Tunable Branchline Coupler Using Microfluidic Channels

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***Abstract*— A branchline coupler is presented that uses 12 microfluidic channels (3 per branch) to tune its center frequency. A lumped-element equivalent circuit model (ECM) is extracted for the fluidic channels and is used to predict the response of the coupler prior to fabrication. The circuit is realized on a 1.524-mm-thick Rogers 4003C substrate with $\epsilon_r = 3.55$. The microfluidic channels are milled through the ground backplane and are filled with ethyl acetate ($C_4H_8O_2$), for which $\epsilon_r = 6.00$. Experiments with the coupler show that starting with empty (i.e., air-filled) channels and progressively filling them with the fluid, the center frequency of the coupler can be tuned from 2.19 to 1.80 GHz, yielding a tuning range of 19.5%. A comparison between the modeled and measured results shows that the ECM predicted the coupler tuning range with an error below 2.8%.**

***Index Terms*— Branchline coupler (BLC), circuit model, dielectric fluid, ethyl acetate, fluidics, frequency tuning, microfluidics, microwaves, passive circuit, power combiner, reconfigurable.**

I. Introduction

FLUIDS have electrical properties that can be exploited for circuit design. Conductive fluids, such as eutectic gallium, can be used for on/off switching or to implement tunable antennas by changing the length of a transmission line [1], [2]. Meanwhile, a small droplet of dielectric fluid located in the path of a transmission line can cause a sufficient change in the propagation velocity of a guided wave, to have practical engineering uses for phase shifting, tunable filters, and antenna beamsteering [3]–[5]. A recent study on fluidic tuning of oscillators has shown [6], dielectric fluids can have a negligible impact on the internal electronic noise of a circuit. In addition to its low-noise properties, fluidic tuning offers important benefits over varactor tuning such as low-distortion, high-power handling and does not require dc bias. It has been demonstrated that fluidics are a good fit for flexible/wearable electronic devices [7], [8].

In this letter, a fluidically tunable branchline coupler (BLC) is reported. Twelve channels are milled from the backplane of the coupler and are filled with the dielectric fluid ethyl acetate. To simulate the frequency response of the BLC as the channels are filled with fluid prior to fabrication, the use is made of the microfluidic equivalent circuit model (ECM) described in [9].

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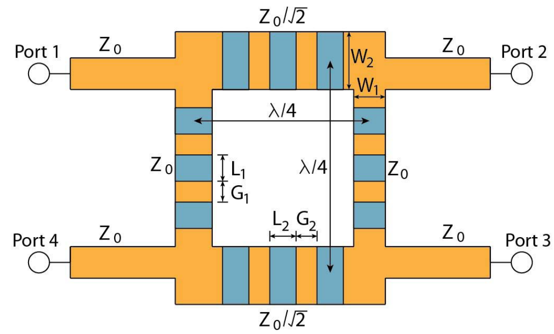
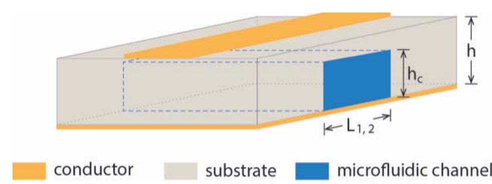


(a)

var.	W_1	W_2	L_1	L_2	G_1	G_2	h_c	Z_0
(mm)	3.51	5.72	3.00	3.00	0.84	0.67	1.52	50 Ω



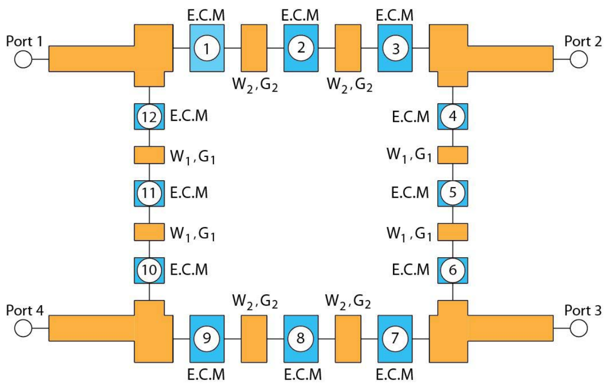
(b)

Fig. 1. (a) Schematic of the proposed microfluidically tuned BLC. (b) Close-up view of the channel geometry.

