Tunable Ferroelectric Filter-Phase Shifter

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Abstract **— Design of a tuneable filter-phase shifter is presented. Thin ferroelectric film varactors are used to provide voltage tuneable phase shift in a silicon Coplanar Waveguide (CPW). Varactors with zero bias capacitance 0.17pf, loss tangent tanδ=0.04 and 20% tuneability provide continuous voltage tuneable phase shift up to 90°±5° at 19 GHz with 10% bandwidth. The figure of merit is about 30°/dB. The sizes of the phase shifter silicon chip are less than 2x5.5mm. The phase shifter is designed for possible integration in silicon MMIC's.**

I. Introduction

Most of microwave electronically scanning Phased Array Antennas (PAA) are controlled by ferrite or P-I-N diode phase shifters [1]. Magnetically controlled PAA are typically bulky and costly, while P-I-N diode PAA consume considerable DC power. PAA based on ferroelectrics shifters [2-5] offer substantial cost and size redaction along with significant reduction of controlling DC power. Feroelectric phase shifters reported in the past [5-8] are mainly of delay line types using regular sections of transmission lines with ferroelectric films. The differential phase shift in these phase shifters increases linearly with frequency, which is not desirable in many applications. In this work, we present a design of a ferroelectric phase shifter based on a tuneable band-pass filter. The design of the filter optimized so that in a given frequency band the phase shift is nearly constant.

It is well known that in band-pass filters the slope of phase-frequency dependence increases with increased number of resonators. Thus a substantial phase shift, which is controlled by a number of resonators, can be achieved if the filter is tuneable. We used this property of filters to develop ferroelectrically tuneable phase shifter where, in contrast to delay-line-type phase shifters [4-9], the frequency dependence of the differential phase shift is substantially reduced. In this work the filter tuning, and hence phase shift, is achieved by using DC field controlled thin film ferroelectric varactors in the resonators periodically loading CPW. The frequency selectivity (filtering) is an added future desirable in some system applications.

For the filter-phase shifter we choose coplanar design based on a silicon substrate with a ferroelectric film [9]. The use Coplanar Waveguide (CPW) with a ferroelectric film makes the design simpler and enables to exclude the on-chip DC biasing network from the phase shifter's design. Additionally, we keep the design symmetric to avoid excitation of slot line mode, and hence to exclude the wire bonding or air bridges between ground plains of CPW.

The equivalent circuit of the device is optimized using ADS circuit simulator. Under two different DC bias fields the equivalent circuit is considered as a periodically loaded line. The load is realized as a resonator with positive or negative admittance above and respectively below its resonance frequency. Different parts of the phase shifter's layout are then simulated separately in ADS's Momentum, where the actual discontinuities of the layout are taken into account. The experimentally measured complex impedance of ferroelectric varactors are used to verify and adjust the layout.

II. Design Of Phase Shifter

A. The substrate

The cross-section of the substrate used in the phase shifter design is sketched in Fig.1. The use of silicon is dictated by the desire to make the phase shifter potentially

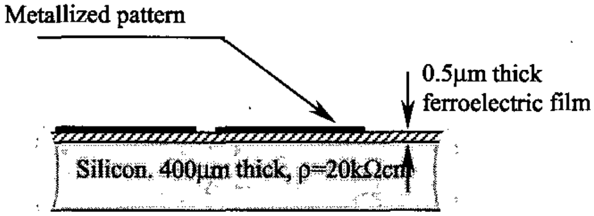

Fig.1 Cross-sectional of the phase-shifter substrate.

compatible with silicon MMIC's. The ferroelectric film covers whole substrate uniformly.

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B. Circuit simulations

First, we simulated the performance of four-pole filter-phase shifter in ADS using its equivalent circuit representation. Fig.2 represents the equivalent π-network and the layout of a tunable unit cell (tunable resonator) used in the phase shifter. The inductance is realized as two coupled 60μm wide slots with 60μm spacing embedded in the ground planes of CPW. Use of two coupled slots instead of a single slot stub makes it possible to reduce the transverse size of the device. Four identical inter-digital capacitors, C_{res}, are used in this cell to maintain the symmetry.

