A Personal Perspective on CRLH Antennas

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***Abstract*—The author presents a personal perspective on the work that he and his collaborators have done in the area of composite right/left-handed (CRLH) antennas over the past decade with some emphasis on recent developments.**

I. Introduction

Since the experimental demonstration of negative refraction in 2001 [1], metamaterials, previously often referred to as composite materials or artificial dielectrics, have known an exploding regain of interest in both the scientific and engineering communities. Over 25 books have been published on the topic since 2005, including [2]–[11], and the topic seems far from being exhausted, particularly with the emergence of multiscale and nano-structured materials that were not realizable a few decades ago.

Antennas have been one of the applications of metamaterials. A lot of creative – although not always practical – work has been done by many groups around the world in this area. One of the practically most successful directions on metamaterial antennas has been that of composite right/left-handed (CRLH) metamaterial antennas [3], [12]. The most practical CRLH antennas have been one-dimensional, and they may therefore be regarded as sub-wavelength unit-cell metastructures, most often (but not always) periodic in nature, as opposed to "metamaterials." However, CRLH antennas really originate in metamaterial concepts such as negative refraction or zero-index medium. Interestingly, these antennas have led to antenna solutions extending beyond the realm of metamaterials.

This paper presents a personal perspective of the author on CRLH antennas. It focuses on the work he has been involved in, and is therefore not attempting to provide a global perspective.

II. CRLH Metamaterials

CRLH metamaterials are 1D, 2D or 3D sub-wavelength unit cell transmission line structures exhibiting negative and positive refractive indices below and above a transition stopband [3], [13]. This stopband is delimited by magnetic and electric plasma-like frequencies, corresponding to the structure's series and shunt resonances, respectively, and degenerates into a gap-less single frequency point with zero refractive index when the two resonances are equalized [3].

CRLH metamaterial structure have lead to a vast number of component, antenna and system applications, including recent dispersion-engineered devices for RF analog signal processing [14]–[17]. The paper focuses on the antenna applications [12].

III. Leaky-Wave Antennas

The field of leaky-wave antennas (LWAs) has known a great regain of interest with the advent of metamaterials. In this area, metamaterials not only produced novel antennas with unique features, such as efficient full-space (including broadside) scanning LWAs [3], [18], but also led to the resolution of issues of non-metamaterial LWAs. An overview of recent advances on LWAs with an emphasis on metamaterial-based, and specifically CRLH-based, LWAs was recently published in [19] and [20].

Since their discovery in 1940 [21], full-space scanning LWAs – periodic leaky structures fed at one edge – had been plagued by the issue of radiation efficiency collapse in the antenna broadside direction, due to unit-cell resonance at the corresponding frequency. CRLH structures have solved this issue for the first time in 2002 [3], via the mutual cancelation of the series (magnetic plasma) and shunt (electric plasma) resonances of the unit cell under the *balanced* (equal series and shunt resonances) condition, where broadside radiation occurs at the zero-index point of the structure's dispersion diagram [3]. It was later understood that this principle of resonance cancelation could apply to non-metamaterial LWAs, where the issue is now considered fully solved, the solution consisting in satisfying the four following conditions: 1) presence of two resonances in the unit cell for non-zero leakage at broadside [22], [23], 2) frequency balancing for stopband closure [3], [23], 3) Q-factor balancing for frequency-independent impedance through broadside [23], [24], 4) common series and shunt radiation direction for radiation efficiency theoretically capable of reaching 100% [25].

CRLH structures have a also led to a number of practically important innovations, such for instance active beamforming LWAs offering comparable functionalities as antenna arrays without a feeding network [26], power-recycling LWAs resolving the issue of poor gain for moderately electrically large structures [27], [28], and gain-enhanced end-switched LWAs [29] mitigating the issue of varactor loss in electronic steering.

IV. Resonant Antennas

CRLH resonant antennas offer complementary properties compared to CRLH LWAs [12]. While CRLH LWAs provide full-space scanning and high directivity without requiring any complex feeding network, CRLH resonant antennas exhibit several other useful features.

CRLH resonant antennas are inherently dual-band [30], since the left-handed and right-handed frequency points corresponding to the same wave number magnitude form equivalent (same guided wavelength, same field distribution, and very close input impedance and radiation patterns) pairs in the standing-wave regime [3].

Another interesting property of CRLH resonant antennas is their zeroth order resonance [3], [31], occurring a the zero-index point. In this regime, the resonance frequency remains constant as the size of the structure varies, leading to unique antennas with sizes that are frequency independent [32]. This property may be exploited to design electrically small or electrically large antennas.

CRLH resonant antennas are also useful for high-directivity performance. Compared to a conventional arrays, they may consist of a single element and therefore may not require any corporate feeding network, while compared to LWAs they provide a higher aperture efficiency because they do not have an exponential decay of power along their aperture [32], [33].

Finally, CRLH resonant antennas have given rise to unique monopole radiators, generally in the zeroth order resonance regime. A magnetic monopole microstrip patch antenna was reported in [34], while a loop antenna with collocated electric and monopole responses was demonstrated in [35]. The potential of the latter has still been little exploited to date

V. Antenna Systems

The unprecedented flexibility of CRLH antennas has stimulated the conception of novel antenna *systems*, counting among the first ones in the case of LWAs.

In [36], a CRLH antenna, operating as a kind of optical grating, was used to realize a novel real-time spectrogram analyzer, involving both temporal frequency dispersion [16] and spatial frequency dispersion [37]. Being real-time in nature, this device is not restricted in processing speed or operation frequency, in contrast to DSP-based (short FFT) approaches.

Another unique system application is a CRLH LWA direction of arrival (DoA) estimator, not requiring a feeding network, and being therefore much simpler and smaller than a conventional array-based DoA system [38].

One may also mention a CRLH ferrite antenna duplexer/diplexer, offering a virtually unlimited LO $\leftrightarrow$ IF leakage due both to the leaky-wave and non-reciprocal natures of the structure [39].

Finally, CRLH LWA antennas have been integrated in multiple input multiple output (MIMO) systems [40], where their unique space diversity with minimal form factor has led to commercial applications with two- to threefold data throughput enhancement compared to conventional commercial systems.

VI. Recent Innovations

Some of the most recent CRLH antenna developments include a non-uniform LWA for side-lobe reduction [41], a novel *uniform* and *non-reciprocal* CRLH LWA [42], and its application to a dual-band LWA [43] and a low-profile monopole antenna [44]. The antenna of [42] was also implemented using recently introduced magnet-less non-reciprocal metamaterials [45], [46], to avoid the magnet requirement, and might be implemented in future in flexible ferromagnetic nanowire metamaterials [47].

VII. Concluding Remarks

Over the past decade, CRLH metamaterial concepts have led to a large number of novel antenna structures and systems. There seems to be room for much further innovation in this area.

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