Progress In Electromagnetics Research Letters, Vol. 21, 89–98, 2011

WCIP APPLIED TO ACTIVE PLASMA CIRCUITS

N. Raveu, G. Prigent, T. Callegari †, and H. Baudrand

Université de Toulouse, INPT, LAPLACE, ENSEEIHT, CNRS
2 rue Charles Camichel, 31071 Toulouse cedex, France

Abstract—The Wave Concept Iterative Procedure is validated for multi-layered substrate with frequency dependent and negative index media. By shifting the plasma frequency, reconfigurable filter design is proposed with a center frequency tunability of 25%. Sensitivity to collisional plasma is proposed.

1. INTRODUCTION

The ever growing demand for compact and low cost communication systems has led to the development of single devices operating at multiple frequency bands that can reduce manufacturing cost and space occupation. Within this context, devices integration and miniaturization is a challenging key point for designers. Reconfigurable devices are generally controlled by the use of switching or tuning elements such as semiconductor varactors, MESFETs or PIN diodes [1–3]. Nevertheless, such components are characterized by a noise level which is detrimental to the system noise figure. Tunable techniques based on electrically controllable material such as ferroelectric [4–6], liquid crystal [7] or ferromagnetic material [8–10] can be used. However, such components suffer from long reaction time and power consumption.

In plasma actuation case, the required voltage level is still high nevertheless plasma performances are of particular interest since their physical properties evolution with external actuation are fast [11]. Moreover, plasma media may have either metallic or dielectric properties as a function of the frequency [12]. The use of plasma media as a substrate allows reconfigurable devices design versus plasma frequency choice. Up to the plasma frequency, its permittivity remains

Received 7 January 2011, Accepted 14 February 2011, Scheduled 1 March 2011
Corresponding author: Nathalie Raveu (raveu@laplace.univ-tlse.fr).
† T. Callegari is also with Université de Toulouse, UPS, LAPLACE, CNRS, 118 route de Narbonne, 31062 Toulouse cedex 9, France.

between 0 and 1 therefore some software can not perform simulations (ADS, Momentum...), whereas below the plasma frequency, it behaves as a lossy conductor therefore other software are also in default considering the all frequency band (HFSS...). To ease the designers' conception, software must allow the plasma HF simulation over the entire frequency band.

The Wave Concept Iterative Procedure is an integral method based on wave concept [13] and particularly well adapted for multilayered circuits [14]. This method allows a complex definition of the permittivity so that the plasma characteristics are defined on the all frequency range below and up to the plasma frequency.

In this paper, the design of a reconfigurable plasma filter is proposed and simulated with the WCIP method. Results are compared to HFSS simulations with success for the dielectric behavior.

2. PLASMA RECONFIGURABLE FILTER

2.1. Plasma Properties

The plasma behavior is resumed in its permittivity definitions (1) or (2) depending if collisions are considered which is the case in the Equation (2).

$$\varepsilon_r = 1 - (\omega_p/\omega)^2 \tag{1}$$

$$\varepsilon_r = 1 - \left((\omega_p/\omega)^2/(1 - j(\nu_p/\omega))\right) \tag{2}$$

with ω the pulsation, ω_p the plasma pulsation and ν_p the plasma collision frequency (its value is now fixed to $0.5\omega_p$ [15]). This value is considered in order to evaluate the filter performance with moderate loss. The purpose of this paper is to validate the simulation tool, if the filter is achieved this data should be reevaluated.

If ideally the plasma frequency is considered as the plasma cutoff frequency, when collision occurs one must take into account ν_p. Therefore around $0.86 f_p$ the plasma behave as a lossy conductor whereas above this value its dielectric properties dominate as depicted in Figure 1.

2.2. Resonator Design

When designing the resonator, the topology must be sensitive to dielectric changes. Therefore the proposed benchmark consists of three dielectric layers, one plasma layer inserted between two alumina layers for top- and bottom-metal layers deposit. The dielectric thicknesses were optimized so as to ensure a wide tenability for the relative

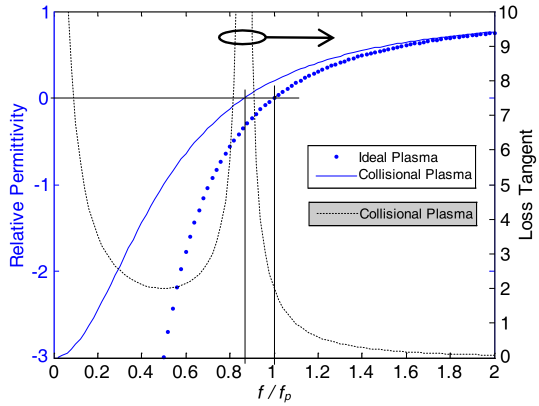


Figure 1. Plasma permittivity versus frequency.

permittivity. Moreover, in a plasma use the dielectric must satisfy good thermal characterization (coefficient of linear thermal expansion, thermal conductivity, etc). Thereby, due to its mechanical and thermal specifications as well as its good electrical characteristics alumina layers have been chosen. An accordable filter is designed based on the plasma property seen in, e.g., (1) and its dimensions are presented in Figure 2.

