Mechanically Steerable Antennas Using Dielectric Phase Shifters

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Abstract

A mechanically steerable antenna was designed using an adjustable phase shifter which employs a dielectric slab placed close to a coplanar TL. Numerical simulations using Ansoft HFSS were conducted at 6 GHz, and a 4-element antenna was tested. A similar design can be used for a digital phase shifter with a matched impedance at the designed frequency.

I. Introduction

A low-cost steerable antenna is one of the missing links of the future flexible wireless communication systems. For example, the most flexible satellite to ground/airplane communication systems are based on the phased-array antenna technology. Unfortunately, the cost of phased array antennas is related to the number of active elements, and the present systems are too expensive for many commercial/military applications. The antenna beam steering can also be done by mechanically moving the reflector. Although the mechanically steerable antennas can be inexpensive, current antennas which use the eletro-mechanical actuators are usually bulky and prone to mechanical failure.

In this paper, we show that a movable dielectric slab placed close to a coplanar waveguide (CPW) can be used as a phase shifter. The effective dielectric constant is calculated as a function of slab height and the characteristics of the basic 4-element array antenna (shown in Fig. 1) is simulated.

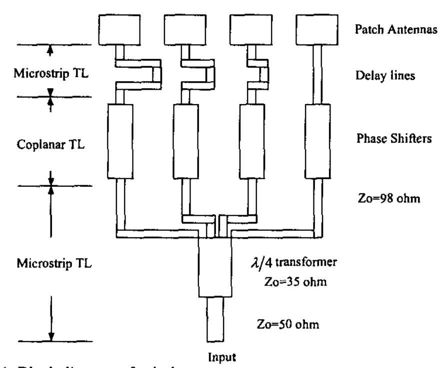


Fig. 1: Block diagram of a 4-element steerable array antenna.

II. Phase Shifter Based on a Movable Dielectric Slab

The basic concept is shown in Fig. 2. The movable high-dielectric constant slab is inserted into the gap of CPW. The effective dielectric constant will be a function of d for a given structure. In our design, CPW for d=5mm (effectively $d = \infty$) has the characteristic impedance $Z_o = 98\ \Omega$ and the effective dielectric constant of $\varepsilon_{effective}$=1.23. As the distance d decreases, $\varepsilon_{effective}$ increases and Z_o decreases. The HFSS simulations were conducted for height d from d=0 to d=5 mm. The effective dielectric constant was estimated from S_{21} data.

A. Analysis

The effective dielectric constant can be calculated using the transmission coefficient (T) of a layered structure where Γ_1 is the reflection coefficient at the boundary and θ is the phase shift due to a change in the effective dielectric constant. Assuming that the reflection is small (Γ_1^2 <0.1), we can approximate T as

$$T = \frac{\left(1-\Gamma_1^2\right)e^{-j\theta}}{1-\Gamma_1^2 e^{-2j\theta}} \approx e^{-j\theta} \tag{1}$$

The phase change at the slab height d is with respect to that without a dielectric slab ($d = \infty$), and we can express it as

$$\theta_d = k_o L_d (\sqrt{\varepsilon_{eff\_d}} - \sqrt{\varepsilon_{eff\_d=\infty}}) \tag{2}$$

where k_0 is wavenumber in free space, L_d is the slab length, $\varepsilon_{eff\_d=\infty}$ represents the effective dielectric constant when the dielectric material is far enough away from the substrate, and ε_{eff_d} represents the effective dielectric constant at the slab height is d.

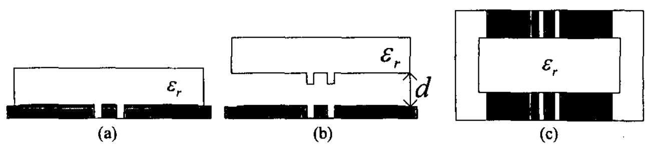


Fig. 2: Phase Shifting Method. 1 (a): frontal view of a ground-signal-ground (G-S-G) CPW when the dielectric material is attached to the substrate. (b): frontal view of G-S-G CPW when the dielectric material is far enough away from the substrate. (c): top view of G-S-G CPW. The width of signal trace is 2 mm and the width of ground trace is 10 mm. The gap between the ground and the signal is 1 mm. Substrate thickness is 1.6 mm and the height of dielectric material is 5 mm. The length of the dielectric material is 10 mm, the dielectric material is alumina $\varepsilon_r = 10$, and the substrate has $\varepsilon_{sub} = 2.2$ (Duroid 5880).

B. Numerical Results

We conducted preliminary numerical simulations of two different configurations shown in Fig. 2. A G-S-G TL with the center gap was found to provide a reasonable amount of phase shift with $\varepsilon_r = 10$. Table 1 presents numerical results for the G-S-G TL with the center gap for cases with and without the dielectric material (alumina).

As Table 1 demonstrates, the characteristic impedance and the effective dielectric constant are changed depending on the distance of the dielectric material from the substrate. Fig. 3 shows the effective dielectric constant as a function of distance d. Beyond d>2 mm, the slab is totally out of CPW and there is no change in $\varepsilon_{effective}$. The effective dielectric constant gradually changes from d=2 mm to d=0.25 mm and then increases rapidly at d=0 mm.

