# High-Performance Transceiver Components for Defense Communications and Sensing

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***Abstract*— University defense funding has over the years produced a number of innovations in components for communications and sensing related to national defense needs. This paper presents an overview of research at the University of Colorado centered around improvements of microwave and millimeter-wave front ends, and its potential impact of fundamental research on future military systems. Examples include: (1) low-loss broadband passives implemented in new technologies such as micro-fabricated air coaxial transmission lines; (2) power amplifier architectures that result in increased efficiency for broadband and high peak-to-average ratio signals; (3) multi-beam antenna arrays that enable faster direction of finding algorithms by means of front-end analog processing. Other developments range from chip-scale atomic clocks with low-phase noise microwave oscillators for synchronization, to heterogeneous integration technologies for advanced phased arrays.**

***Index Terms*— microwave front ends, power amplifiers, phased array, micro-coaxial components, power combining**

## I. Introduction and Background

Defense funding of university-based research in the United States has inherited part of the role played in the past by research institute giants such as Bell Laboratories. Although the main role of university research is to educate new experts that can in the future contribute to the nation's security and economy, it is also an important distributed investment for maintaining research innovation. This paper presents a brief overview of some DoD-funded research in the area of microwave front-end transceiver components, referring to the high-level block diagram in Fig.1:

- The important parameters for the transmitter are output power, efficiency and linearity, addressed here by GaN devices and high-efficiency power amplifier (PA) architectures for high peak-to-average power ratio (PAPR) signals required for communications and some radar, e.g. [1-6], as well as spatial power combining techniques, e.g. [7-9].
- In the receive path, low noise and high dynamic range imply low-loss components [10-14]. Low-loss broadband passive also enable advanced transmitter amplifiers [15-20] and filtering.
- Synchronization at various levels and low-phase noise local oscillators are addressed by developing components for miniaturized atomic clocks [21-22].
- The T/R module from Fig.1 can be an element in a phased array, which performs beamforming and scanning. Adaptive beamforming can be accomplished efficiently by analog front-end processing e.g. [23-27].

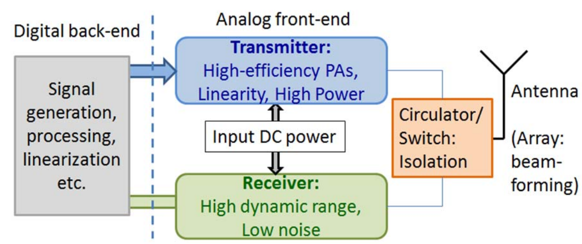


Fig.1. General block diagram of an RF transceiver with specific research topics highlighted in this paper: high-quality passives that enable low loss to increase efficiency and reduce noise figure;

High-quality passive components are essential for achieving efficiency in transmit and low noise in receive, and the next section describes a few examples. This is followed by an overview of some active circuits and finally an introduction to one approach to analog beamforming.

## II. Passive Components

Insertion loss affects efficiency in PAs and noise factor in LNAs. Air-filled coaxial lines using sequential copper deposition referred to as Polystrata$^{TM}$ was developed under a DARPA program with Nuvotronics. Fig.2 shows the geometry of the line, where the center conductor is supported by periodic insulating straps which take less than 1% of the volume, and therefore do not contribute to loss.

