Tuneable Metamaterials Based on Ferroelectric Varactors

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***Abstract*— In a brief introduction the ferroelectric varactors are compared with the other tuneable technologies and identified as one of the most adequate components for utilizing tuneable metamaterials. The main features distinguishing the ferroelectric varactors are the extremely low control power consumption and high speed. Some examples of the ferroelectrically controlled 1D metamaterials are given followed by an example of a microstrip line based on a tuneable ground plane in the form of 2D metamaterial.**

I. INTRODUCTION

Recent advent of the metamaterials concept helps unwrapping new and unexpected properties of microwave circuits, especially in 2D and 3D implementations [1], [2], [3]. A further extension of the performances and functionalities of the metamaterials may be anticipated if the metamaterials, depending on technical implementation, incorporate tuneable components. In general, the tuneable microwave components utilize different physical effects and materials [4], such as semiconductors (p-n, Sckottkey, HBV, transistors); mechanical (micro- and nano, i.e. MEMs); ferromagnetic/ferrite; dielectric (ferroelectric, liquid crystal), plasma etc. MEM varactors [4] have low losses and may be used in applications where the tuning speed and cost are not critical issues. The semiconductor varactors have low Q-factor and large leakage currents. The magnetic components typically require large control power and are bulky. The same applies to devices based on plasma [5]. The liquid crystals [6] have some promising features (i.e. low loss); however, the tuning speed they offer is even slower then that of MEMs. The ferroelectric varactors are one of the most adequate components for applications in 2D and 3D metamaterials consisting of a very large number of varactor tuned unit cells.

In this work examples of tuneable 1D metamaterials based on ferroelectric varactors are given. In a more detail a microstrip line based on a 2D LC network, incorporating ferroelectric varactors, is discussed.

II. ADVANTAGES OF THE FERROELECTRIC VARACTORS FOR APPLICATIONS IN TUNEABLE METAMATERIALS

Low leakage currents make the ferroelectric varactors an ideal candidate for applications in tuneable metamaterials consisting of large arrays of unit cells, especially in power hungry (portable, onboard etc.) systems. Table I attempts to compare the leakage currents of the main tuneable technologies useful for metamaterials applications. Small drive/control powers also ensure avoiding the heat generation and cooling problems.

TABLE I LEAKAGE CURRENT COMPARISON

Type	Material	Leakage current μA	μA/pF
Schottky (UMS)	*GaAs*	0.01 (@-4V)	0.1
Abrupt junction	*Si*	10 (@-30 V)	25
Heterostructure barrier	*GaAs based*	7 (@12V)	240
Parallel-plate (Chalmers)	*BaSrTiO*	$2 \cdot 10^{-4}$(@20V)	$8 \cdot 10^{-4}$
Coplanr-plate (Chalmers)	*NaKNbO*	$1.5 \cdot 10^{-4}$(@20V)	$1.5 \cdot 10^{-3}$

The next important for metamaterials applications feature of the ferroelectric varactors is the low loss. Below 10-20 GHz the losses are comparable with the semiconductor varactors, while above 20 GHz they are superior to semiconductors [7]. In this sense the ferroelectric varactors seems not to have competitors. They offer much faster tuning speeds in comparison with the competing technologies.

The extremely high permittivity (up to several thousands) of the ferroelectrics offers a considerable size reduction. Small sizes of the varactors allow their applications up to THz frequencies and wide band metamaterials. The size reduction may be especially considerable in metamaterials where the ferroelectric is used as a host dielectric medium.

Ferroelectric varactors have simple, fabrication-friendly designs (parallel-plate and coplanar-plate), and offer greater flexibility and integration capability in microwave metamaterials consisting of large arrays. They allow easy scalability in terms of tuning voltages, and trading the loss against the tuning range. It is easy to scale for high voltage/high power and low voltage low power (for mixer, harmonic generators etc.) applications. It is easy trade the losses against lower tuneability. The symmetric *C-V* dependence allows simpler DC bias networks, often making them a part of the metamaterial itself.

