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Tunable feeding network for beam steering applications based on chalcogenide material

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Abstract—This abstract presents a new concept of tunable feeding network for antenna arrays. The objective is to illustrate the potential application of a Phase-Change Material (PCM) to antenna array. We will use chalcogenide thin layer to introduce phase shifters in a one-to-four feeding network. Hence, a wide range of states will be achievable, spanning from normal 0° radiation to a 30° tilted radiation.

Index Terms—feeding network, tunable devices, beamforming, beam steering, chalcogenide glass, PCM, phase shifter

I. INTRODUCTION

With the ongoing increase in high data transfer requirements, operating frequencies tend to rise. As the frequency increases, path losses become more significant. To address this issue, radiation efficiency needs to be as optimal as possible. One solution, employed by the recent 5G specification, and futures ones [1], is the use of multi-antenna arrays, unlike previous approaches. The main challenge of working with thin beams is to accurately target the reception point. One ability of antennas arrays is to change the radiation direction by applying a reversible phase law to the antennas. The reversibility can be done by making the feeding network reconfigurable. Also, with all the embedded systems constraints, it is interesting to study planar technologies. In this context, our study will work toward a solution to apply a phase law to an array, in a microstrip topology.

Usually, reconfigurable arrays are achieved via electronically tunable components, such as Micro-Electro-Mechanical Systems (MEMS), RF diodes or varactors [2], [3]. These components have already shown their advantages, and their limits, among those there are the electrical consumption, the commutation time, the high frequencies compatibility and the integration. Furthermore, managing each tunable cell's control has become a challenging task due to the growing size of

the arrays. This challenge is particularly pronounced because of the coupling between the electronic control circuit and the RF circuit [3], [4]. As a substitute for these electronic components, certain specialized materials have been under investigation for a number of years. These materials possess the capability to alter certain properties when exposed to a stimulus.

When the property is the electrical conductivity, we talk about Phase-Change Material (PCM). The two most studied ones are Vanadium Dioxide (VO₂) [5] [6] and the chalcogenide family (mostly GeTe and Ge₂Sb₂Te₅) [7] [8]. Used in planar topologies, these materials can entirely change the circuit's geometry by transitioning the conductivity value from that of a pseudo-insulator to that of a pseudo-conductor with a conductivity ratio of 10⁴ to 10⁶.

The main difference between these competing materials is the transition temperatures and states stability. The VO₂ transition between the insulator and the conductive states occurs around 68°C, whereas for chalcogenide materials, temperatures of several hundred degrees are expected. However, to keep VO₂ in the conductive state, a heat source must be maintained, while for chalcogenide glasses, both states are stable. This implies that the source can be switched off once the transition is complete.

Additionally, the selection of the heat source type is crucial. There are two primary types of sources. First, it is possible to use an electrode beneath a PCM layer, heating it through the Joule effect [8]. However, this requires electronic control, which faces the same coupling challenges as electronic components. This is why directly heating the PCM layer with a laser diode can also be interesting. Two approaches can be envisioned: heating all layers with a single laser by diffracting its beam to radiate only specific areas, or utilizing multiple lasers via an optical fiber circuit. Both alternatives offer the advantage of minimizing coupling concerns as there would be no longer any electronic control circuit.

Given these advantages, we present here a proof of concept

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of a tunable feeding network based on chalcogenide thin films. First, the concept of the tunable phase shifters will be introduced. Then, the application of these phase shifters to the feeding network.

II. DEVELOPMENT

In this paper, our objective is to design a multi-state feeding network with four output ports. First, in the initial scenario, an equal phase is applied to each port. In this case, the radiation direction will be the same as it would be with a single antenna. Then, the targeted phase law will result in a -90° phase difference between each output. Such a phase law results in a 30° beam steering compared to the first scenario. However, other states could be achieved by applying different phase laws, with phase differences less than -90° . For instance, using the notation shown in Fig. 1, applying equal phase shifts to port 1/2 (-90°) and 3/4 (0°) would represent an intermediate state.

