Recent Developments in RF Front Ends Based Upon Active Antenna Concepts

Jonathan D. Fredrick, Tatsuo Itoh

Abstract – **In this paper several developments in RF front end technology based upon the active antenna concept are presented. RF front ends utilizing active antenna concepts have shown improvements in such areas as power added efficiency, compactness, low noise figure, and increased func-tionality. These improvements are illustrated in this paper with a Class F transmitter with integrated circular patch antenna, a circularly polarized patch antenna with integrated LNAs, a 60 GHz quasi-optics self oscillating mixer, and two designs implementing the recently developed broadband quasi-Yagi antenna.**

Keywords – **Active Integrated Antenna, Self—Oscillating—Mixer, Quasi-Yagi, Circular Patch Antenna.**

I. INTRODUCTION

Next generation wireless communication systems require highly compact and lightweight RF front ends with long operating time, low noise, compactness, and high functionality. Since power amplifiers consume the majority of power in transmitting RF front ends, much attenion is paid to maximizing the eciency of this crucial component. To illustrate advances in RF front end power amplifiers, a circular patch antenna integrated with a Class F power amplifier and a push-pull power amplifier integrated with a quasi-Yagi antenna are presented. On the receiver side, a circularly polarized patch antenna is integrated with LNAs to achieve a very low noise figure. A sub-harmonic Self-Oscillating-Mixer (SOM) with integrated antenna for 60 GHz wireless applications has been designed and pre-sented. To further demonstrate the gains in compactness and functionality, a low noise integrated antenna receiver for monopulse radar applications is discussed. In addition to active antennnas elements in RF front ends, active antenna arrays may provide great functionality as demonstrated by the active retrodirective array.

Throughout this paper numerous examples of RF front ends based upon active antena concepts provide great improvements in power and spectral effciency, noise figure, compactness, and functionality are given.

II. CLASS F POWER AMPLIFIER WITH CIRCULAR PATCH ANTENNA

Since in a RF transmitter front-end the power amplifier consumes the largest part of DC power, there has been great interest in maximizing its PAE. The concept of active integrated antennas has been employed in an effort to design high eciency power amplifiers. In this approach, the antenna element is not only used as the radiating mecha nism, but also as a part of the tuning network to appro-priately erminate the harmonics at the output port of the amplifier.

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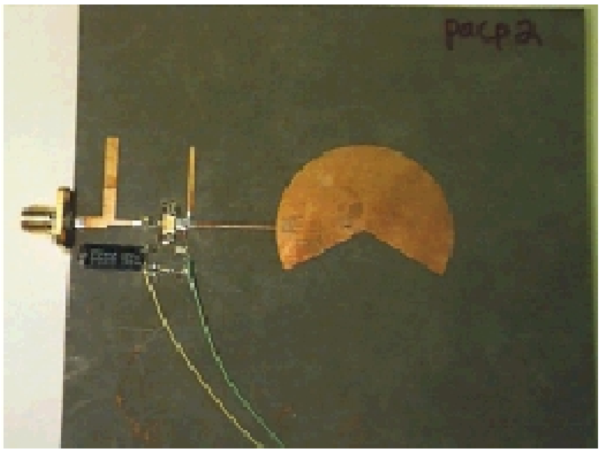


Fig. 1. Class F power amplifier with integrated circular patch antenna.

The choice ofan appropriate antennastructure is critical in designing a successful integrated power amplifier. Figure 1 shows a modified circular segment microstrip antenna with integrated Class F power amplifier, which is capable of reactively terminating both the second and third harmonics, as indicated by the measured input impedance [1]. Figure 2 shows the input impedance of the antenna as used for reactive termination. The operating frequency is 2.55 GHz, which is slightly othe first resonance, and allows easier power matching. The real part of the input impedance at the second and third harmonics frequencies is almost zero. A relatively high PAE of 63% was achieved at 2.55 GHz. No major degradation in radiation patterns was observed, with a cross-polarization level below -6 dB in all direction in both E and H planes.

