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Broadband Superluminal Transmission Line with Non-Foster Negative Capacitor

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***Abstract*—We present a superluminal transmission line (STL) loaded with non-Foster negative capacitors. The loaded negative capacitors decrease the effective capacitance and the effective permittivity of the dielectric substrate of the TL. Since wave propagation velocity depends on effective capacitance of the line, it can be higher than the light speed c_0 in vacuum. The superluminal line is simulated and the results are compared to an experimental investigation of the superluminal phase and group velocities that are extracted from measured *S*-parameters.**

***Index Terms*—superluminal, propagation, transmission line, group and phase velocity measurements.**

I. INTRODUCTION

Superluminal wave propagation appears when electromagnetic waves propagate faster than speed of light in vacuum, c_0. This phenomenon was first associated to anomalous dispersion [1]. Metamaterials such as composite right/left-handed (CRLH) structures also support superluminal propagation [2]. However, both approaches are dispersive due to intrinsic resonance, which reduces the operation bandwidth.

Non-Foster circuits allow broadband superluminal propagation. In [3], Hrabar *et al.* designed a unit cell consisting of a negative capacitor connected to a short transmission line for cloaking applications. A multi-section superluminal structure where negative capacitors were realized with operational amplifier circuits was experimentally tested and presented over [2 MHz - 40 MHz] frequency band [4, 5]. In [5], an operational amplifier circuit was used to realize the negative capacitor with the disadvantage of a relatively low bandwidth. In contrast, high frequency transistor-based circuits can work at higher frequencies. Therefore, transistor-based non-Foster circuits earn more interests in realizing negative capacitors for broadband superluminal applications.

In this paper, we report a superluminal transmission line (STL) based on non-Foster negative capacitor, realized with high frequency transistors. The structure is simulated, fabricated and tested. The retrieved effective material parameters from the measured *S*-parameters show a superluminal propagation with a phase velocity reaching $1.2c_0$ and a group velocity of $2.6c_0$ over more than 200 MHz bandwidth with a fair agreement with simulations.

II. SIMULATIONS AND FABRICATION

A. Simulations

To demonstrate and simulate the superluminal propagation, we use a basic transmission line. The proposed loaded STL is a microstrip airline periodically loaded with negative capacitors C_n, as illustrated in Fig. 1. The intrinsic capacitance per unit length of the unloaded TL C_{in} can be easily derived from [6]. C_n must have an absolute capacitance value smaller than C_{in}. In this case, the effective capacitance of the loaded transmission line is reduced while keeping the new effective line capacitance C_e positive. The intrinsic inductance of the line does not change. Consequently, the phase and group velocities of the line that depend on the capacitance and the inductance increase. To achieve superluminal propagation, the effective capacitance C_e must be smaller than the intrinsic value C_{in}, but with a positive value.

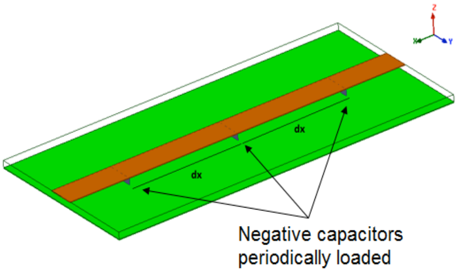

Fig. 1. Transmission line loaded with negative capacitor based non-Foster circuits.

In our case, negative capacitors are placed periodically every 102 mm on a microstrip line of length 306 mm and width 23.5 mm, and the substrate is considered to be air ($\varepsilon_r = 1$). Without negative capacitance, the STL has an intrinsic capacitance of 67 pF/m, *i.e.* 6.8 pF for a length of 102 mm. Thus, to create a superluminal propagation effect the range of capacitance C_n values is limited from -6.8 pF to 0 pF.

B. Fabrication

The STL is fabricated as depicted in Fig. 2. Three circuits of similar negative capacitor design are integrated every 102 mm in the transmission line.

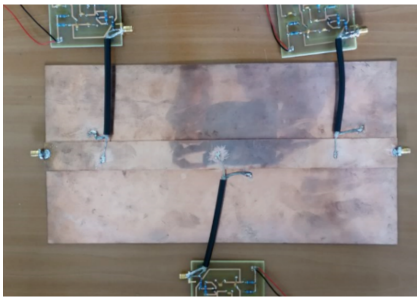

Fig.2. Fabricated superluminal transmission line. 3 Non Foster negative capacitances are solded every 102mm.

To realize the negative capacitor, we design a negative capacitance using a negative impedance converter based on Linvill topology, terminated by a capacitor [7]. The schematic circuit is shown in Fig. 3. With ideal components, and perfect transistors, we obtain:

$$C_n = -\frac{R_1}{R_2} C_L \tag{1}$$

C_n is a shunt element between the line and the ground plane. The circuit uses the high frequency BFR92P BJTs with inductor-resistor biasing. In measurements, C_L is modified while keeping fixed the inversion coefficient $\frac{R_1}{R_2}$ to investigate the tunability of the negative capacitor circuit.

