Beam Shaping for Short-Range Wireless Sensor Application at 2.4GHz using 0.18µm Technology

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Abstract- **This paper describes a phase-shifter and variable gain amplifier block operating at 2.4 GHz as part of a wireless sensor for Smart Grid applications. The reflective type phase shifter (RTPS) is implemented using a lumped element branched-line coupler with identical reflective resonant loads with L-match impedance transformation. The VGA is implemented using a bridged-T attenuator in order to control its gain thus achieving beam shaping and directivity control. The phase shifter is used to control the phase excitation of the signal to allow beam pointing. In addition, the phase shifter is used to compensate for the phase shift due to the VGA and the other blocks.**

Index terms: Variable Gain Amplifier, Beam Shaping, Phase Shifter, Chebyshev Synthesis, Smart Grid.

I. INTRODUCTION

Smart Grid applications require versatile sensors that can perform multiple functions such as scanning, detection and resolving detected objects. It is also desirable to combine the functions of object detection and resolution in one sensor. It is required therefore to employ a transmitter module that can switch between scanning mode and a subsequent alert mode following detection of a moving object within range. Therefore, in addition to an electrically steerable beam it is required to be able to electrically switch between beams with different directivities and sidelobes corresponding to each mode. In addition, we need to be able to adjust the gain of the signal through the transmitter path in order to account for gain loss in some of the blocks in that path. This wireless sensor presents an efficient and cost effective solution for Smart Grid technologies, specifically short range applications deployed indoors.

To achieve the above features we need a device with the following specifications:

1. The ability to control the beamwidth (and thus directivity) thereby switching between different sensor modes by varying the amplitude taper of the driven signal.
2. The ability to control the strength of the sidelobe with respect to the main lobe and maintain it below a maximum amount.
3. Enable beam pointing by controlling the signal phase excitation and also allow for phase compensation due to other blocks in the Tx/Rx chain.

RTPS design using different configurations is demonstrated in [1,2]. Switched control of gain in VGAs is demonstrated in [3]. Phased array systems are discussed in detail in [4]. We extend these ideas to demonstrate the design and the simulation of a variable gain amplifier using bridged-T resistive attenuators and RTPS based phase shifters to drive phased array transmitters.

The paper is divided into 5 sections. Section I gives the basic introduction on the subject. Section II lays down the mathematical basis for beam shaping and beam pointing. Section III describes the RTPS and its design equations. Section IV describes the attenuator based VGA design implementation. Finally, Section V concludes the work done.

II. BEAM SHAPING USING AMPLITUDE TAPERING

In order to control the directivity of the array beam, we adjust the amplitude of each array element by scaling it. Thus for a 5x5 array, we would have 25 coefficients, one for each element and all scaled by the largest value. Thus the largest coefficient would be one and the rest would taper down to zero. It must be noted that amplitude tapering controls trade-off between beam peak performance and sidelobe peaks.

By using Dolph – Chebyshev synthesis, we can optimize the array pattern plot by designing for the nearest sidelobes levels to be below the main lobe level by a minimum amount.

The general expression for the array factor for an array antenna with equal spacing between the elements is given below.