III. PUSH-PULL POWER AMPLIFIER INTEGRATED WITH QUASI-YAGI ANTENNA

A second example is a push-pull power amplifier in-tegrated with a quasi-Yagi antenna [2]. The uniplanar quasi-Yagi antenna, recently developed at UCLA, features a very simple, compact design and extremely broad operating bandwidth (BW>50% for S_{11} < -1 0.0 dB) [3]. The antenna is fabricated on a single dielectric substrate and employs a truncated microstrip ground-plane as a reflector to achieve an endfire radiation pattern with a moderate gain of approximately 5dB. In the present design, we modified the original quasi-Yagi structure so that the antenna is driven by two anti-phase microstrips in a balanced fashion.

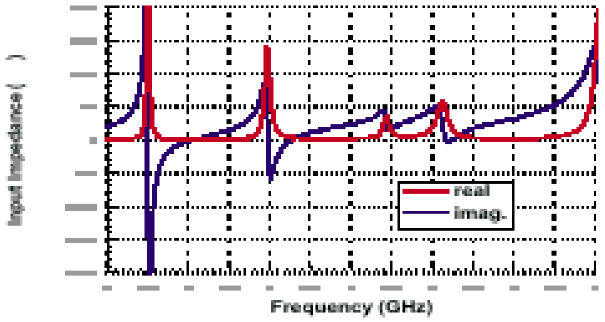
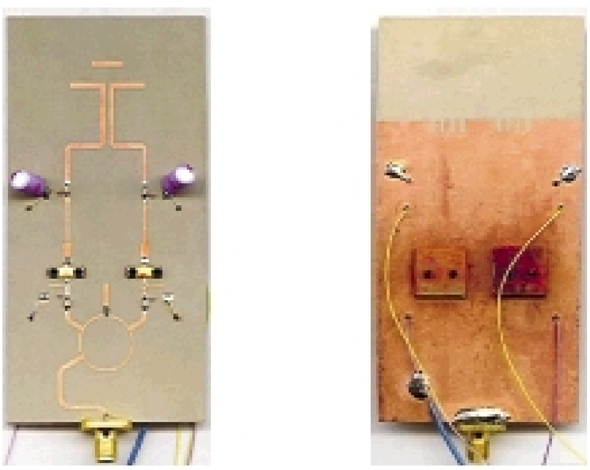


Fig. 2. Input impedance to circular segment microstrip patch antenna.

This structure is therefore naturally suited to combine the anti-phase output of two push-pull PAs. Additionally, in its original form, it was found that at the harmonic frequencies, the CPS lines act as monopole radiators above the truncated microstrip ground-plane and thus radiate considerable energy. To suppress this undesired harmonic radiation, corrugations were added on the truncated ground plane. The depth of corrugation is approximately λ/4 for the slotline mode at thesecondharmonic, causing the modified ground plane to appear as an open-circuit at the second harmonic and therefore eliminating the monopole-type radiation of the feeds. Effects on the fundamental frequency-operating mode of the antenna was found to be minimal. Since the output of a push-pull amplifier contains a series of in-phase even harmonics in addition to the anti-phase fundamental, this modified quasi-Yagi antenna can be used as a harmonically tuned load.



(a) (b)

Fig. 3. Push—Pull PA with integrated Quasi-Yagi Antenna.

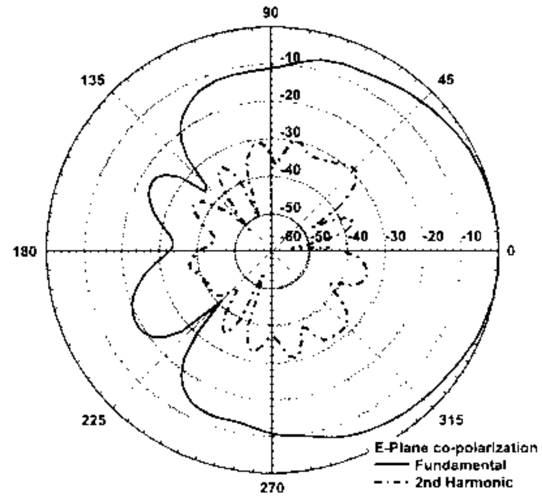


Fig. 4. Fundamental and 2nd harmonic E—plane radiation patterns of the Quasi-Yagi push-pull PA.

