A 60 GHz Integrated Antenna Array for High-Speed Digital Beamforming Applications

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***Abstract* — A 60 GHz integrated four-element planar antenna array is developed. Each antenna is integrated with sub-harmonic I/Q mixer based on APDPs for the convenience of high-speed signal processing such as adaptive beamforming. Average conversion loss of four channels of less than 10.6 dB is achieved. Amplitude imbalance and phase deviation between I and Q outputs of each channel are less than 2.5 dB and 7°, respectively. The array is used to construct a digital beamforming system along with IF circuit block and DSP modules. The beam scanning results are successfully demonstrated.**

I. INTRODUCTION

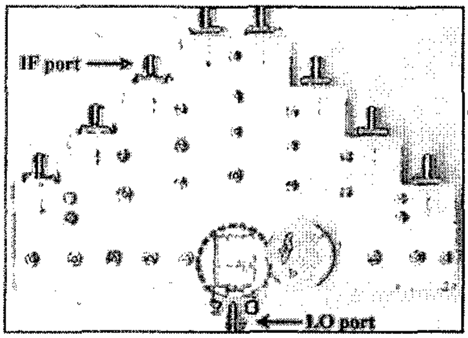
Due to an increase in demand for high-speed and large-channel capacity digital data rates for multimedia wireless communications, the utilization of millimeter-wave frequency bands has received more attention. Specially, a 60 GHz frequency region has been used for short-distance radars and indoor communications. Because of the high levels of atmospheric attenuation, 60 GHz signals can be easily confined to pico-cell zones. However, Brankovic *et al.* suggested outdoor, underground, and large hall types of environmental applications [1]. In order to effectively employ this frequency band in those complex environments, the benefits of a digital beamforming system and multiple-input multiple-output (MIMO) antenna systems can be the key because their antenna arrays can not only generate desirable radiation patterns, but also improve the capacity of systems with multimedia and multi-rate services [2]-[3].

In this paper, a 60 GHz integrated four-element planar antenna array with sub-harmonic I/Q mixers is proposed and combined with IF mixer and amplifier block, A/D, and a digital signal processing module to demonstrate digital beamforming performance at millimeter-wave bands. There is a threefold advantage to the proposed array. First, the planar antenna integration with RF circuits reduces the interconnection loss that is a significant issue at millimeter frequencies. It can also realize compact and low cost millimeter-wave RF module [4]-[5]. Secondly, the sub-harmonic in- and quadrature-phase (I/Q) mixers with anti-parallel diode pairs (APDPs) are used because the LO frequency is half of the RF frequency with LO noise suppression and no bias circuit [6]-[7]. Therefore the 60 GHz integrated antenna array with the mixers can be easily implemented. Finally, the existence of I/Q output channels in the array can greatly reduce the post-stage signal processing load and increase the system throughput for digital beamforming applications [8]-[9].

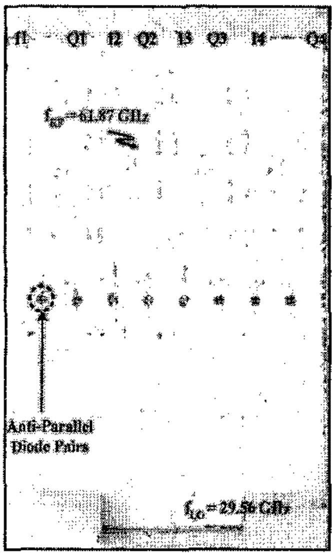
This paper is organized as follows: The overview of a 60 GHz integrated antenna array is first given. Then the design of the array is introduced and RF performance is validated with measured results. Finally, a digital beamformer system is set up by combining an IF circuit block, A/D, and digital signal processing modules to examine beamforming performance.

II. 60 GHZ INTEGRATED ANTENNA ARRAY CIRCUIT OVERVIEW

Figure 1 (a) shows the photograph of the proposed 60 GHz integrated antenna array with 0.6 λ spacing at 61.87 GHz. The array consists of four sub-harmonic I/Q mixers integrated with a microstrip patch antenna as shown in the magnified Figure 1 (b). Each sub-harmonic I/Q mixer is composed of two pairs of APDPs, open and short stubs, a 45° phase delay line at 29.56 GHz, and Wilkinson power dividers for an RF of 61.87 GHz and an LO of 29.56 GHz, respectively. A ten-stage low pass filter on an alumina substrate at an IF port are designed in order to suppress leakages of the RF and the LO. The edge of the low pass filter is connected with a 50 Ω microstrip line with a three-stage low pass filter comprised of two lumped inductors and a capacitive microstrip line on a duroid substrate using wire bonding. The overall low pass filter including a wire is simulated for a cutoff frequency of 4.5 GHz and the suppression of -40 dB at the LO and of -17 dB at the RF. In order to terminate the RF and the LO leakages, open and short stubs are optimized to be a quarter-wave length at the LO and a half-wave length at the RF to obtain lowest conversion loss. Bandpass filters at both the RF and the LO paths are designed for IF decoupling. The phase delay line of 45° at the LO is inserted in one of the LO power split paths after the LO Wilkinson power divider. Because of the third order mixing terms in terms of the phase delay line, two mixers can generate I and Q mixing signals.



