Spatial Demultiplexer based on the Spectral Decomposition Property of the Metamaterial Leaky-Wave Antenna

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Abstract

A novel composite right/left-handed (CRLH) metamaterial leaky-wave spatial demultiplexer is introduced. This spatial demultiplexer exploits the frequency-space mapping property of the CRLH leaky-wave structure to spatially demultiplex the input signal to the antenna. Moreover, this system constitutes an antenna filter providing various advantages including adaptability, flexible system design, frequency scalability and broadband (UWB) operation. The system is demonstrated by both full-wave analysis and experiments.

1 Introduction

Multiplexers are ubiquitous components in modern wireless communication systems. This paper proposes an original multiplexer based on the spectral decomposition property of the CRLH metamaterial leaky-wave antenna.

2 Principle of Spatial Demultiplexing and Applications

A composite right/left-handed (CRLH) leaky-wave antenna is used for steering the radiated beam over the entire space by varying the input frequency [1]. Since the radiation angle depends on frequency, multiple input frequencies will subsequently produce multiple beams with different radiation angles, thereby performing a sectorial division of space based on frequency, as represented in Fig. 1(a). Thus, the antenna operates as a *spatial demultiplexer*. Such spatial demultiplexers may find several applications in various fields, such as wireless communication networks (i.e. WiFi), smart anti-collision systems, demultiplexing components illustrated in Fig. 1(b-d).

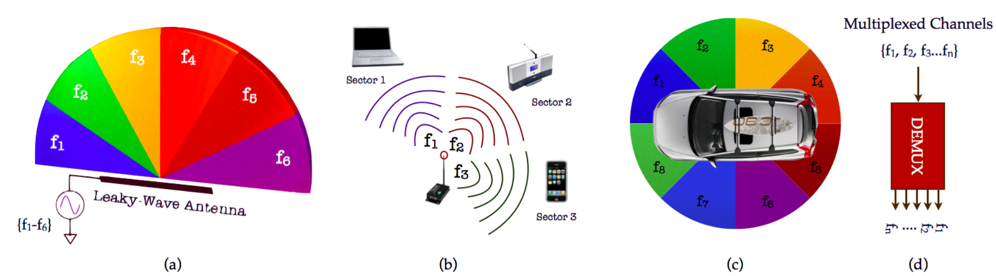

Figure 1: Spatial demultiplexing based on the spectral decomposition property of the CRLH leaky-wave antenna and applications. a) Spectral-to-spatial mapping concept. b) Sectorial demultiplexing for wireless communication. c) Smart anticollision system. d) Demultiplexer component (requiring packaging and miniaturization).

3 Spatial-to-Spectral Mapping

3.1 CRLH Leaky-wave Antenna

The typical dispersion curve of a CRLH structure is shown in Fig. 2(a). This curve always penetrates into the fast-wave region ($\omega \in [\omega_{BF}, \omega_{EF}]$), so that the structure, when open to free space, operates as a leaky-wave antenna within this frequency band. A CRLH leaky-wave antenna thus radiates from backfire ($\theta = -90°$) to endfire ($\theta = +90°$) through broadside ($\theta = 0°$) as frequency is scanned from ω_{BF} (where $\beta = -k_0$) to ω_{EF} (where $\beta = +k_0$) [1, 2]. While radiating, the CRLH leaky-wave antenna maps each frequency within its fast-wave region to a specific angle of space, as shown in Fig. 2(b) following the beam-scanning law

$$\theta_{\text{MB}}(\omega) = \sin^{-1}\left[\frac{\beta(\omega)}{k_0}\right], \quad \text{where} \quad \beta(\omega) = \frac{1}{p}\left(\frac{\omega}{\omega_R} - \frac{\omega_L}{\omega}\right) \quad \text{with} \quad \omega_R = \frac{1}{\sqrt{L_R C_R}}, \omega_L = \frac{1}{\sqrt{L_L C_L}}, \tag{1}$$

where θ_{MB} is the radiation angle of the main beam, $\beta(\omega)$ is the dispersion curve, L_R, C_R, L_L, C_L are the CRLH four circuital parameters with unit cell size p, and k_0 is the free space wavenumber. Following the beam-scanning law of Eq. (1), if the CRLH leaky-wave antenna is excited by a pulse, the various spectral components of the signal will radiate in different directions. Thus, the CRLH leaky-wave antenna performs a *spatial-to-spectral decomposition* of the signal [Fig. 2(b)]. The spatial resolution of the frequencies in this system is the scanning sensitivity of the antenna, $\zeta = \partial\theta_{\text{MB}}(\omega)/\partial\omega$. The relation defines how much two given frequencies are angularly separated in space, thus representing a figure of merit for the performance of the system.

