Metamaterials: Two Decades Past and Into Their Electromagnetics Future and Beyond

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Abstract— **The notion of artificially engineered materials, which has a long history dating back to the late part of the 19th century, gained considerable momentum two decades ago. The excitement associated with such metamaterials and the structures they have inspired has not waned since then. Rather, it has grown substantially. Metamaterial-inspired structures continue to challenge our imagination and our physics and engineering foundations. They are impacting wave-matter interactions across many frequencies and even across diverse fields of science and technology. They are now enabling many commercial opportunities. It is anticipated that they will provide access to yet new physical phenomena and will facilitate many novel future applications.**

Index Terms—**Metamaterials, metamaterial-inspired structures, wave-matter interactions.**

This year marks the 20th anniversary of the DARPA "Meta-Materials" workshop that jump-started the modern era of metamaterials. In the dawn of this new era we gathered together a nascent group of AP/URSI researchers, who had begun exploring the exotic physics and engineering applications of such artificial materials, for special sessions at the 2002 IEEE Antennas and Propagation Society International Symposium and USNC/URSI National Radio Science Meeting in San Antonio TX. At the same time, we had begun openly advertising for submissions for a Special Issue of the IEEE Transactions on Antennas and Propagation on Metamaterials. As we continued to do later in our 2006 IEEE-Wiley book, *Metamaterials: Physics and Engineering Explorations* [1], we gathered together papers reporting various unconventional electromagnetic features of homogenized artificial materials in which the unit cells are much smaller than a wavelength as well as of electromagnetic band-gap structures.

The resulting October 2003 special issue (vol. 51, no. 10, Part 1) presented state-of-the-art research advances that included theoretical, numerical, and experimental contributions to the understanding of the behavior of several classes of metamaterials and to their potential applications to electromagnetic radiating and scattering systems. Several of the articles laid the foundations of future efforts that have persisted in the last two decades and, notably, of many current efforts. Metamaterials, like many other "hot" topics of our time, have experienced the well-known "hype cycle". We believe that it is fair to say that we are now well into the stages of "enlightenment" and "productivity" in which actual devices and systems with superior performance characteristics inspired by their concepts and properties have begun appearing in commercial and governments systems. What are some of the initial ideas that have persisted and have evolved into many current works such as those reported in this special issue?

The paper by R. W. Ziolkowski and A. Kipple entitled, "Application of double negative materials to increase the power radiated by electrically small antennas," [2] led to exciting follow-up efforts on metamaterial-based antennas [3] and later to metamaterial-inspired antennas [4]. The concept that metamaterial unit cells could be resonant *and* much smaller than a wavelength provided an opportunity for the consequent development of a large variety of electrically small near-field resonant parasitic (NFRP) antenna systems [5]. Ziolkowski and his team have since extended this NFPR paradigm from the original basic electric and magnetic radiators to a large variety of multi-functional electrically small antenna systems simultaneously exhibiting high efficiency, large bandwidth and high directivity [6]-[12]. Moreover, it has led to the realization of both passive and active optical nanoantennas based on core-shell nanoparticle systems tailored to either resonantly enhance or jam the fields radiated by the quantum emitters exciting them [13]-[18]. Recent Huygens dipole and multipole antennas [19]-[28], Huygens dipole nanolasers [29], and superdirective Huygens multipole antennas [30] and nano antennas [31] have evolved from the same metamaterial-inspired physics principles.

The paper by A. Alú and N. Engheta entitled, "Pairing an epsilon-negative slab with a mu-negative slab: resonance, tunneling and transparency," [32] led to many following efforts by the authors. These have included the well-known "scattering cancellation" cloaking and transparency [33]-[36] and extreme metamaterial-inspired developments such as epsilon- near-zero (ENZ) resonant tunneling techniques and systems [37], [38]. This was followed by a diverse series of work on light-matter interactions with near-zero-index metastructures, providing exciting platforms for exploring novel wave physics and

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quantum optics [39]-[53]. The notion of optical "lumped" circuit elements, coined "optical metatronics", was then developed by Engheta and his team [54]-[64]. They later proposed ENZ structures as substrates for "D-dot wires" to connect those optical metatronic circuit elements [58], [61]. Optical metatronics has provided a paradigm for transplanting ideas from electronics into nanophotonics and has led to the two-way linkage and merger of these two fields [54]-[65]. For example, the idea of analog computing has now been resurrected and brought into the domain of wave-matter interactions [65]-[68]. Recent developments have shown how metamaterials can be designed to perform mathematical operations with waves such as solving integral equations [69] and can be utilized as edge detectors in image processing [65]-[68].

The seminal paper co-authored by E. F. Kuester and C. L. Holloway entitled "Averaged transition conditions for electromagnetic fields at a metafilm," established the concept of "generalized sheet transition conditions (GSTCs)" [70] and were refined by them in a series of follow-up papers [71]-[75]. The GSTCs now constitute the basis for the analysis of metasurfaces, the most recent focus of much metamaterial research and excitement. The two seminal papers co-authored by G. V. Eleftheriades and his team, "Periodic analysis of a 2-D negative refractive index transmission line structure" [76] and "Periodically loaded transmission line with effective negative refractive index and negative group velocity," [77] firmly established planar (two- dimensional) metamaterials as a research area that comprehensively demonstrated negative refraction. These efforts later led to numerous practical results including sub-wavelength focusing [78]-[82], sub-wavelength microwave-engineered devices [83]-[87], and leaky wave antennas [88]-[92]. The papers "Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications" by F. Yang and Y. Rahmat-Samii [93]; "Two-dimensional beam steering using an electrically tunable impedance surface" by D. F. Sievenpiper et al. [94]; and "Design methodology for Sievenpiper high-impedance surfaces: An artificial magnetic conductor for positive gain electrically small antennas," by Clavijo et al. [95] firmly established the theory of structured ground planes and artificial magnetic conductors. These and a host of later efforts confirmed the importance and utility of mushroom surfaces for antenna applications. The paper "Electromagnetic bandgap antennas and components for microwave and (sub) millimeter wave applications," by P. de Maagt et al. [96] was a prelude to several European Space Agency electromagnetic bandgap (EBG) systems now flying in space. Several other papers in the 2003 special issue analyzed some of the earliest metamaterials, their properties, and their applications [97]-[108].

