Programmable Metasurfaces: State of the Art and Prospects

Fu Liu*, Alexandros Pitilakis†‡, Mohammad Sajjad Mirmoosa*, Odysseas Tsilipakos†,
Xuchen Wang*, Anna C. Tasolamprou†, Sergi Abadal§, Albert Cabellos-Aparicio§,
Eduard Alarcón§, Christos Liaskos†, Nikolaos V. Kantartzis†‡,
Maria Kafesaki†¶, Eleftherios N. Economou†, Costas M. Soukoulis†‖, Sergei Tretyakov*,
*Department of Electronics and Nanoengineering, Aalto University, P.O. Box 15500, Espoo, Finland
†Foundation for Research and Technology Hellas, 71110, Heraklion, Crete, Greece
‡Department of Electrical and Computer Engineering, Aristotle University of Thessaloniki, Thessaloniki, Greece
§NaNoNetworking Center in Catalonia (N3Cat), Universitat Politècnica de Catalunya, Barcelona, Spain
¶ Department of Materials Science and Technology, University of Crete, 71003, Heraklion, Crete, Greece
‖ Ames Laboratory and Department of Physics and Astronomy, Iowa State University, Ames, Iowa 50011, USA
Email: fu.liu@aalto.fi

***Abstract*—Metasurfaces, ultrathin and planar electromagnetic devices with sub-wavelength unit cells, have recently attracted enormous attention for their powerful control over electromagnetic waves, from microwave to visible range. With tunability added to the unit cells, the programmable metasurfaces enable us to benefit from multiple unique functionalities controlled by external stimuli. In this review paper, we will discuss the recent progress in the concept of programmable metasurfaces and elaborate different approaches to realize them, with the tunability from global aspects, to local aspects, and to software-defined metasurfaces.**

I. INTRODUCTION

Metamaterials and metasurfaces are artificial bulk and planar materials with subwavelength structural inclusions. Benefiting from the tailored unit cell structures, metasurfaces have been showing powerful abilities in achieving versatile functionalities, such as perfect absorption, anomalous reflection, focusing, imaging, to mention a few [1], [2]. In the early stages of these metamaterials and metasurfaces research, once the unit cell is designed, its function is fixed, for example, an absorber works at a certain frequency where the input impedance is matched to the free space. However, if we want to change the working frequency or even the functionality, re-design and re-fabrication processes are inevitable due to the structural nature of the unit cells. In fact, the properties of the metamaterials and metasurfaces can be adjusted by adding "tuning" capability in the unit cells [3]–[5]. Then their electromagnetic wave behavior can be tuned externally by modifying the stimuli. Such tuning can be controlled by a computer program. From this point of view, such metasurfaces are programmable and they provide more opportunities in achieving dynamical wave applications, without the re-fabrication process.

There are many tuning mechanisms in achieving the programmable metasurfaces. For instance, the change of the properties of the substrate or structural material can result in a shift of the resonance frequency, e.g., the permittivity of the liquid crystal can be changed under different gate voltages [6]. Change the "on" and "off" state of a diode will switch the metasurface performance from perfect absorption to reflection [7]. In this paper, we will review different tuning mechanisms in achieving programmable metasurfaces, from globally tuning at the metasurface level to locally tuning at the unit cell level. Finally we will direct our discussion to the software-defined metasurfaces which have the ability to tune the properties of each unit cell independently.

II. GLOBAL TUNING AT THE METASURFACE LEVEL

We can make the metasurface programmable by introducing stimuli-responsive materials, which are capable of undergoing relatively large and rapid changes in their physical properties in response to external ambient stimuli [8]. In this case, when the ambient conditions, such as temperature, pressure, humidity, electric/magnetic field, light, alter the material properties will be tuned accordingly and therefore induce the change of the metasurface functionality. As the ambient stimuli apply to the whole metasurface level, we call it global tuning. As the ambient pressure and humidity is hard to change, we will focus on the tunability by electric, magnetic, light, and temperature stimuli, with some examples shown in Fig. 1.

A. *Electric tuning*

There are many electrically sensitive materials, among which nematic liquid crystals (LCs) are very famous due to the massive development of the optical display technology. Nematic LC molecules respond to the bias electric field by rearranging their orientation and thus achieving voltage dependent birefringence. Due to their liquid nature, they can be infiltrated into various metasurface structures providing large refractive index modulation for operation in the microwave, terahertz and optical regime [6], [13]–[15]. To date nematic LCs have been used in various pronounced metasurface applications such as broadband perfect absorbers and cloaks with possibilities of real-time control of invisibility. Due to their large anisotropy, LCs have also been employed in hyperbolic metasurface configurations [9], [16], [17].

