Increasing the Bandwidth of a Metamaterial-Inspired 2D Magnetic-Based Antenna

Chia-Ching Lin* and Richard W. Ziolkowski
Department of Electrical and Computer Engineering, University of Arizona
1230 E. Speedway Blvd., Tucson, AZ 85721
Email: cclin@ece.arizona.edu, ziolkowski@ece.arizona.edu

Introduction

An efficacious, electrically-small antenna design methodology has been presented previously in [1], [2]. Although those antenna systems were electrically small, their designs were demonstrated to achieve an overall efficiency that was greater than 90%, without the need for any external matching circuit. Both microwave engineered (interdigitated capacitor) and lumped element capacitor versions of those designs were obtained. It was found that, the metamaterial-inspired parasitic structures that were placed in the very near field of the radiating element provide reactive and resistive impedance matching to the source. However, the bandwidth still remained small, as was expected, and thereby limited their potential applications. It is desired to develop an approach to enlarge the bandwidth of these 2D magnetic EZ antennas to provide reasonable Q values while still maintaining high overall efficiencies.

Bandwidth Enhancement Design

The 2D magnetic-based EZ antenna integrated with a lumped element capacitor is shown in Fig. 1. The lumped element capacitor is placed in the middle of the outer loop. The value of the lumped element capacitor is 1.7 pF and HFSS version 11.1 simulations showed that the resonant frequency is 299.59 MHz and is matched well to the assumed 50 Ω source since the S_{11} values, which are shown in Fig.2, are less than -30 dB. The minimum radius of an imaginary sphere circumscribing the antenna is 79.2 mm; therefore, the λ_0/a is 12.64 and the corresponding ka is 0.498, respectively. The fractional bandwidth (FBW) is only 1.4036 % at the –3 dB points, which is smaller than the Chu limit value, i.e., $FBW_{max}=2/Q_{min}=19.08$ % where $Q_{min} = 1/(ka)^3+1/ka=10.104$. The reason is that the enclosed volume only occupies a small portion of the radiation sphere [3]. The bandwidth is small; thus its possible use for applications is limited.

From [4], we know that one can achieve different resonant frequencies simply by changing the values of the lumped element capacitors. In particular, the resonant frequency of the antenna is given by the expression:

$$f_0 = \frac{1}{2\pi\sqrt{L_{eff}C_{eff}}} \tag{1}$$

where L_{eff} and C_{eff} are the effective inductance and capacitance of the system. In particular, one should be able to tune the antenna to other resonant frequencies by simply varying these effective L and C values. This simplest approach to this end means simply changing the lumped element capacitor values for the antenna design shown in Fig. 1 to change the resonant frequency. Additionally, we have confirmed that the overall radiation efficiency will not have a significant decrease when the capacitor values are changed over a small range. As a result, if one can design a lumped element capacitor which provides the necessary capacitance at the desired frequencies, a correspondingly large bandwidth would be obtained.

Considering Eq. (1), its derivative with respect to frequency yields the expression

$$\frac{df}{f} = -\frac{1}{2}\frac{dC_{eff}}{C_{eff}} \tag{2}$$

for a fixed value of L_{eff}. Consequently, if one desires to achieve a 10% bandwidth, the corresponding values of the capacitor should be changed by 20%, i.e., with a $\pm 10\%$ variation. For the antenna shown in Fig. 1, this means the capacitor value, C, should be swept from 0.9C to 1.1C, i.e., from 1.53 pF to 1.87 pF. To confirm this result, we first choose to run HFSS simulations corresponding to 11 equally spaced points between 1.53 pF and 1.87 pF; these simulation results are shown in Table 1. A curving fitting method provided by Matlab was then applied for these 11 points in order to find out the best fit to this series of data points; the result is shown in Fig. 3. From Fig. 3, we add another 10 points which were also simulated with HFSS to make a comparison between the outcome defined by the curving fitting and the actual HFSS-predicted resonance frequency values. The outcome is very positive; the actual error ratio is shown in Fig. 4. Additionally, as one can see, the bandwidth is only from 289.95 MHz to 310.435MHz compared to the anticipated bandwidth: from 285MHz to 315MHz. The reason for this decrease comes from the effective capacitance in the antenna system. We define $C_{eff,0} = C_0 + C_1$ at 299.59MHz, where C_0 is the capacitance in the structure (coupling between the inner loop and the outer loop) and C_1 is the lumped element capacitor value (1.7pF). The capacitor values are swept from $0.9C_1$ to $1.1C_1$ ($\pm 10\%$ of C_1). Therefore, we then obtain

$$C_{eff,1} = C_0 + 0.9C_1$$

$$C_{eff,2} = C_0 + 1.1C_1$$

$$\Rightarrow \quad \frac{C_{eff,2} - C_{eff,1}}{C_{eff,0}} = \frac{0.2C_1}{C_0 + C_1} < \frac{0.2C_1}{C_1} = 0.2$$

