

Equivalent Circuit Modelling of Active Reflectarray Antenna

M. Y. Ismail, M. Inam

Abstract—This paper presents equivalent circuit modeling of active planar reflectors which can be used for the detailed analysis and characterization of reflector performance in terms of lumped components. Equivalent circuit representation has been proposed for PIN diodes and liquid crystal based active planar reflectors designed within X-band frequency range. A very close agreement has been demonstrated between equivalent circuit results, 3D EM simulated results as well as measured scattering parameter results. In the case of measured results, a maximum discrepancy of 1.05dB was observed in the reflection loss performance, which can be attributed to the losses occurred during measurement process.

Keywords—Equivalent circuit modelling, planar reflectors, reflectarray antenna, PIN diode, liquid crystal.

I. INTRODUCTION

EQUIVALENT circuit representation of antenna provides a deep insight for the investigation of different factors that affect the performance of the antenna. Reflectarray is one of the high gain, low cost and low profile antenna that consists of a planar reflector and feed horn. This type of antenna is introduced in 1963 [1] and is considered as a potential alternate for the bulky parabolic reflector antennas as well as expensive phased arrays.

The performance of a reflectarray antenna is governed by the efficiency of the passive or active planar reflector design. In order to steer the main beam of an active planar, the reflected phase from each of the resonant element can be controlled. Hence, the reflected beam can be directed in the desired direction which makes a reflectarray capable of achieving a wide-angle electronic beam scanning. Such beam forming approach can have many advantages over traditional tunable antenna array architectures, including a major reduction in hardware required per element and increased efficiency [2]. There have been a considerable research in beam steering antennas such as the use of non-linear dielectric materials [3]-[5], the integration of Radio Frequency Micro Electro Mechanical Systems (RF MEMS) as switches [6], [7] and using aperture coupled elements where the tuning circuit can be located on the non-resonating surface of the element in order to control the contributed phase from each element [8].

Equivalent circuit modelling and analysis of passive reflectarrays designed with different dielectric substrates were

presented in [9]. This work is based on the similar concept, however a thorough analysis was carried out for active planar reflectors designed with resonant elements integrated with PIN diodes for beam switching and use of liquid crystals for frequency tuning.

II. BASIC THEORY

Reflectarrays with different materials were designed and simulated with lumped components in [9]. The work presented in [9] was based only on the passive reflectarray antenna design while in this work active reflectarray antenna equivalent circuit modelling has been established. The values of the lumped components for both passive and active reflectarrays can be calculated by the following relationships.

$$C = \frac{\sigma_r}{8\pi\eta_r} \quad (1)$$

$$L = \frac{2\eta_r}{\pi f_r \sigma_r} \quad (2)$$

where, $\eta_r=377\Omega$ is the characteristics impedance of vacuum and σ_r is the phase derivative at f_r . The value of the resistor can be approximately calculated by:

$$R \approx \frac{1-\Gamma_r}{1+\Gamma_r} \frac{16\eta_r}{f_r^2 \sigma_r^2} \quad (3)$$

where, Γ_r is the reflection coefficient at the resonant frequency f_r . The above equations were used for the calculation of the values of R, L and C which were then used in the equivalent circuit.

III. EQUIVALENT CIRCUIT ANALYSIS OF PIN DIODES BASED DESIGN

Equivalent Circuit analysis of PIN diodes embedded planar reflectors was carried out using commercially available computer model of MULTISIM^{V10} in order to investigate the reflectarray performance based on lumped components characteristics. The design proposed in this work comprises of a slot and gap embedded patch element. Rectangular slot in the centre of patch element with a vertical gap on the patch surface was used for investigation of passive and active reflectarray characteristics. Extra capacitance and resistance have to be added in the circuit design given in order to represent PIN diode embedded unit cell planar reflector. Fig. 1 shows the circuit design after embedding the PIN diode. The value of the extra capacitance and resistance depends on the

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characteristics of the PIN diode used in the design of switchable planar reflector.