Currently much of the metamaterial literature has been dominated by metasurface designs, properties, and their applications [109]-[120]. The title of this special issue emphasizes this fact. Metasurfaces undoubtedly will continue to drive part of the future research in metamaterials.

Most, if not all, of the original proclaimed optical metamaterials were actually metasurfaces. Nanofabrication is necessary at visible frequencies and the registration of layers becomes increasingly difficult. This made bulk optical artificial materials initially inaccessible. Nevertheless, advanced fabrication techniques were developed and true bulk optical metamaterials were achieved. Another issue associated with optical meta-structures based on metal inclusions in their unit cells are the large losses associated with metals at visible frequencies. They have limited the performance of perfect lenses and many plasmonic applications. Active materials have been included in theory and in practice to achieve designs and metastructures that overcome those losses [121]-[123]. All dielectric metamaterials have provided an alternate route to lower losses at all frequencies [124]. Mitigation of these losses will translate into the realization of practical metamaterial-inspired optical devices.

Whatever the frequency range, being able to achieve the desired wave-matter interactions and structured output fields in one or two subwavelength thick layers is highly desirable if not essential for many practical applications. The flexibility of metasurfaces to provide both spatial and temporal spectral performance has been facilitated by modulating them in both space and time. Space-time modulated metasurfaces have given access to broken symmetries that have enabled exotic phenomena such as magnet-free non-reciprocal devices that have facilitated diode-like unidirectional propagation systems [125]-[136].

The adaptable nature of the unit cells of metamaterials and metasurfaces have also provided opportunities to locally reconfigure and tune their responses. This has furthered their applicability in numerous electromagnetic radiating and scattering systems [137]-[141]. For example, reconfigurable reflecting or transmitting metastructures may facilitate future 5G antenna systems that will require multiple steerable beams [142], [143].

Even more astounding is the fact that since their original electromagnetic inception, metamaterial concepts have proven useful in controlling other forms of wave phenomena. They have now gone well beyond their electromagnetic origins into the acoustic [131], [133], [144]-[147], thermal [148]-[150], mechanical [151], [152], seismic [153], and even quantum [154]-[158] domains. Whether the mitigation of earthquake triggered waves or the modification of phonon behaviors at terahertz frequencies, meta- and EBG-structures have provided a path forward to realizable acoustic possibilities. Metastructures have changed heat flow behaviors. Quantum properties of emitters have been modified with properly designed extreme metastructure environments. Waves of one type, e.g., acoustic waves, have been able to modify the material properties of metastructures and, hence, their electromagnetic responses and vice-versa. It is expected that these multi-physics aspects of metamaterial-inspired structures will lead to many new research opportunities in the future.

While we never could have anticipated where the original special issue results would take the antennas and propagation community, we believe it is fair to say it has spawned an amazing number of important results. Moreover, it has been exciting for each of us to participate in the growth of the metamaterials research area. We believe the true magic of metamaterials is that they opened an unknown door into looking at field and wave-matter interaction phenomena in entirely novel manners. Thus, their legacy will extend far beyond our initial expectations of particular scattering phenomena and radiating systems. It is anyone's guess what their actual future will hold, BUT we anticipate that metastructures will provide many research opportunities to many fields of science and engineering in the near future and beyond.

References

[1] N. Engheta and R. W. Ziolkowski, Eds., *Metamaterials: Physics and Engineering Explorations*, IEEE Press, Wiley Publishing, Hoboken, NJ, 2006

[2] R. W. Ziolkowski and A. D. Kipple, "Application of double negative materials to increase the power radiated by electrically small antennas," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2626 – 2640, Oct. 2003.

[3] R. W. Ziolkowski and A. Erentok, "Metamaterial-based efficient electrically small antennas," *IEEE Trans. Antennas Propag.*, vol. 54, pp. 2113 – 2130, Jul. 2006.

[4] A. Erentok and R. W. Ziolkowski, "Metamaterial-inspired efficient electrically-small antennas," *IEEE Trans. Antennas Propag.*, vol. 56, no. 3, pp. 691 – 707, Mar. 2008.

[5] R. W. Ziolkowski, P. Jin and C.-C. Lin, "Metamaterial-inspired engineering of antennas," *Proc. IEEE*, vol. 99, pp. 1720 – 1731, Oct. 2011.

[6] N. Zhu and R. W. Ziolkowski, "Active metamaterial-inspired broad bandwidth, efficient, electrically small antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 10, pp. 1582 – 1585, 2011.

[7] P. Jin, C.-C. Lin and R. W. Ziolkowski, "Multifunctional, electrically small, conformal near-field resonant parasitic antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 200 – 204, 2012.

[8] P. Jin and R. W. Ziolkowski, "High directivity, electrically small, low-profile, near-field resonant parasitic antennas," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 305 – 309, 2012.

[9] M.-C. Tang, N. Zhu and R. W. Ziolkowski, "Augmenting a modified Egyptian axe dipole antenna with non-Foster elements to enlarge its directivity bandwidth," *IEEE Antennas Wireless Propag. Let*t., vol. 12, pp. 421 – 424, 2013.

[10] M.-C. Tang, R. W. Ziolkowski, S. Xiao and M. Li, "A high-directivity, wideband, efficient, electrically small antenna system," *IEEE Trans. Antennas Propag.*, vol. 62, no. 12, pp. 6541 – 6547, Dec. 2014.

[11] M.-C. Tang, B. Zhou and R. W. Ziolkowski, "Frequency-agile, efficient, circularly polarized, near-field resonant antenna: Designs and measurements," *IEEE Trans. Antennas Propag.*, vol. 63, no. 11, pp. 5203-5209, Nov. 2015.

