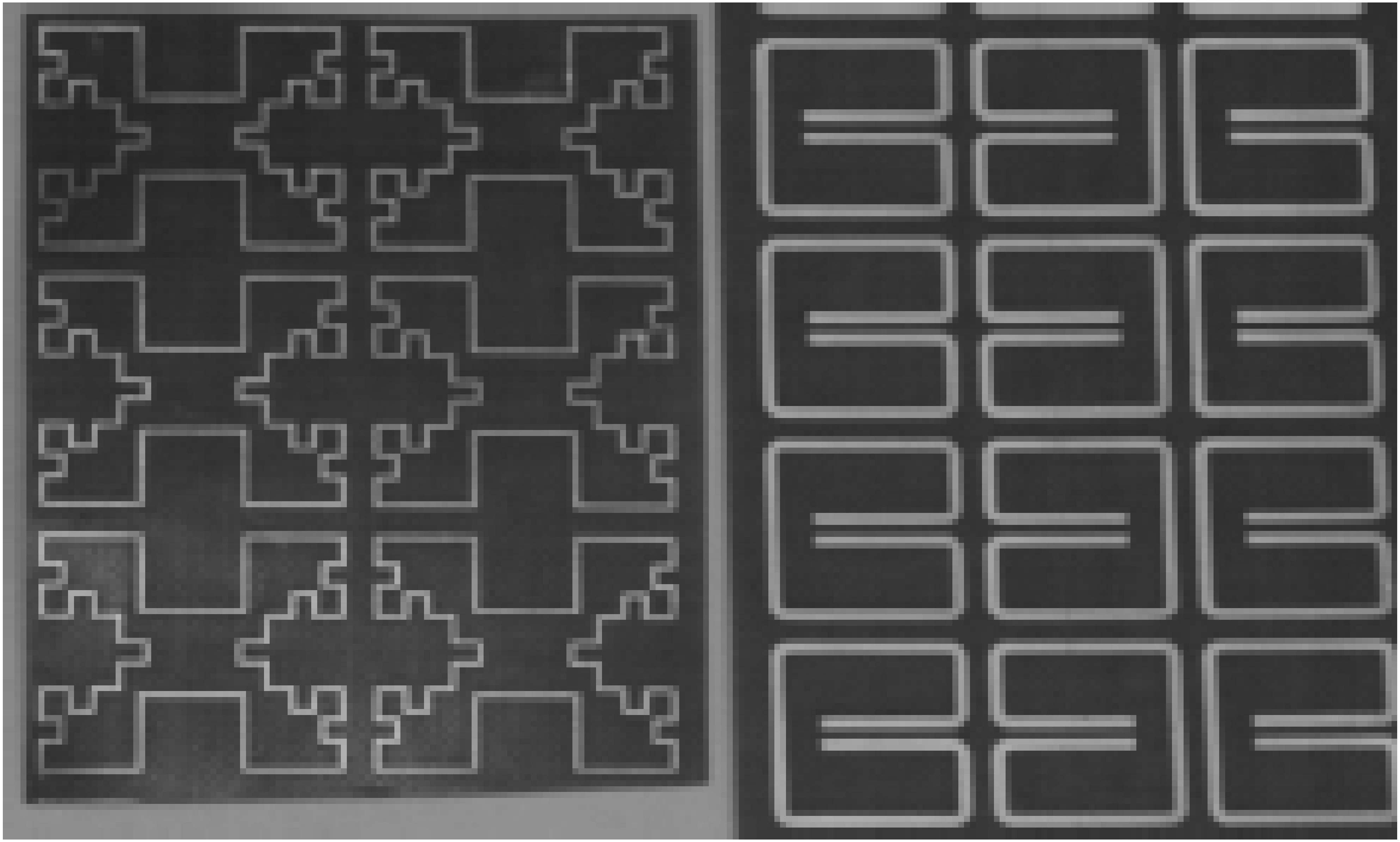
DIAGRAMS SHOWING SUCCESSFUL HUMAN INVISIBILITY CLOAK.

(TOP) PETER BLOCKS 'DIRECT PATH' & REDUCES INTENSITY BETWEEN TWO µWAVE ANTENNAS

(BOTTOM) PETER INSIDE CLOAK, DIVERTS INTENSITY AROUND PETER, & MAKES HIM INVISIBLE OVER 50% BANDWIDTH AT 1 GHz

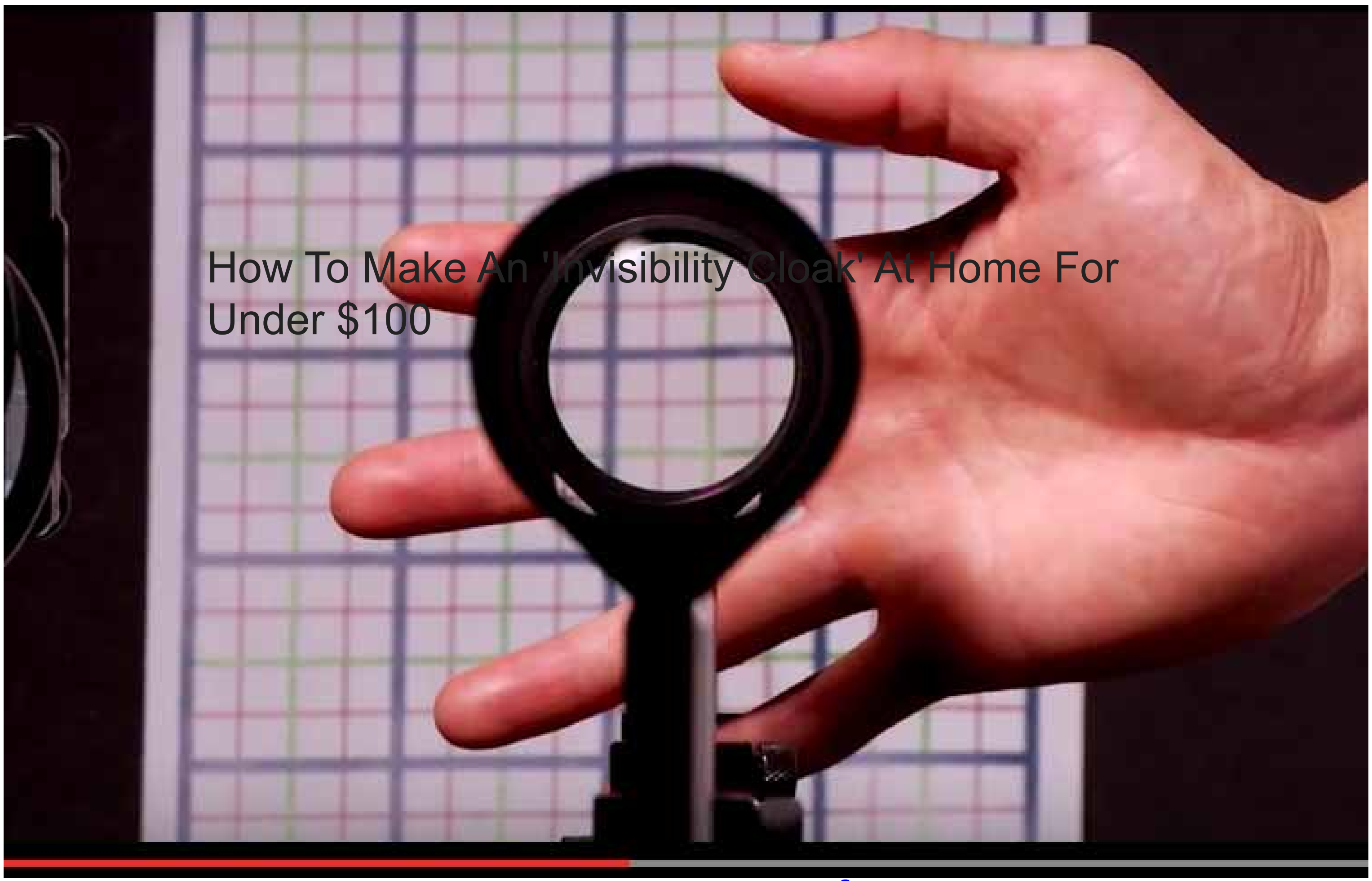
(2012 FRACTAL ANTENNA SYSTEMS, INC. SOURCE: FRACTAL ANTENNA SYSTEMS, INC)

COMPARISON OF CLOAKING FRACTAL AND SPLIT RING RESONATORS SURFACES



(NATHAN COHEN, FRACTALS, NOS. 3 & 4 (2012) 227-232

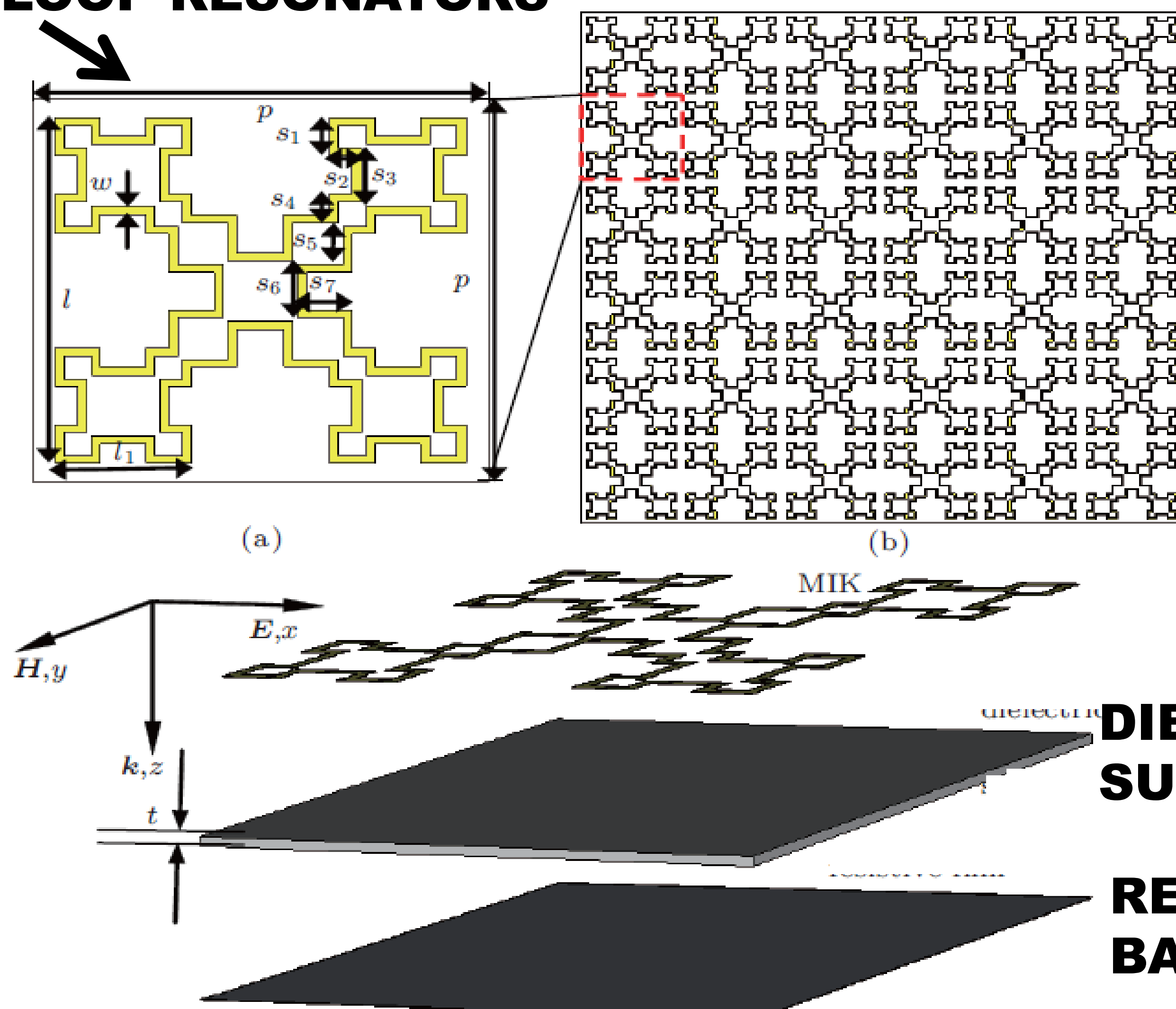
HOW TO MAKE AN 'INVISIBILITY CLOAK' AT HOME FOR UNDER $100 ROCHESTER UN.



(HTTP://WWW.BUSINESSINSIDER.COM/HOW-TO-MAKE-A-ROCHESTER-INVISIBILITY-CLOAK-2014-9)

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

FRACTAL LOOP RESONATORS

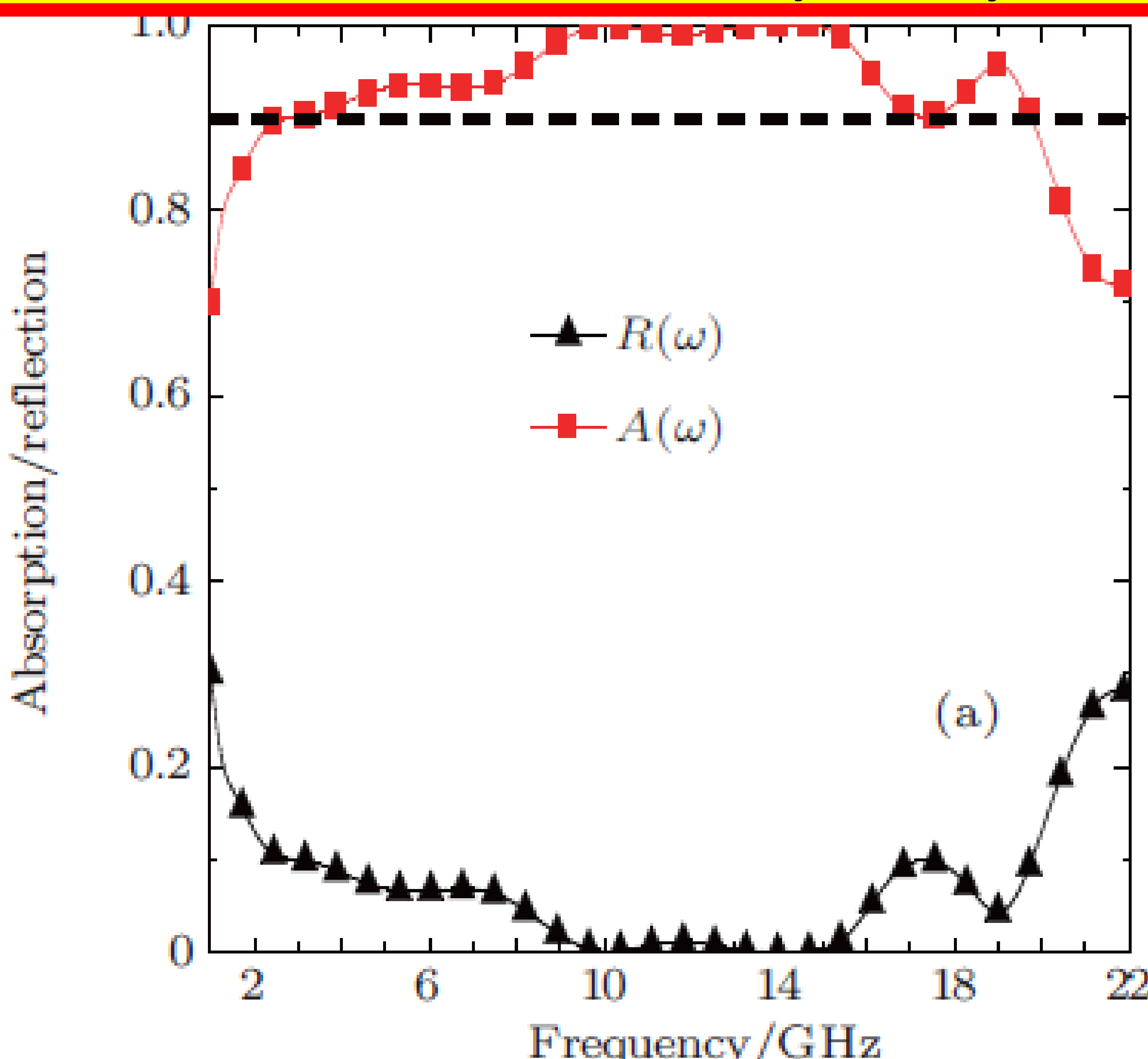


DIELECTRIC SUBSTRATE

RESISTIVE FILM BACKING

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

WIDEBAND STEALTHING, <1mm THICK
90% ABSORPTION 2-20 GHZ; 99%, 10-15 GHZ



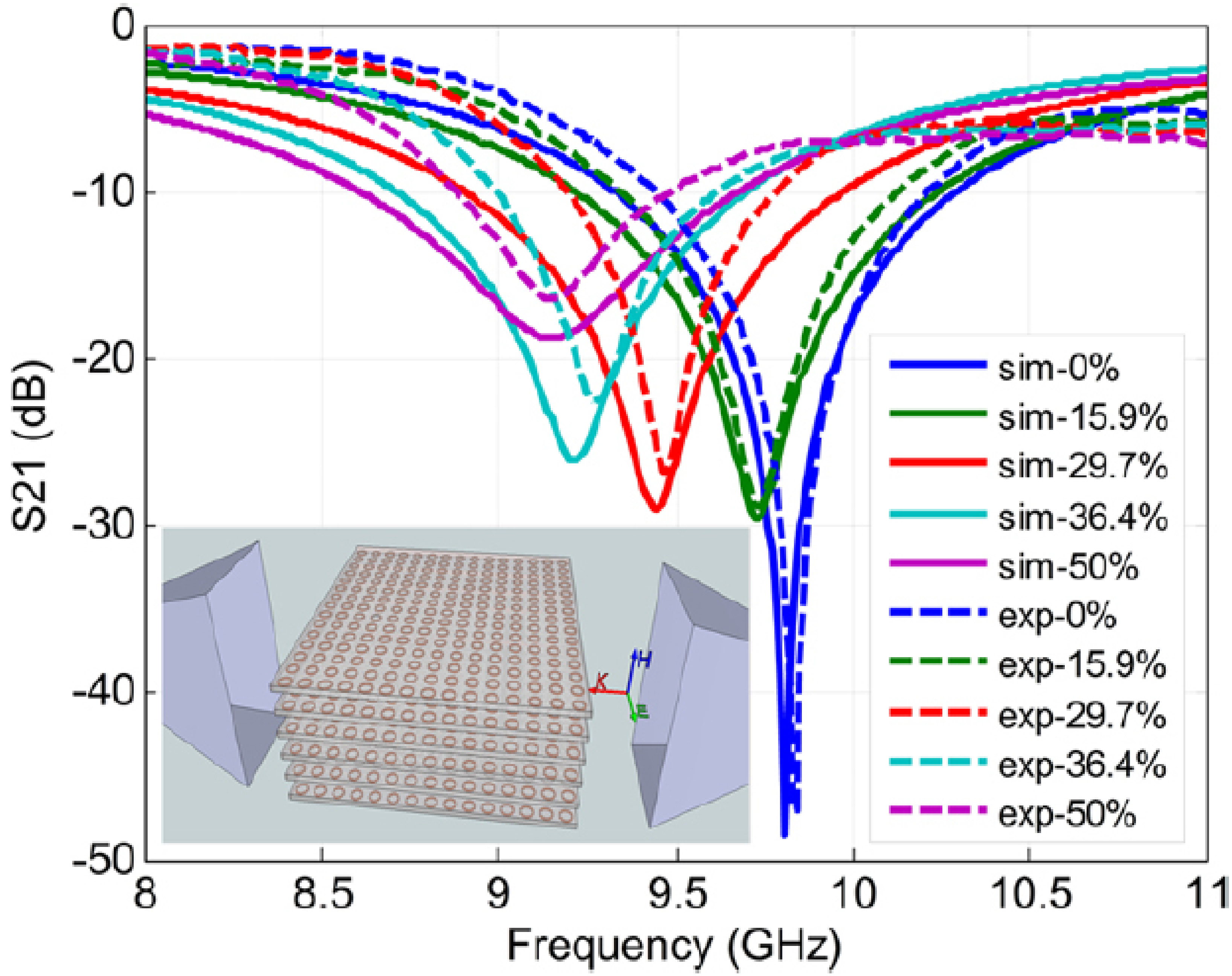
(F. YUE-NONG, ET AL, CHINA PHYS. B VOL. 22, NO. 6, 2013, 067801)

METAMATERIAL STEALTH 75% ABSORBTION 8-10 GHZ

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

META-SKIN

ABSORBTION DB



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

METAMATERIAL GOES COMMERCIAL

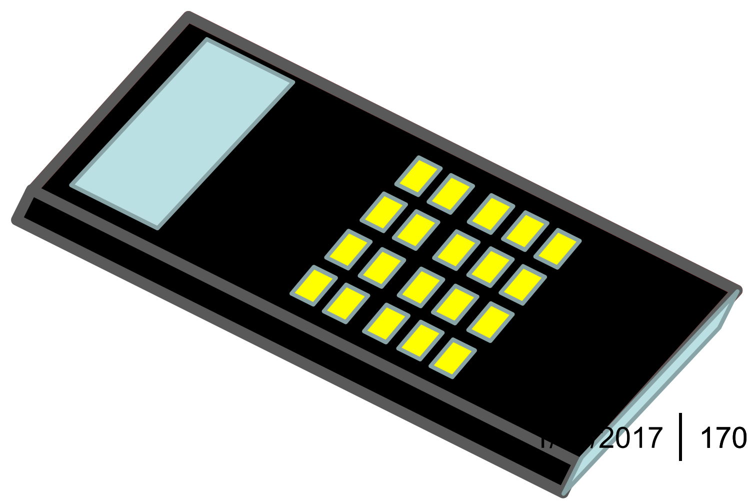
Used In Our Cell Phones

Advantages Of Metamaterial Antennas:

- Antennas 5x Smaller, 1/10th λ
- **WIDEBAND: 0.7 to 2.7 GHz**

  1 Antenna: GPS, Blue Tooth, WiFi, Wi Max
- 2-4 Weeks To Develop; Inexpensive
- Lowers Radiation To User

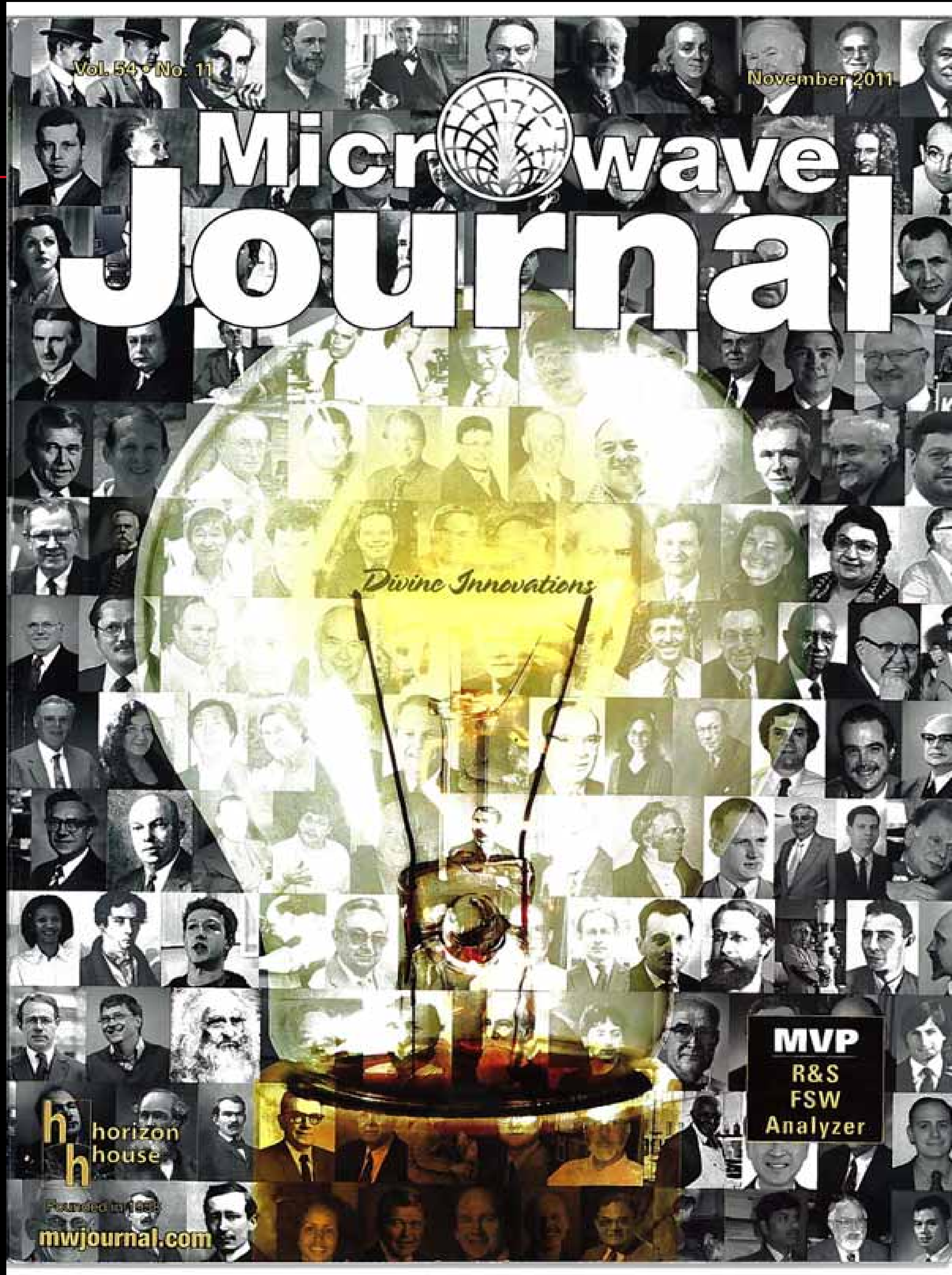
LG Electronics' BI40 Chocolate Phone



(DA,S.,IEEE Spectrum, 9/09; Poilsne, G., "RAYSPAN® Proprietary Metamaterial Antennas", www.rayspan,com; KIM, ET AL, IEEE AP-S, '09)

