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Active antenna for improved efficiency and reduced harmonic radiation

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Harmonic suppressed active antenna integrated with power amplifier yields improved efficiency, higher output power and reduced harmonic radiation from transmitter front end. This paper presents different harmonic suppression techniques of active antenna integrated with power amplifier. This paper also proposes and demonstrates novel PBG engineered structures to suppress higher order harmonics of integrated active antenna.

Keywords: Active antenna; Power amplifier; Harmonic suppression

1. Introduction

Efficiency, output power level, harmonic radiation and compactness are the most important parameters of the systems for RF transmitter end applications. Harmonic suppressed integrated-antenna power amplifier can provide improved system efficiency, higher power output, compact size and reduced harmonic radiation.

Since the power amplifier consumes most of dc power in the transponder, much attention has to be paid to maximizing the efficiency of the power amplifier. High efficiency power amplifiers allow compact and light-weight power sources, and reduced cooling requirements. Over recent years, high-efficiency power amplifiers have been designed and realized by controlling higher order harmonics from the non-linear solid state active devices (Bahl *et al.* 1989, Walker 1993, Lim *et al.* 2001, Chung *et al.* 2002). High-efficiency of power amplifier is achieved when the harmonics of the output voltage and current are terminated with the right magnitudes and phase. In this case, harmonics are terminated reactively, so that only fundamental signal power is delivered to the output load. Thus, harmonic termination not only provides improved efficiency and higher power output, but it also reduces the transmission of the harmonics to the output load.

When the power amplifiers are conventionally connected with the transmitting antenna, it suffers from the cable or feed line losses, which lead to degradation of the system efficiency and reduction of radiated output power. Moreover, when multiple systems operating at neighbouring frequencies exist in close physical proximity, there

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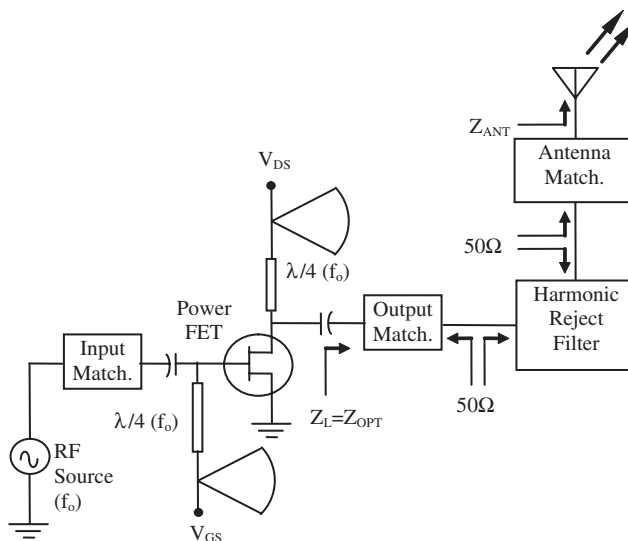


Figure 1. Schematic of the conventional power amplifier integrated with microstrip antenna through harmonic reject filter.

is an increasing EMI problem. To overcome this problem, a harmonic reject filter (HRF) is often used in between antenna and power amplifier to suppress the output harmonic radiation. Schematic of such a conventional power amplifier integrated with antenna and HRF is shown in figure 1. Conventionally, these circuits are designed individually with $50\ \Omega$ input and output impedances and are connected with RF cables or wave-guides. However, at microwave and mm-wave frequencies, interconnects become lossy and may possibly radiate or couple with other elements. This leads to degradation of the overall system performance, even though individual components meet their specifications.

For high performance transmitter applications, a new power-amplifier design methodology, based on active integrated antenna (AIA) design concept, has been proposed and demonstrated (Lin and Itoh 1994, Radisic *et al.* 1997, 1998a, Deal *et al.* 1999, Microstrip Antenna Design Handbook 2000, Hang *et al.* 2001, Chung *et al.* 2003, Kwon *et al.* 2003, Kim *et al.* 2004). A schematic of such an integrated-antenna power amplifier is shown in figure 2. In this approach, the amplifier and antenna are combined into a single unit. In this method, the antenna is used as a filter, part of the output matching-network of the power amplifier, harmonic tuner in addition to its own function as output load and radiating element. In this case, components are not terminated at $50\ \Omega$, but rather at the values that optimize the overall system performance. Thus, this approach eliminates the number of interconnecting elements and components, such as harmonic reject filter and individual matching networks for the amplifier output and antenna, resulting in a significant reduction of system size, cost and improving the power output and system efficiency.