[12] M.-C. Tang, B. Zhou, Y. Duan, X. Chen, and R. W. Ziolkowski, "Pattern-reconfigurable, flexible, wideband, directive, electrically small near-field resonant parasitic antenna," *IEEE Trans. Antennas Propag.*, vol. 66, no. 5, pp. 2271 – 2280, May 2018.

[13] J. A. Gordon and R. W. Ziolkowski, "The design and simulated performance of a coated nano-particle laser," *Opt. Express*, vol. 15, no. 5, pp. 2622 – 2653, Mar. 2007.

[14] S. Arslanagić and R. W. Ziolkowski, "Active coated nano-particle excited by an arbitrarily located electric Hertzian dipole - resonance and transparency effects," *J. Opt.*, vol. 12, 024014, Feb. 2010.

[15] S. Arslanagić and R. W. Ziolkowski, "Directive properties of active coated nano-particles," *Advanced Electromagnetics*, vol. 1, no. 1, pp. 57 – 64, May 2012.

[16] S. Arslanagić and R. W. Ziolkowski, "Jamming of quantum emitters by active coated nano-particles," *IEEE J. Sel. Topics Quantum Electron.*, vol. 19, no. 3, 4800506, May/June 2013.

[17] S. Arslanagić and R. W. Ziolkowski, "Influence of active nano particle size and material composition on multiple quantum emitter enhancements: Their enhancement and jamming effects," *Prog. Electromagn. Res.*, vol. 149, pp. 85 – 99, 2014.

[18] S. Arslanagić and R. W. Ziolkowski, "Cylindrical and spherical active coated nano-particles as nano-antennas," *IEEE Antennas Propag. Mag.*, vol. 59, no. 6, pp. 14 – 29, Dec. 2017.

[19] P. Jin and R. W. Ziolkowski, "Metamaterial-inspired, electrically small, Huygens sources," *IEEE Antennas Wireless Propag. Lett.*, vol. 9, pp. 501 – 505, May 2010.

[20] R. W. Ziolkowski, "Low profile, broadside radiating, electrically small Huygens source antennas," *IEEE Access*, vol. 3, pp. 2644 – 2651, Dec. 2015.

[21] M.-C. Tang, H. Wang, and R. W. Ziolkowski, "Design and testing of simple, electrically small, low-profile, Huygens source antennas with broadside radiation performance," *IEEE Trans. Antennas Propag.*, vol. 64, no. 11, pp. 4607 – 4617, Nov. 2016.

[22] M.-C. Tang, T. Shi, and R. W. Ziolkowski, "Electrically small, broadside radiating Huygens source antenna augmented with internal non-Foster elements to increase its bandwidth," *IEEE Antennas Wirel. Propag. Lett.*, vol. 16, pp. 712 – 715, 2017.

[23] M.-C. Tang, B. Zhou, and R. W. Ziolkowski, "Low-profile, electrically small, Huygens source antenna with pattern-reconfigurability that covers the entire azimuthal plane," *IEEE Trans. Antennas Propag.*, vol. 65, no. 3, pp. 1063 – 1072, Mar. 2017.

[24] M.-C. Tang, T. Shi, and R. W. Ziolkowski, "A study of 28 GHz, planar, multi-layered, electrically small, broadside radiating, Huygens source antennas," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6345 – 6354, Dec. 2017.

[25] W. Lin and R. W. Ziolkowski, "Electrically-small, low-profile, Huygens circularly polarized antenna," *IEEE Trans. Antennas Propag.*, vol. 66, no. 2, pp. 636 – 643, Feb. 2018.

[26] M.-C. Tang, Z. Wu, T. Shi, and R. W. Ziolkowski, "Electrically small, low-profile, planar, Huygens dipole antenna with quad-polarization diversity," *IEEE Trans. Antennas Propag.*, vol. 66, no. 12, pp. 6772 – 6780, Dec. 2018.

[27] W. Lin and R. W. Ziolkowski, "Electrically small Huygens antenna-based fully-integrated wireless power transfer and communication system," *IEEE Access*, vol. 7, pp. 39762 – 39769, Apr. 2019.

[28] W. Lin and R. W. Ziolkowski, "Electrically small, low-profile, highly efficient, Huygens dipole rectennas for wirelessly powering Internet-of-Things devices," *IEEE Trans. Antennas Propag.*, vol. 67, no. 6, pp. 3670 – 3679, Jun. 2019.

[29] I. Liberal, I. Ederra, R. Gonzalo, and R. W. Ziolkowski, "Induction theorem analysis of resonant nanoparticles: Design of a Huygens source nanoparticle laser," *Phys. Rev. Applied*, vol. 1, 044002, May 2014.

[30] R. W. Ziolkowski, "Huygens multipole arrays to realize unidirectional needle-like radiation," *Phys. Rev. X*, vol. 7, 031017, Jul. 2017.

[31] S. Arslanagić and R. W. Ziolkowski, "Highly subwavelength, superdirective cylindrical nanoantenna," *Phys. Rev. Lett.*, vol. 120, 237401, Jun. 2018; "Erratum: Highly subwavelength, superdirective cylindrical nanoantenna," *Phys. Rev. Lett.*, vol. 120, 237401, Dec. 2018.

[32] A. Alù and N. Engheta, "Pairing an epsilon-negative slab with a mu-negative slab: resonance, tunneling and transparency, *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2558 – 2571, Oct. 2003.

[33] A. Alù and N. Engheta, "Achieving transparency with metamaterial and plasmonic coatings," *Phys. Rev. E*, vol. 72, 016623, 2005.

[34] A. Alù and N. Engheta, "Multifrequency optical invisibility cloak with layered plasmonic shells," *Phys. Rev. Lett.*, vol. 100, no. 11, 113901, Mar. 2008.

[35] A. Alù and N. Engheta, "Cloaking a Sensor," *Phys. Rev. Lett.*, vol. 102, 233901, Jun. 2009.

[36] B. Edwards, A. Alù, M. Silveirinha, and N. Engheta, "Experimental verification of plasmonic cloaking at microwave frequencies with metamaterials," *Phys. Rev. Lett.*, vol. 103, 153901, Oct. 2009.

