Analysis of a non-symmetrical, tunable microstrip patch antenna at 60 GHz

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Abstract: An exploration of tunable antenna properties when losing midline symmetry is presented as both the feed and tunable IMPATT diode move away from the centerline. A professional EM simulation tool from Sonnet is used for evaluation of the resonance frequency, input impedance, and far field pattern of the microstrip patch antenna designed to operate at 60 GHz.

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

1. Introduction

The tunable antenna is an attractive design alternative to the fixed antenna as it can offer controllable radiating properties such as resonance and bandwidth for wireless communications systems. This added degree of control could allow for future-proofing a system to changing standards, compensating for production defects, or tuning in the field to match a sensitive wireless environment. Tuning is typically achieved through a varactor diode or tuned resistance [1], or as has been shown recently [2]-[4], via a tunable combination of resistance and reactance offered by the IMPATT diode [5]-[7].

Tuning via the IMPATT brings several important benefits beyond varactors or resistors. First, real-time tunability is achieved by adjusting the reverse bias on the diode, offering a simple control for changing the antenna's operating point. Second, the combination of both resistance and reactance allow the designer to not only change resonance frequency (varactor) or bandwidth (resistor), but to maintain control over both properties simultaneously. Finally, the IMPATT diode can deliver varying positive and negative resistance along with inductance and capacitance, respectively. To this point, Figure 1 illustrates the achievable impedance tuning range of the IMPATT diode.

Design of an IMPATT-tuned microstrip patch antenna is challenging, though. Three vital pieces of information must be analyzed: 1) dimensions of the base patch antenna, 2) tuning range of the IMPATT diode to meet the antenna specifications, and 3) location of the feedline and diode(s) at the antenna's edges for optimum tunability. Figure 2 captures the design challenge for offering tuning flexibility: the placement of the feedline and tuning diode must be chosen carefully to ensure optimal performance. A sophisticated design model is needed to weigh these three aspects to achieve the desired performance.

One popular model for evaluating patch antenna designs is the microstrip transmission line model (TLM) from Pues et al. [8]-[10]. While a quick and easy model to construct with any mathematics software package, the TLM from Pues is symmetry bound, meaning the feed as well as any additional components must lay on the midline of the patch antenna. A moment of methods model, such as that utilized by Sonnet Software, is more rigorous at evaluating antenna performance at the expense of computing resources like memory and compute time, especially in the case of non-symmetrical antennas involving external components. The exploration of antenna design presented here seeks to use Sonnet's EM simulator to analyze the impact of removing the structural symmetry from the real-time tunable antenna with regards to the feedline and the IMPATT diode.

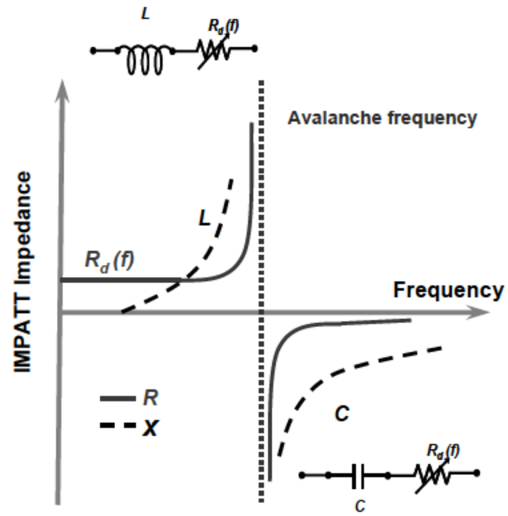

Fig. 1. Model for IMPATT impedance vs. frequency, for both sides of avalanche frequency.

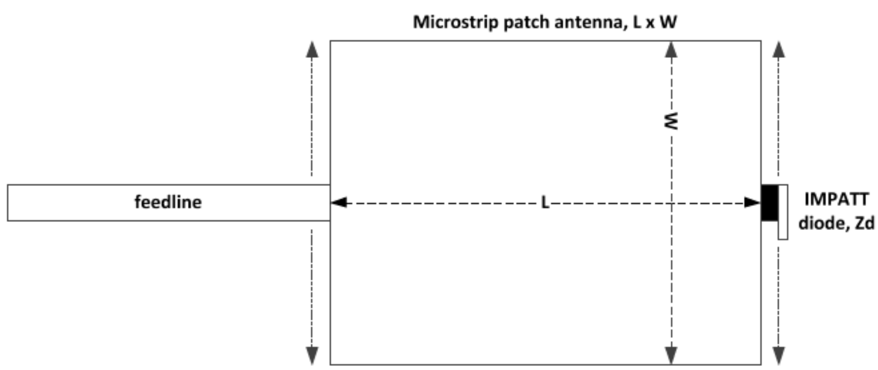

Fig. 2. Illustration of the tunable antenna design challenge: where to place the feed and tuning diode.