The proposed topology is based on the Dual Behavior Resonator (DBR) concept [16]. It consists of two open-ended stubs that act as stop-band resonators centered at different frequencies. When the resonators are set in parallel a reconstructive combination occurs that creates a resonant frequency. Thus the DBR is characterized by two transmission zeros on either side of the pass-band. Moreover, either transmission zero or resonant frequencies are independently controllable. Thereby, when a plasma media is created the permittivity modification led to a variation of the characteristic frequencies. Since the plasma permittivity is a function of the frequency, the frequency variation is not the same whatever the frequency (resonance, low- and high-frequency transmission zeros). Such a resonator can then be used in a plasma media characterization application.

2.3. Results

Transmission and reflection coefficients of this filter are presented in Figure 3 for constant real permittivity on the frequency range. Simulations are achieved with HFSS. The center frequency of the bandpass filter is accordable with the plasma frequency, from 2.27 GHz ($\varepsilon = 1$) to 2.93 GHz ($\varepsilon = 0.1$) with the intermediate frequency of

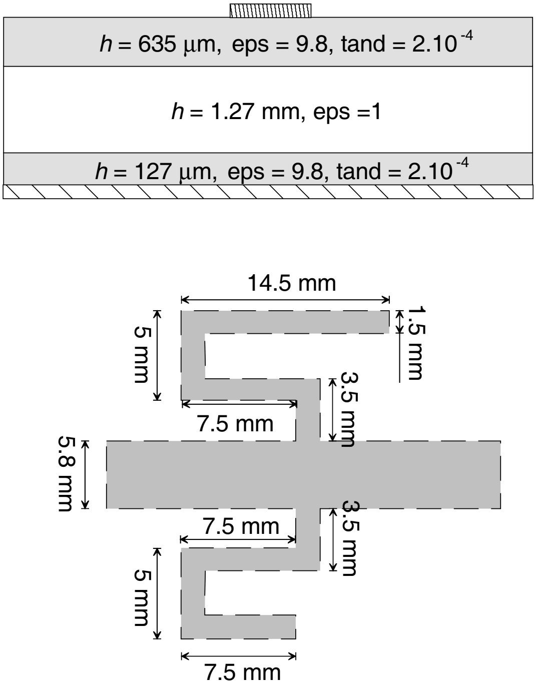


Figure 2. Filter design and dimensions.

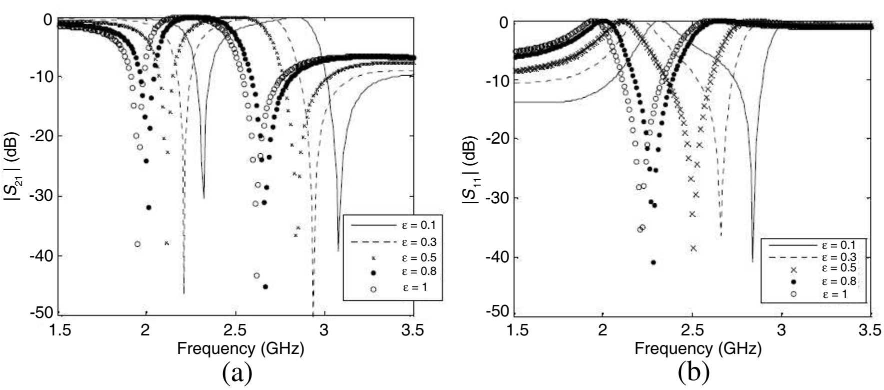


Figure 3. (a) Transmission and (b) reflection coefficients of the filter depicted in Figure 2 with substrate of real constant permittivity instead of the plasma.

2.37 GHz ($\varepsilon = 0.8$), 2.55 GHz ($\varepsilon = 0.5$) and 2.72 GHz ($\varepsilon = 0.3$).

If ideal plasma permittivity (e.g., (1) without collisions) is considered, the plasma frequency must be 2.779 GHz, 2.275 GHz, 1.8 GHz, 1.06 GHz to achieve respectively 0.1, 0.3, 0.5 and 0.8 relative effective permittivity of the substrate at the bandpass filter center frequency. Under the plasma frequency the relative permittivity is negative which is not allowed in HFSS simulations therefore new software must be used to characterize this structure behind this frequency.