[37] M. G. Silveirinha and N. Engheta, "Tunneling of electromagnetic energy through sub-wavelength channels and bends using epsilon-near-zero (ENZ) materials," *Phys. Rev. Lett.*, vol. 97, 157403, Oct. 2006.

[38] M. Silveirinha and N. Engheta, "Theory of supercoupling, squeezing wave energy, and field confinement in narrow channels and tight bends using epsilon-near-zero metamaterials," *Phys. Rev. B*, vol. 76, 245109, Dec. 2007.

[39] B. Edwards, A. Alù, M. Young, M. Silveirinha, and N. Engheta, "Experimental verification of epsilon-near-zero metamaterial coupling and energy squeezing using a microwave waveguide," *Phys. Rev. Lett.*, vol. 100, 033903, Jan. 2008.

[40] A. Alù and N. Engheta, "Dielectric sensing in epsilon-near-zero narrow waveguide channels," *Phys. Rev. B*, vol. 78, 045102, Jul. 2008.

[41] A. Alù and N. Engheta, "Light squeezing through arbitrarily shaped plasmonic channels and sharp bends," *Phys. Rev. B*, vol. 78, 035440, Jul. 2008.

[42] E. J. R. Vesseur, T. Coenen, H. Caglayan, N. Engheta, A. Polman, “Structure with near zero effective refractive index for visible light,” *Phys. Rev. Lett.*, vol. 110, 013902, Jan. 2013.

[43] F. J. Rodríguez-Fortuño, A. Vakil, and N. Engheta, “Electric levitation using epsilon-near-zero metamaterials,” *Phys. Rev. Lett.*, vol. 112, 033902, Jan. 2014.

[44] A.M. Mahmoud and N. Engheta, “Wave-matter interaction in epsilon-and-mu-near-zero structures”, *Nat. Commun.*, vol. 5, 5638, Dec. 2014.

[45] J. S. Marcos, M. Silveirinha, and N. Engheta, “Mu-near-zero (MNZ) supercoupling, *Phys. Rev. B*, vol. 91, 195112, May 2015.

[46] I. Liberal, A. M. Mahmoud and N. Engheta, “Geometry-invariant cavity resonators,” *Nat. Commun.*, vol. 7, 10989, Mar. 2016.

[47] I. Liberal and N. Engheta, “Nonradiating and radiating modes excited by quantum emitters in open epsilon-near-zero (ENZ) cavities,” *Sci. Adv.*, vol. 2, e1600987, Oct. 2016.

[48] I. Liberal and N. Engheta, “Zero-index structures as an alternative platform for quantum optics,” *Proc. Nat. Acad. Sci.*, vol. 114, no. 5, pp. 822 – 827, Jan. 2017.

[49] I. Liberal and N. Engheta, “Near-zero refractive index photonics”, *Nat. Photonics*, vol. 11, pp. 149 – 158, Mar. 2017.

[50] I. Liberal, A. Mahmoud, Y. Li, B. Edwards, and N. Engheta, “Photonic doping of epsilon-near-zero media,” *Science*, vol. 355, no. 6329, pp. 1058 – 1062, Mar. 2017.

[51] I. Liberal and N. Engheta, “The rise of near-zero-index technologies,” *Science*, vol. 358, no. 6370, pp. 1540 – 1541, Dec. 2017.

[52] I. Liberal and N. Engheta, “Multi-qubit subradiant states with N-port waveguide devices: Epsilon-and-mu-near-zero hubs and nonreciprocal circulators,” *Phys. Rev. A*, vol. 97, 022309, Feb. 2018.

[53] I. Liberal and N. Engheta, “Manipulating thermal emission with spatially static fluctuating fields in arbitrarily-shaped epsilon-near-zero bodies,” *Proc. Nat. Acad. Sci.*, vol. 115, no. 12, pp. 2878-2883, Mar. 2018.

[54] N. Engheta, “Circuits with light at nanoscales: Optical nanocircuits inspired by metamaterials”, *Science*, vol. 317, no. 5845, pp. 1698 – 1702, Sep. 2007.

[55] N. Engheta, A. Salandrino, A. Alù, “Circuit elements at optical frequencies: Nano-inductor, nano-capacitor, and nano-resistor,” *Phys. Rev. Lett.*, vol. 95, 095504, Aug. 2005.

[56] A. Alù and N. Engheta, “Tuning the scattering response of optical nanoantennas with nanocircuit loads”, *Nat. Photonics*, vol. 2, pp. 307 – 310, May 2008..

[57] A. Alù and N. Engheta, “Wireless at the nanoscale: Optical interconnects using matched nanoantennas,” *Phys. Rev. Lett.*, vol. 104, 213902, May 2010.

[58] N. Engheta, “Taming light at the nanoscale,” *Phys. World* , vol. 23, no. 9, pp. 31 – 34, Sep. 2010.

[59] A. Alù and N. Engheta, “Optical metamaterials based on optical nanocircuits,” *Proc. IEEE*, vol. 99, no. 10, pp. 1669 – 1681, Oct. 2011.

[60] Y. Sun, B. Edwards, A. Alù, and N. Engheta, “Experimental realization of optical lumped nanocircuit elements at infrared wavelengths,” *Nat. Mater.*, vol. 11, pp. 208 – 212, Mar. 2012

[61] B. Edwards and N. Engheta, “Experimental verification of displacement-current conduits in metamaterial-inspired optical circuitry,” *Phys. Rev. Lett.*, vol. 108, 193902, May 2012.

[62] N. Engheta, “From radio-frequency circuits to optical nanocircuits,” *IEEE Microw. Mag.*, vol. 13, No. 4, pp. 100 – 113, Jun. 2012.

[63] H. Caglayan, S.-H. Hong, B. Edwards, C. Kagan, and N. Engheta, “Near-IR metatronic nanocircuits by design,” *Phys. Rev. Lett.*, vol. 111, 073904, Aug. 2013.