RAYTHEON EMPLOYEE BEATS EINSTEIN

Raytheon



Vol. 54 • No. 11
November 2011
Microwave Journal
Divine Innovations
MVP
R&S
FSW
Analyzer
horizon
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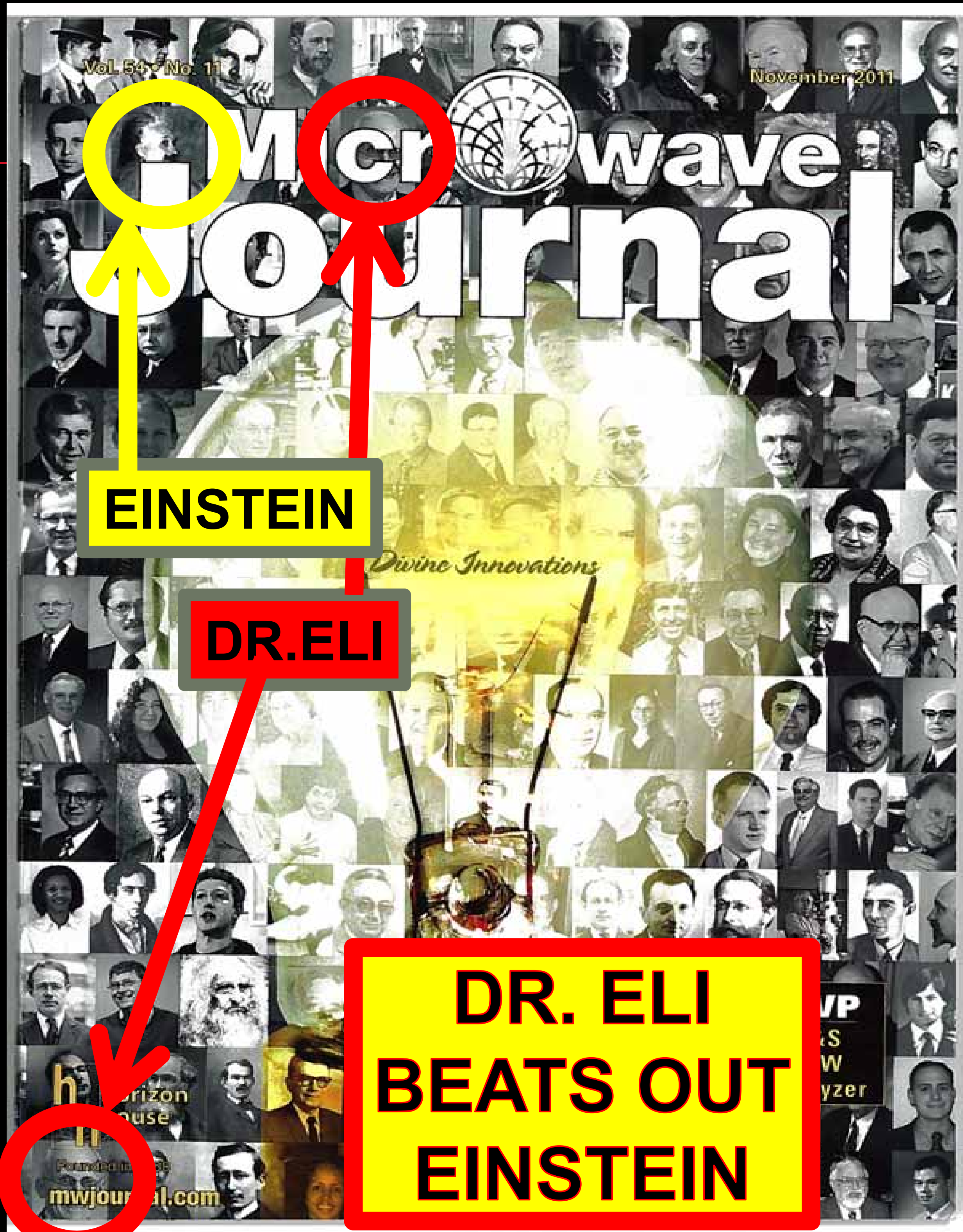
mwjournal.com

Raytheon


Vol. 54 • No. 11
November 2011
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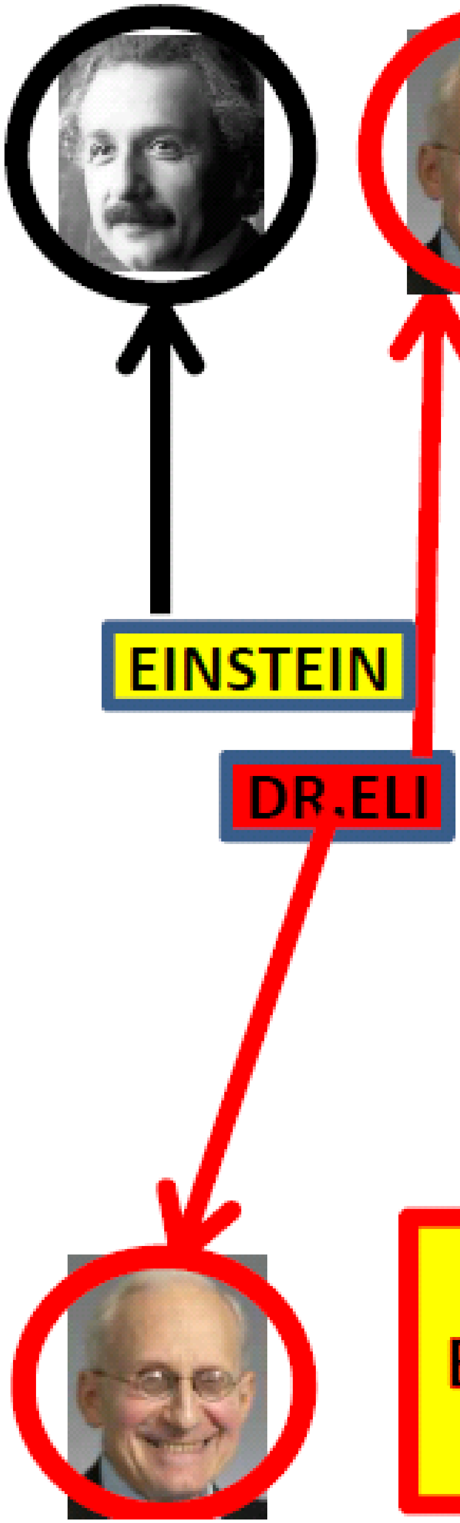
DR.ELI
DR. ELI BEATS OUT EINSTEIN
mwjournal.com



Microwave
Journal
Cover
Nov. 2011

DR. ELI
BEATS OUT
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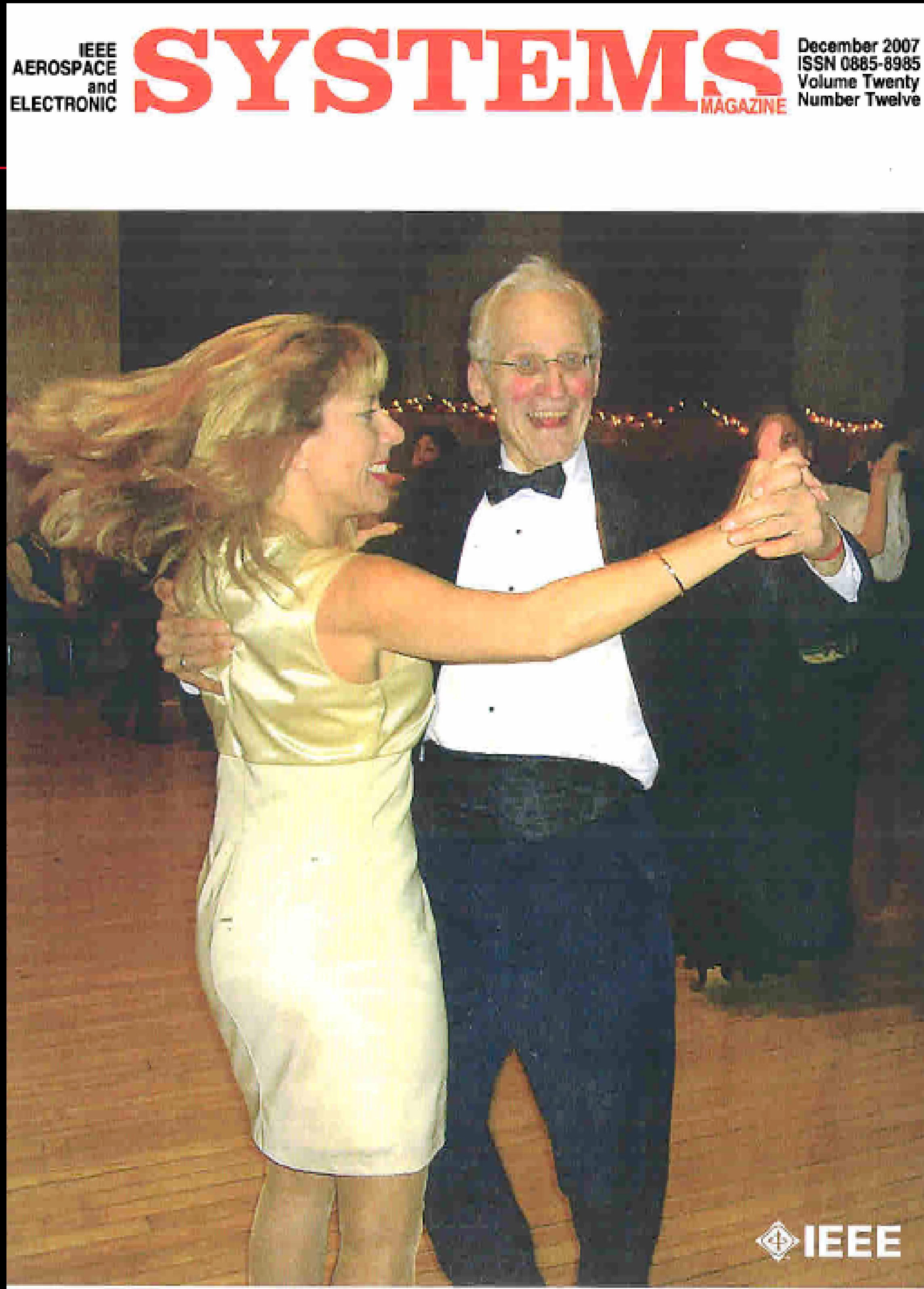
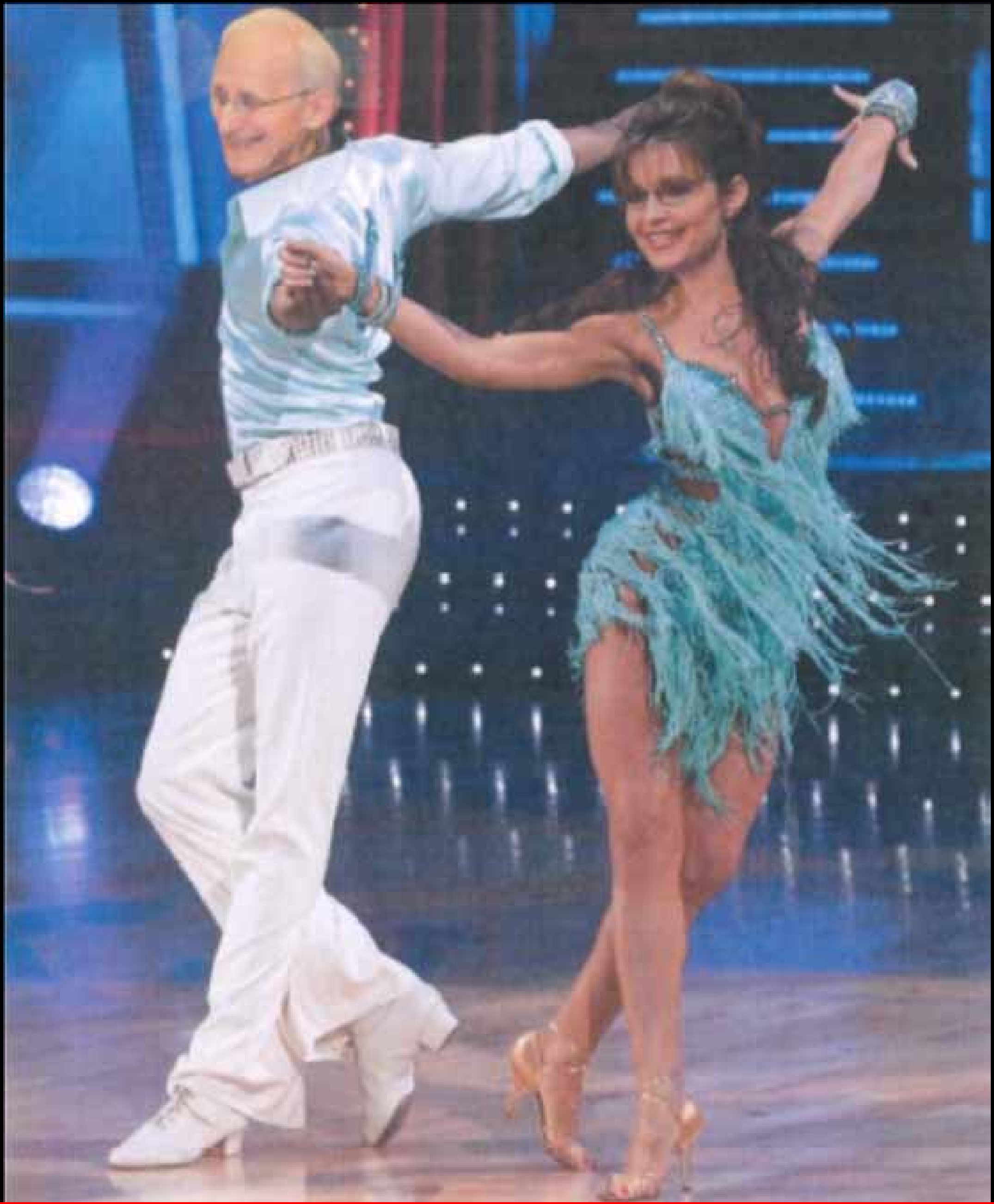
Raytheon


IEEE
AEROSPACE
and
ELECTRONIC
SYSTEMS
MAGAZINE
December 2007
ISSN 0885-8985
Volume Twenty T
Number Twelve
IEEE



DR. ELI AND SARAH PALIN ON DANCING WITH THE STARS

DR. ELI APPEARS 3 TIMES ON CHRONICLE TV DANCING

EPLRS Metamaterial Antenna

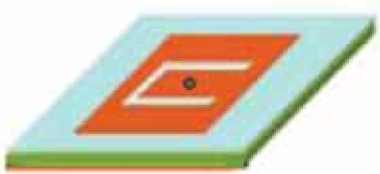
Problem: Large antenna visual signatures on military platforms result in the ability of an enemy to detect/target the platform at a far distance.

EPLRS Antenna

Capability Required: A technology to minimize the size of the antenna while maintaining similar electrical performance characteristics.

Technical Solution: By using Meta-Materials technology, the visual signature can be substantially reduced.

Meta-Materials Antenna



(From: Dr. R. Shahidain, Mil. Antennas 2009)

UNCLASSIFIED//APPROVED FOR PUBLIC RELEASE

U.S. ARMY RDECOM

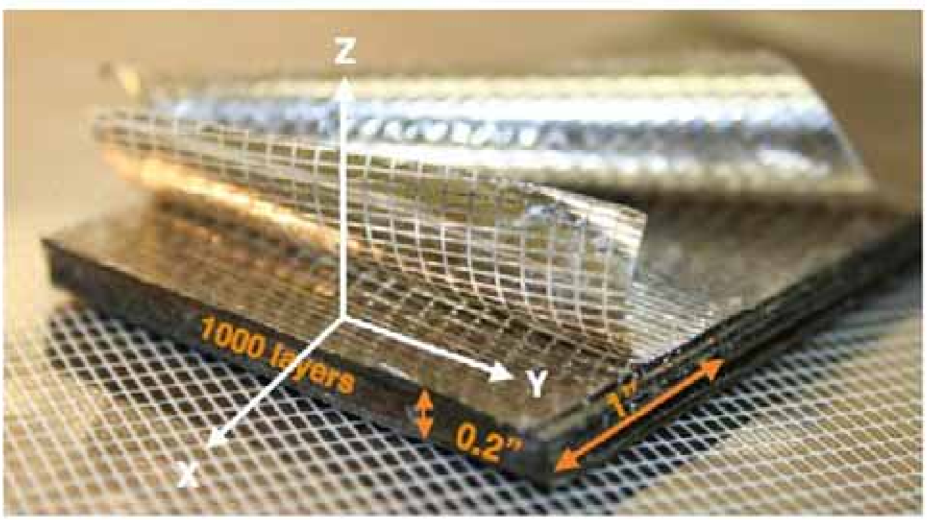
Extremely Low Profile Magnetic Metamaterial Antenna

ARL

Research Objective

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

- **250-505 MHZ; G=5-8.2 DB, VSWR <3**
- **~2500 LAYERS; 3.3" THICK (λ/20 INSTEAD OF λ/4)**
- **ANISOTROPIC MAGNETIC DIELECTRIC METAMATERIAL ANTENNA**
- **POTENTIAL USES: NGJ* VHF ANTENNA; REPLACE TALL VISIBLE WHIP ANTENNA ON ARMY VEHICLES; VHF A/C FOPEN ANTENNAS**
- **ARMY RESEARCH LAB (ARL); CONTRACTED METAMATERIALS INC.**

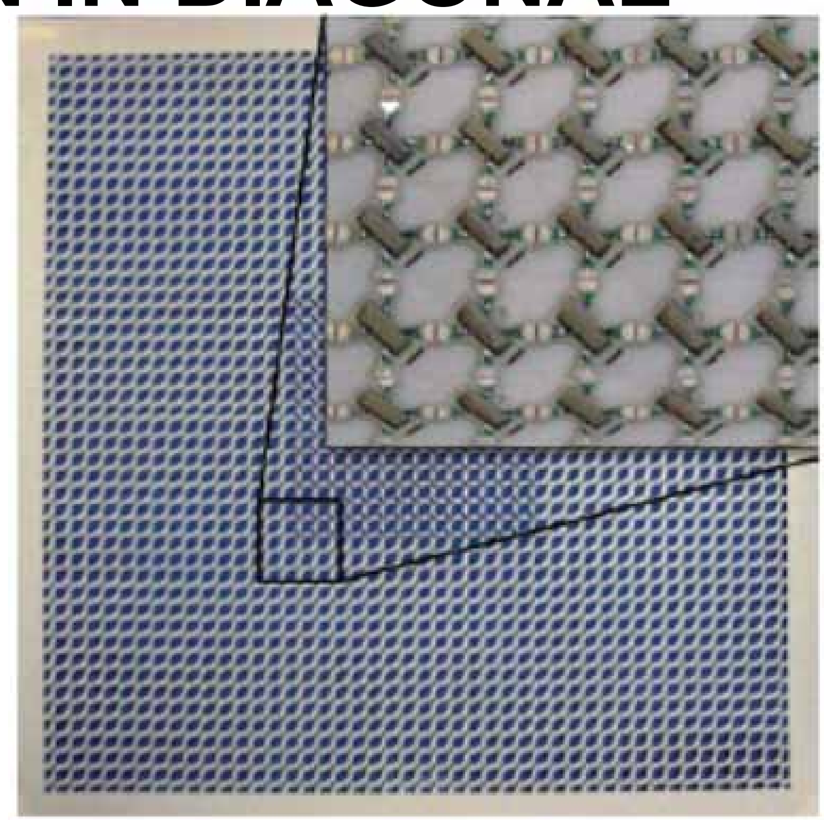


***NEXT GENERATION JAMMER**

(ARL, ABERDEEN, MD, JUNE 4, 2014)

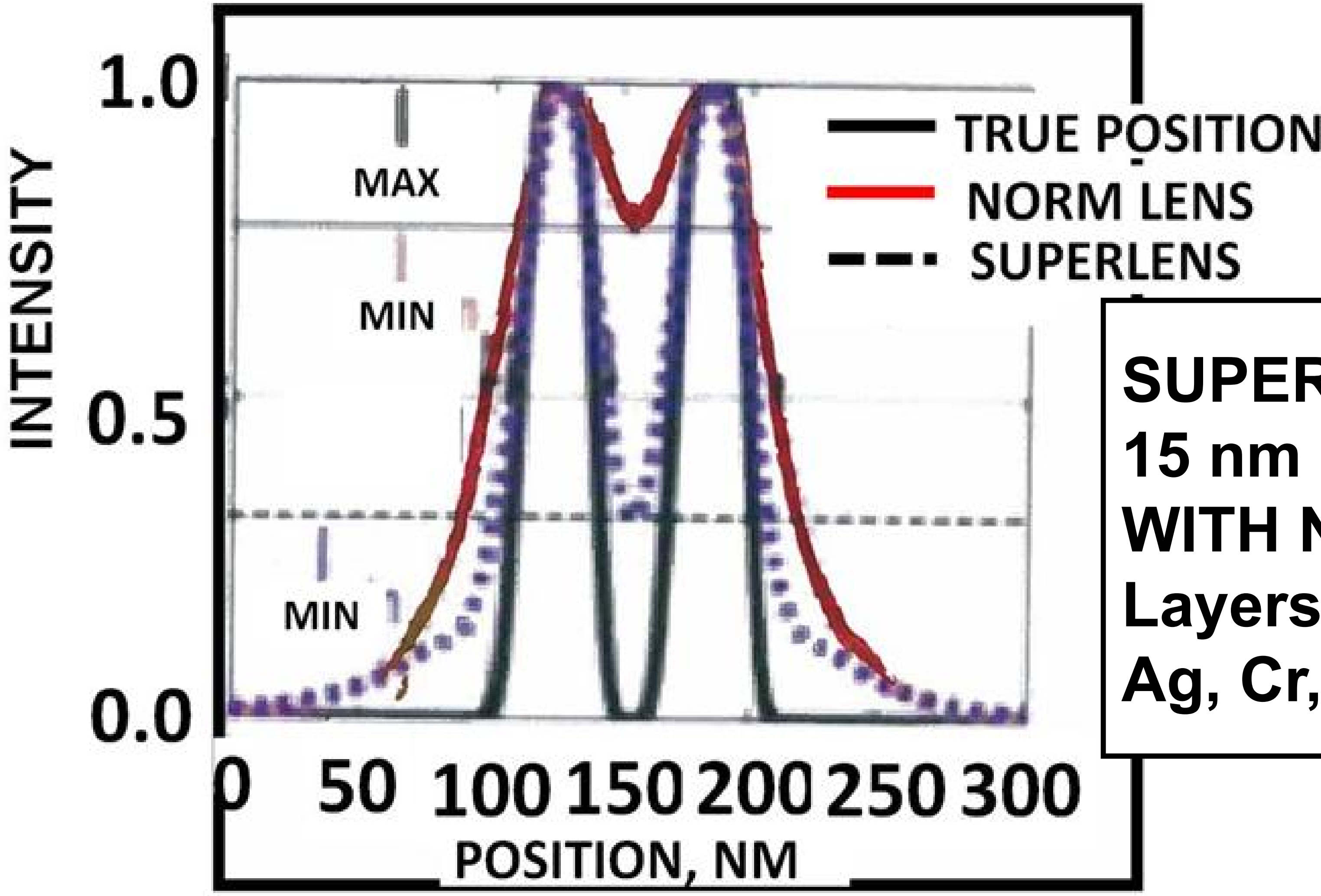
TIGHTLY COUPLED DIPOLE ARRAY (TCDA)