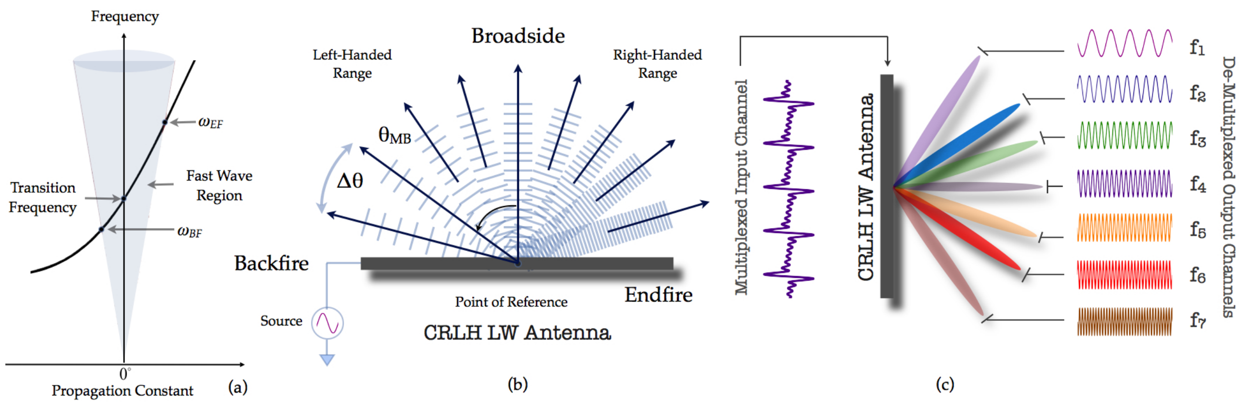

Figure 2: Spectral decomposition property of the CRLH leaky-wave antenna. a) Typical dispersion curve with the radiation (fast-wave) region. b) Illustration of the spatial-to-spectral mapping: Different frequencies are radiated in different directions following the beam scanning law of (a) [Eq. (1)] [2]. c) Proposed CRLH leaky-wave antenna spatial demultiplexer.

3.2 Proposed System

The CRLH leaky-wave antenna maps various spectral components of the signal into space based on its beam-scanning law. Therefore, a signal consisting of various frequencies i.e. a *multiplexed signal* experiences spectral decomposition after propagating through the leaky-wave antenna, resulting in the formation of various spatial *demultiplexed channels* in the form of distinct radiation beams corresponding to distinct frequencies. This phenomenon constitutes the basis of the proposed spatial demultiplexer.

Thus, a $1:N$ spatial demultiplexing system may be devised by exploiting the principle of spatial-to-spectral mapping of the CRLH leaky-wave antenna described above, as shown in Fig. 2(c). This demultiplexer utilizes the CRLH leaky-wave antenna as the main demultiplexing element. Detecting probes are circularly placed in the far-field of the antenna to measure the beams radiated in the different directions corresponding to the different frequencies according to the spacial-to-spectral mapping law of Eq. 1.

3.3 System Features

The proposed spatial demultiplexer provides various unique features and advantages. Firstly, compared to conventional demultiplexing systems used in wireless transmission [3], where N band-pass filters and N transmitting antennas are required for a $1:N$ demultiplexing system, the proposed system requires only one leaky-wave antenna without requiring any band-pass filters. This greatly simplifies the system architecture. The system is thus an integrated *antenna filter*.

