METAMATERIAL ADVANCES FOR RADAR AND COMMUNICATIONS

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Abstract:

Metamaterial antennas have progressed considerably in the last few years. Kymeta expects to have its Ku-band metamaterial antenna commercially available in 2017. It is intended for use on vessels anywhere in the world for high speed internet using satellites. Echodyne and PARC, a Xerox Co., have developed a metamaterial array for radar and cell phone usage. The Army Research Laboratory in Adelphi MD has funded the development of a metamaterial 250-505 MHZ antenna with a $\lambda/20$ thickness. Complementing this a conventional tightly coupled dipole antenna (TCDA) has been developed which provides a 20:1 bandwidth with a $\lambda/40$ thickness. Target cloaking has been demonstrated at microwaves using metamaterials. With cloaking the electromagnetic wave signal transmitted by a radar goes around the target making it invisible. It has also been demonstrated at L-band with a 50% bandwidth using fractals. Stealthing by absorption using a thin flexible and stretchable metamaterials sheet has been demonstrated to give 6 dB absorption over the band from 8-10 GHz, larger absorption over a narrower band. Using fractals material < 1 mm thick simulation gave a 10 dB reduction in backscatter from 2 to 20 GHz, ~20 dB reduction from 9 to 15 GHz. Good results were obtained for large incidence angles and both polarizations. Using metamaterial one can focus 6X beyond diffraction limit at 0.38 μm (Moore's Law marches on); 40X diffraction limit, $\lambda/80$, at 375 MHz. Has been used in cell phones to provide antennas 5X smaller ($1/10^{th}\ \lambda$) having 700 MHz-2.7 GHz bandwidth. Provided isolation between antennas having 2.5 cm separation equivalent to 1m separation. Used for phased array wide angle impedance matching (WAIM). It has been found that n-doped graphene has a negative index of refraction.

1.0 Introduction

Metamaterials are man-made materials in which an array of structures having a size less than a wavelength are embedded [1]; see Fig. 1. These materials have properties not found in nature, like a negative index of refraction.

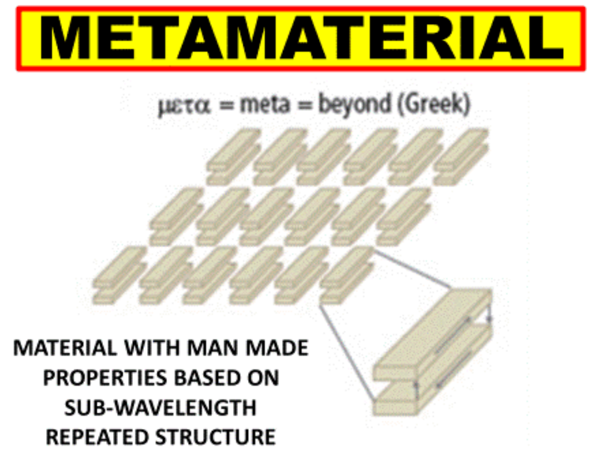


Figure. 1 Metamaterial: What is it? [1]

For one form of metamaterial the permittivity (ε) and permeability (μ) are both negative. When this happens the index of refraction $n = \sqrt{\mu\varepsilon}$ is negative, the negative sign being used for the square root [2, 3]. (Actual materials will have complex-valued ε and μ. The real parts of both ε and μ do not have to be negative to display negative refraction [3].) Material with negative n is rarely found in nature.

However, it can be produced by forming an array of metal split-rings and rods (short parallel wires). The split-ring resonators produce a permeability μ that is negative while the rods produce a permittivity ε that is negative. The dimensions of the metallic rings and rods have to be smaller than the wavelength, but larger than an atomic dimension, to get a negative index of refraction. With metamaterial it is possible to achieve imaging beyond Abbe's diffraction limit which for modern optics is about $\lambda/2$. For regular materials subwavelength imaging is hard to achieve because the evanescent waves containing the subwavelength information decay exponentially with distance making them effectively non-existent at the image plane [4].