(a)



(b)

Fig. 1. (a) The 60 GHz integrated antenna array on alumina substrate including eight output microstrip lines on duroid substrate (b) The magnified array on alumina substrate.

The proposed array and the eight output microstrip lines are fabricated on alumina substrate with a dielectric constant of 9.8 and a substrate thickness of 5 mils and on RT/Duroid 5880 with a dielectric constant of 10.2 and a substrate thickness of 10 mils, respectively. A GaAs Beam Lead Schottky barrier APDP (HSCH-9251) is used for the sub-harmonic I/Q mixers. Agilent ADS 2002 circuit and Momentum full-wave simulator is utilized to predict the sub-harmonic I/Q mixer performance, all characteristics relevant to the antenna and other passive circuits.

III. Measurements and Discussion

A. 60 GHz integrated antenna array RF performance

Figure 2 shows the return loss of a microstrip patch antenna. The center resonant frequency of the antenna is 61.43 GHz and its -10 dB bandwidth is 2.78 %, that is 1.7 GHz, respectively. The patch antenna size is 28.7 × 34.5 mils.

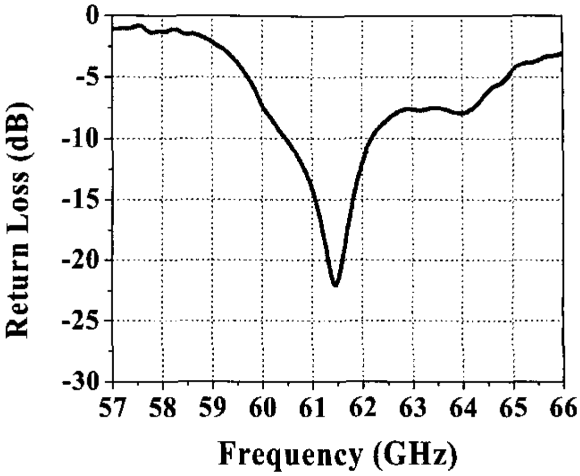


Fig. 2. Measured return loss of the microstrip patch antenna.

In order to measure the RF performance of the sub-harmonic I/Q mixers integrated with an antenna for four channels, a transmitter including a Dorado GH-15 horn antenna, a HP 83557A V-band source module, and a HP 83620A synthesized sweeper is located at the distance of 25.4 cm from the array for the far field pattern measurement. Figure 3 shows the average conversion losses of each four channel as a function of LO power. The conversion loss is defined by the ratio of the RF power right before the microstrip patch antenna array to the IF power at each IF SMA connector as shown in Fig. 1 (a) to be free of measurement errors due to cable losses and other devices in millimeter-wave length [7], [10]. The average conversion loss of all four channels is lower than 10.6 dB with LO power from 21.5 dBm to 27 dBm at the LO port in Fig. 1 (a).

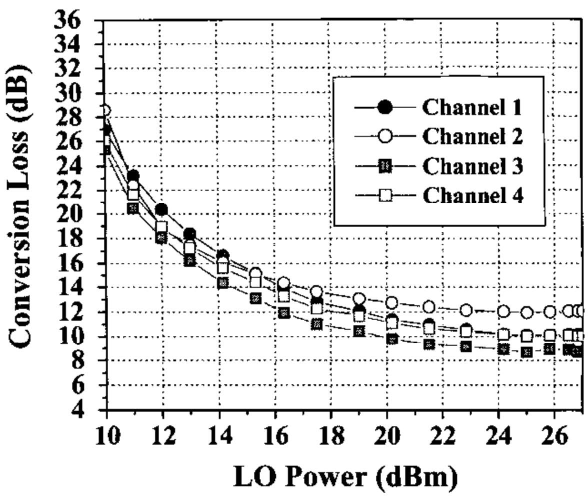


Fig. 3. Measured average conversion losses of each four channel vs. LO power at IF = 2.75 GHz (The RF power is defined as the power intercepted by the antenna).