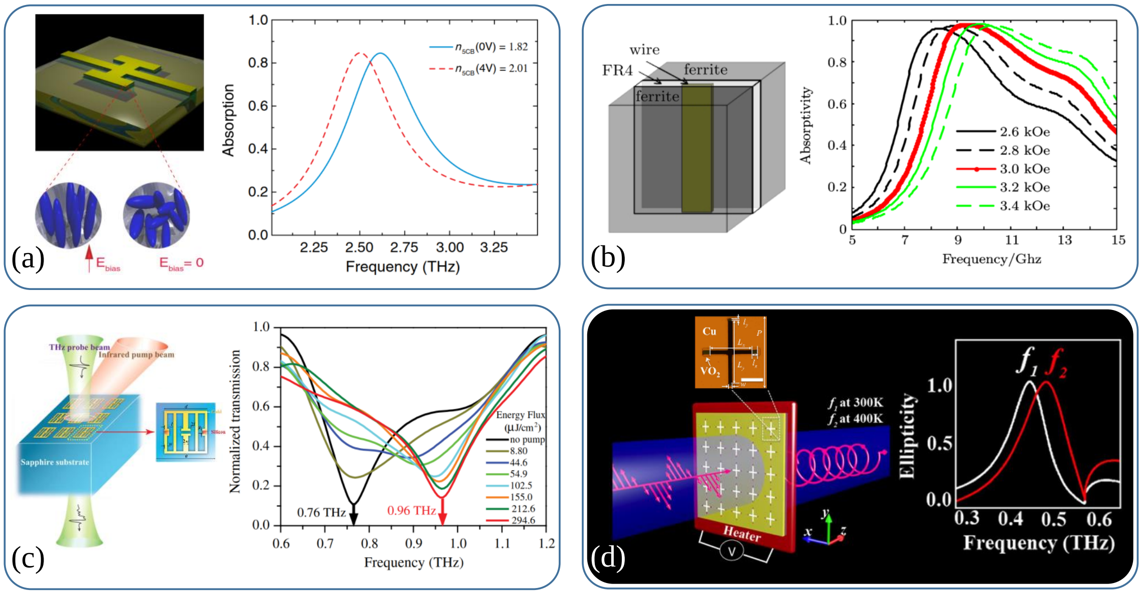

Fig. 1. Tunable metasurfaces with stimuli-sensitive materials. (a) Electric-sensitive liquid crystal-based tunable metasurface absorber [9]. (b) Magnetic-sensitive ferrite-based tunable metasurface absorber [10]. (c) Light-sensitive semiconductor-based tunable metasurface [11]. (d) Thermal-sensitive VO_2-based tunable quarter-wave plate [12]. Permissions of the figures are obtained.

Another famous electrically sensitive material is graphene, of which the Fermi level can be modified by the external electrostatic field. For example, in Ref. [18], researchers have demonstrated tunable plasmon resonances in graphene microribbon arrays on a silicon/silicon dioxide substrate. However, the weak interaction between graphene and light, which is due to the poor obtainable mobility (especially for processed graphene), hinders the tunable functionalities. In fact, from the circuit perspective, the weak interaction comes from the huge impedance mismatch between graphene and the surrounding materials. While the low-quality graphene has very large surface impedance in the terahertz range, the characteristic impedance of the surrounding materials is comparably small. Therefore the tunability of the total impedance of the metasurface is very limited. To circumvent this low tunability, metallic blocks are introduced on the graphene to largely reduce the effective surface impedance. In this way, the graphene-metal hybrid metasurfaces have shown efficient tunability on amplitude, phase, and resonance frequency [19]–[22]. For example, a recent work in Ref. [22] shows that a graphene-metal strip structure can demonstrate strong tunable absorption (with absorbance modulation efficiency 96%) when the Fermi level is tuned from 0.26 eV to 0.57 eV.