2. Baseline Antenna

To begin, a baseline antenna design is needed to establish a point of reference for analysis. All design work assumes a copper top metal layer with a thickness t = 3.4 μm at a height h = 7.09 μm above a lossless ground metal layer. The dielectric between the metal layers is assumed to have $\varepsilon_r = 3.35$ and $\delta_{tan} = 0.05$. At 60 GHz, a 50 Ω feedline given these parameters would have a width of 14.6 μm. From this feedline width, a cell size of 7.3 μm is chosen for analysis in Sonnet and the encompassing box is chosen to be 2000 cells square with the top open to free space. Confining the antenna dimensions to an integer multiple of the chosen cell size, the Pues TLM is used to estimate a patch antenna to resonate at 60 GHz. The final baseline dimensions of the antenna are a length L = 1372 μm and a width W = 730 μm.

The resulting input impedance of the patch antenna is shown in Figure 3, illustrating some inaccuracy in the Pues TLM model at high frequency (resonance at 59.68 GHz instead of 60 GHz). The far field of the designed microstrip antenna was also simulated, resulting in the field pattern depicted in Figure 4. Finally, the range of the tunable antenna is estimated using an embedded component in Sonnet, representing the IMPATT diode tuned to either extreme of its tuning range.

As shown previously in Figure 1, biasing the diode to achieve an avalanche frequency higher than 60 GHz yields an impedance Z_d with positive resistance and inductance. For the R + jωL extreme, the IMPATT behaves at 60 GHz like a resistor R = 33.85 Ω in series with an inductor L = 48.21 pH. To achieve the other extreme, the avalanche frequency is shifted below 60 GHz, where the diode acts as a negative resistance R = -1.25 Ω in series with a capacitor C = 206 fF at 60 GHz. When located at the radiating edge opposite the feed (as in Figure 2), the IMPATT diode's impedance is shunt to the antenna, tuning its electrical properties. Overall, the antenna's f_{res} can be shifted upwards by 1.05 GHz (Z_d = 33.85 + j18.18 Ω) and downwards by 3.53 GHz (Z_d = -1.25 - j12.88 Ω), a total delta of 3.58 GHz.

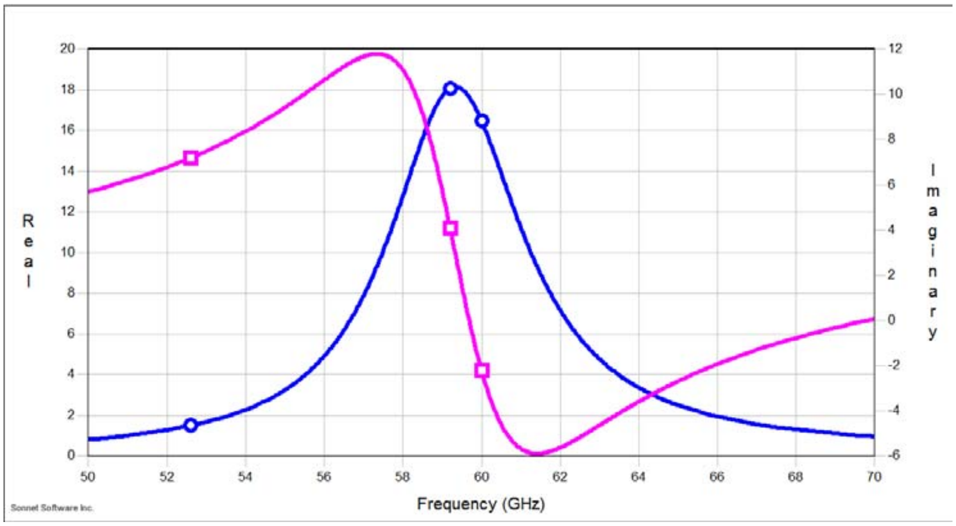

Fig. 3. Real (left y-axis) and imaginary (right y-axis) input impedance of the baseline patch antenna.

