Loss compensation in metamaterials through embedding of negative impedance active transistor circuits

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Abstract

This paper proposes an active transistor based loss compensation approach in metamaterials. As the CMOS and III-V technology continues its aggressive scaling to nanometer feature dimensions, with transit frequency (f_T) reaching terahertz values, active transistor based circuits could be employed in each unit cell of metamaterial structure for a variety of functions including loss compensation for ohmic and dielectric loss. The approach is feasible for metamaterials from microwave up to terahertz frequency range and is only limited by the f_T of the technology. In this paper, we show results on a planar metamaterial composed of electrically coupled LC resonator (ELC) with resonance frequency at 2.62 GHz. Utilizing a 0.25 µm CMOS process, a negative impedance circuit is implemented to compensate for the ohmic and dielectric losses, improving the strength of resonance and increasing the quality factor Q from 11.21 to 2633.

1. Introduction

Metamaterials derive their exotic electromagnetic (EM) property from their artificially engineered structure instead of properties of atoms and molecules [1]. Metamaterials are made of conventional materials such as metal and dielectric, which incur metallic loss and dielectric loss inevitably [1]. These losses weaken the resonance of metamaterials and limit their performance in emerging applications such as cloaking, lenses, absorber, reflector, etc. This issue is exacerbated in the 3D metamaterial fabricated by layer-by-layer technique because the EM wave has to propagate through multiple layers of metallic mesh and lossy dielectric [2]. One popular method of loss compensation is introducing gain medium into metamaterials [2][3].

In this paper, we present an alternate approach for loss compensation employing active transistor based circuits within each metamaterial unit cell. Aggressive scaling of the semiconductor technology to nanometer dimensions with f_T frequencies reaching terahertz allows for such a prospect. This method can be used from microwave up to terahertz frequencies limited only by the transit frequency (f_T) of the process employed to realize the circuits. Combined with current approaches based on optical gain medium at infrared and visible frequencies, loss compensation in metamaterials can be addressed over all useful frequency range.

2. System architecture and implementation

We use the electrically coupled LC resonator (ELC) as a single layer metamaterial for demonstration of the proposed active loss compensation approach [4]. To the first order, the ELC resonator can be viewed as a resonant tank LC circuit with undesirable embedded ohmic and dielectric losses modelled by the resistor R_{ELC}. The strength of the resonance and negative permittivity (or permeability) of the effective medium is affected by R_{ELC}. For loss compensation, we propose an active circuit structure that provides negative impedance connected in parallel with ELC resonator. Since the gap of the ELC resonator constitutes the capacitive element, one could utilize *via* holes to connect the two sides of the ELC resonator's capacitive gap to the integrated active differential negative resistance circuit.

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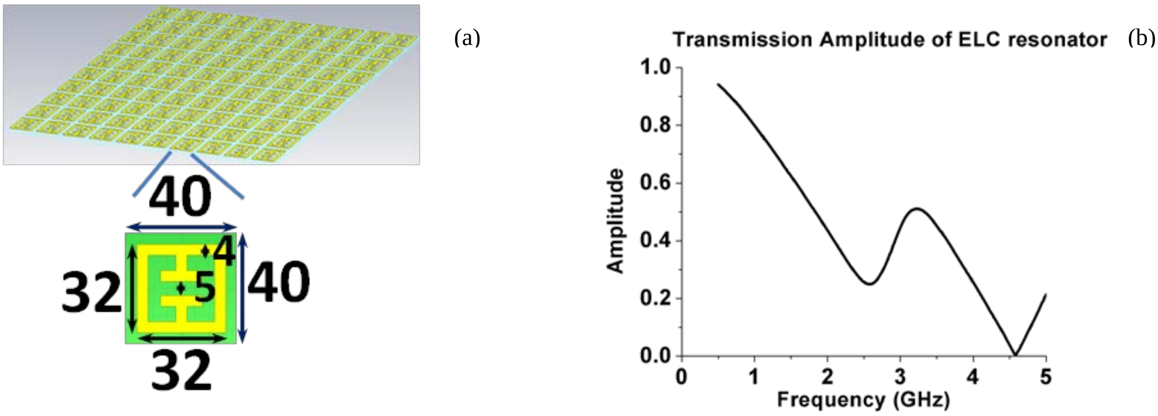

Fig. 1: (a) Metamaterial composed of an array of ELC resonators and the dimension of one metamaterial unit cell, unit in mm. Each plate of the gap is 15mm wide. (b) FDTD simulation of amplitude for through transmission of ELC resonator without the active differential negative resistance circuit

