Recent Advances in Metamaterial Antennas

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Abstract

Some recent advances done by the author and his collaborators in the field of antennas and antenna arrays are presented. These include: multiband systems, an infinite-wavelength antenna array series feeding network, a true time delay system allowing beam squint free scanning, a pencil-beam full-space scanning array, a beam-forming system based on active aperture discretization, a MIMO dynamic radiation pattern diversity transmitter, and a radiative real-time spectrogram analyzer and demultiplexer.

1 Introduction

Electromagnetic metamaterials and related concepts [1, 2] have enabled many novel structures and devices. This paper presents, in a narrative manner, a number of recent innovations in metamaterial antennas and antenna arrays. Detailed information is available in the books and papers of the references.

2 Multiband Systems using Narrowband Dispersion Engineering

Metamaterials are inherently dispersive. This dispersion property may be exploited to realize resonant-type multi-band antennas. Composite right/left-handed (CRLH) [2] metamaterials, which represent the most fundamental class of broadband metamaterials, are naturally *dual-band* from their double-Drude nature, which includes twice the number of primitive electromagnetic parameters compared to purely right-handed materials. Using closed-form solutions available in [2]-Sec. 5.1, conventional mono-band components may be systematically transformed to provide dual-band operation.

In antennas, the fields distribution must also be taken into account for dual-band radiation patterns similarity. In this case, twin left-handed ($\beta_n < 0$) and right-handed ($\beta_n > 0$) resonances with equal wavelength ($\lambda_g = 2\pi/|\beta_n|$) are used for dual-bandwidth, with a single excitation mechanism. Using higher-order metamaterials such as the double-Lorentz or the extended-CRLH metamaterials introduced in [3], *tri-band* and *quad-band* operation, respectively, may be achieved.

3 Infinite-Wavelength Antenna Array Series Feeding Network

When a CRLH structure is balanced (i.e. has mutually cancelling series and shunt resonances), a previously unknown phenomenon of *infinite wavelength propagation* takes place at the transition frequency ($\beta = 0$) between the left-handed and right-handed bands [2]-Sec. 3.3.

The phenomenon may be exploited to realize a uniform-field divider/combiner with arbitrarily spaced outputs. This device represents an ideal series feeding network for an antenna array with perfectly phase- and magnitude- balanced ports [4]. Moreover, the number of its ports may be dynamically controlled for real-time beam shaping [5].

4 True Time Delay System for Beam Squinting Elimination

Scanning antenna arrays generally suffer of beam squinting ($[\partial\theta/\partial\omega]_{\theta_0} \neq 0$) caused by the frequency-constant phase shifters used to steer the beam. In contrast, true time delayers exhibit a tunable phase shift which is proportional to frequency so as to cancel this parasitic effect, but they tend to be bulky, cumbersome and expensive.

An efficient time delay phase shifting system *allowing scanning while suppressing squinting* was presented in [7]. This system is based on the pulse delayer introduced in [6] and represents to our knowledge the first instance of an *impulse-regime dispersion-engineered* metamaterial devices; we propose here to call such a device a *disperser*, in analogy with magnitude-engineered filters. In this phase shifter, the RF signal is modulated onto a faster LO, transmitted through a CRLH transmission line, and demodulated back to the RF frequency before being sent to the antenna element. The LO, by virtue of the dispersive nature of the CRLH line, controls the amount of delay of the RF signal along the line, and thereby the time delay or phase shift of the overall device. Using the quadratic region of the CRLH dispersion, the group delay becomes linear and the group delay difference between adjacent antenna elements becomes therefore independent of the RF by subtraction. As a consequence, the beam is steered by LO tuning without any beam squint (no RF dependence) in the different angles scanned.

5 2D-Aperture Pencil-Beam Full-space Scanning Array

The backfire-to-endfire CRLH leaky-wave antenna discovered in [8] and detailed in [2]-Sec. 6.2 was a breakthrough in the field of antennas because it was the first time that a leaky-wave antenna could scan the entire space in a continuous manner, including at broadside under the balanced condition, while in addition being based on the fundamental space harmonic of the structure and therefore allowing an elementary feeding mechanism. This antenna was demonstrated both as a frequency-scanned antenna [8] and as a fixed-frequency electronically-scanned (using varactors) antenna [9]. It was also used in smart reflectors (e.g. [2]-Sec. 6.4).

These antennas were mono-dimensional and restricted to a unique plane scanning with a fan beam. Some attempts were made to extend the capability of this antenna to *pencil-beam scanning of the entire space*. The most practical of them was presented in [10]. This antenna incorporates the CRLH infinite-wavelength series feeding network described in Sec. 3 (in a shielded system to avoid leaky-wave radiation loss [11]) to feed an array of CRLH leaky-wave antennas occupying a 2D aperture. Steering in the plane of these antennas (elevation) is accomplished by frequency or electronic control while steering in the perpendicular plane (azimuth) is achieved by conventional phase shifters, which enables pencil-beam scanning of the entire space. This antenna provides the same functionality as a conventional phase array without using any space-consuming feeding network.

