Analogue phase-shifter employing fluid-filled connected micro-cavities

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Abstract

In this paper, a novel analogue phase-shifter based on a simple coplanar waveguide (CPW), over-laying E-shape-connected micro-cavities, was presented. High dielectric constant fluid filled the volumes of cavities to variable fractions. By employing micro-pumps to regulate the volume of fluid in the vicinity of the transmission line, it has the potential of achieving dynamic phase-shifting. Both numerical and experimental analyses have been undertaken from 1.9 GHz to 2.2 GHz for application to semi-smart base-station antenna systems. A maximum phase-shift of 81° was measured at 2.0 GHz and simulation yielded 93°. The measured return loss was better than -15 dB and average insertion loss was -1.5 dB. According to exponential mixing rules and non-linear least square method, an empirical formula was obtained to match the measurement.

1. INTRODUCTION

A microwave phase-shifter is a key component in the operation of phased-array radar, satellite communication or wireless communication systems. The driving concern for developing compact bidirectional phase-shifters is reduction in cost and power consumption and, the elimination of inter-modulation products. The advent of nano-technology and the ability to fabricate micro-pumps on dielectric ICs offers the possibility of pumping high dielectric constant fluid under a microstrip line to enable a continuous phase-shift. Applications for a linear RF phase-shifter include use in “smart and semi-smart” [1] mobile communication base stations. In recent years, several kinds of analogue phase-shifters with different principles of operation have been demonstrated [2-3]. In particular liquid crystal loaded phase shifters, which mainly work at millimeter-wave frequencies, offer only very small phase shifts at 2 GHz [2] (generally less than 10°) and ferroelectric phase-shifters, which generally require kilovolts for control [3].

In this paper, a novel analogue phase-shifter is presented based on a simple coplanar waveguide (CPW) over-laying a structure of E-shape-connected micro-cavities operating from 1.9 GHz to 2.2 GHz. The potential for achieving dynamic phase-shifting is being explored by employing micro-pumps to regulate the volume of a fluid dielectric in the vicinity of the transmission line. In this prototype PTFE is used as the substrate for its low relative permittivity (ε_r = 2.08) and chemical inertness. A substrate with low relative permittivity is selected to maximize the dielectric contrast presented between the CPW and dielectric fluid. The dielectric-liquid has a high dielectric constant of 53.3 and conductivity of 1.5 S/m. This kind of phase-shifter affords advantages of potential low cost, low power consumption, no inter-modulation products and nano-technology fabrication. The micropump is an important actuator for many applications [4]. Over the past ten years, several kinds of micropump have been proposed based on different principles of actuation. Micropumps have already served many applications in medical, mechanical and biological engineering, and their performance is constantly improving.

Here we demonstrate a relationship between phase-shifting and the principle of micropump actuation (i.e. the change of signal phase with volume of high dielectric constant fluid under a CPW). The micropumps will be regulating the mass of dielectric (i.e. the specific dielectric constant ε_{re}), in the vicinity of the CPW, thereby affecting the phase of signal propagation. When the state of the cavities change from empty to fully-filled, the relative change of specific effective dielectric constant causes variation of the phase constant β. This leads to a differential phase-shift after a certain distance of wave propagation. With an appropriate electronically-controlled micropump, a dielectric fluid may be accurately metered to give a controllable, continuous, differential phase-shift.

2. DESIGN AND MEASURMENT

The prototype phase-shifter operating from 1.9 to 2.2 GHz with connected micro-cavities has been fabricated and characterized to test this approach, following optimisation of the design by using Ansoft HFSS 9.0 [5]. Phase-shifting was obtained by variously filling the cavities with a high dielectric constant fluid (ε_r=53.3).Electronically-controlled micropumps may be employed on this principle to deliver a metered flow

[6]. In order to demonstrate the feasibility and reliability of such a phase-shifter, experiments were initially developed employing simple cavities without pumps.