Purdue Un. has with simulation shown metamaterial can provide imaging beyond diffraction limit for visible light having a wavelength of 0.7 μm using two layers of anisotropic material [4]. Un. of Illinois experimentally got a 1/12th λ resolution at 0.38 μm by using thin layers of silver, germanium and chromium [5]. The silver provided a negative permittivity which was sufficient for achieving the focusing beyond the diffraction limit. The germanium was needed to allow the silver film to be smooth. Using what is called a resonant metalens Inst. Langevin ESPCI Paris Tech & CNRs achieved a resolution of $\lambda/80$ in the far field at microwave frequencies [6]. They believe that metalenses can be built at visible wavelengths using nanoparticles or nanowires as resonators. Applying imaging beyond diffraction limit to integrated circuit lithography can help Moore's Law to keep moving further.

The definition for which metamaterials apply has been extended to include material having any combination of positive and/or negative ε and μ. It includes electromagnetic band gap (EGB) material (also called photonic crystals) [2]. For some in the RF community it includes frequency sensitive surfaces (FSS) [2]. Included here are fractal frequency selective surfaces.

2. Antennas

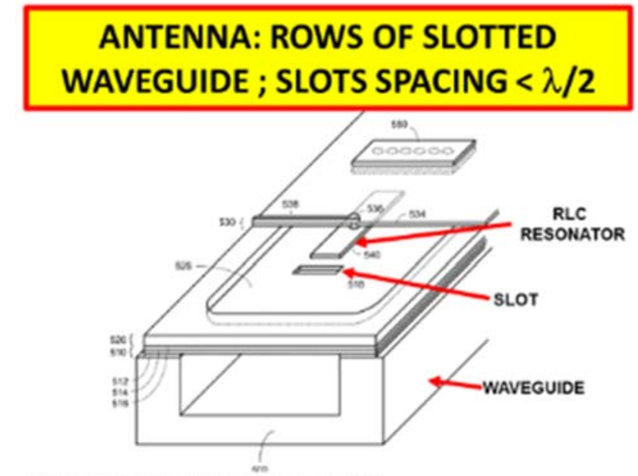
2.1 Kymeta Array Antenna

Kymeta Array

Kymeta is developing a metamaterial antenna for communications via satellites; see Fig. 2 [7-11]. 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.

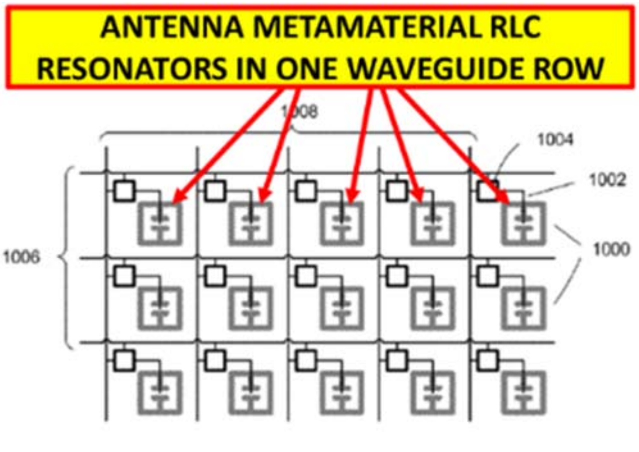
Figure 2. Kymeta electronically steered metamaterial communications antennas. (From Kymeta web sites.)

The details on how the antenna works are not released. Given here is an explanations of how the antenna might scan based on published material. For one architecture, they show the array formed from several rows or traveling wave feeds that could be a leaky waveguide over which a slotted metal cover is placed (see Fig. 3) [7,11]. Think of it as a slotted waveguide. The antenna consists of rows of these slotted waveguides which are end fed (see Fig. 4). Assume that it is desired 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 these slots is the signal allowed to radiate. The signals from the other slots are blocked. The switch is a bandpass filter resonator placed over each slot that controls whether the signal is or is not radiated from the slot. When the resonator center frequency is at the frequency of the signal coming out of the slot, the signal passes through the resonator to radiate. If frequency of the resonator is shifted away from the signal frequency, the signal from that slot is blocked by the resonator and does not radiate. The resonators use liquid crystals whose dielectric constants can be controlled by bias voltages to shift their resonant frequencies [7]. 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 [12, 38]. 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 [13]. 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



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

Figure. 3. Waveguide row showing slot and resonator location. (From [11])



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

Figure 4. Rows of waveguide architecture.(From [11])

use changes in the dielectric constant [38]. 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 ~λ/2. This can facilitate scanning orthogonal to the rows.

