High-Efficiency Push–Pull Power Amplifier Integrated with Quasi-Yagi Antenna

Cynthia Y. Hang, *Student Member, IEEE*, William R. Deal, *Member, IEEE*, Yongxi Qian, *Senior Member, IEEE*, and Tatsuo Itoh, *Fellow, IEEE*

***Abstract*—This paper presents a C-band push–pull power amplifier integrated with a modified uniplanar quasi-Yagi antenna. In this circuit, corrugation is added to the truncated ground plane of the antenna so that it can be used for both out-of-phase power combining and second harmonic tuning. By using the active integrated antenna concept, this novel circuit eliminates the usage of an ordinary 180° hybrid at the power-amplifier output stage, therefore eliminating the losses associated with the hybrid, resulting in a compact and high-efficiency power-amplifier design with intrinsic second harmonic suppression. At an operating frequency of 4.15 GHz, a maximum measured power-added efficiency (PAE) of 60.9% at an output power of 28.2 dBm has been achieved. The measured PAE is above 50% over a 260-MHz bandwidth. Additionally, the second harmonic radiation is found to be 30 dB below the fundamental in both E- and H-planes. When the circuit is subjected to a two-tone test, the measured third-order intercept point is 37 dBm, about 10 dB above the $P_{1\text{ dB}}$ point.**

***Index Terms*—Active integrated antenna, FET amplifier, harmonic tuning, power-added efficiency, push–pull power amplifier.**

I. Introduction

NEXT-GENERATION wireless communication systems require highly compact and lightweight transmitters with long operating life times. Since the power amplifier (PA) consumes the majority of the power in the transmitter, much attention is paid to maximizing the efficiency of this crucial component. Several new design architectures for PAs with high efficiency and good linearity have been proposed, including the design of a dynamic supply voltage amplifier with on-chip dc–dc converter [1], and the use of periodic structures for harmonic tuning [2], [3]. Another technique for achieving high efficiency and minimum circuit size was demonstrated by using the active integrated antenna (AIA) concept. The AIA approach has been taken in the design of various circuits, such as mixers, transceivers, frequency doublers, and high-efficiency PAs [2], [4]–[9]. Recently, this concept has been extended to the push–pull PA [9]–[12], where the power of two antiphase-driven class-B PAs are directly combined through a dual-feed planar antenna.

The push–pull PA has a number of advantages over single-ended amplifiers, including the potential for broad-band performance [13] and twice the output power of a single-ended amplifier, which allows the use of two lower cost devices for a specified output power. In the conventional push–pull PA architecture, the input power is split and fed in antiphase to the two FETs through an 180° hybrid. The resulting two output currents consist of two antiphase half-sinusoids. The Fourier analysis of the device drain current waveform can be expressed as

$$I_{d1} = I_{pk}\left(\frac{1}{\pi}+\frac{1}{2}\sin\omega_0 t-\frac{2}{\pi}\sum_{n=2,4,\ldots}^{\infty}\frac{1}{n^2-1}\cos n\omega_0 t\right) \tag{1}$$

$$I_{d2} = I_{pk}\left(\frac{1}{\pi}-\frac{1}{2}\sin\omega_0 t-\frac{2}{\pi}\sum_{n=2,4,\ldots}^{\infty}\frac{1}{n^2-1}\cos n\omega_0 t\right) \tag{2}$$

where I_{pk} is the magnitude of the drain peak current and ω_0 is the operating frequency. As shown in (1) and (2), the output currents consist of antiphase fundamental terms and in-phase higher harmonic components. In the traditional microwave-frequency push–pull PA, the two FET devices are typically combined using a broad-band 180° hybrid or a balun. However, the loss associated with the output stage hybrid directly limits the practical efficiency of this class of amplifier at microwave and millimeter-wave frequencies [14]. Additionally, the load impedance is extremely crucial in designing a highly efficient PA, and should provide a reactive termination at higher harmonics to reflect the power back to the FET with the proper phase [11].

In the AIA approach, active devices are directly integrated with the antenna, allowing the antenna to serve as a power combiner and a harmonically tuned load, in addition to its original role as a radiating element, thus minimizing circuit size and insertion loss. In this paper, the AIA concept is applied to design a compact and high-efficiency C-band push–pull PA using a modified quasi-Yagi antenna. Fig. 1 shows the schematic of this circuit. As in a conventional push–pull PA, a ring hybrid is used at the input stage to split the input power and feed the two FETs with two antiphase waveforms. At the output stage, the balanced waveforms provide the proper antiphase excitation of the antenna, thereby eliminating the need for a 180° balun, while simultaneously achieving a high level of integration with the push–pull PA.

Manuscript received February 1, 2000; revised January 2, 2001. This work was supported by the Army Research Office Multidisciplinary University Research Initiative under Contract DAAH04-96-0005.

C. Y. Hang and T. Itoh are with the Department of Electrical Engineering, University of California at Los Angeles, Los Angeles, CA 90095 USA.

W. R. Deal was with the Department of Electrical Engineering, University of California at Los Angeles, Los Angeles, CA 90095 USA. He is now with Malibu Networks Inc., Calabasas, CA 91302 USA.

Y. Qian was with the Department of Electrical Engineering, University of California at Los Angeles, Los Angeles, CA 90095 USA. He is now with Micro WaveSys, Microsemi Corporation, Los Angeles, CA 90045 USA.

Publisher Item Identifier S 0018-9480(01)04435-0.