Figure 3 shows the push-pull power amplifier integrated with the quasi-Yagi antenna. The maximum measured PAE is 60.9% at an output power of 28.2 dBm, and the PAE is better than 50% from 4.08 GHz to 4.29 GHz. Additionally, the second harmonic suppression of about –30 dBhas been measured inboth the E and H planes. Figure 4 shows the fundamental and second harmonic radiation patterns for the E-plane. The power level of the third harmonic was found to be very small and is therefore ignored. In addition, this circuit was also subjected to a two-tone test that provides a rough measurement of power amplifier linearity. The third order intercept point of the two-tone test is at 37dBm, which is about 1 0 dB above the P dB point.

IV. Circularly Polarized Patch Antenna with Integrated LNAs

A low noise receiver does not generally require a harmonic tuning network, however it does require a special impedance match in order to achieve a desired performance. In this work, a novel method for the design and testing of a circularly polarized low noise receiver is presented [4]. The circularly polarized receiver provides an ideal example of the benefits of the integration of an antenna into the low noise receiver front end. The integration of the low noise amplifier (LNA) with the antenna leads to a further reduction in system noise figure due to the fact that the LNAs are before the combining network. Thus, an improvement in performance is obtained by setting the noise figure of the system at an earlier stage, thereby rendering losses in the combining network negligible.

A. Receiver Description

The low noise circularly polarized receiver may be seen in Fig. 5. It is crucial to note in this figure that the patch antenna's two feeds are placed at the edge of the patch, not inset, and the lack of quarter wave transformers. In addition to the patch antenna not having any traditional impedance matching, the LNAs have no gate-side impedance matching elements such as tuning stubs. Thus the sole tuning element in the receiver's front end is that of the square, dual feed, patch antenna.

B. Measurement Procedure and Results

Due to the fact that the LNAs in the circularly polarized receiver are not matched to a standard impedance, such as 50 Ohms, measurement becomes more dicult. There is no "input" connector to which we may attach our receiverto a network analyzer or noise figure meter. A method of substituting the low noise receiver with a passive receiver version has been utilized to characterize the performance of the LNAs. This technique is described in detail in [4]. The measured and simulated noise figures are presented in Fig 6. It is clear that simulation accurately accounted for the behavior of the circuit. A minimum noise figure of 0.4 dB was measured at 5.74 GHz, whereas simulation predicted a minimum of 0.3 dB. Three sets of measured power gain are presented in Fig. 7. The solid line represents simulation. The remaining two curves represent measurements from the anechoic chamberand noisefigure meter methods. A gain of 11 dB is obtained at the design frequency. Higher gain is observed at a slightly lower frequency due to the fact that the noise figure match, Gamma Opt., is not a conjugate match. Figure 8 illustrates radiation patterns of the low noise receiver with and without LNAs, showing that the integration process does not affect radiation.

V. Dielectric Resonator Balanced Second Harmonic Quasi-Optical Self Oscillating Mixers for 60 GHz Wireless Applications

In addition to power amplifier transmitters utilizing the active antenna concept, a 60 GHz SOM has been designed for wireless applications [5]. The design utilizes characteristics of the antenna to enable broadband performance.

Figure 9 shows the layout of the quasi-Yagi SOM mixer. No power is dissipated on the drain side, and at the gate side only the fundamental frequency power is dissipated to establish the oscillation conditions. Diplexers are used to separate the fundamental frequency and the incoming RF and the second harmonic of the LO. In this case the antenna serves also as a balun, the circuit is completely symmetric and thus potentially broadband. For the second harmonic of the LO the antenna is a reactive load. The cavity and antenna can be placed very close to each other due to end-fire radiation pattern of the quasi-Yagi antenna. The wave guide of the cavity block is in cutoat the fundamental frequency to reduce radiation.

