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***Abstract*— A new approach for tuning the resonant frequency of metamaterial transmission lines (TLs) by using electrowetting on dielectric (EWOD) is presented. Coplanar Waveguide (CPW) metamaterial TLs were designed and used as digital microfluidic platforms, where tunable resonance frequency was demonstrated for RF/microwave applications. A repeatable tuning mechanism was realized by exploiting the interface deformation of a liquid metal (mercury) droplet by an applied voltage. The maximum tuning range achieved is around 400 MHZ (from 3.51 GHz to 3.92 GHz) with a DC actuation voltage of 110 V.**

***Index Terms*— Digital microfluidics, Electrowetting on Dielectric, liquid metal, metamaterial, zeroth-order-resonator**

I. Introduction

The composite right/left-handed (CRLH) transmission line (TL) is composed of a periodically repeating unit cell, which consists of a series capacitance and a shunt inductance and also a series inductance and a shunt capacitance [1]. Typical TL structures implemented for RF/microwave applications such as coplanar waveguide (CPW) present certain parasitic series inductance and shunt capacitance, which can provide the right handed (RH) behavior at higher frequencies [1]. Also, by adding the series capacitance and the shunt inductance to TLs, the left-handed (LH) behavior can be provided artificially. Switchable and tunable metamaterials have recently gained significant research interest, as they can be integrated with various RF/microwave devices such as resonators, switches, filters and antennas to enhance their performances [2]. In creating tunable metamaterials based on structural changes, different materials such as liquid crystals, ferrites, graphene, and superconductors whose properties can be manipulated by using different stimulation methods including light, temperature, strain, magnetic field, and bias voltage have been proposed in the literature [3]. Also, liquid metal filled elastomeric microfluidic channels were proposed as a switchable metamaterial platform [4].

In this paper, we propose a novel open structure, where a controllable liquid metal droplet is manipulated by using *electrowetting on dielectric (EWOD*), which is a well-known voltage-induced manipulation technique of small droplets placed on a dielectric surface. This open structure is then integrated with a CPW TL to realize tunability in its resonance frequency. This integrated device has been designed, fabricated and characterized. The results obtained from simulations and measurements agree well demonstrating the tunability range of ~400 MHz from 3.51GHz to 3.92GHz.

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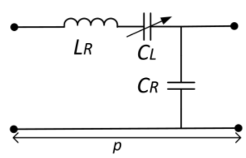
II. Design

A. Capacitor Loaded Coplanar Waveguides

The CRLH TL has a particular aspect of supporting *an infinite-wavelength wave* at a finite and nonzero frequency defined as *a zeroth-order resonance*, which is solely dependent upon the series and shunt, inductances and capacitances of the unit cell [5]. Fig. 1 shows the equivalent circuit of a capacitor loaded TL unit cell, where the shunt inductance is removed eliminating the shunt resonance. This circuit supports the zeroth-order and positive resonances that can be tuned by adjusting the capacitor value (C_L) as shown in Fig. 1.



p: unit cell length
L_R: right handed inductance
C_R: right handed capacitance
C_L: left handed tunable capacitance

Fig.1. Equivalent circuit of a capacitor loaded CPW.

In this work, a CPW was chosen as the host TL due to its uniplanar design and since it enables easy realization of the series and shunt connections of inductors and capacitors. Also, the coplanar electrode design makes it particularly appropriate platform for an electrowetting actuation. The proposed CPW metamaterial TL can be modeled with the equivalent circuit shown in Fig. 1. The zeroth-order resonant frequency occurs, when the phase constant of Bloch wave along the structure equals zero, $\beta = 0$. The phase constant can be expressed in terms of the scattering parameters of the unit cell as given in equation (1). The proposed 2-port unit cell was also simulated by a full-wave analysis and measured in determining its scattering (S-) parameters. The propagation constant (β) is then extracted from the measured scattering-parameters to determine the resonant frequencies [6].

$$\beta p = \cos^{-1}\left(\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{2S_{21}}\right) \tag{1}$$

B. Tunable Zeroth Order Resonance based on Electrowetting on Dielectric (EWOD)

The zeroth order resonant frequency of the proposed CPW metamaterial TL is L_R/C_L as is seen from the equivalent circuit shown in Fig.1. Therefore, one can adjust the resonant frequency by changing C_L through EWOD technique. A Capacitor loaded CPW TL was used as EWOD stage by simply adding a dielectric layer on the top of the TL metal layer. Fig. 2 shows the unit cell geometry along with the dimensions of critical design parameters. This structure has an interdigitated finger like pattern, which creates the left handed capacitance, C_L and also serves as the actuation electrodes for EWOD. The interdigitated section is covered by a Parylene/Teflon dielectric layer, on top of which a liquid metal (mercury) droplet is placed. Fig. 3 depicts the cross section (A-A') view of the structure and also shows EWOD phenomenon taking place. By using the EWOD phenomenon, this droplet is spread by DC actuation voltage applied between input and output ports of the structure as shown in Fig. 2 [7]-[9]. This movement of the liquid metal droplet increases its base contact area, which in turn changes (increases) the effective left handed capacitance, C_L. Thus the resonant frequency is changed (decreased) resulting in the desired tuning. The approached followed in our design allows building low cost and low complexity tunable RF/microwave components with a simple bias network.