3. PLASMA SIMULATION SOFTWARE

Even if only its macroscopic behavior is considered, HF software tolerating complex and negative permittivity must be chosen. ADS — Momentum do not accept dielectric specification behind 1. HFSS do not accept negative dielectric, but tolerate dielectric behind 1 including variation versus frequency through table of template. This last simulator can therefore be used to validate results for the range where the plasma behave as a dielectric. To achieve the negative index permittivity the software could be used with a variable conductivity instead, but the all band negative to positive index can not be achieved once with only one parameter specification.

3.1. Wave Concept Iterative Procedure

This integral method [13] is based on waves concept defined in spectral and space domains around interfaces of same shape. Boundary conditions are applied in the space domain while homogeneous media are taken into account in the spectral domain. Iterations are processed until convergence of the parameter under interest. This method has proved to be efficient to characterize passive circuits [14], antennas...

3.2. Multilayer Substrate Integration

The multilayer media is undertaken into the spectral operator. Instead of using the classical modal impedance of a homogeneous media, the impedance seen from the interface is evaluated for each mode as in transmission line theory. The new modal impedance is deduced for the cascade of each layer through (3).

$$Y_{in}^{\alpha} = Y_o^{\alpha}(Y_{out}^{\alpha} + Y_o^{\alpha} th(\gamma^{\alpha} h)) / \left(Y_o^{\alpha} + Y_{out}^{\alpha} th(\gamma^{\alpha} h)\right) \quad (3)$$

with Y_{in}^{α} the admittance seen from the upper interface;
Y_{out}^{α} the admittance seen from the lower interface;
Y_o^{α} the free space admittance;

h the substrate height;
γ^α the propagation constant;
α stands for TE or TM modes.

The negative permittivity affects only the propagation constant and the modal impedance values. If ideal plasma is considered, the propagation constant is real, all the modes remain evanescent. Usually, evanescent modes are inductive for TE modes and capacitive for TM modes. For negative permittivity both modes are inductive. As far as modal admittance remain purely imaginary or real positive, the convergence is assured as the spectral coefficient are lower than 1 [13]. This property is satisfied for negative permittivity with and without a complex part. The relative permittivity may be complex with a positive or negative real part without any change for the method formulation, the problems convergence is still assured.

4. RESULTS

If collisions are negligible, the permittivity is defined through (1). WCIP and HFSS results are similar for positive permittivity as depicted in Figures 4 and 5. WCIP results in Figure 5 seem physically exact for negative permittivity (i.e., below 2.275 GHz in this case), the filter response seem not altered by the negative permittivity probably because the effective permittivity of the whole substrate remains positive.

Considering only the WCIP results with variation of the permittivity in the frequency band, the frequency shift is observed

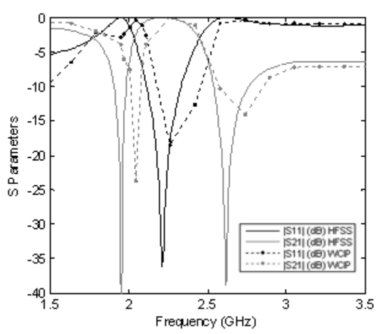


Figure 4. Filter response with plasma actuation with a plasma frequency of 1.06 GHz (relative permittivity 0.8 at 2.37 GHz).

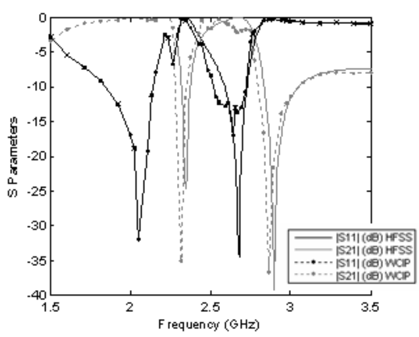
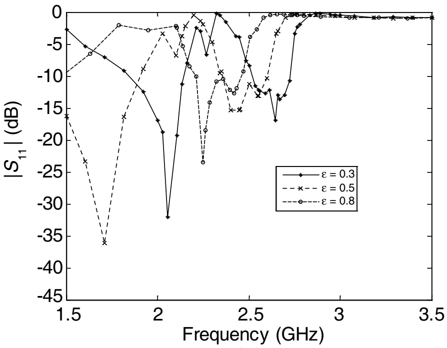
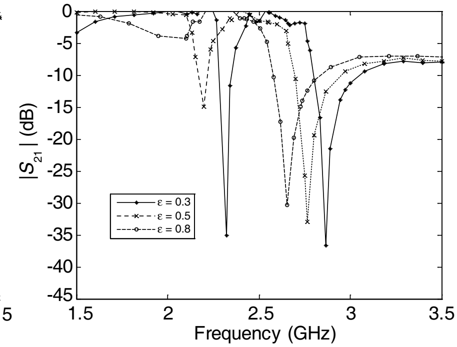


Figure 5. Filter response with plasma actuation with a plasma frequency of 2.275 GHz (relative permittivity 0.3 at 2.72 GHz).