In this case the conversion eciency is measured with an RF signal of 58 GHz to 62 GHz. Figure 1 0 showsthe measured response together with simulated values. Conversion effciency is 6 dB better than in the patch antenna case due to better reception eciency of the antenna, lower coupling losses and better intrinsic conversion effciency. The channel balance is 5 dB worse due to higher wire bond inductances. Phase noise and output noise are the same as before, second harmonic radiation is -26 dBm. The optimum conversion effciency is obtained at a drain voltage of 1 .5 V. The conversion effciency improves steadily up to the highest applied bias of 2.0 V, where the performance is recorded.

Fig. 5. Photograph of the integrated low noise receiver.

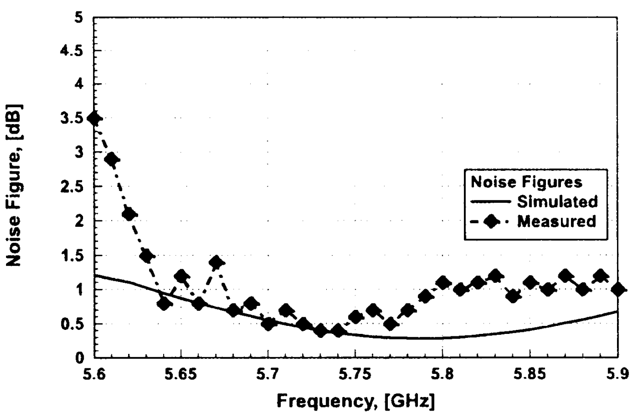


Fig. 6. Measured and simulated noise figure.

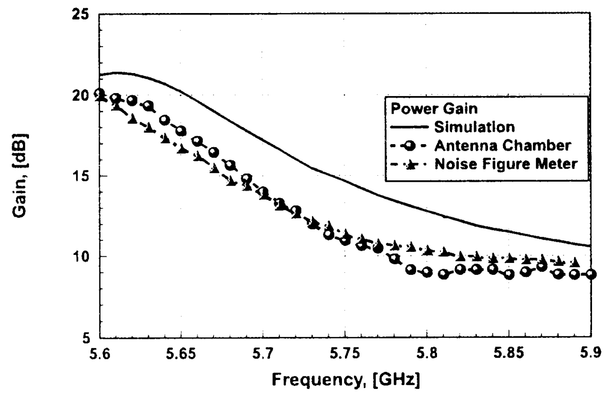


Fig. 7. Measured and simulated power gain.

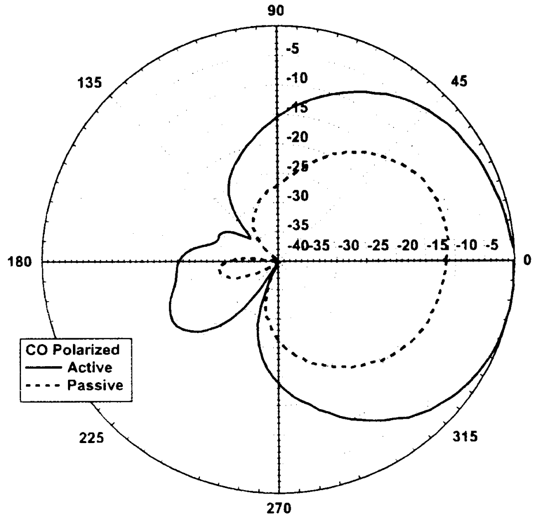


Fig. 8. Measured radiation patterns of active and reference receivers.

VI. A LOW NOISE ACTIVE INTEGRATED ANTENNA RECEIVER FOR MONOPULSE RADAR

A high degree of interest remains in developing economical and compact radar systems for automotive applications. Thus, the concept of active antenna, in which the circuit is matched directly to the antenna rather than a 50 ohms common interface, can be used advantageously to enhance the design and performance of the radar front-end.