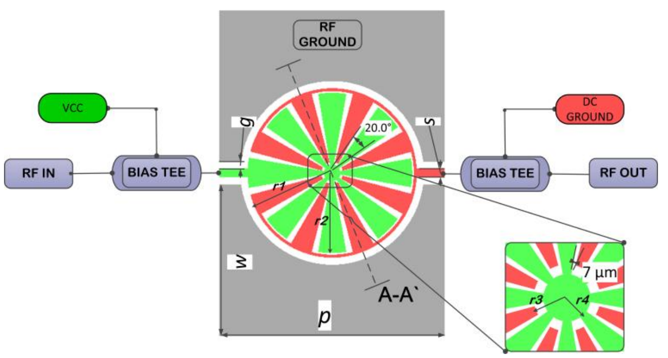


Fig. 2. The layout and test schematic of the tunable CPW metamaterial TL. *p =2, w =1.395, s=g = 0.07, r1=0.75, r2=0.7, r3=0.1, r4=0.05 (units in mm).*

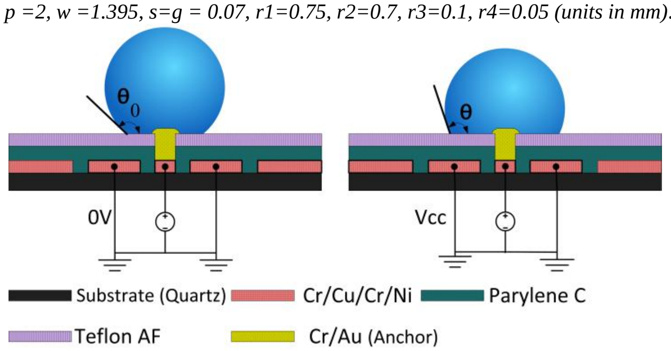


Fig.3. Cross section (A-A') view of the structure and EWOD principle.

III. FABRICATION

Fig. 3 is used to describe the microfabrication processes, where 4-inch Quartz wafer (ε_r = 3.9) with a thickness of 0.525 mm is used as a substrate material. For the metal layers of the CPW TL, a 20 nm Chromium (Cr), 200 nm Copper (Cu), 20nm Cr and 30nm Nickel (Ni) metals were electron-beam (e-beam) evaporated successively and patterned by lift-off technique. This multilayer metal also serves for the EWOD actuation electrodes. Ni was used to avoid reaction with mercury droplet, which is known to react with most of the metal materials. On top of the multilayer metal, a 1µm thick dielectric layer of Parylene C was deposited at room temperature by vapor deposition, which was then patterned by reactive-ion-etch (RIE) using Oxygen (O_2) plasma. In addition to Parylene C, another dielectric layer of hydrophobic Teflon AF with a thickness of ~80 nm was spun coated to minimize contact angle hysteresis improving the robust repeatable operation. After coating, Teflon AF layer was baked at 200 ◦C for 2 hours. Finally, this hydrophobic AF film was patterned by O_2 plasma to define an opening of a circular-shape at the center, which was, subsequently, filled by an additional 20nm/30 nm Cr/Au layer deposited by E-beam evaporation and patterned by lift-off. This circular pattern with a 100 µm diameter at the center acts as an anchor providing a mechanical stability for the manually dispensed mercury droplet of 1mm diameter [10]. In dispensing the droplets Gilson Microman® micropipette was used.

The photographs of a fabricated device are shown in Fig 4. The manually dispensed mercury droplet has a volume of 1µL with a diameter of approximately 1mm. After the applied voltage the mercury droplet spreads, which results in an increase of ~150 µm in the radius of the contact base area. The measured initial contact angle was ~140^o for the dielectric layer of Parylene C with a thin layer of hydrophobic Teflon AF on top. Some other dielectrics such as SU-8 and SiO_2 were also used and tested, where Parylene C provided better frequency tuning with a robust repeatable operation.

