ACTIVE ANTENNA APPROACH TO HIGH EFFICIENCY POWER AMPLIFIERS WITH EMI REDUCTION

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ABSTRACT
This paper reports two techniques for optimizing harmonic termination in power amplifiers. In the first technique, the active antenna approach, the antenna element acts as radiator and as part of the output tuning circuit. The second method, based on photonic band-gap (PBG) structure, incorporates a periodic harmonic tuning structure for microstrip lines. In this structure, a periodic 2-D pattern is etched in the microstrip ground plane. A wide stopband, suitable for broadband harmonic tuning, has been demonstrated experimentally. These methods yield high efficiency power amplifiers, and reduce unwanted radiation from the antenna at harmonics. Two power amplifier examples are presented.

INTRODUCTION
Advanced wireless communication systems require a compact and low-cost transmitter front end without sacrificing system performance. Ways of achieving this are through high system integration and improved performance. Typically, because most of power is consumed in the output power amplifier and higher DC powers adds to both system cost and weight, this requires increasing power-added efficiency (PAE). Another critical system component in wireless systems is the antenna. It is typically designed separately and connected to the amplifier by an interconnect. Additionally, when multiple systems operating at neighboring frequencies exist in close physical proximity, there is an increasing EM interference problem. To remedy this, a filter is often placed between the amplifier and antenna to reduce unwanted radiation. Traditionally, these components are designed with 50 Ω input and output impedance and connected together. This conventional method works well at low frequencies and when system design requirements are not tight. However, at high frequencies, interconnects become lossy and may possibly radiate or couple with other elements. This leads to the degradation of the system performance even though the individual components meet their specifications.

One technique for reducing this problem is the active integrated antenna approach. In this method, the amplifier and antenna are combined into a single unit. This concept can be used to explore new design topologies for the output stage. In this approach, the antenna can serve as filter, output matching circuit, and harmonic tuner in addition to being a load and radiating element. A key issue is that circuit components are not terminated in 50 Ω, but rather in the values that optimize system performance. The number of tuning or interconnecting elements between the amplifier and antenna can therefore be significantly reduced, with the effect of reducing system cost and losses.

DESIGN APPROACH
High power devices such as power FETs or HEMTs typically have low output impedance, which is incompatible for 50 Ω systems. Therefore, the device designers have been trying to increase the device output impedance toward 50 Ω at the expense of compromised output power. Additionally, antenna designers have been modifying antennas for 50 Ω match as well. This dilemma can be circumvented if the amplifier and antenna are combined together. Many planar antennas such as the patch or slot antennas can be designed for low input impedance and good radiation characteristics when operated away from resonance. Therefore, the antenna and amplifier can be combined together with minimal matching circuitry in between.

Additionally, the PAE of the power amplifier circuit can be improved by optimizing the load impedance at the fundamental and higher harmonics. Conventionally, second harmonic tuning is accomplished by adding a short circuited stub at the output (most often at the drain bias line) [1]-[2]. A similar stub is used for the third harmonic tuning. However, in the active antenna approach the antenna can perform this function. If the antenna input impedance is purely reactive (or zero) at harmonic frequencies, it can be used to tune harmonics. The effect is twofold: harmonic tuning increases PAE or output power of the amplifier, and it also reduces unwanted harmonic radiation which causes EM interference and ultimately degrades system performance.
ACTIVE ANTENNA APPROACH

Planar microstrip antennas are an ideal choice for the active antenna approach since they can be fabricated directly with the amplifier circuit. When designing antennas with this method, the resonant frequency is found first. Then, the input impedance and the radiation properties are determined over a wide frequency range. The ideal antenna should have input impedance that closely matches the optimum device impedance for maximum PAE at the fundamental, and is purely reactive at the second and third harmonics. It should maintain good radiation characteristics at the fundamental and low radiation characteristics at harmonic frequencies.

One such antenna is the circular sector microstrip antenna with 120° cut-out, shown in Fig. 1(a). The measured input impedance is given in Fig. 1(b) for the antenna with 740 mil radius on 31mil-thick RT/Duroid 5870 ($\varepsilon_r = 2.33$). As seen in Fig. 1(b) the input impedance at the first resonance is above 200 $\Omega$ and is difficult to match to 50$\Omega$ or lower impedance. Therefore, the operating frequency is chosen off resonance at 2.55 GHz where the impedance is (19.8-j14) $\Omega$. Also, the real part of the impedance at the second and third harmonics is close to zero. The measured input impedance is then incorporated into a harmonic balance circuit simulator to design a class F power amplifier [3]. The design was done using Hewlett Packard’s Microwave Design System (MDS) using a Microwave Technology MWT-8HP GaAs FET with a 1200-micron gate width. The drain bias voltage is 5 V and the gate bias voltage is set so that the DC drain current is 10% $I_{dss}$. The measurement was done in an anechoic chamber and calibrated using Friis free space transmission formula [4]. To do this, the gain of the passive antenna was measured to be 5.8 dB at broadside. Then, the active antenna amplifier was substituted in its place. Fig. 2 shows PAE and output power versus input power at 2.55GHz. These results are for the amplifier gain only and do not include the antenna gain. The maximum measured PAE is 63% at an output power of 24.4dBm. MDS predicted the maximum PAE of 61% at 24.2dBm.

