Chapter-7

Reconfigurable Antennas–A Review

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The current chapter discusses some basic concepts of antennas with special emphasis on microstrip patch antennas. Also it throws light on the aspect of reconfigurability in gain, frequency response, radiation patterns, or a combination of several radiation patterns. Furthermore, this paper presents a survey of the development of reconfigurable and tunable metamaterial as well as of the applications specific to patch antenna technology.

1. INTRODUCTION

Antennas are a very important component of communication systems. By definition, an antenna is a device used to transform an RF signal, travelling on a conductor, into an electromagnetic wave in free space. Antennas demonstrate a property known as reciprocity, which means that an antenna will maintain the same characteristics regardless if it is transmitting or receiving. Most antennas are resonant devices, which operate efficiently over a relatively narrow frequency band. An antenna must be tuned to the same frequency band of the radio system to which it is connected; otherwise the reception and the transmission will be impaired. When a signal is fed into an antenna, the antenna will emit radiation distributed in space in a certain way [1]. The Fig. 1 shows some of the most commonly seen antennas. Microstrip patch antennas are one of them and this article complies with studies on microstrip patch antenna. The first experiments that involved the coupling of electricity and magnetism and showed a definitive relationship was that done by Faraday somewhere around the 1830s. He slid a magnetic around the coils of a wire attached to a galvanometer. In moving the magnet, he was in effect creating a time-varying magnetic field, which as a result (from Maxwell's Equations), must have had a time-varying electric field. The coil acted as a loop antenna and received the electromagnetic radiation, which was received (detected) by the galvanometer - the work of an antenna. Interestingly, the concept of electromagnetic waves had not even been thought up at this point.

Heinrich Hertz developed a wireless communication system in which he forced an electrical spark to occur in the gap of a dipole antenna. He used a loop antenna as a receiver, and observed a similar disturbance. This was 1886. In 1893, Nikola Tesla demonstrated the first public radio communication. One year later, during a November 1894 public demonstration at Town Hall of Kolkata, Sir J.C Bose ignited gunpowder and rang a bell at a distance using millimetre range wavelength microwaves. By 1901, Marconi was sending information across the Atlantic. For a transmit antenna, he used several vertical wires attached to the ground. Across the Atlantic Ocean, the receive antenna was a 200 meter wire held up by a kite [2].

In 1906, Columbia University had an Experimental Wireless Station where they used a transmitting aerial cage. This was a cage made up of wires and suspended in the air, resembling a cage [3]. The developments in the antenna field during the World War II, the result of intensive and combined efforts of radio engineers and physicists, were marked by the invention of many new types of antennas, and also by advances in fundamental antenna theory. Indeed, the whole subject of microwave optics was born and grew to maturity during the war years [4].

A rough outline of some major antennas and their discovery/fabrication dates are listed [3]:

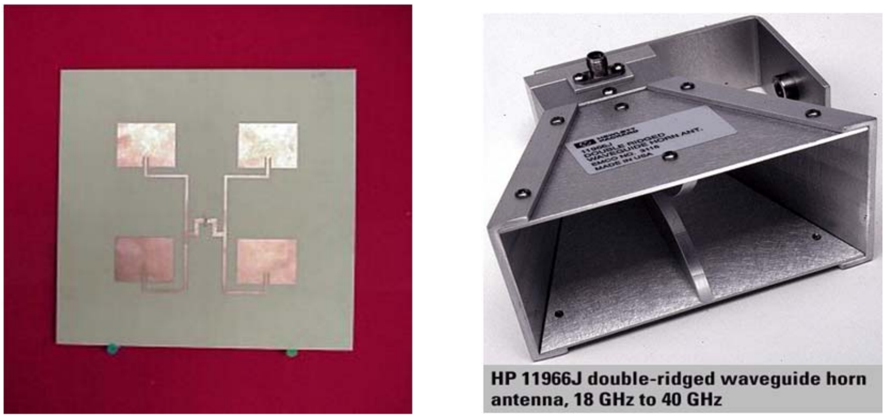


Fig. 1: Some antenna types(in clockwise direction): Reflector (parabolic) antenna; Yagi-Uda antenna; horn antenna; microstrip patch antenna.(Image courtesy: Google Images)

- Yagi-Uda Antenna, 1920s
- Horn antennas, 1939
- Antenna Arrays, 1940s
- Parabolic Reflectors, late 1940s, early 1950s
- Patch Antennas, 1970s.
- PIFA, 1980s.

The first "microstrip" entry ever in the IEEE transaction on Antennas & Propagation was the paper by Munson in 1974 [5]. But early literature on microstrip patch antennas date back to a paper by Deschamps and Sichak [6] and a French patent by Gutton and Boissinoit [7].

2. MICROSTRIP PATCH ANTENNAS

Microstrip patch antennas (MPA) are attractive due to their light weight, conformability and low cost. These antennas can be integrated with printed strip-line feed networks and active devices. This is a relatively new area of antenna engineering.

The radiation properties of microstrip structures have been known since the mid 1950's. The application of this type of antennas started in early 1970's when conformal antennas were required for missiles. Rectangular and circular microstrip resonant patches have been used extensively in a variety of array configurations. A major contributing factor for recent advances of microstrip antennas is the current revolution in electronic circuit miniaturization brought about by developments in large scale integration. As conventional antenna is often bulky and costly part of an electronic system, micro strip antennas based on photolithographic technology are seen as an engineering breakthrough.