III. TUNEABLE FREQUENCY SELECTIVE (SSF) AND IMPEDANCE SURFACES FOR FREE SPACE APPLICATIONS

Typically the tuneable impedance surfaces, or artificial impedance surfaces, are built as a lattice of sub-wavelength metallic patches on grounded dielectric substrates. Using varactor diodes, the surfaces impedance of these structures may be reconfigured. Tuneable impedance meta-surfaces are proposed for applications in reconfigurable beam steering reflector" for steering and/or focusing a radio frequency beam. In spite of the potential advantages of the ferroelectrics, not many free space tuneable metamaterials, based on ferroelectrics, are reported [8]. The scanning antennas reported by [9] [10], may be regarded as prototypes for metamaterials implementation. A tuneable "metasurface" based on ferroelectric films have been proposed in [11], which is based on mushroom structure. In [12] a tuneable high impedance surface based on ferroelectric films is reported with measured tuneability of 62%

IV. INTEGRATED TUNEABLE METAMATERIALS BASED ON FERROELECTRIC FILMS

A. 1D microstrip and CPW metamaterial devices

Recently a number of 1D tuneable metamaterials based on ferroelectric varactors have been reported. An experimental CPW periodically loaded by ferroelectric varactors [13] had tuneable electromagnetic bandgap performance, useful for applications as a tuneable low pass filter. A synthetic coplanar strip transmission line ultra wide band tuneable delay line was reported in [14]. Tuneable Left Hand (LH) [15], and Composite LH and Right Hand (CLHRH) 1D [16] metamaterial structures based on ferroelectric varactors and coplanar waveguides have also been demonstrated.

B. Tuneable ground planes in microstrip lines

1D [17] and 2D [18] tuneable ground planes in microstrip lines, using ferroelectric varactors, have been reported recently. In these designs the integration includes three metal levels. An extra low loss low permittivity polymer (BCB) layer is used for fabrication of the low loss microstrip. The ground planes are implemented in the bottom metal layers M1 and M2 separated by a ferroelectric film. The parallel plate varactors are formed where the M1 and M overlap. The advantages of the tuneable ground planes may be summarised as follows:

- Safety for DC field sensitive components mounted on the surface of the substrate,
- Wider bandwidth. The bandwidth is limited by the bandwidth of the metamaterial ground plane, which may be quite large, given the fundamental properties of the metamaterials,
- The ground plane may be designed to have anisotropic properties, bandpass, bandstop or other useful metamaterial properties opening up extra design flexibilities and new functionalities
- More space on the substrate surface for other/useful circuit components
- Due to the more uniform (in comparison with the microstrip line itself) current distribution in the ground plane the devices based on metamaterials may have rather low losses in comparison with the 1D metamaterials implemented in the top microstrip line.

A fragment of the 2D *LC* network based ground plane [18] is shown in Fig.1. Fig.1a shows a 5μm x 5 μm parallel-plate ferroelectric varactor connected to the inductive strips. Fig.1b shows the input section of the microstrip line and the large DC decoupling inductors connected to the DC bias pads. In Fig.1b the tuneable ground plane is seen through a 10 μm thick transparent BCB layer. The main 30 μm wide microstrip is on top of the BCB layer. To ensure no reflections from the edges of the "metaground" plane it has to be loaded by matched resistors. However, in this initial experiment, to keep the fabrication process simple, no resistors are included. As a result the DC decoupling inductors, Fi.1b, have a rather substantial effect, especially at lower frequencies. The details of the design and the fabrication procedure are given in [18]. The measured transmission coefficient S21 at 0 and 20 V DC bias, and differential phase shift are shown in Fig.2.

