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Matthias Maasch

Tunable Microwave Metamaterial Structures

Doctoral Thesis accepted by
Technische Universität Darmstadt, Germany

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M. Gil, C. Damm, M. Sazegar, M. Maasch, A. Giere, M. Schuessler, F. Aznar, A. Velez, J. Bonache, R. Jakoby, and F. Martin, "Tunable Sub-Wavelength Resonators based on Barium-Strontium-Titanate Thick-Film Technology," *IET Microwaves, Antennas & Propagation*, vol. 5, no. 3, pp. 316–323, Feb 2011.

M. Puentes, M. Maasch, M. Schüßler, and R. Jakoby, "Frequency Multiplexed 2-Dimensional Sensor Array based on Split-Ring Resonators for Organic Tissue Analysis," *IEEE Transactions on Microwave Theory and Techniques*, vol. 60, no.6, pp. 1720–1727, June 2012.

M. Roig, M. Maasch, C. Damm, and R. Jakoby, "Liquid Crystal-based Tunable CRLH-Transmission Line for Leaky Wave Antenna Applications at Ka-Band," *International Journal of Microwave and Wireless Technologies*, vol. 6, Special Issue 3–4, pp 325–330, June 2014.

M. Maasch, M. Roig, C. Damm, and R. Jakoby, "Voltage Tunable Artificial Gradient-Index Lens based on a Liquid Crystal Loaded Fishnet Metamaterial," *IEEE Antennas and Wireless Propagation Letters*, vol.13, pp. 1581–1584, 2014.

Conference and Workshop Contributions

M. Maasch, C. Damm, M. Schüßler, and R. Jakoby, "Electrically Controllable Double Series (DS) Line with Left- or Right-Handed Propagation," in *39th European Microwave Conference (EuMC), 2009*, pp. 516–519, 29 Sept. 29–1 Oct. 2009.

C. Damm, M. Maasch, R. Gonzalo, and R. Jakoby, "Tunable Composite Right/Left-Handed Leaky Wave Antenna based on a Rectangular Waveguide using Liquid Crystals," in *I*EEE MTT-S International Microwave Symposium Digest (MTT), 2010, 23–28 May 2010.

M. Maasch, C. Damm, E. González-Rodríguez, and R. Jakoby, "Measurement Setup for Effective Material Parameter Extraction of DC Biased Artificial Material Structures," in *41st European Microwave Conference (EuMC), 2011*, pp. 357–360, 10–13 Oct. 2011.

M. Maasch, C. Damm, M. Schüßler, E. González-Rodríguez, and R. Jakoby, "Varactor Loaded Tunable Split Ring Resonators with Simple Biasing Network," in *German Microwave Conference (GeMIC), 2011*, March 2011.

M. Maasch, O. Karabey, C. Damm, M. Roig, and R. Jakoby, “Investigation on the Beam-Scanning Capability of a Gradient Index Fishnet Structure,” in *IEEE Antennas and Propagation Society International Symposium (APSURSI), 2012,* pp. 1–2, 8–14 July 2012.

M. Maasch, A. Groudas, O. H. Karabey, C. Damm, and R. Jakoby, “Electrically Tunable Open Split-Ring Resonators based on Liquid Crystal Material,” in *6th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (METAMATERIALS), 2012*, 17–20 Sept. 2012.

M. Maasch, M. Roig, C. Damm, and R. Jakoby, “Planar Metamaterial with Separately Voltage Tunable Electric and Magnetic Dispersion based on Liquid Crystal,” in *7th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (METAMATERIALS), 2013*, pp. 556–559, 16–21 Sept. 2013.

M. Maasch, M. Roig, C. Damm, and R. Jakoby, “Efficient Farfield Computation from Eigenmode Simulations for Leaky-Wave Antennas,” in *IEEE Antennas and Propagation Society International Symposium (APSURSI), 2013*, pp. 1656–1657, 7–13 July 2013.

M. Maasch, M. Roig, C. Damm, and R. Jakoby, “Realization of a Voltage Tunable Gradient-Index Fishnet Loaded with Liquid Crystal,” in *8th International Congress on Advanced Electromagnetic Materials in Microwaves and Optics (METAMATERIALS), 2014*, pp. 196–198, 25–28 Aug. 2014.