Total capacitance and total resistance in the circuit of Fig. 1 can be calculated by:

$$C_t = \frac{C_p C_d}{C_p + C_d} \quad (4)$$

$$R_t = \frac{R_o R_d + R_p R_d}{R_p + R_o + R_d} \quad (5)$$

where, L_p , C_p and R_p represent the inductance, capacitance and resistance of passive planar reflector respectively while C_d , R_d and R_o are introduced to cater the effects of PIN diode characteristics.

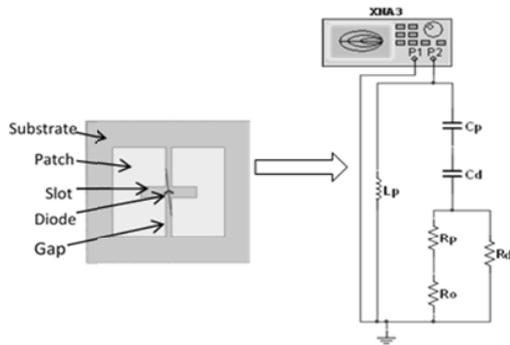


Fig. 1 Equivalent circuit model for a PIN diode embedded planar reflector unit cell

Using (1)-(5) and basic circuit solving techniques, the values of lumped components for X-band switchable planar reflector with PIN diodes integrated on the patch elements were calculated. The values of the lumped components calculated were based on the APD 0805-000 PIN diode. The patch element with dimensions, $L_p \times W_p = 9.4 \text{ mm} \times 10 \text{ mm}$ was printed on a $15 \text{ mm} \times 15 \text{ mm}$ dielectric substrate of Rogers RT/duroid 5880. The length and width of the slot was $0.125 L_p$ and $0.5 W_p$ respectively while the gap width was kept 0.5 mm . It was observed that in the OFF state of PIN diode the capacitance decreases significantly from 1.17 pF to 1.00 pF while the resistance decreases slightly from $58 \text{ m}\Omega$ to $56 \text{ m}\Omega$. This is because of the fact that in the OFF state, the PIN diode can be represented by a capacitor with a very small parallel resistance. The significant decrease in capacitance changed the resonant frequency of planar reflector unit cell from 8.63 GHz to 9.39 GHz . On the other hand, the slight change in resistance also caused a minimal change in reflection loss from 1.47 dB to 1.37 dB . In the ON state of PIN diode, the circuit capacitance varied slightly from 1.17 pF to 1.10 pF which caused a variation in resonant frequency from 8.63 GHz to 8.96 GHz . However, a significant change in circuit resistance from $58 \text{ m}\Omega$ to $66 \text{ m}\Omega$ can be observed which caused a variation of reflection loss from 1.47 dB to 1.64 dB . This significant change in resistance and hence in the reflection loss can be attributed to the fact that in the ON state of PIN diode, it is represented by a resistance.

Fig. 2 depicts the values of lumped components for equivalent circuit representation for ON and OFF states of PIN diode embedded on a planar reflector resonant patch element. The lumped component values were calculated using the analysis presented in this section in order to simulate circuits in MULTISIM^{V10} and compare the results with the results obtained from 3D EM simulators.