$$F(\theta,\phi) = \sum_{m}\sum_{n} a(m,n)e^{j\alpha(m,n)}e^{j(mSx+nSy)}$$

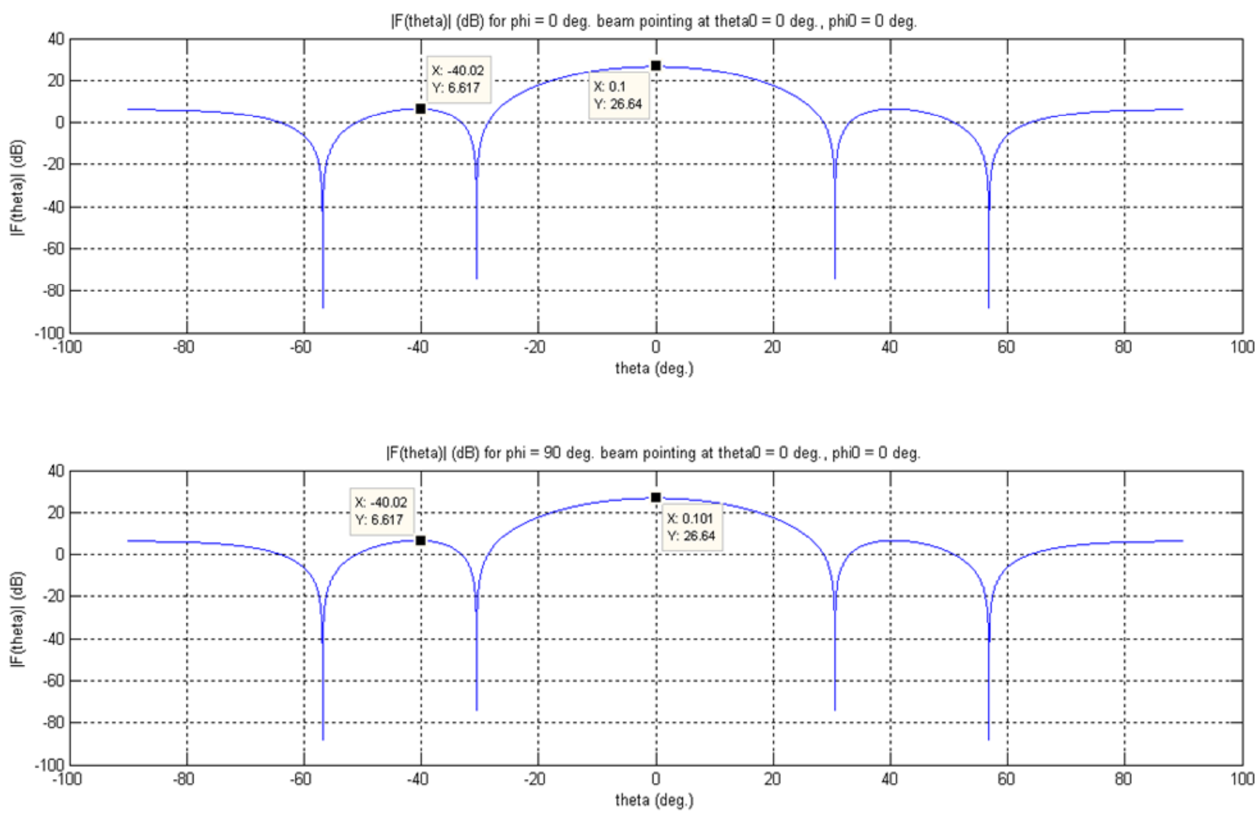

Figure 1: Array Factor 9dB) for a 5x5 array with amplitude tapering for Φ=0 and 90º respectively.

Where,

$$Sx = \frac{2\pi}{\lambda} dx \sin\theta \cos\phi$$

$$Sy = \frac{2\pi}{\lambda} dy \sin\theta \sin\phi$$

a(m,n) is the amplitude taper coefficient for the (m,n) element as found by the Dolph-Chebyshev synthesis. α(m,n) is the phase excitation for the (m,n) element. Beam pointing is accomplished by adjusting the values of α(m,n). Beam shaping (Directivity control) is done by controlling a(m,n).

Assuming equal element spacing (dx = dy = d) and linear phase progression, the above expression can be rewritten by separating the two summation series as:

$$F(\theta,\phi) = \sum_{m} a(m)e^{j\alpha(m)}e^{jmSx} \sum_{n} a(n)e^{j\alpha(n)}e^{jnSy}$$

$$a(m,n) = a(m) \times a(n).$$

Where, $\alpha(m)$ and $a(m)$ are phase and amplitude for the mth element in the x-direction and $\alpha(n)$ and $a(n)$ are phase and amplitude for the nth element in the y-direction, respectively.

Thus, each of the 25 elements of the 5x5 array are scaled by its respective coefficient in order to get the required directivity and sidelobe attenuation, 20db down from main lobe in the case shown in Figure 1.

III. PHASE SHIFTER

A reflective type phase shifter with identical resonant loads with L-match impedance transformation. Figure 2 shows the RTPS as a lumped element branch line coupler with identical resonant loads.