Fig. 5 shows an actual resonator circuit consisting of an etched capacitor and inductor in parallel [7]. The etched circuit is placed over a liquid crystal dielectric (previously described) which is placed on top of a ground plane. The liquid crystal's permittivity can be changed by applying a bias voltage between the etched RLC circuit and the ground plane. This bias voltage allows control of the resonator center frequency, placing it at the frequency of the signal when it is to be radiated and away from the signal frequency when it is to be blocked. The amplitude and phase shift of a generic resonator is shown in Fig. 6. The resonators were originally developed to create a metamaterial with a negative permittivity [14]. A close-up of the antenna face with its closely spaced elements is shown in Fig. 7. The Kymeta antenna is thin. Instead of a leaky waveguide with slotted cover one can use a microstrip, coplanar waveguide, parallel plate waveguide, dielectric slab or lossy waveguide [11]. It is a clever and novel concept wherein the need for phase shifting (as in traditional phased array solutions) and active phase shifters is eliminated. Because there are no active components, the cost of building this antenna with many slots, or elements, is low. Kymeta's technology is heavily protected by a portfolio of global patents and trade secrets. The reader is referred to the Kymeta and Intellectual Ventures web sites for additional information.

A potential competing technology to the Kymeta approach is to use a conventional AESA built using low cost extreme MMIC [15, 16].

A second company Echodyne has developed metamaterial arrays for radar and radars using these antennas; see Fig. 8 and Tables 1-3, [17]. Echodyne like Kymeta has funding from Intellectual Ventures and Bill Gates. The switching times needed for the intended radar applications are much shorter than needed for communications; like 1 μs. Metawave, a spinoff from PARC a Xerox Co., is developing metamaterial electronically steered antennas for self-driving cars using AI and for cell towers using MIMO; see Fig. 9. They have built a prototype operating at 24 GHz which has ~14° beamwidth near boresight. It uses digital beam forming (DBF) and voltage controlled metamaterial phase shifters to steer the beam. It has a 120 degrees field of view. Remember, XEROX PARC gave us the PC mouse as we know it and laser printing.

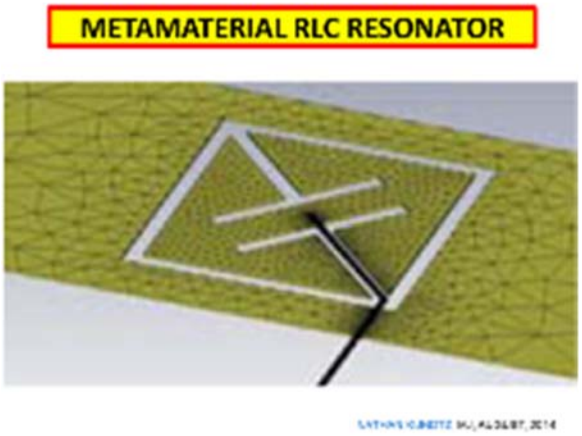


Figure 5. Metamaterial RLC Resonator. (From [7])

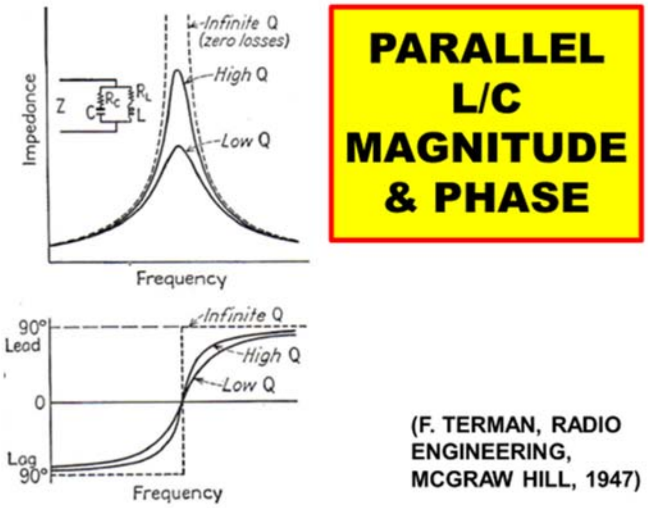


Figure 6. Generic parallel RLC resonator filter.