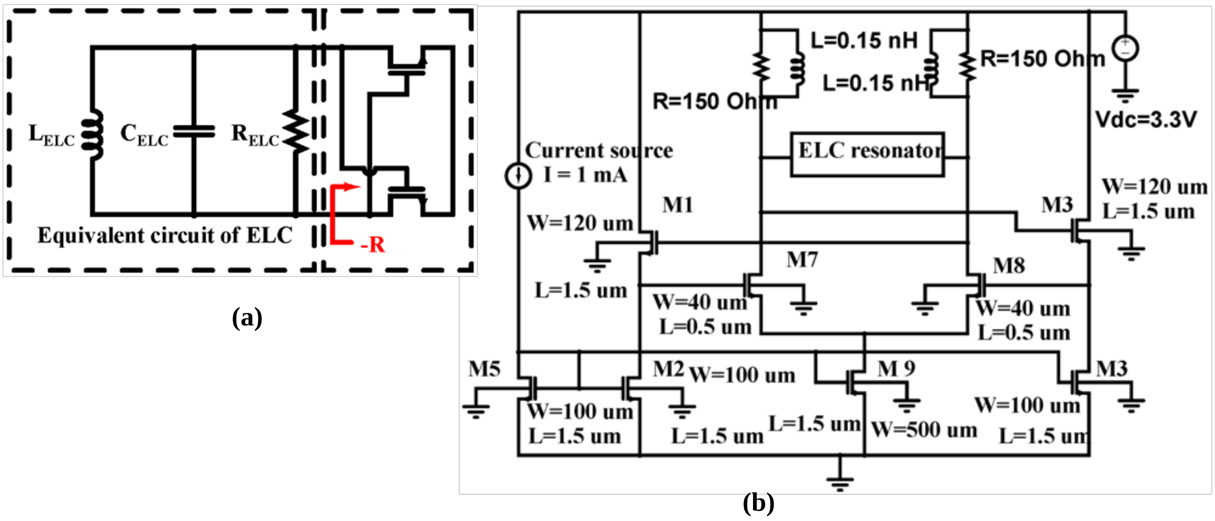

Fig. 2: (a) Representative circuit model: The ELC resonator is modeled by an RLC parallel circuit, in which the R_{ELC} stands for the entire loss of the ELC resonator. -R models the active differential negative resistance circuit seen by the ELC resonator as means for loss compensation (b) Implementation of negative impedance -R: integrated active differential negative resistance circuit using CMOS 0.25 µm process. M7 and M8 are differential pair cross-coupled by M1 and M3. W is width of transistor and L is length.

The dimension of the ELC resonator is shown in Fig. 1(a). The metallic structures are made of 0.03 mm thick gold layer. The dielectric substrate is a 5 mm thick Rogers RO4003C layer, whose dielectric constant and loss tangent are 3.38 and 0.0021, respectively. The ELC resonator was simulated with commercially available software–Microwave Studio by CST. The simulation result of through transmission amplitude is shown in Fig. 1 (b). The resonant frequency is 2.62 GHz and the transmission amplitude at this frequency is undesirably high and equals to 0.253. The equivalent circuit model of our proposed system is shown in Fig. 2 (a). The active differential negative resistance circuit, which is marked as –R in Fig. 2(a), can be regarded as a 1-port network implemented as shown in Fig. 2 (b). Its impedance is a negative resistance at 2.62 GHz with absolute value closer to but less than the total loss of ELC resonator R_{ELC}. The circuit in Fig. 2 (b) has been simulated in Advanced Design System (ADS) by Agilent. The circuit consists of a cross coupled transistor pair biased in saturation. In Fig. 2 (b), M7 and M8 are differential pair cross coupled by M1 and M3. This circuit is implemented in 0.25 µm CMOS technology. The negative resistance value of this circuit seen by the ELC resonator is tunable by changing the bias current. By running an EM-circuit co-simulation in CST using the S parameter file of negative resistance circuit acquired in ADS together with the 3D EM simulation result of ELC resonator, we obtain the new transmission amplitude for the ELC resonator as shown in Fig. 3.

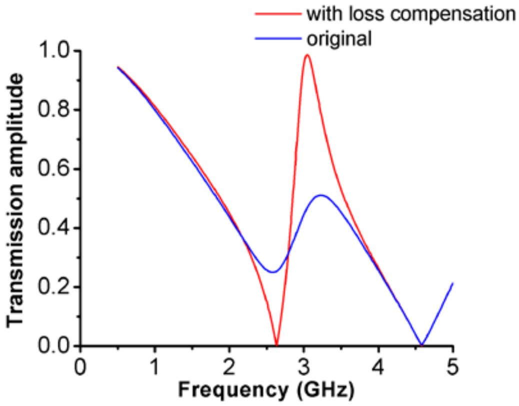

Fig. 3: Amplitude of through transmission of ELC resonator with embedded active transistor based loss compensation circuit (red curve) and that of original ELC resonator without loss compensation circuit (blue curve)

With loss compensation, the quality factor Q is increased from 11.21 to 2633 and the resonance strength is improved. The entire differential negative resistance circuit occupies negligible area due to small transistor sizes compared to the metamaterial unit cell and it could physically shadow the metal traces in the back plane, such that it will not interfere with the incident radiation. There is still concern about routing power and ground lines. In future, one can envision approaches to embed electrochemical battery sources in each metamaterial unit cells if feasible. Since continued transistor scaling also comes with reduced power dissipation, the overall power consumption for loss compensation may not be very prohibitive for practical implementation. Also it is expected that the resonance frequency may shift due to the parasitic LC components of the circuit, but this issue can be resolved during design phase in ELC resonator design or through additional varactors in the negative resistance circuit for tuning the resonance frequency of ELC resonator.

3. Conclusion

This paper provides a method of loss compensation in metamaterials through embedding of active transistor based negative resistance circuit into each metamaterial unit cell. The proposed loss compensation can be used to make ideal reflectors, absorbers, cloaks, luneberg lens etc. with applications in radar imaging, communications and security screening in the millimeter-wave/terahertz frequencies.

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