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Teleprompter Script for Dr. Mark Rosker, Program Manager, Microsystems Technology Office

The Monolithic Radio Frequency Array & the Coming Revolution of Convergence

» **MARK ROSKER:**
An enormous radar array scans the sky for strategic missiles directed at the US mainland.

At what range can it *sense* threats?

A HMMWV speeds down a road; its crew struggles to spot IED emplacements by the roadside.

What sensors will allow them to *image* threats?

A UAV loiters over a suspected terrorist cell.

How much detailed imagery can it *communicate* to its operators about threats?

Sensing, imaging, communications: the radio-frequency (or RF) spectrum offers inherent advantages to the warfighter in the collection and communication of information.

RF sensing, imaging, and communications systems reside on a vast number of platforms extending across all services.

I’m Mark Rosker…
and I’m at DARPA to incite *a revolution*:
a revolution *in*
RF electronics –
a revolution that will fundamentally alter the way we sense the world around us and how we communicate information.

It will transform military systems and the platforms that support them, making them smaller, more ubiquitous, and more effective.

Today, I’m going to tell you about the next big leap in RF electronics: the Monolithic RF Array.

I’ll explain what it is,
why it will be so important, and what challenges must be overcome to realize it.

But what I *really* want to tell you about is how creating the Monolithic RF Array will be but the leading example –
the first battle, if you will – in a larger RF revolution: what I call, the “Electronics Convergence Revolution.”

As we will see,
this revolution will spring from a new capability to combine *the very best materials and device technologies – both analog and digital – together in ultra-compact, high-speed circuits.*

Let me start by reminding you about the *last* RF revolution.

RF integrated circuits are so ubiquitous today that it is hard to remember when they did not exist.

Twenty years ago, though, no one knew how to combine the highest speed microwave transistors of the day in manufacturable and affordable packages.

The challenge *then* was learning how to design and produce RF integrated circuits at high yield and reasonable cost.

DARPA took on this challenge in a celebrated program called “MIMIC.”

This required major advances in GaAs fabrication technology,
in microwave computer aided design,
in packaging, and
in automated testing.

The result was a breakthrough:
compact RF circuits that radically outperformed the previous discrete electronics.

And a breakthrough in cost: manufacturing processes that could produce affordable,
high-performance, packaged microwave circuits.

In your pocket or on your belt is one astounding product of that leap: the cellular phone handset.

Its GaAs power amplifier is a direct consequence of the MIMIC program.

Because of its linearity and efficiency,
and because it can be made in volume at low cost, it enabled the cellular communications revolution.

That was the *last* breakthrough in RF integration: the Monolithic Integrated Circuit.

The *next* big leap will be the *Monolithic RF Array*.

To illustrate,
let's go back to that example of the cell phone.

In comms,
more is <u>always</u> better.

More meaning
more bits per second;
in other words,
more channel capacity.

Your cell phone, which works at about 2 GHz frequency, has a very modest channel capacity.

Great for calling Mom; not so good for transmitting, say, multi-channel HDTV video from a loitering UAV.

The problem with your cell phone is that it sends its signal in all directions –
so that very little energy goes to where we really want it to go.

We could increase your cell phone's channel capacity tremendously
if we could swap its omni-directional antenna for a *phased array*.

A phased array is a collection of elements, or "cells", each transmitting and receiving its signal with a very precise, controlled relative phase.

By allowing us to send information only in the direction of the receiver,
a phased array could easily give us a 1000 times increase in
channel capacity.

It is for exactly this reason that RF phased arrays have become a mainstay of military systems across a wide number of platforms.

The penalty, though, is *size*: to work effectively, the array elements must be spaced by half the radiated wavelength.

At cell-phone frequencies, that would make your phased array huge.

Pretty hard to fit it in your pocket anymore!

Here’s the challenge:
I want a wireless,
all-weather,
free-space data link,
like your cell phone,
but with the capacity of an entire fiber optic cable – 10 Gbits per second or more!

And I want it in a device that you can hold in your hand!

Forget the latest cell phone fad – what I want, what the warfighter needs, is something with orders of magnitude more capacity.

Call it… *the MTO Phone*.

And I know how to realize this dream.

It’s easy, really.

All we have to do is shrink the *size* of an RF array – by a factor of, oh, maybe *a million*.

Now *there’s* a grand challenge!