(a)



(b)

Figure 6. (a) Transmission and (b) reflection coefficients of the filter depicted in Figure 2. With ideal plasma model see Equation (1).

with the plasma frequency control as represented in Figure 6. The dielectric constant varies in the frequency band therefore the filter band is slightly modified however the global behavior remains intact.

When Equation (2) is considered to qualify the plasma performances, the plasma frequencies, required to get the same real permittivity as in Figures 3 or 6 for the bandpass filter center frequency, change from 1.06 GHz to 1.87 GHz for a relative permittivity 0.8 at 2.37 GHz and from 2.275 GHz to 2.505 GHz for a relative permittivity 0.3 at 2.72 GHz.

WCIP results are compared to HFSS for 0.3 and 0.8 relative permittivity of the plasma layer at the bandpass filter center frequency in Figures 7 and 8. A good agreement is found for positive permittivity.

Considering only the WCIP results with variation of the permittivity and losses in the frequency band, the frequency shift is observed with the plasma frequency control as represented in Figure 9. HFSS and WCIP are in very good agreement for the highest frequencies while a little shift can be noticed on Figures 4, 5, 7 and 8 at lower frequencies. The WCIP computes mesh and operators at each frequency, while HFSS computes its mesh at the highest frequency and evaluates results on this adapted grid even at lower frequency. This slight shift may be due to mesh approximation at the lowest frequencies correlated to the strong variation of the permittivity in the frequency range. The shift may also be reduced if the number of calculation point in the WCIP is increased and the convergence criteria reduced. However, the low permittivity substrates present also important losses, in the 1.5 to 3.5 GHz range which avoid the filter use for this plasma frequency range behind 0.8.

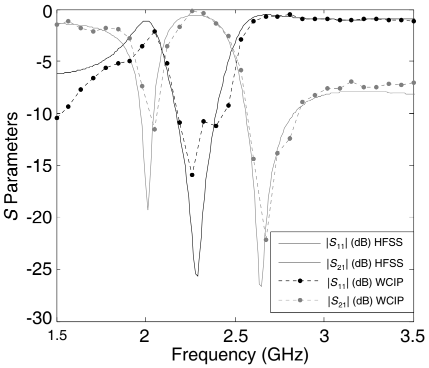


Figure 7. Filter response with plasma actuation with a plasma frequency of 1.087 GHz (relative permittivity 0.8 at 2.37 GHz).

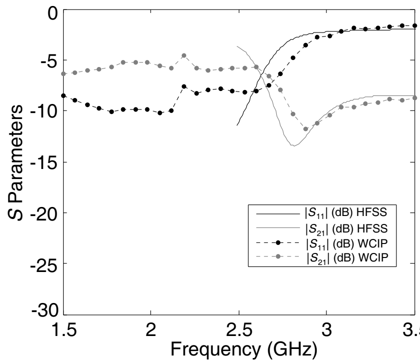


Figure 8. Filter response with plasma actuation with a plasma frequency of 2.505 GHz (relative permittivity 0.3 at 2.72 GHz).

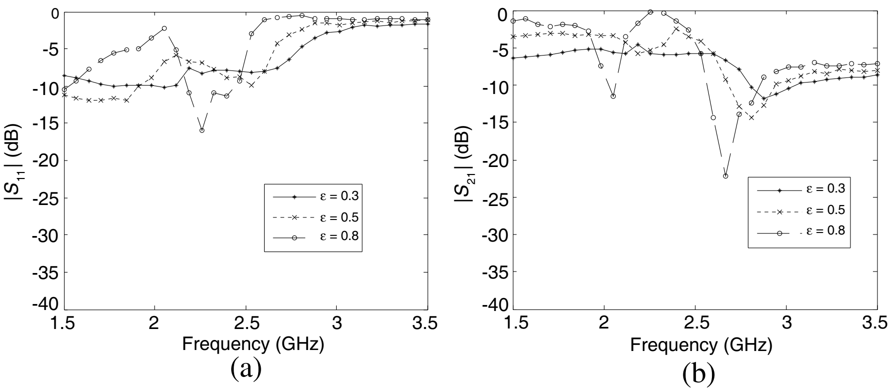


Figure 9. (a) Transmission and (b) reflection coefficients of the filter depicted in Figure 2. With real plasma model see Equation (2).