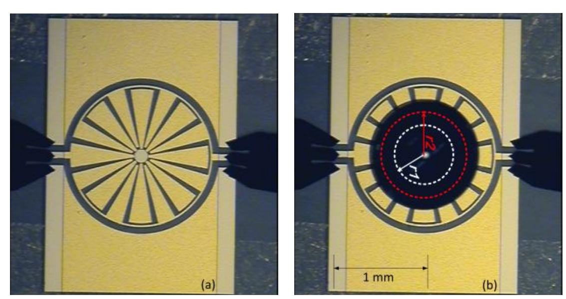


Fig. 4. The photographs of a fabricated device (a) before and (b) after mercury droplet dispensing. The boundaries of the base contact areas are illustrated with white and red dash lines before and after EWOD spreading, respectively (r_2 - r_1~150µm).

IV. EXPERIMENTAL RESULTS

The scattering parameter measurements of the fabricated CPW TLs have been performed by using Agilent 8722ES network analyzer with a 2-port Short Open Load Transmission (SOLT) calibration in the 50 MHz - 12 GHz frequency band. DC actuation voltage was supplied by a separate voltage source, which was applied to the terminals of RF input and output ports via bias tees as shown in Fig. 2. In this measurement set-up, the DC voltage was superimposed with the RF source signal provided by the network analyzer, where the bias tees were used to prevent high DC voltages going into

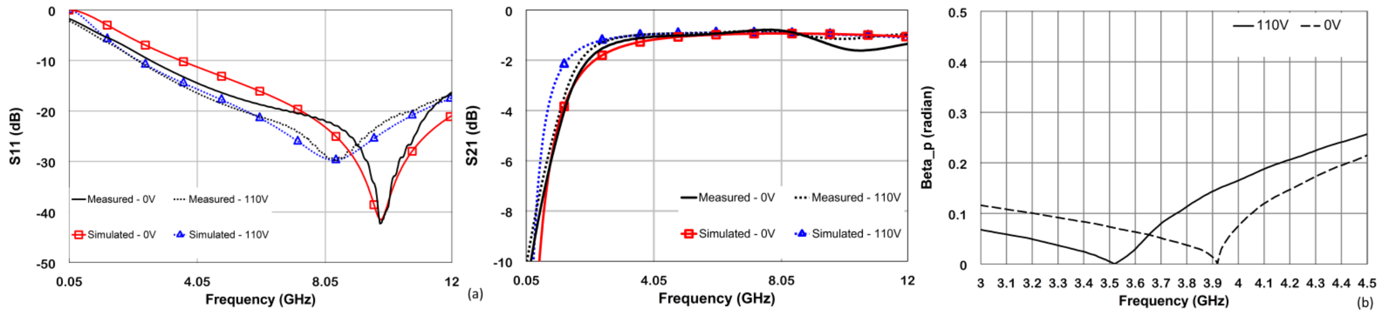


Fig. 5. (a) Simulated and measured *S*-parameters before and after applied voltage of 110 Volts and (b) calculated propagation constant of the unit cell structure

the network analyzer. In order to observe the reversible operation of the fabricated devices, the measurements started by applying the DC voltages in increments of 10 Vs (10 V, 20 V, 30 V…and 110 V), where the DC source was turned off at each step. We clearly observed that the spread mercury droplet returned back to its original non-spread stage every time the source was turned off. After obtaining the simulated and measured *S*-parameters of which variations with respect to frequency are given in Fig. 5(a), the dispersion behavior, which is represented by the variation of phase constant β as a function of frequency has been obtained by using equation (1). As shown in Fig. 5(b), the zeroth-order resonance frequency was shifted from 3.92 to 3.51 GHz by the applied DC voltage of 110 V providing a maximum tuning range in excess of 400 MHz. The actuation voltages above 110V cause the mercury droplet to be freed from the anchor thereby the droplet starts moving. As the device operation relies on the spread of the droplet while it is fixed at the central anchor location, the normal device operation mechanism is lost above 110V. Slight variations in the RF responses from device-to-device on the wafer were also observed, which could mainly be attributed to the small variations in the hand dispensed volume.

V. Conclusion

A new method based on EWOD for tuning the zeroth-order resonant frequency of a CPW metamaterial TL unit cell has been demonstrated. The unit cell structure has been designed, fabricated and characterized. The proposed structure eliminates complex biasing scheme by combining the CPW architecture with EWOD mechanism. EWOD phenomenon was exploited to expand the base contact area of a liquid mercury droplet placed on the unit cell, which resulted in changing the left-handed capacitance thereby tuning the resonant frequency. The main advantages of the proposed unit cell structure are its reliable operation with a simple structure and easy manufacturing processes needed to fabricate it. The design also offers flexibility where not only liquid metal but also liquid dielectric could be used. A new class of tunable phase shifters, antennas, and microwave filters could be realized by using this digital microfluidic platform as building blocks.

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