There are different techniques for the integrated-antenna power amplifier, depending upon the choice of antenna and power amplifier topology. The following

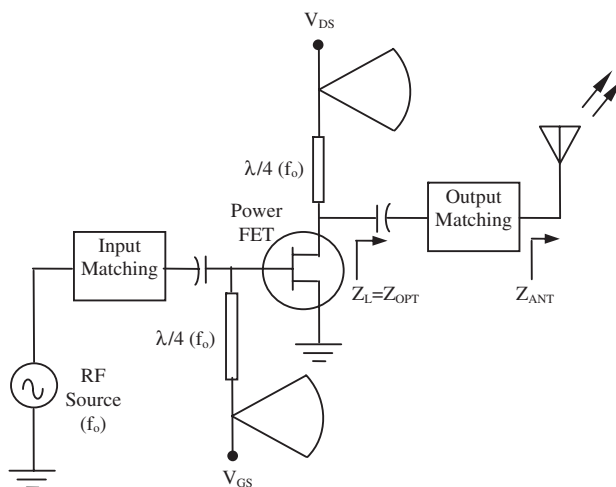


Figure 2. Schematic of the power amplifier integrated with a microstrip antenna. Antenna impedance (Z_{ANT}) is directly transformed to the optimum load impedance (Z_{OPT}) for maximum power and efficiency of the power FET.

sections will discuss the different approaches for the harmonic suppressed active integrated-antenna power amplifier.

2. Different antenna configurations for harmonic suppressor

Some antennas have the characteristic of higher order harmonic suppression, e.g. microstrip circular strip antenna and different types of microstrip slot antennas. Integrating these harmonic suppressed antennas, with the high power amplifier, it is possible to terminate the higher order harmonics of the non-linear power amplifier at proper phase and amplitude. The following subsections will discuss these types of antennas.

2.1 Microstrip circular strip antenna as harmonic suppressor

Chung *et al.* (2002) and Radisc *et al.* (1998a) proposed to use a microstrip circular sector antenna, both as a radiator and frequency-dependent output load of the power amplifier. Higher order harmonics from the non-linear power amplifier are reactively terminated because of the harmonic termination characteristic of the circular sector antenna. Layout of the 120° cut-out circular sector antenna is shown in figure 3. Selecting an operating frequency near the first resonance, the real part of the input impedance will be small at both second and third harmonics. This antenna is therefore suitable to provide optimum input impedance at both the second and third harmonics, which is an advantage over the rectangular patch antenna. In this approach, the antenna impedance can be directly transformed to the optimum load impedance of the MESFET and FET power amplifiers. Due to the antenna's characteristics, better than 30-dB

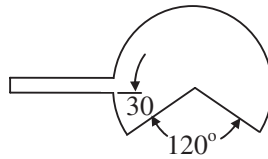


Figure 3. Layout of the circular-sector microstrip antenna.

harmonic suppression has been achieved at both the second and third harmonic frequencies.

2.2 Microstrip patch with shorting pins along the centre line for harmonic suppression

Radisic *et al.* (1997, 1998a) presented modified microstrip rectangular patch antenna design to suppress the even order harmonics. Figure 4(a) shows the geometry of a rectangular patch antenna and the mode profile for the (1, 0) and (2, 0) modes. The operating frequency is chosen slightly away from the resonance of the (1, 0) mode to avoid overly large input impedance. Therefore, the second harmonic would fall near the resonance of the (2, 0) mode. The use of this feature is undesirable for harmonic termination.

Figure 4(b) shows the geometry of the modified rectangular patch antenna to eliminate the (2, 0) mode. Referring to the mode profiles in figure 4(a), the peak of the (2, 0) mode and null of the (1, 0) mode electric field are at the centre of the patch. Therefore, the (2, 0) mode is eliminated by inserting a row of shorting pins along the centre line. This modification ensures almost zero input impedance for (2, 0) mode is without affecting the (1, 0) mode. However, one disadvantage of the modified patch is that the (3, 0) mode remains unaffected, therefore, this structure is not suitable for terminating the third harmonic of the power amplifier.

