A Novel Fluid-Reconfigurable Advanced and Delayed Phase Line Using Inkjet-Printed Microfluidic Composite Right/Left-Handed Transmission Line

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***Abstract*—In this letter, a novel fluid-reconfigurable advanced and delayed phase line using a microfluidic composite right/left-handed (CRLH) transmission line (TL) is proposed. A CRLH-TL prototype is inkjet-printed on a photo-paper substrate. In addition, a laser-etched microfluidic channel in poly(methyl methacrylate) (PMMA) is integrated with the CRLH TL using inkjet-printed SU-8 as a bonding material. The proposed TL provides excellent phase-tuning capability that is dependent on the fluidic materials used. As the fluid is changed, the proposed TL can have negative-, zero-, and positive-phase characteristics at 900 MHz for different fluids. The performance of the TL is successfully validated using simulation and measurement results.**

***Index Terms*—CRLH TL, inkjet printing, metamaterial, microfluidics, phase shifter.**

I. Introduction

OVER the last decade, it has been shown that a composite right/left-handed (CRLH) transmission line (TL) exhibits extraordinary phase characteristics. For example, a CRLH TL can introduce negative (phase-delay or lag), zero, and positive phases (phase advance or lead), while a conventional TL always has a negative phase response [1]. When these unique phase-response characteristics are used in applications involving phase shifters, the characteristics of compact size and linearity can be accomplished over broad frequency bands.

Recently, electromagnetic interaction with fluids has been studied for RF applications [2], and microfluidic systems have been loaded on inkjet-printed antennas [3]. Because conductive patterns can be written directly on a substrate using additive manufacturing techniques such as inkjet printing, fabrication time and cost can be significantly reduced. Further, there are no byproducts, and inkjet printing is more eco-friendly than the typical chemical etching process. In addition, inkjet-printed electronics can be easily bonded with microfluidic channels using appropriate inkjet printable materials such as SU-8.

Inkjet-printed microfluidic papers have been introduced for chemical sensing and diagnosing applications [4], [5]. Chemical or biochemical sensors have been realized by using capacitive electrodes. For instance, microfluidic channels are loaded on interdigitated electrodes, and fluidic samples can be detected by observing variations of voltage waveforms [6], [7].

In this letter, we propose a novel microfluidic CRLH TL using inkjet printing technology. The proposed structure is simple and compact because it does not require any electronic devices or bias networks. The structure can be easily used as a fluid sensor (in oil exploration or water quality monitoring, for example) by simply monitoring its fluid-dependent phase characteristics. The structure can be also used as a fluidic sensor by varying its phase. As a sensor application, the proposed device provides higher sensitivity than other voltage-dependent capacitive sensors mentioned in [6] and [7]. In addition, the proposed device is compatible with wireless devices because it operates on the radio frequency (RF).

II. Microfluidic CRLH TL Design

Fig. 1(a) shows the equivalent circuit model of a CRLH TL. The series capacitance (C_L) and shunt inductance (L_L) for the LH TL in Fig. 1 are realized using interdigitated capacitors and a shorted stub, respectively. A 50 Ω coplanar waveguide (CPW) is designed for the input and output conventional RH transmission lines, as shown in Fig. 2.

Fig. 1(b) illustrates a phase response (ϕ) of a general LH, RH, and CRLH TL [1]. In particular, ϕ_{LH} in Fig. 1 is given by

$$\phi_{LH}(f) \approx \frac{1}{2\pi f\sqrt{L_L C_L}}. \quad (1)$$

A conventional TL shows only phase-delay and linear-phase response, whereas an LH TL features only phase-advance and nonlinear-phase responses. When the RH and LH TLs are cascaded, as shown in Fig. 1(a), the CRLH TL features a phase advance below frequency f_0 and a phase delay above frequency f_0, while it provides a zero phase shift at f_0. When C_L is varied, its phase response also changes from (1).

In this study, the interdigitated capacitor and the shorted stub are designed on a photo-paper substrate with a thickness of 0.254 mm. The relative permittivity and loss tangent of the

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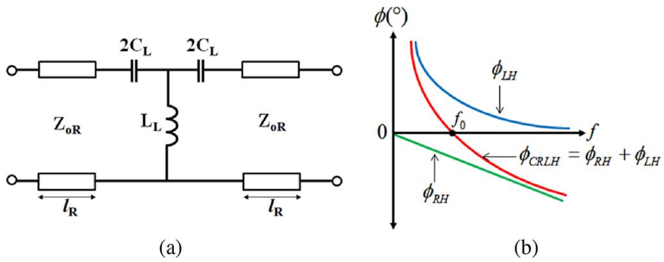

Fig. 1. (a) Equivalent circuit model and (b) phase response of a conventional CRLH TL.