6 Beam-Forming System based on Active Aperture Discretization

The metamaterial radiators discussed in Sec. 5 were passive. Incorporating active elements along their structure not only compensates for losses, achieves higher bandwith for an electrically small size or provides large directivity from increased aperture, but also leads to more fundamental concepts.

An example is the *active aperture discretization beam shaping* CRLH leaky-wave antenna introduced in [12]. Since the (far-field) radiation pattern of an antenna is essential the Fourier transform of its aperture field distribution, modifying this distribution achieves beam shaping. Due to the subwavelength nature of a metamaterial unit cell, variable gain transistors may be conveniently distributed along the structure so as to approximate a desired ideal continuous aperture distribution (e.g. uniform for maximum directivity or binomial for minimum SSL). Fortunately, the integration process of the Fourier transform tends to smooth out the imperfect fit to the target distribution, which leads to excellent pattern results (indistinguishable from those of a perfect distribution down to -20 dB to -40 dB) even for rough approximations using amplifiers only every K cell (say $K = 2 \ldots 8$). It was further suggested that, with intensive engineering efforts, this antenna might become a *universal smart antenna* allowing DSP-controlled full-space pencil beam scanning and shaping with possible beam width/gain equalization and beam squinting suppression [13].

7 MIMO Dynamic Radiation Pattern Diversity Transmitter

The flexibility and low cost of the antennas described in Sec. 5 are currently being exploited in the design of novel MIMO systems. Conventional MIMO systems are most often static; if the transmitter is placed in at an “unlucky” (shadow) zone, no DSP algorithms, no matter how sophisticated, will lead to acceptable channel capacity and data rate.

In order to solve this problem, the concept of *dynamic radiation pattern diversity* was proposed in [14]: Agile and low-cost electronically-steered CRLH leaky-wave antennas dynamically scan the entire scattering environment in order to pick up the best channel available for the specific position of the transmitter, which leads to the maximal capacity and thereby the highest possible data rate for the given position of the transmitter. This dynamic pattern scanning is a simple and slow process, which is made at the scale of the millisecond, so as to calibrate the system to its scattering environment. Each time a drop in the signal level is detected, for instance due to the motion of the transmitter, a new scanning is performed for re-calibration. Once the best channel has been detected, traditional MIMO algorithms are applied most efficiently. The interest of CRLH antennas here is that they may achieve full-space scanning at very low-cost, since they require neither phase shifters nor cumbersome feeding networks.

8 Radiative Real-Time Spectrogram Analyzer and Demultiplexer

It is frequency dispersion which provides beam scanning in a leaky-wave antenna, since the beam direction is given by $\theta(\omega) = \sin^{-1}\left[c\beta(\omega)/\omega\right]$ which is indeed frequency dependent only if β is a nonlinear function of ω. A CRLH structure provides this dispersion and in addition backfire-to-endfire radiation as a consequence of its balanced dispersion law $\beta(\omega) = \omega/\omega_R - \omega_L/\omega$ [Sec. 5].

In [15], the CRLH leaky-wave angle-scanning law $\theta(\omega)$ was interpreted as a *frequency-space mapping* and subsequently applied to realize a novel *real-time Fourier transformer*. Conventional real-time Fourier transformers (instruments providing simultaneous frequency-time representation, or spectrogram, of complex signals) are based on short-term Fourier transform. This approach inherently suffers of restricted time-frequency resolution from the fundamental uncertainty principle $\Delta t\Delta\omega \geq \pi$ [16]: if the time gate is very small high time resolution (small Δt) is achieved but, by Fourier transformation, the frequency resolution is poor (large $\Delta\omega$), and conversely. Thus, a tradeoff is necessary and it is impossible to achieve simultaneously high time and frequency resolutions. In the CRLH analyzer of [15], this restriction does not exist. The signal under test is injected into the CRLH leaky-wave antenna. This signal is typically a pulse with a given spectrum. Due to the frequency-space mapping of the antenna, the different spectral components of the spectrum are radiated toward different angles in a continuous manner (possibly unlimitedly small $\Delta\theta \rightarrow \Delta\omega$). Probe detectors are forming a circular around the antenna receive each a different frequency with a different intensity, which after appropriate processing, produces the spectrum of the signal for each time interval. This time interval (detection rate) can be made arbitrarily small without affecting the spectrum resolution. In this manner, an unrestricted time-frequency resolution real-time transformer is realized.

Many variants and applications of such a system are possible. For instance, a spatial demultiplexer for sector-selective wireless communications and smart anticollision sensors is presented at this conference [17].

9 Conclusions

CRLH metamaterials have enabled many novel concepts and applications. This paper has presented some recent advances in the field of antennas and antenna arrays done by the author and his collaborators. These concepts, rather than incremental, are of fundamental nature and may therefore have a lasting impact. Several applications presented already constitute practical devices which may be soon commercialized.

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