2.3 Shorting pin and slots in the rectangular antennas for harmonic suppression

As discussed in the previous section, the shorting pins on the centre line of the microstrip patch antenna do not affect the current distribution of the (3, 0) mode. Kwon *et al.* (2003) had proposed a microstrip-fed slot antenna with a shorting pin and slots to suppress the second as well as third harmonic, as shown in figure 5. The (1, 0) and (3, 0) mode is perturbed by slots near radiating edges. The (3, 0) mode is perturbed more than (1, 0) mode. Thus, the (3, 0) mode is controlled by slots near radiating edges. With the shorting pin and slot loaded antenna, the antenna return losses are suppressed by 6.7 dB and 17.7 dB, respectively. Another advantage of the slot loaded antenna over the conventional rectangular antenna is the smaller geometry of the antenna due to the lower resonant frequency of the structure.

2.4 Slot antennas for harmonic suppression

Kim *et al.* (2004) proposed rectangular and meander type slot antennas for the harmonic suppressor. These structures have the capability to suppress both

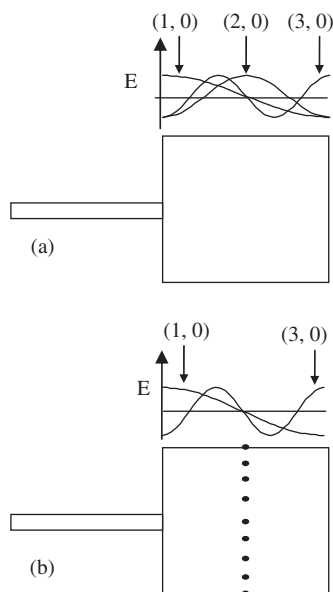


Figure 4. Layout and mode generation of the rectangular patch antenna; (a) conventional; (b) modified.

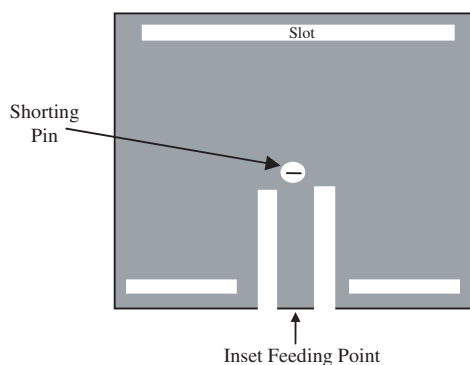


Figure 5. Geometry of the slot loaded antenna.

the second and third harmonics. The configuration of the rectangular slot antenna and meander type slot antennas are shown in figure 6a and 6b, respectively. They are the modified rectangular and meander slots in the ground plane with a microstrip feed line on the other side. The harmonic suppression characteristic is achieved by connecting the conductor lines within the slot with the ground plane. The conductor line and the gap between the slot and conductor lines act as inductor and capacitor, respectively. Therefore, the conductor line and gap can be represented as a shunt and series resonator, which has wide band stop operation over the second and third harmonic frequencies. A meander type slot is used to obtain miniaturized slot which leads to size reduction of the antenna.

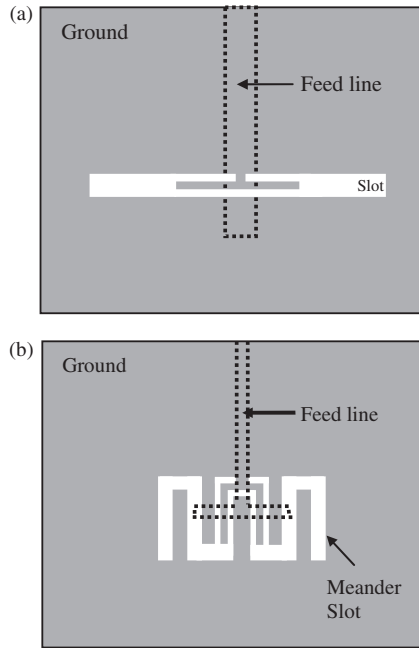


Figure 6. Configuration of the slotted antenna; (a) rectangular slot; (b) Meander slot.

3. Integrated-antenna push-pull power amplifier

Deal *et al.* (1999) demonstrated the integrated-antenna concept to push-pull power amplifiers. In this approach, the antenna serves as an out-of-phase power combiner as well as tuned load for higher harmonics. This architecture effectively has a near-zero loss hybrid, and results in a high efficiency power amplifier.