Figure 1. (a) Layout of circular sector microstrip antenna used in active antenna approach. (b) Measured input impedance of the antenna shown in (a).

Figure 2. Measured and simulated PAE and output power versus input power for the class F power amplifier integrated with circular sector antenna shown in Fig. 1(a).
ACTIVE ANTENNA AND PBG APPROACH

One difficulty with the active antenna approach is the difficulty in finding structures with the proper terminating impedance at both second and third harmonics. An example of this is the patch antenna with pins [5], shown in Fig. 3. The patch is 1550mil wide and 2320mil long. Again, the operating frequency (2.45GHz) is chosen off resonance to reduce the load impedance and the real part at the second harmonic is almost zero (1.9Ω), and at the third harmonic is too high (15.3Ω), as shown in Fig. 4. In order to tune the third harmonic, a periodic structure based on the photonic band-gap (PBG) concept is introduced. PBG materials are periodic structures with frequency bands where electromagnetic waves are highly attenuated or do not propagate [6]. Fig. 3 shows a recently proposed PBG structure based on partial etching of the microstrip ground plane [7]. It consists of 2-D square lattice of circles etched into the microstrip ground plane. The number of cells is 4x3, period is 500mil, and circle radius is 110mil. Conductor width is 90mil, corresponding to 50Ω line for conventional microstrip. The measured S-parameters of the PBG structure fabricated on 31mil-thick RT/Duroid 5870 (ε_r = 2.33) are shown in Fig. 5. The real part of the input impedance of the PBG structure and patch antenna is 1.4Ω at the third harmonic.

To demonstrate the usefulness of this structure, a class AB power amplifier was designed with the PBG structure used for termination of the third harmonic [8]. The device and measurement procedure were the same as in the previous amplifiers. Measured output power and PAE versus input power are shown in Fig. 6. Maximum measured PAE is 61% at an output power of 21.9dBm. MDS predicts maximum PAE of 58% at 22.7dBm.
Figure 6. Measured and simulated PAE and output power versus input power for the class AB power amplifier integrated with patch antenna and periodic structure.

EMI REDUCTION

If the power amplifier generates significant harmonics, they may radiate through the antenna and degrade system performance. For example, co-site interference, is a serious problem when a large number of antennas operating at different frequencies are mounted in close proximity. Employing additional filters to solve the resulting EMI problem is not only expensive, but decreases the transmitter efficiency and may degrade the receiver noise figure.

The harmonic tuning techniques presented here can not only improve the amplifier efficiency, but also reduce unwanted harmonic radiation. This has been observed by measuring the second and third harmonic radiation from the amplifiers presented previously. Since harmonic frequencies may have different radiation pattern from that of the fundamental, the harmonic radiated power has to be measured in all directions, as shown in Fig. 7. For the power amplifier integrated with circular sector antenna the second harmonic was 33.8 dB and the third was 31.4 dB below the fundamental frequency peak, as shown in Fig. 7(a). For the power amplifier integrated with patch (with pins) and PBG, the second harmonic was 33.1 dB and the third was 32.2 dB below the fundamental frequency peak, as shown in Fig. 7(b). In both cases the input power was set to the level that gives maximum PAE. The output power was calibrated using receiving antenna gain and the Friis transmission formula at corresponding frequencies. Therefore, the fundamental and harmonic power levels are referenced at the output of the antenna integrated with amplifier.

Figure 7. Normalized co-polarization E and H plane radiation pattern of fundamental, second and third harmonic for the amplifier integrated with (a) circular sector microstrip antenna and (b) patch antenna and PBG structure.
CONCLUSION

We presented two techniques for designing high efficiency amplifiers with low harmonic radiation. The first technique is based on the active integrated antenna approach. In this approach the antenna is integrated with the amplifier. Additionally, the antenna functions as a filter at both harmonics frequencies. The second technique uses the active antenna approach at one harmonic and a microstrip periodic structure for the other. One power amplifier integrated with microstrip antenna for each technique was presented. PAE's better than 60% were demonstrated at frequencies around 2.5 GHz. Both amplifiers radiate very low harmonic powers in all directions.

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