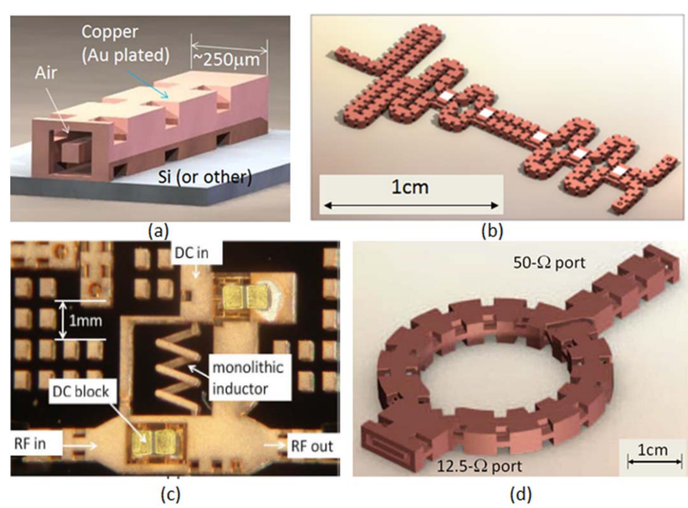


Fig. 2. (a) Micro-coaxial Polystrata line. (b) 2-22GHz Wilkinson divider. (c) broadband high-current bias line. (d) 4:1 impedance transformer, 2-22GHz.


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The micro-coaxial line can be designed to have a wide range of characteristic impedances, from 8 to 120Ω for a 11-layer process. The 250-μm 50-Ω coaxial line is purely TEM up to 450GHz and therefore has very low dispersion, so extremely wideband components can be designed. The loss of a low-loss coaxial line is given by

$$\alpha \cong \frac{R'}{2}\sqrt{\frac{C'}{L'}} + \frac{G'}{2}\sqrt{\frac{L'}{C'}}$$

where $R'$,$G'$,$C'$ and $L'$ are distributed line parameters. For a perfect dielectric, the second term is zero, but the loss nevertheless grows with relative permittivity since $C' \propto \varepsilon_r$, so a vacuum (air) filled coaxial line has the lowest loss, for lines in Fig.3 measured to be less than 0.1dB/cm up to 50GHz [10]. Q-factors exceeding 800 were demonstrated in 2.5-D Ka-band resonators [11]. Extremely broadband and low-loss components were demonstrated, such as over a decade bandwidth Wilkinson combiner/dividers (2-22GHz) [12] and coaxial 4:1 impedance transformers [13]. The sequential deposition process and closed structure of the coaxial line allows straightforward integration with surface-mount components and actives with practically no parasitics [14]. At higher millimeter-wave frequencies, the same technology has been applied to G-band TE10 waveguide scanning arrays, with possibly lower-cost 3D-printed versions under current investigation.

## III. Active Circuit Components

Efficiency of transmitters is limited by the final stage power amplifier, especially for broadband signals (>100MHz) with high PAPR (>10dB). Improving PA efficiency is critical in phased arrays which are often thermally limited. There are several methods for improving efficiency in such cases, e.g. envelope tracking, or supply modulation [1-5], outphasing [15], Doherty [16] and harmonic injection [17]. Dynamic supply modulation is an approach where the power supply voltage provided to the PA is dynamically varied in accordance with the time-varying envelope of the signal so that the PA is kept nearly always in compression, where its efficiency is high.

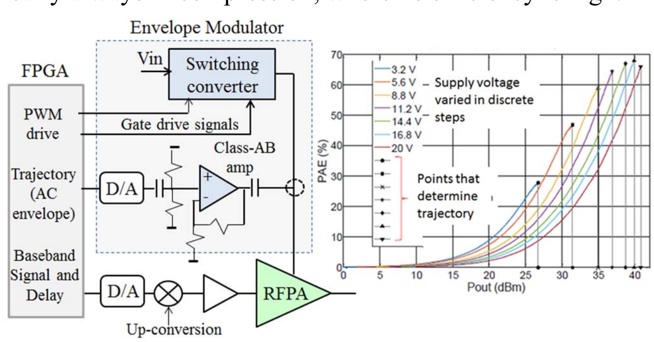


Fig.3. Block diagram of a typical envelope tracking transmitter and measured static PAE curves for varying supply voltages of a X-band GaN MMIC PA with 10W of peak output power.

