Simulation and Design of a Tunable Patch Antenna

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Abstract: A method for designing a tunable microstrip patch antenna is presented, suggesting cooperation between a theoretical transmission line model and a professional electromagnetic simulation tool. Tunable impedance elements are used to disturb the microstrip patch to alter the tuning range of the antenna. Results show excellent correlation between theoretical calculations and simulation data from Sonnet. Finally, guidelines for designing an antenna to be excited by an IMPATT diode are discussed.

Keywords: Tunable Antenna, IMPATT Diode, Sonnet, Impedance Matching, Microstrip, Patch Antenna

1. Introduction

Tunable antennas offer several intriguing properties for wireless communications [1-5], ranging from cost savings by combining several analog components into one to introducing new uses, such as an adaptive element for smart antenna systems. The ideal element would offer dynamic control of a significant tuning range of resonance frequencies and bandwidths on a single antenna. To date, attempts to design a truly tunable antenna have been rudimentary, attaining a piece of the goal, such as a shift in resonance frequency at the cost of bandwidth, or vice versa. Some focus is needed to determine the type of excitation needed to offer total control over the electrical properties of an antenna.

Previously, a theoretical method was presented for tuning microstrip patch antennas by way of a dynamic "black box" impedance element [6]. Such an ideal scenario helps explore the impact to the antenna's field pattern and presents more evidence on the usefulness of tunable antenna elements. Subsequently, this transmission line model has been improved to include the impact of feedline width and mutual effects, which in turn allows for more accurate design guidelines.

As a check against this work, a professional software tool, Sonnet, was used to simulate the antenna basis and tuning results derived from the theoretical model. Sonnet uses a method of moments [7] to analyze the electromagnetic properties from the physical dimensions of a circuit. By using Sonnet for this comparison, the previous work can be evaluated versus a different method and a cooperative procedure is suggested for designing tunable antennas. This new procedure takes advantage of the accuracy of the theoretical model and the speed in simulation time from the easy-to-use Sonnet package.

While the basis of the work is an ideal impedance "black box", the IMPact Avalanche Transit Time (IMPATT) diode [8-10] has shown significant promise as a real-world means for achieving tunable antennas. Sonnet design and simulation considerations for integrating an IMPATT diode with a microstrip patch antenna are also discussed.

2. Theory

The cornerstone of the tunable antenna model is the classic Pues and Van de Capelle [11-13] transmission line model for microstrip antennas. This methodology is well-known for being simple yet accurate. The model allows one to visualize the antenna as a network of elements as shown in Fig. 1.

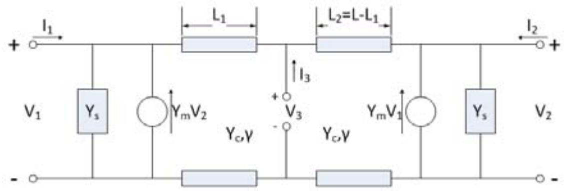

Fig. 1. Three-port network diagram for Pues transmission line model.

Procedurally, the Pues model computes effective parameters for line width W_e and length L_e, dielectric constant ε_{eff}, and loss tangent δ_e that have been adjusted to compensate for the total dimensions of the strip, the strip thickness, and dispersion at the operating frequency. These parameters are then used to find the appropriate characteristic admittance Y_c, propagation constant γ, slot self-admittance Y_s, and mutual admittance Y_m. They combine via:

$$Y_{in} = \frac{Y_c^2 + Y_s^2 - Y_m^2 + 2Y_sY_c \coth(\gamma L) - 2Y_mY_c \operatorname{csch}(\gamma L)}{Y_s + Y_c \coth(\gamma L)} \quad (1),$$

to yield an input admittance for the designed antenna at a feed line located at one edge of the strip.