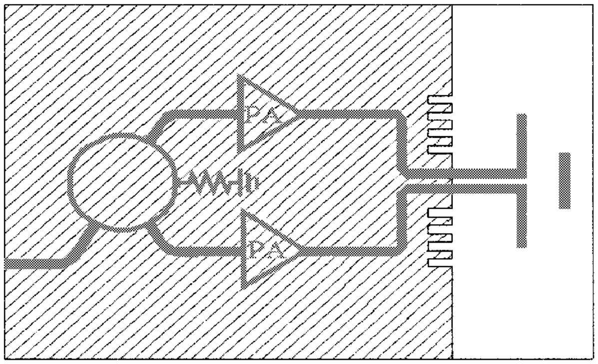


Fig. 1. Schematic of the push–pull PA integrated with a quasi-Yagi antenna with corrugation on the ground plane.

II. Quasi-Yagi Antenna Design

Recently at the University of California at Los Angeles (UCLA), we have developed a new type of microstrip-compatible planar end-fire antenna based on the classical Yagi–Uda antenna [15]–[17]. This new quasi-Yagi antenna features a very simple, yet compact, design that offers extremely broad operating bandwidth ($\mathrm{BW} > 50\%$ for $S11 < -10.0$ dB) with a moderate gain of approximately 5 dBi [17]. Unlike the traditional Yagi–Uda antenna, the quasi-Yagi antenna employs the truncated microstrip ground plane as a reflector, thus eliminating the need for a reflector dipole. In addition, the quasi-Yagi antenna uses a microstrip-to-coplanar strip (CPS) transition to feed the printed dipole, which, in turn, is used to excite the TE_0 surface wave in the high dielectric-constant substrate. Since the reflected TE_0 surface wave from the truncated ground plane and the driven dipole share the same field polarization, they are strongly coupled. A shorter dipole is used to steer wave propagation toward endfire while simultaneously serving as a parasitic impedance matching element. In the presented PA design, we have modified the original quasi-Yagi structure so that the antenna is driven by two antiphase microstrip feeds in a balanced fashion. This topology is, therefore, naturally suited to combine the antiphase output waveforms produced by the push–pull PAs.

Any antenna designed using the AIA approach must radiate efficiently with acceptable patterns [11]. Otherwise, the high level of integration gained by the AIA approach is wasted. Figs. 2 and 3 show the measured radiation patterns and antenna gain for the modified quasi-Yagi antenna. These patterns are consistent with those of an unmodified quasi-Yagi antenna. To achieve a highly efficient AIA design, a parametric study of the radiating mechanisms of the antenna was needed. The driven element of the antenna is a printed dipole antenna. Ideally, a dipole will radiate efficiently when antiphase excitation is applied. No radiation should occur if in-phase excitation is applied. In this ideal situation, the dipole represents a perfect tuned load for the push–pull PA, which has antiphase fundamental outputs as well as in-phase higher even harmonics. Unfortunately, the balanced-CPS-fed quasi-Yagi was found to be less than ideal in this respect. Simulations showed that in-phase excitation of the antenna led to fairly significant radiation at the second harmonic of the structure. Closer investigation reveals that this is due to the truncated ground plane of

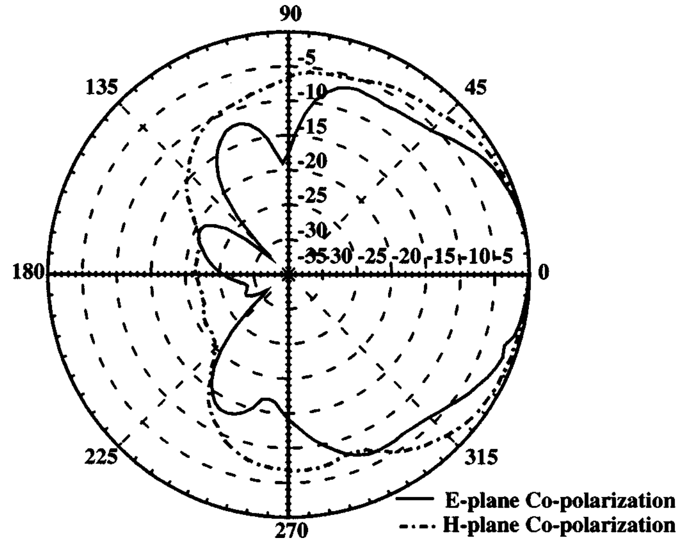


Fig. 2. Radiation patterns of the uniplanar quasi-Yagi antenna with a corrugated ground plane at 4.15 GHz.