B. Magnetic tuning

Magnetically tunable structures are attractive thanks to their instantaneous response to external contactless magnetic stimuli. The magnetic field-guided self-assembly of colloidal particles is one of the leading fabrication methods: The induced dipole-dipole interactions between these particles can be accurately controlled (attractive or repulsive), so that by properly adjusting the controlling magnetic field profile their assembly process can tuned, from the movement of a single nano-sized object to a globally synchronized motion. Applications include adaptive microplate arrays, i.e., magnetically responsive nanostructures for tuned optics [25], hybrid devices [26] and generation of resonant-assisted tunneling phenomena [27]. Magnetically responsive structures have been exploited also in tunable-resonance metamaterials: ferrite-wire metamaterials for tunable negative index [28], ferrite-rod structures with different saturation magnetization for wide-band tunable microwave filters [29] and tunable broadband absorbers consisting of ferrite slabs and copper wires [10].

C. Light tuning

Photoconductive semiconductor materials, such as Si and GaAs, have been employed for implementing tunable metasurfaces by tuning their conductivity through carrier photoexcitation with an infrared pump beam. Several implementations with split-ring-resonator-based metasurfaces operating in the THz have been proposed. In [30], [31] the semiconductor (GaAs) is included as the substrate material. Alternatively, the semiconductor (Si) can be incorporated as a section in the resonant structure [11], [32]. In this case, carrier photoexcitation effectively modifies the resonator geometry. This can lead to a redshift of the fundamental resonance [32] or trigger a transition to a different, blue-shifted resonance [11]. Semiconductor inclusions have been also utilized in chiral metasurfaces for switching their handedness [33] or tuning the ellipticity and optical activity [34].

D. Thermal tuning

Heat is another ambient stimulus for tunable metasurfaces. Metamolecules or substrate whose macroscopic parameters are sensitive to temperature variation can lead to the change of the electromagnetic response of the metasurface. In this context, phase change materials (PCMs) with temperature-dependent permittivity are promising candidates [12], [35]–[40]. For

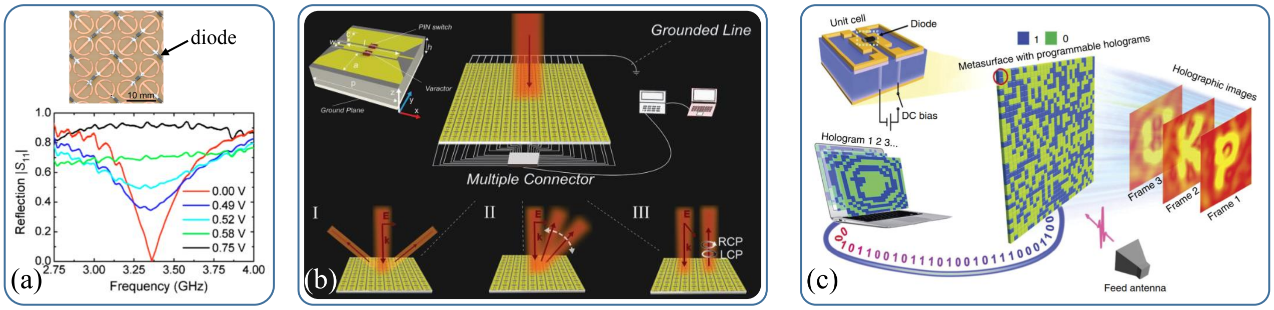

Fig. 2. Varactor-loaded tunable metasurfaces with incrasing complexity and ability. (a) A diode switches the functionality from total absorption to total reflection. [7]. (b) Column-controlled varactors enable a tunable metasurface to perform multiple functions: splitting, steering, and polarization conversion [23]. (c) Patterned coding-metasurface enables dynamic hologram [24]. Reprinted with permissions.

instance, vanadium dioxide, as one of the well-known PCMs, behaves as an insulator at room temperature and transits to a metal state at higher temperatures due to the enhancement of the free carriers concentration. It has been employed in tunable metasurfaces to shift the resonance frequency varying the transmission amplitude [35], [36], or switch the polarization of the transmitted wave at two different frequencies [12]. A structure which consists of two materials with different thermal expansion coefficients is also a plausible solution. In Ref. [41], a metasurface made of such a structure can have different transmission amplitude when the temperature varies. Moreover, superconductors can be also employed for tuning the transmission resonance and its strength since the conductivity of superconductors is temperature dependent [42].