This model also allows the ability to visualize any element along a transmission line connecting the radiating slots of an antenna. Using this, another factor impacting antenna tunability is suggested: the location of the "black box" on the patch at design time. This is done by using the transmission line admittance transfer function [5] with (1) and combining the elements in Fig. 1 with the "black box":

$$Y_i = Y_c \frac{Y_c + Y_l \coth(\gamma L)}{Y_l + Y_c \coth(\gamma L)} \quad (2).$$

Generally, the tunable impedance element provides a disturbance that, in turn, modifies the input impedance to the patch. With the relationship between input impedance and patch dimensions {in light of the documented Pues model and (1)}, this tuned antenna system behaves like a static antenna with a new W and L at the operating frequency. It is as if the tunable "black box" impedance can electrically stretch or squeeze the patch antenna. For the analysis, the following process is utilized:

i. *Design a basic microstrip patch antenna to establish a baseline for the design*
ii. *Choose a location for the tunable impedance element*
iii. *Use (2) to find the transferred shunt impedance of the far radiating slot and mutual effects at the location of the "black box"*
iv. *Combine the tunable and transferred impedances, and use (2) to transfer to the input*
v. *Combine the new transferred impedance with the near radiating slot (modified to account for feedline width) and mutual effects to get the new patch input impedance*
vi. *Repeat the design process in reverse to find the 'tuned' width and length*

This procedure can be used to evaluate the impact of the tuned impedance values from the "black box" at several different locations on the baseline antenna. Checking this work against an accepted software tool is vital to ensuring its reliability. Comparison with results from Sonnet is presented below.

3. Results

As a baseline, a microstrip patch antenna is designed with a resonance frequency at f_o=2.4 GHz. The dimensions of the patch are W=2.42259 cm and L=4.15922 cm with strip thickness t=35 μm on a substrate having ε_r=2.2 and height h=0.15875 cm. The feedline is matched to 50 Ω at 2.4 GHz with a width of 0.484517 cm. Figure 2 illustrates the layout of the patch antenna with a black box element added at the input. The theoretical model yielded an antenna with Z_{in}=979.58 Ω, Z_c=14.3269 Ω, Z_s=15.432-j185.92 Ω, Z_m=1150.1+j4130.6 Ω, and γ=0.0326+j72.3651. Sonnet simulated this antenna to resonate slightly higher at 2.404 GHz with Z_{in}=979.9 Ω. The nearly identical input impedance responses for the theoretical model and Sonnet are plotted in Figs. 3 and 4, respectively.

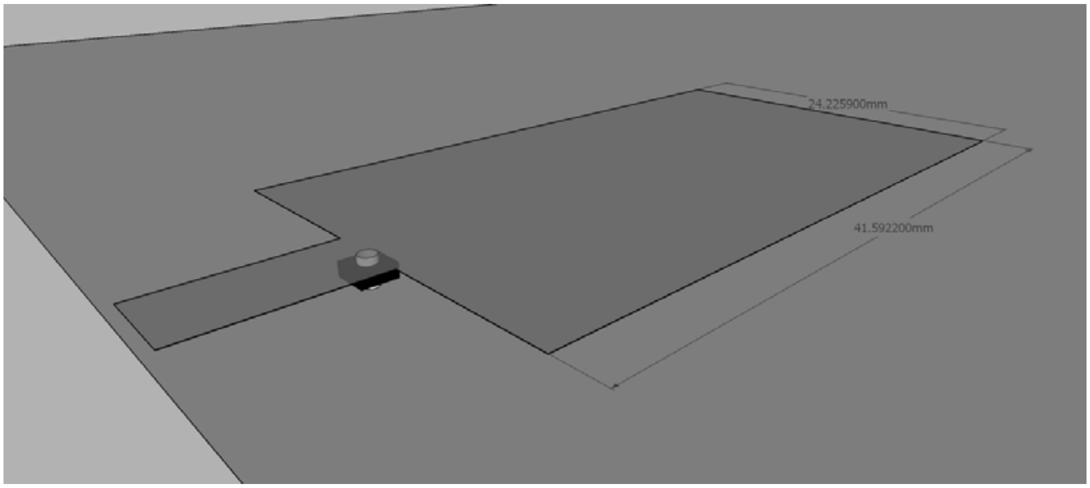

Fig. 2. Physical layout of microstrip patch antenna with black box element at the input.