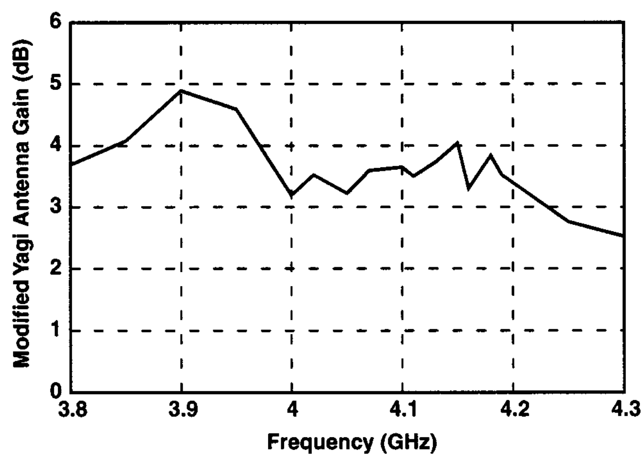
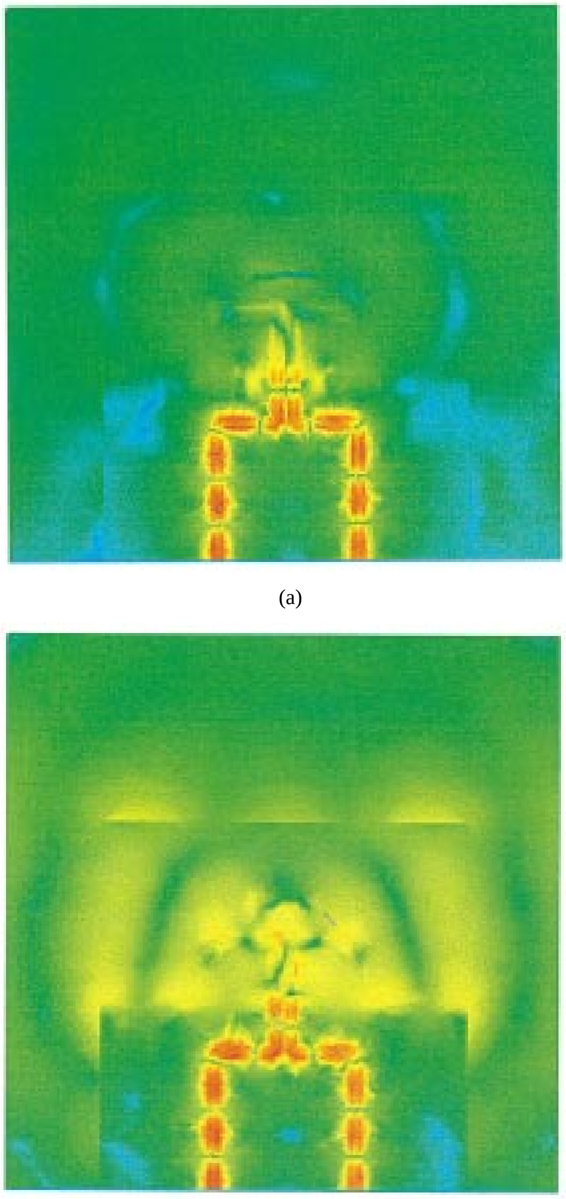


Fig. 3. Measured quasi-Yagi antenna gain as a function of frequency.

the antenna. In a balanced-CPS-fed quasi-Yagi antenna design, the CPS lines are fed by coupled microstrip lines, which support both even and odd modes. At the higher even harmonics, which signify in-phase excitation of the antenna, it was found that the CPS lines feeding the driven dipole were themselves radiating as a monopole-like structure at the truncated ground plane. Therefore, in its original state, the quasi-Yagi antenna will radiate undesired harmonics if integrated with a class-B push–pull PA, which generates an antiphase fundamental component, as well as in-phase even harmonics.

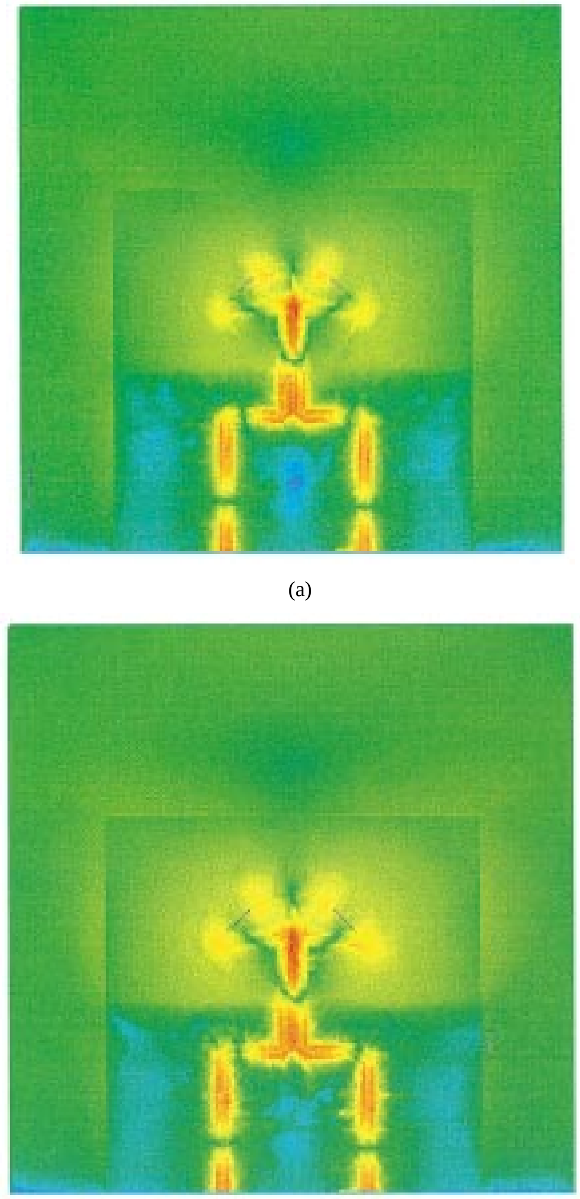
In a high-efficiency PA design, the load impedance should provide a reactive termination at the higher harmonics. Thus, to use the quasi-Yagi antenna in the design of a high-efficiency AIA push–pull PA, the monopole-type radiation at the even harmonics must be eliminated. A simple, yet effective, technique for performing this task is to add corrugation to the truncated ground plane. The depth of corrugation is chosen to be approximately $\lambda/4$ for the slotline mode at the second harmonic. The monopole-type radiation will excite the TE surface wave in the substrate, which will then excite the slotline mode at the truncated ground plane. Since the corrugation depth is $\lambda/4$ at the



(a)

(b)

Fig. 4. Simulated electric-field intensity of quasi-Yagi antenna: (a) with corrugation and (b) without corrugation at the second harmonic.



