A Dual-Polarized 1024-Element Ku-band SATCOM Phased-Array with Embedded Transmit Filter and >10 dB/K G/T

Gökhan Gültepe*1, Samet Zihir#2, Tumay Kanar#3, Gabriel M. Rebeiz*4

*1University of California, San Diego, La Jolla, CA, USA
#2Renesas Electronics America, Inc, San Diego, CA, USA

1ggultepe@ucsd.edu, 2samet.zihir.jc@renesas.com, 3tumay.kanar.jc@renesas.com, 4rebeiz@ece.ucsd.edu

Abstract — This paper presents a 1024-element Ku-band (10.7-12.7 GHz) polarization agile phased-array SATCOM receiver (RX). The phased array is built on a printed circuit board (PCB) surface-mount low-noise amplifiers (LNAs) and silicon beamformer chips are assembled. The phased-array, with a size of 40x39 cm and a directivity of 34 dB at 11.7 GHz, covers a scan volume of ±70° in all planes, and enables a low-noise operation with a receive G/T 10.5 dB/K at broadside. Its wide angle electronic scanning capability makes it suitable for affordable Ku-band SATCOM ground terminals.

Keywords — SATCOM, Ku-Band, receiver, RX, beamformer, LNA, dual-polarized, G/T, active phased arrays, phased array antennas, satellite communications

I. INTRODUCTION

Active electronically scanned phased-array antennas (AESA) have become feasible solutions for commercial satellite systems due to advances in low-cost and low-noise silicon beamformer chips at Ku-band and Ka-band. Their fast beam-steering capabilities provide uninterrupted links between the ground terminals and the fast-moving low earth orbit (LEO) satellites, or for SATCOM on the move, where the satellite is fixed but the ground-terminal is constantly moving.

In this paper, an affordable 1024-element dual-polarized Ku-band phased-array receiver is presented for Ku-band SATCOM applications. The design, shown in Fig. 1a, is implemented using all-silicon BGA (ball grid array) chips. The array architecture is based on 2x2 dual-polarized antennas connected to 4 separate dual-channel LNAs and an 8-channel beamformer chip, and results in a symmetrical design requiring minimal calibration (Fig. 1b) [1]-[7]. The 1024-element phased-array is built using four 256-element sub-array tiles, and the RF outputs are combined together using an external 4:1 Wilkinson combiner. An IF down-converter is used at the sum point as shown in Fig. 1b.

II. KU-BAND SATCOM RX ARRAY DESIGN

The 1024-element Ku-band phased array operates at 10.7-12.7 GHz, and each sub-array tile consists of 256 dual-polarized antenna elements. The array PCB is cut to grid on three sides, making the design scalable as 2xN so as to increase the array area and the antenna G/T. The 256-element arrays are built on a 12-layer FR4-based PCB. The substrate is Panasonic Megtron6, with $\varepsilon_r=3.63$ and $\tan\delta=0.004$ at 12 GHz. Such a low-cost PCB implementation with antennas on one side and chips on the other side have been used in multiple presentations over the past 4 years. The dual-polarized stacked-patch antennas are designed to operate between 10.7-12.7 GHz with $S_{11}<-9$ dB up to 60° scan angle. The antenna spacing is 0.5λ at 12.2 GHz in an equilateral triangular grid, and the array scans to ±70° in all planes throughout the RX band.

The V and H signals are amplified using a commercial dual-channel silicon LNA (Renesas F6921) with a gain of 19 dB and a NF of 1.5 dB at 11 GHz, placed directly at the antenna port. The use of an external LNA located at the antenna port, instead of using an LNA inside the beamformer chip, removes the transmission-line loss between the antenna and the silicon beamformer (0.25-0.3 dB) and improves the G/T by 0.5-0.6 dB (for $T_{ant}=20$ K). Thus, for the same G/T specification, the external LNA reduces the phased-array...
size and antenna count by 10-14% thus saving 10-14% of LNAS and silicon beamformers and associated DC power consumption.

The received V and H signals then pass by low-pass stripline filters before entering the 8-channel silicon beamformer chip (Renesas F6101, Gain=15.5 dB, NF=5 dB at 11.7 GHz) at the center of each 2x2 antenna quad. The 64 beamformer chips are then combined together using a symmetrical equal-length 64:1 Wilkinson network. Digital control lines and power distribution are laid out on stripline layers inside the PCB.