The conventional push-pull architecture is shown in figure 7(a). The MESFET transistors are biased for class-B, i.e. at pinch-off gate voltage. The input power is split and fed antiphase to the two FETs through a 180° hybrid. The resulting two output currents consist of two anti-phase half sinusoids. The Fourier analysis of the device drain current wave form can be expressed as:

$$I_{d1} = I_{ph} \left(\frac{1}{\pi} + \frac{1}{2} \sin \omega_o t - \frac{2}{\pi} \sum_{n=2,4,\dots}^{\infty} \frac{1}{n^2 - 1} \cos n\omega_o t \right) \quad (1)$$

$$I_{d2} = I_{ph} \left(\frac{1}{\pi} - \frac{1}{2} \sin \omega_o t - \frac{2}{\pi} \sum_{n=2,4,\dots}^{\infty} \frac{1}{n^2 - 1} \cos n\omega_o t \right) \quad (2)$$

where I_{ph} is the magnitude of the drain peak current and ω_o is the fundamental frequency. Equations (1) and (2) show that the output currents consist of anti-phase fundamental terms and in-phase all even order harmonic components. In the conventional microwave push-pull power amplifier, the two FET devices are combined using a 180° hybrid or a balun. However, the loss associated with the output hybrid directly reduces the efficiency and output power of the power

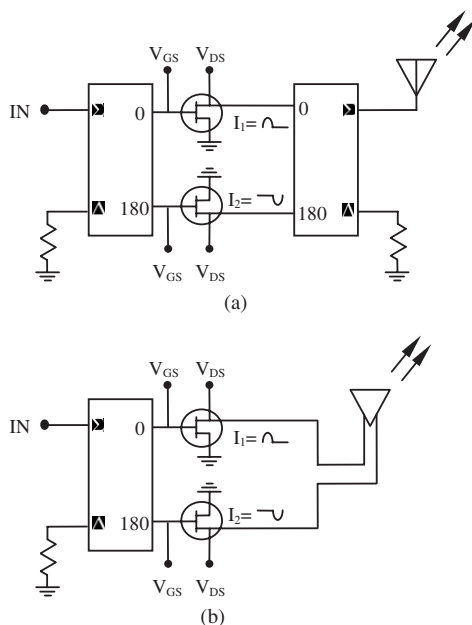


Figure 7. Schematic of the push-pull power amplifier (a) conventional (b) integrated-antenna.

amplifier at microwave and millimeter-wave frequencies. Moreover, the load impedance is crucial in designing a highly efficient power amplifier and should provide a reactive termination for the higher order harmonics to reflect the power back to the FET with proper phase.

The architecture of the active integrated-antenna push-pull power amplifier is shown in figure 7(b). In this approach, a multi-feed planar antenna has replaced the output 180° hybrid.

The two structures are the microstrip patch and slot antennas, along with their radiation mode profiles, shown in figure 8. The patch antenna has microstrip feeds placed at opposite radiating edges to excite the proper radiation mode. The λ -long slot uses two microstrip lines oriented in opposite directions and placed $\lambda/2$ apart on the slot. The microstrip feeds of the slot extend $\lambda/4$ across the slot to form a virtual short circuit for strong coupling to the antenna. In this case, each structures with push-pull excitation, will radiate identical radiation modes with identical phase in the antenna. Therefore, the radiated power will combine in free space. Deal *et al.* (1999) have demonstrated the maximum power added efficiency of 55% for both the antenna architectures.

Hang *et al.* (2000) had demonstrated the integrated push-pull power amplifier with quasi-yagi antenna. They have demonstrated the maximum power added efficiency of 60.9% at a frequency of 4.15 GHz.

4. Harmonic control by PBG effect-antenna power amplifier

The electronic band gap (EBG) and the defected ground structure (DGS) have various applications in microwave and millimeter-wave frequency bands with