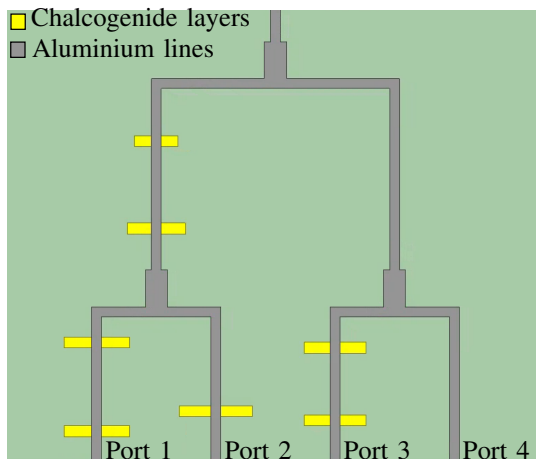


Fig. 1: Top view of the simulated feeding network

A. Phase shift modeling

To model and design our phase shifters, we use filtering theory. The model is based on typical known phase response of first order filters. These filters are known to imply a phase difference up to -90° between its accesses. The 0° to -90° variation is led by a special point which is corresponding to the cut-off frequency of the filter. At these specific frequency, the phase should be -45° .

More specifically, we chose to use an RC filter for our model. The advantage of this topology lies in its simplicity and the relatively straightforward implementation of the capacitive component in a microstrip line. Indeed, the resistance can be readily associated with the losses of the transmission line, which are related to the characteristic impedance, while the capacitive component can be achieved through local widening of the line. When widening a transmission line, the capacitive behavior is favored relative to its inductive behavior.

To estimate the equivalent value C of the low impedance Z_c , which is the impedance of the wide line, it is possible to use the following relation :

$$C = \frac{l}{Z_c v_\phi}$$

where l is the length of the capacitive line, Z_c the characteristic low impedance of the line and v_ϕ the phase velocity, which depends on the substrate characteristics (basically dielectric permittivity and thickness).

From the values of these two component R and C , the cut-off frequency of the model filter is given by : $f_0 = 1/(2\pi RC)$. The phase variation ϕ is then described by the following relation :

$$\phi = -\arctan(\omega/\omega_0)$$

Finally, the relation between the impedance of the capacitive line and the phase difference of the filter is :

$$Z_c = -\frac{\omega l R}{\tan(\phi) v_\phi}$$

where ϕ is the phase shift from the RC filter at the pulsation $\omega = 2\pi f$. For the approximation to be accurate, the length of the line l has to be small compared to the wavelength.

This relation makes us able to compute the impedance Z_c to introduce in the transmission line to have the desired phase variation ϕ from the initial line. Then, the phase shift is realized through the introduction of an impedance step in an initial transmission line. The global phase response of this line is composed by the classic phase variation of the line plus the phase response of the impedance step, modeled by the RC filter.

However, this model filter is a low-pass filter. This means the transmitted wave magnitude over the cut-off frequency will decrease quickly. So, from the 0° to -90° phase variation interval, only the 0° to -45° part can be usable. Also, the magnitude level is -3 dB at f_0 , the real usable interval should even be smaller than $[-45^\circ, 0^\circ]$.

The application of these phase shifters to antenna array feeding network is illustrated in the next point.

B. Realization

The widening is realized by deposition of thin chalcogenide layers, that have the ability to change its state, from a pseudo-insulator one to a pseudo-conductor. For every circuits that will be discussed thereafter, we consider a $350 \mu m$ thick silicon substrate with high resistivity ($> 10\,000 \Omega.cm$) and $1 \mu m$ aluminium thick lines. The chosen chalcogenide composition is the nominal composition $Ge_2Sb_2Te_5$, deposited by RF magnetron sputtering with a thickness of 600 nm. Furthermore, to avoid any chalcogenide film breaks because of the level difference between silicon and aluminium lines, the whole surface is fully planarized by an insulating layer of SiO_2 in combination with dry etch back technics, before the deposition of the chalcogenide layer. The final structure is shown in Fig. 2.

