Doctor *honoris causa*

Tatsuo Itoh

Universitat Autònoma de Barcelona

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Tatsuo Itoh

Discurs llegit
a la cerimònia d'investidura
celebrada a la
Sala d'Actes del Rectorat
el dia 14 d'octubre
de l'any 2015

Universitat Autònoma de Barcelona

PRESENTACIÓ
DE
TATSUO ITOH
PER
FERRAN MARTÍN

Excel·lentíssim i Magnífic Rector,
Il·lustríssims Vicerectors i Vicerectores,
Director de l'Escola d'Enginyeria,
Autoritats Acadèmiques,
Professors i Col·legues,
Estudiants,
Senyores i Senyors,

És per a mi un gran honor que l'Escola d'Enginyeria i el seu director m'hagin confiat l'apadrinament del nou doctor *honoris causa* de la Universitat Autònoma de Barcelona, el professor Tatsuo Itoh, i encara més com a primer doctor *honoris causa* impulsat per l'Escola. El professor Itoh reuneix unes qualitats científiques i tècniques, una trajectòria acadèmica, de recerca i de transferència, i uns valors que el fan mereixedor d'aquesta altíssima distinció, i em permeto expressar en nom de l'Escola d'Enginyeria la gran satisfacció que representa que la UAB proclami doctor *honoris causa* tan il·lustre enginyer i científic, com dic, el primer promogut per l'Escola.

Tatsuo Itoh és actualment *Distinguished Professor and Northrop Grumman Endowed Chair in Electrical Engineering* de la Universitat de Califòrnia a Los Angeles (UCLA), on imparteix docència i porta a terme una intensa activitat de recerca en el camp de l'enginyeria de radiofreqüència i microones, i de les telecomunicacions en general. Tasuo Itoh va obtenir la llicenciatura i el màster d'Enginyeria Elèctrica a la Universitat Nacional de Yokohama (Japó) el 1964 i el 1966, respectivament. Només tres anys després (1969) es va doctorar per la Universitat d'Illinois a Urbana-Champaign (EUA), amb la tesi titulada *Sub-Optical Resonators with Grating Mirrors*, sota la direcció del professor Raj Mittra (una altra icona i investigador prolífic en aquest camp). El que Tatsuo Itoh va definir com a «desert rural», referint-se a l'ambient d'assossec de la Universitat d'Illinois, li va permetre de concentrar-se en les seves activitats de recerca, i ja com a postdoc després de 1969 i amb col·laboració amb Raj Mittra, va generar un elevat nombre d'articles científics sobre tècniques d'anàlisi de línies de transmissió fins al 1976. Entre aquests treballs de referència, destaquen les seves aportacions a l'anàlisi i caracterització de la dispersió a alta freqüència en línies de transmissió mitjançant tècniques basades en el domini espectral.

Després de passar per l'Stanford Research Institute, on va treballar en circuits actius (amplificadors en banda C per a enllaços de microones) i per la Universitat de Kentucky (on va reprendre les seves activitats orientades a l'anàlisi de línies de transmissió), l'any 1978 va obtenir una plaça de professor associat a la Universitat de Texas a Austin, i tres anys més tard es va convertir en catedràtic. En aquesta universitat va ser on Tatsuo Itoh va fer l'enlairament més important de la seva carrera com a investigador, treballant principalment en circuits integrats de microones i ones mil·limètriques, i en rebre un important finançament a través del programa JSEP (*Joint Services Electronics Program*), fundat l'any 1946 per l'Office of Naval Research, l'Army Signal Corps i l'Air Force dels Estats Units, per donar suport a universitats i grups de recerca d'excel·lència en diverses disciplines. Durant la seva estada a la Universitat de Texas a Austin va publicar prop de noranta articles i va supervisar més de vint estudiants de doctorat. A més, entre 1982 i 1985 va ser director de la revista de referència en enginyeria de microones *IEEE Transactions on Microwave Theory and Techniques* (revista en la qual ha publicat més de 230 articles), i l'any 1990 va ser president de l'IEEE Microwave Theory and Techniques Society, una de les societats del centenari Institute of Electrical and Electronics Engineers (IEEE), fundat el 1884 per personatges tan il·lustres com Thomas Alva Edison o Alexander Graham Bell (actualment té més de 425.000 membres i és l'associació professional més gran del món orientada al progrés tecnològic i la innovació per al benefici de la humanitat).

L'any 1991 Tatsuo Itoh es va traslladar a la Universitat de Califòrnia a Los Angeles (UCLA), en part per motius professionals i en bona part també per motius personals, ja que la seva família residia a Califòrnia, lluny, per tant, de la texana Austin. En aquesta universitat Tatsuo Itoh va consolidar el mite de treballador infatigable (pràcticament vivia, si més no els primers anys, al seu despatx de la Universitat). Aquell mateix any (1991) va sortir a la llum el primer número de la nova revista d'articles de format curt (*Letters*) de la IEEE Microwaves Theory and Techniques Society. El nom de la nova revista, de la qual el professor Itoh va ser el primer director (1991-1994), *IEEE Microwaves and Guided Wave Letters*, va ser modificat l'any 2001 pel nom actual, *IEEE Microwave and Wireless Components Letters*. Vull fer esment que aquesta revista concedeix anualment el Premi Tatsuo Itoh al millor treball publicat, en honor de qui en va ser el primer director.

Ja essent un científic i enginyer molt reconegut internacionalment, Tatsuo Itoh va liderar a l'UCLA una intensíssima activitat de recerca en diversos camps (antenes actives, components superconductors de microones, mètodes analítics, etc.), però val la pena de destacar l'interès que va mostrar pel llavors camp emergent (cap a mitjan anys noranta) dels anomenats *photonic bandgaps* (PBG), en part influenciat per un dels pioners en aquest camp, Eli Yablonovith, que en aquell moment era professor del Departament d'Enginyeria Elèctrica i Electrònica de l'UCLA. A Tatsuo Itoh i al seu equip investigador es deuen els treballs pioners relatius a l'aplicació de les PBG en circuits de microones (passius i actius), antenes i superfícies selectives en freqüència. Els treballs d'Itoh sobre PBG, i en particular el fet que combinant circuits de microones amb estructures PBG es poguessin obtenir millors prestacions en components de comunicacions (eliminació d'espuris, millora de l'eficiència en dispositius actius i reducció de dimensions, entre d'altres), van atreure molts investigadors, entre ells qui us parla, veient les possibilitats d'aquestes noves estructures PBG, també anomenades cristalls fotònics per la seva similitud amb els cristalls semiconductors i la seva capacitat de produir bandes prohibides de freqüència (d'energia en semiconductors), com a conseqüència del conegut efecte Bragg, derivat de la periodicitat.

A la segona meitat dels noranta i primers anys del nou mil·lenni, els cristalls fotònics i la seva aplicació en circuits de microones van esdevenir sens dubte un dels temes més emergents i «calents» dins del camp de l'enginyeria de microones. Però ben aviat els cristalls fotònics, o PBG, van quedat apantallats pel que avui dia es coneix amb el nom de *big bang*, o explosió, dels anomenats metamaterials, que es va produir l'any 2000. L'any 1968, el científic de l'antiga Unió Soviètica Víctor Veselago va estudiar les hipotètiques propietats electromagnètiques que tindrien (en cas que existissin a la natura) substàncies amb permeabilitat i permitivitat simultàniament negatives, i va concloure que haurien de presentar un índex de refracció negatiu, haurien de suportar la propagació d'ones de retrocés (fenomen contraintuïtiu, pel qual els fronts d'ona es propaguen en direcció contrària a la propagació de l'energia) i certs fenòmens com la radiació Cerenkov o l'efecte Doppler s'haurien d'invertir en aquests hipotètics medis. Malgrat aquestes propietats inèdites i exòtiques, el treball de Veselago va passar inadvertit durant més de trenta anys per la inexistència d'aquest medis a la natura. Però l'any 2000, el grup del professor David Smith, de la Universitat de Califòrnia a San Diego (UCSD), va proposar la primera estructura artificial amb permeabilitat i permitivitat simultàniament negatives, utilitzant anells metàl·lics gravats sobre substrats dielèctrics i pals metàl·lics. Aquest treball va suposar l'inici d'una intensa activitat de recerca a escala mundial sobre el que avui dia coneixem amb el nom de metamaterials. Aquests medis artificials presenten propietats electromagnètiques que es poden controlar a voluntat (fins a cert punt, és clar) estructurant-los de manera adient. De fet, es poden aconseguir efectes i propietats que no es poden assolir en medis naturals coneguts, com la ja mencionada refracció negativa, demostrada experimentalment el 2001 pel grup de David Smith (treball publicat a la revista *Science*), o la invisibilitat, basada en el guiatge punt a punt de la radiació electromagnètica, i demostrada experimentalment per primer cop l'any 2006 (encara que en condicions molt específiques i a freqüències de microones), en un altre treball publicat a *Science*.

Atès que les primeres estructures metamaterials es van implementar amb elements metàl·lics gravats sobre substrats dielèctrics, de la mateixa manera que s'implementen molts circuits de comunicacions en tecnologia plana, sembla obvi plantejar-se si les propietats úniques dels metamaterials es podrien aplicar al camp de la radiofreqüència i de les microones per millorar les prestacions en circuits de comunicacions, o bé per obtenir noves funcionalitats. El temps ha demostrat que sí, encara que hem de reconèixer el mèrit d'aquells que a principis del 2000 van fer-se tal plantejament, realment no gens obvi, ans tot el contrari, i van proposar els primers metamaterials unidimensionals en tecnologia plana, o línies de transmissió metamaterial, entre ells Tatsuo Itoh i el seu col·laborador, acabat d'arribar a l'UCLA, Christophe Caloz (actualment professor a l'Escola Politècnica de Montreal). Els treballs seminals d'Itoh i Caloz sobre línies de transmissió metamaterial, i també de George Eleftheriades (de la Universitat de Toronto) i del ja desaparegut Arthur Oliner (figura indiscutible en tecnologia de microones i investigador de referència en el camp de les antenes basades en ones *leaky*) han inspirat molts grups de recerca, i en particular el grup que jo mateix dirigeixo (CIMITEC), que només un any després que sortissin a la llum els treballs d'Itoh-Caloz, Eleftheriades i Oliner, va proposar una estratègia alternativa per a la implementació de línies de transmissió artificials basades en metamaterials. Em refereixo al model ressonant, inspirat també en les primeres estructures metamaterials proposades per Smith, i especialment útil per a la implementació de filtres de microones, entre altres circuits de comunicacions.