5. CONCLUSION

The WCIP method proved to be efficient to qualify negative permittivity substrate achieved in this paper through plasma use in filter design. This filter is sensitive to the plasma frequency which can be used as sensor to evaluate the plasma properties. However for plasma frequency close to the band-pass center frequency, losses dominate and the filter is no more efficient.

REFERENCES

1. Brown, A. R. and G. M. Rebeiz, "A varactor tuned RF filter," *IEEE Trans. Microwave Theory & Tech.*, Vol. 48, 1157–1160, July 2000.
2. Tanné, G., E. Rius, F. Mahé, S. Toutain, F. Biron, L. Billonnet, B. Jarry, and P. Guillon, "Improvement in losses and size of frequency tunable coplanar filter structures using MMIC negative resistance chips for multistandard mobile communication systems," *IEEE MTT-S Int. Microwave Symp. Dig.*, 1165–1168, Boston, MA, 2002.
3. Eriksson, A., A. Deleniv, S. Gevorgian, B. Lumetzberger, and N. Billström, "GaAs varactor tuned filter for low power applications," *IEEE MTT-S Int. Microwave Symp. Dig.*, Vol. 4, 2211–2214, 2005.
4. Nath, J., D. Ghosh, W. Fathelbab, J. P. Maria, A. I. Kingon, P. D. Franzon, and M. B. Steer, "A tunable combline bandpass filter using barium strontium titanate interdigital varactors on an alumina substrate," *IEEE MTT-S Int. Microwave Symp. Dig.*, 4, June 12–17, 2005.
5. Vendik, I., O. Vendik, V. Pleskachev, and A. Svishchev, "Design of tunable ferroelectric filters with a constant fractional bandwidth," *IEEE MTT-S Digest*, Vol. 3, 1461–1464, 2001.
6. Pleskachev, V. and I. Vendik, "Figure of merit of tunable ferroelectric planar filters," *33rd European Microwave Conference*, Munich, 2003.
7. Martin, N., P. Laurent, G. Prigent, P. Gelin, and F. Huret, "Technological evolution and performances of a tuneable phase-shifter using liquid crystal," *Microwave and Optical Technology Letters*, Vol. 43, No. 4, 338–341, November 2004.
8. Salahun, E., G. Tanné, P. Queffelec, P. Gelin, A. L. Adeno, and O. Ache, "Ferromagnetic composite-based and magnetically tunable microwave devices," *IEEE MTT-S Digest*, 1185–1188, 2002.
9. Salahun, E., G. Tanné, and P. Quéffélec, "Enhancement of design parameters for tunable ferromagnetic composite-based microwave devices: Application to filtering devices," *Proc. IEEE MTT-Symposium 2004*, Fort Worth, USA, 2004.
10. Tsutsumi, M. and T. Fukusako, "Magnetically tunable superconducting microstrip resonators using yttrium iron garnet single crystals," *IEEE MTT-S Digest*, 1491–1494, 1997.
11. Starikovskii, A. Y., A. A. Nikipelov, M. M. Nudnova, and

D. V. Roupassov, "SDBD plasma actuator with nanosecond pulse-periodic discharge," *Plasma Sources Sci. Technol.*, Vol. 18, No. 3, 034015, 17 pages, 2009.

12. Stix, T. H., *Waves in Plasmas*, Springer, December 1, 1992.
13. Baudrand, H. and R. S. N'Gongo, "Application of wave concept iterative procedure in planar circuits," Special Issue on Recent Research Developments in Microwave Theory and Techniques, Vol. 1, 187–197, Transworld Research Network, January 1999.
14. Wane, S., D. Bajon, H. Baudrand, and P. Gamand, "A new full wave hybrid differential-integral approach for the investigation of multilayer structures including nonuniformly doped diffusion," *IEEE Trans. on MMT*, Vol. 53, No. 1, 200–214, January 2005.
15. Sakai, O., T. Sakaguchi, and K. Tachibana, "Photonic bands in two-dimensional microplasma arrays. I. Theoretical derivation of band structures of electromagnetic waves," *Journal of Applied Physics*, Vol. 101, 073304, 2007.
16. Quendo, C., E. Rius, and C. Person, "Narrow bandpass filter using dual behavior resonator," *IEEE Trans. Microwave Theory & Tech.*, Vol. 51, No. 3, 734–743, March 2003.