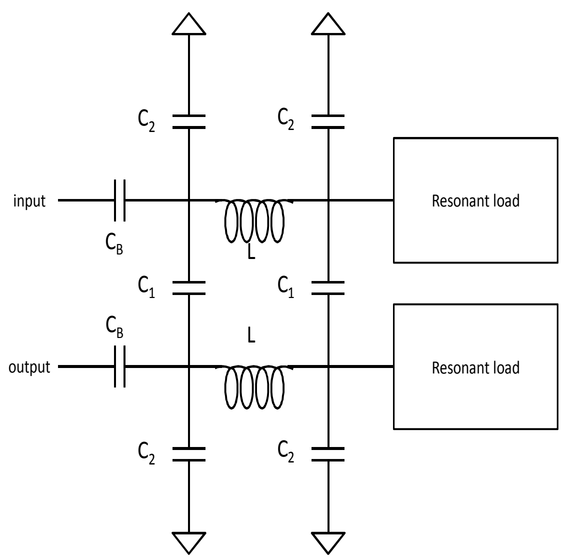

Figure 2: RTPS with identical resonant loads

The blocking capacitors C_B present low impedance at frequencies around 2.4 GHz. At resonant frequency and with a characteristic impedance of Z_o, L_1 and C_1 can be determined from:

$$C_1 = (\omega_0 Z_0)^{-1}$$
$$L_1 = Z_0(\sqrt{2}\omega_0)^{-1}$$
$$C_2 = (\omega_0^2 L_1)^{-1} - C_1$$

Figure 3 shows the type of resonant load chosen to provide a phase shift between -90 and -180 degrees.

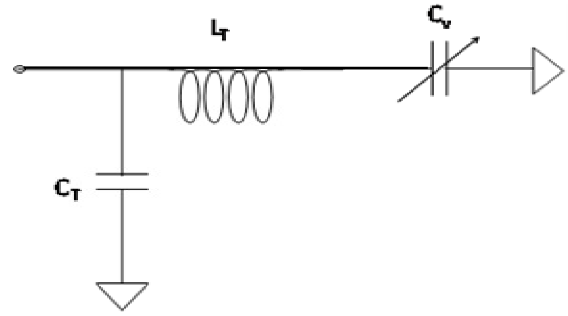

Figure 3: Resonant load with L-match impedance transformation.

The value of C_V is varied between C_{MIN} and C_{MAX} to give us the required phase shift. For the resonant loads, L_T is chosen such that it resonates with C_V. The phase shift provided by the circuit is decided by its reflection coefficient, given by:

$$\Gamma = \frac{Z_r - Z_o}{Z_r + Z_o}$$

Where Zr is the impedance of the resonant load and Zo is the characteristic impedance. The total phase shift, for a load of reactance X, is given by:

$$\phi = -180 - 2\arctan\left(\frac{X}{Z}\right)$$

We select values of L_T such that resonance occurs at $C_V = C_{MIN}$. Design equations for L_T and C_T are given by:

$$L_T = (\omega_o^2 C_{MIN})^{-1}$$

$$C_T = (\omega_o^2 L_T - (C_{MIN})^{-1} - (C_{MAX})^{-1})^{-1}$$

The full range of phase shift occurs as C_V is varied between C_{MIN} and C_{MAX}.