Les contribucions d'Itoh en el camp dels circuits de microones basats o inspirats en metamaterials són impressionants. Moltes estan recollides en el seu llibre de referència de l'editorial John Wiley (coescrit amb Caloz), titulat *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*. La particularitat de les línies de transmissió metamaterial és el fet que, gràcies a la presència d'elements reactius, es pot controlar la impedància característica de la línia i la constant de fase (o dispersió), els paràmetres fonamentals en el disseny de circuits basats en paràmetres distribuïts, més enllà de com es pot fer en línies de transmissió ordinàries. D'aquesta manera, la flexibilitat de disseny que proporcionen aquestes línies artificials permet el disseny de circuits de radiofreqüència/microones sobre la base del que avui dia s'anomena enginyeria de dispersió. Components amb amplada de banda eixamplada, circuits multibanda i multifuncionals, acobladors d'altes prestacions, antenes amb ones *leaky* amb capacitat d'escombratge endavant i endarrere, nous components actius, i l'aplicació de conceptes de metamaterials en tecnologies avançades (p. e., guies d'ona integrades en substrat o dispositius de THz) són només algunes de les nombroses aportacions fetes per Itoh i els seus col·laboradors en el camp dels metamaterials. Podem dir que els treballs de Tatsuo Itoh han obert el camí a una nova manera de concebre el disseny de circuits de comunicacions, on els elements constitutius clàssics (línies de transmissió ordinàries) són substituïts per línies artificials inspirades en metamaterials, i que és possible aconseguir prestacions i funcionalitats impensables fa uns anys gràcies a la flexibilitat i a les propietats úniques i singulars dels metamaterials. Els seus treballs recents apareixen entre les citacions de qualsevol publicació relacionada amb aquest camp.

El professor Tatsuo Itoh és probablement l'enginyer i científic en actiu més rellevant i influent en el camp de l'enginyeria de radiofreqüència/microones en l'actualitat. Amb més de quaranta-cinc anys de carrera i de dedicació exhaustiva a la recerca, transferència de coneixement i formació, i havent fet contribucions i aportacions científiques extraordinàries, que han suposat un avenç clar en l'estat de l'art, Tatsuo Itoh s'ha convertit en un referent internacional per a qualsevol enginyer, científic, estudiant de postgrau o acadèmic dedicat a l'enginyeria de radiofreqüència/microones i a les comunicacions en general. Tatsuo Itoh es troba avui plenament actiu. Assisteix als congressos més importants del camp, on les seves presentacions (o les dels seus estudiants i col·laboradors) sempre desperten un gran interès, i publica desenes d'articles científics per any en les revistes més importants de l'àrea de recerca. Vull destacar que Tatsuo Itoh sempre ha respost positivament a les meves propostes de participar en diversos esdeveniments científics sobre metamaterials, molts d'ells organitzats per mi mateix, de tal manera que ha contribuït a fer conèixer a la comunitat científica la potencialitat dels metamaterials en el camp de les comunicacions, així com també a la visibilitat i internacionalització del grup de recerca que lidero. De fet, aquest setembre ha obert un *workshop* organitzat per mi a París, dins l'European Microwave Week, que li ha implicat viatjar a Europa dues vegades en poc més d'un mes, amb un viatge al Japó entre mig. El suport a la UAB, a més, s'ha materialitzat acollint postdocs, participant en projectes de recerca i en publicacions conjuntes, i amb l'elevació al grau de *Fellow* de l'IEEE de qui us parla.

El currículum de Tatsuo Itoh és extraordinari: 48 llibres o capítols de llibre, més de 440 articles publicats, 880 comunicacions a congressos, 80 tesis dirigides, 10 patents i un nombre de citacions altíssim per a un enginyer (més de 35.000 segons Google Scholar el 8-7-2015, índex $h = 84$). Cal mencionar que molts dels seus deixebles són actualment científics molt rellevants i influents en el camp de l'enginyeria de microones. Tanmateix, el nombre de projectes i contractes de transferència i la seva capacitat d'aconseguir recursos evidencien el gran impacte acadèmic i el potencial de les seves idees en la generació de productes d'interès per a la indústria.

Els premis, les distincions i els honors rebuts per Tatsuo Itoh al llarg de la seva carrera professional han estat igualment extraordinaris, i són tan nombrosos que no els podem mencionar tots en aquest acte. Destaquem-ne, però, algun, com ara l'IEEE Microwave Career Award (2011), l'European Microwave Association Outstanding Career Award (2009), l'IEEE Millennium Medal (2000) o el Japan Microwave Prize (1998). A més, Tatsuo Itoh és membre de la National Academy of Engineering dels Estats Units des del 2003, *Fellow* de l'IEEE des del 1982, i membre honorari de l'IEEE Microwave Theory and Techniques Society des del 1994.

Com es pot apreciar, Tatsuo Itoh té un perfil marcadament «IEEE». Per a l'Escola d'Enginyeria de la UAB i per a molts dels seus membres amb activitat orientada al camp de les tecnologies de la informació i les comunicacions (TIC), l'IEEE és un institut cientificotecnològic de referència, amb més de 425.000 membres i una llarga història, com ja hem comentat abans. L'Escola d'Enginyeria té molts professors i investigadors que són membres de l'IEEE i, per tant, el nomenament de Tatsuo Itoh com a doctor *honoris causa* és sens dubte un acte de reconeixement molt merescut i coherent.

És per tot això que tinc el plaer, l'honor i el privilegi de demanar al Magnífic Rector de la Universitat Autònoma de Barcelona, en nom de l'Escola d'Enginyeria, que s'atorgui el grau de doctor *honoris causa* al professor Tatsuo Itoh.

Let me now use few English words to express my acknowledgement and gratitude to professor Itoh for many years of endless effort and sacrifice dedicated to the profession. Your long and fruitful academic and research trajectory has inspired and influenced many people and many research groups worldwide, including myself. The microwave community is in debt to you for many outstanding contributions to the topic of RF/microwave engineering, and I would like to express my most sincere gratitude for your support to the activities of my University in the field of microwaves. The elevation to the doctor *honoris causa* degree is fully justified, and I am asking my Rector, on behalf of the Engineering School, to give you such prestigious degree.

Thank you very much, professor Itoh.

DISCURS
DE
TATSUO ITOH

METAMATERIALS

Rector,
Dean,
Ladies and Gentlemen,
Friends,

It is a great honor and ultimate pleasure to receive the title of *doctor honoris causa* from Universitat Autònoma de Barcelona. This degree not only provides academic recognition but also intensifies collaborative friendship between us. For the past several years, my research group at the University of California Los Angeles (UCLA) has strong collaboration effort with UAB research cluster headed by Professor Ferran Martín in the area of electronics and wireless communication, more specifically applications of metamaterials to be described shortly. It is hoped that collaboration would become stronger as this speaker is now a part of UAB influence.

Let us talk about metamaterial. In human history, discovery of new materials and improvement of their performance have contributed to enhancement of quality of life. Change was often revolutionary. In these circumstances, we have used the intrinsic character of the material. Metamaterial is not a material in ordinary sense. Metamaterials are artificially synthesized structures that exhibit unique electromagnetic properties not found in nature.

In this talk, we deal with electromagnetic behavior of the so-called left handed metamaterial made of unit cells much smaller in size than the wavelength. These unit cells, often called the particles, are periodically aligned in one, two and three dimensions. Because of such tiny unit cells, the realized metamaterials are “homogenized.”

In general, any natural materials can be characterized by electric permittivity (ε) and magnetic permeability (μ) which do not become negative simultaneously in nature. If both were negative, the refractive index also becomes negative. To realize this situation, use of metamaterial is needed. The left handed metamaterial is also called negative index metamaterial. The light beam obliquely incident at the interface from the air to the negative index material refracts in the opposite direction as compared to the ordinary case with positive parameters. Therefore, the convex lens acts as a diverging device and the concave lens becomes a focusing device. A flat lens can also be realized in principle. A microwave model of a flat lens is shown here.

In the metamaterial with a negative refractive index, the phase front propagates opposite to the signal flow direction. The electric field direction, magnetic field direction and the phase propagation direction forms a left hand triad, thus called left hand material.

The concept of negative index material was proposed by a Russian scientist Viktor Veselago in 1968 but no experimental verification was carried out by David Smith and colleagues at University of California San Diego until 2000. There are essentially two different approaches in fabrication and realization of left hand (LH) material, resonant structure approach and transmission line approach. In the former, structures exhibiting negative permittivity and negative permeability in narrow frequency ranges are physically combined. Therefore the operating range with a negative index is quite narrow. On the other hand, the transmission line approach provides wider frequency range of operation.

This structure can be realized by topologically interchanging the inductive elements and the capacitive elements in the transmission line. In reality, however, pure interchange is not possible due to parasitic inductive and capacitive elements that remain in existence. Therefore, what can be realized is a mixture of the LH and RH (ordinary) elements and is termed Composite Right/Left Handed (CRLH) configuration which has exhibited remarkable properties and has enlarged range of applications.