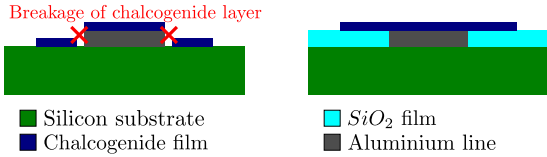
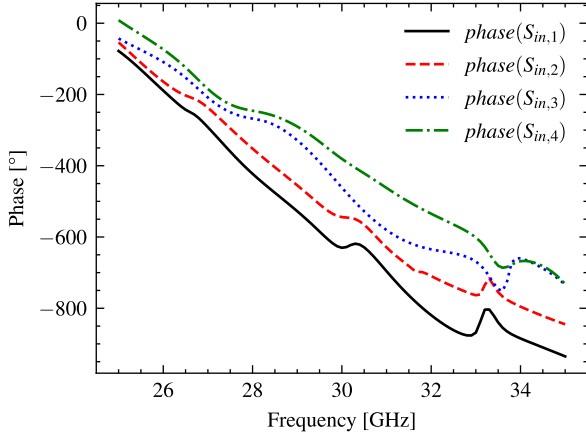


Fig. 2: Illustration of the reason to use SiO_2 to avoid chalcogenide film breaks



	Phase value at 30 GHz	Phase difference at 30 GHz
$phase(S_{in,1})$	-630°	-86°
$phase(S_{in,2})$	-544°	
$phase(S_{in,3})$	-460°	-84°
$phase(S_{in,4})$	-380°	-80°

Fig. 3: Phase response of the feeding network

Our chalcogenide layers have a thickness of 600 nm and exhibit a crystalline electrical conductivity of approximately 10^5 S/m. However, this non-ideal conductivity introduces some transmission losses. These characterizations were performed using four-point probe measurements and retro-simulation techniques.

All the chalcogenide parts in the feeding network are shown in yellow in Fig. 1.

C. Results

To handle the initial goal of a 90° phase difference between each outputs, more than one filter have been necessary to implement by output as it can be seen in Fig. 1. By placing multiple impedance steps in series, the phase differences accumulate, allowing us to reach, at 30 GHz, respectively -86° , -84° and -80° between ports 1 and 2, 2 and 3, 3 and 4. The simulated response is shown in Fig. 3. The difference of a few degrees between the ideal -90° and the simulated phase differences is acceptable, considering that the -90° uniform phase differences result in a 30° steering angle, whereas it supposed to be 28° with the simulated values.

However, once the phase differences between the outputs are established, a discrepancy in magnitude becomes apparent. These discrepancies are evident in Fig. 4. The greater the number of steps, the less power is transmitted. It is

also worth noting that each step is designed to possess a model cutoff frequency significantly higher than the 30 GHz operational frequency. This implies that the model filter is not intended to attenuate the signal at the operational frequency. Concurrently, the steps are likely to induce some parasitic reflections, contributing to the losses observed in Fig. 4.

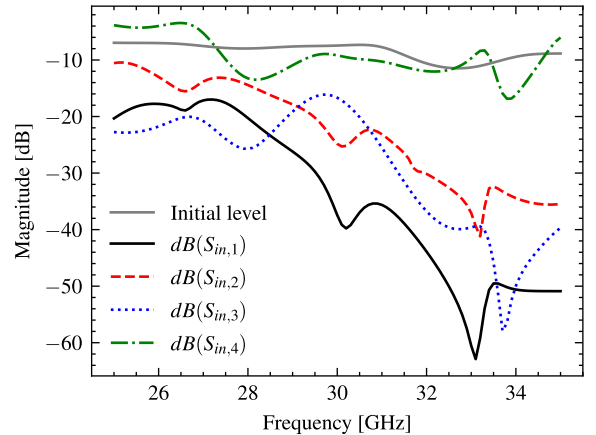


Fig. 4: Magnitude response of the feeding network

To address or mitigate this concern, two approaches are currently being investigated. Firstly, introducing gradual transitions between the steps could potentially reduce the parasitic reflections and subsequently lower the losses. These types of gradual variations have been explored in greater depth within this paper [9].