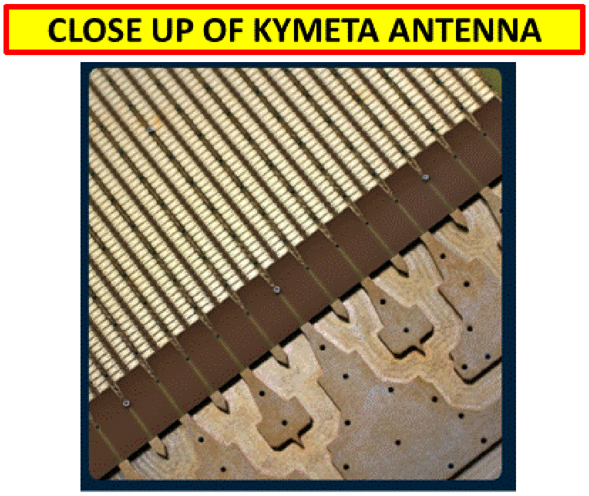
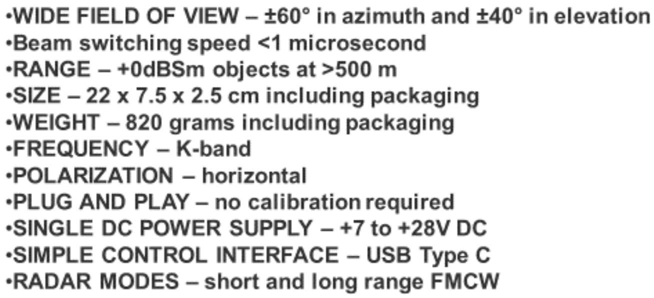


Figure 7. Kymeta antenna. (From Kymeta web sites.)

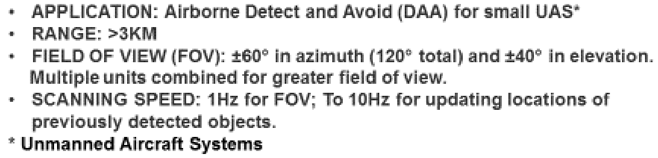
Figure 8 Echodyne metamaterial antennas and radars using these antennas [17].

Table 1. MESA-DEV K-Band Radar [17].



- •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

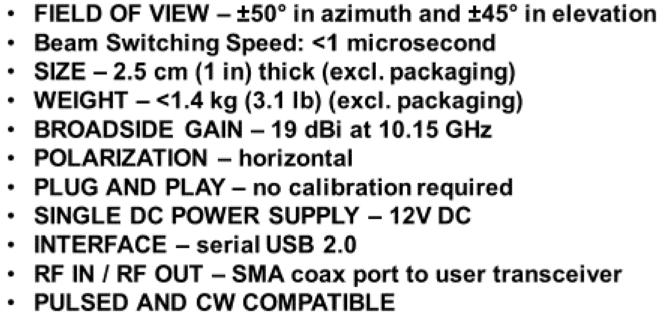
Table 2. MESA-DAA K-Band Radar (Tentative Specs) [17]



- 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

Table 3. MESA-X-EUV X-Band Passive Array [17]



- 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

Figure 9. Metawave is developing metamaterial arrays for self drivng car radars and cell phone tower usage. [18].

2.2 Conformal Antennas

2.2.1 Army Low Profile VHF

Metamaterial with a negative ε produce what is called an artificial magnetic ground plane or a magnetic dielectric. Such a material would allow a dipole antenna (which ordinarily needs to be a ¼ wavelength above a metallic ground plane) to be flush with the artificial magnetic ground plane. This is possible because the electric field in the artificial magnetic ground plane can be equal and parallel to that in the dipole just above the ground plane. This is in contrast to a conducting ground plane where the electric field would be opposite in the ground plane and thus cancel out the electric field from the dipole if it was just above the ground plane. The promise here is that it would allow the construction of conformal dipole arrays. Such an antenna could be used to replace the highly visible by the enemy few feet high whip antennas which are mounted vertically on the side of HMMWVs. This leads to greater survivability. The Army Research Laboratory in Adelphi MD has funded the development of a VHF/UHF metamaterial antenna [19-21]; see Fig. 10. It is expected that magnetic dielectrics having very wide bandwidths should be achievable in the band from 50 MHz to 20 GHz [22].