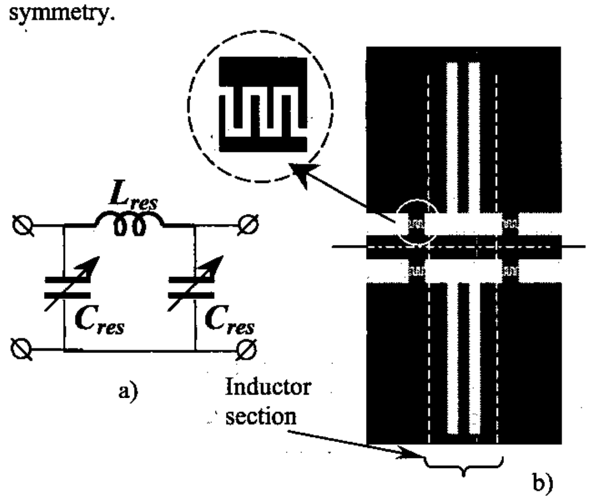


Fig.2 Equivalent circuit (a), and layout (b) of the resonator.

There is no an adequate model for two coupled slot lines in ADS circuit simulator. To overcome the problem we used duality principle enabling to adopt the ADS model of coupled lines (with common ground plane) to represent two coupled slot lines[10]. The dual circuit representation of the structure from Fig.2b is given in Fig.3.

We consider the equivalent circuit of phase shifter as a four-pole band-pass filter consisting of simple transmission line sections for coupling the resonators

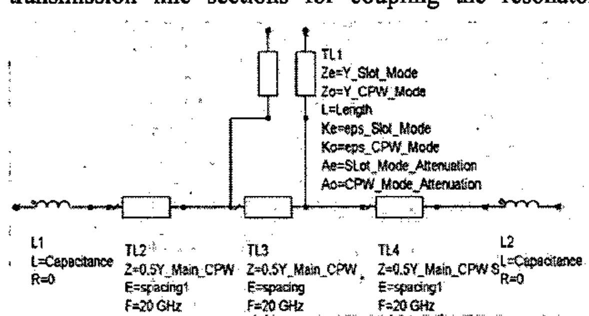


Fig.3 Dual circuit representation for the layout from Fig.2b.

shown in Fig.3. In principle, one can use series capacitances or parallel inductances to realize the invertors. However, this may lead to having complex DC bias networks, which is not desirable from performance and size points of view. In order to reduce the number of discontinuities in the final layout the impedance of the lines used for inter-resonator coupling was fixed to be 50 Ohm. This restriction was compensated for by an extra degree of freedom associated with the arbitrary lengths of coupled slot line sections used in resonators, Fig.2, and transmission line sections used for inter-resonator coupling. Than an optimization, targeted on the input matching and differential phase shift, with specified deviations, is carried in ADS. As a result, the equivalent circuit of the phase shifter (tunable filter) with known parameters of a varactor and all characteristic sizes is found.

C. The layout and performance

In the next step all parts of the equivalent circuit where assembled and simulated in ADS Momentum to verify the design and account for all discontinuities. Due to the uncertainties in fabrication process the parameters (permittivity, losses) of the ferroelectric film are hard to specify correctly beforehand and use them in Momentum simulations. The tuneability of ferroelectric film is of importance only for varactors since the width of the gaps in varactors is typically 1μm and a DC bias applied between the center strip and ground planes of the CPW induces substantial change in the underplaying ferroelectric films under these 1.0 μm gaps. Due to the large width of the slots the rest of the circuit is practically insensitive to permittivity of ferroelectric film. Instead of Momentum simulations we use experimentally found parameters of varactors. A number of test structures are fabricated and measured to extract the loss tangent, capacitance and tuneability under applied DC voltage. A section of CPW loaded with two test varactors is shown in Fig 4. Another unloaded CPW is also fabricated and measured to enable accurate extraction of varactors parameters, which are