It is found that the CRLH is left handed at lower frequencies and right handed at higher frequencies. Therefore, at lower frequencies, the phase front of the forward signal goes backward and the phase is advanced when the signal is traveling forward. At higher frequencies, the wave is propagating in a normal way and both the phase front and the signal travel in the same direction. The wave phenomena are animated as shown. Also, at certain frequencies, the CRLH dispersion curve traverses radiation region that can be used for antennas.

For passive component applications, a unique feature of the CRLH can be used for dispersion engineering in which the CRLH characteristic or frequency dependence can be controlled by changing the element values in the circuits. Based on this property, several dual-band components have been fabricated and tested successfully.

Your wireless phone needs to deal with radio signals at several different frequencies. Therefore, multi-band components are essential. One example to this end by the use of CRLH structure is a dual-band coupler (for signal flow control) operating at two arbitrary frequencies, typically one in the LH region and another in the RH region.

Another unique characteristic is the infinite wavelength or zero phase phenomenon obtainable at the transition between the LH and RH regions. At this point, the field is uniform with zero phase variation along the guided wave structure. An in-phase series divider was developed in which the phase and amplitude of output branches placed at arbitrary locations are constant. A variant of this structure can be used as an infinite-wavelength antenna in which the resonant frequency does not depend on the size.

Speaking of the antennas, the leaky wave antenna made of a CRLH transmission line is one of the most unique accomplishments in the area of transmission line metamaterials. When the input frequency is within the radiation region, the CRLH transmission line acts as an antenna. The direction of radiation depends on the frequency and is varied over 180 degrees from the back-fired to the end-fired direction. This full-scan capability is difficult or impossible with an ordinary antenna. Full-scan capability is needed for radar and direction finding. In the mean time, CRLH leaky wave antenna has been demonstrated experimentally up to low terahertz (THz) frequencies in conjunction with THz Quantum Cascade Laser (QCL). THz spectrum is located between light and microwaves and is useful for applications in imaging and security.

Various forms of metamaterial or metamaterial-inspired small antenna have been reported including those based on CRLH configuration. The size of a resonant type antenna can be made small easily if a negative order resonance in the LH region is used. However the insertion loss is typically quite high and fundamental limitations of small antenna such as narrow band characteristics are dictating. The example shown here intends to use coupling of several resonances to enlarge the operating bandwidth.

The unique dispersive characteristics of the CRLH structure can be utilized in active circuits containing diodes and transistors. In the first example, controllable phase characteristics at multiple frequencies are used for the output tuner for a high power amplifier which is required to be terminated open and short for the even and odd harmonics generated due to nonlinear behavior of the active devices. In the conventional approach, several tuning circuits are used whereas only one tuner is needed if the CRLH is used. The next example is a dual-band millimeter-wave transistor oscillator making use of the dual mode resonance of the LH resonator.

Before concluding, let us present an example of collaborative effort between UCLA group and that of Professor Ferran Martín. What is illustrated is a photo of a quad-band component developed by the complementary experience of the two groups.

In conclusion, it is demonstrated that unconventional left hand properties of the metamaterials can be realized. Transmission line approach, in particular CRLH format, provides many useful and unconventional microwave components and structures. It is expected many more to follow.

Metamaterial

Tatsuo Itoh

Electrical Engineering Department
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What is Metamaterial?

Artificially synthesized structure with unusual (electromagnetic) characteristics not found in nature

Typically made of unit cells (particles) much smaller than the wavelength

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   - Antennas
   - Active Circuits
4. Conclusions

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Left-Handed (LH) Metamaterials and Transmission Line Approach**

** Also called Negative Index Materials

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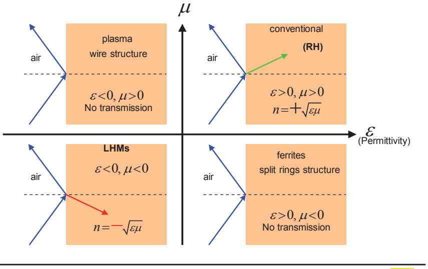
General Classifications of Material Based on (ε,μ)



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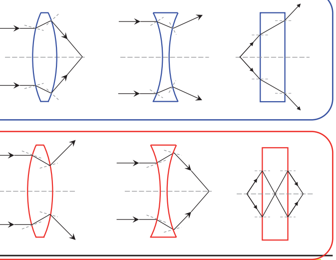
RH & LH Lenses

RH Lenses

LH Lenses



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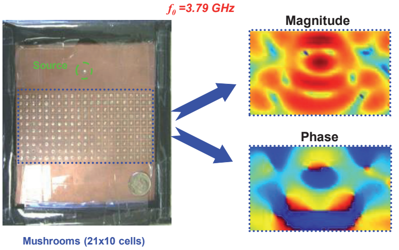
Flat Lens (Measured)

f_0 =3.79 GHz



Mushrooms (21x10 cells)

* Entire structure built on ε_R=10.2 substrate

Anti-parallel Phase / Group Velocities

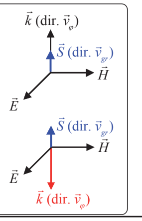
• **Definition of LHMs:** $\varepsilon<0$ and $\mu<0$ or $v_p=-\|v_g$

E: Electric field

H: Magnetic field

S: Signal

K: Phase

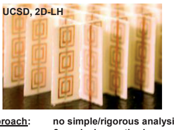


Different Approaches of LH Metamaterials

Historical Milestones
- **1968** : theoretical analysis of hypothetical LH materials by **Veselago**
- **1996/9** : introduction of electric (ε<0) / magnetic (μ<0) plasmon by **Pendry**
- **2000** : experimental demonstration of LH structure by **Smith**

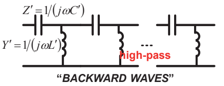
LH definition: → materials with $\varepsilon<0$ and $\mu<0$ $\Rightarrow n<0$ and $v_p-\|v_g$
→ unit-cell << λ → effective / macroscopic / homogeneous

Resonant Structure Approach



• **approach**: no simple/rigorous analysis & no design method
• **structures**: RESONANT ⇨ lossy & narrow bandwidth & highly dispersive

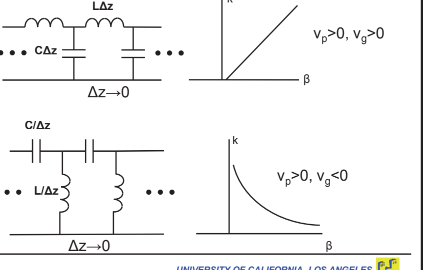
Transmission Line Approach



"BACKWARD WAVES"
(e.g. Brillouin, Pierce)

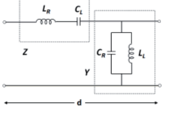
• **approach**: Transmission line analysis & circuit design methods
• **structures**: NON-RESONANT ⇨ low loss & broad bandwidth & moderate dispersion

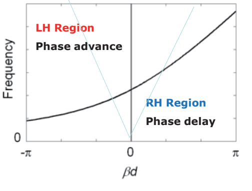
Distributed Model of transmission Line LH structure



Composite Right / Left-Handed (CRLH) Metamaterials

CRLH Transmission Line





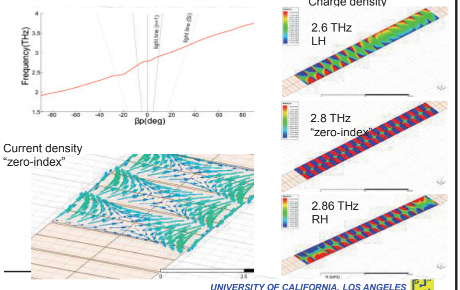
In the balanced condition,

$L_R C_L = L_L C_R$

$\beta^{CRLH} = \omega\sqrt{L_R C_R} - \frac{1}{\omega\sqrt{L_L C_L}}$ ⇨ Phase advance + Phase delay

$Z_c^{CRLH} = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{L_R}{C_R}} = \sqrt{\frac{L_L}{C_L}}$ ⇨ Broad-bandwidth

Graphene CRLH animations



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Passive Components Applications

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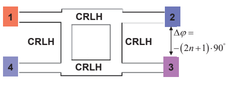
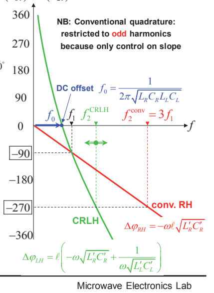
Dual-Band Components, E.g.: Quadrature Hybrid





$\Delta\varphi = -(2n+1)\cdot 90^\circ$

$\Delta\varphi = \varphi(S_{31}) - \varphi(S_{21})$ (deg)

$f_0 = \dfrac{1}{2\pi\sqrt{L_R C_R L_L C_L}}$, $f_2^{conv} = 3f_1$

$\Delta\varphi_{RH} = -\omega\ell\sqrt{L_R' C_R'}$

$\Delta\varphi_{LH} = \ell\left(-\omega\sqrt{L_R' C_R'} + \dfrac{1}{\omega\sqrt{L_L' C_L'}}\right)$

Dispersion Engineering:

- dual-band functionality for an arbitrary pair of frequencies f_1, f_2
- principle: transition freq. (LH-RH) provides *DC offset* additional degree of freedom with respect to the *phase slope* $\varphi(S_{31}) - \varphi(S_{21})$
- BW does not become narrower!
- applications in multi-band systems
- can be extended to many components

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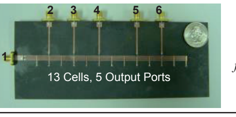
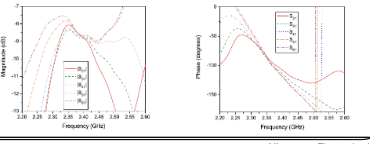
N-Port In-Phase Series Divider Based on Infinite Wavelength



f_∞=2.37 GHz

Experimental Results



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Leaky Wave Antennas

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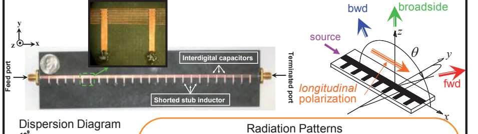
Conventional Planar CRLH Leaky-Wave Antenna