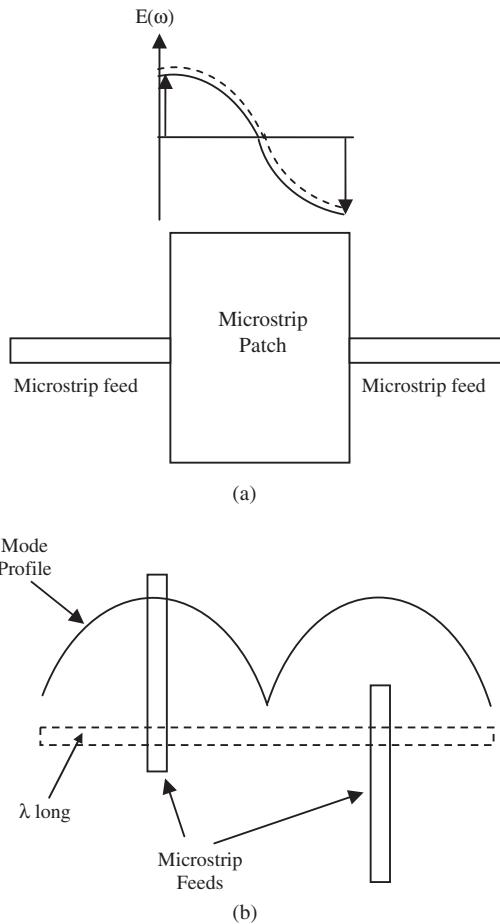


Figure 8. Two dual feed antenna structures and mode profile; (a) microstrip patch; (b) slot antenna.

various configurations (Kormanyos *et al.* 1994, Radisc *et al.* 1998b, c, Hang *et al.* 1999, Hori and Tsutsumi 1999, Jeong *et al.* 2003, Yi and Kang 2003, Nishio 2004, Sung *et al.* 2004, Lim *et al.* 2005, Woo and Lee 2005, Bera *et al.* 2005, 2006). The DGS is implemented by making an artificial defect on the ground, i.e. by etching the ground metallization of the microstrip circuit. DGS on the ground plane provides band rejection properties at the resonance frequency depending on the size of the defect and the pattern of the microstrip circuit. The DGS provides additional equivalent inductance of the transmission line leads to slower wave propagation, which enables size reduction of the microwave circuits. The band rejection characteristic with slow wave property is utilized to design an efficient and compact integrated antenna power amplifier.

Broad-band harmonic tuning is typically difficult to achieve for active integrated-antenna power amplifiers. All the techniques mentioned in the previous sections are narrow band in nature. Thus, additional harmonic filtering is required for broad-band operation. For this purpose, electromagnetic band

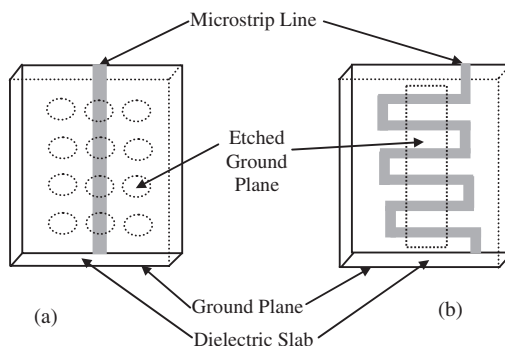


Figure 9. 3-D view of the periodic structure in the ground plane; (a) periodic circular etched pattern; (b) single rectangular etched ground pattern with meander $50\ \Omega$ line.

gap (EBG) structures are required, which have the property of a very wide band stop characteristic. Although any type of microstrip filter with appropriate band stop characteristic can be used for harmonic rejection, it is always preferable to use a PBG engineered structure for its low loss in the pass band with broad stop-band characteristic. The most important characteristic of the PBG engineered structures is the usefulness of the top conductor layer for other purposes, such as matching circuits and biasing of the FET, feeding the antenna or using as an antenna. Use of PBG engineered structure is also advantageous for deducing the overall size of the circuit for its inherent slow wave characteristics. Different techniques for the harmonic tuning using the PBG effect can be divided in three categories: (a) in the antenna feed line; (b) in the antenna itself; and (c) in the power combiner of the antenna array applications. These different techniques are discussed below separately.

4.1 PBG effect in the antenna feed line

There are two periodic structures for microstrip lines shown in figure 9. The dotted circles are the periodic ground etched patterns in figure 9(a) Radisc *et al.* (1997). Recently Bera *et al.* (2006) developed periodic structure as shown in figure 9(b). Here a single rectangular ground etched pattern is given. Periodicity is obtained due to the use of a meander $50\ \Omega$ transmission line. The periodicity of the structure is $21\ \text{mm}$ and size of the etched ground pattern is $24\ \text{mm} \times 8\ \text{mm}$. The test result of the PBG structure of figure 9(b) is shown in figure 10. This is a compact PBG structure, with very wide band stop characteristic with less ripple in the pass band. This type of PBG engineered structure can be used for feed of the microstrip patch antenna for broadband harmonic tuning.