Parameters	d=5	d=0
|S21|	0.99	0.96
Characteristic impedance (Ω)	98	51
Effective dielectric constant	1.23	7.75

Table 1: Simulated results at d=5 mm and d=0 mm.

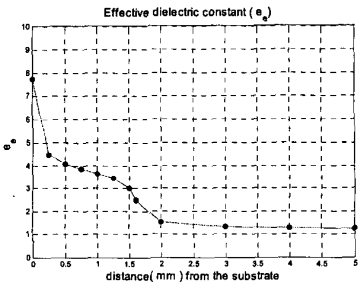


Fig. 3: Effective dielectric constant as a factor of distance from the substrate.

III. Design and Fabrication of Phase Shifter

Fig. 4 shows the layout of the test phase shift circuit. The CPW with gap ($Z_o = 98\,\Omega$) is matched to the microstrip TL with $Z_o = 50\Omega$ for testing purposes. The dielectric slab will be machined using alumina. The desired amount of phase shift can be obtained by adjusting the slab length L_d and slab height d. Fig. 5 shows the radiation patterns for two dielectric slab positions based on the antenna configuration shown in Fig. 1. Although we have an impedance mismatch at the phase shifter, the adverse effects on the radiation patterns are not significant.

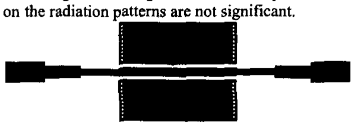


Fig. 4: A top view of the test circuit layout which includes the CPW and microstrip TL. This circuit has a 360 degree phase shift at d=0 mm. The bottom layer of the CPW section does not have a ground plane and *via* is used for connecting the ground.

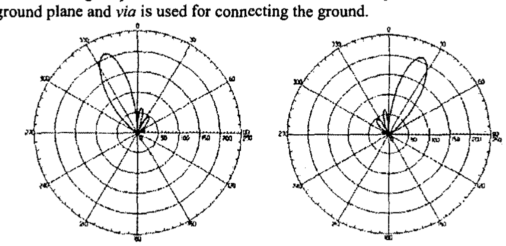
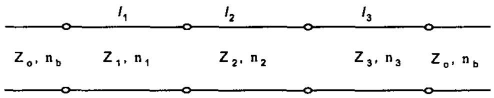


Fig. 5: Radiation patterns of a 4-element array antenna shown in Fig. 1. The initial phase is shifted to create -90° phase difference at d=0 mm (left figure). At d=5 mm, the phase difference becomes +90° (right figure).

IV. Impedance Mismatch and Possible Solutions

If we change the slab height continuously, we can adjust the phase shift. Unfortunately, this also changes the characteristic impedance of the CPW section and introduces reflection. However, we can eliminate the impedance mismatch problem by using two positions ($d = 0$ and $d = \infty$). To minimize reflection when the material is added to TL, we will set the length of the modified section to be $\lambda/2$ (or $m\lambda/2$ where m is an integer). Suppose we want a 3-bit phase shifter as shown below. The phase shift is given by 8 states (0, 45, 90, 135, 180, 225, 270, and 315 degrees).



The non-enhanced section is given by Z_o and n_b. The center sections will be enhanced, and they are given by (Z_1, n_1), (Z_2, n_2) and (Z_3, n_3) where Z and n are characteristic impedance and the index of refraction of each section. We want to create impedance matching for all states. This can be done by satisfying the following conditions:

Phase shift requirements:

Section 1: $(n_1 - n_b)\beta_b l_1 = \pi/4$ (45°, bit 0)

Section 2: $(n_2 - n_b)\beta_b l_2 = \pi/2$ (90°, bit 1)

Section 3: $(n_3 - n_b)\beta_b l_3 = \pi$ (180°, bit 2)

Matched impedance requirements: m_1, m_2, and m_3 are integers.

$$n_1\beta_b l_1 = m_1\pi,\ n_2\beta_b l_1 = m_2\pi,\ \text{and}\ n_3\beta_b l_1 = m_3\pi$$

Then, if we use $n_1 = n_2 = n_3 = 4/3\, n_b$, m_1=1, m_2=2, and m_3=4, we find

For $\pi/4$ section: $l_1 = 3/8(\lambda_o/n_b)$

For $\pi/2$ section: $l_2 = 3/4(\lambda_o/n_b)$

For π section: $l_3 = 3/2(\lambda_o/n_b)$

If we satisfy these conditions, the reflection due to dielectric slabs can be eliminated. The details of this approach will be discussed in another paper [1].

V. Conclusions

A novel design was proposed for a low-cost mechanically steerable array antenna. The phase shifter is based on a movable dielectric slab placed close to CPW. The impedance mismatch can be avoided by choosing the slab dielectric constant and length carefully. A mechanical actuator is required to move the dielectric slab in our configuration. One idea is the use of an electro-active polymer (EAP) to move a small slab which may be suited to high MMW frequencies [2].

References

1. Y. Kuga, J-H Cha, A. Ishimaru, and S-I Lee, "Mechanically controllable microwave phase shifter," to be submitted to *IEEE Trans. Antenna and Propagation.*
2. M. Le Guilly, C. Xu, V. Cheng, M. Taya, L. Opperman, and Y. Kuga, "Flemion based actuator for mechanically controlled microwave switch," *SPIE Meeting, Smart Structure and Materials*, San Diego, CA, March 2-6, 2003.