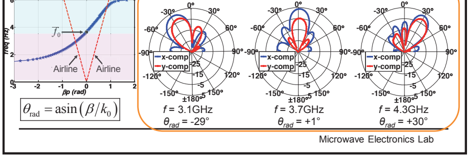
25-cell 2-port CRLH LW-TL

Antenna Configuration



Dispersion Diagram

Radiation Patterns



$\theta_{rad} = \text{asin}(\beta / k_0)$

f = 3.1GHz, θ_{rad} = -29°

f = 3.7GHz, θ_{rad} = +1°

f = 4.3GHz, θ_{rad} = +30°

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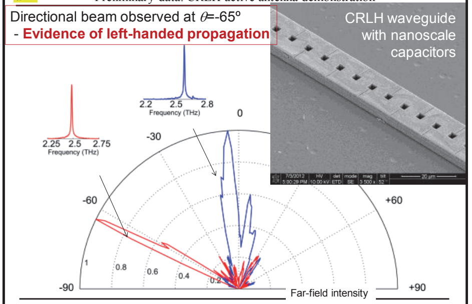
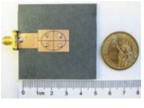
Preliminary data: CRLH active antenna demonstration

Directional beam observed at θ=-65º
- **Evidence of left-handed propagation**

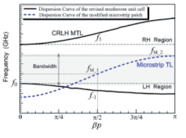


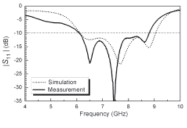
Small Antennas

Broadband CRLH Mushroom Antennas



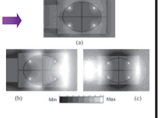
Measured bandwidth (-10 dB): 36%





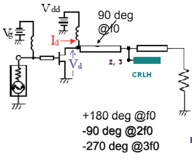
0[th] resonance of the inside patch

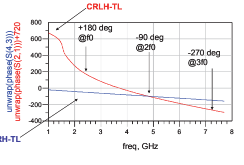
+1[st] and +2[nd] resonances of the overall patch



Active Circuit Applications

CRLH Harmonic Tuning Approach

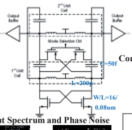




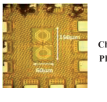
- Single CRLH-TL for two harmonics (Dispersion Engineering)
- Reduced number of stubs leads to: Compact circuit size, Reduced associated loss

f=2.4 GHz	P_{1dB}	P.A.E
Class F	24 dBm	63%

A Dual-Band CMOS mm-Wave Oscillator with Left-Handed Resonator (RFIC 2009)

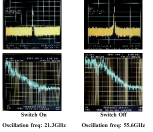


Complete Circuit Schematic



Chip Micro-Photograph

Output Spectrum and Phase Noise



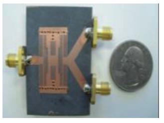
Switch On
Oscillation freq: 21.3GHz
Phase Noise -100.8 dBC/Hz at 1MHz offset

Switch Off
Oscillation freq: 55.6GHz
Phase Noise -86.67 dBC/Hz at 1MHz offset

Measurement Summary

Process	IBM 90-nm Digital CMOS Process
Frequency Band	21 GHz and 55 GHz
Frequency Switching Range (GHz)	34.3 GHz
Frequency Switching Range (%)	62% of highest oscillation frequency
Running at 21 GHz Phase Noise @ 1 MHz offset (dBC/Hz)	-100.8
Running at 55 GHz Phase Noise @ 1 MHz offset (dBC/Hz)	-86.7
VCO-Core Power (mW)	14
VCO-Core Area	150 μm × 60 μm

Collaboration Example



"Novel fully-planar extended-composite right/left handed transmission line based on substrate integrated waveguide for multi-band applications," 42nd European Microwave Conference, Oct. 28-Nov. 2, 2012, Amsterdam, The Netherlands, pp.578-581, (M. Duran-Sindreu, J. Bonache, F. Martin and T. Itoh).

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Conclusions

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Metamaterials can exhibit unconventional phenomena

CRLH approach can realize many such phenomena and can provide useful devices up to THz regime

The author is fortunate to have encountered with this research area

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DE
TATSUO ITOH

Tatsuo Itoh

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Northrop Grumman Endowed Chair
May 5, 1940, Tokyo, Japan

EDUCATION:

Yokohama National University, EE, B.S. 1964
EE, M.S. 1966
University of Illinois,
Urbana-Champaign, EE, Ph.D. 1969

CURRENT AND PREVIOUS POSITIONS:

University of California, Los Angeles
Professor and TRW Endowed Chair, January 1, 1991 to 2003
Distinguished Professor and Northrop Grumman Endowed Chair 2003 to date

University of Texas
Hayden Head Professor, September 1983 to Dec. 31, 1990
Director, Electrical Engineering Research Laboratory, Sept. 1984 to Dec. 1990
Associate Chairman for Research and Planning,
Dept. of Electrical and Computer Engineering, 1984-1990

Professor, September 1981 to Dec. 31, 1990
Associate Professor, July 1978 - August 1981

University of Kentucky
Associate Professor, August 1977 - June 1978

Stanford Research Institute
Senior Research Engineer, April 1976 - August 1977

University of Illinois
Senior Research Engineer, August l974 - April 1976
Research Assistant Professor, September 1971 - August 1974
Research Associate, March 1969 - August 1971

Tamagawa University (Tokyo)
Teaching Assistant, April 1966 - August 1966

CONSULTING:

AEG-Telefunken, Ulm, West Germany, 1979
Selenia, s.p.A., Rome, Italy, 1979
Texas Instruments Equipment Group, Dallas, Texas, 1980
Institute for Future Technology, Tokyo, Japan, 1982
Georgia Institute of Technology, Engineering Experiment Station, Atlanta, 1981
Marconi Electronics Devices, Lincoln, England, 1981
Hughes Aircraft Company, Torrance, CA, 1980 to 1994
Teledyne Microelectronics, Los Angeles, CA 1984
Superconductor Technologies, Inc., Santa Barbara. CA. 1989 to 1990
David Sarnoff Research Center, NJ, 1992 Hughes Space and Communication, El Segundo, CA 1995 to 1996
Daimler-Benz AG, Stuttgart, Germany, 1997
Matsushita Electric, Kawasaki, Japan, 1997
Expert Witness, 2006

HONORS AND AWARDS:

Microsoft Academic Search, Listed No.1 in Electrical Engineering 2014
Thompson Reuters, Highly Cited Researcher 2014
Fellow, National Academy of Inventors, 2014
University of Illinois College of Engineering Alumni Award for Distinguished Service, 2012
IEEE Microwave Career Award, 2011
European Microwave Association Outstanding Career Award, 2009
Member of National Academy of Engineering, 2003
Distinguished Microwave Educator Award, IEEE MTT-S, 2000
Millennium Medal, IEEE, 2000
IEEE Distinguished Microwave Lecturer, 2004 - 06
Shida Rinzaburo Award, Ministry of Post and Telecommunications, Japan, 1998
Japan Microwave Prize, 1998
Honorary Life Member, IEEE Microwave Theory and Techniques Society, 1994
Fellow, IEEE, 1982
Life Fellow, IEEE, 2006
Billy and Claude Hocott Distinguished Centennial Engineering Research Award, University of Texas, 1988
Distinguished Alumnus Award, University of Illinois, 1990
Fellow, Center for Advanced Study, Univ. of Illinois, 1972-73
Arthur J. Schmidt Scholar, National Electronics Conference, 1973
Listed in Who's Who in Technology Today, 1979 to date
Listed in World's Researchers, 1980 to date
Listed in Who's Who in America
Listed in American Men and Women of Science, 1981 to date
Listed in Men of Achievement, 1988 to date
Listed in 5,000 Personalities of the World, 1989 to date
Listed in the International Directory of Distinguished Leadership, 1989 to date
Listed in Who's Who in Electromagnetics, 1989, 1990
Engineering Foundation Awards, Univ. of Texas, 1980-1981
U.S. Delegate to NATO Symposium on Millimeter-Wave Propagation and Circuits, 1978
U.S. Delegate and National Academy of Science's National Research Council Representative to the General Assembly of International Scientific

Radio Union,1981, 1984, 1987, 1990, 1993
Honorary Visiting Professorship, Nanjing Institute of Technology, 1985
United Nations' International Telecommunication Union Expert for Telebras
Research Center, Brazil, 1985
Invited to European Space Agency Workshop on Radiometer by IEC, Madrid, Spain,1985
Guest Professor, National Defense Academy, Japan, 1991
IEEE Australian Council Distinguished Lecturer, 1992
Visiting Professor, University of Leeds, United Kingdom, 1994 - 2000
Visiting Professor, Beijing Univeristy of Aeronautics and Astronautics, China, 1995 - 1996.
Distinguished Research Chair Professor, National Taiwan University, 2009- 2012.