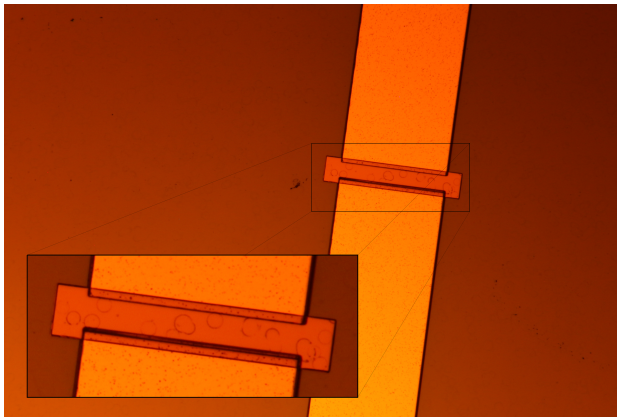
Furthermore, some issues happened during the deposition of our circuits, disabling the chalcogenide layers to fully crystallize and reach a sufficient conductivity at the crystalline state. The main reason we study at this point is an unwanted reaction between the SiO_2 and the chalcogenide layers. Indeed, some kind of "bubbles" are appearing inside the chalcogenide layers only above SiO_2 , as Fig. 5 illustrates.

III. CONCLUSION

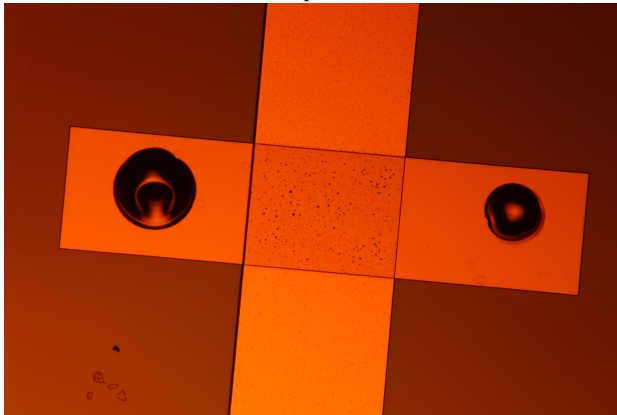
This paper presents a new type of phase shifter achieved through the use of phase-change material and a modeling method based on filter theory. This method uses the capability to modify the geometry of a transmission line to introduce a first-order RC filter. The phase-change material is employed to create a highly low-impedance region within the original transmission line. Subsequently, filter theory predicts the phase response of such a filter. By operating below its cutoff frequency, the filter exclusively adjusts its phase.

An application of these phase shifters is suggested. It aims to achieve a 30° beam steering through the application of a phase law in the feeding network. Given the objective to reach the -90° phase difference between the four outputs of the array, multiple phase shifter are needed.

Finally, the achievable phase differences between each successive couple of outputs are respectively -86° , -84° and -80° . From this perspective, the initial objective is achieved



(a) Amorphous state



(b) Pseudo-crystalline state

Fig. 5: Bubbles apparition illustration.

with an expected error of only 2° in the beam steering goal, but other issues have been highlighted. Indeed, the power distribution becomes highly uneven and prevents us from expecting a good radiation response. More developments are required to reduce this effect. Among the potential solution, using non uniform transmission line [9] to transform our brutal impedance steps to progressive impedance steps could help us to reduce the losses we observed at this point.

From the realization point of view, some studies have to be done before a real measurement, due to some issues between the materials used in this proof of concept.

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