Recent Progress in Applications of CRLH Structure for Active Microwave Circuits

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Abstract

Over the last decade, the composite right/left-handed (CRLH) transmission line structures have received great interest in the microwave community due to their unique physical characteristics that have been exploited for a number of applications, mostly for antennas and passive components. CRLH structures can also be applied to active circuits. This paper reviews some of the examples of active circuit applications of the CRLH structures.

1. Introduction

Applications of the composite right/left-handed (CRLH) metamaterials improve the circuit properties or add new features. The equivalent circuit of the CRLH structure consists of a series inductance L_R and a series capacitance C_L as well as a shunt capacitance C_R and a shunt inductance L_L, leading to the non-linear dispersion relation. The artificial CRLH structures are able to support backward wave propagation, exhibit a uniform phase across the entire structure at a non-zero frequency, and furthermore, their dispersion relations can be easily tailored via the proper selection of the equivalent circuit parameters. In this paper, several examples of the active microwave circuits [1-7] will be revisited to demonstrate the advantageous capability of the CRLH structures.

2. Class-F Power Amplifier

Power amplifiers play an important role in microwave systems. The class-F amplifiers are a format to achieve high power-added efficiency. To this end, in the class-F amplifier the output impedances at harmonic frequencies need to be designed so that a short-circuit impedance and open-circuit impedance can be used to terminate the even-order and odd-order harmonics, respectively. The CRLH transmission lines can be used as the harmonic tuner to decrease the required number of open-ended stubs for individual harmonics [1]. Furthermore, the CRLH-based antenna is well suited to be a load under the consideration [2]. At the 2^{nd} and 3^{rd} harmonics, the antenna resonance behavior can be suppressed by engineering its dispersion curve and the ideal terminations were realized by simply

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adding a microstrip line. Fig. 1 shows the fabricated power amplifier integrated with the CRLH antenna which provides required harmonic termination while the circuit complexity and footprint size are reduced with a measured PAE of 58%.

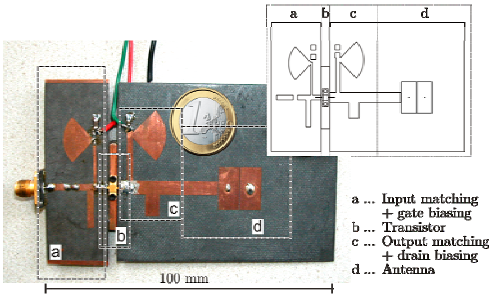

Fig. 1. The fabricated power amplifier with the metamaterial antenna. Data from [2] © [2009] IEEE.

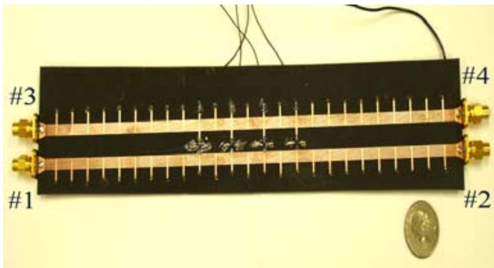

Fig. 2. The re-radiating CRLH leaky wave antenna using the distributed amplifiers. Data from [4] © [2009] IEEE.

3. Distributed Amplifier

Recently, distributed amplifiers operating in the radiation (fast wave) region using the CRLH transmission lines have demonstrated continuous frequency-dependent beam scanning capability from backward to forward directions [3]. Moreover, the employment of the CRLH transmission lines on both drain and gate sides of the FETs realized the re-radiating leaky wave antenna system shown in Fig. 2 [4]. When excited by the plane wave, the gate-side CRLH transmission line serves as the receiving antenna for the incoming signal, which is subsequently amplified through the FETs and will be re-radiated from the drain-side CRLH transmission line. The re-radiated wave is directed at the same angle but opposite direction to the receiving wave.