Figure 4 shows the measured average conversion losses of each four channel as a function of the RF frequency with LO power of 21.5 dBm. Within the frequency range of 61.5 GHz to 62.2 GHz (700MHz), it has a 1.7 dB power imbalance among four channels. Table 1 and 2 summarize power amplitude imbalances of less than 2.5 dB and phase deviations of less than 7° between I and Q outputs of each channel in the frequency range from 61.5 GHz to 62.2 GHz, respectively. Once we apply this circuit for digital beamforming, those errors can be recovered using digital signal processing.

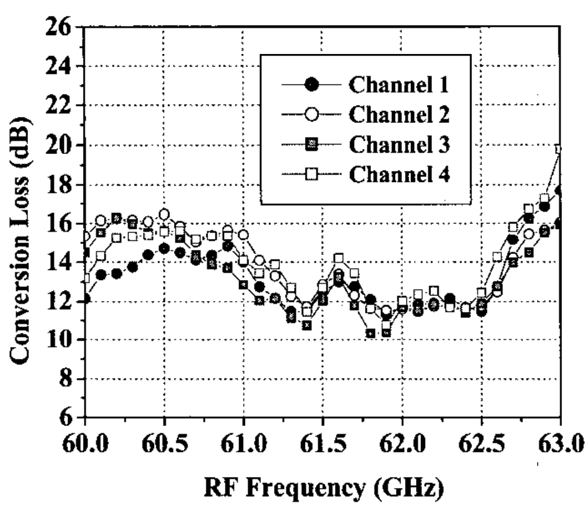


Fig. 4. Measured conversion losses of each four channel vs. RF carrier at LO = 21.5 dBm (The RF power is defined as the power intercepted by the antenna).

Table 1. Amplitude imbalances of I and Q outputs at each channel (Unit: GHz, dB).

RF	Ch. 1	Ch. 2	Ch. 3	Ch. 4
61.5	1.5	2.0	0.8	0.5
61.6	1.1	1.6	0.6	0.5
61.7	1.3	2.3	0.6	0.6
61.8	1.0	2.3	1.1	0.0
61.9	1.5	2.5	1.6	0.0
62.0	1.3	2.1	1.6	0.5
62.1	1.1	2.3	2.0	0.5
62.2	1.3	2.1	2.3	0.1

Table 2. Phase deviations of I and Q outputs at each channel.

Ch. 1	Ch. 2	Ch. 3	Ch. 4
7 °	3 °	5.6 °	2.8 °

B. 60 GHz Band Digital Beamforming Implementation

Figure 5 shows the block diagram of a digital beamformer comprised of a 60 GHz integrated antenna array, an IF circuit block, A/Ds, and digital signal processing. The RF carrier of 61.875 GHz is first down converted to an IF of 2.755 GHz by I/Q mixers integrated with four-element array. The IFs, I and Q signals at 2.755 GHz are then amplified and mixed with a second local oscillator of 2.75 GHz in the IF circuit block to obtain baseband I and Q signals of 5 MHz at each channel. The downconverted baseband signals pass through each low pass filter and are again amplified. They are then sampled by sampling rates of 200 MS/s using a digital oscilloscope instead of A/D converters and sampled data is transferred to a PC for digital signal processing by a MATLAB code which works as a digital signal processor.

In order to generate digital beamforming, the array patterns are finally calculated by the collected data of the baseband signals. An adaptive beamformer called sample matrix inversion (SMI) is used here to calculate the weighting coefficient vector $\mathbf{W}_{smi}^{H}$ [11]. Therefore the total linear array's output in Fig. 5 becomes:

$$f(\theta) = \mathbf{W}_{smi}^{H}\mathbf{v}(\theta)\cdot e(\theta) \qquad (2)$$

where $\mathbf{v}(\theta)$ is the array manifold vector and $e(\theta)$ is the element pattern.

The synthesized beamforming patterns of the 60 GHz array are shown in Figure 6. The main beams are scanned from -25° to 25°. However, the peak of main beam at -25° is slightly shifted to broadside due to non-uniform phase errors. The side lobe levels are slightly higher than the calculated side lobes of four-element isotropic array. Multi-paths in measurement environment and fabrication error cause higher side lobes.

Since the RF carrier is at millimeter-wave frequencies, the bandwidth is inherently broad so that the system can be extended for wireless applications with high-speed and large-channel data rates.