In its most fundamental form, a microstrip patch antenna consists of a radiating patch on one side of a dielectric substrate which has a ground plane on the other side as shown in Fig. 2. The patch is generally made of conducting material such as copper or gold and can take any possible shape. The radiating patch and the feed lines are usually photo etched on the dielectric substrate.

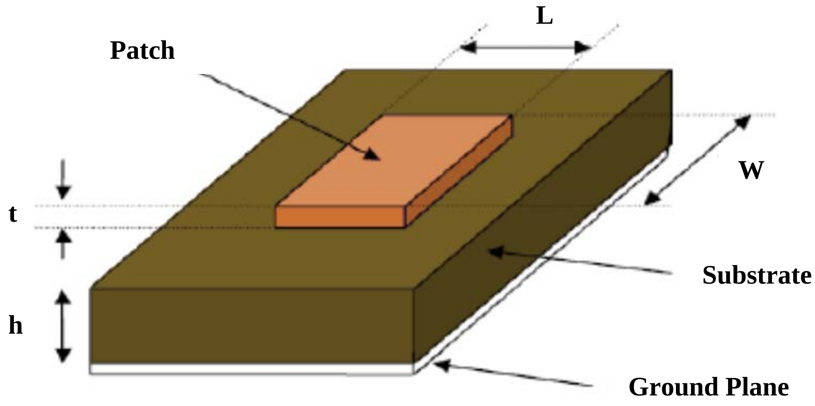


Fig. 2: Structure of a microstrip patch antenna.
(Image courtesy: Google Images)

In order to simplify analysis and performance prediction, the patch is generally square, rectangular, circular, triangular, and elliptical or some other common shape as shown in Fig. 1.3.

For a rectangular patch, the length L of the patch is usually $0.3333\lambda o < L < 0.5\ \lambda o$, where λo is the free-space wavelength. The patch is selected to be very thin such that $t \ll \lambda o$ (where t is the patch thickness). The height h of the dielectric substrate is usually $0.003\ \lambda o \leq h \leq 0.05\ \lambda o$.

The dielectric constant of the substrate (ε_r) is typically in the range $2.2 \leq \varepsilon_r \leq 12$.

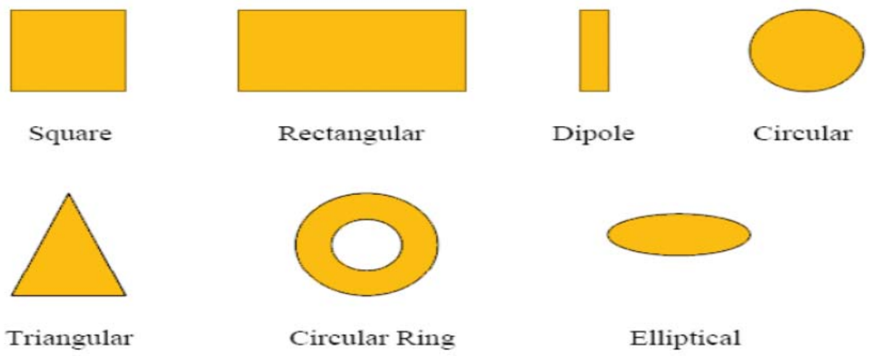


Fig. 3: Common shapes of microstrip patch elements. (Image courtesy: Google Images)

Microstrip patch antennas radiate primarily because of the fringing fields between the patch edge and the ground plane. For good antenna performance, a thick dielectric substrate having a low dielectric constant is desirable since this provides better efficiency, larger bandwidth and better radiation. However, such a configuration leads to a larger antenna size. In order to design a compact microstrip patch antenna, substrates with higher dielectric constants must be used which are less efficient and result in narrower bandwidth. Hence a trade-off must be realized between the antenna dimensions and antenna performance.

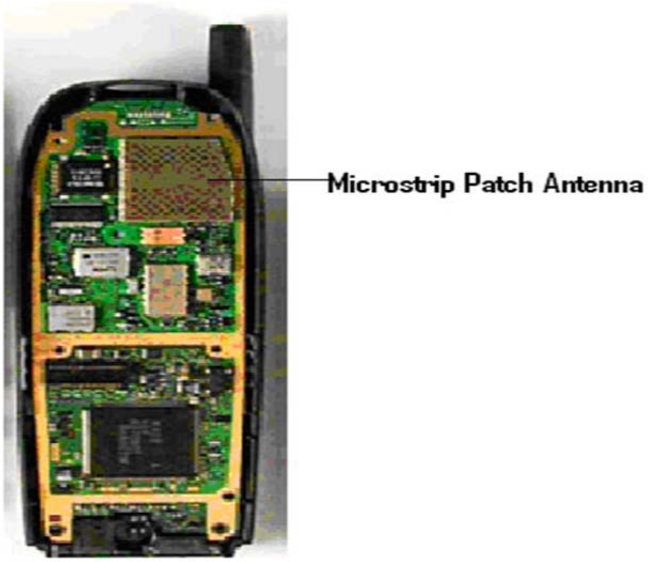


Fig. 4: Patch antenna in mobile handset.
(Image courtesy: Google Images)