Supervisor's Foreword

I have the honor to introduce Dr.-Ing. Matthias Maasch, who worked with great success on his Ph.D. thesis under my guidance in the field of tunable metamaterials. Dr. Maasch was born in 1980 in Herzberg/Elster, Germany. After his professional training as communications and radio technician, he studied Electrical Communication Engineering at the Hochschule Mannheim, where he received the Dipl.-Ing. (FH) degree in July 2007 as the best student of the semester. He decided to start working on his Ph.D. thesis at the Technische Universität Darmstadt and obtained a one-year qualification scholarship from the German Research Foundation (DFG) to prepare for his Ph.D. thesis. Thereafter he received a 3-year DFG scholarship meant to foster excellent Ph.D. candidates within the graduate school GRK 1037 TICMO coordinated by Prof. Jakoby at the Technische Universität Darmstadt, Institute of Microwave Engineering and Photonics, where he worked under my guidance on tunable microwave metamaterial structures. After an excellent Ph.D. defense with the highest possible mark *summa cum laude* in December 2014 he continued his work in my group as postdoc.

The presented thesis is a well-balanced mixture of theory and experiments. It deals with fundamental concepts and practical realizations of tunable microwave components based on metamaterials and liquid crystals. Possible applications are tunable components like filters, matching networks, antennas, and general beam forming devices for communication applications. Future mobile communication with strongly increasing data rates on multiple frequency bands and increasing operation frequencies will require more and more reconfigurable and tunable components. A simple example is an antenna with beam steering capabilities, where the beam can follow a moving end user to ensure a high signal quality and high data rate. Known approaches for such beam steering are not satisfying, especially not for higher frequencies, e.g., for 60 GHz future Wi-Fi applications. The presented work demonstrates several promising solutions for this problem which are enabled by the combination of the two new concepts of metamaterials and liquid crystals for electric tuning and reconfiguration.

The original contribution with the highest impact is to my humble opinion the design and demonstration of the electrically tunable gradient-index lens based on liquid crystals, which to the best of my knowledge has not been shown by anybody else before. The candidate demonstrates impressively the mastery of numerous scientific methods for the well-directed development of liquid crystal-based tunable components using fishnet unit cells as metamaterial building block. A beam steering of ±5° is already demonstrated with the built prototype, and a way to overcome the present angular steering limitation using a Fresnel lens approach is provided and confirmed by simulations, enabling beam steering of nearly ±90°. This original contribution is of great value due to the inherent suitability of the fishnet approach combined with liquid crystal technology for mm- and even THz-wave applications. For the future market of mobile communication with ever-increasing transfer rates and operation frequencies, the developed concept seems a unique solution for beam steering and beam forming applications. Both the presented concept and the developed method of far-field calculation have the potential to pave the way for these new agile communication system components.

Darmstadt
October 2015

Prof. Christian Damm

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This dissertation is the result of my time as doctoral student at the Institute for Microwave Engineering and Photonics at Technische Universität Darmstadt. Since such a work would not have been possible without the support and guidance of colleagues and partners, I would like to thank those people who contributed to this work.

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Finally, I would like to thank my family for their support, especially my parents who always supported me on my chosen paths through life.

Darmstadt Matthias Maasch
October 2015

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About the Author

Matthias Maasch was born in Herzberg/Elster, Germany in 1980. After his professional training as Communications and Radio Technician, he studied Electrical Communication Engineering at Hochschule Mannheim, where he received the Dipl. Ing. (FH) degree in 2007. After a DFG scholarship within the graduate school GRK 1037 TICMO and working as a research assistant at Technische Universität Darmstadt, Institute for Microwave Engineering and Photonics, he received the Dr.-Ing. degree with *summa cum laude* from Technische Universität Darmstadt in 2014. His current research activities focus on the design of tunable microwave metamaterials for antenna applications as well as on terahertz sensors for biomedical analysis and process and environmental monitoring.