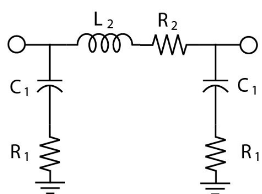
Experimental measurements on a fabricated BLC show that the circuit can be tuned over a bandwidth of nearly 20% and that the ECM can predict the response of the BLC with an error below 2.8%.

II. Fluidically Tuned Branchline Coupler

A schematic of the proposed tunable BLC is shown in Fig. 1(a) and a close-up of the microfluidic channels is depicted in Fig. 1(b). The circuit was designed to have a center frequency of 2 GHz using a 1.524-mm-thick substrate having $\epsilon_r = 3.55$ and $\tan\delta = 0.0027$. The fluid used for this investigation was ethyl acetate ($C_4H_8O_2$), which has $\epsilon_r = 6.00$, $\tan\delta = 0.0059$, and melting point of -83.6°C [10]. Ethyl acetate was used because the difference between the substrate and the liquid's relative permittivity is $\Delta\epsilon_r = 6.0 - 3.55 = 2.45$ and the difference of the permittivities of the substrate and air is $\Delta\epsilon_r = 3.55 - 1 = 2.55$. Since $\Delta\epsilon_r$ for both cases differs by less than 4%, the coupler's upward frequency shift when all channels are empty is approximately the same as the downward frequency shift when all channels are filled with the liquid relative to the coupler's baseline center frequency. Each arm of the BLC was loaded with three microfluidic



(a)



(b)

Material	Width	C_1(pF)	L_2(nH)	$R_1(\Omega)$	$R_2(\Omega)$
Air	W_1	0.16	1.85	3.66	0.11
$C_4H_8O_2$	W_1	0.32	1.82	9.88	0.07
Air	W_2	0.25	1.29	3.15	0.08
$C_4H_8O_2$	W_2	0.51	1.27	6.66	0.05

Fig. 2. (a) BLC segmentation into subnetworks. (b) ECM used for BLC schematic simulations plus the extracted circuit model values based on the channel filling material.

channels, for a total of 12 channels. All channels have the same height, h_c, and length, $L_{1,2}$, but their width was made equal to the width of the transmission line above it ($W_1 = 3.51$ or $W_2 = 5.72$ mm). The lengths of the channels were chosen such that multiple channels could fit on each arm and also large enough so they could be filled with liquid. The height of the channels is slightly less than the height of the substrate, h, so that a thin layer of substrate remains to support the transmission line above.

The BLC was segmented into subnetworks as depicted in Fig. 2(a) in order to analyze its frequency tuning response in a time-efficient manner using a schematic simulator [Keysight Advanced Design System (ADS)] for different fluidic loading arrangements. The four identical corner sections of the coupler were first simulated using a full-wave field solver as a three-port network and their S-parameters were imported into the ADS schematic environment. The same approach was used for the short straight sections of transmission line along the branches.

To model the microfluidic channels, the ECM [9] depicted in Fig. 2(b) was used. The ECM component values were extracted from S-parameter data for the microfluidic channels, calculated with ANSYS HFSS from 1 to 3 GHz using a frequency step size of 0.05 GHz. Applying the procedure described in [9], two circuit models were extracted for each microfluidic channel: one for the fluid-loaded channel and another model for an empty, air-filled, channel. The extracted values for the ECMs can be seen in the table in Fig. 2.

TABLE I
SIMULATED BLC CENTER FREQUENCY (f_0)

Case	Channels containing $C_4H_8O_2$	f_0 (GHz)
0	none (air-filled)	2.16
1	2, 5, 8, 11	2.05
2	1, 3, 4, 6, 7, 9, 10, 12	1.92
3	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12	1.75

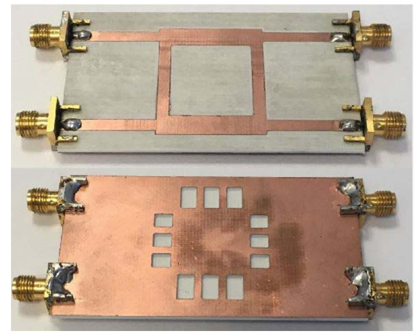


Fig. 3. Top and bottom views of the fabricated BLC. Bottom view shows the 12 fluidic channels milled out of the substrate.