3. APPLICATIONS OF MPAS

Microstrip patch antenna has several applications. Some of these applications are as below:

- Mobile and satellite communication application
- Global Positioning System applications
- Radio Frequency Identification (RFID)
- Worldwide Interoperability for Microwave Access (WiMax)
- Radar Application
- Rectenna Applicatio
- Telemedicine Application (Wearable antennas)

4. ADVANTAGES AND LIMITATIONS OF MPAS

Microstrip patch antennas are increasing in popularity for use in wireless applications due to their low-profile structure. Therefore they are extremely compatible for embedded antennas in handheld wireless devices such as cellular phones, pagers etc. The telemetry and communication antennas on missiles need to be thin and conformal and are often in the form of microstrip patch antennas. Another area where they have been used successfully is in satellite communication. Some of their principal advantages discussed by Kumar and Ray [8] are given below:

- Light weight and low volume.
- Low profile planar configuration which can be easily made conformal to host surface.
- Low fabrication cost, hence can be manufactured in large quantities.
- Supports both, linear as well as circular polarization.
- Can be easily integrated with microwave integrated circuits (MICs).
- Capable of dual and triple frequency operations.
- Mechanically robust when mounted on rigid surfaces.

Microstrip patch antennas suffer from more drawbacks as compared to conventional antennas. Some of their major limitations discussed by [8] and Garg et al [9] are given below:

- Narrow bandwidth, low efficiency& low Gain
- Extraneous radiation from feeds and junctions
- Poor end fire radiator except tapered slot antennas
- Low power handling capacity.

- Surface wave excitation

5. OVERCOMING LIMITATIONS OF MPAS – MULTIBAND AND RECONFIGURABLE ANTENNAS

As mentioned previously, the microstrip patch antenna in the basic form of a conducting patch in a grounded substrate is inherently narrowband and is not able to meet the requirements of wireless communication systems. Whereas bandwidth can be increased by using lossy substrates, this is usually not desirable as efficiency will be reduced. In the last two and a half decades, a number of techniques have been developed to broaden the bandwidths of microstrip patch antennas, without compromising efficiency. The various designs provide bandwidths in the range from 10% to 60%. The methods developed for efficient wideband patch antenna design are based on one or more of the following principles:

a) by means of parasitic elements or slots, additional resonances are introduced so that, in conjunction with the main resonance, an overall broader band response is obtained;

b) thick substrates of low permittivity are used to reduce the quality factor;

c) scheme is devised to reduce the mismatch problem associated with thick substrates.

It is sometimes possible that a broadband microstrip antenna can cover the frequencies of interest. However, the disadvantage of using a broadband antenna is that it also receives non-desired frequencies unless some kind of filtering network is introduced to reject such frequencies. Moreover, the radiation characteristics of the antenna is not consistent through out the bandwidth. In such cases, multiband microstip patch antennas (antennas resonating at more than one frequency in different bands) are useful. The advantage of a dual- and multiband frequency design is that it focuses only on the frequencies of interest and is thus more desirable and more efficient. Several patch designs have been developed which leads to multiple resonating frequencies. These include stacked patches, slotted patches and fractal patches. However, with incresing external features in handheld communication devices, limts the antenna volume, making the antenna patch design quite challenging.

Recently reconfigurable multiband antennas have gained tremendous research interest for many different applications, for example, cellular radio system, radar system, satellite communication, airplane, and unmanned airborne vehicle (UAV) radar, smart weapon protection. Reconfiguring an antenna is achieved through deliberately changing its frequency, polarization, or radiation characteristics. This change is achieved by many techniques that redistribute the antenna currents and thus alter the electromagnetic fields of the antenna's effective aperture. Reconfigurable antennas can address complex system requirements by modifying their geometry and electrical behavior, thereby adapting to changes in environmental conditions or system requirements (i.e., enhanced bandwidth, changes in operating frequency, polarization, and radiation pattern). Reconfigurable antennas can be classified into four different categories [10].

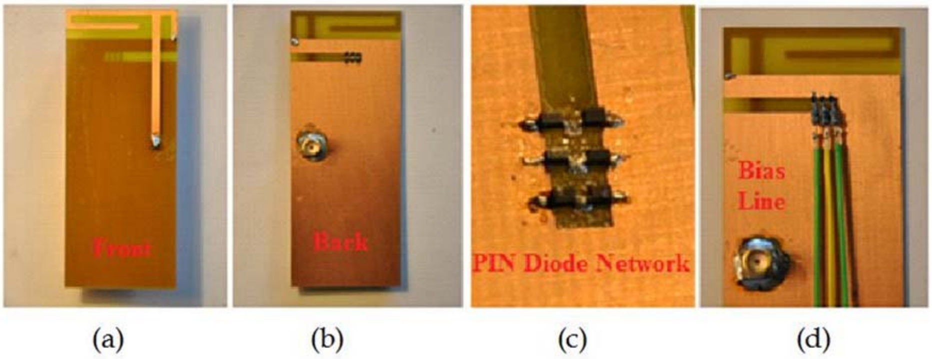
- Category 1: A radiating structure that is able to change its operating or notch frequency by hoping between different frequency bands is called frequency reconfigurable antenna. This is achieved by producing some tuning or notch in the antenna reflection coefficient.