[64] D. Dregley, K. Lindfors, M. Lippitz, N. Engheta, M. Totzeck, H. Giessen, “Experimental demonstration of wireless power transfer with optical nanoantennas,” *Nat. Commun.*, vol. 5, 4354, Jul. 2014.

[65] A.Silva, F. Monticone, G. Castaldi, V. Galdi, A. Alù, and N. Engheta, “Performing mathematical operations with metamaterials,” *Science*, vol. 343, no. 6167, pp. 160 – 163, Jan. 2014.

[66] A. Pors, M. G. Nielsen, and S. I. Bozhevolnyi, “Analog computing using reflective plasmonic metasurfaces,” *Nano Lett.*, vol. 15, no. 1, pp. 791 – 797, 2015.

[67] T. Zhu, Y. Zhou, Y. Lou, H. Ye, M. Qiu, Z. Ruan, and S. Fan, “Plasmonic computing of spatial differentiation,” *Nat. Commun*., vol. 8, 15391, May 2017.

[68] H. Kwon, A. Cordaro, D. Sounas, A. Polman, A. Alù, “Nonlocal metasurfaces for optical signal processing,” *Phys. Rev. Lett.*, vol. 121, 173004, Oct. 2018.

[69] N. Mohammadi Estakhri, B. Edwards, and N. Engheta, “Inverse-designed metastructures that solve equations,” *Science*, vol. 363, no. 6433, pp. 1333 – 1338, Mar. 2019.

[70] E. F. Kuester, M. A. Mohamed, M. Piket-May, and C. L. Holloway, “Averaged transition conditions for electromagnetic fields at a metafilm,” *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2641 – 2651, Oct. 2003.

[71] C. L. Holloway, M. A. Mohamed, E. F. Kuester, and A. Dienstfrey, “Reflection and transmission properties of a metafilm: With an application to a controllable surface composed of resonant particles,” *IEEE Trans. Electromagn. Compat.*, vol. 47, no. 4, pp. 853 – 865, Apr. 2005.

[72] C. L. Holloway, A. Dienstfrey, E. F. Kuester, J. F. O’Hara, A. K. Azad, and A. J. Taylor, “A discussion on the interpretation and characterization of metafilms/metasurfaces: The two-dimensional equivalent of metamaterials,” *Metamaterials*, vol. 3, no. 2, pp. 100 – 112, Oct. 2009.

[73] C. L. Holloway, E. F. Kuester, and A. Dienstfrey, “Characterizing metasurfaces/metafilms: The connection between surface susceptibilities and effective material properties,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 10, pp. 1507 – 1511, 2011.

[74] C. L. Holloway, E. F. Kuester, J. A. Gordon, J. F. O'Hara, J. Booth, and D. R. Smith, “An overview of the theory and applications of metasurfaces: The two-dimensional equivalents of metamaterials,” *IEEE Trans. Antennas Propag.*, vol. 54, no. 2, pp. 10 – 35, Apr. 2012.

[75] C. L. Holloway and E. F. Kuester, “A homogenization technique for obtaining generalized sheet-transition conditions for a metafilm embedded in a magnetodielectric interface,” *IEEE Trans. Antennas Propag.*, vol. 64, no. 11, pp. 4671 – 4686, Nov. 2016.

[76] A. Grbic and G. V. Eleftheriades, “Periodic analysis of a 2-D negative refractive index transmission line structure,” *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2604 – 2611, Oct. 2003.

[77] O. F. Siddiqui ; M. Mojahedi ; G.V. Eleftheriades, “Periodically loaded transmission line with effective negative refractive index and negative group velocity,” *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2619 – 2625, Oct. 2003.

[78] G. V. Eleftheriades, A. K. Iyer, and P. C. Kremer, “Planar negative refractive index media using periodically LC loaded transmission lines,” *IEEE Trans. Microw. Theory Techn.*, vol. 50, no. 12, pp. 2702 – 2712, Dec. 2002.

[79] A. Grbic and G. V. Eleftheriades, “Subwavelength focusing using a negative-refractive-index transmission line lens,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 2, pp. 186 – 189, 2003.

[80] A. Grbic and G. V. Eleftheriades, “Overcoming the diffraction limit with a planar left-handed transmission-line lens,” *Phys. Rev. Lett.*, vol. 92, no. 11, 117403, 2004.

[81] A. M. H. Wong and G. V. Eleftheriades, “Sub-wavelength focusing at the multi-wavelength range using superoscillations: an experimental demonstration,” *IEEE Trans. Antennas Propag.*, vol. 59, no. 12, pp. 4766 – 4776, 2011.

[82] A. M. H. Wong and G. V. Eleftheriades, “Broadband superoscillation brings a wave into perfect three-dimensional focus,” *Phys. Rev. B*, vol. 95, no. 7, 075148, 2017.

[83] M. A. Antoniades and G. V. Eleftheriades, “Compact linear lead/lag metamaterial phase shifters for broadband applications,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 2, pp. 103 – 106, 2003

[84] M. A. Antoniades and G. V. Eleftheriades, “A broadband series power divider using zero-degree metamaterial phase-shifting lines,” *IEEE Microw. Wirel. Comp. Lett.*, vol. 15, no. 11, pp. 808 – 810, Oct. 2005.

[85] G. V. Eleftheriades, “Microwave devices and antennas using negative-refractive-index transmission-line metamaterials,” in *Negative-Refraction Metamaterials: Fundamental Principles and Applications*, G. V. Eleftheriades and K. G. Balmain, Eds. , John Wiley & Sons, 2005, pp. 53 – 91.

[86] G. V. Eleftheriades, “Enabling RF/microwave devices using negative-refractive-index transmission-line (NRI-TL) metamaterials,” *IEEE Antennas Propag. Mag.*, vol. 49, no. 2, pp. 34 – 51, Apr. 2007.

[87] G. V. Eleftheriades and R. Islam, “Miniaturized microwave components and antennas using negative-refractive-index transmission-line (NRI-TL) metamaterials,” *Metamaterials*, vol. 1, no. 2, pp. 53 – 61, Dec. 2007.