This means that even though we sweep the capacitor value between $\pm 10\%$ of the center value, the real sweeping range is smaller than $\pm 10\%$. Consequently, the corresponding sweeping frequency is smaller than the expected one. Moreover, from the HFSS simulation results, the 10 dB bandwidth is 0.491% for the 1.53 pF case and 0.433% for 1.87 pF case, respectively. We therefore chose 0.433% as a reference value from which we calculated the maximum tolerable error for the capacitor values. The reasoning evolves from Eq. (2). Since the minimum bandwidth is 0.433%, we then obtain the ratio

$$\frac{df}{f} = \pm\frac{0.433}{2} = \pm 0.2165\,\% \quad \text{so that the corresponding ratio} \quad \frac{dC}{C} = \mp\, 0.433\,\%$$

Therefore, the maximum error that capacitor can tolerate and still maintain the resonance frequency is $\pm 0.433\%$. As one can see from Fig. 4, the maximum error was 0.1693%, which is more than half the maximum allowed value.

Conclusion

We have demonstrated that the metamaterial-inspired, electrically small, 2D magnetic-based EZ antennas integrated with a swept lumped element capacitor can provide a larger bandwidth without any corresponding degradation of the overall efficiency. In particular, the results predict that one can ideally obtain an approximately 10% bandwidth with a ±10% variation for the lumped capacitor value. The result is theoretically possible and we are currently investigating possible solutions that would provide the desired swept capacitor values over the frequency band of interest to achieve a proof-of-concept experimental verification of our proposed approach.

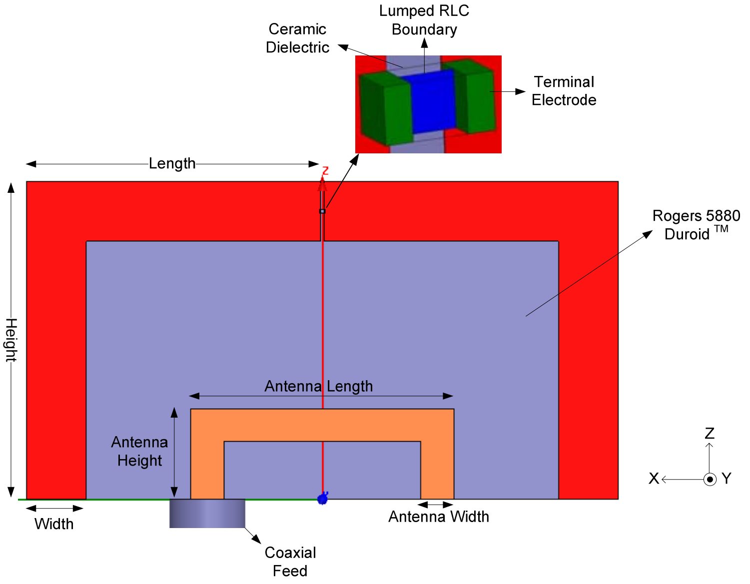

Fig. 1: Geometry of the 2D magnetic-based EZ antenna integrated with a lumped element capacitor

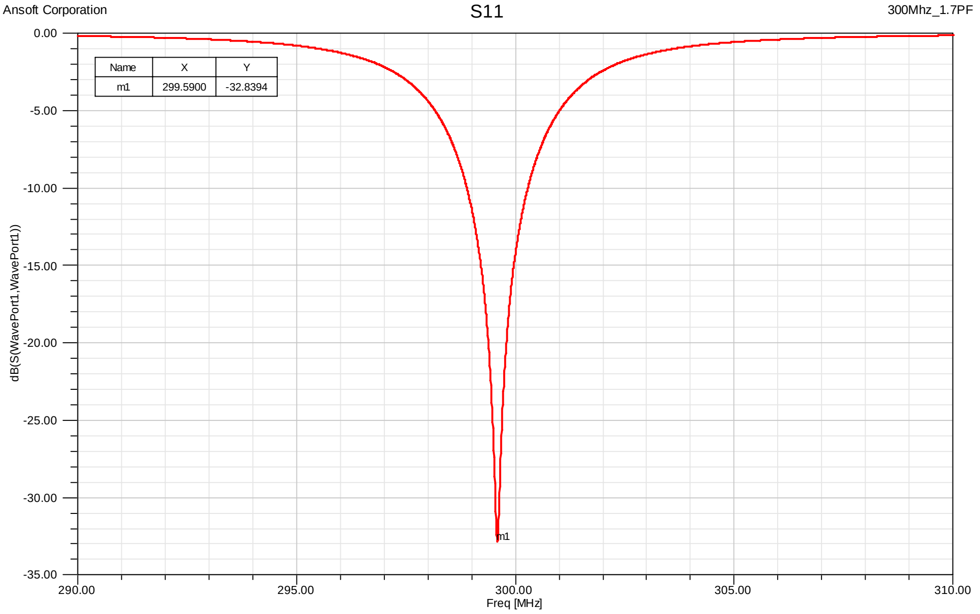

Fig. 2: HFSS predicted S11 values for the electrically small 2D magnetic-based EZ antenna.