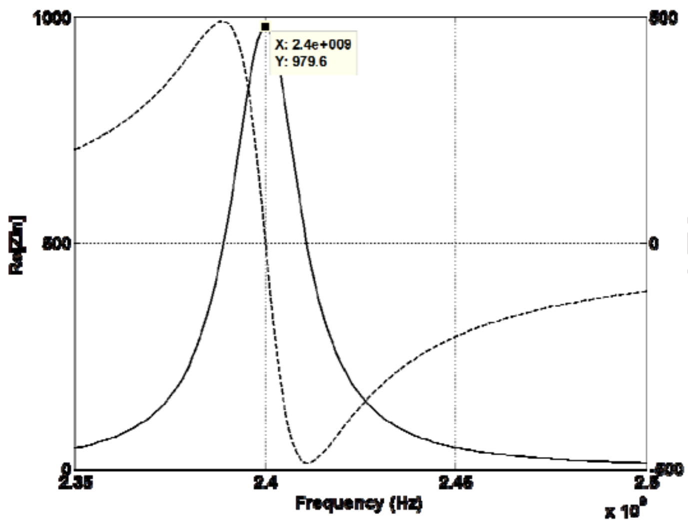

Fig. 3. Input impedance versus frequency for designed patch antenna from the theoretical model.

Similar to the previous approach [6], it is assumed that the tunable "black box" has two extremes: 1) positive resistance with inductance (extreme value of 30+j190 Ω), 2) negative resistance with capacitance (extreme value of -5-j100 Ω). Using the procedure for an element tuned to -5-j100 Ω and placed at the input to the patch, the resultant Z_{in} is calculated and plotted in Fig. 5, highlighting the resonance frequency at 2.293 GHz. Correspondingly, the Sonnet Netlist function is used to combine the designed antenna with an impedance data file and plot the results in Figs. 6 and 7.

Additionally, Figs. 6 and 7 display a "stretched" antenna based on the tuned input impedance at 2.4 GHz (labeled 'stretch'). For this scenario, the equivalent patch dimensions are a longer length of 4.46902 cm and a shorter width of 1.74059 cm, demonstrating the ability to tune beyond the physical area of the antenna. The "stretched" and Netlist curves differ, with resonance frequencies at 2.278 and 2.29 GHz, respectively. This highlights the important distinction between operating and resonance frequencies.

It should be mentioned that this is as far as the correlation work between the transmission line model and Sonnet simulation can extend. The theoretical model can also evaluate the impact of the tunable impedance element at any point along the midline of the patch antenna. At this time, Sonnet does not offer an easy manner for evaluating such a disturbance inside the edges of the antenna.