- Category 2: A radiating structure that is able to tune its radiation pattern is called radiation pattern reconfigurable antenna. For this category, the antenna radiation pattern changes in terms of shape, direction, or gain.
- Category 3: A radiating structure that can change its polarization (horizontal/vertical, lefthand or right-hand circular polarized, etc.) is called polarization reconfigurable antenna. In this case, the antenna can change, for example, from vertical to left-hand circular polarization.
- Category 4: This category is a combination of the previous three categories. For example, one can achieve a frequency reconfigurable antenna with polarization diversity at the same time.

In terms of techniques for reconfiguring the antenna system, broadly are the four techniques as mentioned below:

5.1 Electrically reconfigurable antennas

An electrically reconfigurable antenna relies on electronic switching components (RF-MEMs, PIN diodes, or varactors) to redistribute the surface currents, and alter the antenna radiating structure topology and/or radiating edges. The integration of switches into the antenna structure makes it easier for designers to reach the desired reconfigurable functionality. The ease of integration of such switching elements into the antenna structure has attracted antenna researchers to this type of reconfigurable antennas despite the numerous issues surrounding such reconfiguration techniques. These issues include the nonlinearity effects of switches, and the interference, losses, and negative effect of the biasing lines used to control the state of the switching components on the antenna radiation pattern.



(a) (b) (c) (d)

Fig. 5: Implementation of PIN Diode switches for electrically reconfiguring the antenna

Image Courtesy: Ahmad Rashidy Razali, Amin M Abbosh and Marco A Antoniades (2013). Compact Planar Multiband Antennas for Mobile Applications, Advancement in Microstrip Antennas with Recent Applications, Prof. Ahmed Kishk (Ed.), InTech, DOI: 10.5772/52053.

5.2 Optically reconfigurable antennas

An optical switch is formed when laser light is incident on a semiconductor material (silicon, gallium arsenide). This results in exciting electrons from the valence to the conduction band and thus creating a conductive connection. Integrating such a switch into an antenna structure and using it to reconfigure the antenna behavior is called an optically reconfigurable antenna. The linear behavior of optical switches, in addition to the absence of biasing lines, compensates for their lossy aspect and the need for laser light to activate them. The main issue focuses on the activation mechanism of such switches on the antenna structure.

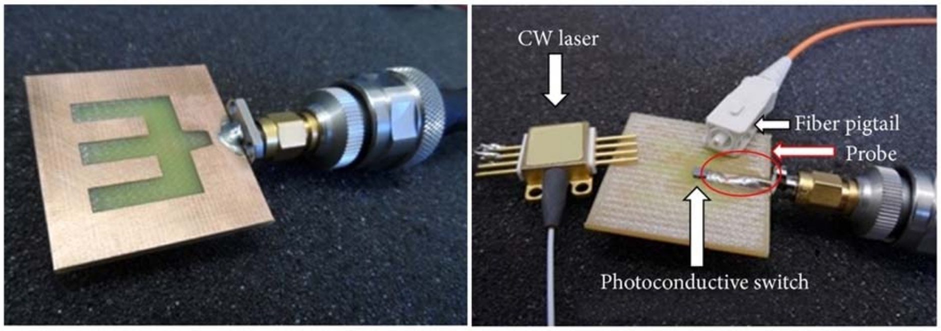


Fig. 6: An optically reconfigurable antenna

Image Courtesy: Arismar Cerqueira Sodré Junior, Igor Feliciano da Costa, Leandro Tiago Manera, and José Alexandre Diniz, "Optically Controlled Reconfigurable Antenna Array Based on E-Shaped Elements," International Journal of Antennas and Propagation, vol. 2014, Article ID 750208, 8 pages, 2014. doi:10.1155/2014/750208

5.3 Physically reconfigurable antennas

Antennas can also be reconfigured by physically altering the antenna radiating structure. The tuning of the antenna is achieved by a structural modification of the antenna radiating parts. The importance of this technique is that it does not rely on any switching mechanisms, biasing lines, or optical fiber/laser diode integration. On the other hand, this technique depends on the limitation of the device to be physically reconfigured.

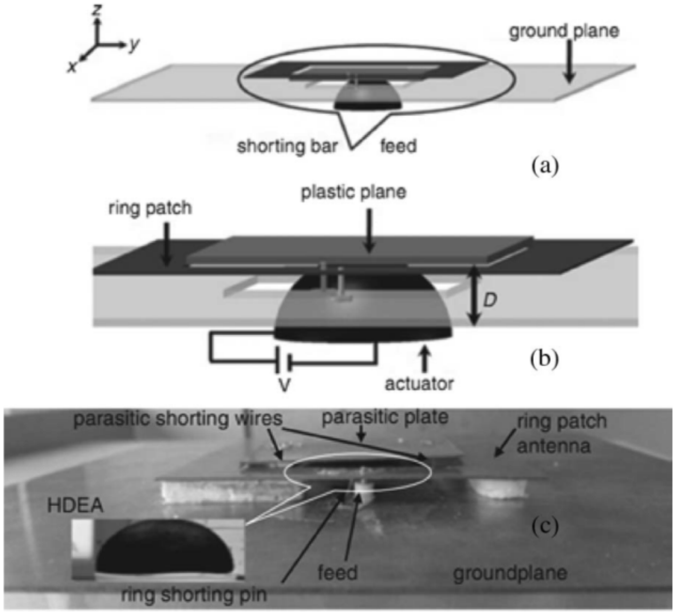


Fig. 7: (a) Representation of the mechanically reconfigurable system. (b) Antenna structure after actuation (parasitic above ring). (c) Fabricated antenna prototype