- 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)

6X DIFFRACTION LIMIT (λ/12) ACHIEVED AT 0.36 μm

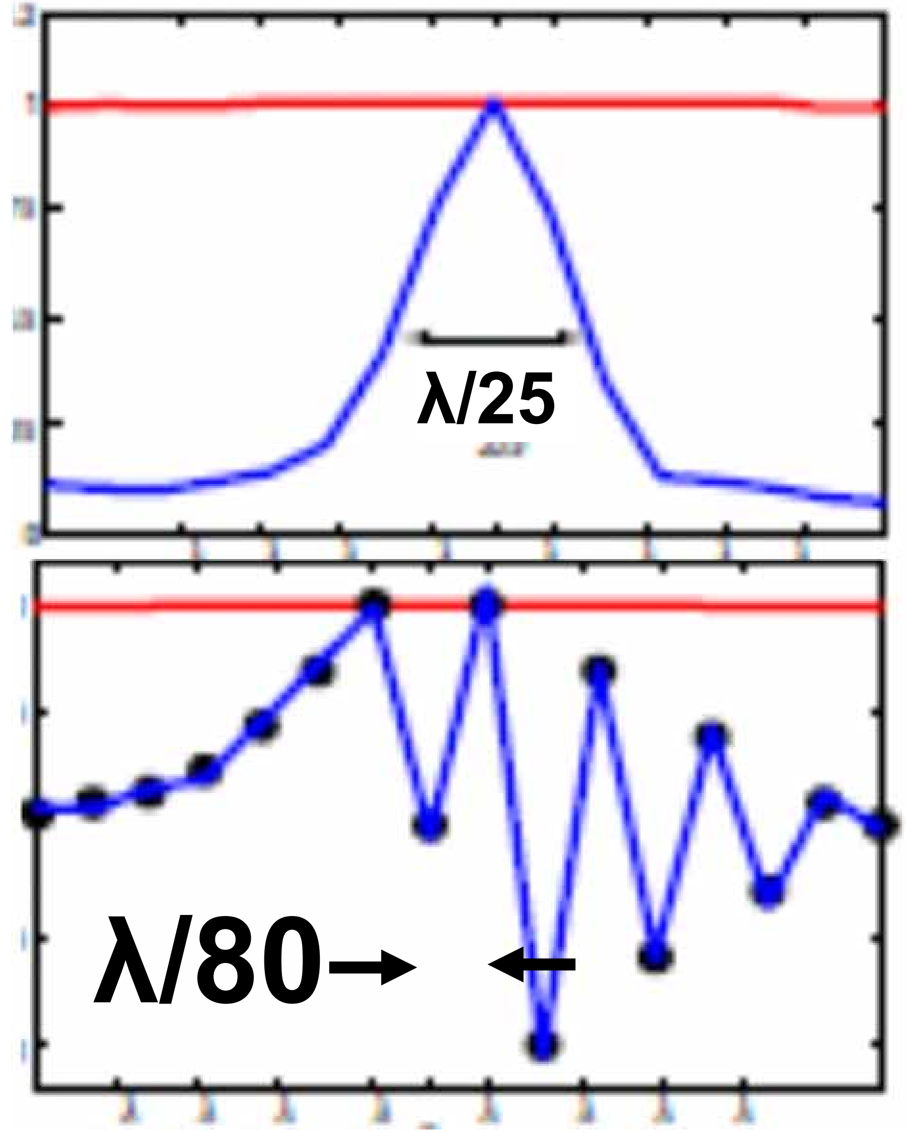


SUPERLENS OF 15 nm SILVER FILM WITH NEG ε; Layers of Ag, Cr, Quartz

(NICHOLAS FANG, APP. PHYSICS LET., 2010, UN. ILLINOIS)

40X DIFFRACTION LIMIT (λ/80) ACHIEVED AT 375 MHz

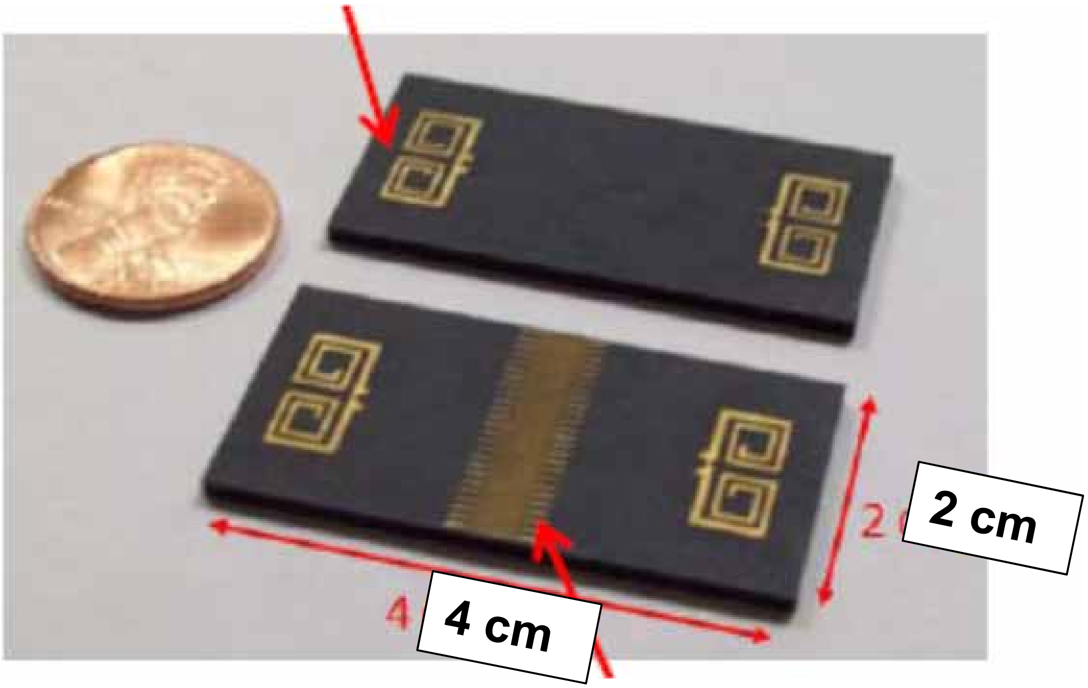
METALENS
‘SUPERLENS’ OF 8X8
λ/2 = 40 cm LONG
VERT. Cu WIRES
1.2 cm APART



(G. LEROSEY, ET AL, PHYSICS REV. LET., 2010, ESPCI PARISTECH)

USING ELECTROMAGNETIC BAND GAP (EBG) 2.5 CM SEPATION⇔1 M

Vertically-Polarized Planar Antenna



F = 2.72 GHz

Antenna Sizes:

1.12x0.51x0.157 cm;

or $\lambda_o/10 \text{ X } \lambda_o/22 \text{ X } \lambda_o/70$

Isolation: 18 DB without,

42 DB with,

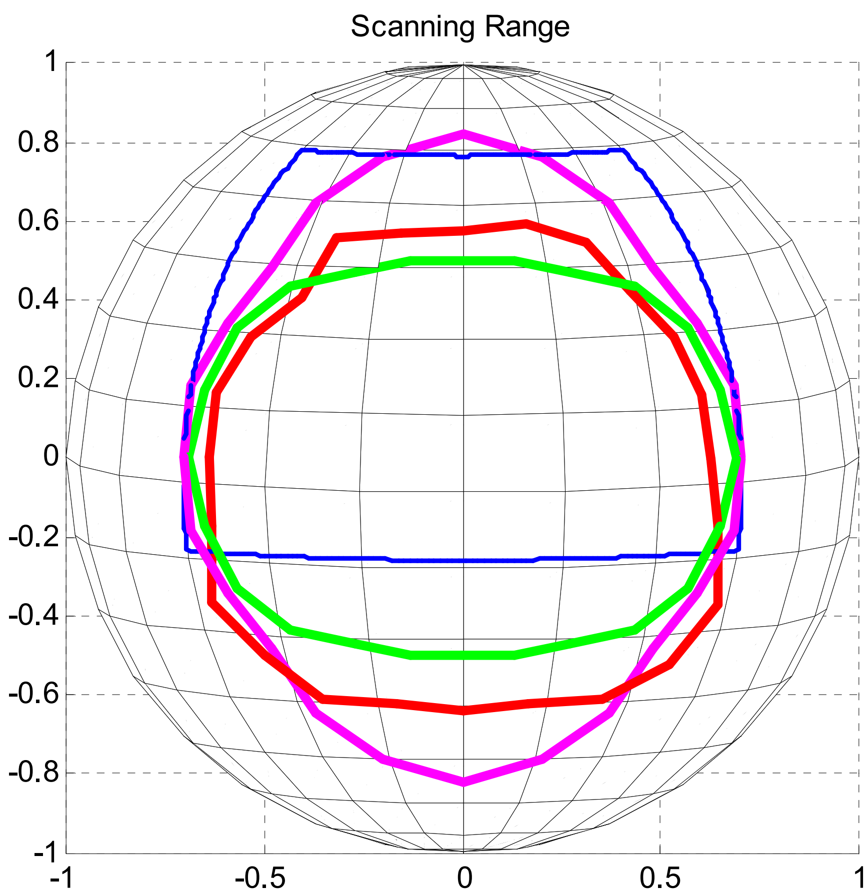
An Increase of 24 DB

Electronic Bandgap Equivalent to Separating Antennas by 1 m

(COURTESY OF PROF. K. SARABANDI, UN. OF MICHIGAN; THANKS ALSO TO JOSEPH MAIT, ARMY RESEARCH LAB, ADELPHI, MD; SEE K. SARABANDI & Y. J. SONG, "SUBWAVELENGTH TRANSPONDER USING METAMATERIAL ISOLATOR," IEEE AP TRANS., 7/11, PP 2183-2190)

WIDE ANGLE SCAN USING ELECTROMAGNETIC BAND GAP (EBG) MATERIAL

- **Array w/ Wide Angle Scan & Possibly No Circulator**
- **Electromagnetic Band-Gap (EBG) Material Between Patch Layers Shown To Reduce Mutual Coupling By 8 DB**



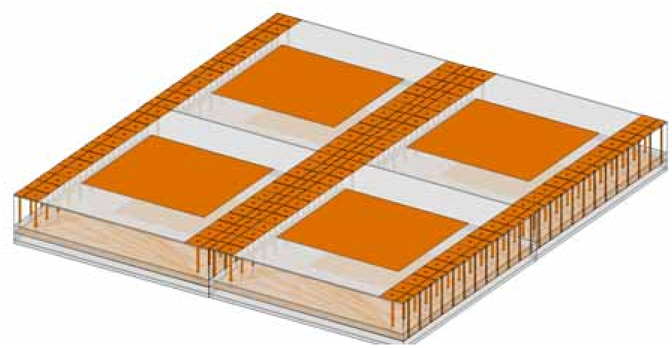
Scanning range in k-space with 5° tilt

green: simulated infinite array

red: measured finite array

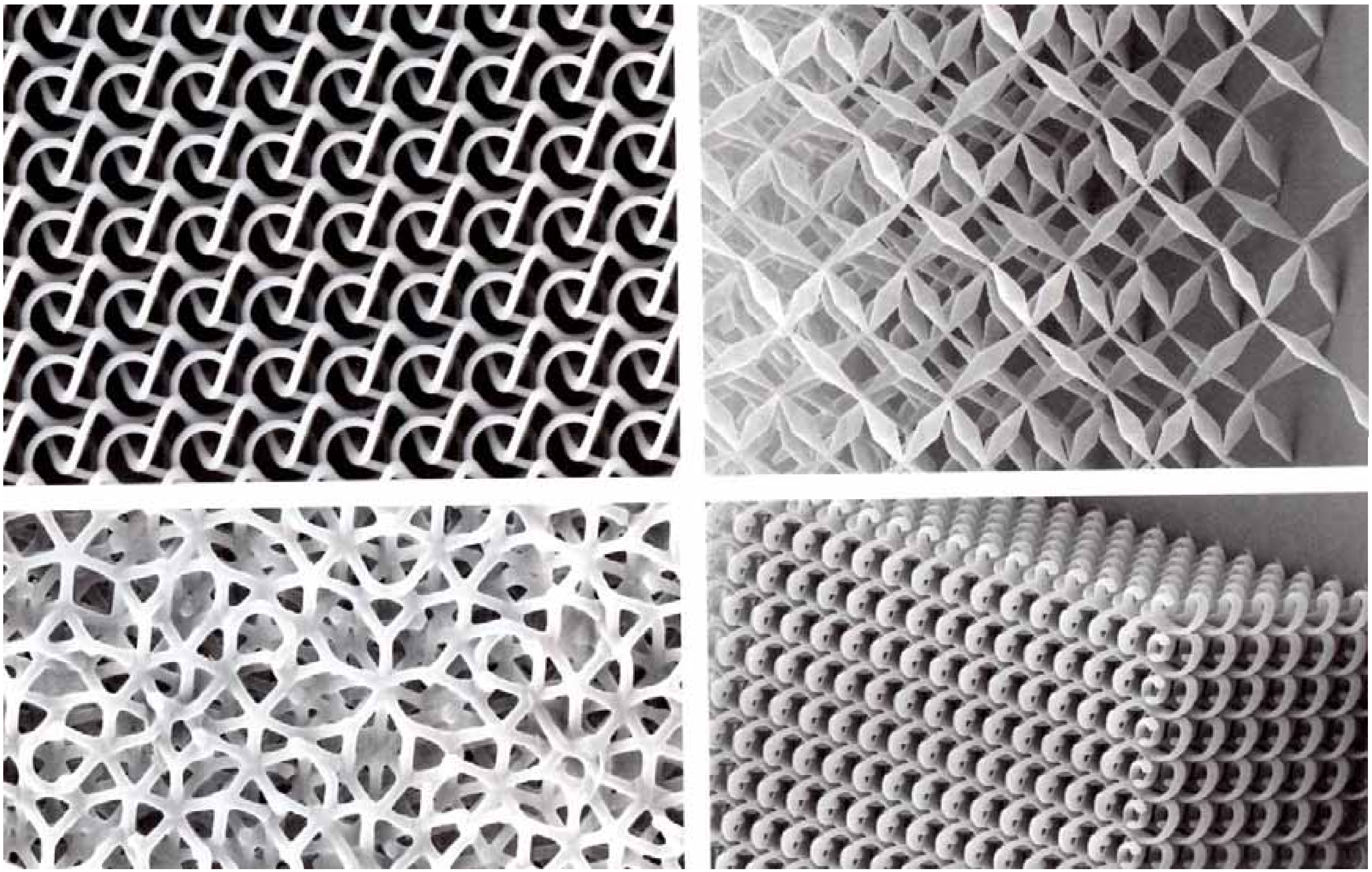
blue: specification

purple: array with EBG



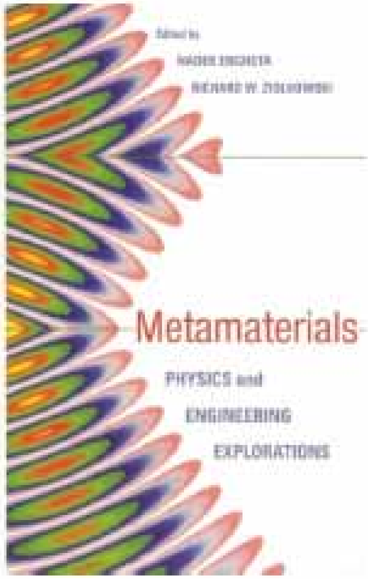
(COUTESY OF DR. C. FULTON; SEE C. FULTON,"DIGITAL ARRAY RADAR", PHD THESIS, PURDUE UN., 12/10; SEE ALSO FULTON, W. & CHAPPELL , W., IEEE COMCAS 2008)

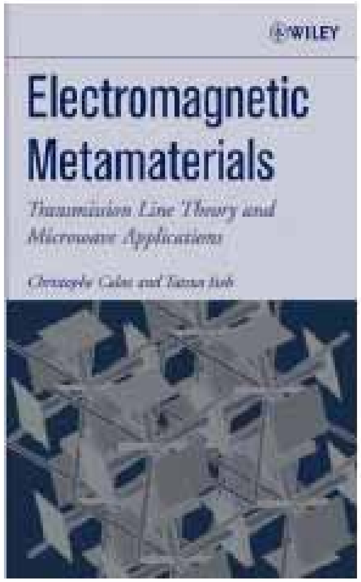
3-D METAMATERIALS NOW MADE TO ORDER AT VISIBLE WAVELENGTHS

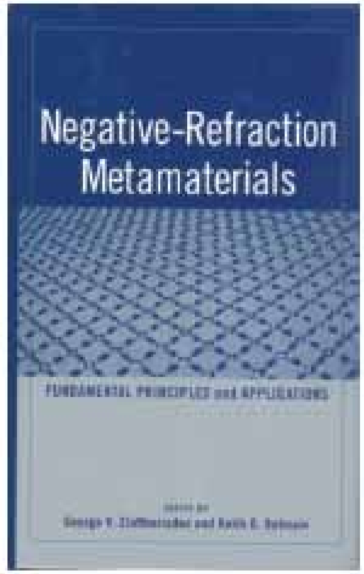


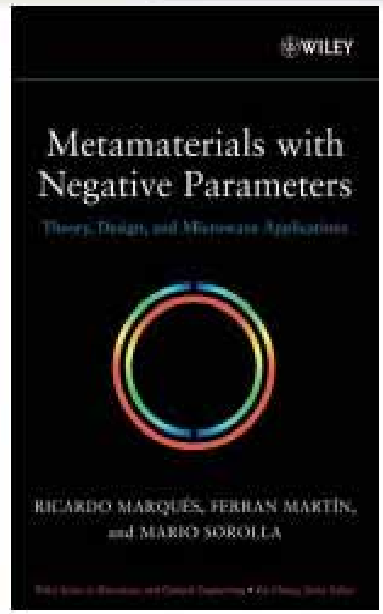
(J. JISCHER ET AL, IEEE SPECTRUM, 2/14P.35-.)

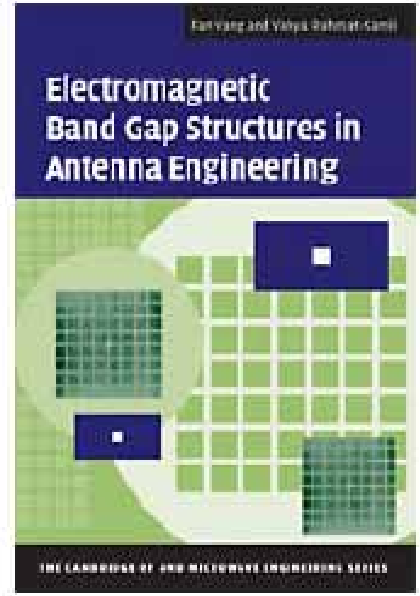
METAMATERIAL BOOKS

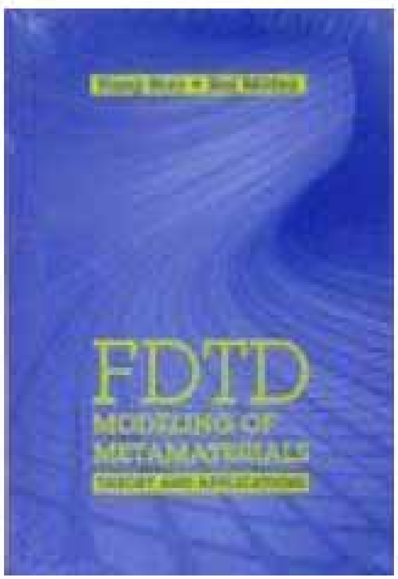


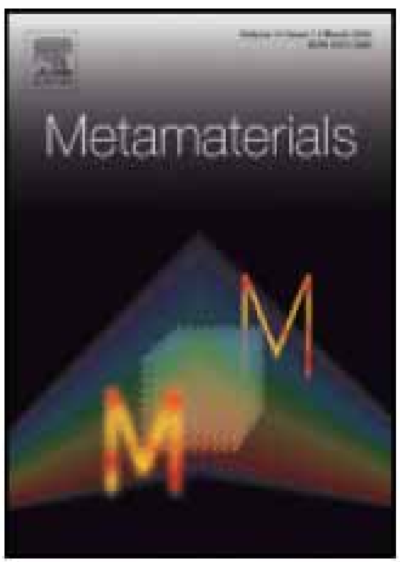


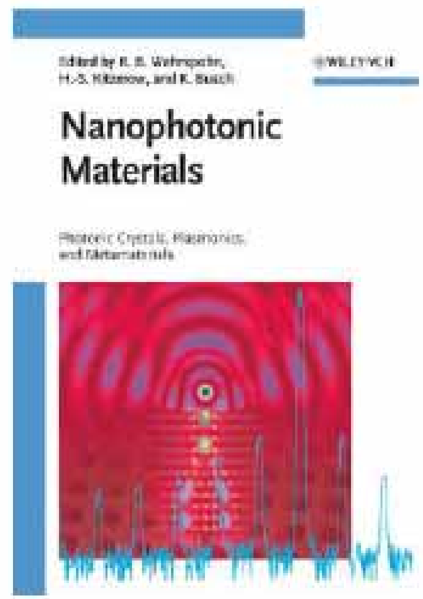


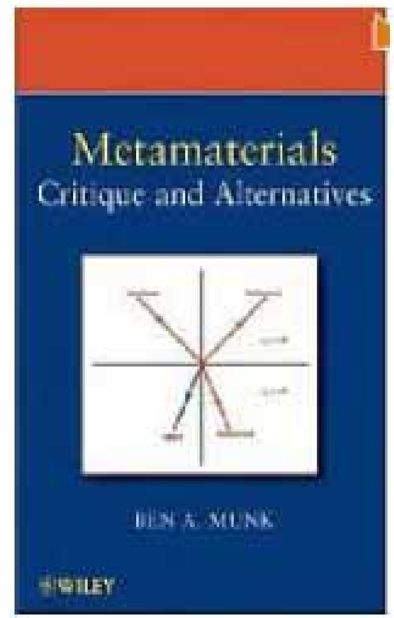












(AFTER S. MACI, UN. SIENA, SIENA, ITALY)

METAMATERIALS NOT NEW: USED BY MARCONI & FRANKLIN IN 1919 PATENT

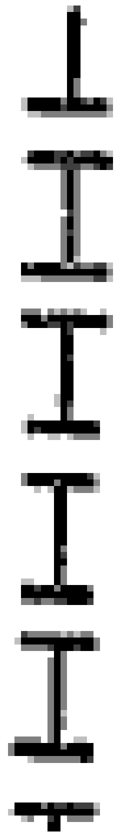


Fig. 11.