(a)

(b)

Fig. 5. Simulated electric-field intensity of quasi-Yagi antenna: (a) with corrugation and (b) without corrugation at the fundamental frequency of 4.15 GHz.

second harmonic, this corrugation will appear as an open circuit at all even harmonics, effectively canceling the monopole radiation at the truncated ground plane at these frequencies. In addition, since the corrugation is $\lambda/8$ at the fundamental frequency, we expect the corrugation to have minimal impact at the fundamental frequency. To demonstrate this, Agilent's High Frequency Simulator System (HFSS) is used to simulate the electric field intensity on the antenna plane for the quasi-Yagi antenna with and without corrugation. As shown in Fig. 4, the E-field intensity is significantly reduced at the second harmonic when corrugation is added to the ground plane, while the effect at the fundamental frequency was found to be minimal, as observed in Fig. 5. Since the output of a push–pull amplifier contains a series of in-phase even harmonics in addition to the antiphase fundamental, this modified quasi-Yagi antenna can be used as a harmonically tuned load.

III. PA Design

The C-band push–pull PA integrated with a quasi-Yagi antenna with corrugated ground plane was designed and optimized using Hewlett-Packard's Series IV harmonic-balance simulator. The modified dual-feed uniplanar quasi-Yagi antenna is directly incorporated into the simulator as a two-port network containing measured S-parameter data. The active devices used are Microwave Technology MWT-8HP GaAS power FETs with 1.2-mm gatewidth and are modeled using the built-in large-signal model within the Series IV simulator. The RF chokes were implemented using 100-nH coil inductors. To achieve maximum power-added efficiency (PAE), the FETs are biased at class AB, where the devices have slightly higher gain. The drain voltage is fixed at 5 V, and the gate is biased so that the quiescent drain current is 10% of I_{DSS} of the device.

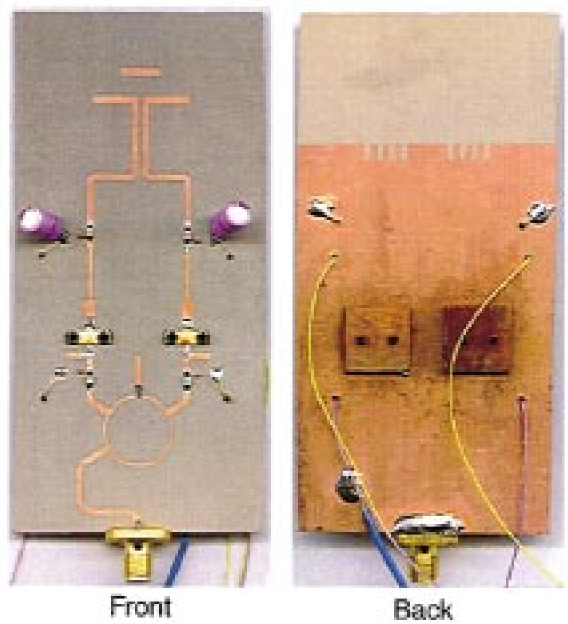


Fig. 6. Push–pull PA integrated with modified quasi-Yagi antenna.

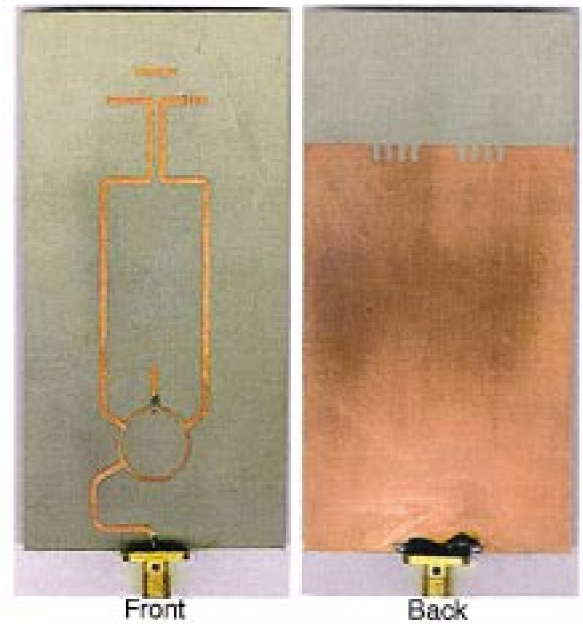


Fig. 7. Reference quasi-Yagi antenna.

The complete circuit is fabricated on an RT/Duroid with a dielectric constant of 10.2 and substrate thickness of 50 mil. The prototype C-band AIA PA is shown in Fig. 6.

Unlike a conventional 50-Ω PA design, the load of a PA integrated with an antenna is free space. The measurement of such a circuit is, therefore, more difficult when compared to a standard active circuit. The gain must first be measured in an anechoic chamber with a receive antenna. To obtain the exact gain of the amplifier, care must be taken to calibrate the antenna gain out of the amplifier gain measurement using a passive quasi-Yagi antenna as a reference (Fig. 7). In this calibration, the same input power is applied to both the active and passive antennas. This calibration technique assumes that the radiation patterns of both antennas are identical. This has been confirmed by measuring the radiation patterns of both the active and passive versions of the antenna.