Image Courtesy: S. Jalali Mazlouman, M. Soleimani, A. Mahanfar, C. Menon, and R. G. Vaughan, BPattern reconfigurable square ring patch antenna actuated by hemispherical dielectric elastomer,[Electron. Lett., vol. 47, no. 3,pp. 164–165, Feb. 2011.

5.4 Reconfigurable antennas based on smart materials

Antennas are also made reconfigurable through a change in the substrate characteristics by using materials such as liquid crystals [11], [12] or ferrites [13], [14]. The change in the material is achieved by a change in the relative electric permittivity or magnetic permeability. In fact, a liquid crystal is a nonlinear material whose dielectric constant can be changed under different voltage levels, by altering the orientation of the liquid crystal molecules. As for a ferrite material, a static applied electric/magnetic field can change the relative material permittivity/permeability.

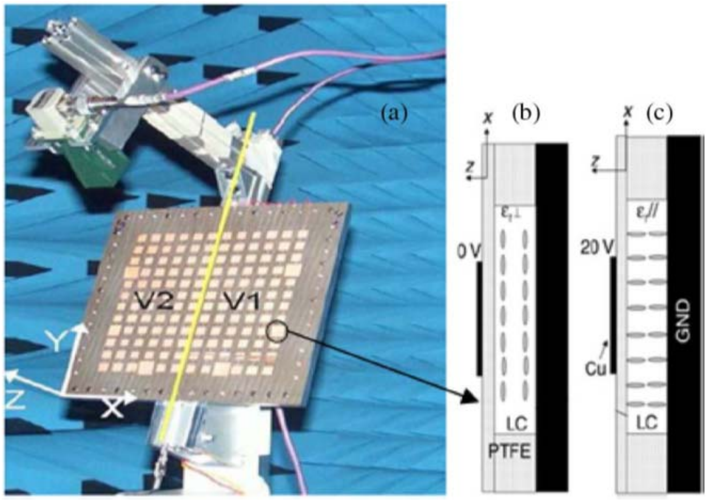


Fig. 8: (a) Reconfigurable reflectarray antenna with liquid crystal substrate. (b) Liquid crystal molecules under 0 V. (c) Liquid crystal molecules under 20 V.

Image Coutesy: W. Hu, M. Y. Ismail, R. Cahill, J. A. Encinar, V. Fusco, H. S. Gamble, D. Linton, R. Dickie, N. Grant, and. P. Rea, BLiquid-crystal-based reflectarray antenna with electronically switchable monopulse patterns, [Electron.Lett., vol. 43, no. 14, Jul. 2007.

6. COMPARISON BETWEEN DIFFERENT RECONFIGURATION TECHNIQUES

Electronic switching components have been widely used to reconfigure antennas, especially after the appearance of RF-MEMS in 1998 [15]. One of the major advantages of such components is their good isolation and low-loss property. While RF-MEMS represent an innovative switching mechanism, their response is slower than PIN diodes and varactors which have a response on the order of nanoseconds [16]–[18]. All these switches and especially varactors add to the scalability of reconfigurable antennas. The ease of integration of such switches into the antenna structure is matched by their nonlinearity effects (capacitive and resistive) and their need for high voltage (RF-MEMS, varactors) [19]. The activation of such switches requires biasing lines that may negatively affect the antenna radiation pattern and add more losses. The incorporation of switches increases the complexity of the antenna structure due to the need for additional bypass capacitors and inductors which will increase the power consumption of the whole system.

Even though optical switches are less popular, they definitely present a reliable reconfiguration mechanism especially in comparison to RF-MEMS. The activation or deactivation of the photoconductive switch by shining light from the laser diode does not produce harmonics and intermodulation distortion due to their linear behavior. Moreover, these switches are integrated into the antenna structure without any complicated biasing lines which eliminates unwanted interference, losses, and radiation pattern distortion. Despite all these advantages, optical switches exhibit lossy behavior and require a complex activation mechanism [20], [21]. The advantages of using physical reconfiguration techniques lie in the fact that they do not require bias lines or resort to laser diodes or optical fibers. However, their disadvantages include slow response, cost, size, power source requirements and the complex integration of the reconfiguring element into the antenna structure.

Thus if we consider, the implementation of switching techniques in a simpler manner, using smart materials becomes the most advantageous way. However, bulk ferrites and liquid crystals impose high losses, due to which researchers have been constantly working on new materials that can be used instead. Recently, there has been a rise in a new class of artificially constructed material called “Metamaterial”.