The planar quasi-Yagi antenna developed at UCLA [3] is an ideal antenna to develop a low noise active integrated antenna. This single-feed antenna is fabricated on a single layer of high-dielectric substrate and uses the truncated ground plane of the microstrip feed line as a reflector so that a well-defined endfire beam is achieved. In this work, we demonstrate that by properly combining the dual-feed nature of the quasi-Yagi antenna with a hybrid circuit, excellent monopulse operation can be achieved with the simplicity of using only one single antenna. The new de sign concept has been verified by both simulation and mea-surement, showing great potential of this novel design for ultra-low-cost microwave and millimeter-wave radar applications.

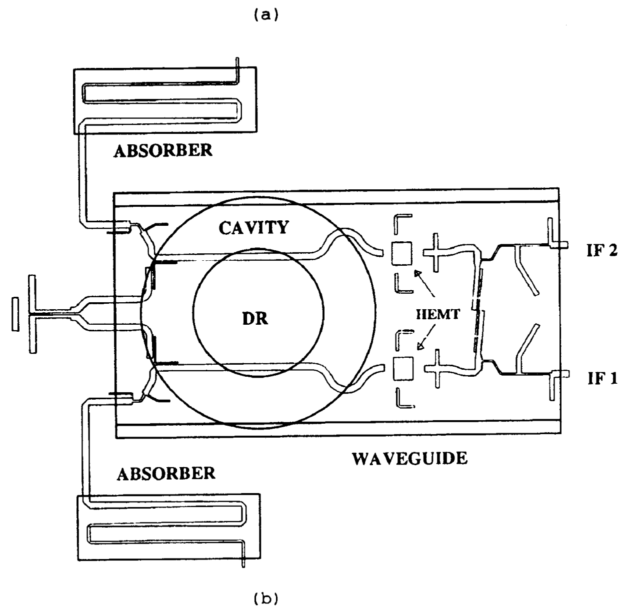


Fig. 9. 60 GHz SOM with quasi-Yagi antenna for wireless applications.

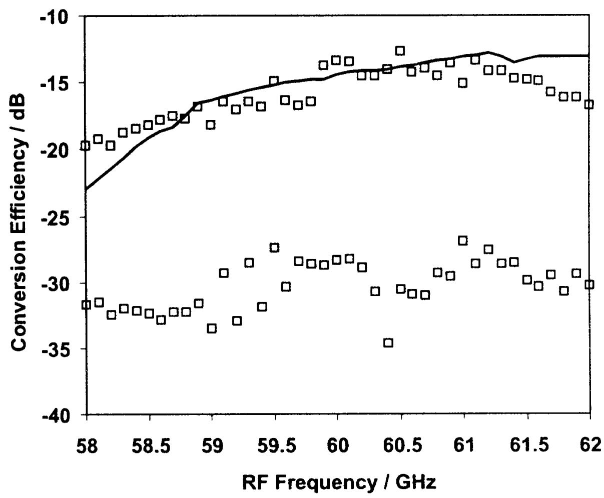


Fig. 10. Measured (marks) and simulated (line) conversion eciency of the quasi-Yagi antenna SOM.

A. Antenna Design

A conventional quasi-Yagi antenna, as reported in [3], has a single microstrip feed, with a microstrip-to-coplanar strips (CPS) transition that acts as a balun. Thus in single-feed operation, each dipole driver element is driven out-of-phase, and the antenna operates similar to printed dipole antenna. Additionally, when operated with two feeds, it is possible for each driver element to operate independently, similar to two monopoles. This characteristic is exploited in this work to form sum and dierence radiation patterns by combining the outputs from each feed out-of-phase, and in-phase, respectively. A sum pattern is obtained when the two ports are excited out-of-phase, similar in operation to a conventional quasi-Yagi antenna, and a dierence pattern is obtained when the two ports are excited in-phase. The picture of the proposed dual-feed antenna is shown in Fig. 11. Thus, sum and dierence beams can be formed from one antenna, in contrast to a traditional monopulse system, which requires an array of at least two antennas separated by about one-half free-space wavelength. This feature of the dual-feed quasi-Yagi antenna can be utilized to create a compact receiver front-end for monopulse radar applications.