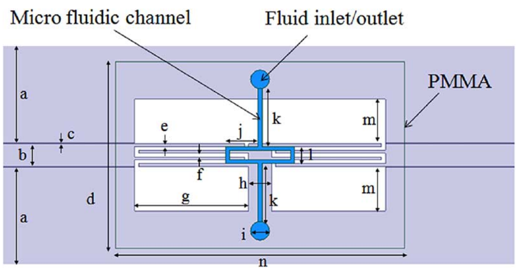

Fig. 2. Layout of the proposed CRLH TL integrated with the microfluidic channel (a = 13.4, b = 3, c = 0.1, d = 25, e = 0.375, f = 0.5, g = 15, h = 3, i = 2.5, j = 4.25, k = 7.75, l = 2.25, m = 6, and n = 38) [units: mm].

paper substrate are extracted as 3.1 and 0.06, respectively. To effectively modify its capacitance for different liquids, the microfluidic channel is placed in the gap between the fingers of the capacitor, as shown in Fig. 2. Therefore, the phase of the proposed CRLH TL can be changed depending on the permittivity of the injected fluids. Higher permittivity results in higher capacitance. A longer microfluidic channel (larger j in Fig. 2) generates a larger variation in capacitance and phase response. Nevertheless, as its performance becomes considerably sensitive to fluids, its impedance value changes dramatically, and the insertion loss increases. Therefore, the proper length of the microfluidic channel must be determined after considering both insertion loss and phase variations.

The proposed microfluidic CRLH TL is designed to achieve both phase delay and phase advance at 900 MHz, depending on the fluids selected to fill the microfluidic channel. ANSYS HFSS is used to create an electromagnetic simulation. A PMMA layer with a 1.5-mm thickness and a layer of SU-8 with 15 μm thickness are utilized for the realization of the microfluidic channel and bonding layer, respectively. The dielectric constant and loss tangent of the PMMA are 3.5 and 0.04, respectively. The dielectric constant and loss tangent of the SU-8 are 3 and 0.04, respectively. The final dimensions are shown in Fig. 2.

III. Fabrication Process

The fabrication process of the proposed TL is shown in Fig. 3. First, the 1.3-um-thick CRLH TL pattern is printed on a sheet of 0.254-mm-thick Kodak photo paper (from Office Depot, Atlanta, GA USA), utilizing ANP Silver Jet 55 LT-25C silver nanoparticle ink (Advanced Nano Products, Sejong, Korea) and the Dimatix DMP-2831 printer (Fujifilm Dimatix, Santa Clara, CA USA) with a 10-pL cartridge and a drop spacing of 20 μm. Subsequently, the CRLH TL is cured for 60 min at 120°C, then for 5 min at 180°C. In order to bond and seal the microfluidic channel onto the host substrate, a

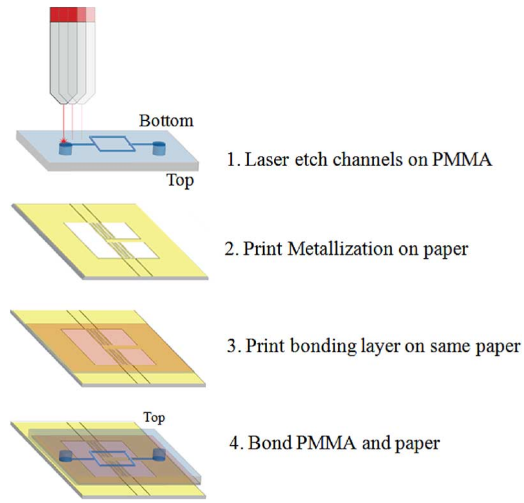

Fig. 3. Fabrication process of the proposed microfluidic CRLH TL.

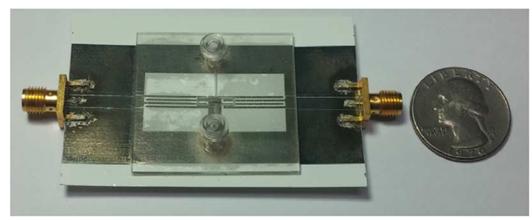

Fig. 4. Fabricated microfluidic CRLH TL prototype.

15-μm-thick polymer adhesion layer is printed on top of the CRLH TL using SU-8 polymer ink (MicroChem, Newton, MA USA). Because the SU-8 polymer can endure both organic and inorganic fluid, it is a good material to isolate paper from fluid. Therefore, the proposed device can endure most liquid samples.

To create the microfluidic channels, a 1.5-mm-thick PMMA substrate (McMaster-Carr, Atlanta, GA USA) is laser etched with an Epilog Mini 45-W infrared laser (Epilog Laser, Golden, CO USA), to produce micron-sized channels and fluid inlets/outlets. Bonding is accomplished by flipping the substrate that houses the channels onto the host substrate, and placing weight on the top of the device while heating the entire structure to 80°C. The finished system is then allowed to cool with the weight on it. Fig. 4 shows the prototype of the fabricated microfluidic CRLH TL. SMA connectors for measurement purposes are attached using silver epoxy.