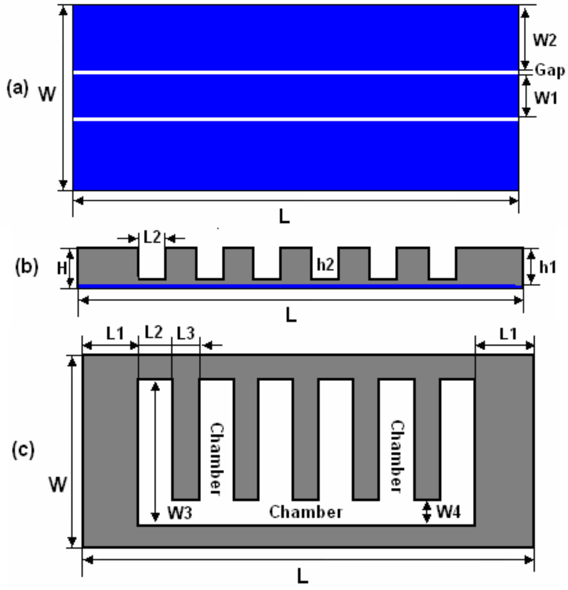
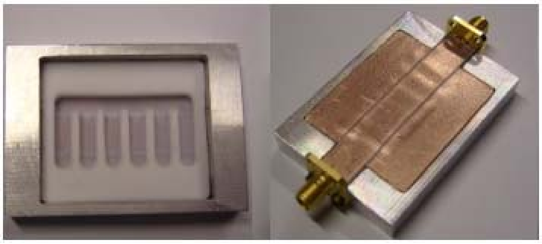


Fig. 1: Geometry of the phase-shifter consisting of E-shape-connected micro-cavities.(a) the bottom plan-view, (b)side-view and (c) top plan-view (L = 56 mm, W = 34 mm, L1 = 11 mm, L2 = 4 mm, L3 = 2 mm, w1 = 9 mm, w2 = 12 mm, w3 = 18 mm, w4 = 4 mm, Gap = 0.5 mm, H = 4.1 mm, h1 = 4 mm, h2 = 3.7 mm, εr = 2.08)



(a) (b)

Fig. 2: Prototype of phase shifter based on CPW with E-shape-connected micro-cavities. (a) top-view; (b) bottom-view

The geometry of the phase-shifter with E-shape-connected micro-cavities is shown in Fig.1. Fig.1 (a) gives the bottom-view with a central strip width of 9 mm and gap of 0.5 mm. The substrate has a thickness of 4 mm. Fig.1 (b) shows the side-view with a distance of 0.3 mm between the bottom of the cavity and the bottom of the substrate. The E-shape-connected micro-cavities are shown in Fig.1 (c) with heights of h2 = 3.7 mm. The test bench of the structure is based on a CPW having E-shape-connected micro-cavities as shown in Fig. 2. Since there is no PCB with PTFE substrate, the desired CPW structure for this prototype was obtained by evaporating copper onto the surface of PTFE.

It is clear from the numerical analyses that the horizontal electric fields are mostly concentrated along the two gaps of CPW when the cavities were empty; with fully-filled cavities however, the horizontal electric field expands into the region of E-shape cavities. This is expected since the fluid has a conductivity of 1.5 S/m and a high dielectric constant of $\varepsilon_r = 53.3$, and the specific dielectric constant changed from 1.7 to 5.1 in the simulation. The increase of specific dielectric constant leads to the variation of phase constant to achieve the desired phase-shifting. However, the majority of field still filled the gaps in both cases so that the variation of S-parameter performance was quite acceptable throughout the frequency band.

The high dielectric constant fluid used here has $\varepsilon_r = 53.3$ and conductivity $\sigma = 1.5$ s/m. The S-parameter performance was measured using a HP8720ES network analyzer. The fluid was injected into the inverted, level-lying, E-shape-connected micro-cavities (i.e. with the CPW facing the floor, the fluid was pipetted into a given cavity thereby filling from the surface closest to the CPW outwards). The simulated and measured results of return loss for five different conditions are shown in Fig. 3, namely: (a1,b1) empty, (a2,b2) quarter-filled, (a3,b3) half-filled, (a4,b4) three-quarters filled and (a5,b5) fully-filled cavities. Both predicted and experimental return loss results were better than -15 dB throughout the frequency band. The phase-shifter was designed to operate at 2.0 GHz with the fully-filled condition having a return loss of -33 dB. The measured return loss for the fully-filled condition has a resonant frequency of 2.05 GHz with a 50 MHz frequency shift due to the elongation of the central strip. This resulted in a small difference between the simulated and measured structure. The measured return loss for the fully-filled condition at 2.0 GHz and 2.05 GHz were respectively -27 dB and -32 dB. The performance of S_{11} decreases gradually with decreasing specific dielectric strength due to the increase in resonant frequency from a fully-filled to empty cavity state. For instance, it decreases 49% for simulation and 38% for measurement at 2.0 GHz. For the empty (air-filled) state, the S_{11} performance for both simulation and measurement varied from -15 dB to -19 dB over the required frequency band.