III. LOCAL TUNING AT THE UNIT-CELL LEVEL

While the global tuning applies to the whole metasurface, local tuning provides a possibility to tune the properties of each unit cell locally. In this way, we can achieve more tunable functions, such as steering, imaging and hologram creation. For local tuning, we can use the same stimuli-sensitive materials. But in this case we need to apply the stimuli locally in each unit cell. For example, we need a heater/cooler in each unit to effectively control the temperature, a coil (capacitor) in each unit to change the local magnetic (electric) field, and a LED in each unit to apply different illumination [43]. These, however, are usually implausible solutions due to additive large objects compared to the unit cell size even in the GHz-range metasurfaces. Probably the best option is to use voltage-driven elements, for example diodes and varactors, which have comparably small sizes. Figure 2 lists some examples with different levels of complexity.

A. *Switch diode*

A switch diode, which has two states "on" and "off", enables people to obtain dual-functional metasurfaces in GHz band, if we apply the same control voltage on the diodes. For example, total absorption and total reflection can be switched by changing the state of the diodes [7]. In this case, the diode changes the input impedance of the metasurface to match (total absorption) or mismatch (total reflection) with the free space impedance. In another design in Ref. [44], both the polarization and scattering properties can be modified. While the incident linear polarized wave is reflected to the same polarization when the diodes are on, the same incident wave will be transmitted with perfect polarization rotation when the diodes are switched off.

B. *Continuous tuning varactors*

Actually, the varactor diodes (capacitors) can be adjusted in a continuous way [45]. In the simplest scenario, all varactors are controlled by one and the same voltage, which effectively gives frequency tunability to the functionality the metasurface is designed for [46]–[49]. The most widely investigated functionality is tunable perfect absorption, where a change in the reverse biasing voltages of the varactors shifts the spectrum of the perfect absorption resonance [50]–[53]. Typical values for the (reverse) voltage range are 0-20 V corresponding to an equivalent capacitance range of a few pico-Farad, e.g. 0.5-3.5 pF, for commercially available diodes that are compact enough to be integrated on these GHz-band metasurfaces. The corresponding frequency tunability accessible by this capacitance range is in the order of a couple of GHz, e.g. 4-6 GHz. Similarly, microelectromechanical systems (MEMS), in which the capacitances is tuned from the piezoelectric effect, provides another option for continuous tuning high impedance metasurfaces [54].

C. *Collective tuning varactors*

Moving one step towards more elaborate functionality, the locally-applied continuous tuning voltage is allowed to be different for each unit cell of the metasurface. For example, we can apply a voltage profile on the varactors in one direction while keep the voltage unchanged in the other direction. In this way, a specific one dimensional phase profile can be actively "imprinted" on the metasurface. This enables us to achieve a range of tunable applications, such as tunable reflection (steering) [23], [55]–[57], beam splitting [23], and even writing a letter by dynamically changing the focal point with a tunable "Huygens' metasurface" [58]. Evidently, the price to pay for this enhanced functionality is the increased complexity in the electrical network that controls the voltages biasing the varactor diodes of the metasurface.

On the other hand, instead of modulating the unit cell properties only in one direction, we can dynamically program the metasurface into different two dimensional patterns. In this

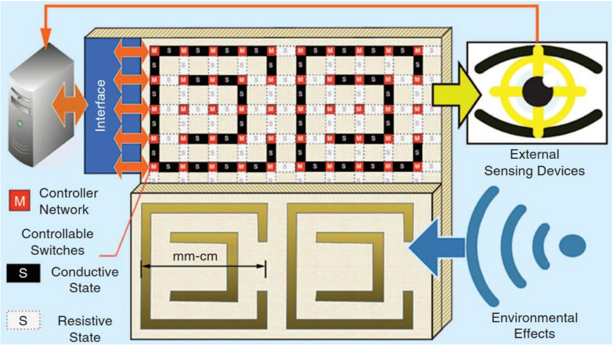

Fig. 3. Software-defined programmable metasurface enables structural reconfiguration at the unit cell level [60]. Reprinted with permission.

case, the individual varactors can be controlled independently and therefore we can obtain a huge number of available patterns, which enable researchers to demonstrate dynamical hologram [24]. Of course, the electrical network of such programmable metasurface is very complex and we need to feed 20×20 group of diodes. A simpler way is to use two diodes in each unit cell and connect one in column and one in row. By doing so only two sets of control voltages are required, while the programmable metasurface can still give promising functionality, for example, single-sensor imaging by utilizing many available configuration patterns [59].