Secondly, the proposed spatial demultiplexer is *adaptive*. The addition of new spectral components at the input automatically creates a new spatial channel without affecting the existing frequency channels. The system is thus adaptive to any change in the input signal's spectral contents. Therefore, an arbitrary number of channels may be formed (corresponding to various numbers of sectorial divisions) depending on the spatial resolution ζ of the leaky-wave antenna.

Thirdly, the proposed system provides a *variable spatial resolution* for the input spectral components. Depending on the location of the transition frequency of the antenna, the bandwidth of the left-handed ($-90^\circ < \theta_{MB} < 0^\circ$) and the right-handed ($0^\circ < \theta_{MB} < 90^\circ$) ranges of the leaky-wave antenna can be controlled. As a result, a desired spatial resolution (ζ) can be obtained by easily changing the design of the leaky-wave antenna.

Finally, the proposed spatial demultiplexer is a *frequency-scalable* and *broadband* system. The CRLH leaky-wave antenna may be designed at any arbitrary frequency to meet the requirements of specific applications [1]. Therefore, it is suitable for a wide-variety of signals, from microwaves potentially up to optical frequencies.

4 System Demonstration

4.1 Simulation Results

The spatial demultiplexing system setup shown in Fig 2(c) is simulated with the commercial package CST Microwave Studio (Finite difference approach) for a 16-cell configuration whose beam scanning law is shown in Fig. 3(a). The corresponding fast-wave region extends from 1.915 GHz to 3.415 GHz. Firstly, to theoretically visualize the radiation pattern of a CRLH leaky-wave antenna, the array factor approach [4] was extended for multiple frequency signals as:

$$AF(\theta) = \sum_{m=1}^{M}\sum_{n=1}^{N} I_n e^{j(n-1)k_{0,m}p\sin\theta + j\xi_n} \text{ where } \xi_n = -(n-1)k_{0,m}p\sin\theta_{MB} \text{ and } I_n = I_0 e^{-\alpha(n-1)p} \tag{2}$$

where M is the number of frequencies of the multiplexed signal, N is the number of unit cells and α is the leakage factor of the antenna. The array factor patterns are shown in Fig. 3(b) for two-tone and three-tone multiplexed signals, respectively, illustrating the bi- and tri-sectorial division of the half radiation space (two/three dedicated beams forming two/three corresponding channels). Next, CST Microwave Studio full-wave simulations were performed for

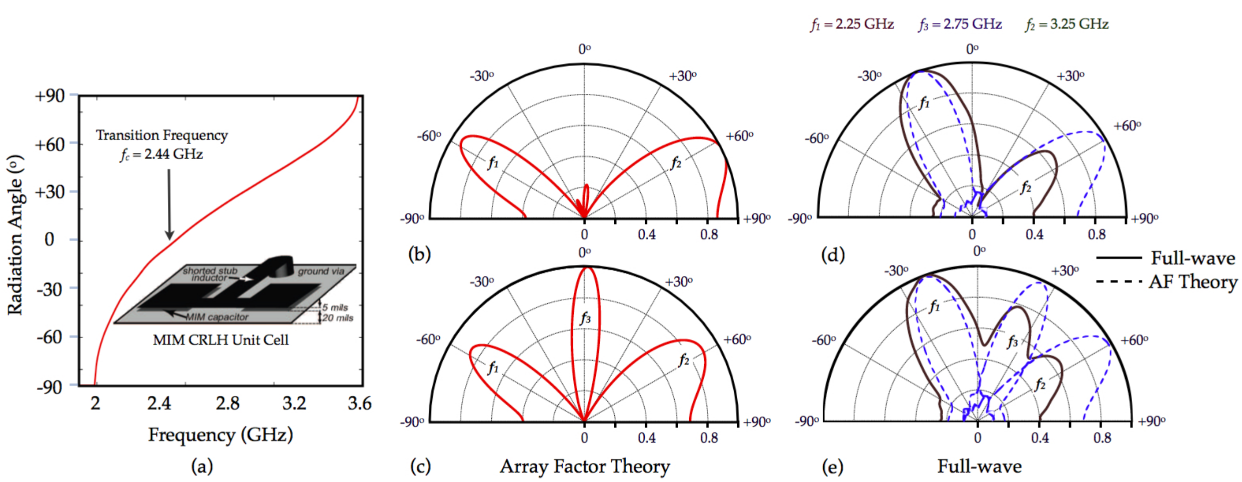

Figure 3: Theoretical results. a) Beam-scanning law of a 16-cell (design of [5]) CRLH structure obtained by full-wave simulations. b) Corresponding radiation pattern obtained by array factor theory [Eq. (2)] for a symmetric-pattern two-tone signal, c) for a symmetric-pattern three-tone signal, d) for an equidistant-frequency two-tone signal, including full-wave result, (e) and for an equidistant-frequency three-tone signal, including full-wave result.