Therefore, using this type of PBG engineered feed line for the microstrip patch antenna, broadband tuning of the higher order harmonics to achieve improved efficiency and higher power output from the integrated-antenna power amplifier is possible.

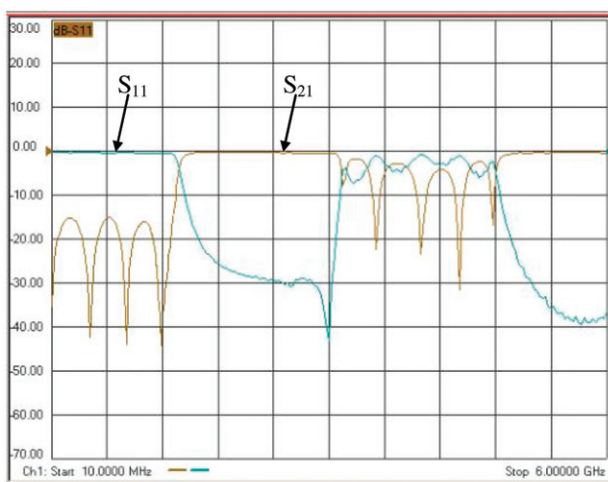


Figure 10. Test results of the PBG engineered filter of figure 7b.

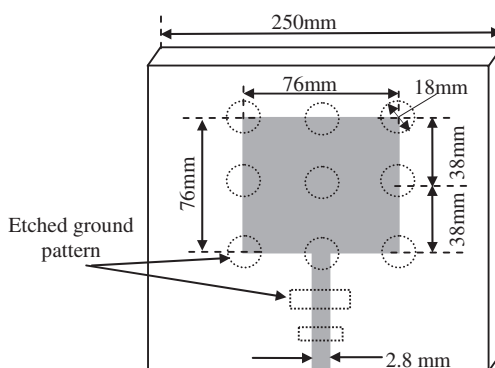


Figure 11. Microstrip patch antenna with PBG in the ground plane.

4.2 PBG effect in the microstrip patch antenna itself

Hori and Tsutsumi (1999) demonstrated the harmonic control by photonic bandgap on the microstrip patch antenna, which has two-dimensional PBG pattern of 3×4 circles with a diameter of 18 mm in the plane beneath the square patch. Their experiment shows the third harmonic suppression by 15 dB.

Liu *et al.* (2005) had proposed to use a DGS structure beneath the feed line in addition with the PBG pattern beneath the rectangular patch antenna as demonstrated by Hori and Tsutsumi (1999) to suppress the higher harmonic. The 3D figure of such an antenna is shown in figure 11. Here, a $76 \times 76 \text{ mm}^2$ patch antenna with a $200 \times 76 \times 1.6 \text{ mm}^3$ glass epoxy substrate and $\epsilon_r = 4.8$ is shown in this figure. The 3×3 circles of 18 mm diameter are etched in the ground plane at the periodicity of 38 mm, and 1-D DGS with two unit cells is etched in the ground plane beneath the 50Ω feed line of width 3.8 mm. This structure shows quite effective

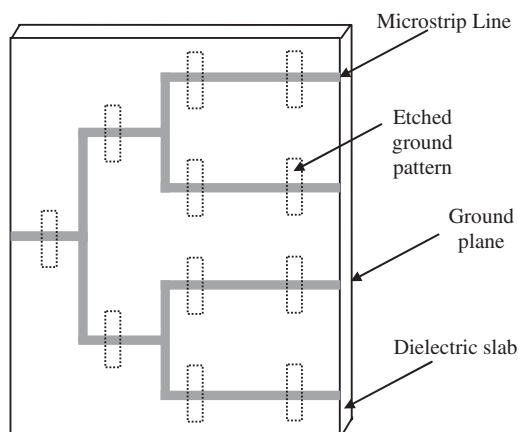


Figure 12. 3-D view of the modified 4-way Wilkinson power divider with ground etched periodic PBG structure.

harmonic suppression with a size reduction of 70% compared to the conventional PBG engineered antenna.