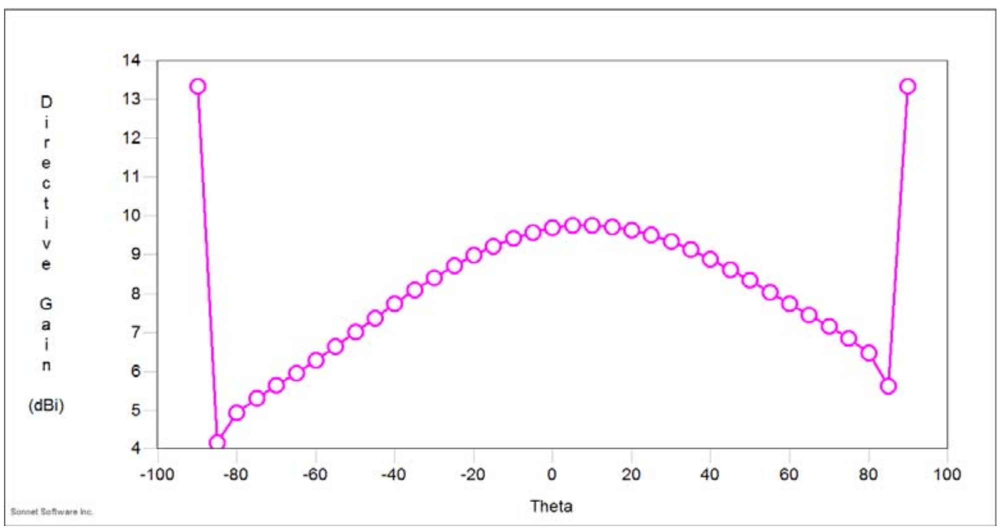

Fig. 4. Electric field pattern of the baseline patch antenna, evaluated at f_{res} = 60 GHz.

To evaluate the antenna performance when shifting away from midline symmetry, several scenarios are analyzed with Sonnet's EM engine. At first, the effects of individually moving the feedline and IMPATT diode laterally along their respective edges are simulated, followed by a combination of the two, with Figure 5 depicting an extreme case of placing the feed on one corner of the patch and the IMPATT on the opposite corner. One would expect to see at least some shift in the input impedance when moving these vital pieces away from the centerline of the patch antenna.

3. Results and Analysis

Each of the scenarios produced interesting results, highlighting some important design rules. Table 1 collates the results from all scenarios as both the feedline and tuning diode are relocated on the patch antenna. First, and most noticeably, it can be seen that the largest shift in resonance frequency occurs when the IMPATT diode is moved from the midline to the top of the far edge. This impacts both ends of the tuning range, shifting much lower to 52.69 GHz and, correspondingly, higher to 61.43 GHz, for a total tuning range of 8.74 GHz. By a 2.4x increase in tuning range of the antenna, the IMPATT offers the designer the ability to design with a smaller footprint that resonates at significantly lower frequency.

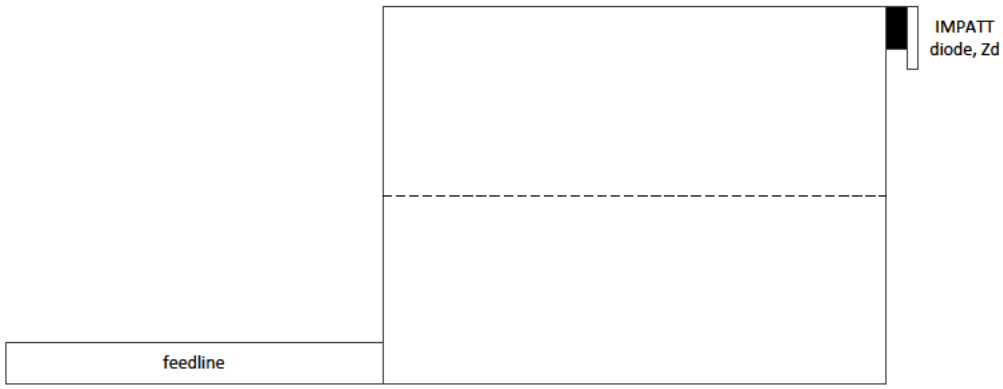

Fig. 5. Pushing boundaries: feedline (bottom) and IMPATT (top) relocated to opposite corners.

Table 1: Results summary of varying feedline and IMPATT location

Feedline location (on near edge)	IMPATT location (on far edge)	Z_d (@60 GHz)	f_{res}	Z_{in} (@60 GHz)	Z_{eff} (@60 GHz)
Center	None	inf	59.68 GHz	16.47-j2.21 Ω	N/A
Center	Center	-1.25-j12.88 Ω	56.15 GHz	3.19-j4.87 Ω	1.76-j6.93 Ω
Center	Center	33.85+j18.18 Ω	60.73 GHz	12.86+j2.85 Ω	17.97+j30.28 Ω
Center	Top	-1.25-j12.88 Ω	52.69 GHz	0.719-j1.40 Ω	0.635-j1.53 Ω
Center	Top	33.85+j18.18 Ω	61.43 GHz	10.40+j3.67 Ω	12.16+j17.93 Ω
Bottom	None	inf	60.27 GHz	16.59+j1.40 Ω	1.35+j76.62 Ω
Bottom	Top	-1.25-j12.88 Ω	55.15 GHz	1.67-j0.005 Ω	1.86+j0.021 Ω
Bottom	Top	33.85+j18.18 Ω	62.53 GHz	13.32+j5.41 Ω	4.04+j28.71 Ω
Top	Top	-1.25-j12.88 Ω	55.15 GHz	1.64+j0.124 Ω	1.81+j0.178 Ω
Top	Top	33.85+j18.18 Ω	62.53 GHz	13.36+j5.44 Ω	3.85+j28.76 Ω