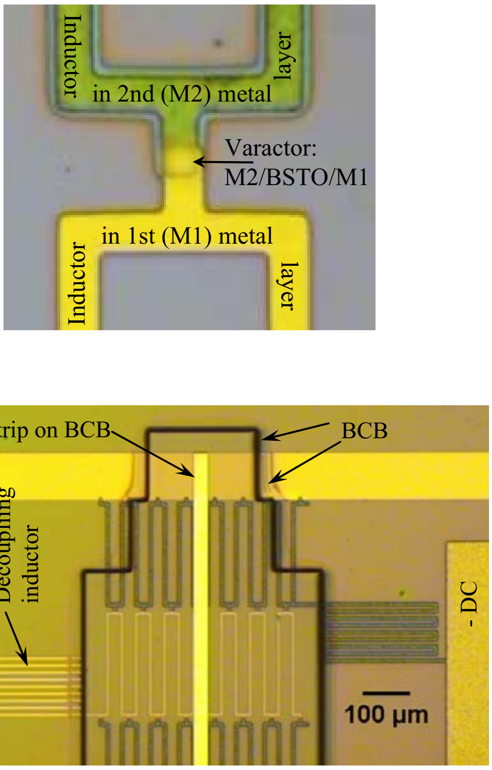
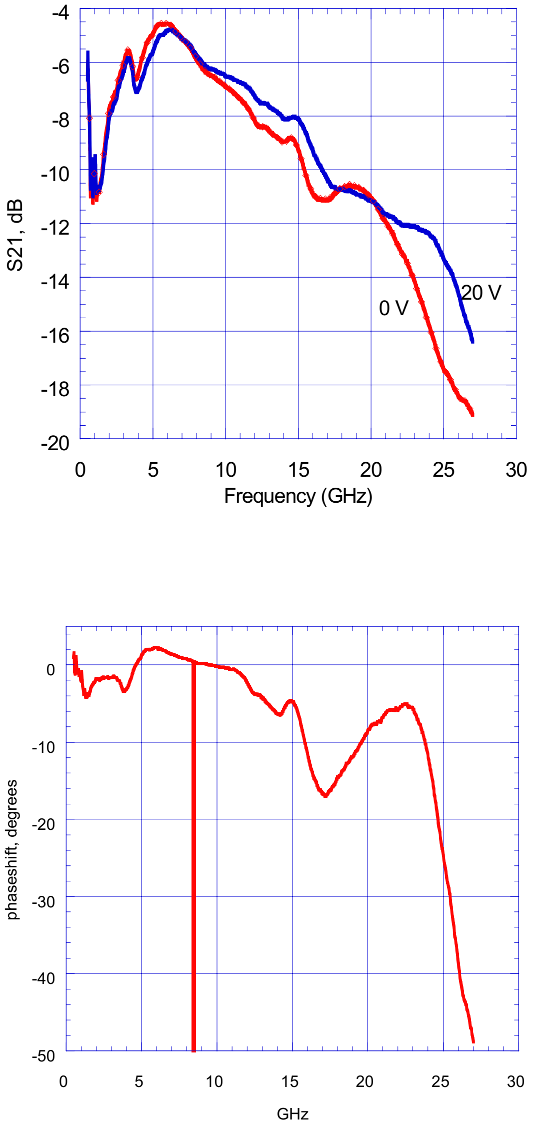


Fig. 1 The ferroelectric varactor and inductive strips (a) and a fragment of the microstrip based on tuneable "metaground" plane (b)

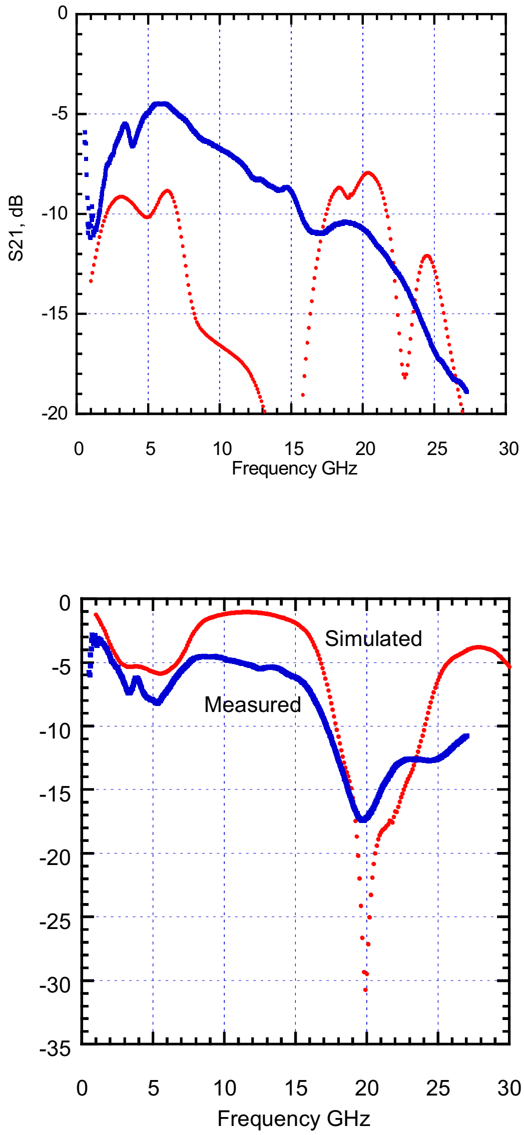
The series resonant frequency of the simple unit LC cell is about 30 GHz. However, due to parasitic capacitive and inductive couplings it appears to be at about 20 GHz, which may be observed in measured performances. The measured and simulated S-parameters shown in Fig.3. The MOMENTUM simulated distribution of the current in the microstrip and ground plane at three frequencies of interest are shown in Fig.4. The effect of the DC decoupling network is seen from the current distributions shown in Fig.4.