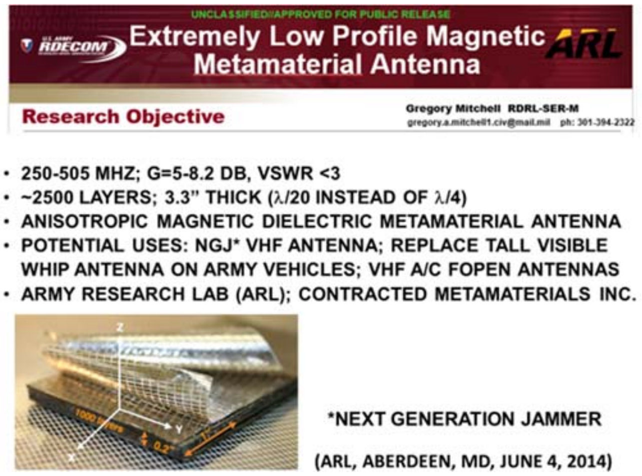
2.2.2 Very Wideband

Thales has demonstrated the placement of a conformal spiral antenna on a metamaterial with this antenna having a bandwidth from 2-8 GHz [23].

While covering low profile wideband metamaterial antennas it is worth mentioning that a low thickness wideband antenna can be built without metamaterials using tightly coupled dipole antennas (TCDA) [24, 25]; see Fig. 11.

2.3 For Isolation and WAIM

Purdue Univ. has used EBG material for a patch array to reduce mutual coupling. This results in a wider scan angle [26]; see Fig. 12. It serves to provide a wide angle impedance match (WAIM). In a program funded by the Army Research



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Extremely Low Profile Magnetic Metamaterial Antenna

Research Objective

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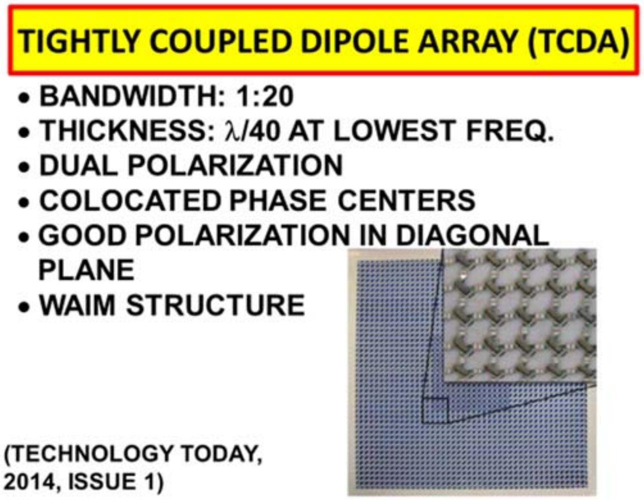
- 250-505 MHZ; G=5-8.2 DB, VSWR <3
- ~2500 LAYERS; 3.3" THICK (λ/20 INSTEAD OF λ/4)
- ANISOTROPIC MAGNETIC DIELECTRIC METAMATERIAL ANTENNA
- POTENTIAL USES: NGJ* VHF ANTENNA; REPLACE TALL VISIBLE WHIP ANTENNA ON ARMY VEHICLES; VHF A/C FOPEN ANTENNAS
- ARMY RESEARCH LAB (ARL); CONTRACTED METAMATERIALS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

*NEXT GENERATION JAMMER

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

Figure 10. Extremly Low profile 250-505 MHz magnetic metamaterial antenna; after G. Mitchell and S. Weiss [21].

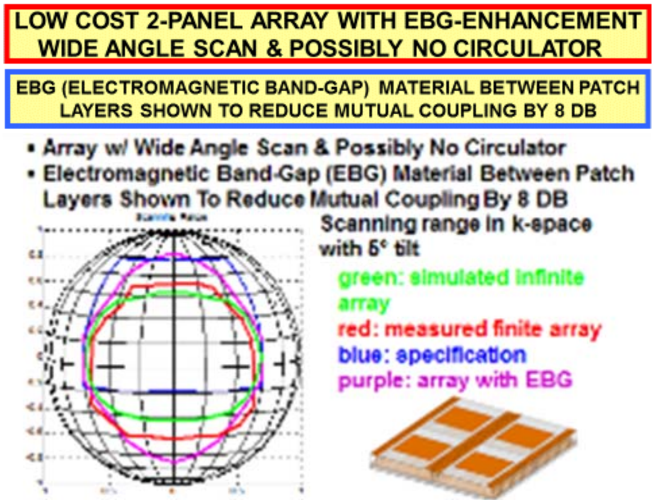


TIGHTLY COUPLED DIPOLE ARRAY (TCDA)

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

(TECHNOLOGY TODAY, 2014, ISSUE 1)

Figure 11. Extremely low thickness wideband antenna using tightly coupled dipole antennas (TCDA) [24, 25].