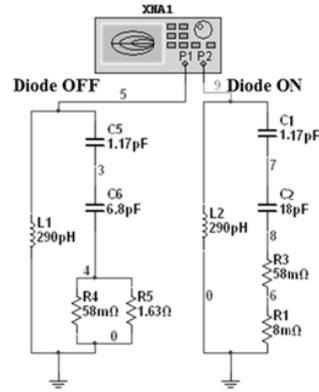
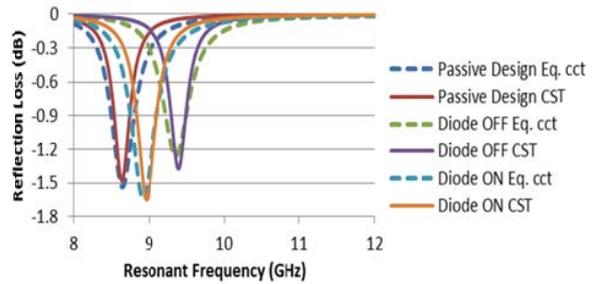
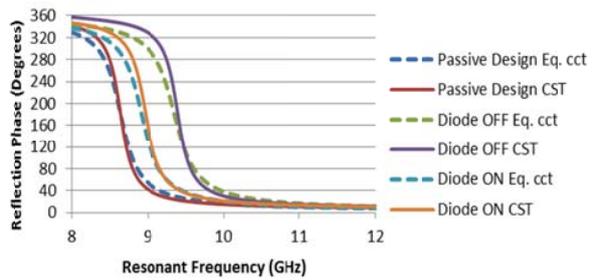


Fig. 2 Equivalent circuit representation of PIN diode based design

Fig. 3 shows a comparison between equivalent circuit results and the results obtained from CST MWS for reflection loss and reflection phase curves. A good agreement can be observed specially around the resonant frequency between the results obtained using two different techniques.



(a)



(b)

Fig. 3 Comparative equivalent circuit and CST MWS simulated results (a) reflection loss and (b) reflection phase curves

There are some discrepancies in the results away from the

resonance as shown in Fig. 4 which can be justified as the equations used for equivalent circuit modelling were derived for resonance while around the resonance mathematical approximations were used. Moreover, for the sake of reduction of complexity, the inductance values were also kept constant which can also affect the results. In ideal case, the inductance values should also be change slightly after the introduction of PIN diodes because it contains a small inductance which was ignored in this work.

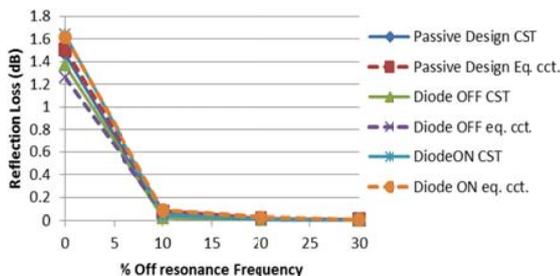


Fig. 4 Comparison and discrepancy between the results

IV. EQUIVALENT CIRCUIT ANALYSIS OF LIQUID CRYSTAL BASED DESIGN

Equivalent circuit modelling was also carried out for the liquid crystal based planar reflector unit cells. In the case of liquid crystal based cells, because of anisotropy, the properties of the dielectric substrate changes by applying certain voltage to its molecules. Therefore, the values of lumped components in the equivalent circuit will also vary with the applied voltage. This detailed analysis carried out for X-band planar reflector design has been presented in this section.

The liquid crystal was deposited in 0.787 mm thick cavity engraved in Rogers RT/duroid 5880. In this case, additional inductors and capacitors can be used in parallel to the inductor and capacitor in the basic design keeping in view that the inductance will decrease and capacitance will increase in the proposed active design. On the other hand, because of properties of liquid crystals, a series resistance has to be added in order to represent high losses caused by the introduction of high loss liquid crystal material. Fig. 5 shows the proposed equivalent circuit design of a liquid crystal based active planar reflector design.

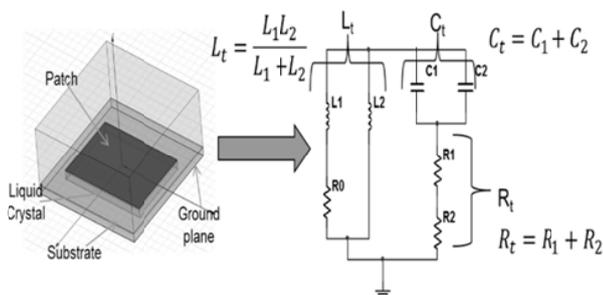


Fig. 5 Liquid crystal based design of planar reflector and its equivalent circuit representation

It can be observed from Fig. 5 that the lumped component combinations will increase capacitance and decrease inductance which will affect the resonant frequency while increase in resistance will vary the reflection loss of the planar reflector. In the design of Fig. 5, L_1, C_1, R_1 and R_0 are constant inductance, capacitance and resistances respectively obtained from the design of passive elements. On the other hand L_2, C_2, R_2 are variable inductance capacitance and resistance respectively which will vary with the applied voltage.