IV. TOWARD SOFTWARE-DEFINED METASURFACES

A more elaborate way in making tunable metasurfaces is to have the tunability in the change of the unit cell structural configurations. Differently from those approaches which mechanically change the structure shape by external stimuli, such as piezoelectric materials [54], [57] and thermal-sensitive materials [41], this approach reconnects parts of the unit cell to achieve different structural configurations, as proposed in Ref. [60] and shown in Fig. 3. By controlling the connectivity at different locations, reconfiguration of the structure is obtained, thus providing multiple and tunable functionalities. At this point, one challenge resides in the development of a platform that allows users to easily characterize and reconfigure the metasurface. A few recent works [60], [61] aim to achieve this goal using a software-defined approach, where there is a clear separation between electromagnetic functions offered by the metasurface at the macroscopic level and the unit cell configuration that yields them.

The realization of a software-defined metasurface requires a hardware system that applies the software primitives and effectively reconfigures the metasurface. To this end, some researchers propose to integrate a network of tiny controllers within the metasurface structure and to wirelessly interface it with an external entity [60], [61]. Each controller is capable of interpreting global instructions and of acting locally by, for instance, tuning its corresponding varactors to achieve the desired impedance configuration. The main challenges here are, first, to develop an ultra-low cost network of controllers and, second, to co-integrate it with the metasurface within a single structure.

In the software-defined platform, the metasurface profile, which refers to the systematic, measurements-based registration of functions offered by a given metasurface, constitutes the linchpin between academic knowledge and real-world applications. The information contained in the profile allows software developers and engineers to design systems that contain the electromagnetic behavior of objects into their control loops, without required knowledge of the underlying physics. This evolution comes as a timely extension of the concept of Internet-of-Things (IoT) [62], which constitutes a robust, complete hardware platform for connecting anything-to-anything, under a considerable range of conditions and use-cases. Novel IoT products are being released almost daily, at a trend that is expected to yield 20-30 billion connected IoT devices by 2020 [63]. Software-defined metasurfaces can give IoT concept a new application field over the electromagnetic behavior of objects. Coupled with the efforts seeking to provide control over mechanical properties [64], IoT can extend to Internet-of-Materials (IoM), offering unprecedented capabilities.

V. CONCLUSION

Tunable metasurfaces benefiting from both global tuning and local tuning have led us to a greater control of electromagnetic waves by artificial skins. The capacity to host multiple functionalities concurrently or switch between them opens a door to a myriad of applications. We envisage that the software-defined metasurfaces have the potential to automatically adapt to environmental changes.

ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon 2020 research and innovation programme-Future Emerging Topics (FETOPEN) under grant agreement No 736876.

REFERENCES

[1] S. B. Glybovski, S. A. Tretyakov, P. A. Belov *et al.*, "Metasurfaces: From microwaves to visible," *Phys. Rep.*, vol. 634, pp. 1 – 72, 2016.
[2] H.-T. Chen, A. J. Taylor, and N. Yu, "A review of metasurfaces: physics and applications," *Rep. Prog. Phys.*, vol. 79, no. 7, p. 076401, 2016.
[3] I. V. Shadrivov and D. N. Neshev, *Tunable Metamaterials*, ch. 9, pp. 387–418.
[4] N. I. Zheludev and E. Plum, "Reconfigurable nanomechanical photonic metamaterials," *Nat. Nanotechnol.*, vol. 11, p. 16, Jan. 2016.
[5] J. P. Turpin, J. A. Bossard, K. L. Morgan *et al.*, "Reconfigurable and tunable metamaterials: A review of the theory and applications," *Int. J. Antennas. Propag.*, vol. 2014, p. 429837, 2014.
[6] F. Zhang, Q. Zhao, W. Zhang *et al.*, "Voltage tunable short wire-pair type of metamaterial infiltrated by nematic liquid crystal," *Appl. Phys. Lett.*, vol. 97, no. 13, p. 134103, 2010.
[7] B. Zhu, Y. Feng, J. Zhao *et al.*, "Switchable metamaterial reflector/absorber for different polarized electromagnetic waves," *Appl. Phys. Lett.*, vol. 97, no. 5, p. 051906, 2010.
[8] B. Sieklucka and D. Pinkowicz, *Molecular Magnetic Materials: Concepts and Applications*. John Wiley & Sons, 2016.
[9] D. Shrekenhamer, W.-C. Chen, and W. Padilla, "Liquid crystal tunable metamaterial absorber," *Phys. Rev. Lett.*, vol. 110, p. 177403, 2013.
[10] Y. Yong-Jun, H. Yong-Jun, W. Guang-Jun *et al.*, "Tunable broadband metamaterial absorber consisting of ferrite slabs and a copper wire," *Chin. Phys. B*, vol. 21, no. 3, p. 038501, 2012.