B. LNA Design, Integration, and Results

Due to the low isolation (<6 dB) between the two feeds of the quasi-Yagi antenna, designing an LNA matched to the antenna presents a unique challenge. The source impedance seen by one LNA depends on the impedance of the antenna, and also on the impedance looking into the other LNA integrated on the second feed of the antenna. So the source impedance varies during the design process, as a function of the input matching network of the LNAs. Consequently, the source impedance cannot simply be specified as a termination network element available in most commercial simulation software. Special simulation procedures are presented in [6]. All measurements of the low noise active integrated receiver were conducted inside an anechoic chamber. Figure 1 2 shows the measured E-plane co-polarization pattern for the sum port. Figure 1 3 shows the monopulse sum and dierence pattern measured in the E-plane. A null depth of greater than 20 dB is obtained from 5-6 GHz (8% bandwidth), with a null better than 30 dB obtained for most of the band. The null depth is most likely limited by the bandwidth of the output ring hybrid. With a wide main beam sum pattern, this active integrated antenna is suitable for applications that require wide angular coverage, such as side sensing automotive radar, as discussed in [7]. The measured gain and noise figure of the low noise amplifier is compared against simulated results in Fig. 14. A peak gain of 7.7 dB and minimum noise figure of 3.6 dB is measured at 5.5 GHz, compared to a simulated gain of 8.7 dB and noise figure of 1.5 dB.

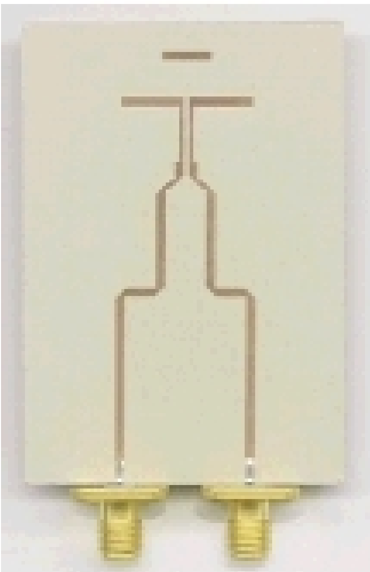


Fig. 11. Picture of dual-feed quasi-Yagi antenna.

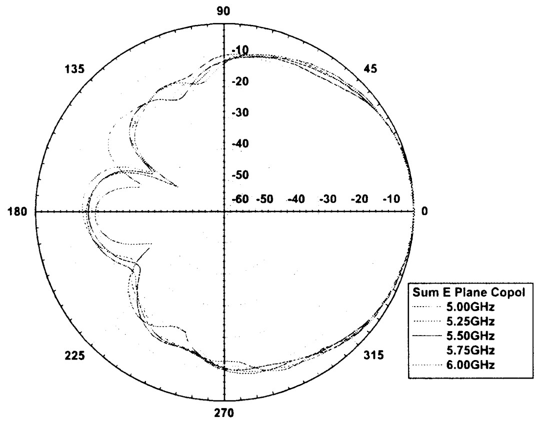


Fig. 12. E-Plane co-polarized pattern measured at the sum port.

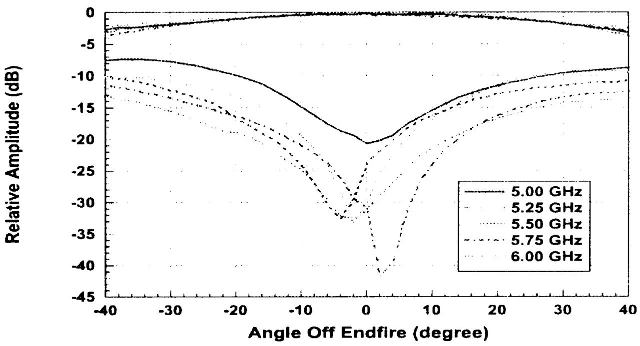


Fig. 13. Sum and dierence radiation patterns.