G. MARCONI & C. S. FRANKLIN.

REFLECTOR FOR USE IN WIRELESS TELEGRAPHY AND TELEPHONY.

APPLICATION FILED FEB. 26, 1919.

1,301,473. Patented Apr. 22, 1919.

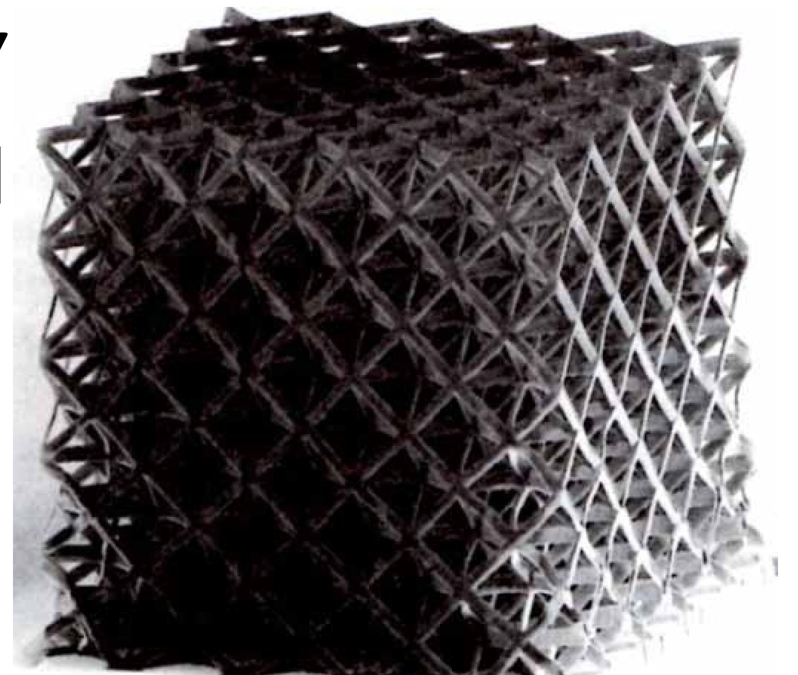
NANOSTRUCTUAL CERAMICS

- NANOMATERIALS EXHIBIT NEW PROPERTIES
- < 10 nm CERAMIC TUBES ARE NOT BRITTLE
- **SPONGELIKE,** BUCKLE THEN RECOVER SHAPE
- **SUPER-LIGHT, SUPER-STRONG**
- POTENTIAL USE: **BATTERY ELECTRODES**

FAST CHARGING, LOT OF ENERGY

- PROF. JULIA GREER, CAL TECH

ELECTRON MICROSCOPE IMAGE SHOWS NANO-LATTICES →

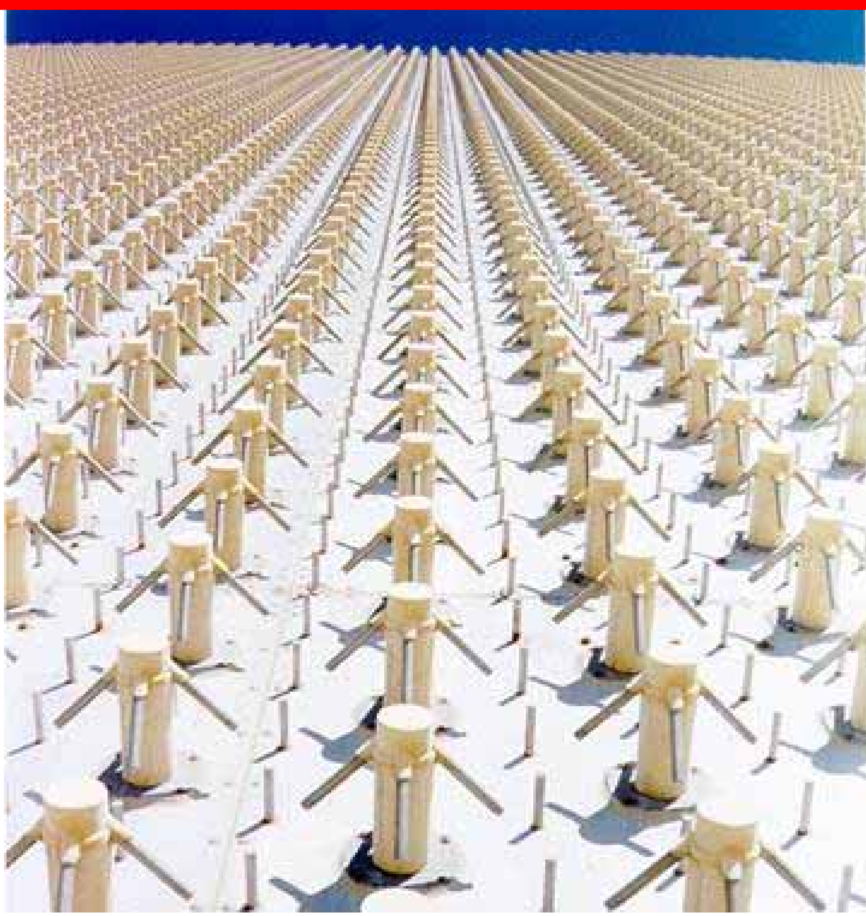


(K. BOURZAC, MIT TECHNOLOGY REVIEW, NOV-DEC, 2014, P. 19)

BROOKNER BREAKTHROUGH REFS:

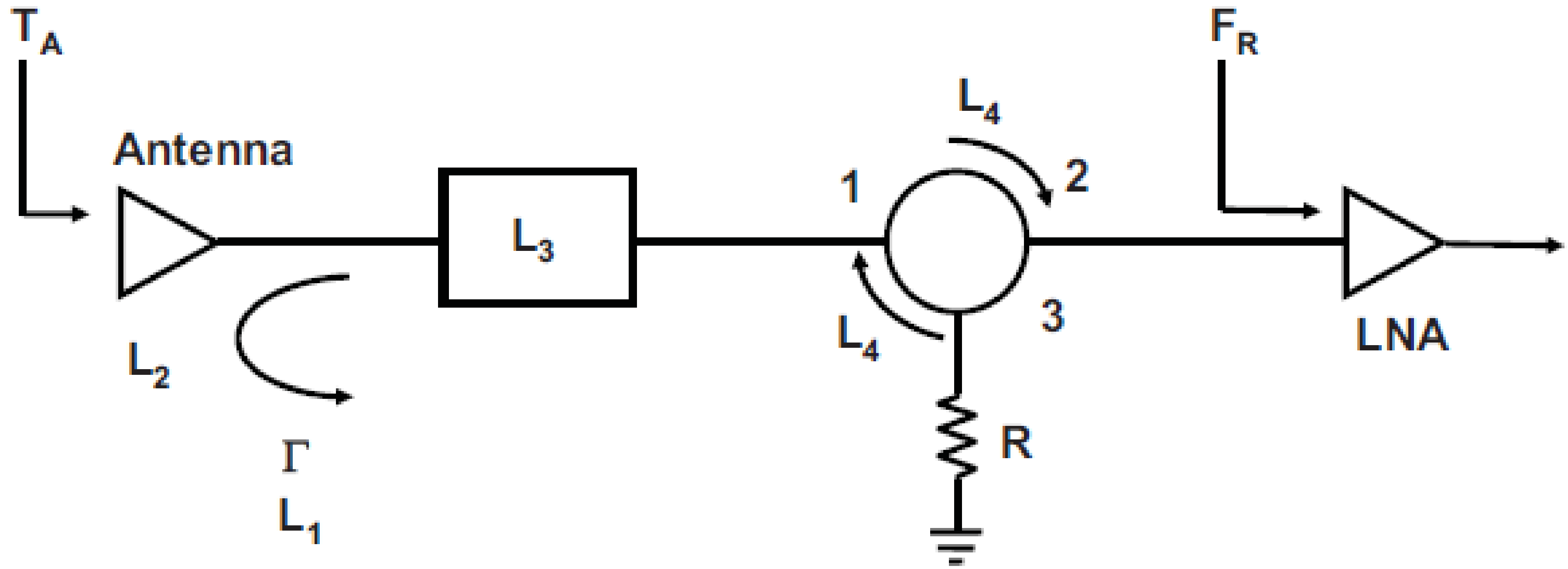
- RadarConf 2008, Rome, Breakthrough[illegible]
- Microwave J. (MJ) 1/2008, Breakthrus
- RadarConf 2007, Boston
- Military Radar Conf. 10/09, 10/08, 10/07, Breakthrus
- Radar 2007, Bangalor, India, Breakthrus
- RF Alliance Conf.: Enabling Multi-antenna & Broadband Systems, April 5-6, 2010, Breakthrus
- IEEE Array-2010, Boston, Breakthrus
- Microwave J. 1/2013, MIMO
- ARRAY-2013, Boston, “MIMO” & “Breakthrus”, 10/13
- Radar-2014, Lille, France, 10/14
- 8th Military Radar Summit 2/15, VA, ‘MIMO’; ‘Breakthrus’
- Radar-2015, VA, MIMO, 5/15
- IET Radar-2015, Breakthrus, 10/15, Hangzhou, CHINA
- IET Radar-2015, MIMO, 10/15, Hangzhou, CHINA
- Microwave J. 11/2016, Radar & Phased Array Breakthrus
- ARRAY-2016, Advances and Breakthrus in Radar and Phased-Arrays

HFSS PREDICTS EMBEDDED PAVE PAWS UHF ELEMENT ANTENNA PATTERN TO WITHIN 0.25 DB



BROOKNER, ET AL, ARRAY 2010

CORRECT ARRAY SYSTEM TEMPERATURE T_S

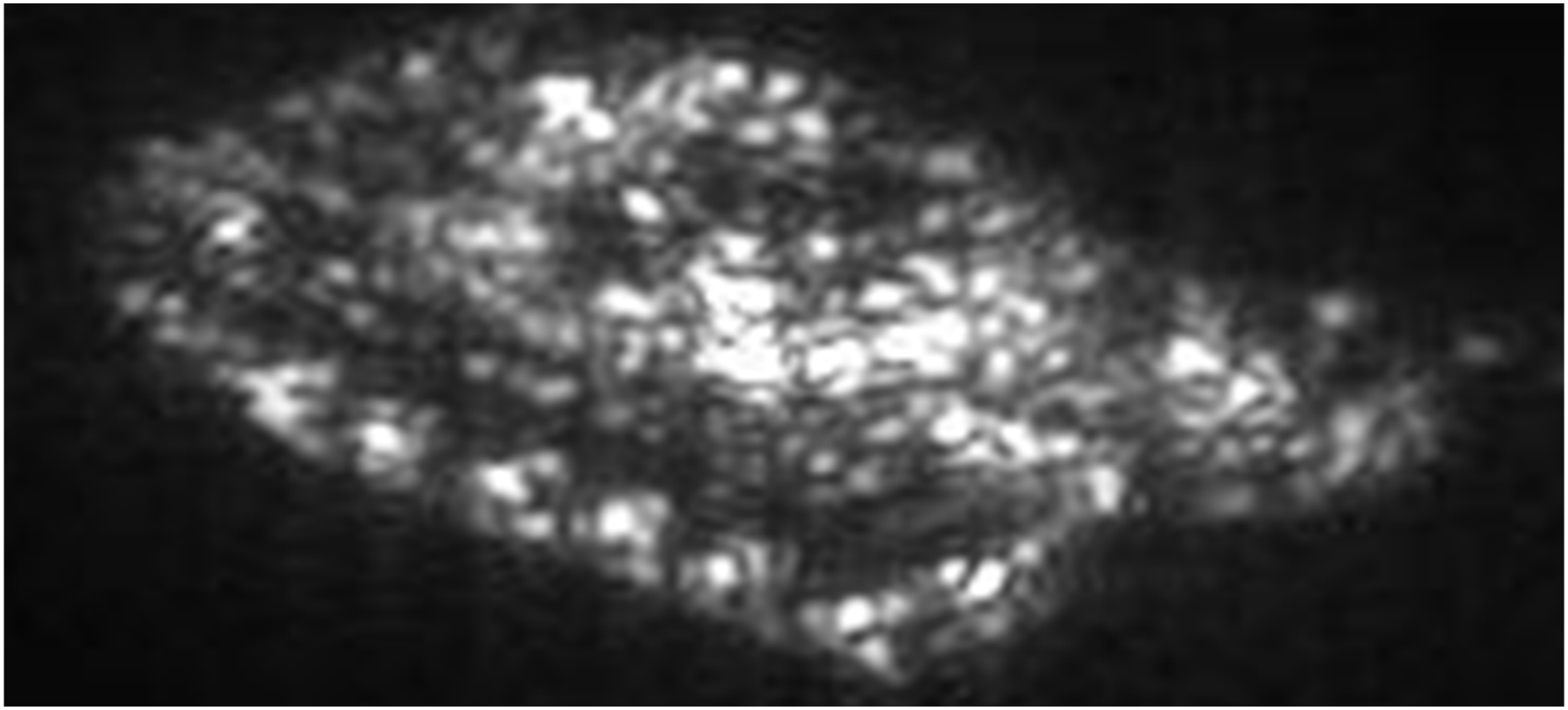


At Large Scan Angles, like 60°:

- **Can Underestimate System Temperature T_S by 1.2 to 2.4 dB if effects of Phased Array Mismatch not taken into account**
- **Mismatch loss can be treated as Ohmic**

(BROOKNER, E. “ARRAY NOISE TEMPERATURE”, IEEE ARRAY-2013

HIGH RESOLUTION ISAR OF TANK OVER ROUGH TERRAIN USING MOTION COMPENSATION BASED ON PROMINENT SCATTERERS USING GEOMETRIC INVARIANT TECHNIQUE (GIT)



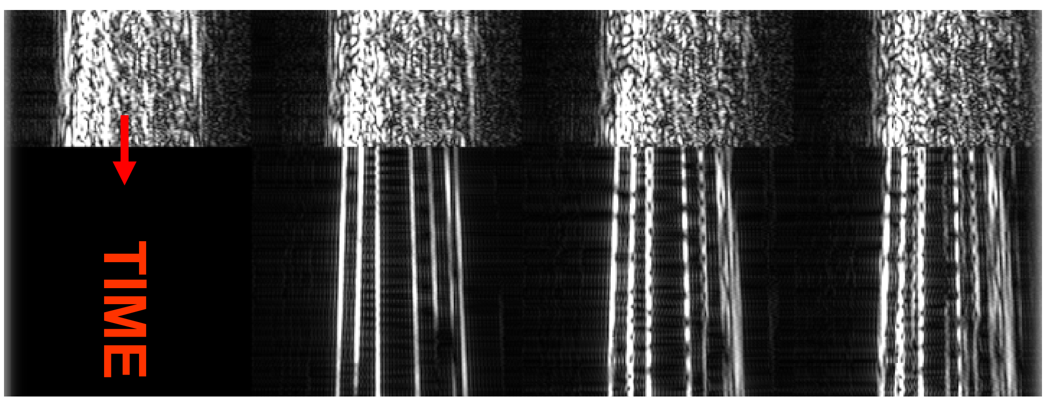
(STUFF, M.,GOOGLE IEEE EXPLORER.IEEE, SHIP & MOTION RECONSTRUCTION FROM 3D & 1D ORTHOGRAPHICALLY

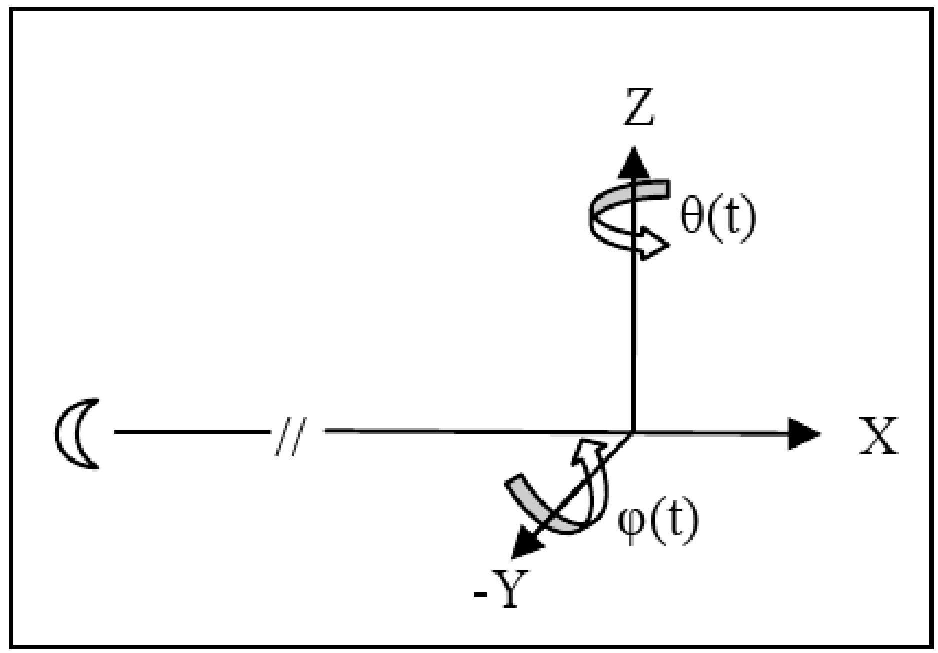
PRINCIPAL COMPONENT ANALYSIS (PCA) FOR INVERSE SYNTHETIC APERTURE RADAR (ISAR) IMAGING OF TARGET WITH UNKNOWN ROTATIONAL MOTION

- GET RANGE HISTORY OF SCATTERS
- PUT INTO ROWS OF A MATRIX R
- FORM COVARIANCE MATRIX $C=R^TR$ (WITH MEANS OF R REMOVED)
- GET PRINCIPAL EIGENVECTORS OF MATRIX C
- GIVES ROTATION AXES OF THE TARGET - AMAZING

$$R_m = [R_{m1}, R_{m2}, \ldots, R_{mN}]$$

$$C=R^TR$$





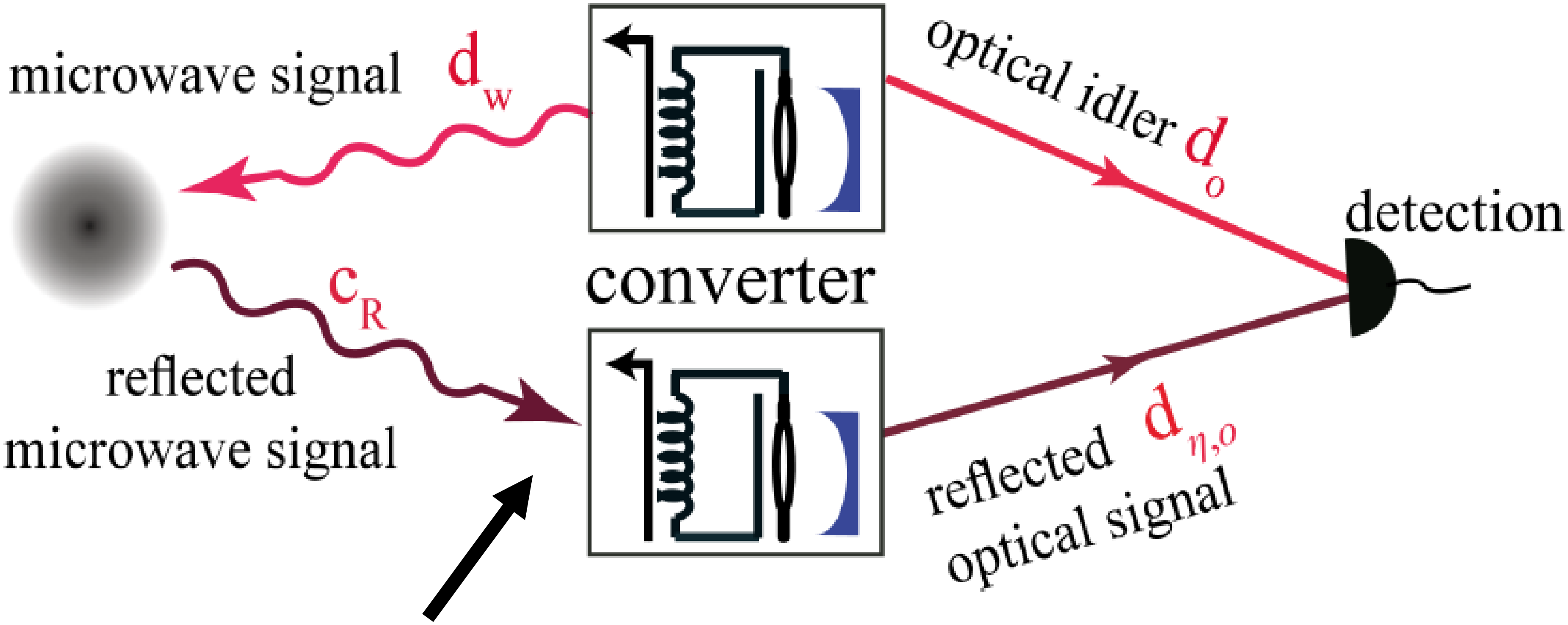
(W. Nel, et al, Radar 2009, Bordeaux, France)

STEALTH DEFEATING QUANTUM RADAR

- MAKES USE OF QUANTUM ENTANGLEMENT
- DETECTION OF SINGLE PHOTON
- CAN BE USED TO DETECT CANCER CELLS
- ELECTRONICS TECHNOLOGY GROUP CORPORATION (CETC) OF CHINA
- TECHNOLOGY USED IN CHINA QUANTUM SATELLITE

HTTPS://WWW.RT.COM/NEWS/358664-CHINA-QUANTUM-RADAR-TEST/

QUANTUM RADAR



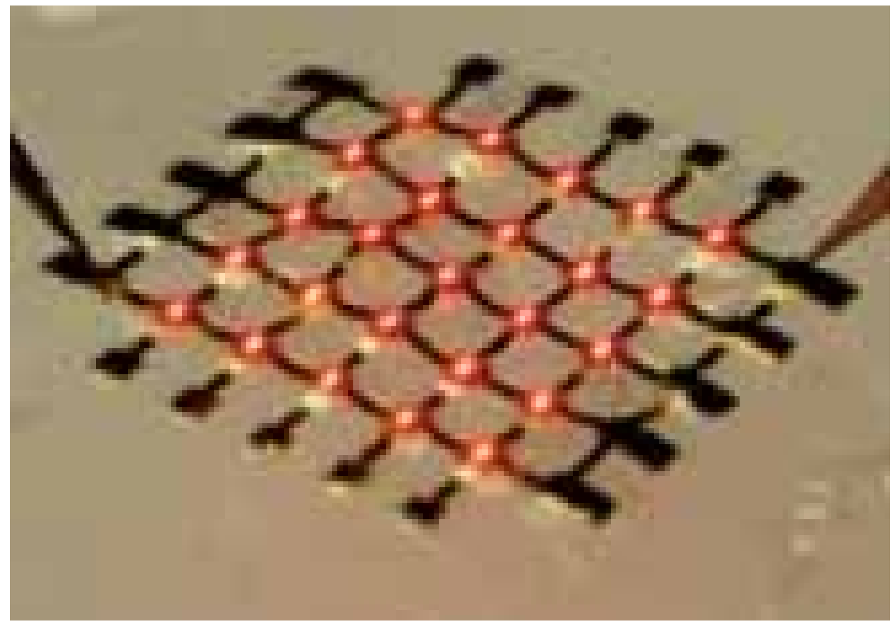
ELECTRO-OPTO-MECHANICAL (EOM) CONVERTER

- **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)