LOW COST 2-PANEL ARRAY WITH EBG-ENHANCEMENT WIDE ANGLE SCAN & POSSIBLY NO CIRCULATOR

EBG (ELECTROMAGNETIC BAND-GAP) MATERIAL BETWEEN PATCH LAYERS SHOWN TO REDUCE MUTUAL COUPLING BY 8 DB

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

Figure 12. WAIM using EBG [26].

Lab, Adelphi, MD., the Un. of Michigan used EBG in between the transmit and receive antennas separated by about 3 cm on a transponder operating at 2.72 GHz to realize an isolation of 42 dB, 24 dB above what would have been realized without the EBG; see Fig. 13. This is the isolation one would have realized for 1 m separation [27].

2.4 Commercial Wireless Use

Metamaterials have been used commercially in the wireless 2.5, 5 GHz NDR3300 router [28]. Here eight antennas were placed on a RAYSPAN® metamaterial which allowed the antennas to be smaller and have better isolation. Metamaterial antennas were also used in cell phones to provide smaller antennas and better isolation between them. They were 2-D antennas that could be less than 10 mm by 50 mm and paper thin [29]. Typically they were at least five times smaller than conventional antennas, i.e., 1/10th λ in size. Metamaterial antennas can be made broadband to support multiband like 700 MHz to 2.7 GHz or GPS, Blue Tooth, WiFi and Wi Max within one antenna array. It was claimed that they could be developed in a short time (like two weeks to a month), inexpensive to build, and provide low RF exposure to the user [29].

USING EBG 2.5 CM SEPARATION ⇔ 1 M

Vertically-Polarized Planar Antenna

F = 2.72 GHz
Antenna Sizes:
1.12x0.51x0.157 cm;
or $\lambda_o/10$ X $\lambda_o/22$ X $\lambda_o/70$
solation: 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;

Figure 13. EBG used to achieve isolation between and transmit and receive antennas [27].

3. Cloaking and Stealthing

Target cloaking was first demonstrated using metamaterials at microwaves Duke Un. With cloaking the electromagnetic wave signal transmitted by a radar goes around the target making it invisible; see Fig. 14. Fig. 15 shows the Duke Un, microwave metamaterial cloaking implementation. It uses concentric 1 cm (~0.4 inchs) wide substrates rings on which are etched split ring resonators which guide the microwave signal around the 5 cm (~2 inchs) center region which contains the object being stealthed. The outer diameter is 13 cm (~5 inchs). The cloaking is achieved over a narrow bandwidth. Cloaking has more recently been demonstrated using fractals by Fractal Antenna Systems [31, 32], see Fig. 16a. Here Peter, an 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, see left hand curve in Fig. 16b. When Peter was placed inside a cylinder with the fractal coating around it and placed again in the path between the transmitter and receiver the signal was no longer blocked, only being attenuated by a fraction of a dB over the same 50% bandwidth; see right hand curve of Fig. 16b. Fig. 17 compares the fractal surface (on left) used with the split ring resonator surface used by Duke Un.

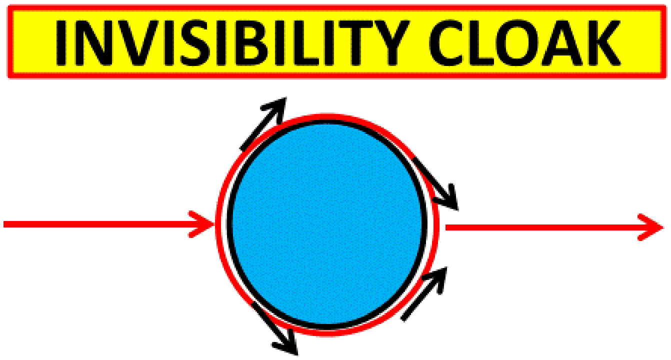


Figure 14. Invisibility cloak.