VII. ACTIVE RETRODIRECTIVE ANTENNA ARRAYS

Phase conjugation with heterodyne mixing is a simple and eective technique to achieve retrodirectivity using an LO that has twice the RF frequency [8][9][1 0]. In this scheme, the lower sideband product has the same frequency as the RF, but with a conjugated phase. When combined with an antenna and placed in an array, the phase-conjugated signal from each antenna element will be reradiated towards the source direction. The phase conjugation technique has several advantages. One thing is that phase conjugators can provide conversion gain by using active devices for the mixer circuitry. Another is it is easy to apply modulation to the re-sent signals, allowing the pass of information. In this method, one task that should be achieved is riddance of undesired signals, i.e. non-phase-conjugated signals. Especially burdensome in the phase conjugation approach is that the IF frequency is the same as that of the RF. This fact makes it impossible to filter out undesired signals. For this reason, hybrids are usually used to eliminate undesired signals.

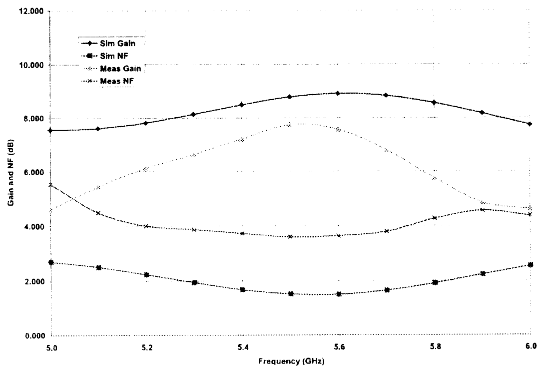
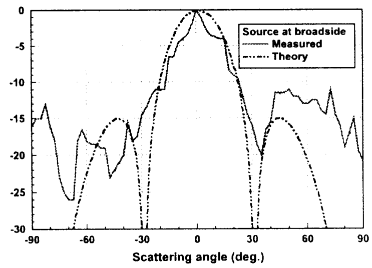


Fig. 14. Measure and Simulated gain and noise figure.

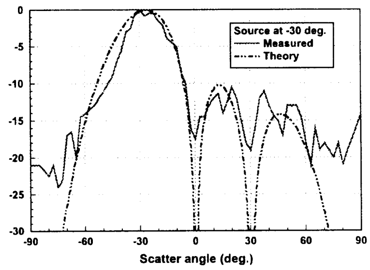
Our group has been developing retrodirective arrays, which are particularly advantageous for RF tag applications and remote information retrieval-on-demand. Adopting active devices, the phase conjugating circuitry provides conversion gain in addition to phase conjugating performance. The RF and IF signals share one port, resulting in reduced system size. The novel active circuitry architecture is simple and extremely compact, enabling array spacing small enough to avoid grating lobes. The prototype 4-element array showed excellent retrodirectivity as show in Fig. 1 5. As seen in Fig. 1 5c, there is no null in the monostatic RCS pattern. A prototype 4-element array was fabricated and shown in Fig. 1 6. The operating frequency is 6GHz. The whole circuitry can be fabricated on the same substrate as the antennas, enabling one card transponder. This is one of the major advantages in retrodirective arrays. Using a modulated LO allows the retrodirective array to send a unique ID code or other local information back to the source location. A BPSK signal transmitted by the array was successfully recovered at the source location. These characteristics make the retrodirective array a good candidate for future remote tagging and wireless sensor applications.

VIII. Conclusion

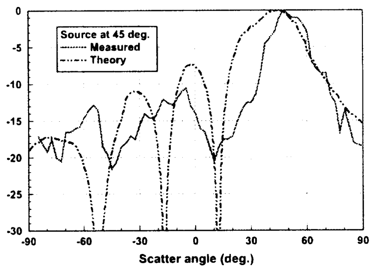
From the examples given, we see that many advances in RF front end technology have been made recently using the active antenna approach. The active antenna design concept has been demonstrated as an eective and elegant way to increase power added eciency and reduce harmonics in a Class F and push pull power amplifier, reduce noise figure, it has been demonstrated for a 60 GHz SOM receiver in which compactness is a priority. A C-band ultra-compact low noise receiver for monopulse radar applications has also been designed. Using the quasi-Yagi antenna element as a multifunction circuit element in this design, providing both sum and dierence monopulse patterns from one antenna element. In addition, a retrodirective array has been de-signed to illustrate a novel balanced mixer which provides both phase conjugation and conversion gain.