Table 1. Capacitor values and corresponding HFSS-predicted resonant frequencies

Capacitor Value (PF)	Frequency (MHZ)	S11(dB)	Overall Efficiency (%)
1.53	310.435	-30.3827	94.671
1.564	308.43	-33.6237	94.413
1.598	305.93	-41.4337	94.355
1.632	303.9	-53.8611	94.187
1.666	301.82	-38.4833	93.980
1.7	299.59	-32.8234	93.716
1.734	297.62	-29.7821	93.447
1.768	295.675	-27.4976	93.199
1.802	293.535	-25.5637	92.875
1.836	291.645	-24.1306	92.623
1.87	289.95	-23.0347	92.267

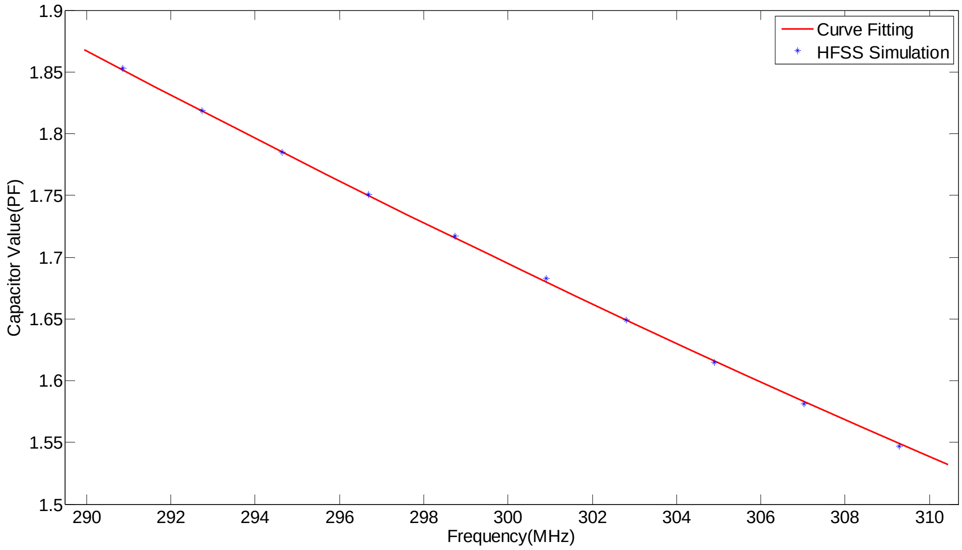

Fig. 3: Comparison between capacitor values and predicted resonant frequencies obtained by curving fitting and HFSS simulations

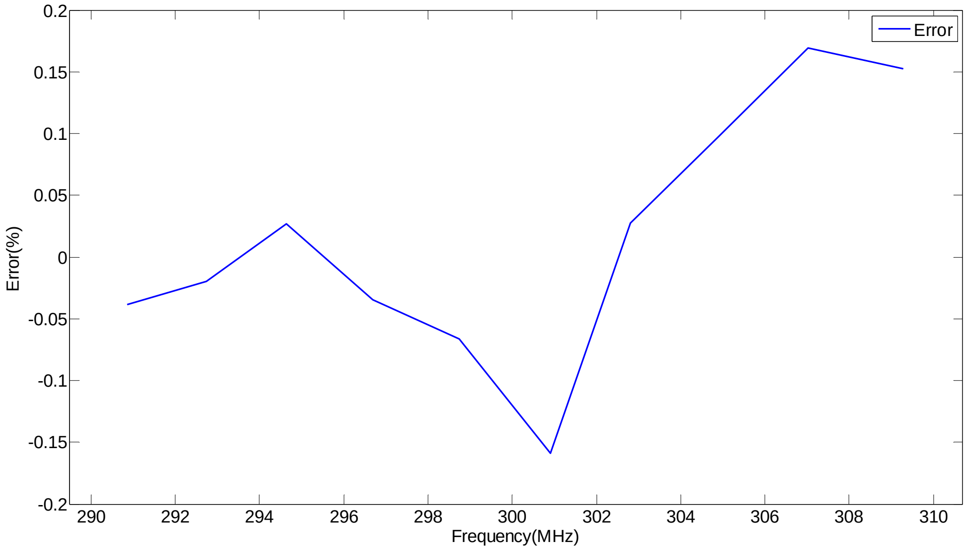

Fig. 4: Error ratio of the curve fitting and HFSS simulation results

References

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