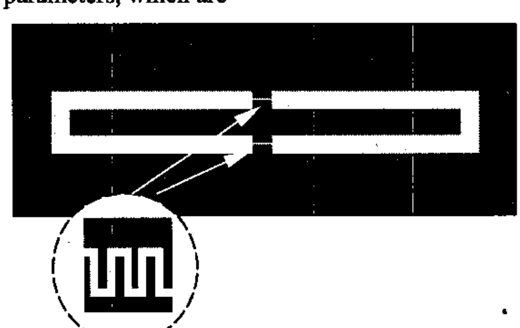
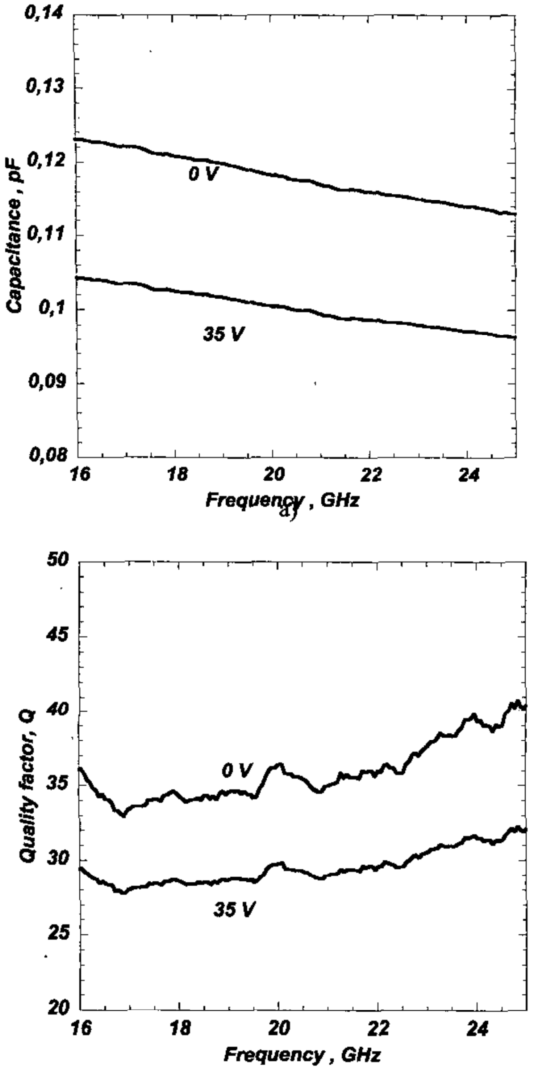


Fig.4 CPW with embedded varactors

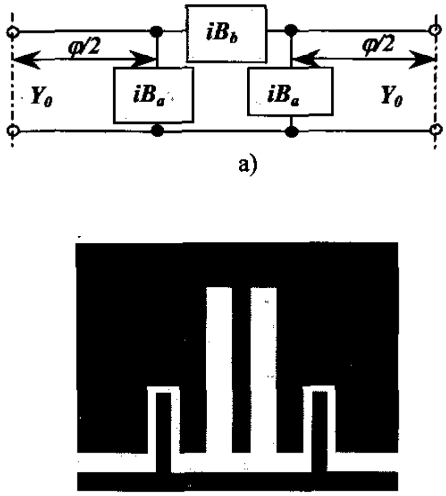
than used in final simulations. Typical results of measured ferroelectric varactors for two different DC bias voltages are given in Fig.5.



b)

Fig.5 Extracted parameters of a varactor: a) capacitance; b) quality factor.

As an intermediate designing step we also put some efforts in circuit miniaturization: nearly two times physically shorter inverters where designed to replace all 90° sections of transmission lines (inverters). The equivalent circuit and the layout (only symmetric half) of the designed in "Momentum" inverters are presented in Fig.6a, b respectively.



b)

Fig.6 An equivalent circuit of inverter (a), and utilized CPW layout (b).

Finally, the inductor stubs, Fig.2b, are simulated in Momentum to account for discontinuities and losses associated with the design of the slots.