4. Dual-Band CMOS mm-Wave Oscillator

CRLH metamaterials have engineerable dispersion properties that permit the resonances at non-harmonic frequencies of interest. Fig. 3 illustrates such an example of the dual-band CMOS oscillator based on the left-handed resonators [5]. In this case, the loop resonator composed of two CRLH unit cells is able to resonate at f_L=21.3 GHz and f_H=55.3 GHz for resonance order n=-1 and n=0, respectively. In order to satisfy the resonance conditions, each unit cell is responsible for 180^o and 0^o phase shifts, respectively, at the designated frequencies that can be read from the dispersion diagram of the unit cell. Furthermore, the band selection switches in this implementation are not located on the critical signal paths, reducing the size of switches and improving the resonator quality factor Q. The proposed dual-band CMOS oscillator is only 150 μm × 60 μm with the total power consumption 14 mW while exhibiting an increased frequency switching range, 34 GHz.

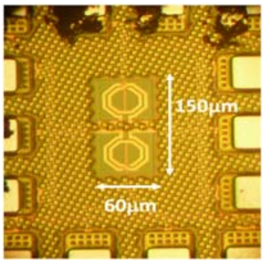

Fig. 3. Chip photograph of the proposed dual-band oscillator. Data from [5] © [2009] IEEE.

Fig. 4. Photograph of integrated balanced mixer with antenna. Data from [6] © [2008] IEEE.

5. Mixer Application

The CRLH antenna [6] not only enables continuous beam scanning from backfire to endfire direction but also provides the inherent RF-LO or LO-RF isolation when working in the integrated balanced mixer as shown in Fig. 4. Under the differential-mode excitation, the antenna behaves as the balanced CRLH antenna with continuous transition from the left-handed to right-handed regions while the antenna is cutoff below the transition frequency when excited in the common mode. Therefore, below the transition frequency, the metamaterial antenna is able to support left-handed differential-mode radiation with common-mode suppression. The LO leakage appears as a common-mode excitation at the RF port and will be suppressed from radiation. On the other hand, the differential RF signal from the antenna will add out of phase. The RF-LO isolation was greater than 20 dB. The fabricated antenna has a maximum gain 5.8 dBi at broadside and the common-mode radiation is suppressed on the order of 20 dB to 40 dB. The unique implementation eliminates the need for additional RF and LO filters, reducing system complexity and saving the space.

6. Quantum Cascade Laser

The active CRLH metamaterial concept can be extended into the terahertz frequency range. THz quantum-cascade lasers fabricated with double-metal waveguide can readily be adapted into a planar CRLH by the addition of lumped element capacitance and inductance into the series and shunt branches of the transmission line as shown in Fig. 5. In this scheme, GaAs/AlGaAs multiple quantum wells comprise the dielectric of the transmission line – when properly biased they provide amplification via stimulated emission of photons due to intersubband THz radiative transitions. Active waveguides and laser resonators based on this artificial configuration will exhibit novel propagation characteristics. One example is the so-called zero-index laser [7] that is proposed to oscillate in a mode with a uniform field distribution in the longitudinal direction. Such a laser would suppress the phenomenon of spatial hole burning associated with a conventional standing wave mode, in which a spatially non-uniform saturation of the gain medium can lead to unwanted multimode oscillation. In addition, this zero-index mode is strongly coupled to radiating modes, exhibiting a highly directional beam in the broadside direction. In a nutshell, new functionality in lasers can be developed by exploiting the phase-engineerable characteristics of metamaterial waveguides such as the flexible control of spectral and radiation properties, beam shaping and steering, wavelength tuning, and polarization control.

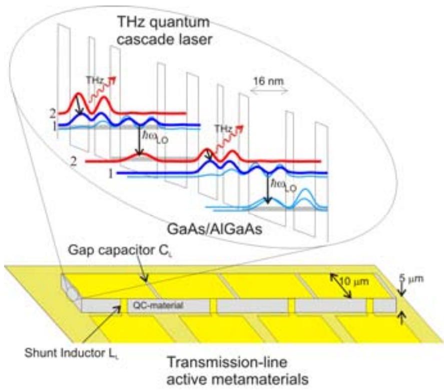

Fig. 5. Illustration of the THz active CRLH metamaterial fabricated in double-metal waveguide where THz quantum-cascade gain material comprises the dielectric. Data from [7] © [2010] IEEE.

7. Conclusion

In this paper, the advantages of employing CRLH structures for active circuits are presented. The unique dispersion characteristics of the CRLH structures provide more design flexibility to carry out novel applications or improve the overall performance.

8. References

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