Metamaterials for RF Applications

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Abstract-**This paper presents progress in microwave applications of metamaterial structures, specifically the so-called left handed materials or double negative materials. Emphasis is placed on the Composite Right/Left Handed (CRLH) transmission line structures. Several microwave components with unique properties based on the engineered dispersion and mode characteristics are presented. A different approach based on the evanescent wave coupling is briefly mentioned.**

I. INTRODUCTION

Metamaterials are defined as artificial or man-made media that have unique properties not found in nature. There are several types of metamaterials including photonic crystals, artificial magnetic conductors and high impedance surfaces. In this paper, however, we deal only with the so-called the negative index materials or double negative materials. In these materials, the effective permittivity and permeability are simultaneously negative so that the phase velocity and group velocity are anti-parallel. This was demonstrated by using the split ring resonators and wire array [1]. The negative permittivity and permeability were realized near the resonances of the split ring and the wire array. The bandwidth is therefore typically small. Although such limitation may not pose problems at optical frequencies, their applications at microwave frequencies face practical limitations. An alternative approach based on the transmission line structures was introduced which is called the composite right/left handed (CRLH) structure [2,3].

II. CRLH Structure

CRLH structure is a ladder network with its unit cell consists of a series capacitance (C_L) and a shunt inductance (L_L) in addition to naturally existing series inductance (L_R) and shunt capacitance (C_R). The structure has a broad passband consisting of a left handed portion and a right handed portion. Since the LH operation does not depend on the resonance, the structure provides broadband characteristics. In addition, the dispersion characteristics can be engineered to accomplish desired characteristics not available in a naturally existing transmission line. At lower frequencies, LH nature is exhibited while RH characteristics are obtained at higher frequencies. The dispersion curve may be continuous or discontinuous when the propagation constant is zero, resulting in spectral gap.

III. Examples of Applications

A substantial list of microwave components and antennas with unique characteristics has been demonstrated. Included are the leaky wave antennas, super-compact antennas, directional couplers, filters, power dividers/combiners, harmonic filters for high efficiency amplifiers, dual frequency components. Throughout these applications, the concept of dispersion engineering is introduced by manipulating the unit cell structures of the constituent. Due to space limitation, only selected examples will be presented in this paper.

IV. Antennas

The dispersion characteristics of the CRLH have been used for development of a leaky wave antenna with unique capabilities. Unlike conventional leaky wave antenna, this CRLH leaky wave antenna can scan from the backfire to endfire direction either by frequency scanning [4] or electronic scanning [5]. In addition, electronic beam shaping was demonstrated whereby the antenna gain can be controlled [5]. More recently, this antenna was installed on a conformal surface with beam correction capability [6]. Also, when a leaky wave antenna is made of a symmetric CRLH line, the antenna can made to radiate in the left handed region only if the line is operated in a differential mode. This phenomenon was recently used for a balanced quasi-optical mixer with LO leakage suppression [7]. CRLH leaky wave antenna at millimeter wave frequency was reported for automotive application.

Extremely compact resonant antenna (similar to patch in structure) has been realized by operating a section of CRLH structure in the left handed

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region where the wavelength becomes extremely small. The resonant antenna at n = -1 order mode was found to reduce the size by 90% in comparison to the conventional patch antenna at the same frequency [9].

V. Passive Components

A coupled line directional coupler with up to 0dB coupling was realized with CRLH structure [10]. This structure takes advantage of the dispersion characteristics that provides stop band in the coupled mode operation. Several dual band components have been developed including branch line coupler and rat-race coupler [11]. This is made possible by engineering the dispersion characteristics so that the desired electrical length of the line is realized by arbitrary two frequencies. One of the first applications of the CRLH structure for active microwave circuit is the harmonic filter for a Class F amplifier [12]. Here, appropriate impedance is realized by a single stub of CRLH line to cover the second and third harmonics.

Since the dispersion curve of the CRLH crosses the propagation axis where the propagation constant is zero at non-zero frequency, we have realized an infinite wavelength structure [13]. On this structure, the phase and the amplitude are independent of the location. This provides an infinite wavelength resonator in which there is no standing wave and the resonant frequency is not dependent on the size of the resonator but on the constituent circuit parameters in the CRLH structure. An immediate application is a power divider/combiner for which the amplitude and phase at tapping points are constant regardless of their locations [14].