IV. Experimental Results

To evaluate the PAE and output power directly at the output of the push–pull amplifier, the AIA circuit shown in Fig. 6 and the reference quasi-Yagi antenna shown in Fig. 7 are measured using the testing method mentioned previously. The measured PAE and output power versus input power for the push–pull PA at 4.15 GHz are shown in Figs. 8 and 9, respectively. The maximum measured PAE is 60.9% at an output power of 28.2 dBm. Fig. 10 shows the measured drain current for the two FETs versus input power. Notice that the measured currents for the two devices are different. This can be explained by the mismatch between the two FETs. When the measured PAE and output power is plotted versus frequency, as shown in Figs. 11 and 12, it is observed that the measured PAE is better than 50% from 4.08 to 4.29 GHz.

As mentioned in the previous section, high-efficiency PAs generate substantial harmonics that can radiate out through the antenna. These undesired harmonics can significantly degrade the overall system performance. In this paper, the novel uniplanar quasi-Yagi antenna with corrugated ground plane is used

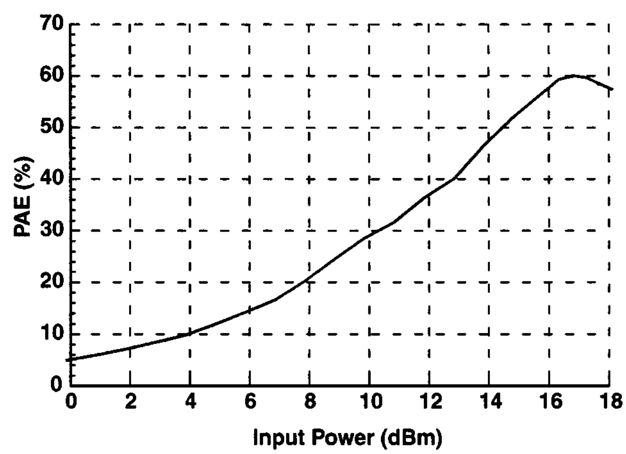


Fig. 8. Measured PAE versus input power for the modified quasi-Yagi antenna push–pull PA.

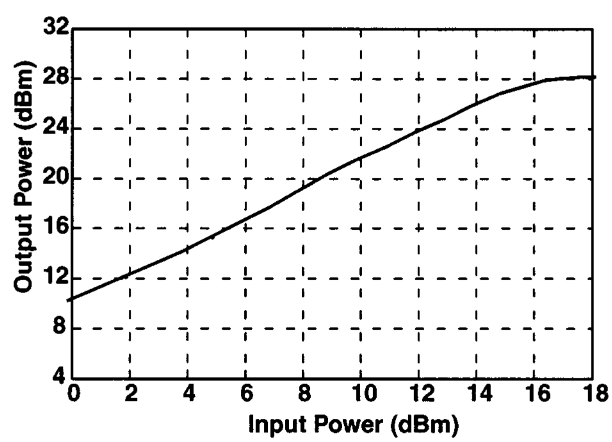


Fig. 9. Measured output power versus input power for quasi-Yagi antenna push–pull PA.

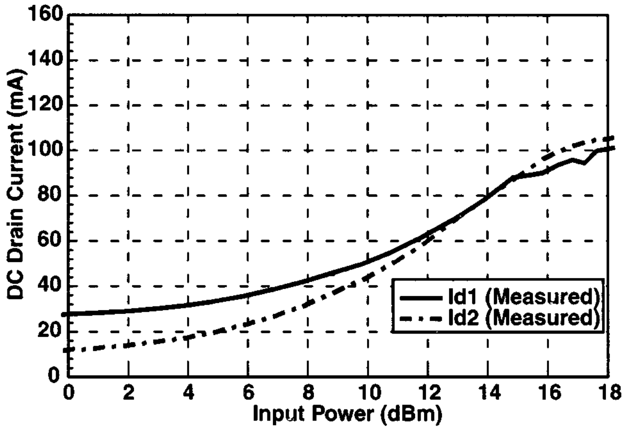


Fig. 10. Measured dc drain currents for two FETs versus input power for quasi-Yagi antenna push–pull PA.

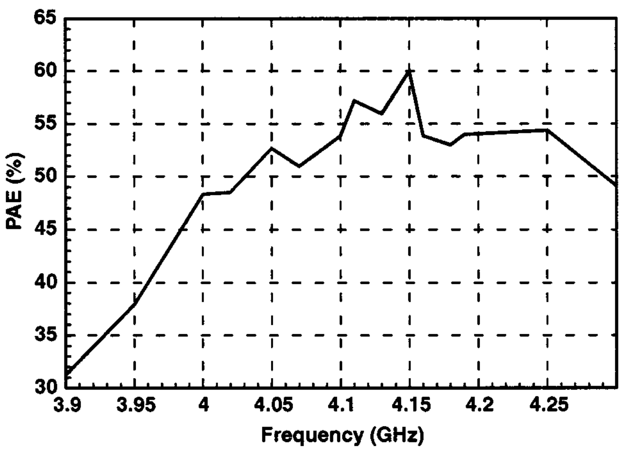


Fig. 11. Measured PAE versus frequency for quasi-Yagi antenna push–pull PA.