7. METAMATERIAL BASED TUNABLE ANTENNAS

Metamaterials are engineered material and have simultaneously negative permittivity and permeability [22], which can modify the EM properties of the incident wave. Metamaterials are sometimes also referred as left handed materials (LHM) or negative index materials (NIM). At microwave frequencies, metamaterials can be designed using ‘unit cell’ resonator structures whose sizes are less than that of operational microwave wavelength. The versatility of designing unit cells gives metamaterials uniqueness in manipulating their permittivity and permeability. This possibility of localized structural modification of the unit cells to obtain desired performance and their low losses over frequencies of interest gives the metamaterials an edge over the use of conventional materials in reconfigurable antennas.

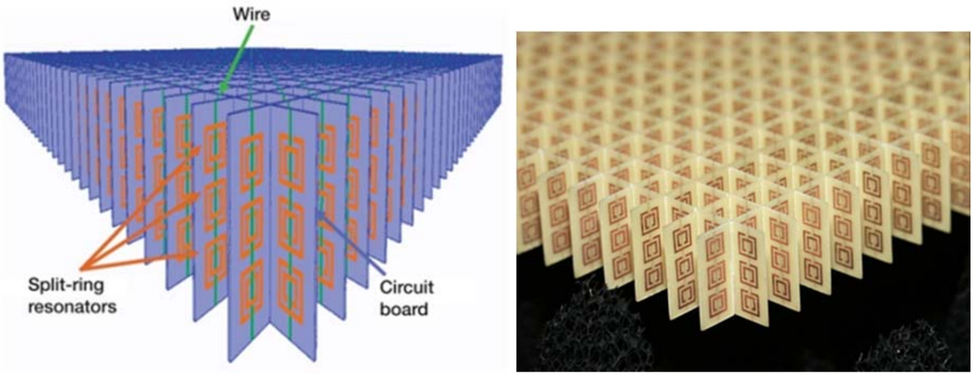


Fig. 9: Images of metamaterials: Schematic representation (left) & actual prototype (right). (Image courtesy: Google Images)

Fig. 10: Schematic of a single resonating structure (usually called a unit cell) in a metamaterial. It is composed of a dielectric substrate in between (as shown in blue) and copper wire (as shown in golden) on one side of the substrate and on the other side copper rings (as shown in yellow). Metamaterials are composed of period arrangement of such structures in different directions. (Image courtesy: Google Images)

While changing the shape (by mechanical tuning) and the electrical length (by using switches such as PIN diodes, varactor diodes etc) of resonant elements provides a range of opportunities for tuning, the constituent materials that make up the unit cell ultimately control the properties of the metamaterial. In the literature, a variety of constituent materials have been evaluated and exploited for tuning metamaterials by controlling the permittivity, permeability, and conductivity of parts of the unit cell.

The electrical size of the conducting resonant elements is affected by the permittivity of the surrounding medium. For instance, a dipole element in free space is resonant when its length is approximately half of the wavelength. However, if this dipole is embedded in a dielectric, it becomes resonant at half the wavelength size in the dielectric. This means that if tunable dielectric materials can be incorporated in the unit cell, the resonance wavelength of the metamaterial can be tuned as the constituent material permittivity changes. Several papers have theoretically investigated the effects of changing the substrate permittivity on a metamaterial response [23–25]. There are a few candidate materials that have been used for permittivity tuning of metamaterials, including $Ba_{0.5}Sr_{0.5}TiO_3$ (BST) ferroelectric films, liquid crystal, and Ga-Sb-Te (GST) phase-change materials. BST films provide a permittivity change under voltage bias and have been used as a substrate for tuning SRR elements along a transmission line at microwave frequencies [26, 27]. BST can also be tuned via change in temperature as demonstrated in [28] for tuning the resonance frequency of SRRs. Liquid crystals offer dielectric tuning over a broad range of the electromagnetic spectra from RF all the way through optical wavelengths. Liquid crystals are anisotropic in permittivity due to their composition of long, aligned molecules and exhibit changes in permittivity due to applied voltage, induced magnetic field, optical excitation, and even thermal change, which can be exploited to tune metamaterials. There are a number of theoretical and practical demonstrations showing the tuning of negative index materials and magnetic resonances at optical wavelengths [29–32]. The same shift in magnetic resonance has been explored for designing a metamaterial that switches between being highly transmissive and reflective by re-orienting liquid crystal molecules included in the unit cell [33]. GST phase-change materials have discrete crystalline and amorphous phases that possess distinct electrical properties at infrared wavelengths and that can be switched between by subsequently melting and cooling the material. Several papers have investigated the use of GST as a constituent material for tuning metamaterials [34]. GST was used as the resonant element in [35] to change scattering behavior among being highly reflective, transmissive, or absorptive. GST was also explored as a substrate in [34] that can switch a metamaterial mirror between reflection polarization states. Permeability tuning can also be achieved at RF using ferrite materials. In [36], yttrium iron garnet (YIG) rods having a negative permeability are incorporated into a metamaterial unit cell. Applying a magnetic field bias allows the permeability of the YIG rods to be tuned from negative to positive, causing a change in response of the metamaterial. While negative permeability constituent materials are not available at THz or higher frequencies, ferrite materials can be a useful tuning method at RF. The third general area for constituent material tuning is conductivity. Conductivity change is frequently accomplished using semiconductor materials with applied voltage [37] or optical pumping [38–42]. The semiconductor can be incorporated as a substrate under all elements [37, 42] or as an inductive load over part of the resonant elements [39–41] to tune their resonant frequency. Graphene has also been used to inductively load resonant elements in a HIS when under a voltage bias [43]. A variety of techniques have also been employed to change the conductivity of the resonant elements themselves. Semiconductor SRRs have been used with a change in conductivity achieved thermally [44] or by applying a magnetostatic field [45]. Conducting polymers have also been used as resonant elements in metamaterial absorbers [46]. The conducting polymers exhibit large changes in conductivity (i.e., from resistive to conductive) when stimulated by certain chemical analytes. This enables the metamaterial to reconFig. from reflecting to absorbing or to change resonant frequencies. VO2 phase change materials also exhibit large conductivity changes with a voltage bias and have been used to form the resonant elements in several metamaterial experiments [47–49].