MEMBERSHIPS IN PROFESSIONAL AND HONORARY SOCIETIES:

IEEE, Life Fellow
Institute of Electronics and Communication Engineers of Japan, member
URSI (International Scientific Radio Union) Commission B and D, member

PROFESSIONAL SOCIETY AND MAJOR GOVERNMENTAL COMMITTEES:

IEEE Division IV
Representative to TAB Periodicals Council and PUB Board, 1992 to 1993

IEEE Microwave Theory and Techniques Society
Chairman, Past President Council, 1994 to 96
President, 1990
Vice President, 1989
Editor, IEEE Transactions on Microwave Theory and Techniques, July 1982-85
Editor-in-Chief, IEEE Microwave and Guided Wave Letters, 1990 to 1994
Chairman, Publications and Standards Activities, 1986-88
Administrative Committee, January 1982 to date

Chairman, Technical Committee on Microwave Field Theory, 1979-88, Member 1988 to date
Standard Committee on Planar Transmission Lines 1982-1986
Publications Evaluation Committee, 1982 to 1987
MTT Representative to URSI, 1984-87, 2006-date
Fellow Selection Committee, 1984 to 1987
Editorial Board, 1972 to date
Guest Editor, IEEE Transactions on Microwave Theory and Techniques
(Special Issue on Open Guided Wave Structures) September 1981,
(Special Issue on Computer Aided Design) February 1988
(Special Issue on Metamaterial Structures, Phenomena and Applications) April 2005

Technical Program Committee, IEEE MTT-S International Microwave Symposium, 1977 to date
Technical Program Committee Co-chair, IEEE MTT-S International Microwave Symposium, Dallas, TX, 1990.
Technical Program Committee Chair, IEEE MTT-S International Microwave Symposium, Honolulu, HI, 2007.
Steering Committee, 1982 IEEE MTT-S International Microwave Symposium, Dallas, Texas, June 1982
Session Chairman and Session Organizer, IEEE MTT-S International Microwave Symposium, 1977 to date
Technical Program Committee, IEEE Microwave and Millimeterwave Monolithic Circuits Symposium, 1983
Steering Committee, International Conference on Infrared and Millimeter Waves, 1979 to 1990
Workshop organizer, IEEE MTT-S International Microwave Symposia, 1984 to 1999

IEEE Solid State Circuit Council
Panel Member, International Solid State Circuit Conference,
Feb. 1978, Feb. 1981

IEEE Antennas and Propagation Society
Technical Program Committee, IEEE AP-S Symposium, Frequently 1981 to date
Technical Review for IEEE Transactions on Antennas and Propagation, 1978 to date

IEEE Electromagnetic Compatibility
Technical Reviewer for IEEE Transactions on Electromagnetic Compatibility, 1988 to date

IEEE Lasers and Electro-Optics Society
Technical Committee, 1991 Topical Meeting of Optical Millimeter-Wave Interactions: Measurement, Generation, Transmission and Control, July 1991

IEEE Benelux Section
Program Commission, CompEuro'92, May 1992, Hague, The Netherlands

Institution of Electrical Engineers (London)
Technical Reviewer for IEE Electronics Letters 1977 to date
Technical Reviewer for IEE Transactions H (Microwaves, Optics and Antennas), 1978 to date
Organizing Committee, International Conference on Computation in Electromagnetics, November 1991, London

International Scientific Radio Union
Chairman, Commission D, 1993 to 1996
Vice Chairman, Commission D, 1990 to 1993
Chairman, Commission D, USNC, 1988 to 1990
Technical Activities Committee, Commission B, USNC, 1982
Session Chairman, International Symposium on Electromagnetic Theory, Munich, West Germany, August 1980
Chairman, Publicity Committee, International Symposium on Signals, Systems and Electronics, (ISSSE'92),September 1-4, 1992, Paris, France
Vice Chairman, Steering Committee, International Symposium on Signals, Systems and Electronics (ISSSE'95), Oct. 25-27, 1995, San Francisco, CA

U.S. Government
Technical Reviewer for National Science Foundation
Technical Reviewer for National Research Council
Technical Reviewer for U.S. Army Research Office
Session Chairman, Army Research Office Workshop on Modern Millimeter Wave Systems, Estes Park, CO, October 1980
Panel Member, Army Research Office Workshop on Short Millimeter Wave Nonreciprocal Material and Devices, Research Triangle Park, NC, November 1981.

Panel Member, Army Research Office Workshop on Solid State Amplification Schemes for Electromagnetic Waves in MMW/SMMW Region, May 1991
Army Research Office Strategic Planning Workshops, 1989, 1992, 1995, 1998, 2004
Army Research Office Board of Visitors, 2012
National Academy of Science, Committee for Army Basic Research, 1984 -88
National Academy of Science, NRC Panel for Efficient Use of Spectrum, 1994-96 External Evaluator, Naval Research Laboratory 2004, 2006
External Evaluator, NIST, 2007, 2009 National Academy of Engineering Peer Committee, 2006-08

Foreign Government
Adjunct Research Officer, Communications Research Laboratory, Ministry of Post and Telecommunication, Japan, 1994 to 1999
German Research Council, 2007

Others
Advisory Board of Editors, International Journal of Infrared and Millimeter Waves, 1980 to 2000
Editor, Electronics and Communications in Japan , 1982 to 2009
Associate Editor, Electromagnetics, 1983 to 1990
Editorial Board, Asia-Pacific Engineering Journal, 1990 to 1994
Editorial Board, Microwave and Optical Technology Letters, 1988 to 1991

UNIVERSITY OF TEXAS COMMITTEES:

Department

Budget Council	1981 to 1990
Industrial Liaison Committee, Chairman	1981 to 1984
Strategic Goals Committee	1982 to 1990
MO&E Committee	1982 to 1983
VLSI Committee	1982 to 1983
Microelectronics Committee	1983 to 1984
Undergraduate Curriculum Committee	1981 to 1983
Optics Curriculum Committee	1981 to 1984
Field and Waves Area Committee	1978 to 1990
Chairman	1978 to 1983

Graduate Studies Committee	1978 to 1990
Library Committee	1982 to 1983
Catalog Committee	1982
Editor, EE Newsletter	1982 to 1990
Program Committee,	1982 to 1990
Annual Research Review	1983 to 1990
Chairman, Program Committee,	
Annual Research Review	1983

College

Committee on Foreign Student Enrollment	1981
Library Committee	1982 to 1983
Ad Hoc Committee on Faculty Salary Review	1983 to 1984
Internal Review Committee for Hocott Award	1989 to 1990

University

University UCAR Committee	1988 to 1990
University Project Bluebonnet	1989 to 1990
Mitre/UT System Over the Horizon Radar	
Technical Com.	1989 to 1990

Community Activities

Faculty Advisor, University of Texas Japanese	
Student Association	1980 to 1981

UCLA COMMITTEES:

Department
Tenure Review Committee, Chair, 1994-96, 2001-2004
Curriculum Committee, 1991 to 2004
Academic Planning and Faculty Recruiting Committee, Chair 1993 -2004
Advisory Committee, Center for High Frequency Electronic
Electromagnetics Area Committee, Chairman 1991 to 1994, 1998-date
UCLA Research Symposium, Chairman, 1992
Adhoc Committee for Graduate Major, Chair, 1994 to 1996

School of Engineering and Applied Science
Endowed Chair Search Committee Chairman and Member, 1991 to 2007

University
Adhoc Committee for Appointment and Promotion, occasional

PATENTS:

1. Waveguide having strip dielectric structure, U.S. Patent 4028643.
2. Quasi-optical polarization duplexed balanced mixer, U.S. Patent 4509209 (with K. Stephan)
3. Crosstie overlay slow-wave structure and components made thereof for Monolithic integrated circuits and optical modulators, U.S. Patent 4,914,407
4. Microwave and Millimeter Wave Noncontact ID System, U.S. Patent 5,525,993 (with C. Pobanz)
5. Highly Efficient, Ultrafast Optical-to-Electrical Converter, U.S. Patent 5,572,014 (with M. C. Wu)
6. Low Profile Cavity Backed Slot Antenna, U.S. Patent 6,518,930
7. Composite Right/Left Handed Coupler, U.S. Patent 7,508,283)
8. Zeroth Order Resonator, U.S. Patent 7,330.090, 7,398,211
9. Metamaterial Based Small Antennas, U.S. Patent 7,446,712
10. Metamaterial Based Power Combiner, U.S. Patent 7,482,893

Ph.D. SUPERVISIONS COMPLETED:

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D. Goshi 2007
A. Lai 2007
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P. Chi 2010
R. Hashemi 2011
Y. Dong 2012
S. Sun 2013
P. Hon (joint supervision) 2013
C-T. M. Wu 2014
J. Choi 2014

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S. S. Chang, Dec. 1988
K.-S. Kong, Dec. 1988
A. V. Filippas, May 1989
C. W. Kuo, May 1989
B.-K. Kim, May 1991

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C. W. Pobanz December, 1993
K. Khojastegan March, 1994
D.-C. Niu September, 1994
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W. Fu September, 1997
W. R. Deal March, 1998
Q. Chaudhry June, 1998
B.-S. Ke September, 1998
S. Y. Lee December, 1998
Y. Miyamoto June, 1999
R. Broas September, 1999
S. Lin December, 1999
Y. Hang December, 1999
J. D. Fredrick June, 2000

J. Sor September, 2000
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M. DeVincentis March, 2003
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A. Dupuy March, 2005
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E. Ash 2006
P. Hon 2007
J. Sun 2007
C. T. Wu 2009
Ranjan Misra 2010
J. Tanabe 2013
K. Dhwaj 2014

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H. Lee
K. Dhwaj

M.S. IN PROGRESS:

R. Tripati
Z. Shen
A. Waghmare

Visiting Scholars and Post Docs(*)