The values of the lumped components were calculated using the equations provided above. It is worth mentioning here that the values calculated are for L_t, C_t and R_t while L_1, L_2, C_1, C_2, R_1 and R_2 depends on the material properties of liquid crystal used in the design. In order to represent two different configurations of LC molecules at 0V and 20V, two different circuits has been designed and connected to different ports of network analyzer as shown in Fig. 6. The values of the basic components have been taken from the passive equivalent circuit design while the values of additional components are calculated based on given equations. The value of capacitance increases in the case of reconfigurable reflectarray design as compared to passive design because of higher dielectric constant of LC. However, the increase in capacitance is not very high because there is only a minor difference between the permittivity values of LC and Rogers RT/droid 5880.

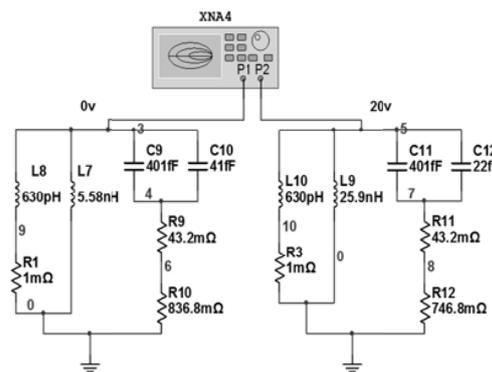


Fig. 6 Equivalent circuit for LC based resonant element of planar reflector

In order to counter the effect of increased capacitance, the inductance has to be decreased (by putting a large inductor in parallel) which will maintain the resonant frequency at the desired point. This was be done by varying the value of variable components in circuit. Moreover, the decrease in the values of variable resistance from 836.8mΩ to 746.8mΩ is because of the fact that the loss tangent of LC decrease from 0.04 to 0.03 as the applied voltage is increased from 0V to 20V.

The circuit provided in Fig. 6 was simulated in MULTISIM^{V10} and the simulated circuit results were compared with the results obtained by 3D computer model simulated in Ansoft HFSS. The two simulated results were also compared with the scattering parameter measured results as shown in Fig. 7. It can be observed from Fig. 7 that the

comparative results of Ansoft HFSS and equivalent circuit provided a very good agreement. However, the measured results for 0V provided 5.65dB loss at 10.06GHz and for 20V, the resonance changed to 9.88GHz with 4.63dB loss. On the other hand, the simulated results demonstrated a resonant frequency of 10.06GHz with 4.6dB loss at 0V and 9.88GHz with 3.6dB loss when 20V was applied. The reason for this discrepancy can be the difference between actual and material properties provided in data sheet as well as the losses introduced during measurement process as explained in [10].

As an array antenna, planar reflector can have different number of elements. In the case of an NxN element planar reflector, the capacitance of the equivalent circuit will increase because of addition of liquid crystal material and increase in the capacitive area of the dielectric material used in planar reflector design. On the other hand, inductance will decrease in order to counter the effect of increasing capacitance and keep the resonant frequency at the desired frequency. The resistance of the equivalent circuit will also increase because of increase in number of conductive resonant elements and increase in the size of lossy dielectric material. Therefore, an NxN element liquid crystal based antenna can be represented as in Fig. 8. It can be observed from Fig. 8 that all the N number of inductors are connected in parallel to have a smaller total inductance (L_t). This will negate the effect of larger total capacitance (C_t) caused by the parallel connection of N number of capacitors.