BIODEGRADABLE ARRAY OF LEDs OR TRANSISTORS FOR DETECTING CANCER OR DISPENSING INSULIN

- USES SILK AS STRUCTURE
- TUFT/UN. ILLINOIS

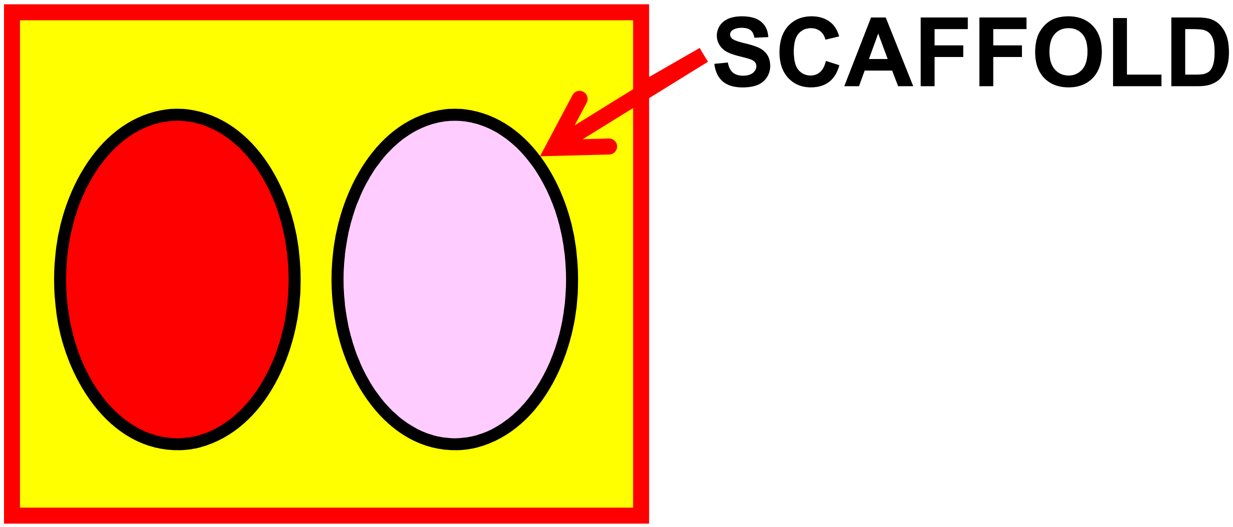


(“EMERGING TECHNOLOGIES”, TECHNOLOGY REVIEW, MAY/JUNE 2010, PP 58-59)

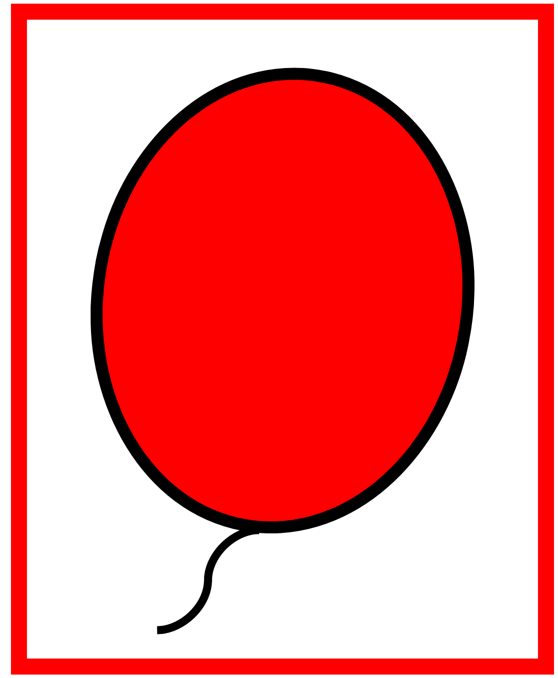
FUZZY LOGIC* EVERYWHERE: IN OUR AUTOFOCUS CAMERAS

***DEVELOPED BY PROF. LOTFI ZADEH**

CAN NOW GROW HEART AND KIDNEY FOR RATS



RAT HEART

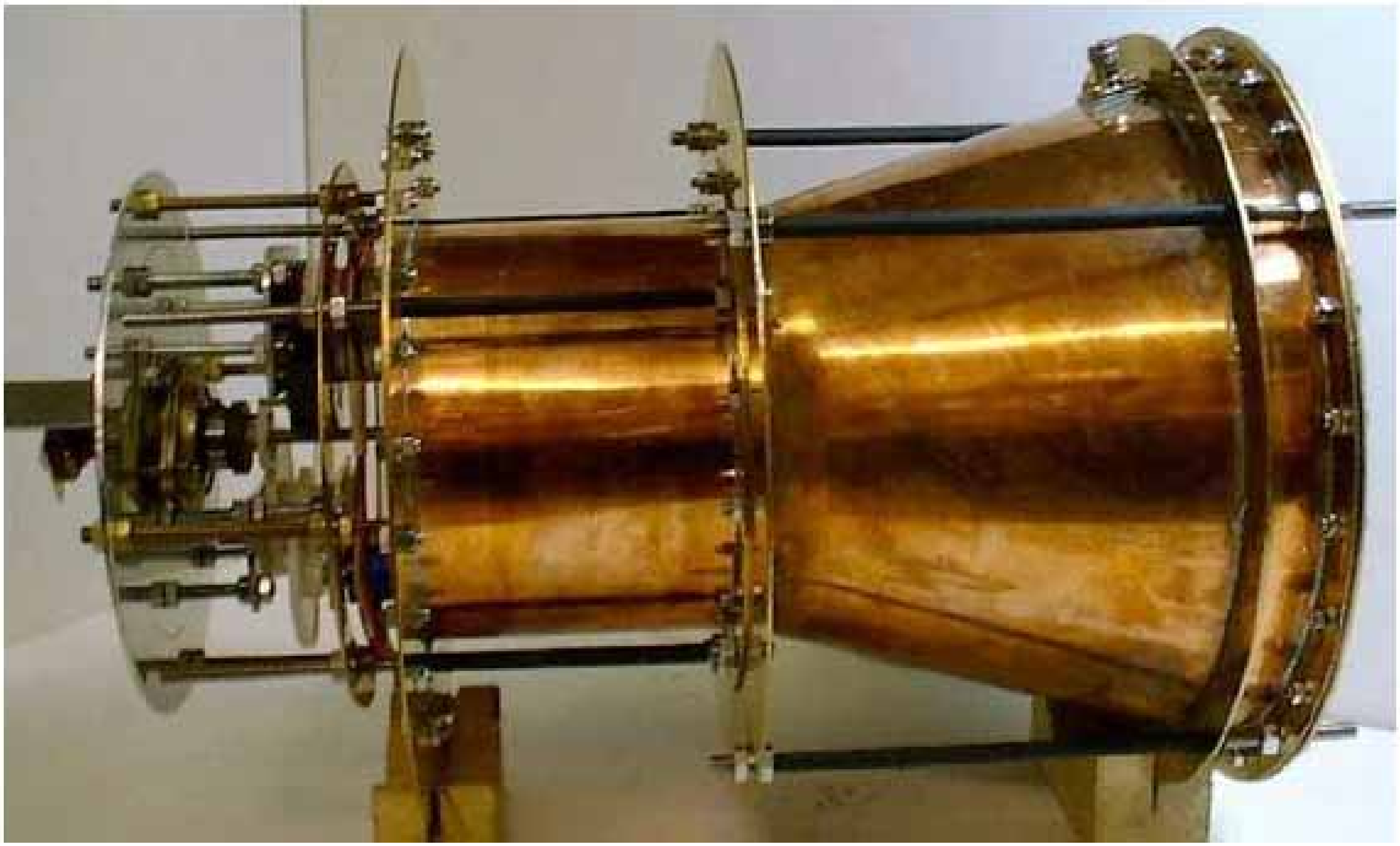


RAT KIDNEY

MASSACHUSETTS GENERAL HOSPITAL

(HAROLD MAASS, THE WEEK, 4/15/13)

THRUST WITHOUT FUEL: GET TO MARS IN 70 DAYS TO MOON IN 4 HRS



http://www.inquisitr.com/3729533/emdrive-nasa-sci-fi-propulsion-system-might-actually-work-emdrive-would-make-mars-70-day-trip-for-elon-musks-spacex/

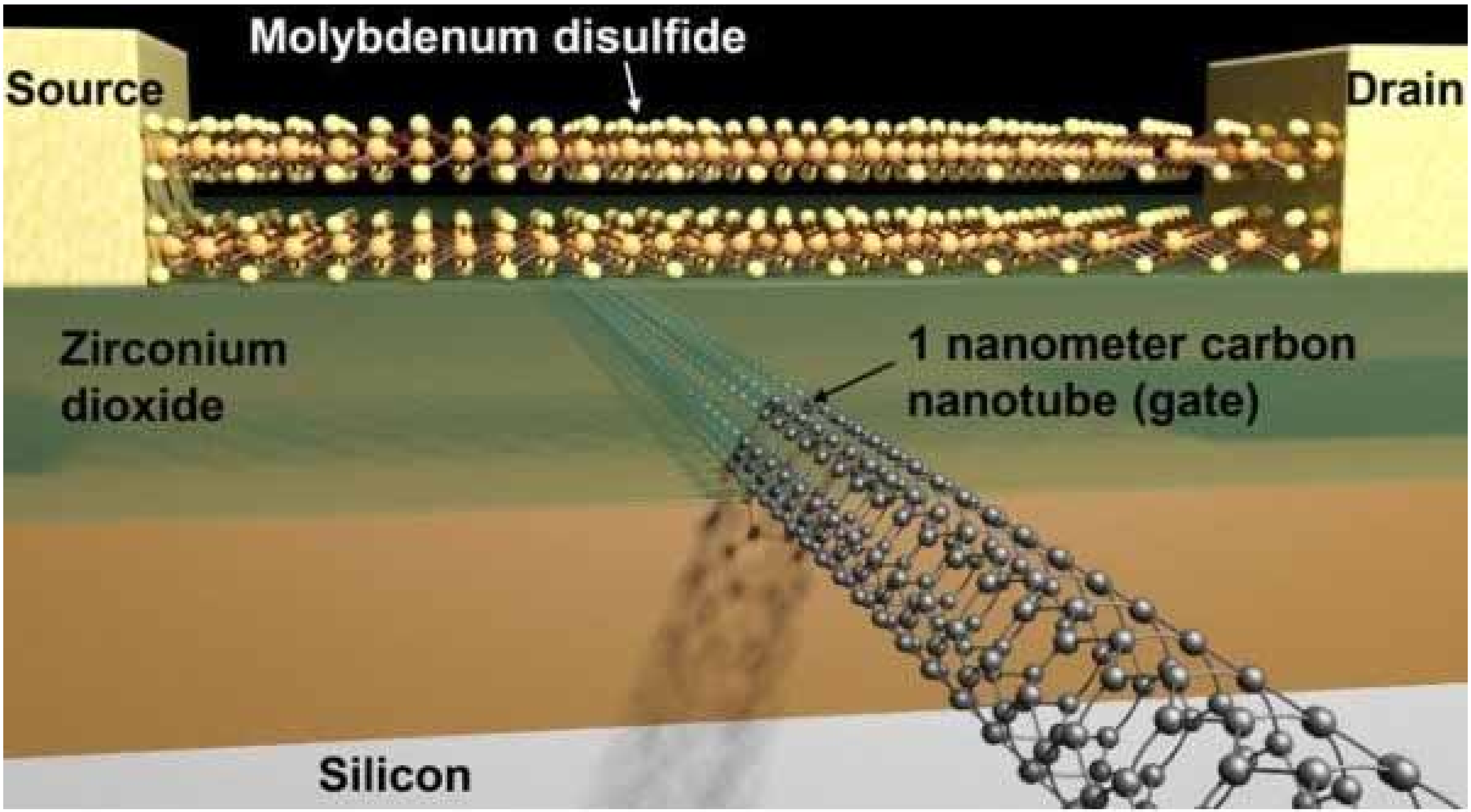
MAGIC LEAP: NEXT BIG THING CHANGE WAY WE WORK, PLAY, SHOP, SEE; COULD KILL $120B FLAT PANEL DISPLAY MARKET, SHAKE $1T ELECTRONICS BUSINESS

RONY ABOVITZ WITH PHOTONIC LIGHTFIELD CHIP

$1.4B VENTURE CAPITAL: GOOGLE, ALIBABA, QUALCOMM

(FORBES MAG., 11/29/2016

BERKELEY LAB TRANSISTOR HAS A GATE WIDTH 1 NM -- 5X SMALLER THAN THE PROJECTED LIMIT



(ENGINEER.COM, 11/27/16; http://www.engineering.com/ElectronicsDesign/ElectronicsDesignArticles/Article

MICROWAVE COOKING USING LDMOS 2450 MHZ RF POWER TRANSISTORS; NXP* SEMICONDUCTORS

*OWNS FREESCALE

CELL PHONE SIZE CAMERA THAT OUT PREFORMS DSLR CAMERA: 28-150 mm; -600mm FUTURE

DR. RAJIV LAROIA

(HTTP://SPECTRUM.IEEE.ORG/CONSUMER-ELECTRONICS/GADGETS/INSIDE-THE-DEVELOPMENT-OF-LIGHT-THE-TINY-DIGITAL-CAMERA-THAT-OUTPERFORMS-DSLRS)

DR. RAJIV LAROIA, SPTECTRUM, NOV. 2016

ROBOTIC KISS TRANSMITTER LETS YOU SMOOCH A LOVED ONE FROM AFAR; "KISSENGER" DEVICE USES HAPTIC TECH

HTTP://SPECTRUM.IEEE.ORG/THE-HUMAN-OS/BIOMEDICAL/DEVICES/ROBOTIC-KISS-TRANSMITTER-LETS-YOU-SMOOCH-A-LOVED-ONE-FROM-AFAR?UTM_MEDIUM=EMAIL&BT_ALIAS=EYJ1C2VYSWQIOIAIMZMZZJJMN2


FIRST PRODUCTION CAR WITH
RETRACTABLE 3D LIDAR
Pulsing lasers intelligently map the world
around you to provide the safest ride
possible, regardless of weather.

PERSONAL ASSISTANT CONSUMER-FRIENDLY ROBOT KURI MADE BY MAYFIELD $699

ANSWERS QUESTONS AND CAN MONITORS PEOPLE, PETS & THINGS WHEN YOU’RE NOT HOME

ROBOT COZMO CAN RECOGNIZE YOUR
FACE, CALL YOU BY YOUR NAME,
RESPONDS EMOTIONALLY,
PLAYS GAMES, DANCES AND TALKS TO
ALL FOR $180,USES AI; MADE BY
ANKI

MIMO

(SEE: E. BROOKNER, MIMO RADAR DEMYSTIFIED, MICROWAVE J., 1/2013, RADARCON 2009, PASADENA, CA; J. LI & P. STOICA, MIMO RADAR SIGNAL PROCESSING, WILEY, '09; FRAZER, ET AL, RADARCON 2008, ROME, ITALY)

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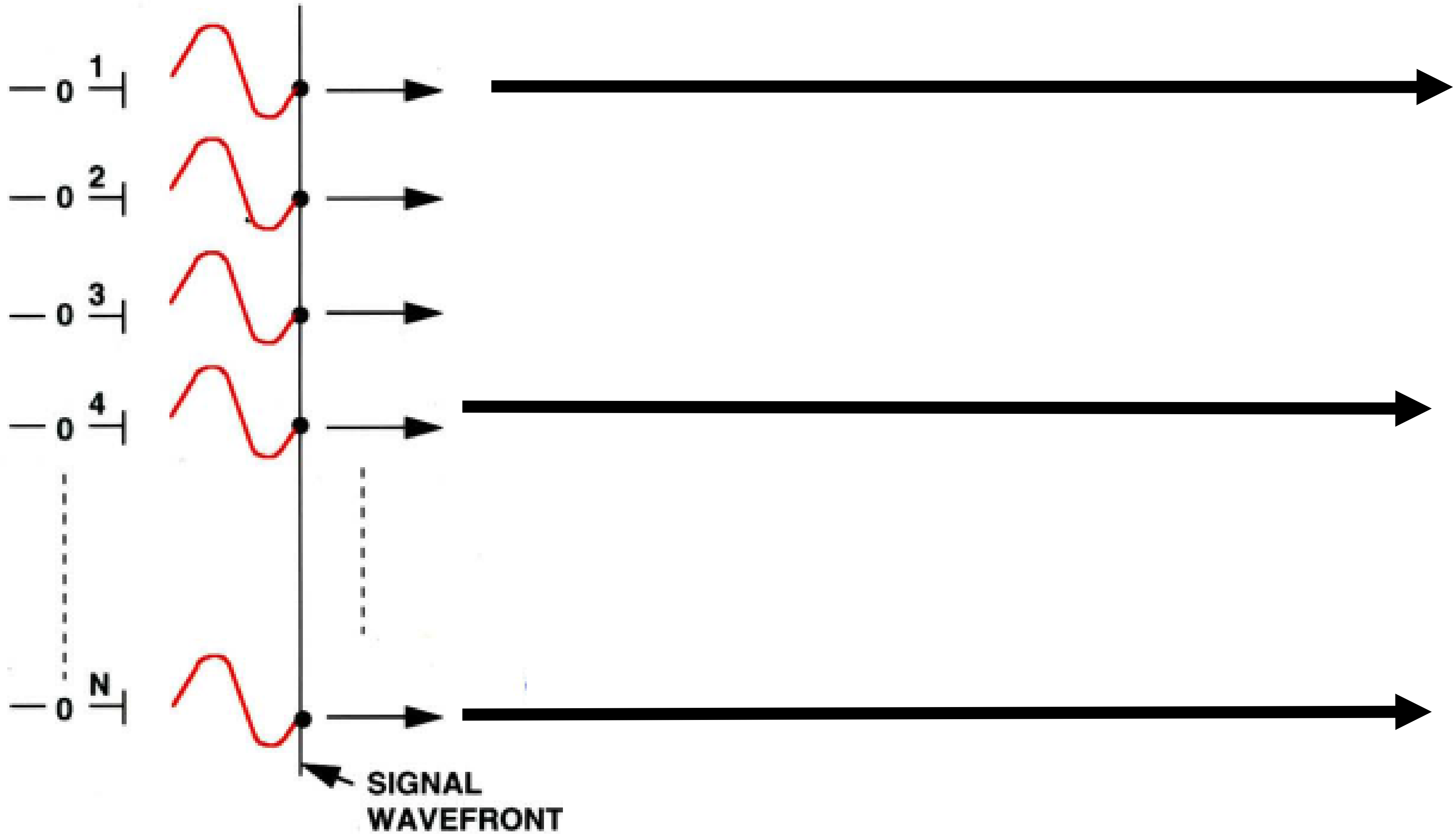
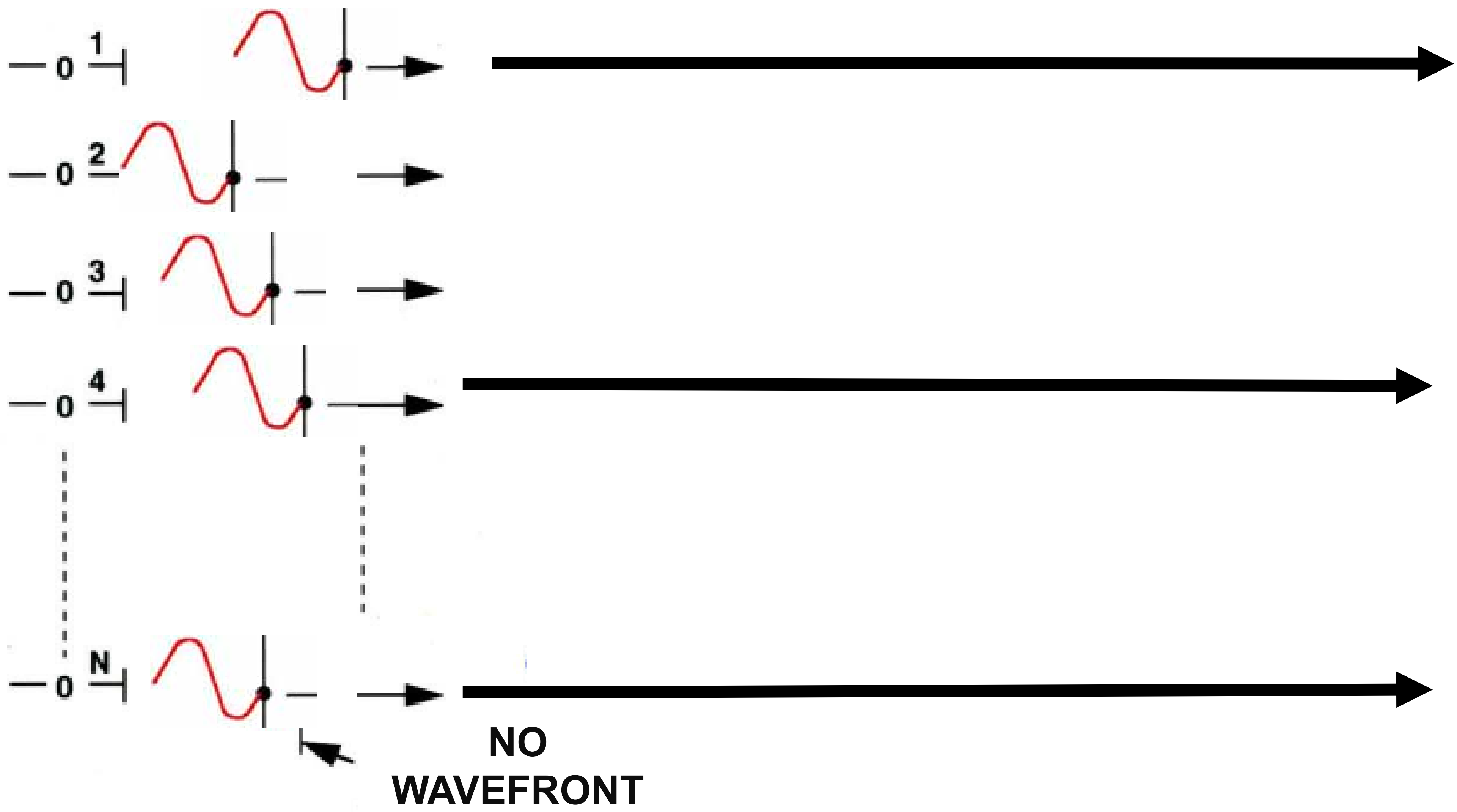
HOW CONVENTIONAL PHASED ARRAYS WORK