1. L. P. Schmidt (Germany)* Prof. Technical University of Erlangen
2. K. Araki (Japan)* Prof. Tokyo Institute of Technology
3. I. Awai (Japan)* Prof. Yamaguchi University
4. J. F. Miao (China) Prof. Emeritus, Southeast University
5. W. B. Zhou (China) Chinese Institute of Electronics
6. L. Su (China)
7. R. Sorrentino (Italy) Dean, University of Perugia
8. H. Ogawa (Japan) Communications Research Lab.
9. T. Uwano (Japan) Central Research Lab. Matsushita Electric
10. M. Geshiro (Japan) Prof. Osaka Prefectural University
11. Y. Nikawa (Japan) Prof. National Defense Academy
12. T. Kitazawa (Japan) Prof. Ritsumeikan University
13. O. R. Biocchi (US) Chair of EE, North Dakota State University (7/91-8/91)
14. Y. Yamamoto (Japan) Prof. Osaka Sangyo University (1/91-3/91)
15. K. Kawasaki (Japan) SONY Electronics in San Diego
16. T. Lee (Korea) Assoc. Prof. Korea Maritime University
17. A. Beyer (Germany) Prof. Duisburg University
18. J.-B. Lim (Korea) Prof. Kookmin University
19. C. W. Kuo (Taiwan) (1/91-6/91)
20. K. S. Kong (Korea) (1/91-6/92)
21. T. Hirota (Japan) NTT (10/91-10/92)
22. B. Houshmand (US)* JPL (7/92-6/94)
23. T. Wakabayashi (Japan) Prof. Tokai University (4/91-3/92)
24. S. Nogi (Japan) Prof. Okayama University (10/91-8/92)
25. T. Yoneyama (Japan) Prof. Tohoku University (4/91-8/92)
26. M. Tanaka (Japan) (10/92-9/93)
27. S. Barbin (Brazil) (7/93-7/94)
28. M. Minegishi (Japan) (Nondegree Student)
29. Yoshida (Japan) (8/94-3/95)
30. I. Sakagami (Japan) Prof. Muroran Institute of Technology (6/93-5/94)
31. M. Hano (Japan) Assoc. Prof. Yamaguchi University (6/94-4/95)

32. D. Pilz (Germany) Assistant, University of Ulm (7/94-10/94)
33. R. B. Wu (Taiwan) Prof. National Taiwan University (8/94-8/95)
34. A. Sanada (Japan) (12/94-4/95)
35. S. Okubo (Japan) (9/95-1/96)
36. J.-T. Kuo (Taiwan) Prof. National Chaio Tung University (8/95-7/96)
37. M. Taguchi (Japan) (3/96-9/98)
38. H. B. Lee (Korea)* (2/96-2/98)
39. R. Coccioli (Italy)* (7/96-12/99)
40. R. Goetzfried (Germany) Daimler Chrysler Research (6/95-12/95)
41. Y. Qian (China)* (4/96-3/98)
42. M. Koshiba (Japan) Prof. Hokkaido University (4/96-5/96)
43. T. Shibata (Japan) NTT (2/96-2/97)
44. E. Takagi (Japan) Toshiba (8/95-2/97)
45. M. Nishida (Japan) Sanyo Electric (8/95-7/96)
46. D. Su (China) Assoc. Prof. Beijing Aeronautical University (5/96-5/98)
47. H. Arai (Japan) Assoc. Prof. Yokohama National University (3/97-4/97)
48. M. Hotta (Japan) Assoc. Prof. Ehime University (4/97-2/98)
49. K. Hirose (Japan) Assoc. Prof. Tokyo Denki University (3/98-2/99)
50. J.-S. Park (Korea) Assoc. Prof. Soonchunhyang University (3/97-3/99)
51. C. Su (Taiwan) (7/97-7/98)
52. A. Rennings (Germany) (7/99-1/00)
53. Y. Wang* (8/99-10/02) UCLA
54. T. Sugiura (Japan) (9/99-7/00)
55. H. Nakagawa (Japan) (10/99-9/00)
56. B. Cetiner (Cyprus) (11/99-10/01)
57. D. Park (Korea) (2/00-1/01)
58. C. S. Ha (Korea) (2/00-2/01)
59. R. Waterhouse (Australia) (7/00-10/00)
60. K. Mori (Japan) (10/00-1/01)
61. D. S. Armagan-Sahinkaya (Turkey) (6/01-6/02)
62. H. Okabe (Japan) (9/00-8/01)
63. T. Iwai (Japan) (9/01-8/02)
64. D. Ahn (South Korea) (2/02-2/03)
65. G. Kim (Korea) (7/02-8/03)
66. Christophe Caloz* (10/00-10/04) Polytech Montreal
67. J. I. Choi (Korea) (9/02-8/03)
68. A. Sanada (Japan) (9/02-8/03) Yamaguchi University
69. A. Hirota (Japan) (6/03-9/03)
70. Y. Horii (Japan) (2/04-3/04)

71. Yong Woo Jeong (South Korea) (4/03-3-04)
72. Hiroshi Okabe (Japan) (9/01-9/02)
73. Chul-Soo Kim (Korea) (3/04-2/05)
74. Hak Kevin Choi (South Korea) (9/03-8/04)
75. Simon Otto (Germany) (1/04-7/04)
76. Delphine Bechevet (France) (6/05-9/05)
77. Kevin Leong* (4/04-12/07)
78. Dal Ahn (South Korea) (3/03-1/05)
79. Wei Yang Wu (Taiwan) (4/05-2/06)
80. Tetsuya Ueda (Japan) (3/05-2/06)
81. Chao_Hsing Tseng (Taiwan) (8/05-7/06)
82. Don Hoon Shin (Korea) (10/05-9/06)
83. Naobumi Michishita (Japan) (5/06-4/07)
84. Darren Goshi* (1/07-6/08)
85. Byung Chul Kim (Korea) (10/06-9/07)
86. Young Kim (Korea) (1/07-1/08)
87. Kohei Mori (Japan) (9/07-8/08) SONY
88. Eisuke Nishiyama (Japan) (10/07-9/08) Saga Universitiy
89. Hidetoshi Nakayama (Japan) (3/08-9/08)
90. Tzong-Lin Wu (Taiwan) (6/08-9/08)
91. Chien-Chung Wang (Taiwan) (10/08-9/09)
92. Tao Yang (China) (9/08-9/10)
93. Alonso Corona (Mexico) (8/09-7/10)
94. Hee Ran Ahn (Korea) (9/09-12/10)
95. Taehee Tang (Korea) (8/10-9/11)
96. Edgar Colin Beltran (Mexico) (9/10-8/11) INAOE
97. Hyeon Cheol Ki (Korea) (1/11-2/12)
98. Humberto Lobato-Morales (Mexico) (4/11-1/12) INAOE
99. Miguel Duran-Sindreu (Spain) (9/11-3/12) Univ Autonoma de Balcelona
100. Hangyan Tang (China) (9/12-9/13) UESTC
101. Hsin-Chia Lu (Taiwan) (8/13-1/14) NTU
102. Young Je Sung (Korea) (1/14-2/15) Kyonggi Univ
103. Lijun Jiang (Hong Kong) (9/14-3/15) U of HK
104. Kohei Enomoto (Japan) (11/14-12/14) KIT
105. Keisuke Ninomiya (Japan) (11/14-12/14) KIT

GRANTS AND CONTRACTS:

Summary of Grants

	Federal	State	Industry	Total
UT Austin	$2,953,893	$1,096,624	$389,682	$4,440,199
UCLA	$15,612,028	$460,570	$2,83,868	$18,911,466

UNIVERSITY OF TEXAS

Quasi-optical techniques for millimeter and submillimeter wave circuits, DAAG29-79-G-00200, U.S. Army Research Office, $99,662, July 1, 1978 - February 28, 1981.

Interface structures for millimeter-wave circuits, DAAG29-81-K-0053, U.S. Army Research Office, $171,335, March 1, 1981 - August 31, 1984.

Studies of non-reciprocal effects in planar submillimeter to optical waveguiding structures, N00014-79-C-0553, Office of Naval Research, $186,305, June 1, 1979 - August 31, 1984.

Millimeter-wave transmission lines study, Texas Instruments Equipment Group, $65,573, June 1, 1979 - December 31, 1984.

Equipment Grant, University Research Institute, $4425, September 1, 1978 - August 31, 1979.

Guided-wave devices for the far-infrared-mm wave spectrum (Co-PI: A. B. Buckman), Joint Services Electronics Program, $207,000, April 1979 - March 1983.

Guided waves in composite structures, Joint Services Electronics Program, $132,000, April 1982 - March 1986.

Guided wave interactions in millimeter-wave integrated circuits, U. S. Army Research Office, $225,346, September 1, 1984 - August 31, 1987.

Pulse transmission in planar transmission structures on a semiconductor substrate, Office of Naval Research, $91,267, September 1, 1984 - August 1986.

Printed line structures for monolithic millimeter-wave circuits, Hughes Aircraft, $78,432, May 15, 1984 - September 30, 1987.

Millimeter wave planar circuits, Hughes Aircraft, $10,000, August 1, 1985 - July 31, 1986.

Millimeter wave research, Martin Marietta, $60,575, September 1, 1985 - August 31, 1987.

Millimeter wave monolithic circuits, $11,700, NTT Electrical Communication Laboratories, October 11, 1985 - May 31, 1987.

Integrated millimeter-wave and optoelectronic components for very high speed communications applications (Co-PI), Texas Advanced Technology Research Program, $400,000, November 1, 1985 - August 31, 1987.

Monolithic Phase Shifter Study, Air Force Office of Scientific Research, (co-PI: D.P. Neikirk) $589,695, November 1, 1985 - October 31, 1988.

Millimeter-wave monolithic array components, Joint Service Electronics Program (Co-PI: D.P. Neikirk) $251,000, April 1, 1986 - March 31, 1989.

Millimeter wave transmission lines, Office of Naval Research, $91,767, September 1, 1986 - September 30, 1988.

Guided Wave Phenomena in Millimeter Wave Integrated Circuits and Components, U.S. Army Research Office, $298,131, April 1, 1988 - March 31, 1991.

GaAs Based Millimeter-Wave Integrated Circuit Characterization and Design, CRAY Research Ins., $45,862, January 1, 1988-December 31, 1988.

E-Plane Filter Analysis and Design, Hughes Aircraft, $20,515, July 1, 1987-July 1, 1988.

Large Signal Modeling of MESFET, Hughes Aircraft, $7,011, Feb. 22, 1988-May 20, 1988.

Monolithic Millimeter-Wave Integrated Circuits, Texas Higher Education Coordinating Board Advanced Technology Program, $198,433, June 15, 1988-Aug. 31, 1989.