The simulated and measured results of insertion loss are shown in Fig. 4 for the same five conditions of S_{11} analysis. The simulation results were better than -0.9 dB with -0.75 dB for 2.0 GHz, however the measured result at 2.0 GHz was -1.65 dB, having a 0.9 dB decrease. Although the variation throughout the frequency band of ε_r is less than ± 0.4 and the variations of σ is less than ± 0.2 s/m about the 2.0 GHz value, it is one of the reasons for the difference between the results of simulation and measurement.

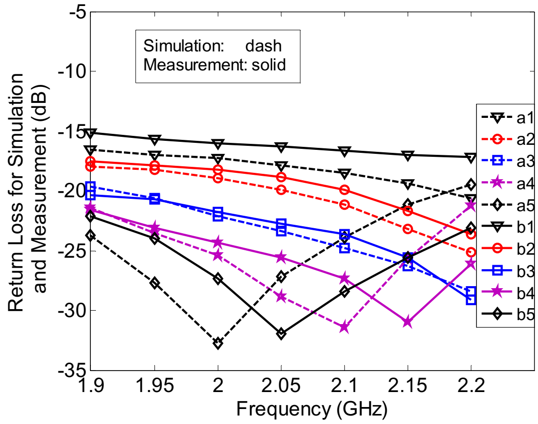


Fig. 3: The simulated and measured results of return loss as a function of the volume fraction of dielectric fluid. (a1,b1)empty, (a2,b2)quarter-filled, (a3,b3)half-filled, (a4,b4)three-quarters filled and (a5,b5)fully-filled cavities.

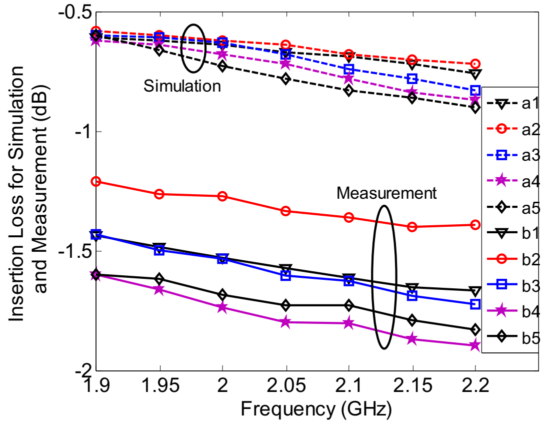


Fig. 4: The simulated and measured results of insertion loss as a function of the volume fraction of dielectric fluid. (a1,b1)empty, (a2,b2)quarter-filled, (a3,b3)half-filled, (a4,b4)three-quarters filled and (a5,b5)fully-filled cavities.

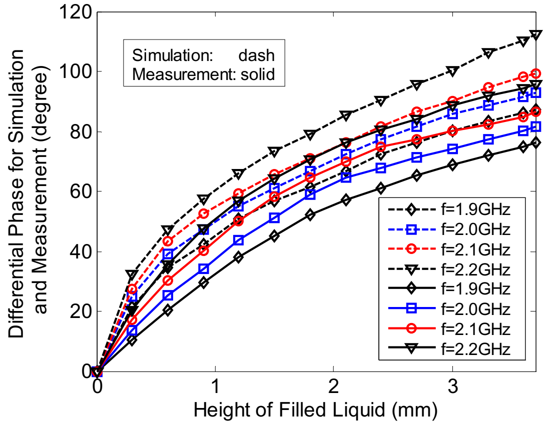


Fig. 5: The simulated and measured differential phase shift at four frequency points as a function of height of filled liquid.