two and three-tone signals. As may be seen in Fig. 3(d), the input two-tone multiplexed channel is spatially demultiplexed, forming distinct radiation beams at two different angles in space (corresponding to the two input frequencies). Close agreement with superimposed array factor results may be observed in terms of angle directions, while the array factor approach does not provide any gain information (the patterns are normalized to the maximum of the highest magnitude of the full-wave simulated beams). Moreover, if a new frequency is added at the input (i.e. three-tone multiplexed channel), a new beam is formed and a third channel is automatically created without affecting the previous two channels as seen in Fig. 3(e). This simple demonstration illustrates the adaptive properties of the proposed spatial demultiplexer described in Sec. 3.3.

4.2 Experimental Verification

For the experimental proof of concept, a 14-cell CRLH inter-digital leaky-wave antenna was designed with the following parameters: $C_L = 0.56$ pf, $C_R = 1.2$ pf, $L_L = 1.4$ nH, $L_R = 3$ nH and unit-cell size of $p = 8$ mm. The operation frequency band of the antenna is shown in Fig. 4(a) [3.1 GHz-4.5GHz]. Fig. 4(b) shows the response of the system to a three-tone multiplexed signal for three receiver locations (corresponding to backward, broadside, and forward radiation angles) directly connected to the spectrum analyzer. It can be clearly seen that the leaky-wave antenna demultiplexes the input three-tone signal into three distinct directions [following the beam scanning law of the antenna, as shown in Fig. 4(a)] where the individual frequencies can be obtained separately.

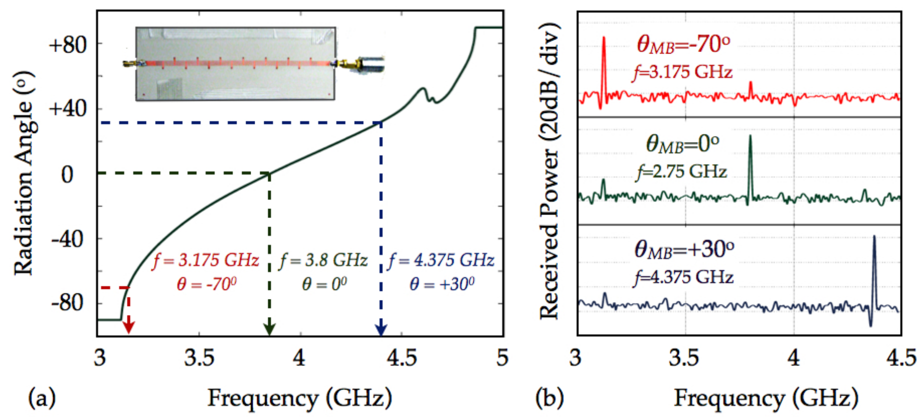

Figure 4: Experimental results for a typical inter-digital CRLH leaky-wave antenna. a) Beam-scanning law of the CRLH line. b) Received power at three indicated discrete receiver positions ($-70°, 0°$ and $+30°$) for a three-tone input signal. The inset in (a) shows the fabricated CRLH leaky-wave antenna.

5 Conclusions

A novel CRLH leaky-wave spatial demultiplexer has been introduced. This spatial demultiplexer exploits the frequency-to-space mapping property of the CRLH leaky-wave structure to separate the spectral components of a multiplexed input signal into distinct radiation patterns corresponding to spatially (spectrally) demultiplexed channel. Moreover, this system is an antenna filter providing various advantages including adaptability, flexible system design, frequency scalability and broadband (UWB) operation. This system was demonstrated by both full-wave analysis and experiments.

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