[88] A. K. Iyer and G. V. Eleftheriades, “Leaky-wave radiation from planar negative-refractive-index transmission-line metamaterials,” in *Proc. 2004 IEEE Antennas and Propogation Society International Symposium*, Monterey, CA, 20-25 June 2004, vol. 2, pp. 1411 – 1414.

[89] T. Kokkinos, C. D. Sarris, and G. V. Eleftheriades, “Periodic FDTD analysis of leaky-wave structures and applications to the analysis of

negative-refractive-index leaky-wave antennas," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 4, pp. 1619 – 1630, Apr. 2006.

[90] M. A. Antoniades and G. V. Eleftheriades, "A CPS leaky-wave antenna with reduced beam squinting using NRI-TL metamaterials," *IEEE Trans. Antennas Propag.*, vol. 56, no. 3 pp. 708 – 721, Mar. 2008.

[91] A. Mehdipour and G. V. Eleftheriades, "Leaky-wave antennas using negative-refractive-index transmission-line metamaterial supercells," *IEEE Trans. Antennas Propag.*, vol. 62, no. 8, pp. 3929 – 3942, Aug. 2014.

[92] A. Mehdipour, J. W. Wong, and G. V. Eleftheriades, "Beam-squinting reduction of leaky-wave antennas using huygens metasurfaces," *IEEE Trans. Antennas Propag.*, vol. 63, no. 3, pp. 978– 992, Mar. 2015.

[93] F. Yang and Y. Rahmat-Samii, "Reflection phase characterizations of the EBG ground plane for low profile wire antenna applications," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2691 – 2703, Oct. 2003.

[94] D. F. Sievenpiper, J. H. Schaffner, H.J. Song, R.Y. Loo, and G. Tangonan, "Two-dimensional beam steering using an electrically tunable impedance surface," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2713 – 2722, Oct. 2003.

[95] S. Clavijo, R. E. Diaz, and W. E. McKinzie, "Design methodology for Sievenpiper high-impedance surfaces: an artificial magnetic conductor for positive gain electrically small antennas," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2678 – 2690, Oct. 2003.

[96] P. de Maagt, R. Gonzalo, Y. C. Vardaxoglou, and J.-M. Baracco, "Electromagnetic bandgap antennas and components for microwave and (Sub)millimeter wave applications," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2667 – 2677, Oct. 2003.

[97] A. Ishimaru, S.-W. Lee, Y. Kuga, and V. Jandhyala, "Generalized constitutive relations for metamaterials based on the quasi-static Lorentz theory," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2550 – 2557, Oct. 2003.

[98] R. Marques, F. Mesa, J. Martel, and F. Medina, "Comparative analysis of edge- and broadside- coupled split ring resonators for metamaterial design - theory and experiments," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2572 – 2581, Oct. 2003.

[99] C. R. Simovski, P. A. Belov, and S. He," Backward wave region and negative material parameters of a structure formed by lattices of wires and split-ring resonators," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2582 – 2591, Oct. 2003.

[100] E. Ozbay, K. Aydin, E. Cubukcu, and M. Bayindir, "Transmission and reflection properties of composite double negative metamaterials in free space," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2592 – 2595, Oct. 2003.

[101] C. L. Holloway, E.F. Kuester, J. Baker-Jarvis, and P. Kabos, "A double negative (DNG) composite medium composed of magnetodielectric spherical particles embedded in a matrix," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2596 – 2603, Oct. 2003.

[102] K. G. Balmain, A. A. E. Luttgen, and P. C. Kremer, "Power flow for resonance cone phenomena in planar anisotropic metamaterials," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2612 – 2618, Oct. 2003.

[103] S. A. Tretyakov, S. Maslovski, and P. A. Belov, "An analytical model of metamaterials based on loaded wire dipoles," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp.2652 – 2658, Oct. 2003.

[104] S. Enoch, G. Tayeb, and B. Gralak, "The richness of the dispersion relation of electromagnetic bandgap materials," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2659 – 2666, Oct. 2003.

[105] Y. Zhang, J. von Hagen, M. Younis, C. Fischer, and W. Wiesbeck, "Planar artificial magnetic conductors and patch antennas," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2704 – 2712, Oct. 2003.

[106] S.P. Skobelev and P.-S. Kildal, "Analysis of conical quasi-TEM horn with a hard corrugated section," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2723 – 2731, Oct. 2003.

[107] G. Kiziltas, D. Psychoudakis, J. L. Volakis, and N. Kikuchi, "Topology design optimization of dielectric substrates for bandwidth improvement of a patch antenna," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2732 – 2743, Oct. 2003.

[108] W. J. Chappell and X. Gong, "Wide bandgap composite EBG substrates," *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, Part1, pp. 2744 – 2750, Oct. 2003.

[109] N. Yu, P. Genevet, M. A. Kats, F. Aieta, F., J. P. Tetienne, F. Capasso, F., Z. Gaburro, "Light propagation with phase discontinuities: Generalized laws of reflection and refraction," *Science*, vol. 334, no. 6054, pp. 333 – 337, Oct. 2011.

[110] E. Hasman, V. Kleiner, G. Biener, A. Niv, "Polarization dependent focusing lens by use of quantized Pancharatnam–Berry phase diffractive optics," *Appl. Phys. Lett.*, vol. 82, no. 3, pp. 328 – 330, Jan. 2003.

[111] X. Ni, N. K. Emani, A. V. Kildishev, A. Botasseva, and V. M. Shalaev, "Broadband light bending with plasmonic nanoantennas," *Science* , vol. 335, no. 6067, 427, Jan. 2012.

[112] D. Lin, P. Fan, E. Hasman, and M. L. Brongersma, "Dielectric gradient metasurface optical elements," *Science*, vol. 345, no. 6194, pp. 298 – 302, Jul. 2014.

[113] C. Pfeiffer, C. Zhang, V. Ray, L. J. Guo, and A. Grbic, "High performance bianisotropic metasurfaces: asymmetric transmission of light," *Phys. Rev. Lett.*, vol. 113, no. 2, 023902, Jul. 2014.