4.3 PBG effect in the power combiner in antenna array applications

Power dividers are used for antenna array applications. Recently, there have been several reports of the power divider combiners with the in-built feature of harmonic rejection (Yi and Kang 2003, Sung *et al.* 2004, Bera *et al.* 2005, Woo and Lee 2005). Among all the power dividers, the Wilkinson power divider is the most popular to use in antenna array applications. Incorporating the harmonic rejection filter inside the divider, the area for the filter in between the power amplifier and antenna can be reduced. Yi and Kang (2003) demonstrated the n th harmonic rejection in the modified Wilkinson power divider, incorporating the open stubs at the centre of the two $\lambda/4$ branches. Nevertheless, in this approach, the size of the coupler becomes more than double that of the normal Wilkinson power divider.

Woo and Lee 2005 had demonstrated the harmonic suppression in the Wilkinson power divider using dual-band rejection by asymmetric DGS. In this approach, DGS not only suppresses the higher order harmonics, but it reduces the size of the divider due to its slow wave characteristics. Here, two asymmetric DGSs are placed at each $\lambda/4$ branch to suppress the second and third harmonics simultaneously. The demonstrated harmonic suppressions are -18dB and -15 dB for second and third harmonics, respectively.

Recently, Bera *et al.* (2005) developed a higher order harmonic suppression power divider/combiner applying periodic DGS structure on a modified Wilkinson power divider. Demonstrated here are the design and test results of a modified 4-way corporate type Wilkinson power divider in microstrip configuration where all the $\lambda/4$ branch line impedances are Z_0 (50 Ω) instead of conventionally used $\sqrt{2}Z_0$. This is realized at a frequency of 4-GHz using a periodic DGS structure by etching a periodic pattern in the ground plane to suppress the unwanted harmonics.

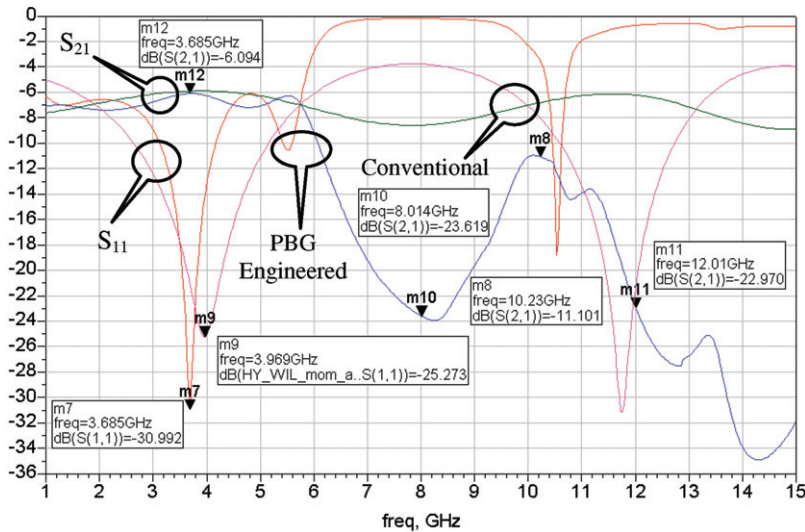


Figure 13. Simulated response of the conventional and PBG engineered 4-way Wilkinson power divider.

It provides flexibility for selecting the width of the branch lines according to power handling capability and eliminates the use of an additional harmonic reject filter due to its harmonic rejection property. The 3D structure of the modified Wilkinson power divider is shown in figure 12. The proposed structure for the modified Wilkinson power divider with PBG effect is designed by etching the rectangular patterns in the ground plane. Here, rectangular etched periodic ground pattern is used to get the PBG effect. This is a non-uniform PBG structure with an average periodicity of 7.2 mm. The dielectric substrate is 25 mil alumina ($\epsilon_r = 9.9$).

All the structures are designed and simulated by momentum simulator of ADS 2004A. Simulated S parameter results of the PBG engineered 4-way power divider is shown in figure 13. From the above results, we can see that the 2nd and 3rd harmonics near 8 GHz and 12 GHz is suppressed below 20 dB. In comparison to the non-PBG power divider there is an improvement in rejection of more than 16 dB at the first and second harmonics.

5. Conclusion

In this review article, the various techniques so far demonstrated for integrated antenna power amplifier have been discussed. These techniques rely on the different types of amplifier architectures or antenna design. These techniques are very useful for improving the power added efficiency of the system with more output power; at the same time, it reduces the harmonic power radiation from the antenna.

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