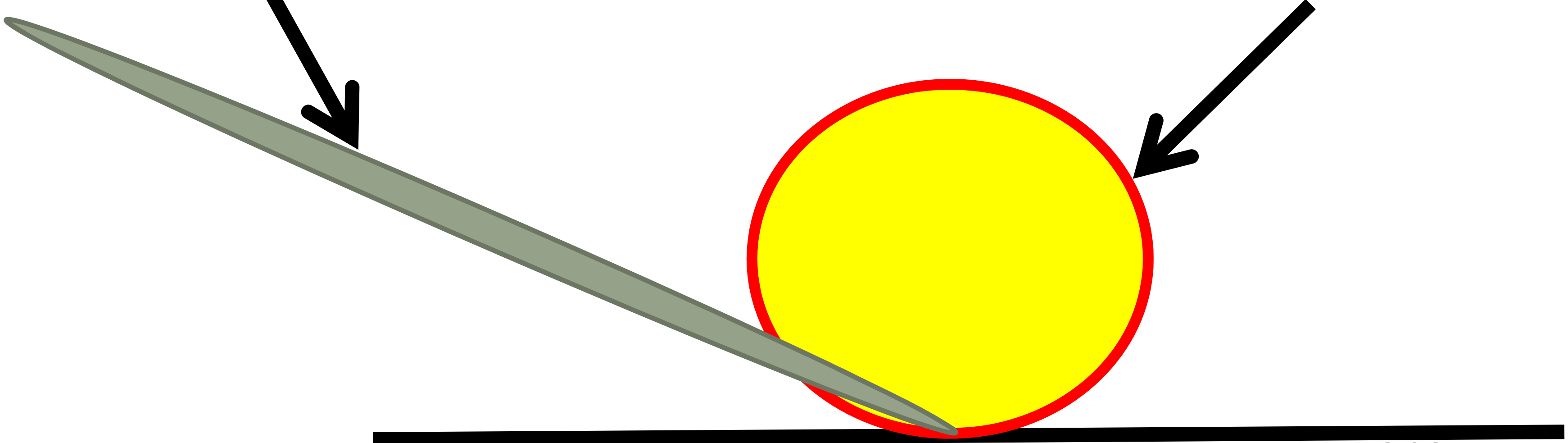
HOW MIMO PHASED ARRAYS WORK



WITH MIMO NO FOCUSED BEAM ON TRANSMIT

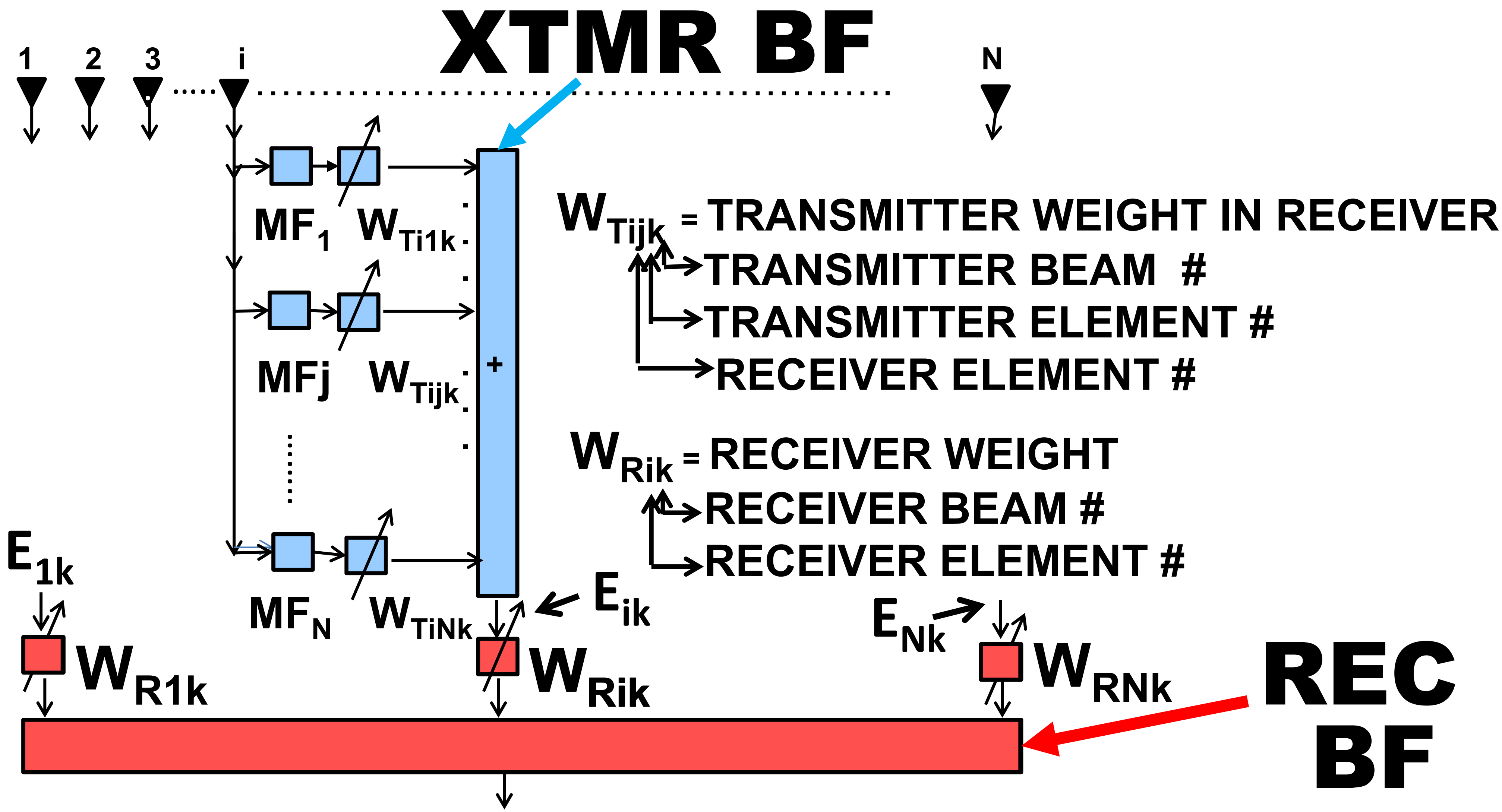
CONVENTIONAL ARRAY BEAM FOCUSED, BW≈10°

MIMO BEAM = ELEMENT BW ≈ 120° , NOT FOCUSED



MIMO MONOSTATIC ARRAY

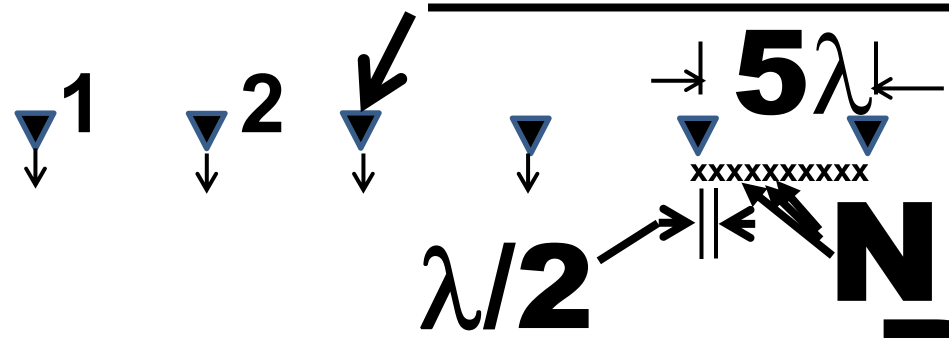
XTMR/REC BEAMFORMER (BF) IN RECEIVER



E_k = kth BEAM OUTPUT

MIMO WITH COLOCATED THIN/FULL ARRAYS

N=10 EL THIN TRANS ARRAY



N=10 EL FULL REC ARRAY

EQUIVALENT TO:

100 EL FULL ARRAY:

MIMO HAS N=10 TIMES ACCURACY & RESOLUTION AS CONVENTIONAL ARRAY OF 10 EL

FOR N=100, 100X ACCURACY & RESOLUTION AS CONVENTIONAL ARRAY

FOR N=1000, 1000X ACCURACY & RESOLUTION AS CONVENTIONAL ARRAY

CONCLUDE:

MIMO HAS ORDERS OF MAGNITUDE BETTER RESOLUTION & ACCURACY THAN CONVENTIONAL ARRAY

NOT TRUE

NOT

TRUE

CONVENTIONAL ARRAY CAN HAVE SAME RESOLUTION & ~ACCURACY AS MIMO ARRAY

WHEN RIGHT CONVENTIONAL EMPLOYED & USED PROPERLY

CLAIM MIMO RADAR CAN USE SPARCE ARRAY

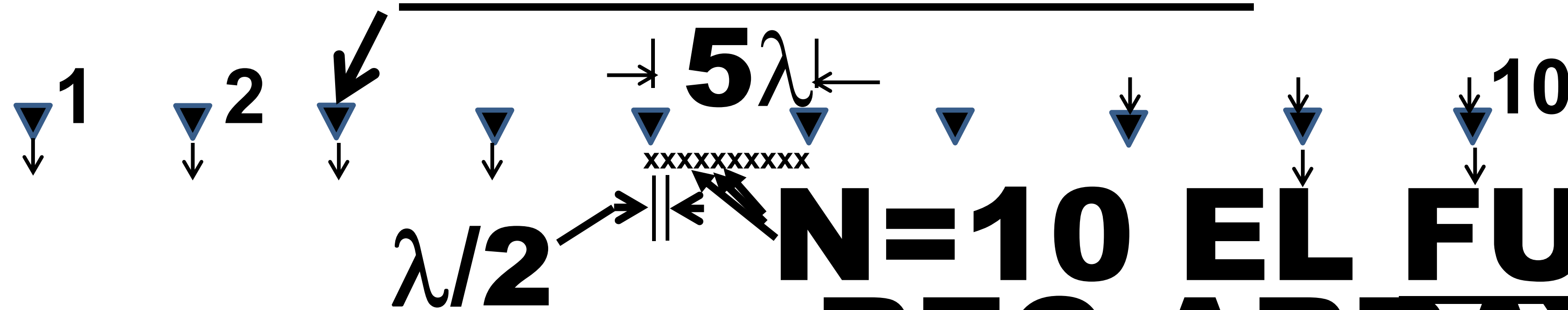
NOT TRUE

NOT

TRUE

MIMO WITH COLOCATED THIN/FULL ARRAYS

N=10 EL THIN TRANS ARRAY



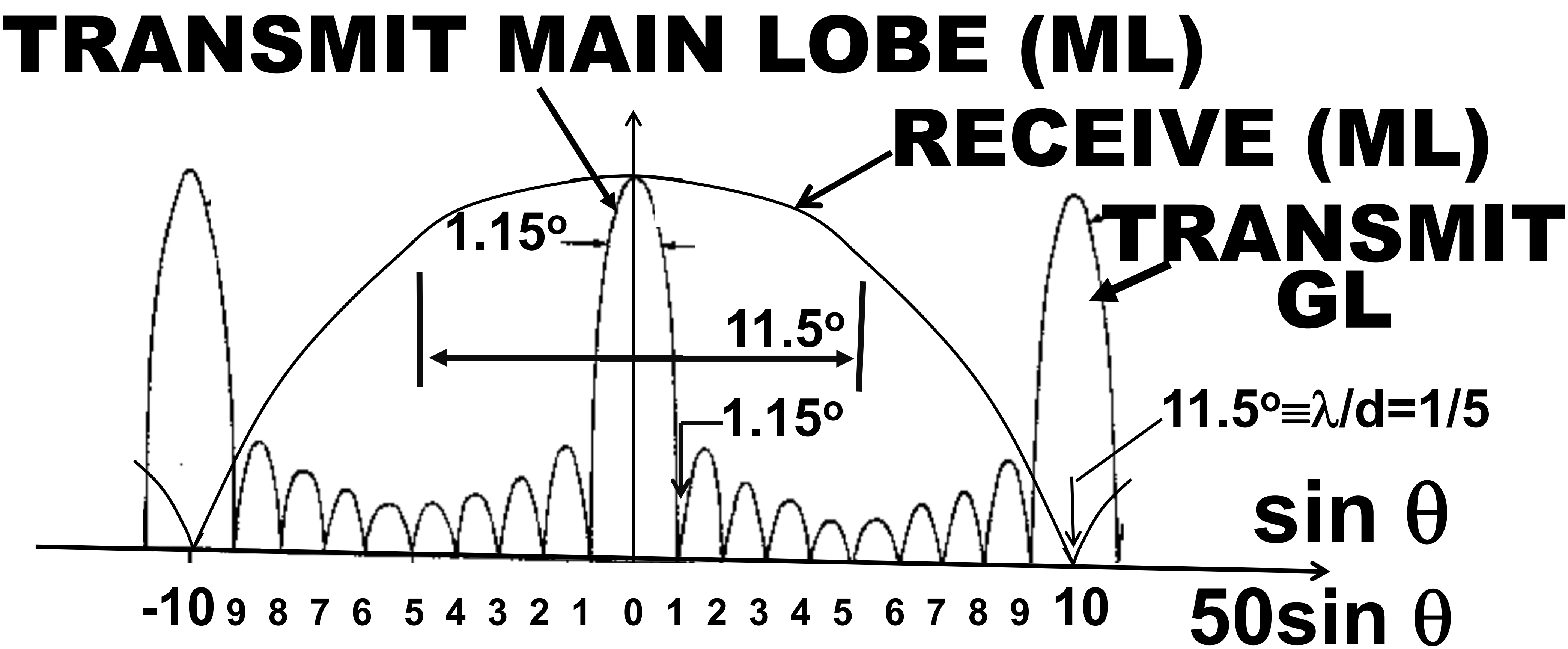
N=10 EL FULL REC ARRAY

EQUIVALENT TO:

100 EL FULL ARRAY:

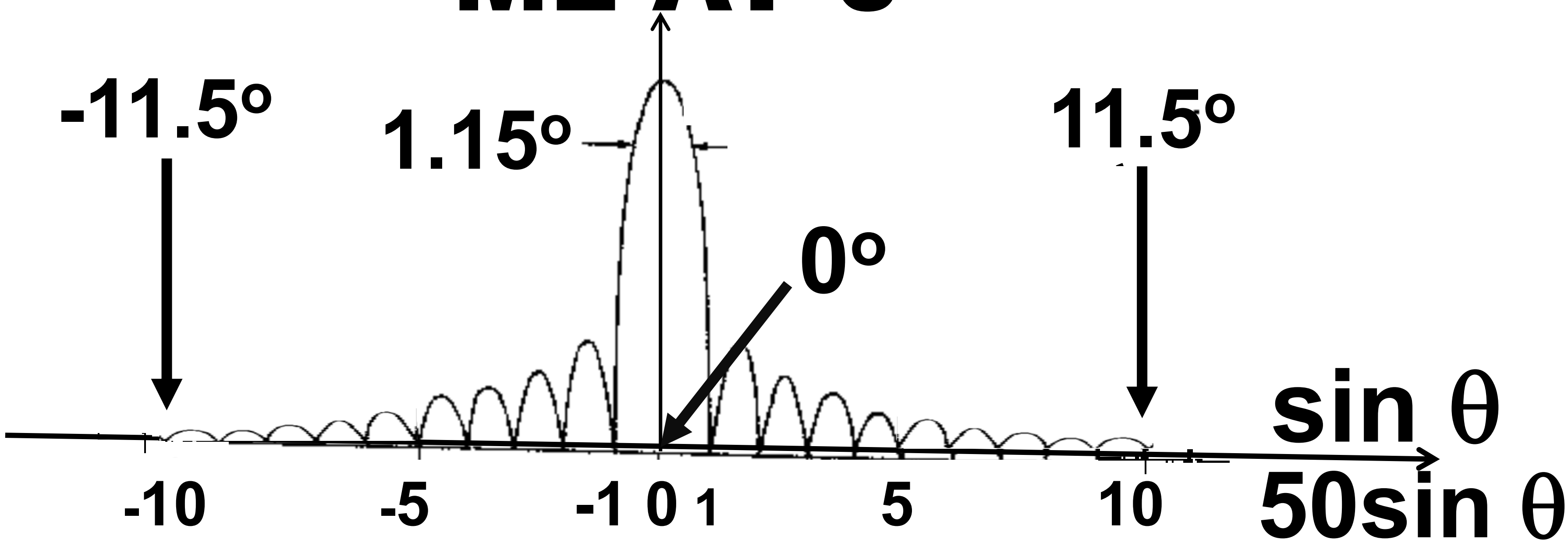
THIN/FULL ARRAY AS CONVENTIONAL ARRAY FOR N=10

1-WAY ANTENNA PATTERNS



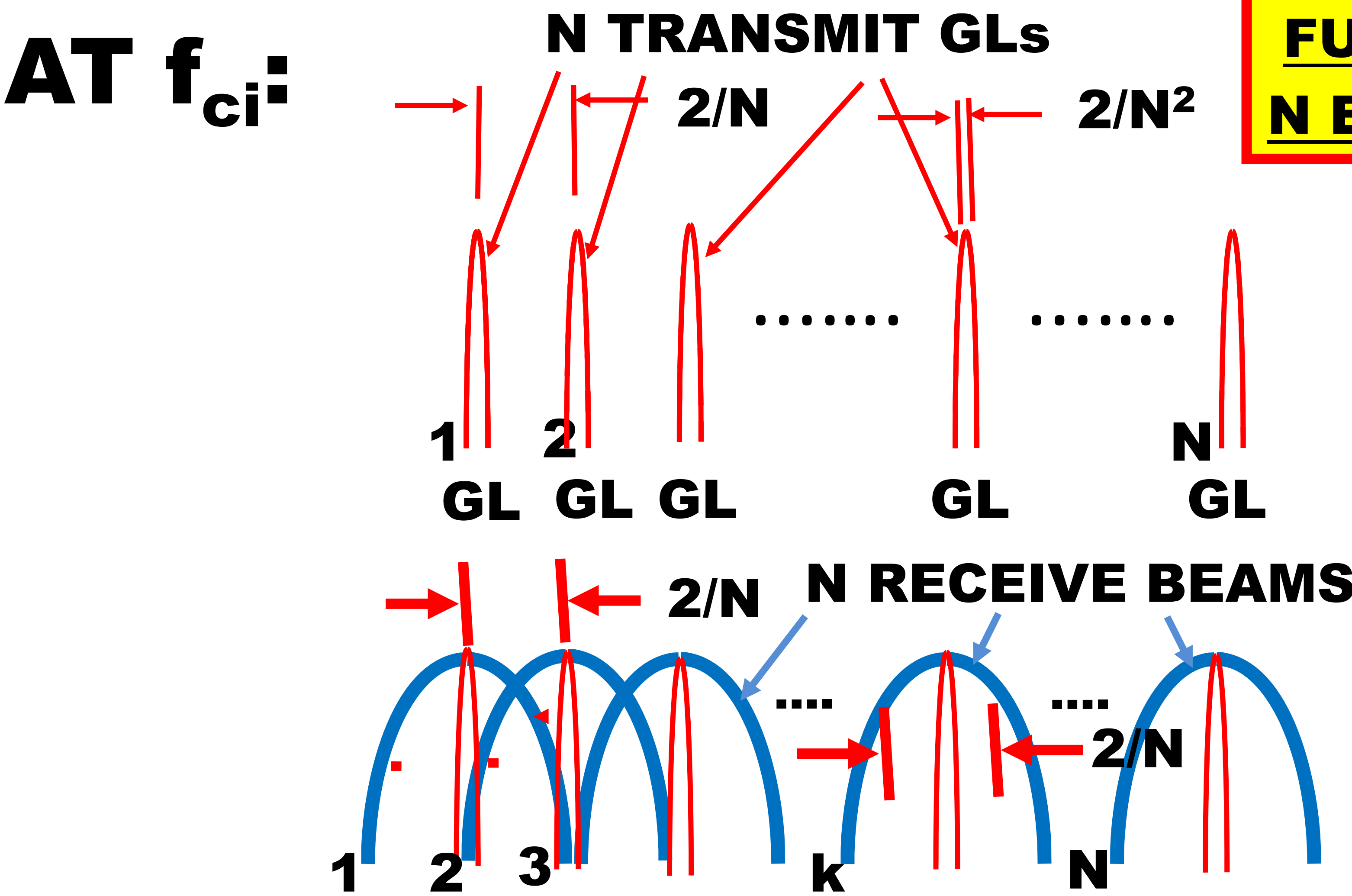
THIN/FULL ARRAY AS CONVENTIONAL ARRAY

2-WAY ANTENNA PATTERN
NO GRATING LOBES
ML AT 0°



CONVENTIONAL THIN/FULL LINEAR ARRAY

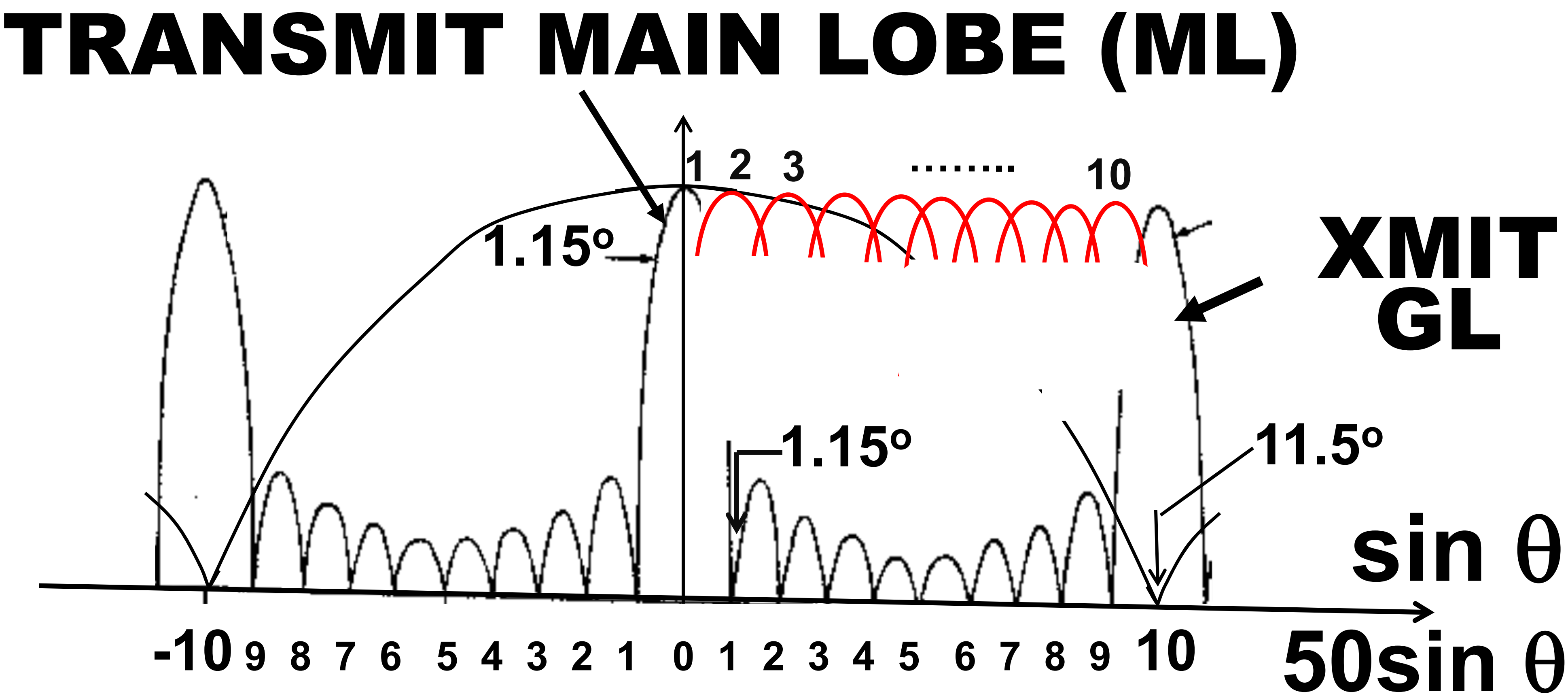
THIN ON XTRM
FULL ON REC;
N ELEMS EACH



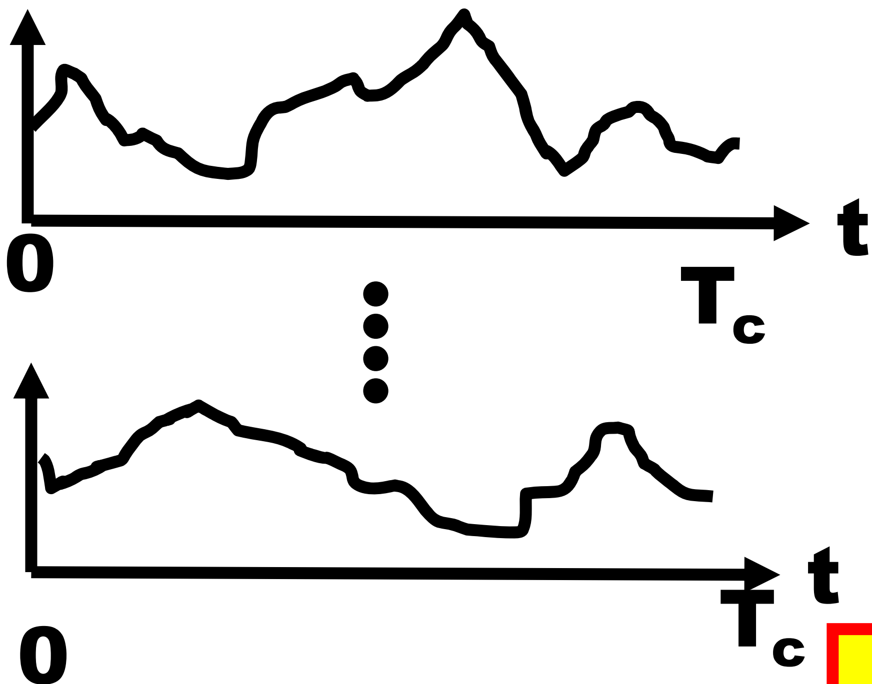
FORM N MLs ON ONE XTRM

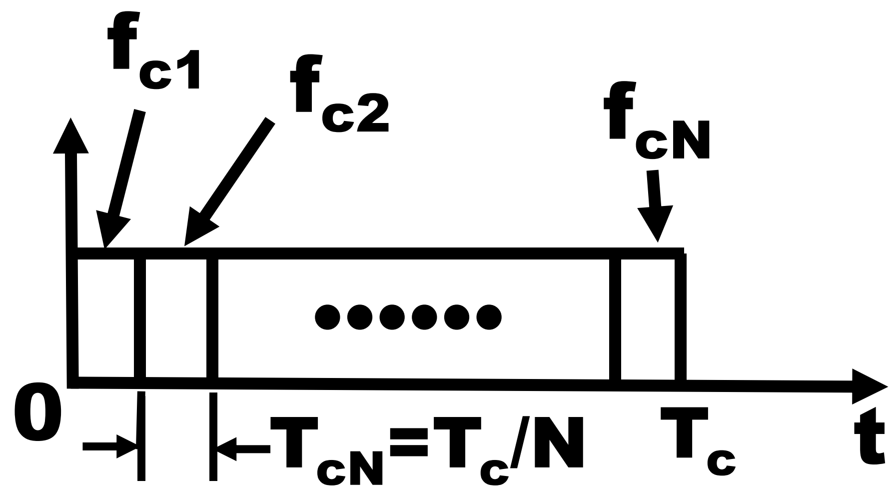
THIN/FULL ARRAY AS CONVENTIONAL ARRAY FOR N=10