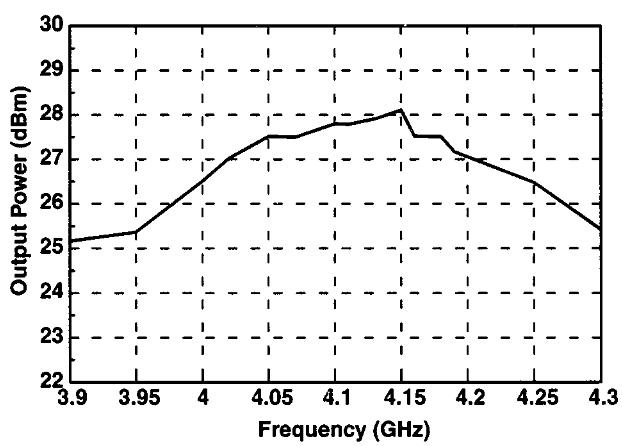


Fig. 12. Measured output power versus frequency for quasi-Yagi antenna push–pull PA.

to reduce the unwanted harmonic radiation that is generated by the high-efficiency push–pull PA. This is observed by measuring the second harmonic radiation from the push–pull PA integrated with the quasi-Yagi antenna. Figs. 13 and 14 show fundamental and second harmonic radiation patterns for the E- and H-plane co-polarizations, respectively. Note that these measurements are done at maximum PAE. The output power is calibrated using the

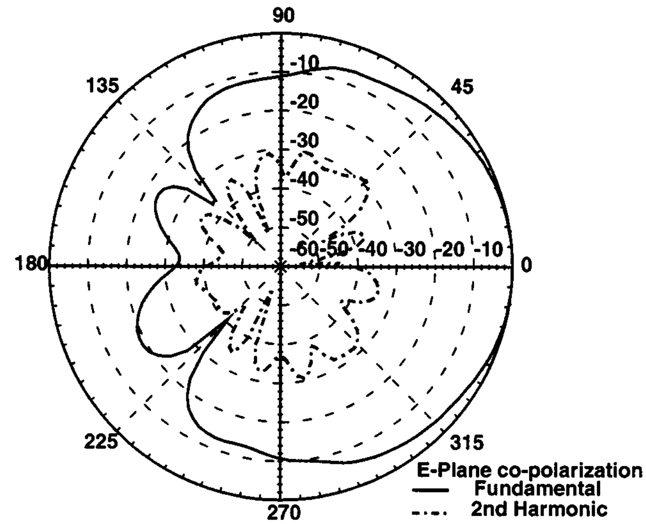


Fig. 13. Measured fundamental and second harmonic E-plane radiation patterns for the push–pull PA with modified quasi-Yagi antenna.

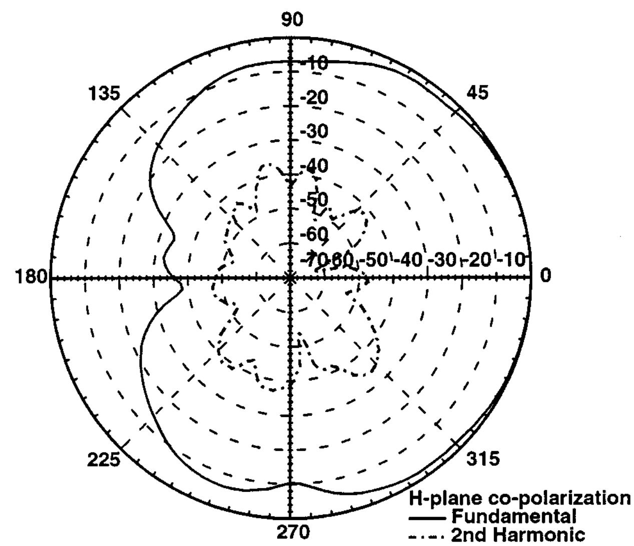


Fig. 14. Measured fundamental and second harmonic H-plane radiation patterns for the push–pull PA with modified quasi-Yagi antenna.

Friis transmission formula, accounting for only the received antenna gain and the free-space loss at the corresponding frequencies, so that the output power levels at both frequencies are referenced at the output of the AIA. Additionally, the fundamental is normalized to 0 dB. As shown in Figs. 13 and 14, second harmonic suppression of about -30 dB has been measured in both the E- and H-planes. Since this push–pull PA is biased at class AB, the power level of the third harmonic was also checked. It was found to be very small and is, therefore, ignored.

A two-tone test is the simplest testing method that can provide a rough measurement of PA linearity. In this test, the output powers at the fundamental frequency and at the third-order intermodulation (IP3) products are measured against the input power. Since the IP3 products are normally very close to the fundamental frequency and fall within the PA bandwidth, high output power at these frequencies can significantly distort the signal at the PA output. Fig. 15 shows the measured two-tone test results of the push–pull PA integrated with the modified

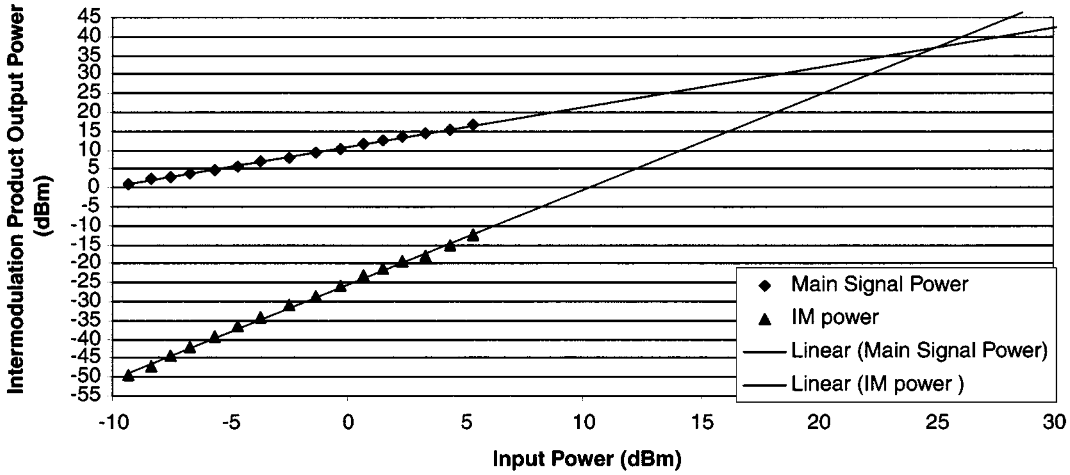


Fig. 15. Output powers of main signal and IP3 versus input power ($f1 = 4.15$ GHz, $f2 = 4.17$ GHz).