Figure 15. Cloaking at microwaves frequencies using metamaterial with split rings by Duke Un. [30].

Another way to hide a target is to have the target absorb the incident radar signal. Such stealthing has been demonstrated by simulation using a fractal frequency selective coating that is < 1 mm thick; see Figs. 18 and 19, [33]. Absorption of better than 90% (10 dB) was achieved from 2 to 20 GHz and better than about 99% (20 dB) from about 10-15 GHz. Good absorption was achieved for all incident angles and polarizations. Recently Iowa State Un. demonstrated stealthing with a stretchable, flexible metamaterial sheet consisting of silicon with split ring resonators embedded in it. They achieved a 6 dB target cross section reduction from 8-10 GHz with higher absorption over narrower bands; see Figs. 20 and 21 [34]. It should be possible to apply this material conformally over the object to be stealthed.

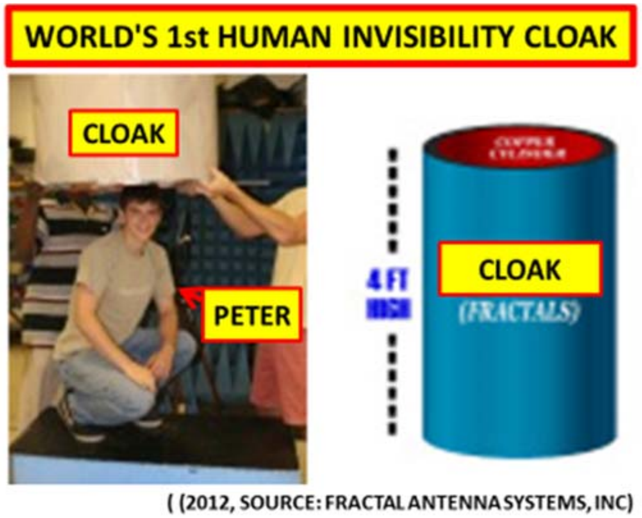


Figure 16a. World’s 1st human invisibility cloak demonstration. [31, 32].

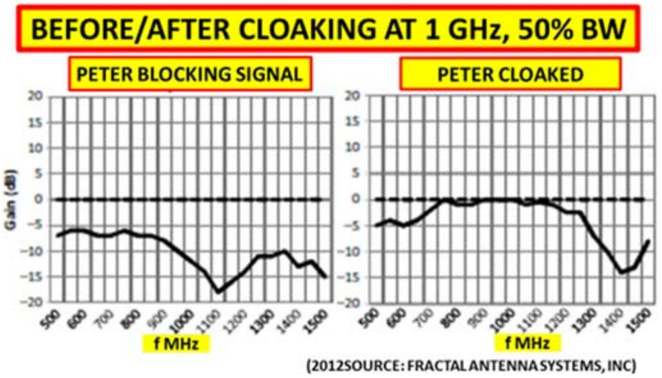


Figure 16b. Effective over 50% bandwidth at 1 GHz [31, 32].

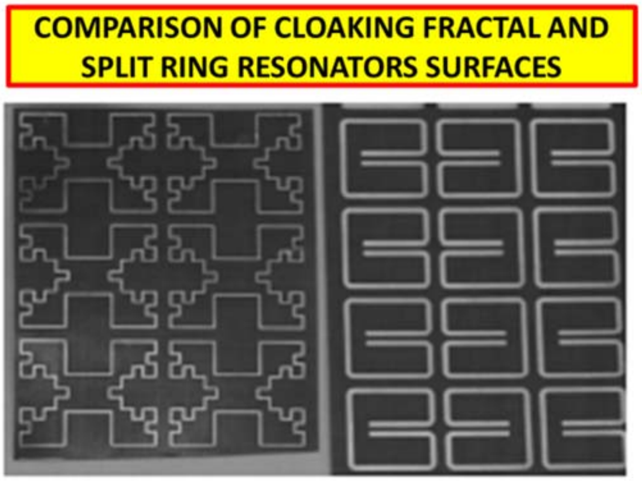


Figure 17. Comparison of cloaking fractat and split-ring resonator surfaces [31].