Although there are advantages in material tuning compared to other systems, bulk material-based tuning is ultimately limited by the range of electromagnetic responses available in the constituent substances, where each material system poses unique implementation challenges. For instance, BST and VO_2 offer useful permittivity and conductivity changes, respectfully, but they are both sensitive to temperature and thus must be used in temperature controlled environments. GST phase change material on the other hand does not suffer from temperature variation, but incorporating the heating and cooling mechanisms into the metamaterial to control the phase transitions between crystalline and amorphous states is challenging. Also, ferrites in bulk form are lossy in nature and is not suitable, especially for antenna based applications

8. CONCLUSIONS

Therefore it can be concluded that, although there has been numerous developments in reconfigurable systems, especially using smart material and metamaterials, research needs to continue in the development of tunable material systems that can be harnessed to meet application specific reconfigurable metamaterial needs. Systems based on nano particles, rods, films etc can be investigated for possibility to be used as tunable materials. Exquisite properties of nano systems, such as low loss in microwave regime [50], ability to respond to a particular external stimuli, can enhance its applicability. Hence, nano material based tunable systems holds great promise for future implementations and can be considered as an exciting field to be explored in microwave material research [51,52].

REFERENCES

[1] Flickenger, R., Fonda, C., Forster, J., & Howard, I. (2007). Wireless networking in the developing world. The Code.

[2] Balanis, C. A. (1992). Proceedings of the IEEE,80(1), 7-23.

[3] Arthur M. Kay, scanned by Alan Crosswell. http://www.w2aee.columbia.edu/history/antenna-history.html.

[4] Van Atta, L. C., & Silver, S. (1962). Proceedings of the IRE, **50(5)**, 692-697.

[5] Munson, R. (1974). IEEE Transactions on Antennas and Propagation, **22(1)**, 74-78.

[6] Deschamps, G. A. (1953, October). In 3rd USAF Symposium on Antennas (pp. 22-26).

[7] Gutton, H., & Baissinot, G. (1955). French patent, **703113**.

[8] Kumar, G., & Ray, K. P. (2003). Artech House.

[9] Garg, R. (2001). Artech house.

[10] Costantine, J. (2009). (Doctoral dissertation, The University of New Mexico).

[11] Hu, W., Ismail, M. Y., Cahill, R., Encinar, J. A., Fusco, V. F., Gamble, H. S., ... & Rea, S. P. (2007). Electronics Letters, **43(14)**, 1.

[12] Liu, L., & Langley, R. J. (2008). Electronics Letters, **44(20)**, 1.

[13] Pozar, D. M., & Sanchez, V. (1988). Electronics Letters, **24**, 729-731.

[14] Dixit, L., & Pourush, P. K. S. (2000). IEEE Proceedings-Microwaves, Antennas and Propagation, **147(2)**, 151-155.

[15] Brown, E. R. (1998). IEEE Transactions on microwave theory and techniques, **46(11)**, 1868-1880.

[16] Rebeiz, G. M., & Muldavin, J. B. (2001). IEEE Microwave magazine, **2(4)**, 59-71.

[17] Rohde, U. L., & Rudolph, M. (2013). John Wiley & Sons.

[18] Gutierrez, I., Meléndez, J., & Hernández, E. (2007). John Wiley & Sons.

[19] Dussopt, L., & Rebeiz, G. M. (2003). IEEE Transactions on Microwave Theory and Techniques, **51(4)**, 1247-1256.

[20] Rebeiz, G. M. (2004). RF MEMS: theory, design, and technology. John Wiley & Sons.

[21] Tawk, Y., Costantine, J., Hemmady, S., Balakrishnan, G., Avery, K., & Christodoulou, C. G. (2012). IEEE Transactions on Antennas and Propagation, **60(2)**, 1075-1083.

[22] Smith, D. R., Padilla, W. J., Vier, D. C., Nemat-Nasser, S. C., & Schultz, S. (2000). Physical review letters, **84(18)**, 4184.

[23] Kern, D. J., Wilhelm, M. J., Werner, D. H., & Werner, P. L. (2004, June). InAntennas and Propagation Society International Symposium, 2004. IEEE (Vol. 2, pp. 1167-1170). IEEE.

[24] Sheng, Z., & Varadan, V. V. (2006, July). In 2006 IEEE Antennas and Propagation Society International Symposium (pp. 4497-4500). IEEE.

[25] Sheng, Z., & Varadan, V. V. (2007). Journal of applied physics, **101(1)**, 014909.