The block diagram shown in Fig.3 shows a typical implementation of the envelope modulator with an efficient switching-mode converter combined with a less-efficient but faster linear amplifier. Fig.3 shows example measured PAE plotted as a function of output power of a PA for several supply voltages. This can result in a substantial increase in average efficiency using a very fast supply. However, the overall system efficiency includes losses in both the PA and the dynamic supply (envelope modulator). This is challenging to implement with high efficiency, high accuracy and high slew rate required for broadband signal amplification. Up to 200-MHz switching dc-dc converters are implemented in a 150-nm GaN microwave process with efficiencies over 90% for up to 10W output power [18]. Fast multi-level supplies [6] are used to track X-band MMIC PAs fabricated in the same process [19], with some results shown in Fig.4 for both OFDM communication signals and radar signals with spectral confinement.

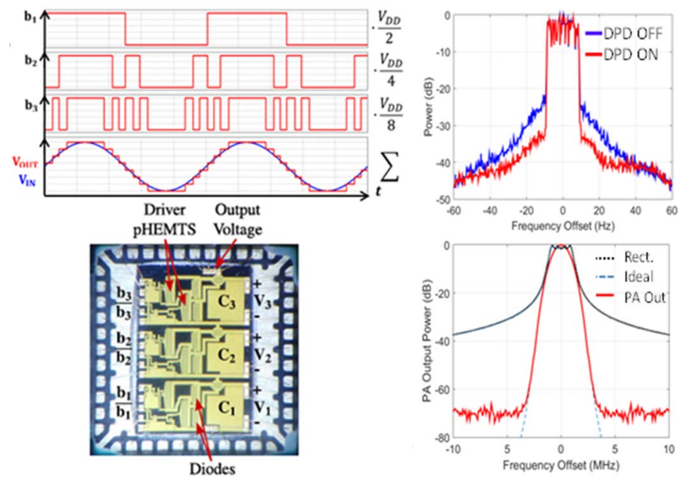


Fig. 4. Photograph of the 8-level GaN MMIC supply. The discrete tracking is illustrated with the sine wave example. The measured spectrum is obtained at the output of the PA, for a LTE signal and an FM radar pulse with a Blackman amplitude modulated envelope, compared to a rectangular pulse. The spectral confinement is dramatically improved, while maintaining a total efficiency >44% at 10GHz.

To increase the power level, power combining is done at the die and circuit level. The power combining efficiency (PCE) drops as the number of PAs grows. For large-scale combining, spatial power combining efficiency remains constant as the number of elements grows [20]. In [7], a FLK052WG 0.61W class-E PA with a compressed gain of 9.8 dB, a drain efficiency of 81%, and a PAE of 72% at 5GHz is integrated in a spatial combining array. Anti-resonant slot antennas are used to present the harmonic terminations. Fig. 5 shows the circuit side of a 10-GHz array, where the 16 class-E GaAs MESFET PAs are fed with a corporate Wilkinson combiner feed network, while the outputs are combined in free space upon radiation from a 16-element in-phase fed patch antenna array. The free-space combining efficiency is estimated to be 80%, which is higher than a 4-level corporate network at 10GHz [9]. A spatial combiner with a low-loss spatial feed is shown in [23], where an grid oscillator combiner feeds a multi-beam discrete lens array that also adds gain and power by distributed amplification. The additional functionality of such an approach is discussed in the next section.


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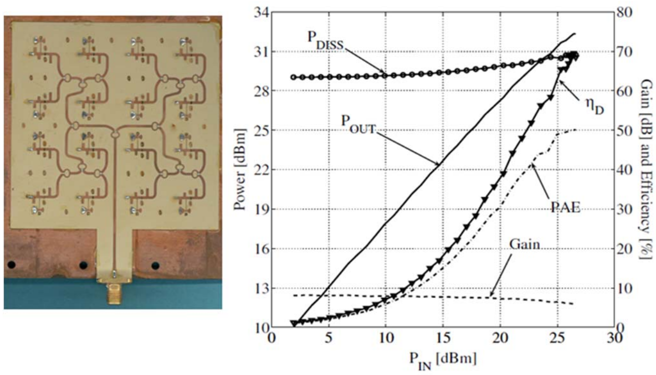


Fig.5. Feed side of patch antenna spatial power combining array with class-E PAs at 10GHz and measured array characteristics.