Symbols

$\mathbf{a}_i$	Normalized incident power wave
$\mathbf{A}$	Chain parameter matrix
AF	Array factor
α	Attenuation constant
$\mathbf{b}_i$	Normalized reflected power wave
$\mathbf{B}$	Magnetic flux density
β	Phase constant
C, C'	Capacitance, capacitance normalized to unit length
c_0	Speed of light in vacuum: $c_0 \approx 299.792 \cdot 10^6$ m/s
χ_m, χ_e	Complex magnetic, electric susceptibility
$\mathbf{D}$	Electric flux density
D	Antenna directivity
δ_μ, δ_ε	Magnetic, electric damping frequency of the Lorentz/Drude dispersion model
$\mathbf{E}$	Electric field strength
e	Charge of an electron $e \approx 1.602 \cdot 10^{-19}$ C
ε_0	Vacuum permittivity: $\varepsilon_0 \approx 8.854 \cdot 10^{-12}$ F/m
ε, ε_{eff}, $\tilde{\varepsilon}$	Complex permittivity, effective permittivity, permittivity of a continuous material
$\bar{\bar{\varepsilon}}$	Complex permittivity tensor of an anisotropic material
$\varepsilon_{r,\text{LC}\parallel}$, $\varepsilon_{r,\text{LC}\perp}$	Relative parallel, vertical permittivity of liquid crystal
ϵ	Relative error
η_0	Vacuum wave impedance: $\eta_0 \approx 376.73\,\Omega$
$\mathbf{f}$	Plane wave spectrum
f	Frequency
$\mathcal{F}\{\}$	Fourier transform
$\varPhi$	Magnetic flux
ϕ	Phase shift
G, G'	Conductance, conductance normalized to unit length

γ	Complex propagation constant
$\mathbf{H}$	Magnetic field strength
$\mathcal{H}\{\}$	Hilbert transform
HPBW	Half-power beam width
I	Current
j	Imaginary unit
J_n	n-th order Bessel function
$\mathbf{k}$, k	Complex wavevector, complex wavenumber
k_x, k_y, k_z	x, y, z component of the wavevector
k_0	Wavenumber in vacuum
$\tilde{k}$	Complex wavenumber in a continuous material
L, L'	Inductance, inductance normalized to unit length
λ	Wavelength
m_e	Mass of an electron: $m_e \approx 9.109 \cdot 10^{-31}$ kg
$\mathbf{M}$	Magnetic polarization
M	Mutual inductance
μ_0	Vacuum permeability: $\mu_0 \approx 1.257 \cdot 10^{-6}$ H/m
μ, μ_{eff}, $\tilde{\mu}$	Complex permeability, effective permeability, permeability of a continuous material
$\bar{\bar{\mu}}$	Complex permeability tensor of an anisotropic material
$\mathbf{n}$	Director
N_m, N_e	Number of molecules per unit volume, number of electrons per volume
ω	Angular frequency
$\omega_{0\mu}$, $\omega_{0\varepsilon}$	Angular magnetic, electric resonance frequency of the Lorentz dispersion model
$\omega_{\mathrm{t}\mu}$, $\omega_{\mathrm{t}\varepsilon}$	Angular magnetic, electric transition frequency of the Lorentz dispersion model
$\omega_{\mathrm{p}\mu}$, $\omega_{\mathrm{p}\varepsilon}$	Angular magnetic, electric plasma frequency of the Drude dispersion model
$\mathbf{P}$	Electric polarization
P	Power
ψ	Radiation direction
R, R'	Resistance, resistance normalized to unit length
$\mathbf{S}$	Poynting vector or scattering parameter matrix
$\bar{\mathbf{S}}$	Time averaged Poynting vector
S	Magnetic coupling factor, orientational order parameter
S_ϵ	Normalized mean squared error
σ	Electric conductivity
$\mathbf{T}$	Scattering transfer matrix
t	Time
V	Voltage
v_p, v_g, v_e	Velocity of phase, group, energy
ξ	Magnetoelectric coupling

$\mathbf{Y}$	Admittance parameter matrix
Y'	Complex admittance normalized to unit length
$\mathbf{Z}$	Impedance parameter matrix
Z_B, Z_w, Z_c	Complex Bloch impedance, complex wave impedance of a homogenous material, complex characteristic impedance of a transmission line
Z'	Complex impedance normalized to unit length
Z_0	Complex reference impedance of a two-port network