1-WAY ANTENNA PATTERNS



WAVEFORMS FOR MIMO THIN/FULL ARRAY & CONVENTIONAL EQUIVALENT:

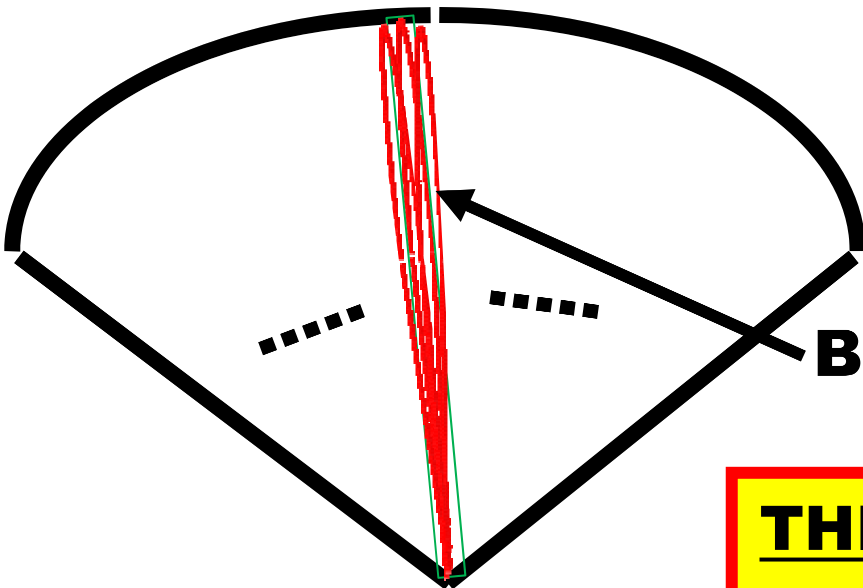




MIMO ARRAY:
N ORTHOGONAL WAVEFORM

CONVENTIONAL:
N CHIRP WAVEFORM AT N CARRIER FREQS, f_{ci}, $i=1-N$, MACHINE GUNNED

MIMO THIN/FULL ARRAY & CONVENTIONAL EQUIVALENT: LINEAR ARRAYS OF N ELEMENTS; VOLUME SEARCH OF 120°

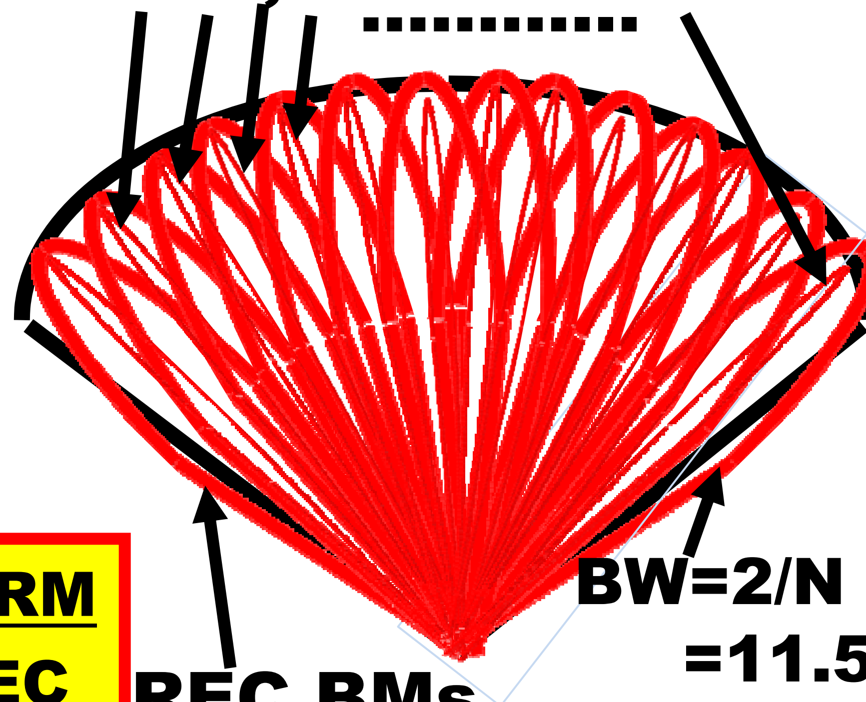


THIN ON XTRM

FULL ON REC

MIMO ARRAY:
N^2 BEAMS
OF BW $2/N^2$

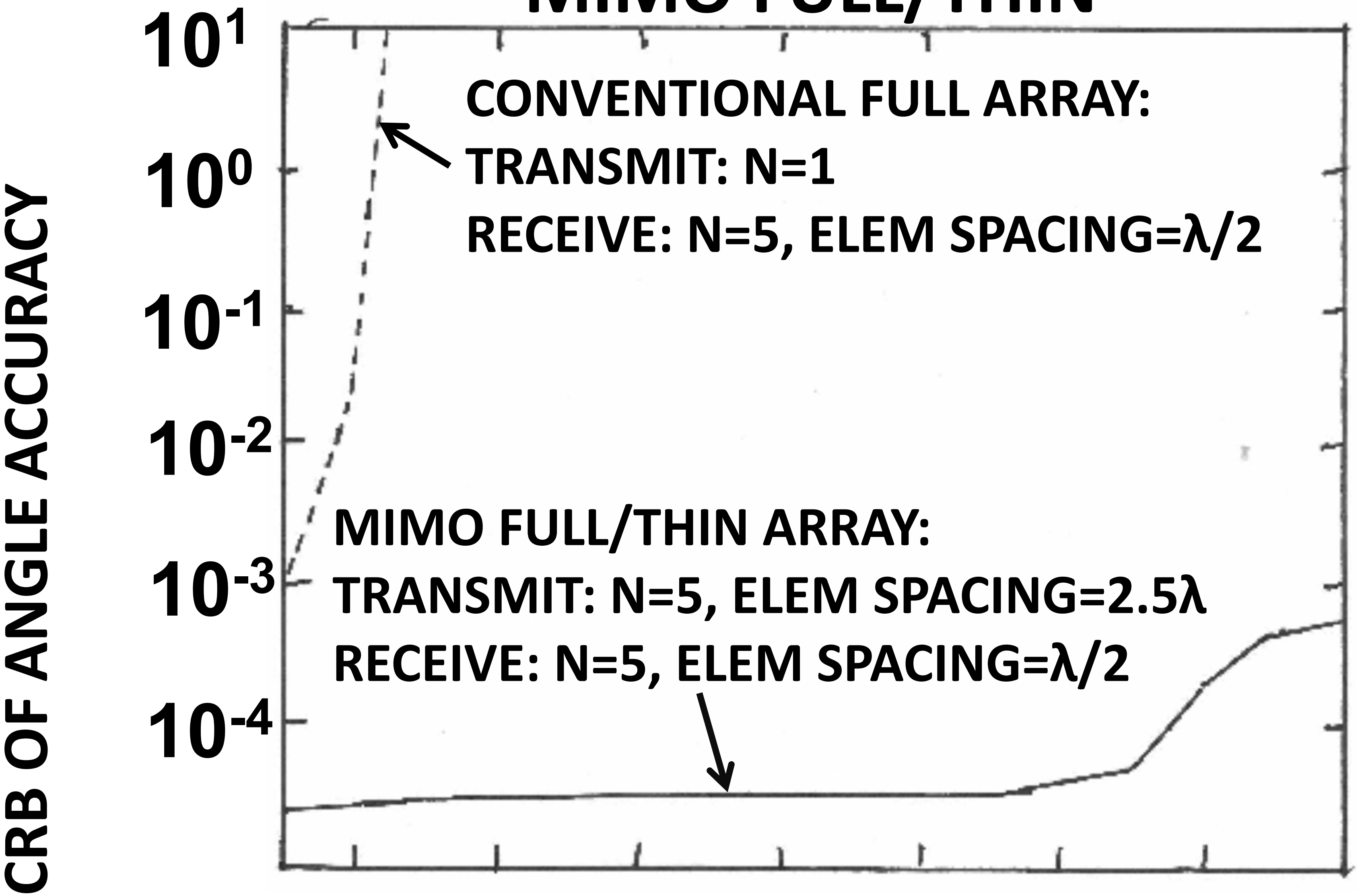
FOR N=10
2/N=11.5°
$2/N^2$=1.15°
ON BORESIGHT



CONVENTIONAL:
SEQUENTIALLY
XTRM N SETS OF
N ALs HAVING
BWs=$2/N^2$ & 2/N
SPACING. EACH SET
IS AT A DIFF f_c.

NOTE: ALs=AMBIGUOUS LOBES; BMs=BEAMs; BW=BEAMWIDTH; BWs GIVEN IN u-SPACE, u=SINθ; f_c=CARRIER FREQ.

CLAIM: MIMO 5X BETTER AT IDENTIFIABLITY --- WRONG COMPARISON: CONVENTIONAL FULL VS MIMO FULL/THIN



NUMBER OF TARGETS 8^o APART IDENTIFIED

(AFTER J.LI, ET AL, IDENTIFIABILITY, IEEE SIG PROC LETT, 12/07, PP. 968-971)

MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO) AT THAIPUSAM FESTIVAL, SINGAPORE

THAIPUSAM FESTIVAL SINGAPORE

DR. ELI BROOKNER

MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO) AT THAIPUSAM FESTIVAL, SINGAPORE

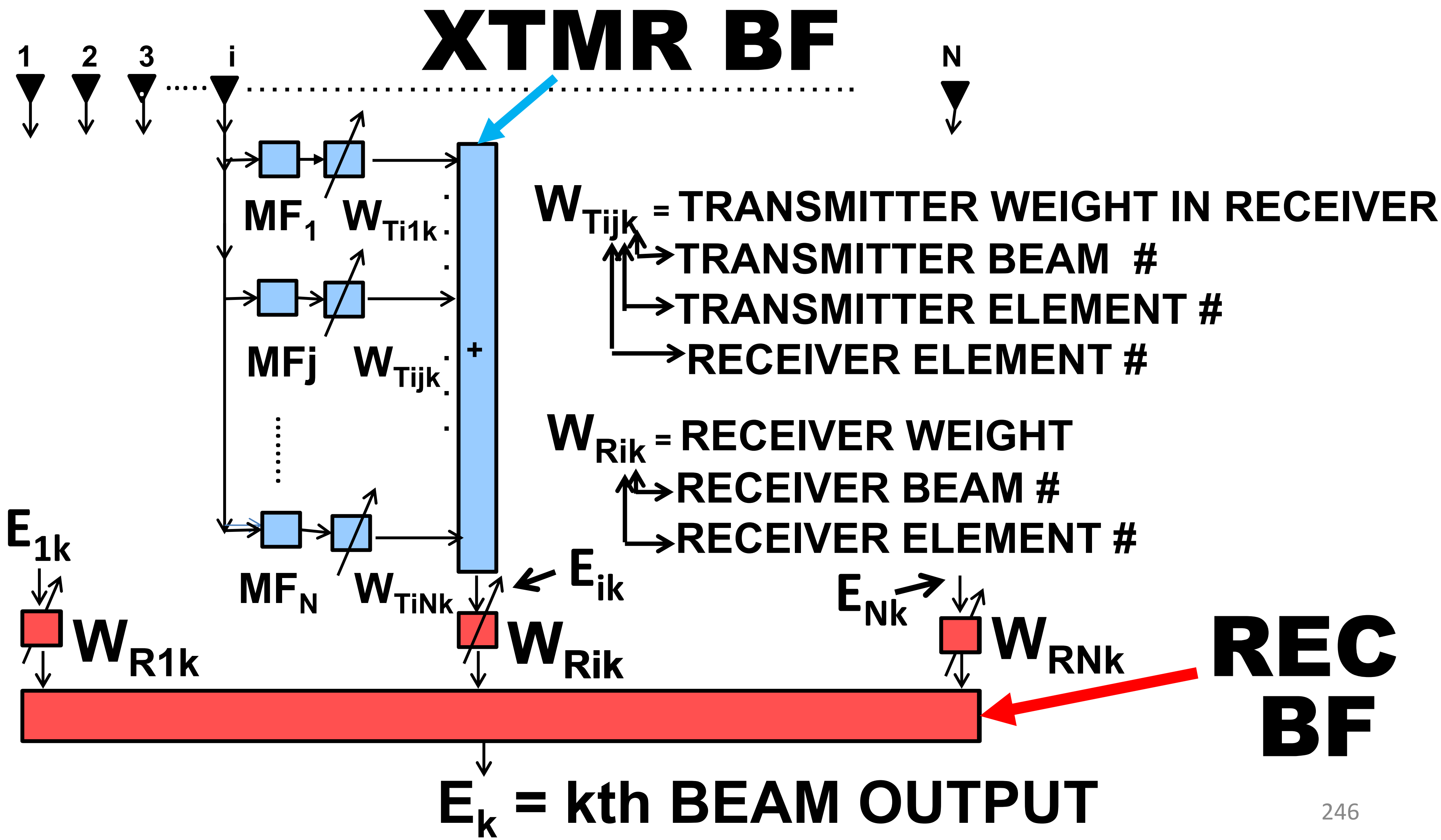
MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO) AT THAIPUSAM FESTIVAL, SINGAPORE

CAN A MIMO ARRAY RADAR HAVE BETTER ACCURACY THAN ITS EQUIVALENT CONVENTIONAL ARRAY RADAR?

CLAIM:
YES
FOR
MONOSTATIC
ARRAY RADAR

MIMO MONOSTATIC ARRAY

XTMR/REC BEAMFORMER (BF) IN RECEIVER



BUT ANGLE ACCURACY ONLY $\sqrt{2}=1.414$ BETTER.

BUT
NOT
ALWAYS

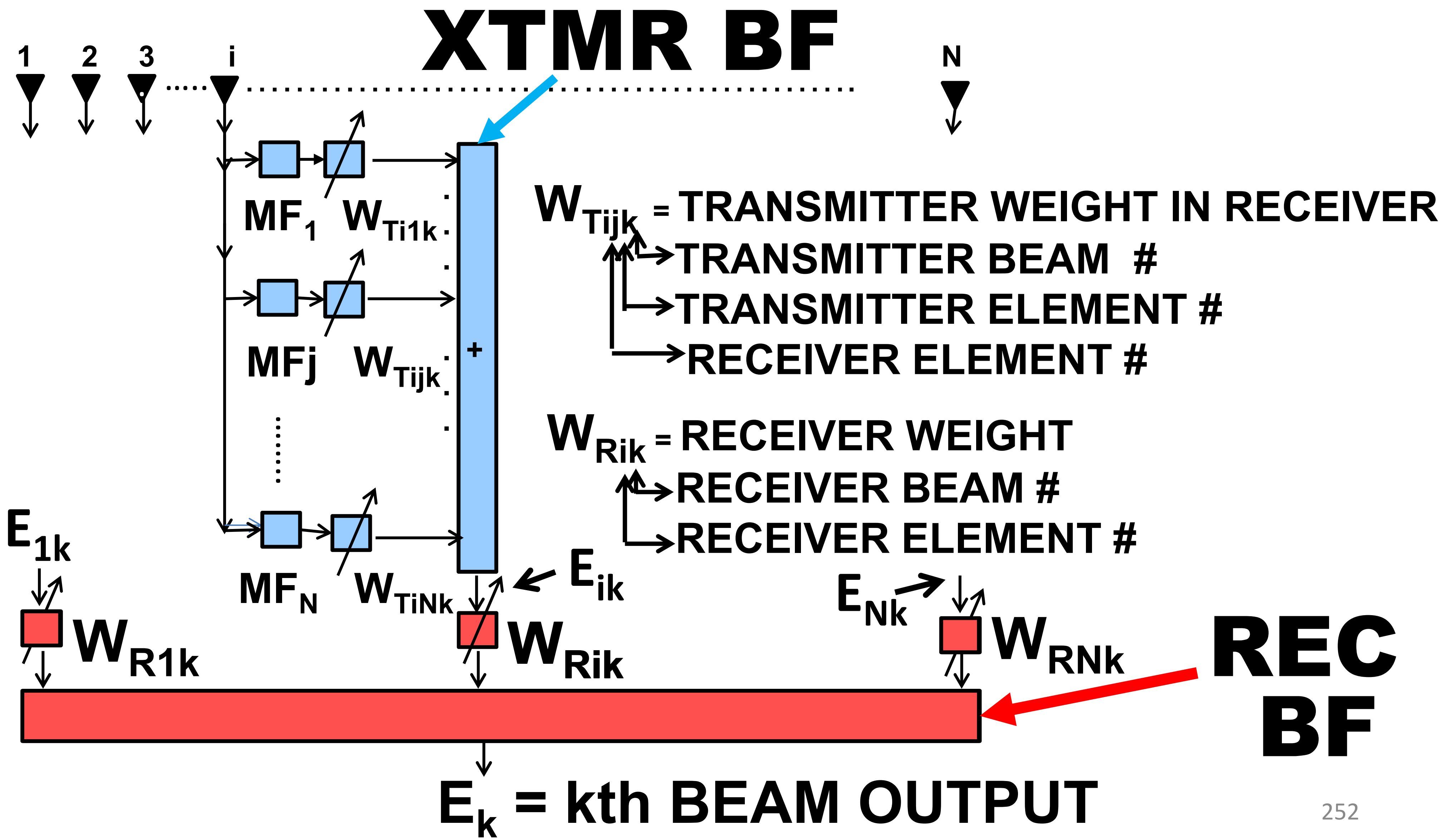
ALSO MIMO TYPICALLY HAS LARGE SIGNAL PROCESSING LOAD

ALSO MONOSTATIC MIMO & CONVENTIONAL FULL ARRAYS HAVE ABOUT SAME ANGLE RESOLUTION

SIGNAL PROCESSING LOAD

MIMO MONOSTATIC ARRAY

XTMR/REC BEAMFORMER (BF) IN RECEIVER



EXAMPLE:

N=100, F=30

NEED

FN^2=300,000 MFs

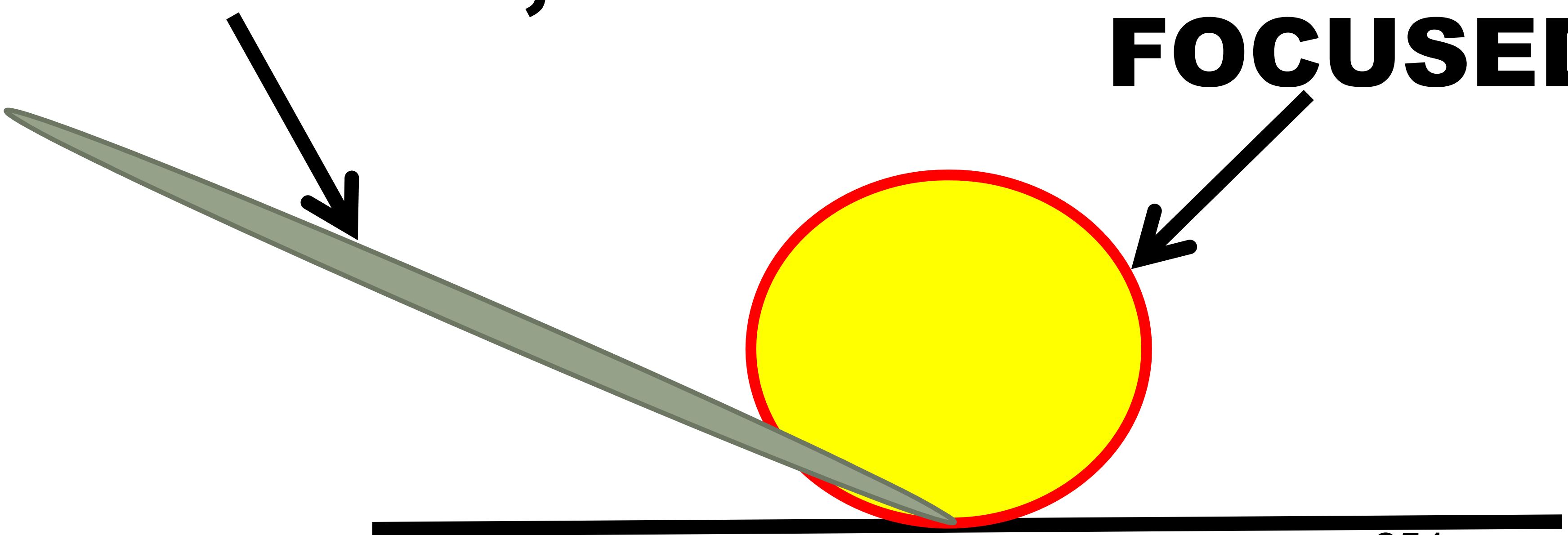
OR FN=3,000

MORE MFs

WITH MIMO NO FOCUSED BEAM ON TRANSMIT

CONVENTIONAL ARRAY BEAM FOCUSED, BW≈10º

MIMO BEAM = ELEMENT BW ≈ 120º , NOT FOCUSED

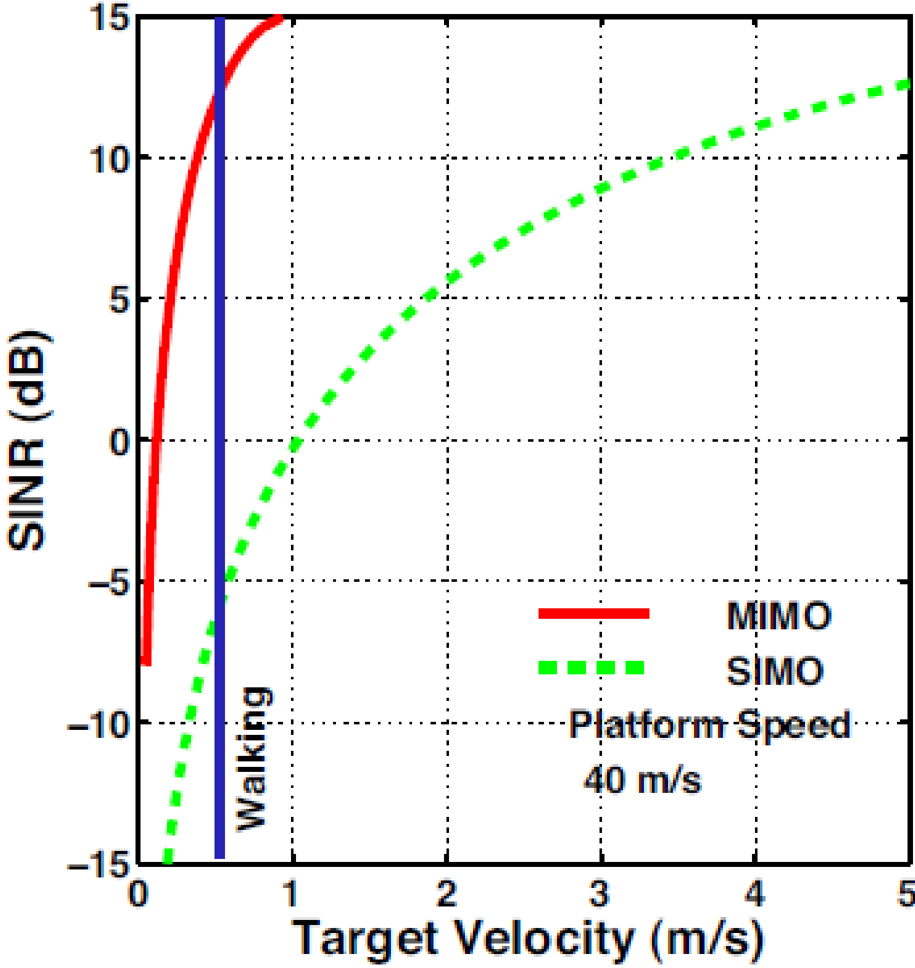


MIMO FOR SEARCH

CONV FOR TRACK

IS MIMO BETTER FOR GMTI? NO!