Components of a front end include low-phase noise voltage-controlled oscillators such as the one shown in Fig.6 [21], used in a chip-scale atomic frequency reference [22]. At 3.4GHz (half of the Rubidium atom ground-state hyperfine transition frequency), the VCO demonstrates low phase noise (-33dBc@100Hz and -92dBc@10kHz) at 4.5mW power consumption with a circuit footprint <0.5cm$^2$. The temperature stability is 0ppm/°C at room temperature, and does not exceed -40ppm/°C over the range of -5°C to +65°C. Locking to the Coherent Population Trapping (CPT) resonance of a NIST Rb clock is enabled by a weakly-coupled varactor diode which provides ~3MHz of tuning range. The oscillator is implemented using low-cost off-the-shelf surface-mount components, and had the smallest published size, phase noise, DC power consumption and thermal drift.

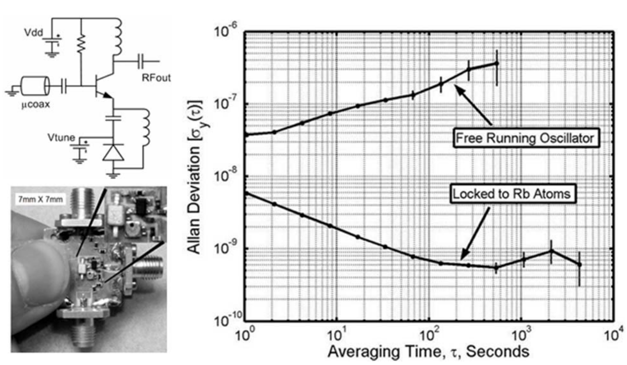


Fig.6. Left: Simplified circuit diagram and photograph of VCO. The high-Q element is a surface-mount, quarter-wave, shorted micro-coaxial resonator, and the capacitors, inductors and varactor are standard surface-mount components. Right: Fractional frequency instability of the free-running VCO and when locked to Rubidium atoms at NIST.

## IV. Antenna Array Front-End Processing

An alternative to a phased array with phase shifters in each element of the array is a discrete lens array, Fig.7 [23-26]. The lens consists of two arrays, referred to as a radiating- and feed-side. A wave incident from direction $\theta_0$ is received by the radiating-side antennas and coupled to the feed side elements via TEM true time-delay lines of varying lengths in such a way that it is focused onto a small region on the focal surface. Assuming the arrays are planar, the parameters in the design of such a lens include: type and number of antenna elements, type of interconnect between radiating and feed sides, relative position of element pairs on the two sides and length of interconnect, Fig. 7a. The lens is amenable to standard pcb fabrication, with the example in Fig.7b of a multi-bean 36-element Ka-band passive lens array [24]. Amplifiers can be easily integrated between the antenna elements to compensate for feed loss and add gain [24]. Fig.7c shows a 28-GHz lens with GaAs MMIC PAs, LNAs and SPDT switches in each unit element. In transmission, the power is combined spatially and in reception, the noises of the individual LNAs are uncorrelated, while the signals add, increasing the dynamic range with minimal additional noise. An $N$-element lens array will have $N$ focal points, and therefore $N$ receivers placed on the focal surface will be able to form $N$ beams and any linear superposition of these beams. Fig.8 shows an X-band 1-m diameter example from [25] where $N$=956 and $M$=32, designed for tracking.