a)

b)

Fig. 2 Measured S_{21} at zero and 20 V bias fields (a), and the differential phase shift (b)



a)

b)

Fig.3 Comparison of the simulated and measured S-parameters

V. CONCLUSIONS

In the discussed experimental example the tuneable ground plane, includes ferroelectric varactors, is considered as a demonstration of potential in terms of the tuneability and losses. In inductive regime it acts as a delay line structure. Near the series resonant frequency the ground plane acts a pass band filter, while above resonant frequency it acts as a capacitive surface ("magnetic wall"), i.e. the ground plane "disappears" resulting in a strong radiation into the substrate and free space.

In spite some problems associated with the effect of the decoupling network, the concept is demonstrated- the complex metamaterials ground plan is tuneable (about 10%) and the losses (about 1dB/mm at 6.0 GHz) are acceptable. The 2D LC network conations 112 ferroelectric varactors connected in parallel. The total current consumption at maximum DC bias 20 V is less then 1.0 μA. A further improvement of the DC decoupling, and LC networks is expected to improve the performance of the 2D ground plane.

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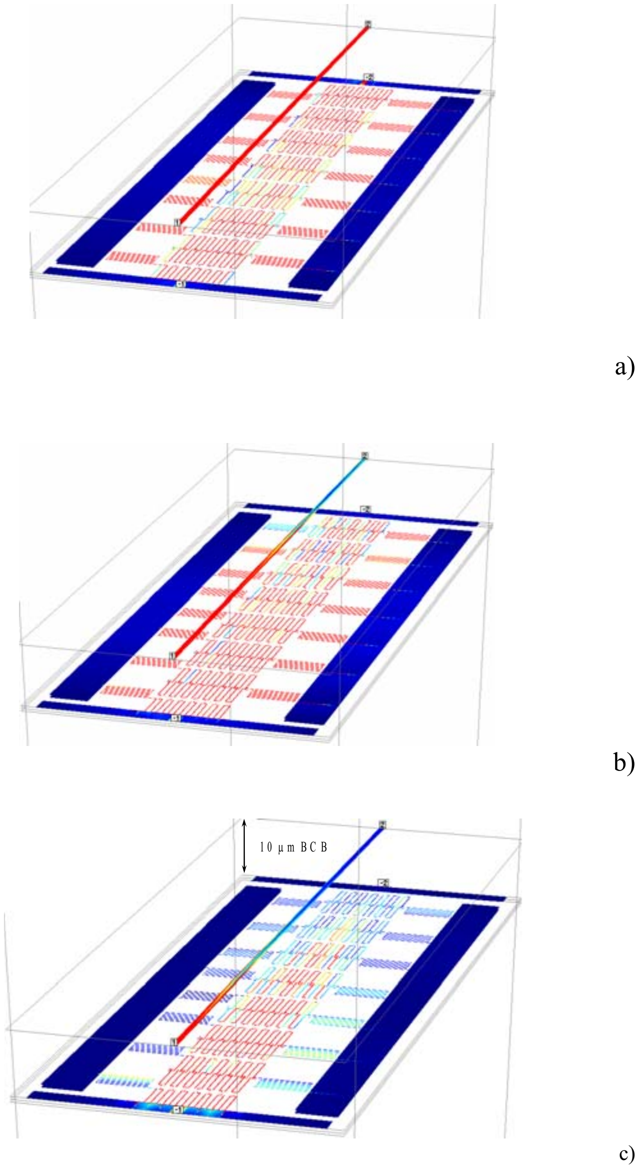

Fig.4 Simulated current distribution at 5.3 (a), 20 (b) and 30 GHz (c)

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