A series of schematic-level simulations in ADS was run using the network in Fig. 2(a) to calculate the BLC center frequency as different channels are filled with fluid. To maintain the even- and odd-mode symmetry of the coupler, the fluidic channels in the arms of the coupler were sequentially loaded such that the structure's overall symmetry was preserved. A summary of the simulation results is presented in Table I. When all channels are empty (Case 0), the simulations predict a center frequency of 2.16 GHz. When only the middle channels are filled with fluid, corresponding to segments 2, 5, 8, and 11 in Fig. 2(a), the BLC's center frequency is 2.05 GHz. For the case that all channels are filled with fluid, the center frequency shifts to 1.75 GHz, which is 0.41 GHz below the center frequency of Case 0, representing a tuning range of 19.5%.

III. Experimental Results

The coupler circuit was patterned on a Rogers 4003C substrate with 0.5-oz copper cladding using an LPKF ProtoMat circuit plotter. The channels were milled out from the backplane also using the LPKF plotter. Fig. 3 shows the top and bottom sides of the coupler.

The channels were filled with a syringe, injecting liquid into the channel slots. After the respective channels are filled, copper tape is placed over the channels to restore the ground plane of the circuit. The coupler was measured using a four-port Keysight M9375A PXIe vector network analyzer from 1 to 3 GHz. Fig. 4 shows the coupler's measured S-parameter response with all channels empty (Case 0). For this case, the center frequency of the coupler is 2.19 GHz. For consistency, the center frequency of the coupler is taken as the minimum of its S_{11} response.

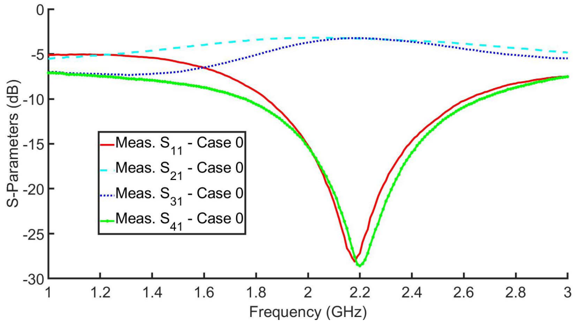


Fig. 4. Measured S-parameter results for the BLC with all 12 channels empty (air)—Case 0.

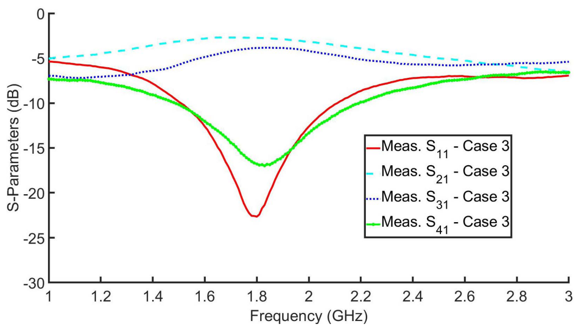


Fig. 5. Measured S-parameter results for the coupler with all 12 channels filled with ethyl acetate—Case 3.

Fig. 5 shows the coupler's measured S-parameter response when all of the channels are filled with ethyl acetate (Case 3). The center frequency of the coupler in this case shifts down to 1.80 GHz. Fig. 5 shows a mismatch in the couplers S_{21} and S_{31} at the center frequency. The variation between the results can be attributed to asymmetries in the couplers arms due to depth variations in the channels and the use of copper tape on the ground plane. Some issues arising from copper tape include: residual air pockets trapped inside the liquid-filled channel and resistive parasitics introduced by the tape's adhesive material. The coupler's S_{11} for Case 3 is plotted in Fig. 6 using the measured data, simulated data using the ECM schematic, and full-wave simulation data from ANSYS HFSS.

Table II shows the center frequency for the ECM method and measured data along with the percent error between the ECM simulation and physical measurements for Cases 0 and 3. For Case 0 (all air), the percentage error in the predicted center frequency is 1.36%, while for Case 3 (all ethyl acetate), the percentage error in the predicted center frequency is 2.77%. Cases 1 and 2 were also measured and they show good agreement with the simulated results but their responses are not included due to space limitations.