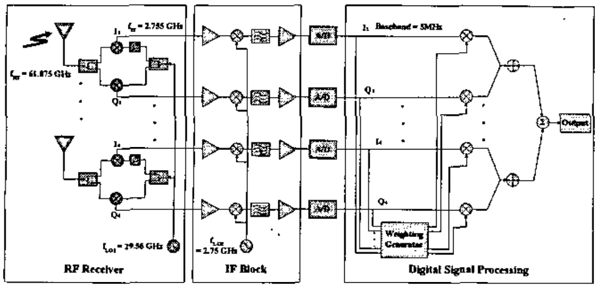


Fig. 5. The block diagram of 60 GHz band digital beamforming.

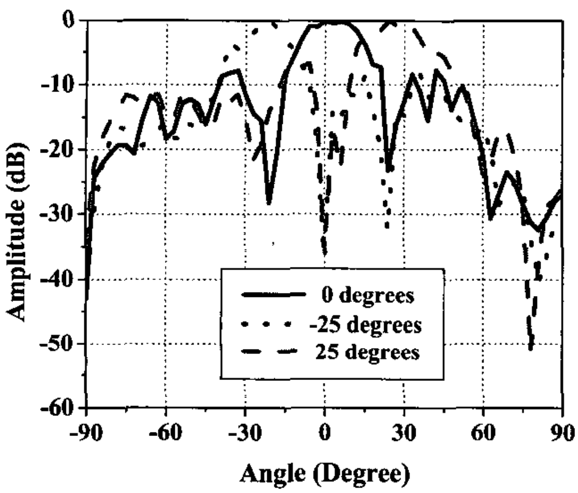


Fig. 6. Synthesized beam patterns toward 0 °, -25 °, and 25 ° direction.

IV. Conclusion

A 60 GHz band integrated four-element planar antenna array with APDP sub-harmonic I/Q mixers for digital beamforming applications has been proposed. In order to predict circuit error, the RF performance of the proposed circuit has been measured. The conversion loss of the overall circuit is less than 10.6 dB and the power imbalance and the phase deviation of each I and Q output are less than 2.5 dB and 7° have been achieved. This array's functionality as a 60 GHz millimeter-wave digital beamformer has been shown by combining it with an IF circuit block, A/D, and digital signal processing.

Acknowledgement

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References

[1] V. Brankovic, K. Kawasaki, K. Sasaki, K. Fukuzawa, Y. Okada, D. Krupezevic, M. Ratni, and H. Alikhani, "60 GHz wireless access system concept," *31st European Microwave Conference*, Sept. 2001.

[2] J. Wu, W. –X. Sheng, K. –P. Chan, W. –K. Chung, K. –K. M. Cheng, and K. –L. Wu, "Smart antenna system implementation based on digital beam-forming and software radio technologies," *2002 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, pp. 323-326, June 2002.

[3] R. L. .Choi, K. M. Letaief, and R. D. Murch, "MIMO CDMA antenna systems," *2000 IEEE International Conference on Communications*, vol. 2, pp. 990-994, June 2000.

[4] Y. Qian and T. Itoh, "Progress in active integrated antennas and their applications," *IEEE Trans. Microwave Theory and Tech.*, vol. 46, pp. 1891-1900, Nov. 1998.

[5] A. Yamada, Y. Amano, E. Suematsu, and H. Sato, "A patch antenna array on a multi-layered ceramic substrate for 60 GHz applications," *31st European Microwave Conference*, vol. 2, pp. 37-40, Sept. 2001.

[6] S. A. Mass, *Microwave Mixers*, Norwood, MA: Artech House, 1993.

[7] J-. Y. Park, S. S. Jeon, Y. Wang, and T. Itoh, "Integrated antenna with direct conversion circuitry for broadband millimeter-wave communications," to be published in *IEEE Trans. Microwave Theory and Tech.*

[8] S. S. Jeon, Y. Wang, Y. Qian, and T. Itoh, "A novel smart antenna system implementation for broad-band wireless communications," *IEEE Trans. Antennas Propagat.* vol. 50, pp. 600-606, May 2002.

[9] S. S. Jeon, Y. Wang, Y. Qian, B. Houshmand, and T. Itoh, "Active quasi-yagi antenna direct conversion receiver array with digital beamforming," *2000 IEEE Antenna and Propagation Society Int. Symp.*, vol. 3, pp. 1268-1271, July 2000.

[10] K. D. Stephan, and T. Itoh, "A planar quasi-optical subharmonically pumped mixer characterized by isotropic conversion loss," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-32, pp. 97-102, Jan. 1984.

[11] H. L. Van Trees, *Optimum Array Processing: IV of Detection, Estimation, and Modulation Theory*, NY : John Wiley & Sons, Inc., 2002.