[114] M. Kim, A. M. H. Wong and G. V. Eleftheriades, " Optical Huygens' metasurfaces with independent control of the magnitude and phase of the local reflection coefficients," *Phys. Rev. X*, vol. 4, no. 4, 041042, Dec. 2014.

[115] Y. Ra'di, C. R. Simovski, and S. A. Tretyakov, "Thin perfect absorbers for electromagnetic waves: Theory, design, and realizations," *Phys. Rev. Applied*, vol. 3, 037001, Mar. 2015.

[116] A. Epstein and G. V. Eleftheriades, "Huygens' metasurfaces via the equivalence principle: Design and applications," *J. Opt. Soc. B*, vol. 33, no. 2, A31 – A50, 2016.

[117] E. Maguid, I. Yulevich, D. Veksler, V. Kleiner, M. Brongersma and E. Hasman, "Photonic spin-controlled multifunctional shared-aperture antenna array," *Science*, vol. 352, no 6290, pp. 1202 – 1206, Jun. 2016.

[118] A. Díaz-Rubio, V. S. Asadchy, A. Elsakka, and S. A. Tretyakov, "From the generalized reflection law to the realization of perfect anomalous reflectors," *Sci. Adv.*, vol. 3, no. 8, e1602714, Aug. 2017.

[119] N. Chamanara, Y. Vahabzadeh, and C. Caloz, "Simultaneous control of the spatial and temporal spectra of light with space-time varying metasurfaces," *IEEE Trans. Antennas Propag.*, vol. 67, no. 4, pp. 2430 – 2441, Apr. 2019.

[120] A.M. Mahmoud, A. R. Davoyan, and N. Engheta, "All-passive nonreciprocal metastructure," *Nat. Commun.*, vol. 6, 8359, Sep., 2015

[121] M. A. Noginov, G. Zhu, M. Bahoura, J. Adegoke, C. E. Small, B. A. Ritzo, V. P. Drachev, and V. M. Shalaev, "Enhancement of surface plasmons in an Ag aggregate by optical gain in a dielectric medium," *Opt. Lett.*, vol. 31, no. 20, pp. 3022 – 3024, Oct. 2006.

[122] J. A. Gordon and R. W. Ziolkowski, "CNP optical metamaterials," *Opt. Express*, vol. 16, no. 9, pp. 6692 – 6716, Apr. 2008.

[123] S. Wuestner, A. Pusch, K. L. Tsakmakidis, J. M. Hamm, and O. Hess, "Overcoming losses with gain in a negative refractive index metamaterial," *Phys. Rev. Lett.*, vol. 105, 127401, Sep. 2010.

[124] A. Kuznetsov, A. E. Miroshnichenko, M. L. Brongersma, Y. Kivshar, and B. Lukyanchuk, "Optically resonant dielectric nanostructures," *Science*, vol. 354, no. 6314, p. 846, Nov. 2016.

[125] N. A. Estep, D. L. Sounas, and A. Alù, "Magnetless microwave circulators based on spatiotemporally modulated rings of coupled resonators," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 2, pp. 502–518, Feb. 2016.

[126] D. L. Sounas and A. Alù, "Non-reciprocal photonics based on time modulation, *Nat. Photon.*, vol. 11, pp. 774 – 783, Dec. 2017.

[127] C. Caloz, A. Alù, S. Tretyakov, D. Sounas, K. Achouri, and Z.-L. Deck-Léger, "Electromagnetic nonreciprocity," *Phys. Rev. Appl.*, vol. 10, 047001, Oct. 2018.

[128] A. Kord , M. Tymchenko, D. L. Sounas, H. Krishnaswamy, and A. Alù, "CMOS integrated magnetless circulators based on spatiotemporal modulation angular-momentum biasing," *IEEE Trans. Microw. Theory Techn.*, vol. 67, no. 7, pp. 2649 – 2662, Jul. 2019.

[129] N. Chamanara, Z.-L. Deck-Léger, C. Caloz, and D. Kalluri, "Unusual electromagnetic modes in space-time-modulated dispersion-engineered media," *Phys. Rev. A*, vol. 97, no. 6, 063829, Jun. 2018.

[130] N. Chamanara, Y. Vahabzadeh, and C. Caloz, "Simultaneous control of the spatial and temporal spectra of light with space-time varying metasurfaces," *IEEE Trans. Antennas Propag.*, vol. 67, no. 4, pp. 2430 – 2441, Apr. 2019.

[131] M. Zanjani, A. Davoyan, A. Mahmoud, N. Engheta, and J. Lukes, "One-way phonon isolation in acoustic waveguides," *Appl. Phys. Lett.*, vol. 104, 081905, Feb. 2014.

[132] A. Shaltout, A. Kildishev, and V. M. Shalaev, "Time-varying metasurfaces and Lorentz non- reciprocity," *Opt. Mater. Express*, vol. 5, no. 11, pp. 2459 – 2467, Nov. 2015.

[133] R. Fleury, D. L. Sounas, C. F. Sieck, M. R. Haberman, and A. Alù, "Sound isolation and giant linear nonreciprocity in a compact acoustic circulator," *Science*, vol. 343, no. 6170, pp. 516 – 519, Jan. 2014.

[134] Z. Yu and S. Fan, "Complete optical isolation created by indirect interband photonic transitions," *Nat. Photonics*, vol. 3, pp. 91 – 94, Jan. 2009.

[135] Y. Hadad and A. Alù, "Breaking temporal symmetries for emission and absorption," *Proc. Nat. Acad. Sci*., vol. 113, no. 13, pp. 3471 – 3475, Mar. 2016.

[136] A. M. Shaltout, K. G. Lagoudakis, J. van de Groep, S. J. Kim. J. Vuckovic, V. M. Shalaev and M. L. Brongersma, "Spatiotemporal light control with frequency-gradient metasurfaces," *Science*, vol. 365, no. 6451, pp. 374 – 377, Jul. 2019.