VI. Evanescent Mode Approach

At higher frequencies, conductor loss increases in the metal. If the metamaterials can be fabricated by dielectric materials, at least where the field concentration is strong, the insertion loss would be expected to decrease. A practical structure was developed under this approach. The structure is made of dielectric resonators placed between the parallel plate waveguides below cutoff. The former provides a negative permeability while the latter provides a negative permittivity background. The fundamental operation of the left handed nature was

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confirmed by a diffraction experiment [15]. An application of this structure to a leaky wave antenna was demonstrated [16].

VII. Conclusions

This paper summarized several microwave applications of the negative index materials based on the CRLH (Composite Right/Left Handed) transmission structure. Very practical application examples were demonstrated. Although most of the examples are based on the CRLH in one-dimensional configurations, the structure has been extended to two dimensional applications as well.

References

[1] R. A. Shelby, D. R. Smith and S. Schultz, "Experimental verification of a negative index of refraction," Science, vol.292, no.5513, pp.77-79, 2001.

[2] A. Lai, C. Caloz and T. Itoh, "Composite right/left-handed transmission line metamaterials," IEEE Microwave Magazine, vol.5, no.5, pp.34-50, September 2004.

[3] C. Caloz and T. Itoh, Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications, Wiley, New York, 2004.

[4] L. Liu, C. Caloz and T. Itoh, "Dominant mode (DM) leaky-wave antenna with backfire-to-endfire scanning capability," Electronics Lett., vol.38, no.23, pp.1414-1416, Nov. 2002.

[5] S. Lim, C. Caloz and T. Itoh, "Metamaterial-based electronically controlled transmission-line structure as a novel leaky-wave antenna with tunable radiation angle and beamwidth," IEEE Trans. Microwave Th. Tech, vol.52, no.12, pp.2678-2690, Dec. 2004.

[6] M. R. Hashemi and T. Itoh, "Dispersion engineered metamaterial-based transmission line for conformal surface application," 2008 IEEE IMS, June 2008, Atlanta, GA.

[7] Y. Kim, E. Kim, A. Lai, D. Goshi and T. Itoh, "Integrated mixer based on composite right/left-handed leaky-wave antenna," 2008 IEEE IMS, June 2008, Atlanta, GA.

[8] K. Sato, et al, "Metamaterials for automotive applications," IEEE AP-S, 1144-1147, June2007.

[9] C-J Lee, K.M.K.H. Leong and T. Itoh, "Composite right/left-handed transmission line based on compact resonant antennas for RF module integration," *IEEE Trans. Antennas and Propagation,* vol.54, no.8, pp 2283-2291, August 2006.

[10] C. Caloz, A. Sanada, and T. Itoh, "A novel composite right/left-handed coupled line directional coupler with arbitrary coupling level and broad bandwidth", *IEEE Trans. Microwave Theory Tech.,* vol. 52, no. 3, pp. 980-992, March 2004.

[11] I. Lin, C. Caloz and T. Itoh, "A branch-line coupler with two arbitrary operating frequencies using left-handed transmission line, 2003 IEEE IMS, pp.325-327, June 2003, Philadelphia, PA.

[12] A. Dupuy, K. M. K. H. Leong and T. Itoh, "Class-F power amplifier using a multi-frequency composite right/left-handed transmission line harmonic tuner," 2005 IEEE MTT-S International Microwave Symposium, Long Beach, CA June 2005.

[13] A. Lai, K. M.K.H. Leong and T. Itoh, "Novel series divider for antenna arrays with arbitrary element spacing based on a composite right/left-handed transmission line," 35th European Microwave Conference, Paris, France, October 3 – 7, 2005, pp.145-148.

[14] K. M. K. H. Leong, A. Lai and T. Itoh, "Application of a series coupler based on infinite wavelength phenomenon," 2005 Asia-Pacific Microwave Conference Proceedings, Suzhou, China, December 4 – 7, 2005, pp.504 – 507. K. M. K. H. Leong, A. Lai and T. Itoh).

[15] T. Ueda, A. Lai and T. Itoh, "Demonstration of negative refractive index in a cutoff parallel-plate waveguide loaded with 2-D square lattice of dielectric resonators," *IEEE Trans. Microwave Theory and Techniques,* vol.55, no.6, pp.1280-1287, June 2007.

[16] N. Michishita, T. Ueda and T. Itoh, "Evanescent-mode dielectric metamaterial structure excited by NRD guide and its application to leaky wave antenna," 2007 IEEEE Antennas and Propagation Society International Symposium, Honolulu, HI, June 11 -15, 2007, pp.2345-2348.

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