quasi-Yagi antenna. The measurement was done by simultaneously injecting the fundamental signal at 4.15 GHz and the second signal with the same input power level, but at the frequency shifted by 1 MHz into the push–pull PA. The IP3 product is obtained as the intersection of the extrapolated 3-dB in-band intermodulation distortion line and the 1-dB linear output power line. As shown in Fig. 15, the intercept point is 37 dBm, which is about 10 dB above the $P_{1\ \mathrm{dB}}$ point.

V. Conclusion

In this paper, we have applied the AIA concept to realize a push–pull PA integrated with a uniplanar quasi-Yagi antenna. The circuit uses a modified quasi-Yagi antenna that effectively radiates the fundamental while simultaneously suppressing higher harmonic radiation. A peak PAE of 60.9% at the output power of 28.2 dBm has been achieved at 4.15 GHz. A PAE greater than 50% is maintained over a 260-MHz bandwidth. Additionally, the second harmonic radiation is found to be 30 dB below the fundamental in both the E- and H-planes. It is also observed that the IP3 point is about 10 dB above the $P_{1\ \mathrm{dB}}$ point when the two-tone test is performed. These results indicate that this compact AIA push–pull PA design can achieve well-balanced performance in terms of good linearity as well as high efficiency.

References

[1] G. Hanington, P. F. Chen, V. Radisic, T. Itoh, and P. M. Asbeck, "A 10 MHz HBT DC–DC converter for microwave power amplifier efficiency improvement," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Baltimore, MD, 1998, pp. 589–592.

[2] V. Radisic, Y. Qian, and T. Itoh, "Novel architectures for high-efficiency amplifiers for wireless applications," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 1901–1909, Nov. 1998.

[3] C. Y. Hang, V. Radisic, Y. Qian, and T. Itoh, "High efficiency power amplifier with novel PBG ground plane for harmonic tuning," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Anaheim, CA, 1999, pp. 589–592.

[4] R. Y. Miyamoto, Y. Qian, and T. Itoh, "Phase conjugator for active retrodirective array applications," *Electron. Lett.*, vol. 36, pp. 4–5, Jan. 2000.

[5] B. K. Kormanyos, P. H. Ostdiek, W. L. Bishop, T. W. Growe, and G. M. Rebeiz, "A planar wide-band 80–200-GHz subharmonic receiver," *IEEE Trans. Microwave Theory Tech.*, vol. 41, pp. 1730–1737, Oct. 1993.

[6] D. Singh, P. Gardner, and P. S. Hall, "Frequency doubling integrated push–pull microstrip transponder," in *European Microwave Conf. Dig.*, 1997, pp. 1181–1185.

[7] V. Radisic, S. T. Chew, Y. Qian, and T. Itoh, "High-efficiency power amplifier integrated with antenna," *IEEE Microwave Guided Wave Lett.*, vol. 7, pp. 39–41, Feb. 1997.

[8] J. Lin and T. Itoh, "Active integrated antennas," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 2186–2194, Dec. 1994.

[9] W. R. Deal, V. Radisic, Y. Qian, and T. Itoh, "Novel push–pull integrated antenna transmitter front-end," *IEEE Microwave Guided Wave Lett.*, vol. 8, pp. 405–407, Nov. 1998.

[10] ——, "A high efficiency slot antenna push–pull power amplifier," in *IEEE MTT-S Int. Microwave Symp. Dig.*, Anaheim, CA, 1999, pp. 659–662.

[11] ——, "Integrated antenna push–pull power amplifiers," *IEEE Trans. Microwave Theory and Tech.*, vol. 47, pp. 1418–1425, Aug. 1999.

[12] C. Y. Hang, W. R. Deal, Y. Qian, and T. Itoh, "Push–pull power amplifier integrated with microstrip leaky-wave antenna," *Electron. Lett.*, vol. 35, pp. 1891–1892, Oct. 1999.

[13] P.-C. Hsu, C. Nguyen, and M. Kintis, "Uniplanar broad-band push–pull FET amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 45, Dec. 1997.

[14] J. L. B. Walker, *High-Power GaAs FET Amplifier*. Norwood, MA: Artech House, 1993.

[15] N. Kaneda, Y. Qian, and T. Itoh, "A novel Yagi–Uda dipole array fed by a microstrip-to-CPS transition," in *Asia–Pacific Microwave Conf. Dig.*, 1998, pp. 1413–1416.

[16] Y. Qian, W. R. Deal, N. Kaneda, and T. Itoh, "A uniplanar quasi-Yagi antenna with broadband characteristics," *Electron. Lett.*, vol. 34, no. 23, Nov. 1998.

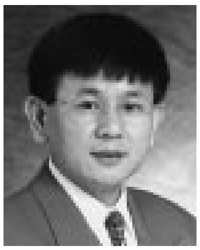
[17] ——, "A uniplanar quasi-Yagi antenna with wide bandwidth and low mutual coupling characteristics," in *IEEE AP-S Int. Symp. Dig.*, vol. 2, Orlando, FL, 1999, pp. 924–927.