[26] Houzet, G., Mélique, X., Lippens, D., Burgnies, L., Velu, G., & Carru, J. C. (2010). Progress In Electromagnetics Research C, **12**, 225-236.

[27] Gil, M., Damm, C., Giere, A., Sazegar, M., Bonache, J., Jakoby, R., & Martin, F. (2009). Electronics letters, **45(8)**, 417-418.

[28] Ozbay, E., Aydin, K., Butun, S., Kolodziejak, K., & Pawlak, D. (2007, October). In Proc. 37th European Microwave Conf., Munich, Germany (pp. 497-499).

[29] Zhao, Q., Kang, L., Du, B., Li, B., Zhou, J., Tang, H., ... & Zhang, B. (2007). Applied Physics Letters, **90(1)**, 011112.

[30] Zhang, F., Zhao, Q., Kang, L., Gaillot, D. P., Zhao, X., Zhou, J., & Lippens, D. (2008). Applied Physics Letters, **92(19)**, 193104.

[31] Kwon, D. H., Wang, X., Bayraktar, Z., Weiner, B., & Werner, D. H. (2008). Optics letters, **33(6)**, 545-547.

[32] Wang, X., Kwon, D. H., Werner, D. H., Khoo, I. C., Kildishev, A. V., & Shalaev, V. M. (2007). Applied Physics Letters, **91(14)**, 143122.

[33] Sieber, P. E., & Werner, D. H. (2013). Optics express, **21(1)**, 1087-1100.

[34] Werner, D. H., Mayer, T. S., Rivero-Baleine, C., Podraza, N., Richardson, K., Turpin, J., ... & Muise, R. (2011, September). In SPIE Optical Engineering+ Applications (pp. 81651H-81651H). International Society for Optics and Photonics.

[35] Kang, L., Zhao, Q., Zhao, H., & Zhou, J. (2008). Optics express, 16(12), 8825-8834.

[36] Chen, H. T., Padilla, W. J., Zide, J. M., Gossard, A. C., Taylor, A. J., & Averitt, R. D. (2006). Nature, **444 (7119)**, 597-600.

[37] Zhu, S., Holtby, D. G., Ford, K. L., Tennant, A., & Langley, R. J. (2013). IEEE Transactions on Antennas and Propagation, **61(4)**, 2301-2304.

[38] Boulais, K. A., Rule, D. W., Simmons, S., Santiago, F., Gehman, V., Long, K., & Rayms-Keller, A. (2008). Applied Physics Letters, **93(4)**, 043518.

[39] Chen, H. T., O'Hara, J. F., Azad, A. K., Taylor, A. J., Averitt, R. D., Shrekenhamer, D. B., & Padilla, W. J. (2008). Nature Photonics, **2(5)**, 295-298.

[40] Xiao, S., Chettiar, U. K., Kildishev, A. V., Drachev, V., Khoo, I. C., & Shalaev, V. M. (2009). Applied Physics Letters, **95(3)**, 033115.

[41] Chowdhury, D. R., Singh, R., O’Hara, J. F., Chen, H. T., Taylor, A. J., & Azad, A. K. (2011). Applied Physics Letters, **99(23)**, 231101.

[42] Padilla, W. J., Taylor, A. J., Highstrete, C., Lee, M., & Averitt, R. D. (2006). Physical review letters, **96(10)**, 107401.

[43] Huang, Y., Wu, L. S., Tang, M., & Mao, J. (2012). IEEE Transactions on Nanotechnology, **11(4)**, 836-842.

[44] Han, J., & Lakhtakia, A. (2009). Journal of Modern Optics, **56(4)**, 554-557.

[45] Han, J., Lakhtakia, A., & Qiu, C. W. (2008). Optics Express, **16(19)**, 14390-14396.

[46] Liang, T., Li, L., Bossard, J. A., Werner, D. H., & Mayer, T. S. (2005, July). In 2005 IEEE Antennas and Propagation Society International Symposium (Vol. 2, pp. 204-207). IEEE.

[47] Bouyge, D., Crunteanu, A., Orlianges, J. C., Passerieux, D., Champeaux, C., Catherinot, A., ... & Blondy, P. (2009, December). In 2009 Asia Pacific Microwave Conference (pp. 2332-2335). IEEE.

[48] Bouyge, D., Crunteanu, A., Massagué, O., Orlianges, J. C., Champeaux, C., Catherinot, A., ... & Blondy, P. (2010, September). In Microwave Conference (EuMC), 2010 European (pp. 822-825). IEEE.

[49] Goldflam, M. D., Driscoll, T., Chapler, B., Khatib, O., Jokerst, N. M., Palit, S., ... & Di Ventra, M. (2011). Applied Physics Letters, **99(4)**, 044103.

[50] Parsons, P., Duncan, K., Giri, A., Xiao, J. Q., & Karna, S. P. (2012, August). In Nanotechnology (IEEE-NANO), 2012 12th IEEE Conference on (pp. 1-5). IEEE.

[51] Christodoulou, C. G., Tawk, Y., Lane, S. A., & Erwin, S. R. (2012). Proceedings of the IEEE, **100(7)**, 2250-2261.

[52] Turpin, J. P., Bossard, J. A., Morgan, K. L., Werner, D. H., & Werner, P. L. (2014). International Journal of Antennas and Propagation, 2014.