[11] N.-H. Shen, M. Massaouti, M. Gokkavas *et al.*, “Optically implemented broadband blueshift switch in the terahertz regime,” *Phys. Rev. Lett.*, vol. 106, no. 3, p. 037403, 2011.

[12] D. Wang, L. Zhang, Y. Gu *et al.*, “Switchable ultrathin quarter-wave plate in terahertz using active phase-change metasurface,” *Sci. Rep.*, vol. 5, no. 15020, 2015.

[13] D. Zografopoulos and R. Beccherelli, “Tunable terahertz fishnet metamaterials based on thin nematic liquid crystal layers for fast switching,” *Sci. Rep.*, vol. 5, p. 13137, 2015.

[14] M. Decker, C. Kremers, A. Minovich *et al.*, “Electro-optical switching by liquid-crystal controlled metasurfaces,” *Opt. Express*, vol. 21, no. 7, pp. 8879–8885, 2013.

[15] J.-Y. Ou, E. Plum, J. Zhang, and N. Zheludev, “An electromechanically reconfigurable plasmonic metamaterial operating in the near-infrared,” *Nat. Nanotechnol.*, vol. 8, no. 4, pp. 252–255, 2013.

[16] G. Pawlik, K. Tarnowski, W. Walasik *et al.*, “Infrared cylindrical cloak in nanosphere dispersed liquid crystal metamaterial,” *Opt. Lett.*, vol. 37, no. 11, pp. 1847–1849, 2012.

[17] Z. Cao, X. Xiang, C. Yang *et al.*, “Analysis of tunable characteristics of liquid-crystal-based hyperbolic metamaterials,” *Liq. Cryst.*, vol. 43, no. 12, pp. 1753–1759, 2016.

[18] L. Ju, B. Geng, J. Horng *et al.*, “Graphene plasmonics for tunable terahertz metamaterials,” *Nat. Nanotechnol.*, vol. 6, pp. 630–634, 2011.

[19] S. H. Lee, M. Choi, T.-T. Kim *et al.*, “Switching terahertz waves with gate-controlled active graphene metamaterials,” *Nat. Mater.*, vol. 11, no. 11, pp. 936–941, 2012.

[20] M. M. Jadidi, A. B. Sushkov *et al.*, “Tunable terahertz hybrid metal–graphene plasmons,” *Nano Lett.*, vol. 15, pp. 7099–7104, 2015.

[21] N. Dabidian, S. Dutta-Gupta, I. Kholmanov *et al.*, “Experimental demonstration of phase modulation and motion sensing using graphene-integrated metasurfaces,” *Nano Lett.*, vol. 16, pp. 3607–3615, 2016.

[22] S. Kim, M. S. Jang, V. W. Brar *et al.*, “Electronically tunable perfect absorption in graphene,” *arXiv preprint arXiv:1703.03579*, 2017.

[23] C. Huang, C. Zhang, J. Yang *et al.*, “Reconfigurable metasurface for multifunctional control of electromagnetic waves,” *Adv. Opt. Mater.*, vol. 5, no. 22, p. 1700485, 2017.

[24] L. Li, T. Jun Cui, W. Ji *et al.*, “Electromagnetic reprogrammable coding-metasurface holograms,” *Nat. Commun.*, vol. 8, no. 1, p. 197, Aug. 2017.

[25] S. Liu, Y. Long *et al.*, “Bioinspired adaptive microplate arrays for magnetically tuned optics,” *Adv. Opt. Mater.*, vol. 5, p. 1601043, 2017.

[26] R. K. Pandey, W. A. Stapleton, P. Padmini *et al.*, “Magnetically tuned varistor-transistor hybrid device,” *AIP Adv.*, vol. 2, p. 042188, 2016.

[27] F. Bourquin, G. Caruso, M. Peigney, and D. Siegert, “Magnetically tuned mass dampers for optimal vibration damping of large structures,” *Smart Mater. Struct.*, vol. 23, no. 8, p. 085009, 2014.