[137] H.-T. Chen, W. J. Padilla, J. M. O. Zide, A. C. Gossard, A. J. Taylor, and R. D. Averitt, "Active terahertz metamaterial devices," *Nature*, vol. 444, no. 7119, pp. 597 – 600, Nov. 2006.

[138] J. Li, C. M. Shah, W. Withayachumnankul, B. S-Y. Ung, A. Mitchell, S. Sriram, M. Bhaskaran, S. Chang, and D. Abbott, "Mechanically tunable terahertz metamaterials," *Appl. Phys. Lett.*, vol. 102, no. 12, 121101, Mar. 2013.

[139] A. Emboras, C. Hoessbacher, C. Haffner, W. Heni, U. Koch, P. Ma, Y. Fedoryshyn, J. Niegemann, C. Hafner, and J. Leuthold, "Electrically controlled plasmonic switches and modulators," *IEEE J. Sel. Topics Quantum Electron.*, vol. 21, no. 4, pp. 276 – 283, Jul./Aug. 2014.

[140] P. Pitchappa, C. P. Ho, L. Dhakar, and C. Lee, "Microelectromechanically reconfigurable interpixelated metamaterial for independent tuning of multiple resonances at terahertz spectral region," *Optica*, vol. 2, no. 6, pp. 571 – 578, Jun. 2015.

[141] A. L. Holsteen, A. F. Cihan and M. L. Brongersma, "Temporal color mixing and dynamic beam shaping with silicon metasurfaces," *Science*, vol. 365, no. 6450, pp. 257 – 260, Jul. 2019.

[142] Y. J. Guo, P.-Y. Qin, S.-L. Chen, W. Lin, and R. W. Ziolkowski, "Advances in reconfigurable antenna systems facilitated by innovative technologies," *IEEE Access*, vol. 6, pp. 5780 – 5794, 2018.

[143] A. O. Bah, P.-Y. Qin, R. W. Ziolkowski, Q. Cheng, and Y. J. Guo, "Realization of an ultra-thin metasurface to facilitate wide bandwidth, wide angle beam scanning." *Sci. Rep*., vol. 8, no. 1, 4761, Mar. 2018.

[144] S. A. Cummer, J. Christensen, and A. Alù, "Controlling sound with acoustic metamaterials," *Nat. Rev. Mater*., vol. 1, no. 3, 16001, Feb. 2016.

[145] B.-I. Popa, L. Zigoneanu, and S. A. Cummer, "Tunable active acoustic metamaterials," *Phys. Rev. B,* vol. 88, no. 2, 024303, Jul. 2013.

[146] P. A. Deymier, ed., *Acoustic Metamaterials and Phononic Crystals*, vol. 173, Springer Science & Business Media, 2013.

[147] R. V. Craster and S. Guenneau, eds., *Acoustic Metamaterials: Negative Refraction, Imaging, Lensing and Cloaking*, vol. 166, New York: Springer Science & Business Media, 2012.

[148] M. Kadic, T. Bückmann, R. Schittny, and M. Wegener, "Metamaterials beyond electromagnetism," *Rep. Prog. Phys.*, vol. 76, no. 12, 126501, Nov. 2013.

[149] T. Han, X. Bai, J. T. L. Thong, B. Li, and C.-W. Qiu, "Full control and manipulation of heat signatures: Cloaking, camouflage and thermal metamaterials," *Adv. Mater*., vol. 26, no. 11, pp. 1731 – 1734, Feb. 2014.

[150] I. Liberal and N. Engheta, "Manipulating thermal emission with spatially static fluctuating fields in arbitrarily-shaped epsilon-near-zero bodies," *Proc. Nat. Acad. Sci. (PNAS)*, vol. 115, no. 12, pp. 2878 – 2883, Mar. 2018.

[151] T. Bückmann, N. Stenger, M. Kadic, J. Kaschke, A. Frölich, T. Kennerknecht, C. Eberl, M. Thiel, and M. Wegener, "Tailored 3D mechanical metamaterials made by dip-in direct-laser-writing optical lithography," *Adv. Mater*., vol. 24, no. 20, pp. 2710 – 2714, Apr. 2012.

[152] T. Bückmann, M. Thiel, M. Kadic, R. Schittny, and M. Wegener, "An elasto-mechanical unfeelability cloak made of pentamode metamaterials," *Nat. Commun*., vol. 5, 4130, Jun. 2014.

[153] S. Brûlé, S. Enoch, S. É. Bastien, S. Guenneau, and R. V. Craster, "Seismic metamaterials: Controlling surface Rayleigh waves using analogies with electromagnetic metamaterials," *Handbook of Metamaterials, Singapore*: World Scientific, 2018, ch. 7, pp. 301 – 337.

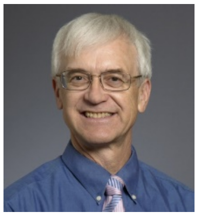
[154] I. Liberal and N. Engheta, "Nonradiating and radiating modes excited by quantum emitters in open epsilon-near-zero (ENZ) cavities," *Sci. Adv*., vol. 2: e1600987, Oct., 2016.

[155] I. Liberal and N. Engheta, "Zero-index structures as an alternative platform for quantum optics," *Proc. Nat. Acad. of Sci.,* vol. 114, no. 5, pp. 822 – 827, Jan. 2017.

[156] I. Liberal and N. Engheta, "Multi-qubit subradiant states with N-port waveguide devices: Epsilon-and-mu-near-zero hubs and nonreciprocal circulators," *Phys. Rev. A*, vol. 97, 022309, Feb., 2018.

[157] I. Liberal, I. Ederra and R. W. Ziolkowski, "Quantum antenna arrays: The role of quantum interference on direction-dependent photon statistics," *Phys. Rev. A*. vol. 97, 053847, May 2018.

[158] I. Liberal, I. Ederra, and R. W. Ziolkowski, "Control of a quantum emitter's bandwidth by managing its reactive power," *Phys. Rev. A*, vol. 100, 023830, Aug. 2019



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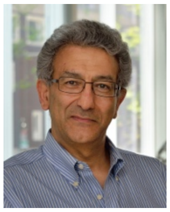

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