The datasets of all separately simulated parts of the filter-phase shifter and lumped equivalent of the measured varactor are used to simulate the performance of complete device. The layout of the final phase shifter topology is shown in Fig.7. Simulated performance of the phase shifter under different voltages is given in Fig 8.

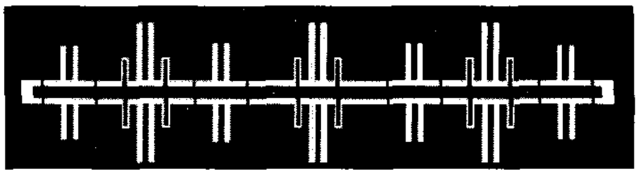
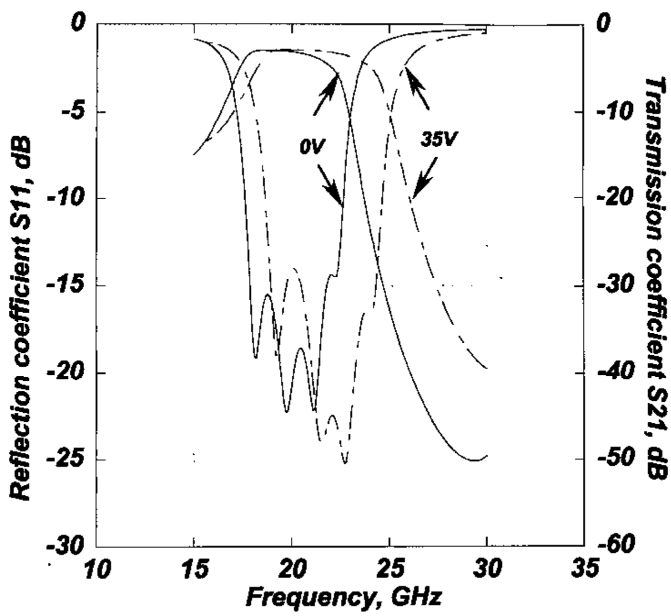


Fig. 7 Layout of the designed phase shifter

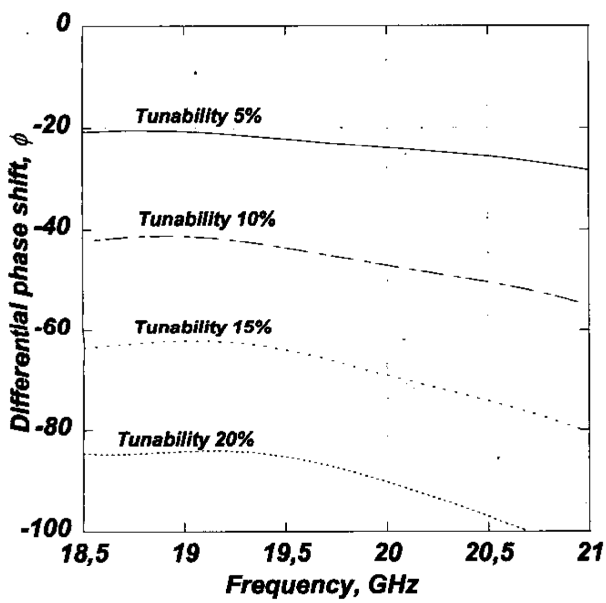
About -14dB input matching is achieved in the entire band 18.5-20.5 GHz. The insertion losses in the pass-band is about –3.3÷3.5dB, which corresponds to a figure of merit 30°/dB. The differential phase shift increases with increased DC bias and remains nearly constant within 10% band.

CONCLUSION

Experiment based design of a tunable filter-phase shifter is presented and discussed in details. The device has a potential of integration with SiMMIC`s and may be useful



a)



b)

Fig.8 Simulated reflection and transmission coefficients (a) and the differential phase (b) with varactors tunability as a parameter.

for applications in adaptive/reconfigurable cellular microwave communication systems.

ACKNOWLEDGEMENT

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