IV. Simulation and Measurement Results

Fig. 5(a) shows the simulated and measured phase response of the transmission coefficient (S_{21}) when the microfluidic channel is filled with air or distilled water. Because the dielectric constants of distilled water and air are 73 and 1, respectively, they show the largest phase difference among the utilized fluids, including ethanol ($\varepsilon_r = 15$) and hexanol ($\varepsilon_r = 3$).

At 900 MHz, the phases of air and water are 30° (phase advance) and −22° (phase delay), respectively. This verifies the fluid-reconfigurable phase advance/delay performance. Therefore, both the proposed phase advance and delay characteristics are achieved.

Fig. 5(b) shows the simulated and measured magnitudes of S_{21} when the microfluidic channel is filled with air or distilled

TABLE I
PERFORMANCE COMPARISON OF PHASE SHIFTERS WITH DIFFERENT TECHNOLOGIES

Ref	Compared Freq. (GHz)	IL (dB)	DC voltage (V)	Size (mm × mm)	Phase range(°)	Technology
[8]	1.95	2.8–4	0–2	0.84 × 0.44	0–120	CMOS
[9]	1	0.6–2	0–25	12.8 × 12.8	0–100	PET metallic perturber
[10]	1.7	0.5–2	2–20	20 × 20	240–580	Microstrip line
[11]	1.8	3–7	N/A	3.4 mm^2	0–340	0.25-μm SOS
[12]	1.75	0.8–1.4	0–28	66 × 90	0–120	Packaged RF MEMS
This work	0.9	4–5.6	Not Required	30 × 68	-22–30	Microfluidics

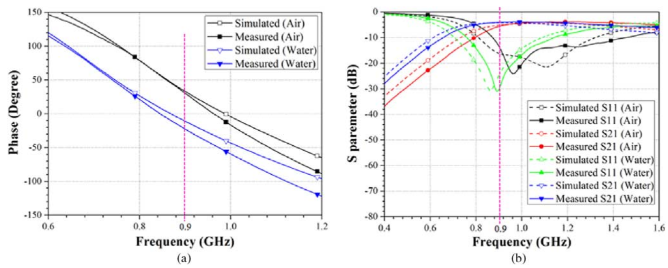

Fig. 5. Simulated and measured (a) phase response of S_{21} and (b) magnitude of S-parameters when the microfluidic channel is filled with air or distilled water.

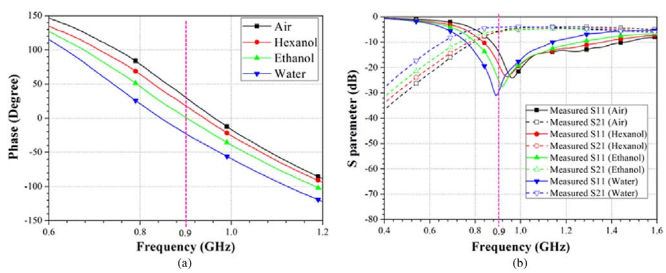

Fig. 6. Measured (a) phase response of S_{21} and (b) magnitudes of S-parameters for different filled fluidic materials.

water. At 900 MHz, the measured return losses with air and water are 13.38 and 30.4 dB, respectively, while the measured insertion losses with air and water are 5.6 dB and 4 dB, respectively. In both cases, impedance matching is preserved while phase variation is maintained. Higher insertion losses result from higher loss tangents of the liquids utilized, effectively shifting the "zero phase shift frequency" lower. These results show that the impedance matching between RH TL and LH TL is sustained even though the phase is largely changed. The measured phase responses of S_{21} for hexanol and ethanol are shown in Fig. 6(a). At 900 MHz, the phases with ethanol and hexanol are 0° and 18°, respectively. As expected from (1), a higher capacitance from a larger dielectric constant results in lower phases. Further, it is observed from Fig. 6(b) that impedance matching is still maintained when hexanol and ethanol are injected into the microfluidic channel.

In Table I, the performance of the proposed TL is compared with previously researched phase shifters using different techniques [8]–[12]. The proposed TL does not require a dc bias or a complex bias network. The proposed TL shows a higher insertion loss and lower phase range compared with other technologies. The proposed microfluidic technology is useful primarily in sensing fluidic and bio samples rather than phased array radar applications which require a low insertion los and wide phase range.

V. CONCLUSION

In this letter, we proposed a novel microfluidic CRLH TL that, for the first time, uses inkjet printing technology. Depending on the fluids used, phase delay, zero phase, and phase advance are achieved. From the experimental results, $-22°$ of phase delay, 0° of phase, 18° of phase advance, and 30° of phase advance are achieved at 900 MHz with distilled water, ethanol, hexanol, and air, respectively. Regardless of the fluid, good impedance matching is continuously maintained. The proposed TL can be used in numerous applications such as fluid-reconfigurable phase shifters as well as flexible low-cost fluid sensors and biosensors.

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