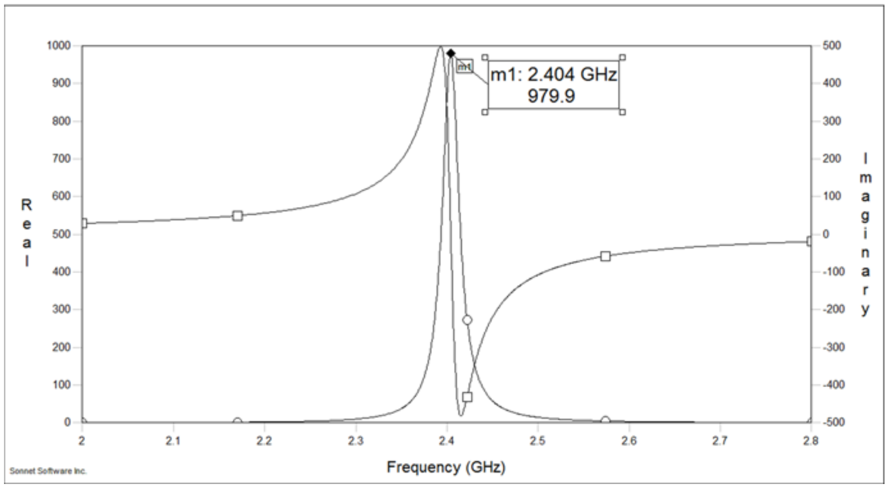

Fig. 4. Input impedance versus frequency for designed patch antenna from Sonnet.

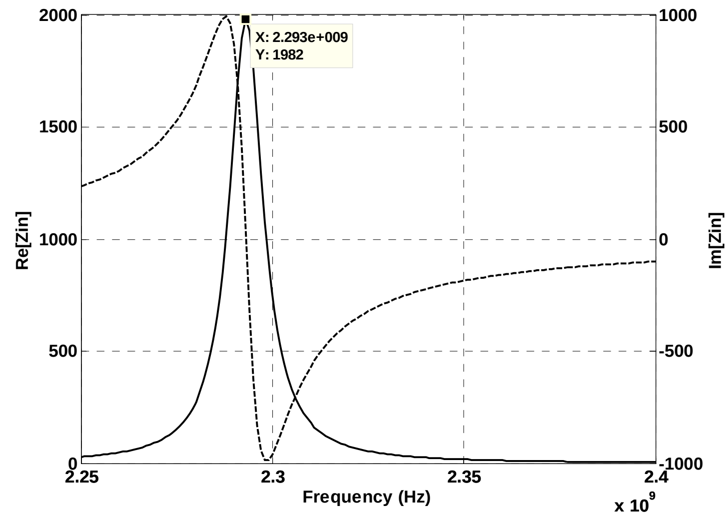

Fig. 5. Input impedance versus frequency for patch antenna tuned with Z_d=-5-j100 Ω from theoretical model with resonance frequency at 2.293 GHz.

Finally, the work presented intuitively leads to a design procedure that leverages the advantages of the two models. The designer can begin constructing the dimensions of the desired antenna and tuning characteristics with an optimization tool like the theoretical transmission line model presented. Once a framework is determined, Sonnet's advanced layout and simulation features can be used to verify performance and establish a design feedback loop with physical data such as area and boundaries.

4. IMPATT Diodes

Several methods for tuning antenna elements have been proposed over the years, most notably the usage of varactors and/or specially-biased FETs [14]. These are often limited to just resistance or capacitance (or inductance) and tend to fall short for improving antenna robustness.

The tuning range chosen for this investigation is based on actual values that have been achieved with the IMPATT diode [8-10], a promising method for achieving a range of impedance values through a single device. A DC bias, which should be well isolated from the RF signal, controls the avalanche frequency, and, hence, the diode impedance. Figure 8 shows the model for the IMPATT diode before and after the avalanche frequency.

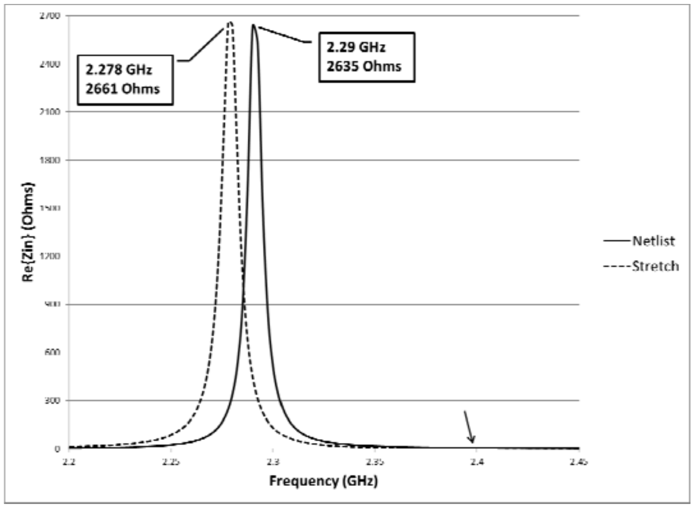

Fig. 6. Input resistance vs. frequency for tuned patch antenna (Z_d=-5-j100 Ω) in Sonnet: networked components versus stretched dimensions. Arrow indicates match at operating frequency of 2.4 GHz.