Second, as Table 1 suggests, it seems moving the feed away from the midline causes an upward shift in resonance frequency from the baseline. Yet a closer look at the simulation shows that the real part of the input impedance is maintained, while the input reactance shifts higher, as seen in Figure 6. This extra reactance could be used to compensate for an antenna footprint that yielded a more capacitive baseline (such as this study's baseline), and could help the designer achieve a purely resistive Z_{in} at resonance. To prove this point, the feed was moved down just 88% from the midline (as opposed to 100% at the bottom corner of the patch) to achieve an exact f_{res} = 60 GHz for the antenna.

Finally, the combination of the two moves is additive, with relocation of the tuned IMPATT diode providing the bulk of the frequency shift while placing the feedline at the bottom of the input edge resulting in an upward shift in resonance frequency. This means less downward tunability (4.53 GHz lower than baseline) but more upward tuning range (2.85 GHz higher than baseline). The bottom 4 rows of Table 1 illustrate that the direction of the feedline relocation does not matter when moving simultaneously with the tuning diode, as both the resonance frequency and Z_{in} are respectively identical.

To evaluate the impact of the various changes to the antenna, Table 1 includes a final column that tabulates the effective shunt impedance as seen at the input. It can be seen that when the IMPATT is tuned to achieve -1.25 - j12.88 Ω, the Z_{eff} doesn't retain the negative resistance. If the end goal of tuning the antenna were to achieve a pure 50 Ω input impedance, a Z_{eff} of -24.25 + j4.90 Ω would be required for this particular baseline antenna, which is far different from the values contained in the final column of Table 1. Some further work on manipulating the tunability of this antenna system is needed to understand how the designer might achieve a desired Z_{in} given a small footprint microstrip patch antenna.

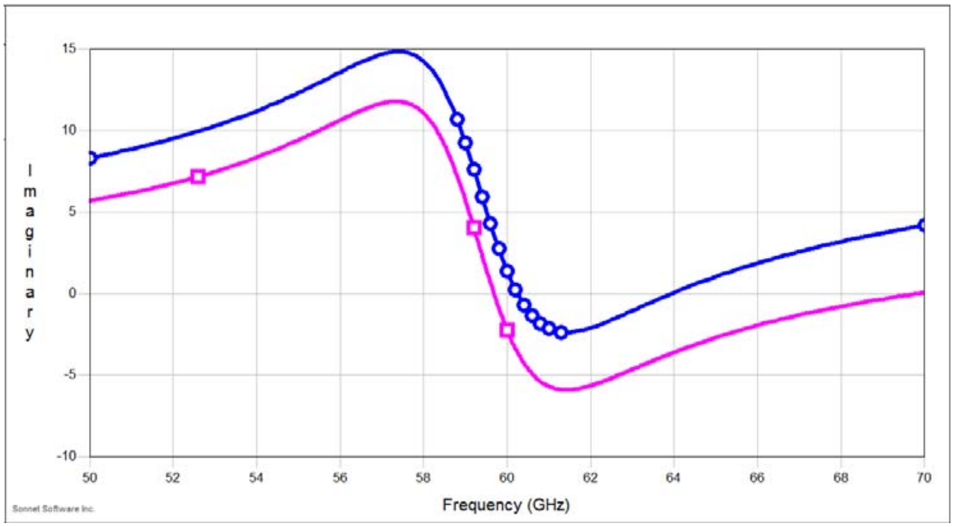

Fig. 6. Im{Z_{in}} for antenna with feed at the bottom of the input edge (blue) versus the baseline (pink).

4. Conclusions and Remarks

With a device such as an IMPATT diode, the capabilities of tunable antennas are significantly expanded, but this tunability comes at the price of design complexity. The work presented analyzes the effects of changing the location of both the IMPATT diode and the feedline input for tuning a microstrip patch antenna. What was discovered was that the tuning range of the system is most greatly affected by the location of the IMPATT, while changing the feed placement offers a chance to finely adjust the tuning range. It is obvious that significant effort is needed to document and model these effects with a focus on the optimal mix of tuned values, antenna size, and feed/diode locations to achieve a specified design.

Over the course of this study, it has become apparent how invaluable Sonnet is as a design tool. As a 3D layout and simulation suite, Sonnet's ability to accurately evaluate the performance of patch antenna systems quickly lets the designer know if they are on the right track. Where it slows down, though, is when making an array of physical changes to the design and keeping tabs on the overall analysis. This is where it is very useful to have a MATLAB script to compile data and an interface like SonnetLab to allow communication between the two tools. It is the intent of the authors to migrate to an automated MATLAB/Sonnet procedure for finding the optimal tunable antenna solution utilizing IMPATT diodes.

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