Cynthia Y. Hang (S'99) was born in Nanjing, China. She received the B.S. degree in electrical engineering from the University of Maryland at College Park, in 1997, the M.S. degree in engineering from the University of California at Los Angeles (UCLA) in 1999, and is currently working toward the Ph.D. degree at UCLA.

From 1997 to 1998, she was with TRW, Redondo Beach, CA, where she was involved with monolithic-microwave integrated-circuit (MMIC) receiver component design. Her research interests include high-efficiency PAs and AIAs.

William R. Deal (S'85–M'85) received the B.S. degree in electrical engineering from the University of Virginia, Charlottesville, in 1996, and the M.S. and Ph.D. degrees in electrical engineering from the University of California at Los Angeles (UCLA) in 1998 and 2000, respectively.

He is currently a Design Engineer with Malibu Networks Inc., Calabasas, CA, where he helps in the development of microwave transceivers for broad-band wireless data. He has performed research in the areas of high-efficiency PAs, AIAs, planar antenna technology, active array, and optically controlled antennas.



Yongxi Qian (S'91–M'93–SM'00) was born in Shanghai, China, in 1965. He received the B.E. degree from Tsinghua University, Beijing, China, in 1987, and the M.E. and Ph.D. degrees from the University of Electro-Communications, Tokyo, Japan, in 1990 and 1993, respectively, all in electrical engineering.

From 1993 to 1996, he was an Assistant Professor with the University of Electro-Communications. In 1996, he joined the University of California at Los Angeles (UCLA), where he was a Post-Doctoral Fellow, Assistant Research Engineer, and Lecturer in the Electrical Engineering Department. He is currently the Director of Technology and Applications at Micro WaveSys, Microsemi Corporation, Los Angeles, CA, where he is involved in research and development of heterojunction bipolar transistor (HBT) MMICs and modules for mobile, wireless local area network (LAN), and 10/40 Gb/s fiber-optic applications. He has performed research on numerical techniques for microwave and millimeter-wave circuits, generation and transmission of picosecond electrical pulses, crosstalk problems in high-density MMICs, 60-GHz focal plane imaging arrays, quasi-optical power combining, broad-band planar antennas, AIAs, high-efficiency microwave PAs, RF interconnect for mixed-signal silicon MMICs, photonic bandgap (PBG) structures, and high-power broad-band RF photonic devices. He has authored or co-authored over 200 refereed journal and conference papers, two books, and several book chapters.

Dr. Qian was the recipient of the 1998 Japan Microwave Prize presented at the Asia–Pacific Microwave Conference, the 1999 Best Student Paper presented at the 29th European Microwave Conference, and the 2000 International Symposium on Antennas and Propagations Paper Award presented at the IEEE Antennas and Propagation Society (IEEE AP-S) International Symposium.

Tatsuo Itoh (S'69–M'69–SM'74–F'82) received the Ph.D. degree in electrical engineering from the University of Illinois at Urbana-Champaign, in 1969.

From September 1966 to April 1976, he was with the Electrical Engineering Department, University of Illinois at Urbana-Champaign. From April 1976 to August 1977, he was a Senior Research Engineer in the Radio Physics Laboratory, SRI International, Menlo Park, CA. From August 1977 to June 1978, he was an Associate Professor at the University of Kentucky, Lexington. In July 1978, he joined the faculty at the University of Texas at Austin, where he became a Professor of electrical engineering in 1981 and Director of the Electrical Engineering Research Laboratory in 1984. During the summer of 1979, he was a Guest Researcher at AEG-Telefunken, Ulm, Germany. In September 1983, he was selected to hold the Hayden Head Centennial Professorship of Engineering at the University of Texas. In September 1984, he was appointed Associate Chairman for Research and Planning of the Electrical and Computer Engineering Department, University of Texas. In January 1991, he joined the University of California at Los Angeles as a Professor of electrical engineering and holder of the TRW Endowed Chair in Microwave and Millimeter Wave Electronics. He was an Honorary Visiting Professor at the Nanjing Institute of Technology, Nanjing, China, and at the Japan Defense Academy. In April 1994, he was appointed Adjunct Research Officer for the Communications Research Laboratory, Ministry of Post and Telecommunication, Tokyo, Japan. He currently holds a Visiting Professorship at The University of Leeds, Leeds, U.K., and is an External Examiner of the Graduate Program of the City University of Hong Kong. He has authored or co–authored 274 journal publications, 540 refereed conference presentations, and 30 books/book chapters in the area of microwaves, millimeter waves, antennas and numerical electromagnetics. He has also generated 48 Ph.D. students.

Dr. Itoh is a member of the Institute of Electronics and Communication Engineers (IEICE), Japan, and Commissions B and D of the USNC/URSI. He was the Editor-in-Chief of the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (1983–1985). He currently serves on the Administrative Committee of the IEEE Microwave Theory and Techniques Society (IEEE MTT-S). He was Vice President of the IEEE MTT-S in 1989 and President in 1990. He was the Editor-in-Chief of the IEEE MICROWAVE AND GUIDED WAVE LETTERS (1991–1994). He was the chairman of the USNC/URSI Commission D (1988–1990), and chairman of Commission D of the International URSI (1993–1996). He is chair of the Long Range Planning Committee of the URSI. He serves on advisory boards and committees of a number of organizations. He has received a number of awards, including the 1998 Shida Award from the Japanese Ministry of Post and Telecommunications, 1998 Japan Microwave Prize, 2000 IEEE Third Millennium Medal, and the 2000 IEEE MTT-S Distinguished Educator Award.