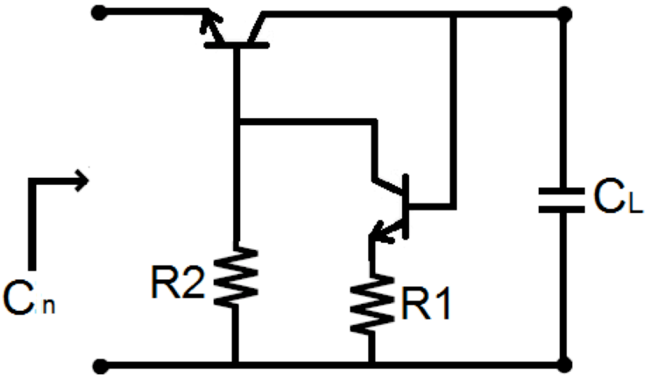

Fig.3. Schematic topology of the transistor-based NIC circuit used to realize negative capacitance.

The calculated and measured tunable negative capacitance values C_n are plotted in Fig. 4. Values of the negative capacitor were de-embedded from the measurements of *S*-parameters. Measurements agree quite well with simulations performed using ADS software. In both cases the value of the negative capacitance depends on the frequency. This is due to the variation of the gain of the transistors with the frequency. Moreover, we can note that if the measured capacitances change with frequency, they remain negative over a wide frequency band spanning from 50 MHz to 400 MHz.

C. *Superluminal propagation*

We insert a negative capacitor C_n = -2.85pF each 102mm in the transmission line. The negative capacitor is obtained from a load capacitor C_L = 6pF at a 125MHz. This capacitor is inserted periodically into a 3-unit-cells transmission line as illustrated in Fig. 2. *S*-parameters of the line are measured using a network analyzer and phase and group velocities are calculated with:

$$v_p = \frac{\omega}{\beta} = \frac{\omega}{\Im(\gamma)} \tag{2}$$

and

$$v_g = \frac{\partial\omega}{\partial\beta} = \frac{l}{\tau} \tag{3}$$

where γ, l and τ are respectively the propagation constant, the length and the time delay of the line.

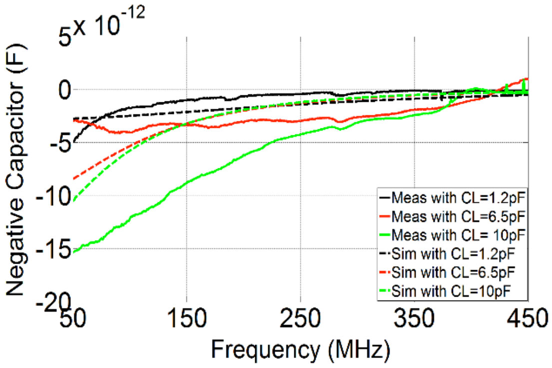

Fig.4. Comparison between calculated negative capacitance and measured ones. As the gain of the transistors depends on the frequency, the negative capacitance varies also with the frequency.

The measured phase and group velocities presented in Fig. 5 illustrate a superluminal propagation with a phase velocity greater than c_0 from 75 MHz to 145 MHz and a group velocity greater than c_0 over the frequency bandwidth [50 MHz – 220 MHz]. The two velocities reach their maximum at about 95 MHz, 1.2c_0 for the phase velocity and 2.6c_0 for the group velocity.

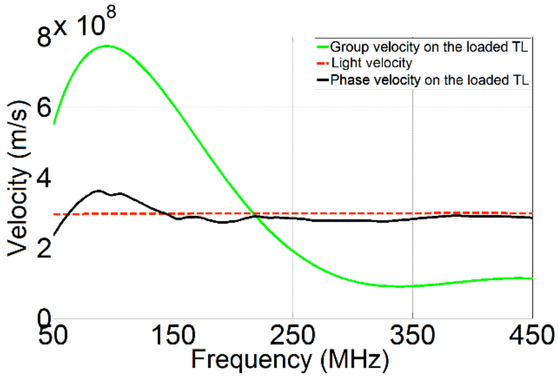

Fig.5. Extracted phase velocity and group velocity from the loaded negative capacitor TL compared to light velocity in vacuum

The line shape of the two velocities can be explained by the variation of negative capacitance with frequency. As frequency decreases, negative capacitance increases and effective capacitance C_e of the line decreases. Therefore, the effective permittivity of the substrate decreases and the two velocities reach their maxima when capacitance C_e is minimum.

III. CONCLUSION

In summary, this work reports a 3-unit-cell negative capacitor-loaded superluminal transmission line. Measurements performed on the TL present a superluminal propagation medium with a maximum of $1.2c_0$ phase velocity and $2.6c_0$ group velocity simultaneously over a frequency bandwidth of 70 MHz with a maximum around 95 MHz, corresponding to a bandwidth of 70%. This superluminal transmission line demonstrates the efficiency of this approach and the possibility to engineer broadband superluminal propagation using non-Foster devices.

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