Computer Aided Design of Millimeter-Wave Integrated Circuits, Texas Higher Education Coordinating Board Advanced Technology Program, (Co-PI: Hao Ling) $143,766, June 15, 1988-Aug. 31, 1989.

Picosecond Laser System for High-Speed Laser System for High-Speed Characterization of Monolithic Devices (Equipment Grant), Dept. of Defense University Research Instrumentation Program, (Co-PI's: M.C. Downer, D. P. Neikirk), $75,303, Sept. 1, 1988-Aug. 31, 1989.

Millimeter Wave Active Guided Structures, Joint Services Electronics Program, (Co-PI: D. P. Neikirk), $255,000 April 1, 1989-March 31, 1992.

High Temperature Superconducting Planar Circuit Structures for High Frequency Applications, Office of Naval Research, $239,352, Oct. 1, 1988-Sept. 30, 1991.

Unrestricted Use, Honeywell, Inc., $3,000, March 20, 1989.

Unrestricted Use, John Wiley and Sons, $800, June 1, 1989-May 31, 1990.

Unrestricted Use, Nippon Telegraph and Telephone Corp., $652, May 15, 1989.

Unrestricted Use, Sony Corp., $8,000, June 1, 1989-May 31, 1990.

Quantum Well Device-Based Circuits for Millimeter Wave Communications Applications, Texas Higher Education Coordinating Board Advanced Technology
Program, (Co-PI: D. P. Neikirk) $150,000, Jan. 1, 1990-Dec. 31, 1991.

Microwave-Optical-Interaction Devices and Circuits, Texas Higher Education Coordinating Board Advanced Technology Program, (Co-PI: J. C. Campbell) $200,000, Jan. 1, 1990-Dec. 31, 1991.

Analysis and Characterizations of Planar Transmission Structures and Components for Superconducting and Monolithic Integrated Circuits, NASA-Lewis Research Center, $40,730, Nov. 13, 1989-Nov. 12, 1990.

Noise Measurement System (Equipment Grant), Hewlett-Packard, $59,100, May 1990.

Research on New Configurations for Microwave and Millimeter-Wave IC's, NTT Radio Communication Systems Lab., $10,000, July 1, 1990-June 30, 1991.

Analysis of Waveguides for Millimeter-Wave and Optical Integration Circuits, ATR Optical and Radio Communications Research Lab., $8,462, June 1, 1990 - June 30, 1991.

UCLA

"Guided Wave Phenomena in Millimeter Wave Integrated Circuits and Components,"
Army Research Office (via Univ of Texas), DAAL03-88-K-0005,
$193,374, January 1, 1991-December 31, 1992.

"High Temperature Superconducting Planar Circuit Structures for High Frequency Applications,"
Office of Naval Research, N00014-91-J-1651,
$150,635, June 1, 1991-September 30, 1993.

"Analysis and Characterization of Planar Transmission Line Structures and Components for Superconducting Integrated Circuits,"
NASA Lewis Research Center, NCC3-192,
$34,328, January 1, 1991-December 31, 1991.

"New Configurations for Microwave and Millimeter-Wave ICs,"
NTT Radio Communication Systems Laboratories,
$34,700, January 1, 1991 - June 30, 1993.

"Analysis of Waveguides for Millimeter-Wave and Optical Integrated Circuits,"
ATR Optical and Radio Communication Laboratory,
$58,396, January 1, 1991- June 30, 1992.

“Extension of Spectral Domain Method for Discontinuities in Monolithic Microwave and Millimeter Wave Integrated Circuits with Thick Metalization,” Hughes (MICRO), $40,000, July 1, 1991 - June 30, 1992.

“Analytical Circuit Modeling for Passive Monolithic Microwave and Millimeter Wave Components,”
TRW (MICRO), $50,000, July 1, 1991-June 30, 1992.

“3-Dimensional Microwave Integrated Circuits,”
Hughes Aircraft Company, $18,359, October 1, 1991 - September 30, 1992.

“Millimeter Wave Electronics,” Air Force Office of Scientific Research, Joint Services Electronics Program (AFOSR),
$1,375,402 July 1, 1992 - June 30, 1995. (Joint with N. Luhmann)

“Wave interactions in active and passive microwave and millimeter wave circuits,”
Army Research Office, DAAH04-93-G-0068,
$313,000, Feb 15, 1993-Feb 14, 1996

“Optoelectronic interactions of active integrated antennas,”
AASERT (ARO), DAAH04-93-G-0174,
$120,000, June1, 1993-May 31, 1996

“Analysis of electromagnetic characteristics for uniplanar structures,”
TRW (MICRO), $42,352, July 1,1992-December 31, 1993

“Extension of spectral domain method for 3-dimensional discontinuities in microwave integrated circuits,”
Hughes (MICRO), $34,069, July 1, 1992-December 31, 1993,

“Microwave and millimeter wave chip antennas,”
NEC Corporation, $20,000, April 1,1993-March 31, 1995

“Frequency Scannable Leaky Wave Antennas Based on Dielectric Waveguides,”
ThermoTrex, $179,996, October 11, 1993-August 15, 1994

“Analysis of electromagnetic characteristics for uniplanar structures,”
TRW (MICRO), $34,857, July 1,1994 - June, 30, 1995

"Comprehensive Electromagnetic Simulation of Microwave Integrated Circuts,"
Hughes (MICRO), $ 87,143, July 1, 1994 - June 30, 1995

"Time Domain Characterization of Selected Waveguide Discontinuities,"
MAG (MICRO), $ 15,000, July 1, 1993 - June 30, 1995,

"Electronically and Optically Controllable Leaky Wave Antennas,"
AASERT (ARO), DAAH04-93-G-0316,
$111,843, September 1, 1993-August 31, 1996

"Active Excitation of 2-dimensional Quasi-Optical Circuits,"
AASERT (ARO), DAAH04-93-G-0139,
$107,000, July 1, 1994-June 30, 1997

"Ultrafast High Power Photodectors" (Joint with M. Wu)
Army Research Office, DAAH04-95-I-0405,
$269,793, July 1, 1995 -June 30, 1998

"Scanning Near-Field Optical Lithographis System," (Equipment)
DURIP (ARO), DAAH04-95-I-0029,
$207,000, Nov. 18, 1994-Nov. 17, 1995

"Ultrafast Streak Camera for 100 Gb/s Optical Network Testbed," (Co-Pi, M. Wu as PI)
DURIP (ARO), DAAH04-95-I-0441,
$169,810, July 1, 1995 - June 30, 1996

"Active Integrated Beam Steering and Switching Array with All Optical Control,"
AASERT (AFOSR), F49620-95-1-0414
$108,255, June 1, 1995- May 31, 1998

"International Symposium on Signals, Systems and Electronics,"
Army Research Office, DAAH04-95-I-0340,
$5,000, August 1, 1995 - July 31, 1996

"International Symposium on Signals, Systems and Electronics,"
Office of Naval Research, N00014-95-1-0641,
$5,000, May 1, 1995 - April 30, 1996

"Frequency Scannable 220 GHz Dielectric Leaky Wave Antennas,"
ThermoTrex Corporation, $179,986, Jan. 1, 1995 - Jan.1, 1996

"UCLA JSEP Program in Millimeter Wave Electronics,"
JSEP (AFOSR), $1,189,110, Oct.1, 1995 – Oct. 31, 1998.

"Comprehensive Electromagnetic Simulation of Microwave Integrated Circuits,"
Hughes (MICRO), $62,363, July 1, 1995 - June 30, 1996

"Analysis of Electromagnetic Characteristics for Non Leakage Coplanar Structures,"
TRW (MICRO), $35,636, July 1, 1995 - June 30, 1996

"Ultrafast High Power Photodetectors," (Co-PI)
ARO, $217,939 (Co-PI $108,919), July 15, 1995 – Dec. 31, 1997

"Low Power/Low Noise Electronics Technologies for Mobile Wireless Communications,"
MURI (ARO), $4,000,000, August 1, 1995 – Dec. 11, 2000

"Study of MMIC Transitions and Interconnects,"
TRW (MAFET II), $200,000, Nov.14, 1995-Sept.30, 1997

"High Efficiency W-Band Power Source,"
TRW (MAFET III), $200,000, Oct.6, 1996-Sept.30, 1998

"Photonic Bandgap Engineering," (Co-PI)
MURI (ARO), $3,000,000(Co-PI $240,000), Sept. 1, 1996 – Aug.31,1999

"RF Photonics and Devices," (Co-PI)
MURI (ONR), $5,444,000 (Co-PI $500,000), April 30, 1997-April 29, 2002

"Velocity-Matched Traveling Wave Photodetectors for Photomixing of Millimeter Waves,"
Associated Universities, Inc. (National Radio Astronomy Observatory)
$265,745, July 1, 1997 – June 30, 1999

"GaN-Based Microwave Power Amplifiers," (Co-PI)
Army Space and Strategic Defense Command,
$4,104,181 (C-PI, $720,000), April 11, 1996 – April 10, 2001

"Integrated Antennas as Contactless Connector for Wireless Systems," Rockwell Science Center (MICRO), $25,0000, July 1, 1997 – June 30, 1998

"RF Front-Ends for 60 GHz Multimedia Wireless System, SONY Electronics, Inc. (MICRO), $30,000, July 1, 1997 – June 30, 1998

"Comprehensive Electromagnetic Simulation of Microwave Integrated Circuits,"
HUGHES (MICRO), $35,000, July 1, 1997 – June 30, 1998

"Analysis of Electromagnetic Characteristics of Flip Chip Interconnects,"
TRW (MICRO), $25,000, July 1, 1997 – June 30, 1998

"Development of a Capstone Integrated Systems Laboratory,"
TRW Cleveland Foundation, $40,000, 1998

"High Efficiency Power Amplifiers Using Photonic Band-Gap Crystals,"
ARO (AASERT), $119,307, July 1, 1997-June 30, 2000