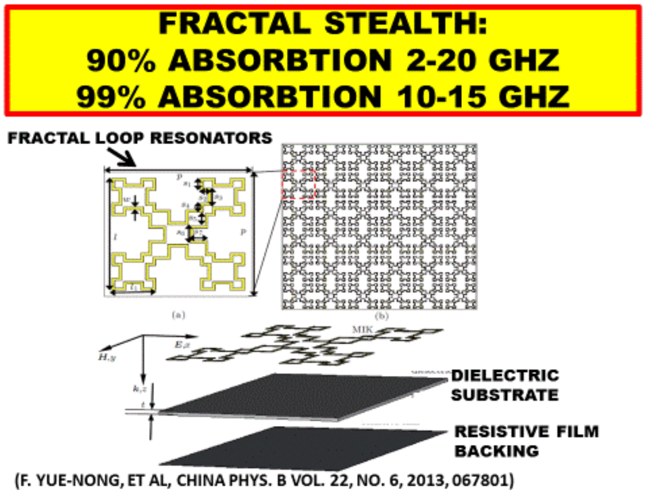


Figure 18. Stealth by absorption with fractal metamaterial coating that is < 1 mm thick [33].

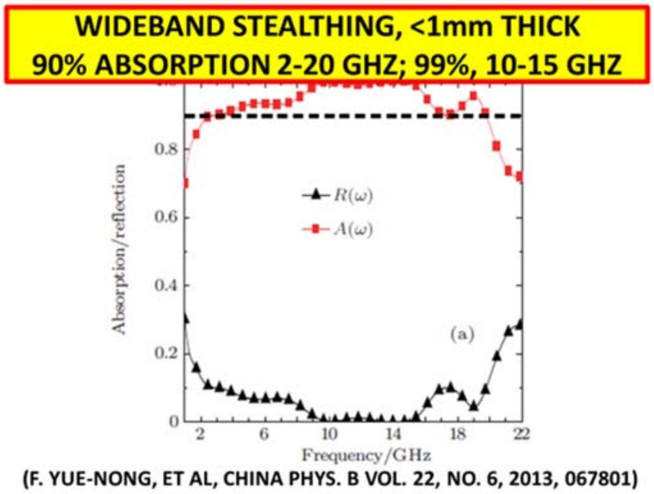


Figure 19. Fractal stealthing from 2-20 GHz with 90% absorption, 10-15 GHz with 99% [33].

Figure 20. Stretchable, flexible metamaterial absorber [34].

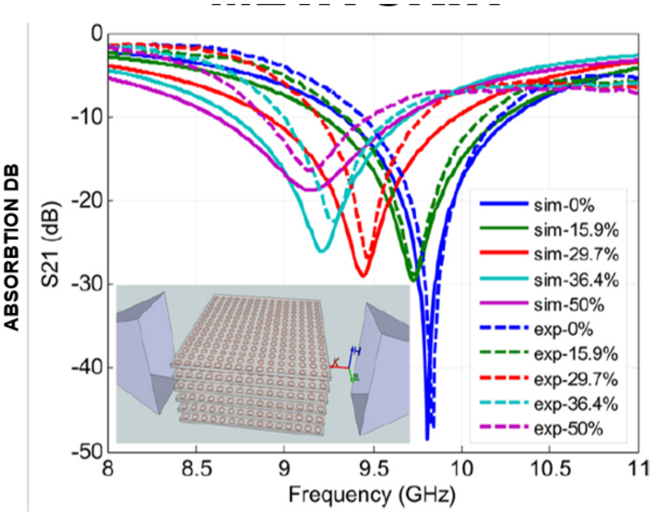


Figure 21. Absorbtion for different percent stretchings [34].

4. Concluding Comments

Metamaterials became an area of great interest as a result of a seminar paper by J. Pendry of the Univ. of Cambridge, England [35, 36]. There are now over a dozen books on metamaterials. One of these books, the one by Prof. Munk [37], questions whether one can actually produce material with a negative index of refraction. Dr. Munk claims that results obtained with what are called negative index of refraction material can be explained with non-negative index of refraction material. No matter what the explanation it has been shown that it is possible to achieve focusing beyond diffraction limit, cloaking and stealthing at microwave frequencies, conformal antennas at VHF/UHF, better isolation, electronic scanning arrays and reduced size antennas.

Aknowledgment: Update of paper published in Microwave J. (MJ) November 2016. They give permission to publish this updated version here.

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