[28] Y. He, P. He *et al.*, “Role of ferrites in negative index metamaterials,” *IEEE Trans. Magn.*, vol. 42, no. 10, pp. 2852–2854, Oct 2006.

[29] K. Bi, W. Zhu, M. Lei, and J. Zhou, “Magnetically tunable wideband microwave filter using ferrite-based metamaterials,” *Appl. Phys. Lett.*, vol. 106, no. 17, p. 173507, 2015.

[30] W. J. Padilla, A. J. Taylor, C. Highstrete *et al.*, “Dynamical electric and magnetic metamaterial response at terahertz frequencies,” *Phys. Rev. Lett.*, vol. 96, no. 10, p. 107401, 2006.

[31] I. Chatzakis, L. Luo, J. Wang *et al.*, “Reversible modulation and ultrafast dynamics of terahertz resonances in strongly photoexcited metamaterials,” *Phys. Rev. B*, vol. 86, no. 12, p. 125110, 2012.

[32] H.-T. Chen, J. F. O’hara, A. K. Azad *et al.*, “Experimental demonstration of frequency-agile terahertz metamaterials,” *Nat. Photonics*, vol. 2, no. 5, pp. 295–298, 2008.

[33] S. Zhang, J. Zhou, Y.-S. Park *et al.*, “Photoinduced handedness switching in terahertz chiral metamolecules,” *Nat. Commun.*, vol. 3, p. 942, 2012.

[34] G. Kenanakis, R. Zhao, N. Katsarakis *et al.*, “Optically controllable thz chiral metamaterials,” *Opt. Express*, vol. 22, pp. 12 149–12 159, 2014.

[35] T. Driscoll, S. Palit, M. M. Qazilbash *et al.*, “Dynamic tuning of an infrared hybrid-metamaterial resonance using vanadium dioxide,” *Appl. Phys. Lett.*, vol. 93, p. 024101, 2008.

[36] T. Driscoll, H.-T. Kim, B.-G. Chae *et al.*, “Memory metamaterials,” *Science*, vol. 325, no. 5947, pp. 1518–1521, 2009.

[37] M. Seo, J. Kyoung, H. Park *et al.*, “Active terahertz nanoantennas based on vo2 phase transition,” *Nano Lett.*, vol. 10, pp. 2064–2068, 2010.

[38] H. Kim, N. Charipar, E. Breckenfeld *et al.*, “Active terahertz metamaterials based on the phase transition of vo2 thin films,” *Thin Solid Films*, vol. 596, no. Supplement C, pp. 45–50, 2015, the 42nd International Conference on Metallurgical Coatings and Thin Films.

[39] J.-H. Shin, K. Moon, E. S. Lee *et al.*, “Metal-vo2 hybrid grating structure for a terahertz active switchable linear polarizer,” *Nanotechnology*, vol. 26, no. 31, p. 315203, 2015.

[40] D. Wang, L. Zhang, Y. Gong *et al.*, “Multiband switchable terahertz quarter-wave plates via phase-change metasurfaces,” *IEEE Photonics Journal*, vol. 8, no. 5500308, 2016.

[41] J. Y. Ou, E. Plum, L. Jiang, and N. I. Zheludev, “Reconfigurable photonic metamaterials,” *Nano Lett.*, vol. 11, no. 5, pp. 2142–2144, 2011.

[42] H.-T. Chen, H. Yang, R. Singh *et al.*, “Tuning the resonance in high-temperature superconducting terahertz metamaterials,” *Phys. Rev. Lett.*, vol. 105, p. 247402, 2010.

[43] I. V. Shadrivov, P. V. Kapitanova, S. I. Maslovski *et al.*, “Metamaterials controlled with light,” *Phys. Rev. Lett.*, vol. 109, p. 083902, 2012.

[44] Z. Tao, X. Wan, B. C. Pan, and T. J. Cui, “Reconfigurable conversions of reflection, transmission, and polarization states using active metasurface,” *Appl. Phys. Lett.*, vol. 110, no. 12, p. 121901, mar 2017.

[45] J. Zhao, Q. Cheng, J. Chen *et al.*, “A tunable metamaterial absorber using varactor diodes,” *New J. Phys.*, vol. 15, p. 043049, Apr 2013.

[46] C. Mias and J. H. Yap, “A varactor-tunable high impedance surface with a resistive-lumped-element biasing grid,” *IEEE Trans. Antennas Propag.*, vol. 55, no. 7, pp. 1955–1962, July 2007.