"Active Integrated Antenna Front-End Technology for Future Millimeter-Wave Wireless Communications,"
NSF, $450,000, Sept. 15, 1999 – August 31, 2002

"Reconfigurable Antennas for Multiband/Multifunction Transceive,"
DARPA/SPAWAR, $2,765,000, Sept. 29, 1999 – Sept, 28, 2002

"Quantum Device Technology for Terahertz Communication Trasceiver,"
DARPA/HRL, $200,000, Oct. 1, 1999 – Sept. 30, 2002

"RF Front-Ends for 60 GHz Multimedia Wireless System,"
SONY (MICRO), $44,866, July 1, 1999 – June 30, 2001

"Three-Dimensional Functional MMIC,"
TRW Foundation, #25,000, Aug. 1, 1998 – June 30, 2000

"Integrated Antenna and Packaging Technology for Future MM-Wave Wireless Systems,"
SONY (MICRO), $44,866, July 1, 1999 – June 30, 2001

"Multifunctional Adaptive Radio, Radar and Sensors,"
ARO/NCSU (MURI), $ 528,800.00, 05/01/01 – 02/28/06

"Scalable and Reconfigurable Electromagnetic Metamaterials and Devices,"
DARPA/NAVY (MURI), $ 500,000.00, 05/01/01 – 07/31/06

"High Performance "Signal Processing" Antenna Array Systems for Wireless Communications,"
National Science Foundation, $500,000.00, 07/01/02 – 08/31/05

"RF Front-Ends for 60 GHz Multimedia Wireless System,"
Sony – UC MICRO, $44,847.00, 07/01/04 - 12/31/05

"Metamaterial Based Small Antennas,"
Qualcomm – UC DISOVERY GRANT, $69,294.00, 08/24/04 – 08/23/05

"Characterization of Periodic Structures,"
Lockheed Martin Aeronautics – Palmdale, $100,000.00, 05/01/05 – 02/24/06

"Investigation of Millimeter Wave Electronic Scanned Array Radar,"
BAE Systems Platform Solutions / UC DISCOVERY GRANT
$147,925.00 05/10/05 – 05/09/06

"Novel Components for 60 GHZ RF Frontends"
Sony Corporation (UC MICRO) – $80,268.00, 08/01/05 – 12/31/06

"Direct Antenna Modulation for Ultra Wide Band Signal Transmission"
Army (ARO) – $59,765.36, 08/01/05 – 10/31/07

"Design of 94-GHz Photonic Bandgap Phased Array"
UC Lawrence Livermore National Laboratory (U.S. DOE)
$9,942.00 12/08/05 – 12/31/06

"Evanescent Mode LHM"
Lockheed Martin – $60,000.00, 04/01/06 – 12/31/06

"Development of Compact Metamaterial Antennas for Antennas for MIMO Systems"
Rayspan Corporation – $110,000.00, 05/01/06 – 04/30/07

“2.4 Ghz Metamaterial Miniature Antennas”
Rayspan Corporation – $3,036.00, 06/15/06 – 06/29/06

“Metamaterial Antennas for MIMO Applications”
Rayspan Corporation (UC MICRO) – $58,159.00, 08/01/06 – 12/31/07

“Novel Components for High Frequency RF Front-Ends 2006”
Sony Corporation – $67,332.00, 08/17/06 – 12/31/07

“Study of Compact Metamaterial Based Filters”
Panasonic Semiconductor Development Center – $70,000.00, 09/01/06 – 08/31/07

“KA Band Quasi-Yagi Antenna Design”
Agile Materials and Technologies – $5,000.00, 11/01/06 – 2/28/07

“Microwave Detection of Laser Ultrasonic for Non-Destructive Testing”
BossaNova Technologies, LLC – $28512.00, 01/19/07 – 01/18/08

“Enhanced Sparse Array Antennas for Millimeter Wave Applications”
MMCOMM (UC Discovery) – $87,681.00, 02/01/07 – 01/31/08

“Compact High-Frequency Antennas”
Pharad, LLC – $30,000.00, 07/31/07 – 03/06/07

“Compact High Frequency Antennas”
Pharad – $255,000.00, 06/01/07 – 08/31/07

“Compact High Frequency Antennas”
Pharad – $255,000.00, 06/01/07 – 08/31/07

“Dual Band Mimo Antenna Module Using Miniature Directional Coupler”
Rayspan Corporation (UC Program-Micro) – $60,374.00, 08/24/07 – 12/31/08

“Feasibility Study of Metamaterial Structure Compatible to Cmos Process”
Sony Corporation (UC MICRO) – $81,625.00, 08/24/07 – 12/31/08

“Tunable Metamaterial Filters and Channelizing Antenna”
LGS Innovations LLC – $63,000.00, 12/10/07 – 09/30/08

"Enhanced Sparse Array Antennas for Millimeter Wave Application"
Honeywell Labs (UC DISCOVERY GRANT) – $86,557.00, 02/01/08 – 01/31/09

"Compact Band-Pass Filter Based on Left Handed Transmission Structures"
Panasonic (UC DISCOVERY GRANT) – $86,557.00, 02/01/08 – 01/31/09

"All Dielectric non-Electronic Radio Front-End (ADNERF) Technology"
DARPA ADNERF / EMPIRE – $250,000, 03/13/08 – 12/12/09

"Investigation on Circularly Polarized Antennas for Planar Array Applications"
Alico Systems, Inc. – $25,000.00, 04/01/08 – 06/30/08

"Microwave Detection of Laser Ultrasonic for non-Destructive Testing"
BOSSA NOVA TECH. LLC – $88,333.00, 06/25/08 – 06/24/10

"CRLH-Based integrated Leaky-Wave Antenna Distributed Amplifier Applications"
Rayspan Corp (State) – $15,392.00, 08/15/08 – 12/31/09

"Integrated CRLH Based Antennas with Class-F Amplifiers"
SONY (STATE) – $51,933.00, 08/15/08 – 12/31/09

"Compact Band-Pass Filter Based on left Handed Transmission Structures"
Panasonic (UC DISCOVERY) – $88,017.00, 04/01/09 – 03/31/10

"Millimeter-Wave Conformal Metamaterial Leaky Wave Antennas"
Honeywell (UC DISCOVERY) – $88,017, 04/01/09 – 03/31/10

"Modified Mushroom Structures for the Metamaterial Antenna Study"
NEC CORP – $70,000.00, 08/01/09 – 03/31/10

"Terahertz Transmission-Line Metamaterial for Quantum Cascade Lasers,"
NSF - $329,749, 09/01/09 – 8/31/12

"Metamaterial-based multiplexer,"
Panasonic/UC discovery - $156,806, 06/01/10 – 08/31/11

"Metamaterial-based leaky wave antenna with dual and circular polarizations,"
Honeywell/UC Discovery - $143,3818, 07/01/10 – 06/30/11

"Frequency dispersive metamaterials for microwave components and systems,"
UC/MEXUS - $12,500, 07/01/2010 – 12/31/2011

"Metamaterial leaky wave antennas with plasma varactors,"
Lockheed Martin - $100,000, 04/14/2011 – 12/01/2011

"Directionally and polarization switched antenna based on metamaterial,"
NEC - $70,000, 04/01/2011 – 03/31/2012

"Four-channel multiplexers based on metamaterial transmission lines,"
Panasonic/UC Discovery - $85,000, 09/01/2011 – 08/31/2012

"Energy efficient HF transmit antennas,"
Pharad, LLC - $33,600, 06/25/2011 – 01/21/2013

"Microplasma for signal processing and electromagnetic control,"
DARPA/Lockheed Martin - $57,800, 03/15/2012 – 01/15/2013

"Dual band dual polarization antennas,"
Tubistech - $64,483, 06/01/2014 – 11/30/2014

"High speed wireless millimeter wave communication study,"
Hybrid Quantum Enterprise - $150,000, 07/01/2014 – 06/30/2016

"Terahertz quantum cascade vertical external cavity surface emitting laser,"
NSF - $120,000, 08/01/2014 – 07/31/2017

SUMMARY OF PUBLICATIONS

A. Books and Book Chapters	48
B. Archival Journal Publications	436
C. Reviewed Conference Publications	881

A. **Books and Chapters of Books**

1. Mittra, R., and T. Itoh, "Some Efficient Numerical Methods," Computer Techniques for Electromagnetics and Antennas, Chapter 6, ed. R. Mittra, Pergamon Press: New York, 1973, pp. 305-350.

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Acord 28/2015, de 19 de març, del Consell de Govern

Vist l'acord de la Junta de l'Escola d'Enginyeria de data 14 de novembre de 2014 pel qual se sol·licita al Consell de Govern el nomenament del doctor Tatsuo Itoh, com a doctor honoris causa de la UAB.

Atès que la Normativa que regula el procediment per a l'atorgament del títol de doctor Honoris Causa aprovada pel Consell de Govern en data 26 de maig de 2004 en el seu article 5.2 estableix que el Consell de Govern podrà atorgar un nomenament cada dos anys a la Facultat de Ciències, la Facultat de Filosofia i Lletres i a la Facultat de Medicina, i un nomenament cada quatre anys a cadascun dels centres restants.

Atès que el Consell de Govern no ha atorgat cap doctor honoris causa de la UAB a l'Escola d'Enginyeria i, per tant, compleix els requisits exigits a la normativa abans esmentada.

Vista la conformitat del Gabinet Jurídic.

Per tot això, a la vista de les consideracions anteriors, a proposta de la l'Escola d'Enginyeria, el Consell de Govern ha adoptat els següents

ACORDS

Primer.- Nomenar el doctor Tatsuo Itoh, doctor honoris causa de la UAB.

Segon.- Encarregar a la secretària general i al vicerector de Relacions Institucionals i de Territori l'execució i el seguiment d'aquest acord.

Tercer.- Comunicar el present acord a l'Escola d'Enginyeria.