Figure 5 shows the simulated and measured differential phase-shift at four frequency points (1.9 GHz, 2.0 GHz, 2.1 GHz and 2.2 GHz), with different filling-heights of dielectric liquid (from 0 to 3.7 mm). Quasi-linear continuous phase-shifting was obtained for both results, particularly for heights from 1 mm to 3.7 mm. The differential phase-shift for heights from 0 to 1 mm has a quicker variation because the dielectric fills the cavity from closest to the conductor, hence the strong initial phase response of the CPW. A maximum phase-shift of 81° was measured at 2.0 GHz (93° by simulation). The offset in phase and the decrease in insertion loss could be improved by structure-optimization and more accurate fabrication.

3. EMPIRICAL FORMULA

According to the correlation between the macroscopic polarization and the microscopic properties of the material, a large number of effective permittivity models for dielectric mixtures have been demonstrated for different applications [7].

For multiphase mixing formulas, there are experimentally based mixing rules giving the connection between the effective permittivity and constituent properties and their volume fractions. The family of experimentally based mixing rules consists of so-called exponential formulas, which for the n-component mixture gives:

$$\varepsilon_{re}^{a} = \sum_{i=1}^{n} f_i \varepsilon_i^{a} \quad . \tag{1}$$

Based on the exponential formula (3), in order to get further degrees of freedom, an additional exponential factor b is incorporated into the right hand side of (3). For our three-phase mixture of PTFE, dielectric liquid and air, we have:

$$\varepsilon_{re} = \left(\sum_{i=1}^{n} f_i \varepsilon_i^{b} \right)^{a} = \left[f_{i1}\varepsilon_{i1}^{b} + f_{i2}\varepsilon_{i2}^{b} + f_r\varepsilon_r^{b} \right]^{a} \tag{2}$$

where $f_{i1} = 0.087(3.7-h)$, $f_{i2} = 0.087h$, $f_r = 0.679$, $\varepsilon_{i1} \approx 1$, $\varepsilon_{i2} = 53.3$, $\varepsilon_r = 2.08$ and h is the height of high dielectric constant fluid in the cavity.

By application of a non-linear least square analysis with Gauss-Newton solution, for curve-fitting experimental data, the following empirical formula was obtained with a=0.3829 and b=1.2860:

$$\varepsilon_{re} = \left[f_{i1}\varepsilon_{i1}^{1.2860} + f_{i2}\varepsilon_{i2}^{1.2860} + f_r\varepsilon_r^{1.2860} \right]^{0.3829} \tag{3}$$

Figure 6 plots the fit against measurements at 2.0 GHz. A good agreement was shown with the standard error of 0.102.

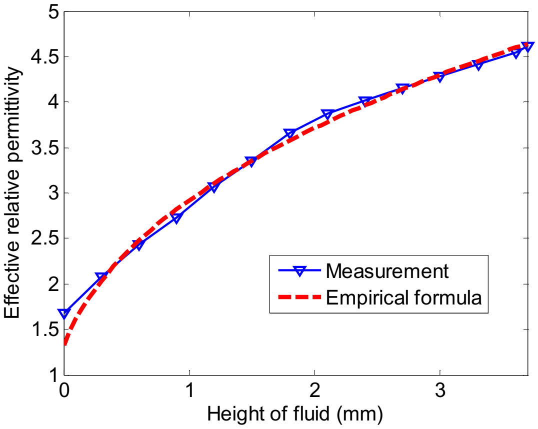


Fig. 6: The comparison of measurement and empirical formula results at 2.0 GHz.

4. CONCLUSION

An analogue phase-shifter based upon a simple coplanar waveguide over-laying fluid-filled E-shape-connected micro-cavities has been described. The performance was characterized by continuous phase-shifting from 1.9 to 2.2 GHz. The feasibility and reliability of achieving dynamic phase-shifting by employing micro-pumps to regulate the volume of dielectric in the vicinity of the transmission line has been computationally demonstrated. A maximum phase-shift of 81° (compared with 93° by simulation), was measured at 2.0 GHz with a measured return loss of -27 dB and a measured insertion loss of -1.65 dB at room temperature (T=22° ± 1°C). With electronically-controlled micropumps regulating fluid volume within the cavities, such a phase-shifter offers advantages of achieving low cost, low power consumption and having a compact profile. These are significant constraints for applications to semi-smart base-station antenna and S-band communication systems.

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