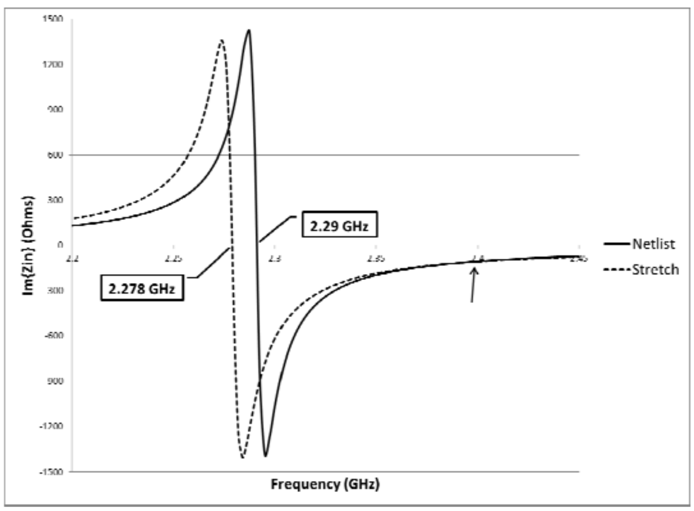

Fig. 7. Input reactance vs. frequency for tuned patch antenna (Z_d=-5-j100 Ω) in Sonnet: networked components versus stretched dimensions. Arrow indicates match at operating frequency of 2.4 GHz.

The impedance capabilities of the IMPATT diode range from R+jωL to -R+1/jωC, as modeled with the "black box". The necessary tuning range can be achieved by careful design of the diode dimensions. This means that when combined with a patch antenna, the properties can be tuned solely by the biasing of the IMPATT diode. Using the model to find ideal locations for IMPATT diodes along the patch, designers could quickly layout and analyze a tunable antenna with co-located IMPATT diodes in Sonnet.

5. Conclusions and Remarks

In summary, the work presented demonstrates a good marriage between results from the transmission line model and Sonnet. This relationship naturally leads to a collaborative design procedure for tunable patch antennas. To further advance the study of exciting a microstrip patch with impedance elements, Sonnet could improve the means of locating shunt impedances inside a structure (not just at edges) for evaluation. Finally, it should be pointed out that the final step of implementing the proposed tunable antenna with an IMPATT diode is made significantly simpler with the advanced layout and analysis features of the Sonnet tool.

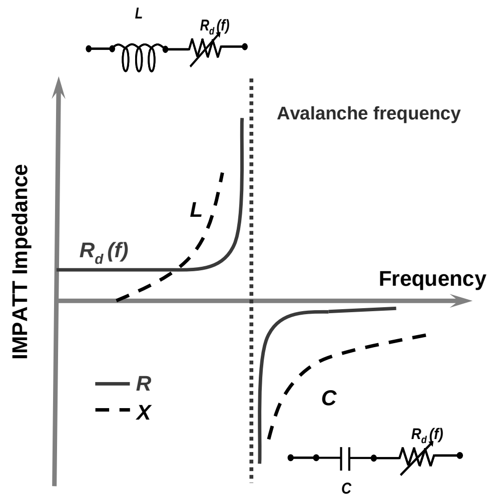

Fig. 8. Model for IMPATT impedance vs. frequency, for both sides of avalanche frequency.

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