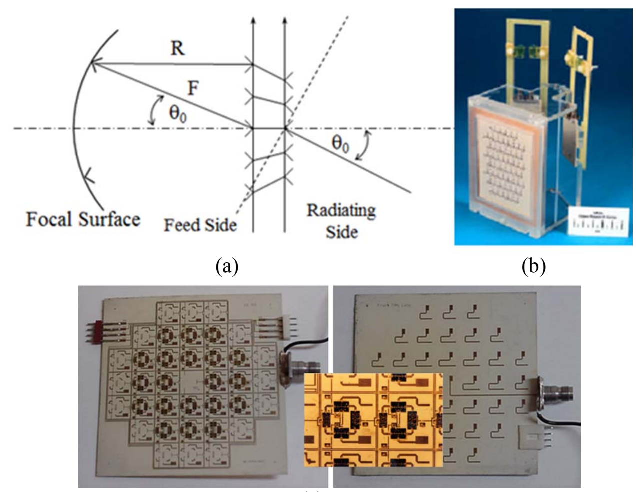


Fig.7. (a) Basic diagram of a planar discrete lens array, F is the focal distance. Photos of a (b) 36-element passive Ka-band lens and (c) 28-GHz active lens with MMIC LNAs, PAs and switches shown in the unit cell.

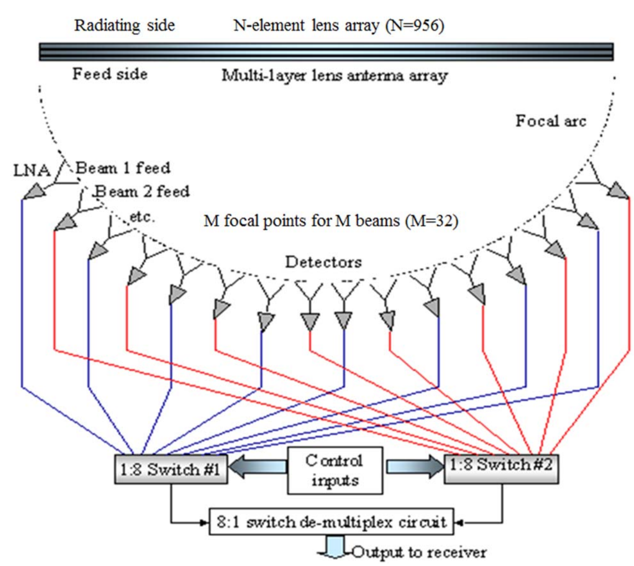


Fig.8. A lens array about 30$\lambda_0$ in diameter with 32 switched beams enabling tracking with or one or more narrow beams with no phase shifters.


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The lens can be used as an adaptive array with no RF phase shifters, with adaptive algorithms that require a much smaller number of complex weights than in the case of a standard phased array, due to the DFT analog front-end processing of the lens. This is illustrated in Fig.9 for a 121 element lens [27] and results in lower-energy processing. Algorithms that can easily be implemented include direction finding, jammer-suppression, and adaptive scanning.

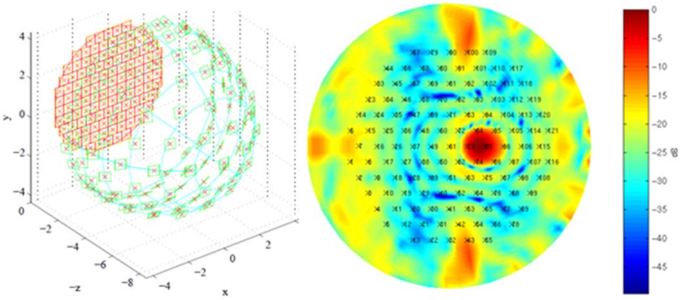

Fig.9. Sampling of a 6 λ- diameter circular lens with F/D=0.5 and 121 detectors placed on the focal surface. The simulation shows normalized received power at the detectors for a source at 20 degrees off the optical axis. It is sufficient to receive and adapt complex weights on only 5 detectors (red area).

In summary, this paper presents a glimpse of DoD-funded research in RF front ends at the University of Colorado, which over the past two decades helped produce over 50 young experts who are contributing to national security and economy.


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