V. CONCLUSION

Equivalent circuit analysis can be utilized for the analysis and performance improvement of active planar reflectors. The extra lumped elements or non-homogenous material used to incorporate active antenna functionality can be characterized

based on the equivalent circuit modelling. Moreover the proposed technique can also be used for quick analysis of planar reflector antennas saving the time consumed during 3D-EM simulations.

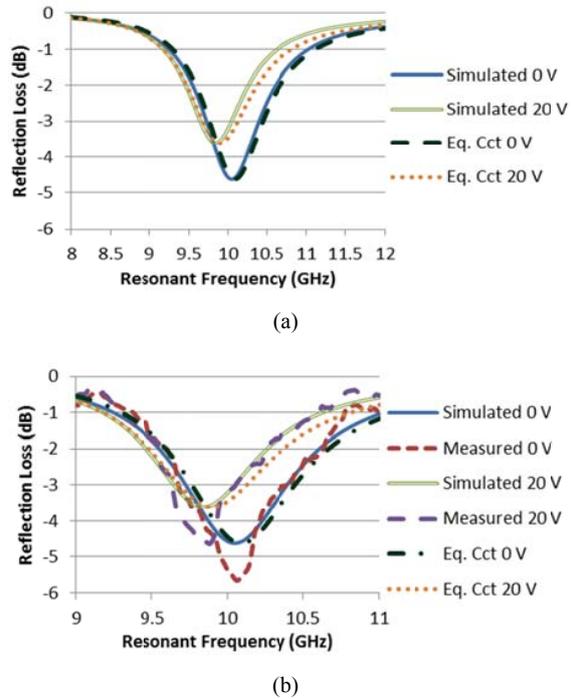


Fig. 7 Comparison of results (a) Ansoft HFSS and equivalent circuit and (b) Ansoft HFSS, equivalent circuit measured results

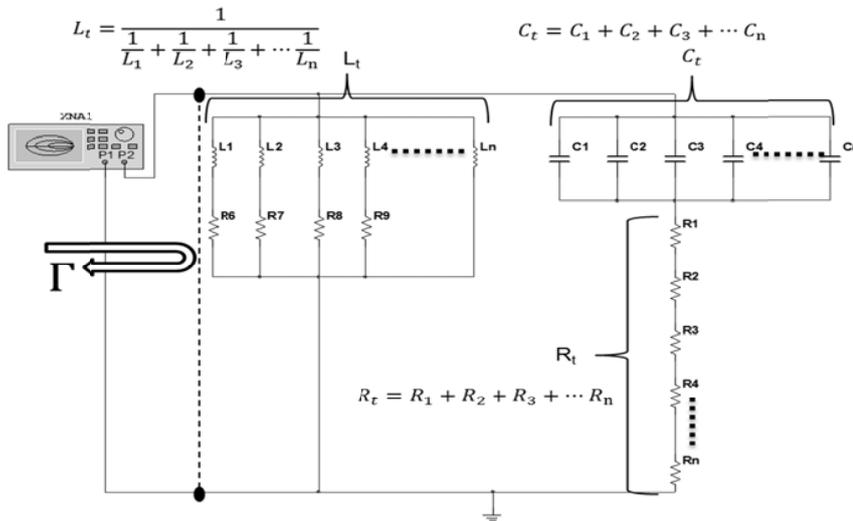


Fig. 8 Equivalent circuit of an NxN element liquid crystal based active planar reflector

ACKNOWLEDGMENT

Research funding for this work is fully provided by the Ministry of Higher Education, Malaysia, under Best Project of Fundamental Research Grant Scheme (FRGS, VOT 0983), Prototype Research Grant Scheme (PRGS, VOT 0904) and Research Acculturation Collaborative Effort (RACE, VOT 1119).

The authors would like to thank the staff of Wireless and Radio Science Centre (WARAS) of Universiti Tun Hussein Onn Malaysia (UTHM) for the technical support.

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