[47] S. N. Burokur, J.-P. Daniel, P. Ratajczak, and A. de Lustrac, “Tunable bilayered metasurface for frequency reconfigurable directive emissions,” *Appl. Phys. Lett.*, vol. 97, no. 6, p. 064101, 2010.

[48] F. Dincer, “Electromagnetic energy harvesting application based on tunable perfect metamaterial absorber,” *J. Electromagn. Waves Appl.*, vol. 29, no. 18, pp. 2444–2453, 2015.

[49] M. M. Masud, B. Ijaz, I. Ullah, and B. Braaten, “A compact dual-band emi metasurface shield with an actively tunable polarized lower band,” *IEEE Trans. Electromagn. Compat.*, vol. 54, no. 5, pp. 1182–1185, 2012.

[50] B. Ma, S. Liu, X. Kong *et al.*, “A novel wide-band tunable metamaterial absorber based on varactor diode/graphene,” *Optik - International Journal for Light and Electron Optics*, vol. 127, pp. 3039 – 3043, 2016.

[51] J. Zhu, D. Li, S. Yan *et al.*, “Tunable microwave metamaterial absorbers using varactor-loaded split loops,” *EPL*, vol. 112, no. 5, p. 54002, 2015.

[52] Z. Luo, J. Long, X. Chen, and D. Sievenpiper, “Electrically tunable metasurface absorber based on dissipating behavior of embedded varactors,” *Appl. Phys. Lett.*, vol. 109, no. 7, p. 071107, 2016.

[53] H. K. Kim, D. Lee, and S. Lim, “Frequency-tunable metamaterial absorber using a varactor-loaded fishnet-like resonator,” *Appl. Opt.*, vol. 55, no. 15, pp. 4113–4118, May 2016.

[54] D. Chicherin, S. Dudorov, D. Lioubtchenko *et al.*, “Mems-based high-impedance surfaces for millimeter and submillimeter wave applications,” *Microwave Opt. Technol. Lett.*, vol. 48, no. 12, pp. 2570–2573, 2006.

[55] D. F. Sievenpiper, J. H. Schaffner, H. J. Song *et al.*, “Two-dimensional beam steering using an electrically tunable impedance surface,” *IEEE Trans. Antennas Propag.*, vol. 51, no. 10, pp. 2713–2722, Oct 2003.

[56] H.-X. Xu, S. Tang, S. Ma *et al.*, “Tunable microwave metasurfaces for high-performance operations: Dispersion compensation and dynamical switch,” *Sci. Rep.*, vol. 6, p. 38255, Nov 2016.

[57] D. Chicherin, S. Dudorov, M. Sterner *et al.*, “Micro-fabricated high-impedance surface for millimeter wave beam steering applications,” in *2008 33rd International Conference on Infrared, Millimeter and Terahertz Waves*, Sept 2008, pp. 1–3.

[58] K. Chen, Y. Feng, F. Monticone *et al.*, “A reconfigurable active huygens’ metalens,” *Adv. Mater.*, vol. 29, no. 17, p. 1606422, 2017.

[59] Y. B. Li, L. L. Li, B. B. Xu *et al.*, “Transmission-type 2-bit programmable metasurface for single-sensor and single-frequency microwave imaging,” *Sci. Rep.*, vol. 6, p. 23731, mar 2016.

[60] C. Liaskos, A. Tsioliaridou, A. Pitsillides *et al.*, “Design and development of software defined metamaterials for nanonetworks,” *IEEE Circuits Syst. Mag.*, vol. 15, no. 4, pp. 12–25, 2015.

[61] S. Abadal, C. Liaskos, A. Tsioliaridou *et al.*, “Computing and communications for the software-defined metamaterial paradigm: A context analysis,” *IEEE Access*, 2017.

[62] A. Mihovska and M. Sarkar, “Smart connectivity for internet of things (iot) applications,” in *New Advances in the Internet of Things*. Springer, 2018, pp. 105–118.

[63] A. Nordrum, “The internet of fewer things [news],” *IEEE Spectr.*, vol. 53, no. 10, pp. 12–13, 2016.

[64] G. Gheorghe, C. Anghel, and I. Iulian, “Scientific evolution from mix-integrating mechatronics to cyber-intelligent mechatronics and to claytronics science.” *Applied Mechanics & Materials*, vol. 841, 2016.