The embedded low-pass filter has a significant role in Ku-band SATCOM phased-array operation, and suppresses the coherent transmit signal at 14-14.5 GHz before it impinges on the Rx beamformer channel. This is especially important when the transmit (TX) and receive (RX) arrays are placed side-by-side on a platform sharing the same radome. Considering that a single transmit antenna radiates 12 dBm at 14-14.5 GHz, and the coupling from a single transmit antenna to a single receive antenna is -65 dB (averaged over multiple antennas in the transmit array and multiple antennas in the receive array), the transmit signal incident on a single LNA is -33 dBm if ~100 transmit antennas from the 1600-element transmit array couple to a single antenna located at the edge of the receive array. The coupled transmit signal of -33 dBm can be easily handled by the LNA (Gain=15 dB, IP1dB=-19 dBm at 14 GHz). However, the transmit-leakage signal is now amplified by the LNA and impinges on the silicon beamformer chip with a power level of -16 dBm. Since the IP1dB of the beamformer chip is only -26 dBm at 14 GHz (for low power operation), the transmit signal will saturate the beamformer chip and impede the phased-array operation in the 10.7-12.7 GHz receive band. Thus, it is imperative that a low-pass filter with 15-20 dB rejection in the TX band (14-14.5 GHz) be inserted after the LNA and before the beamformer chip, and an elliptic stripline filter with <1 dB in-band loss and >20 dB suppression in the TX band is used. Note that using such a filter before the LNA will reduce the G/T by 2 dB and is not allowed.

The LNA/filter/beamformer is first measured using a 2x2 connectorized test-cell (not shown for brevity). The measured electronic gain and NF are 37 dB and 1.68 dB, respectively, at 11.7 GHz. The LNA/filter/beamformer gain drops to 8-5 dB at 14-14.5 GHz (> 30 dB rejection) and is due to the LNA gain drop (4 dB), filter response (20-25 dB), and beamformer gain drop (5-7 dB).

III. MEASUREMENTS

The 1024-element Ku-band receiver is measured by using a horn antenna in an anechoic chamber at 2.5 m, which is in the radiative mid-near-field region of this large array. This is because $2D^2/\lambda$ is ~12 m. Still, a quarter far-field distance is enough to show the operation of the array with low sidelobes. The array is calibrated at the center frequency, 11.7 GHz, as the transmission lines routing to the antennas are not identical due to the triangular grid. The phase and gain of the individual channels are measured one channel at a time, and the phase shifters and the variable gain amplifiers (VGA) in the beamformer chip are adjusted to create an equi-phase front at the horn antenna.

The array frequency response is then measured at broadside for both vertical and horizontal polarizations showing a similar response (Fig. 3). The combined response of the antenna, LNA, embedded filter, beamformer channel, 64:1 Wilkinson combiner and the line amplifier at the edge of the array results in 50 dB suppression in the Ku-band SATCOM transmit band (14-14.5 GHz). Note that the RX antenna itself contributes >12 dB of rejection at 14-14.5 GHz.

The array achieves nearly ideal patterns with very low side lobe levels (SLL) when a 25 dB Taylor amplitude distribution with 4 equal side lobe levels is applied (Fig. 4). The cross-polarization level is nearly -40 dB at broadside, and < -30 dB when the beam is steered to ±60° (not shown for brevity).

The radiation patterns for various scan angles are measured when the array is uniformly illuminated (Fig. 5). At broadside, the 3-dB beamwidth is 3.3° and agrees well with simulations, resulting in an array directivity of 34 dB at 11.7 GHz. The
gain drop at wide scan angles follows a $\cos(\theta)^{1.2}$ response, and the gain decreases by 3.6 dB at $\pm 60^\circ$ scan angles.

The phased-array $G/T$ is measured in an anechoic chamber using the Keysight PNA-X $G/T$ software module, and when the antenna temperature is 295 K (room temperature). Then, considering that in normal operation the array looks at the cold sky to set up a SATCOM link, the measured $G/T$ is then calculated for the case of $T_{\text{ant}}=20$ K. The improvement in $G/T$ ($G/T_{\text{imp}}$) is:

$$G/T_{\text{imp}} = 10 \log_{10}(T_{\text{sys}}/(T_{\text{sys}} - (295 - 20) \times G_{\text{TL}}))$$  \hspace{1cm} (1)$$

where $T_{\text{sys}}$ is the system noise temperature obtained from the measured $G/T$ when the antenna temperature is 295 K by subtracting the $G/T$ from the antenna gain. $G_{\text{TL}}$ account for the loss before the LNA, including antenna metal and dielectric losses. All in all, the array achieves a $G/T$ of 10.5 dB/K at 12.7 GHz results from a 2 dB drop in the LNA gain as well as the aggressive transmit-filter filter response (which shifted to lower frequencies), the drop at 10.7 GHz is due to the antenna impedance bandwidth. In addition, the calibration is done at 11.7 GHz and is not valid at 10.7 GHz and 12.7 GHz due to non-equal line lengths and filters. Note that the electronic gain at 12.7 GHz drops by 9 dB, while the $G/T$ drops by 3 dB since the filter is placed after the LNA.

IV. CONCLUSION

This work presents a dual-polarized 1024-element phased array Ku-band SATCOM receiver built using a cost-efficient PCB and commercial silicon chips. To the authors’ knowledge, this is the first all-silicon phased-array with that achieves $>10$ dB/K $G/T$. Future work includes a wider-band antenna and an optimized transmit-filter.

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REFERENCES