IV. Conclusion

A fluidically tunable BLC was presented with 12 fluidic channels. ECMs were generated for two materials: air and ethyl acetate, to allow for complete simulations at the schematic level. Through the inclusion of fluidic channels

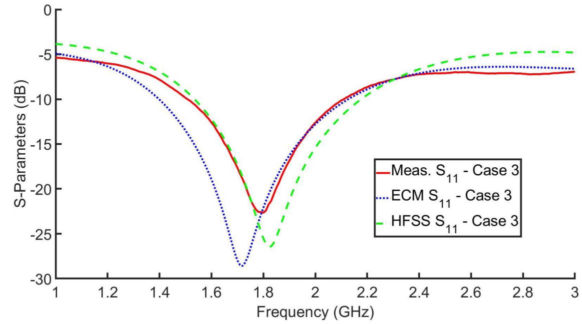


Fig. 6. Reflection coefficient, S_{11}, of BLC for the measured results, ECM and ANSYS HFSS for Case 3.

TABLE II
ECM Measured Data Comparison for BLC

Case	ECM f_0 (GHz)	Measured f_0 (GHz)	% Error
0	2.16	2.19	1.36
3	1.75	1.80	2.77

filled with ethyl acetate, the center frequency of the coupler could be varied. The tuning range was 390 MHz from 2.19 to 1.80 GHz shown through measurements. The ECM simulation method corresponds well with the measured data, with simulations showing a tuning range of the center frequency from 2.16 to 1.75 GHz. With a 1.36% and 2.77% error in tunable center frequency for the BLC between the measured data and ECM simulation results, respectively.

References

[1] A. Dey, R. Guldiken, and G. Mumcu, "Microfluidically reconfigured wideband frequency-tunable liquid-metal monopole antenna," *IEEE Trans. Antennas Propag.*, vol. 64, no. 6, pp. 2572–2576, Jun. 2016.

[2] G. H. Huff, H. Pan, D. J. Hartl, G. J. Frank, R. L. Bradford, and J. W. Baur, "A physically reconfigurable structurally embedded vascular antenna," *IEEE Trans. Antennas Propag.*, vol. 65, no. 5, pp. 2282–2288, May 2017.

[3] S. Choi, W. Su, M. M. Tentzeris, and S. Lim, "A novel fluid-reconfigurable advanced and delayed phase line using inkjet-printed microfluidic composite right/left-handed transmission line," *IEEE Microw. Wireless Compon. Lett.*, vol. 25, no. 2, pp. 142–144, Feb. 2015.

[4] D. L. Diedhiou, R. Sauleau, and A. V. Boriskin, "Microfluidically tunable microstrip filters," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 7, pp. 2245–2252, Jul. 2015.

[5] I. Goode and C. E. Saavedra, "A four element phased patch antenna array using fluidic phase shifter," in *Proc. URSI GASS*, Montreal, QC, Canada, Aug. 2017, pp. 1–2.

[6] M. Abdallah and C. E. Saavedra, "Fluidically-tuned reflection oscillator at C-Band," in *Proc. 18th Int. Symp. Antenna Technol. Appl. Electromagn. (ANTEM)*, Aug. 2018, pp. 1–3.

[7] A. Vorobyov, C. Henemann, and P. Dallemagne, "Liquid metal based antenna for wearable electronic," in *Proc. 10th Eur. Conf. Antennas Propag.*, Apr. 2016, pp. 1–3.

[8] K. Entesari and A. P. Saghati, "Fluidics in microwave components," *IEEE Microw. Mag.*, vol. 17, no. 6, pp. 50–75, Jun. 2016.

[9] M. Brown, I. Goode, and C. E. Saavedra, "Lumped-element circuit modelling of microfluidic channels in microstrip transmission lines," in *Proc. 16th IEEE Int. New Circuits Syst. Conf. (NEWCAS)*, Jun. 2018, pp. 31–34.

[10] B. L. Hayes, *Microwave Synthesis: Chemistry at the Speed of Light*. Matthews, NC, USA: CEM, 2002.