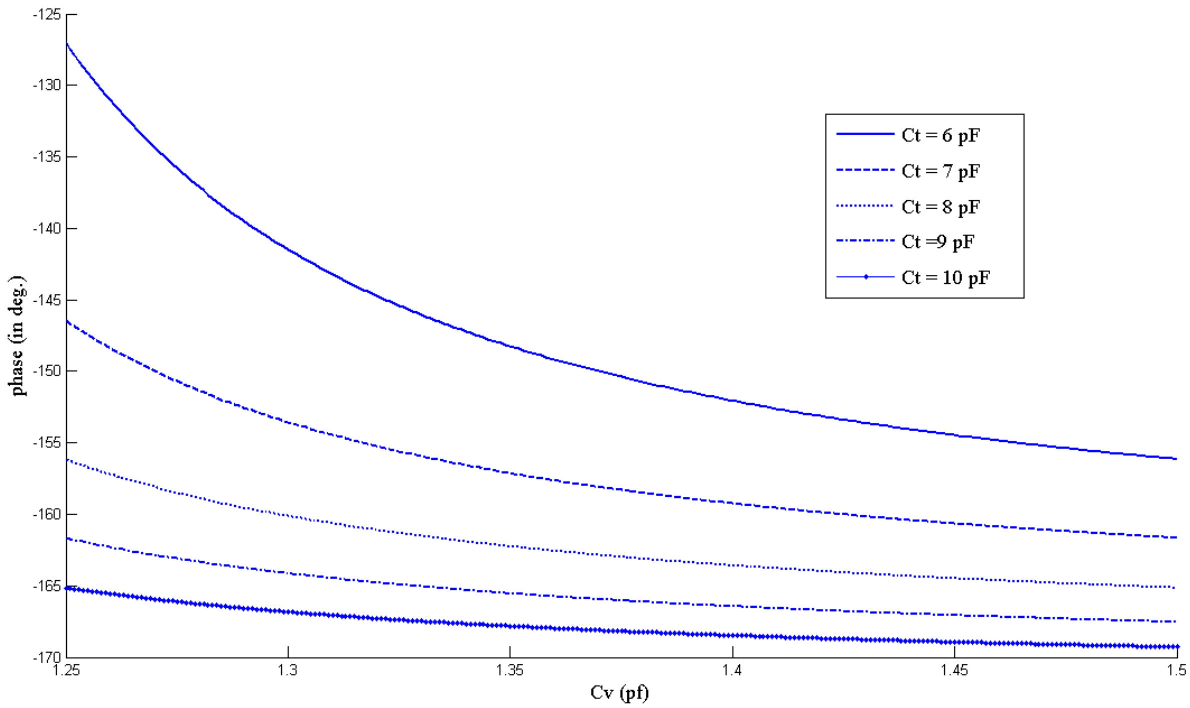

Figure 4: Phase shift (in deg.) vs. Cv (pF) for different values of Ct.

Figure 5 shows the phase shift achieved for different values of C_T as C_V is varied between C_{MIN} and C_{MAX}.

IV. VARIABLE GAIN AMPLIFIER

Amplitude tapering is achieved by incorporating a VGA based on a bridged-T attenuator design with controlled loads. Depending on the tapering required, different combinations of resistors are switched in and out of the T network thus achieving the required attenuation. The basic bridged-T attenuator is shown in Figure 5.

The bridged-T attenuator is designed here to match 50 ohms at the input and output. By controlling the values of $R_1$and R_4 the attenuation (L, in dB) provided by the circuit can be controlled as given by the following equations.

$R_2 = R_3 = Z_O = 50\ \Omega$
$R_1 = Z_O(10^{L/20} – 1)$
$R_4 = Z_O/(10^{L/20} – 1)$

where, Z_O is the characteristic impedance, L is the desired attenuation in dB and Zin and Zout are the input and output impedances respectively.

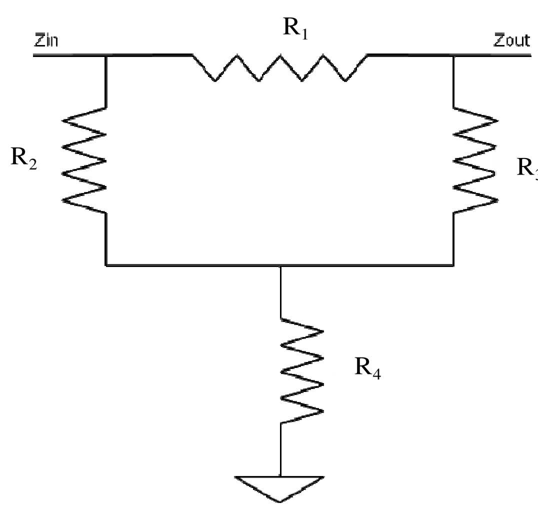

Figure 5: Basic bridged-T attenuator

Figure 6 shows the individual Tx. chain associated with each array element. Therefore, by switching required sets of resistors in and out based on digital control voltages we can control the attenuation of the signal thus setting the amplitude taper of each array element and thus controlling the beam shape and the mode of operation

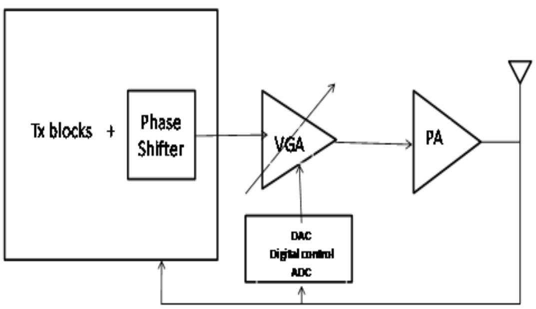

Figure 6: Complete block diagram with VGA and RTPS for the Tx chain for a single array element

The VGA is described below:

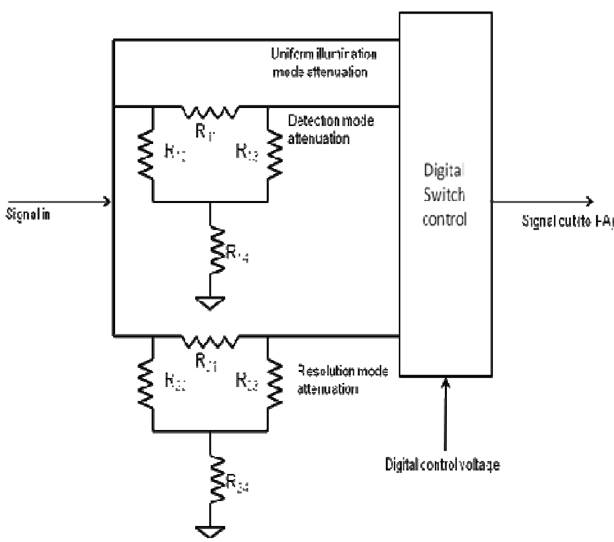

Figure 7: Switched gain VGA output section for each Tx. element.

. As discussed before, multiple Smart Grid Sensor modes such as scanning, detection and resolution need to be supported. This is accomplished by switching resistor sets using control voltages to get different levels of attenuation. In Figure 7, three such modes are supported for each antenna element, namely:

1. Uniform illumination (L = 0 dB).
2. Detection mode (L = 3.52 dB).
3. Resolution mode (L = 9.54 dB).

The figure below shows the time domain simulation of the circuit above. The three waveforms represent the non-attenuated input, detection mode attenuation and resolution mode attenuation respectively.

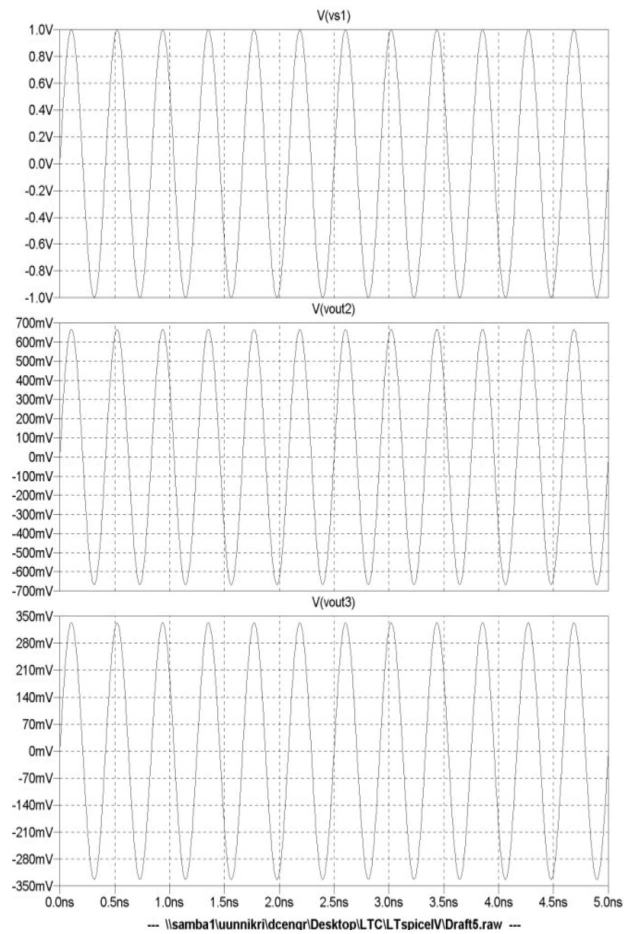

Figure 8: From top to bottom- Uniform illumination, detection mode and resolution mode.

Figure 8 shows the three modes we can switch between and how the attenuation changes from 0 dB for uniform illumination of all elements to 3.52 dB

(0.6667) down for detection mode to 9.54 dB (0.3333) down for resolution mode.

V. CONCLUSION

The RTPS and VGA can be used in various Smart Grid applications where compact, low power, integrated sensors are needed. This design could be adapted for use in other phased array systems requiring a completely integrated low cost solution. This CMOS sensor provides an ideal integrated solution for residential and commercial applications including SmartGrid power conservation systems based on automatic control using low cost and low power CMOS motion detectors integrated on a single chip.

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