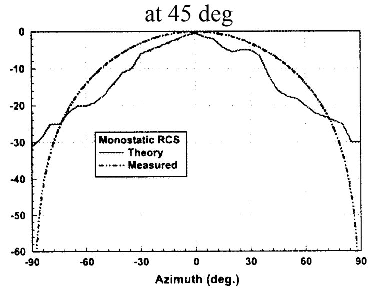
(a) Bistatic RCS (dB rel.), source at broadside (0 deg)



(b) Bistatic RCS (dB rel.), source at -30 deg



(c) Bistatic RCS (dB rel.), source at 45 deg



(d) Monostatic RCS (dB rel.)

Fig. 15. Radar cross section of the retrodirective array.

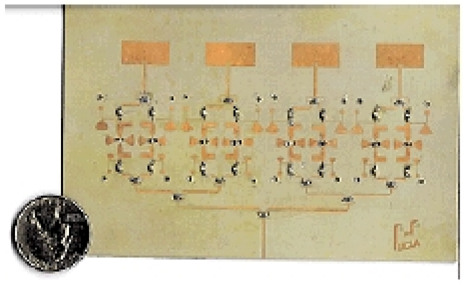


Fig. 16. Photo of the four-element retrodirective array.

REFERENCES

[1] V. Radisic, Y. Qian, and T. Itoh, "Class F power amplifier in-tegrated with circular sector microstrip antenna", IEEE MTT-S Digest, pp. 687-690, 1997.

[2] C.Y. Hang, W.R. Deal, Y. Qian, and T. Itoh, "Push-pull power amplifier integrated with quasi-Yagi antenna for power combining and harmonic tuning", IEEE MTT-S Digest, pp. 533-536, 2000.

[3] Y. Qian, W.R. Deal, N. Kaneda, and T. Itoh, "A uniplanar quasi-Yagi antenna with wide bandwidth and low mutual coupling characteristics", IEEE AP-S Intl. Symp. Dig., pp. 924-927, 1999.

[4] J.D. Fredrick, Y. Qian, and T. Itoh, "Novel Design Technique for A Low Noise Receiver Front End With Integrated Circularly Polarized Patch Antenna ", 30th European Microwave Conference Proceedings, vol. 2 pp. 333-336, 2000.

[5] M. Sironen, Y. Qian, and T. Itoh, "A dielectric resonator balanced second harmonic quasi-optical self oscillating mixer for 60 GHz applications", IEEE MTT-S Digest, pp. 139-142, 1999.

[6] S. Lin, Y. Qian, and T. Itoh, "A Low Noise Active Integrated An-tenna Receiver for Monopulse Radar Applications", IEEE MTT-S Digest, 2001.

[7] J.D. Fredrick, Y. Qian, and T. Itoh, "A novel single card FMCW radar transceiver with on board monopulse processing", Proc. of 29th European Microwave Conf, vol. 2 pp. 1-4, 1999.

[8] C.W. Pobanz and T. Itoh, "A conformal retrodirective array for radar applications using a heterodyne phased scattering element", IEEE MTT-S Digest, pp. 905-908, 1995.

[9] R.Y. Miyamoto, Y. Qian, and T. Itoh, "A novel active retrodirective array for RF tagging and remote information retrieval", IEEE MTT-S Digest, pp. 1431-1434, 2000.

[10] R.Y. Miyamoto, Y. Qian, and T. Itoh, "A novel retrodirective array using balanced quasi-optical balanced FET mixers with con-version gain", IEEE MTT-S Digest, pp. 655-658, 1999.