CONVENTIONAL MIMO SHOULD DO AS WELL USING SAME THIN/FULL ARRAY & SAME COHERENCE TIME



ASSUMPTIONS:

BOTH: fc=2GHz, PRF=7.2 KHz

MIMO: THIN/FULL ARRAY, N=5

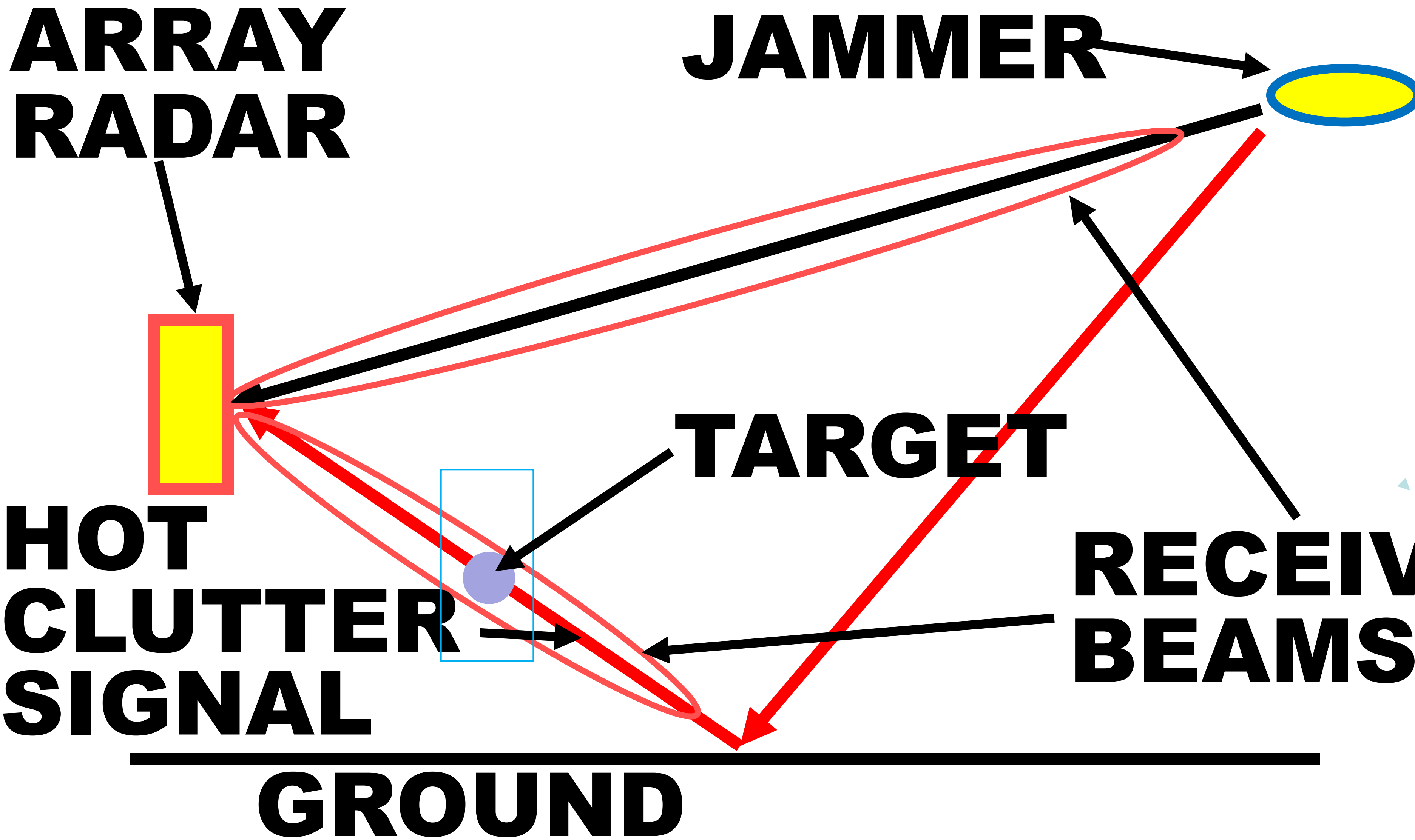
SIMO(CONVENTIONAL): FULL ARRAY, N=5

(PLOT FROM: D. BLISS, ET AL, GMTI MIMO Radar, 2009 International Waveform Diversity & Design Conf.)

CLAIM

MIMO HANDLES HOT CLUTTER, CONVENTIONAL CAN NOT

HOT CLUTTER


ARRAY
RADAR
JAMMER
TARGET
HOT
CLUTTER
SIGNAL
RECEIVE
BEAMS
GROUND

NOT TRUE

NOT

TRUE

CONVENTIONAL ARRAY CAN CANCEL HOT CLUTTER

CLAIM

MIMO BETTER FOR REPEATER JAMMER

NOT TRUE

NOT

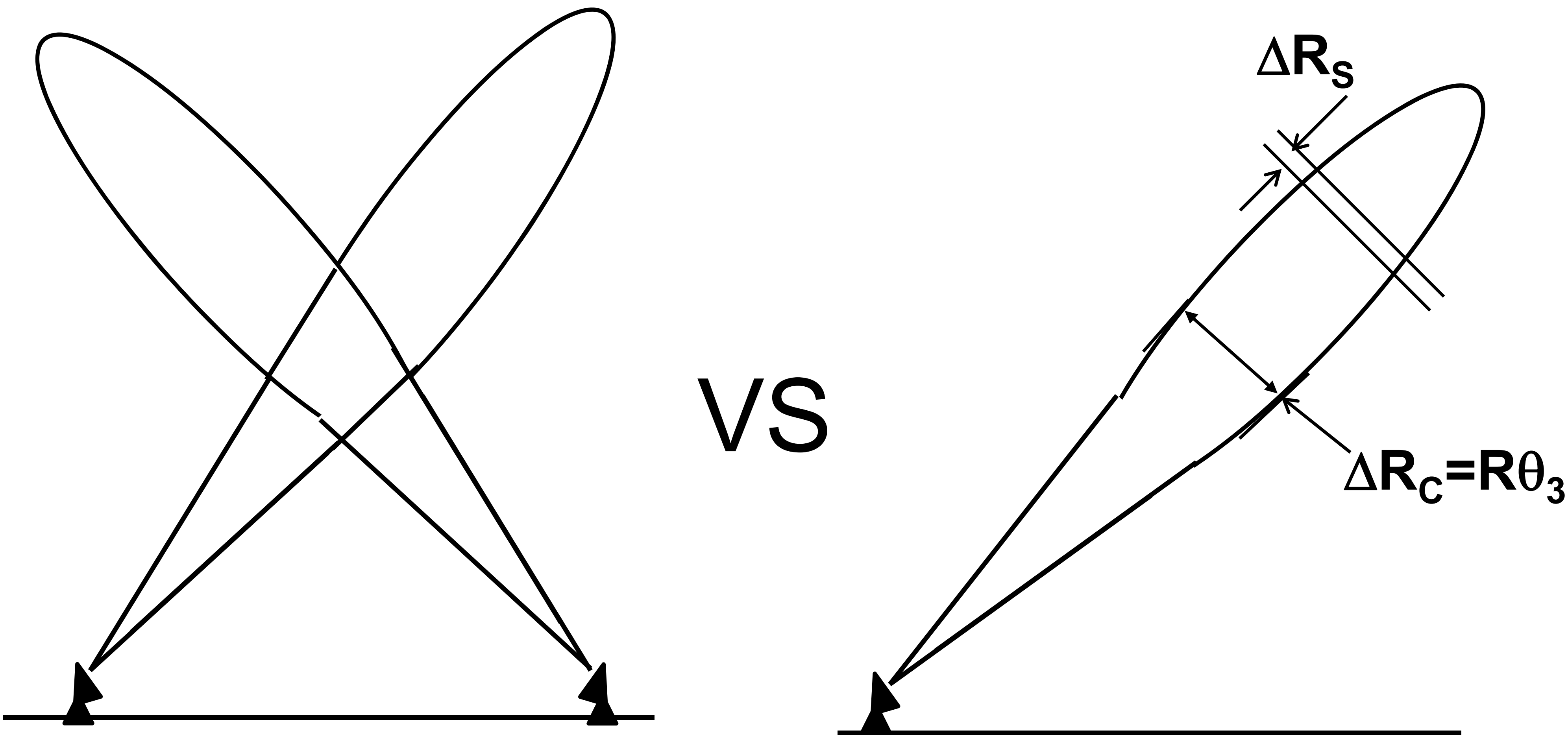
TRUE

MIMO NO BETTER FOR REPEATER JAMMER

BARRAGE JAMMER CANCELLATION SAME FOR CONVENTIONAL AS FOR MIMO

BARRAGE JAMMER CANCELLATION SAME FOR CONVENTIONAL AS FOR MIMO

BISTATIC MIMO VS CONVENTIONAL MONOSTATIC SYSTEMS: APPLES & ORANGES COMPARISON



BISTATIC MIMO RADAR

MONOSTATIC CONVENTIONAL RADAR

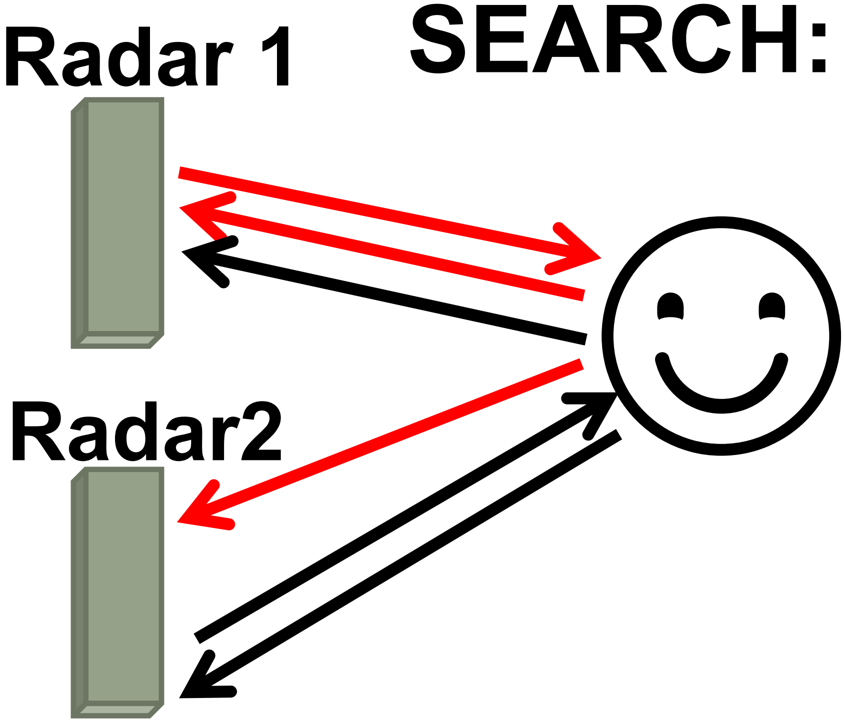
WHERE MIMO MAKES SENSE

NEAR TERM APPLICATION OF MIMO: COHERENT COMBINING OF RADARS

HERE **N=2**

FOR TRACK: **9DB PAG** ADVANTAGE

SEARCH: **6DB PA** ADVANTAGE



DO NOT NEED ORTHOGONAL WAVEFORMS

(BOB ENZMANN/GEORGE THOME & LEON GREEN PATENTS;
SEE ALSO: COUTTS & COUMO, IEEE SAM 2006,BOSTON;
AND BROOKNER, ET AL, PATENT, US 2005/0231420 A1, 10/20/2005
)

ANOTHER POTENTIAL APPLICATION OF MIMO

AUTOMOBILE RADARS AT 70 GHZ WITH 4 GHZ BW SIGNALS

ANOTHER POTENTIAL NEAR TERM APPLICATION OF MIMO

OTH RADARS

ARE THERE ANY OPERATIONAL MIMO RADARS?

NO

WHAT WOULD I DO TODAY IF I NEEDED ORDERS OF MAGNITUDE BETTER ACCURACY AT LOW COST?

I WOULD USE CONVENTIONAL THIN/FULL ARRAY NOT MIMO

WHERE MIMO USEFULL?

PRESENT VERY SUCCESSFUL USE OF MIMO

COMMUNICATION IN PRESENCE OF MULTIPATH

BROOKNER MIMO REFS:

[1] E. Brookner, MIMO Radar: Demystified, Microwave J, Jan. 2013

[2] E. Brookner, “MIMO Radars and Their Conventional Equivalents”, Radar 2015, Arlington, VA, May 10-15, 2015.

[3] E. Brookner, “MIMO Radar Demystified and Where it Makes Sense to Use”, Radar 2014, Lille, France, Oct.13-17, 2014.

[4] E. Brookner, “MIMO Radar Demystified and Where it Makes Sense to Use”, IEEE International Symposium on Phased Array Systems and Technology (ARRAY-2013), Oct. 15-18, 2013

[5] E. Brookner, “MIMO Radar Demystified and Where it Makes Sense to Use”, IEEE ICASSP May 4-9, 2014, Florence, Italy

[6] E. Brookner, “MIMO Radar Demystified and Where it Makes Sense to Use”, RadarCon 2014, Cincinnati, Ohio, May 19-23, 2014

[7] E. Brookner, “MIMO Radars and Their Conventional Equivalents – An Update”, IET International Radar-2015 Conference, Oct. 14-16, 2015, Hangzhou, China.

[8] E. Brookner, “MIMO Radars and Their Conventional Equivalents”, Radar 2015, Arlington, VA, 5/11-15/15

[9] E. Brookner, “ MIMO Radars Demystified - And Their Conventional Equivalents”, IEEE International Symposium on Phased Array Systems and Technology (ARRAY-2016), Oct. 18-21, 2016

BROOKNER BREAKTHROUGH REFS:

- RadarConf 2008, Rome, Breakthroughs, 5/08
- Microwave J. (MJ) 1/2008, Breakthrus
- RadarConf 2007, Boston
- Military Radar Conf. 10/09, 10/08, 10/07, Breakthrus
- Radar 2007, Bangalor, India, Breakthrus
- RF Alliance Conf.: Enabling Multi-antenna & Broadband Systems, April 5-6, 2010, Breakthrus
- IEEE Array-2010, Boston, Breakthrus
- Microwave J. 1/2013, MIMO
- ARRAY-2013, Boston, “MIMO” & “Breakthrus”, 10/13
- Radar-2014, Lille, France, 10/14
- 8th Military Radar Summit 2/15, VA, ‘MIMO’; ‘Breakthrus’
- Radar-2015, VA, MIMO, 5/15
- IET Radar-2015, Breakthrus, 10/15, Hangzhou, CHINA
- IET Radar-2015, MIMO, 10/15, Hangzhou, CHINA
- Microwave J. 11/2016, Radar & Phased Array Breakthrus
- ARRAY-2016, Advances and Breakthrus in Radar and Phased-Arrays

Advances and Breakthroughs in Radars and Phased-Arrays

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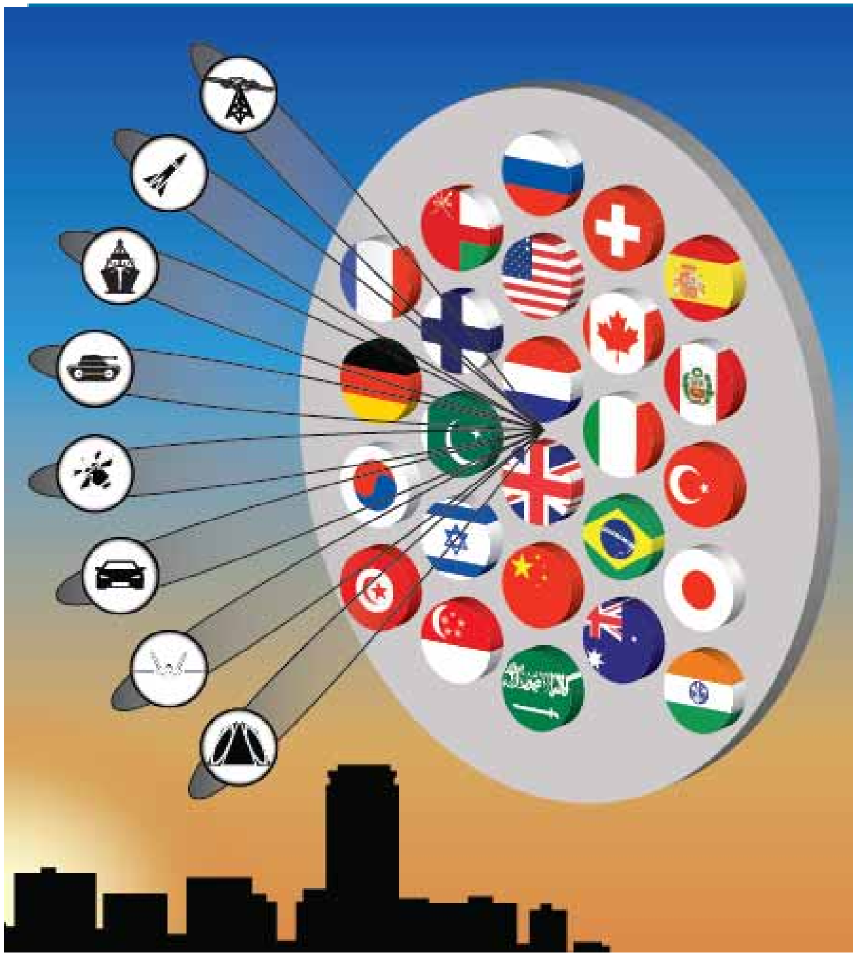
www.array2016.org



Suggested Topics

- System Architecture
- Phased Array Applications and Platforms
- Module Design
- Solid-State Technologies
- Antenna Elements
- Beam Steering Techniques

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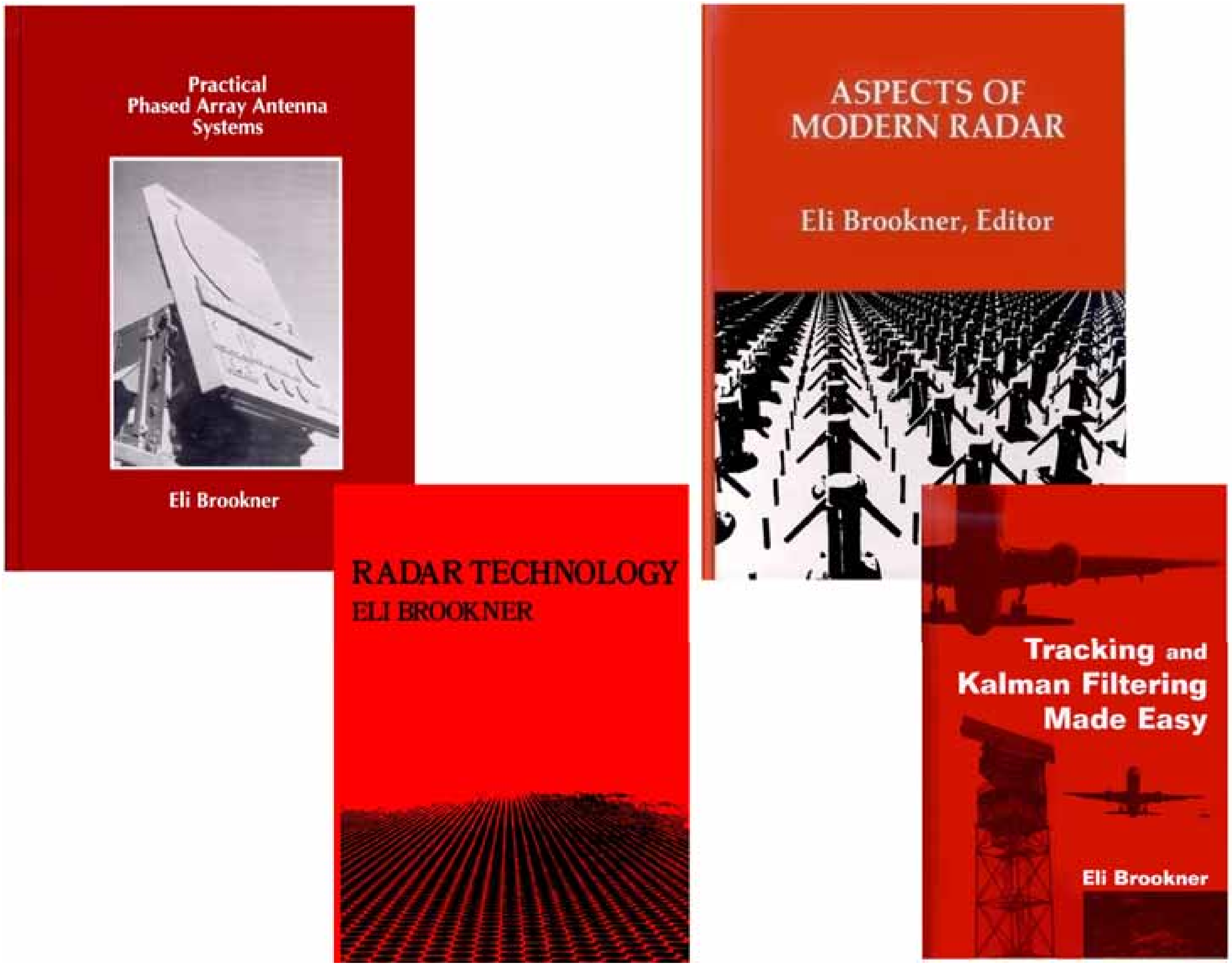
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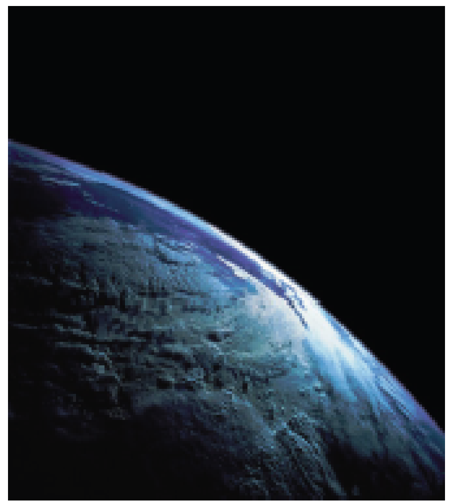
All truths are easy to understand once they are discovered; the point is to discover them.

- Galileo Galilei (1564-1642)



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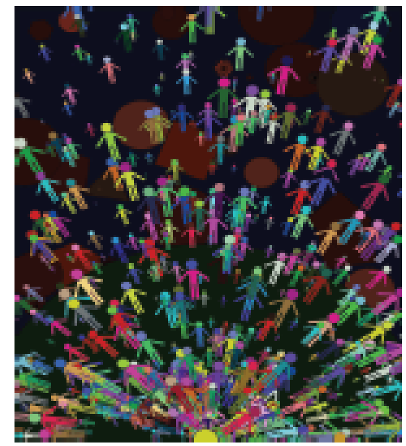

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Pat Arena

BEFORE **AFTER**

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