To perform this neat trick, we must solve two sets of technical problems:

First, we must develop RF electronic devices that operate with high performance at
ultrahigh-speed, and

Second, we must develop 3D and heterogeneous integration methods to combine these devices together in cells whose volumes are almost infinitesimal.

Let's start with the ultrahigh-speed part.

I told you that the cells of the phased array must be spaced by half the wavelength.

So one key way to reduce size is to *reduce the operating wavelength*; or, in other words,
to increase the frequency.

If we were in vacuum, we'd want to keep going to higher and higher frequencies: from microwave to millimeter-wave to terahertz.

But in the real world,
we have to worry about the atmosphere and its rather *annoying* inclination to attenuate
high-frequency radiation.

And when we take *that* into account,
we find that there is actually an *optimum* operating frequency:
the specific value depends on range and weather but is around 200GHz.

Unfortunately,
this has been beyond our technical reach:
there have never been RF integrated circuits operating at frequencies above 200GHz.

Until now.

This is the world's fastest monolithic integrated circuit, operating at an incredible 340GHz;
that also makes it the world's first sub-millimeter wave RF integrated circuit.

Micro-miniaturization
is its key:
the InP transistor at its heart has a gate length of just 35-nm.

This is a breakthrough, but it is still a first step.

Next, we must develop an entire range of circuit components that function at these incredibly high speeds – without sacrificing component or system performance.

To do *that*, we will have to exploit the most efficient materials possible.

For example, the engine that drives the transmit side of an array is called the power amplifier.

In phased arrays today, power amplifiers are primarily based on GaAs transistors.

But we know they are a long way from ideal.

This transistor, using a wide-bandgap material called GaN, delivers more than *ten* times as much power density as GaAs.

We are currently working hard to realize GaN power amplifiers, but at lower RF frequencies.

Our next job must be to drive the frequency capability of GaN transistors *much* higher.

When we succeed it will lead to the realization of the *ideal* solid-state power amplifier:
one that provides the ultimate combination of speed, power, bandwidth, linearity, and efficiency.

But even if we can build high-frequency versions of all the circuit elements that comprise an RF array cell – the low-noise amplifier, power amplifier, phase shifter, digital control, and so forth,
we still must overcome our second, more daunting task:
how to squeeze those elements into an infinitesimal volume.

To achieve this,
we must go beyond the RF integrated circuit.

We must develop the *Monolithic RF Array.*

Here is a first example.

It is an entire 16 element transmit array –
4 elements on a side – operating around 100GHz; it is literally an RF array on a dime.

This is not a CAD drawing; you are looking at an X-ray picture of an actual active array.

This is not just the antenna:
it's the whole RF array.

It is composed of 5 layers bonded together in a wafer-scale process;
so it is the first truly
3-dimenstional millimeter-wave electronic circuit.

It is much more than 100X thinner than an array at this frequency would be if conventionally assembled; so small, in fact,
that each of its cells is not much larger than the head of a pin.

Now we can imagine fabricating an entire array in a single batch process.

That's going to lead to *enormous* cost reductions and, for the first time, make millimeter-wave arrays affordable.

Great news if you want an MTO phone!

But it's going to do more.

Which leads at last to what I told you I *really* wanted to talk about today: the electronics convergence revolution.

The Monolithic RF array can be understood as a dense integration of dissimilar materials and devices – a *heterogeneous* integration – including, maybe,
GaN transistors for the power amplifier, perhaps InP for the receiver circuit, certainly silicon for the digital processing; dielectric materials, and metals for the interconnects.

Each material has different physical properties –
how much it expands when heated, for example.

And these various materials must be positioned very close to one another,
separated by perhaps
100 microns or so.

So, such an integration of materials is extraordinarily difficult to construct.

But let's not stop there.

Imagine going further, zooming in to the scale of the transistors within the cells, to scales of a micron or so.

What if we can learn how to heterogeneously integrate the highest performing transistor of one material literally *within* a circuit made of a completely different material?

For instance,
what if we can place –
or epitaxially grow –
our highest speed analog InP transistors *within* a highly complex digital silicon CMOS circuit.

We are accustomed to thinking of two separate kinds of electronics: digital and analog.

For many years,
they have moved along their separate paths.

But here is a new thing.

It is a marriage –

a *convergence* –
not *just* of different materials, but of completely different *kinds* of transistor electronics.

Now, we will be able use the digital parts of a circuit to control and optimize the analog parts.

So when we shrink the integration scale in this way, the dream of the Monolothic RF array becomes something more: a SMART RF array, able to optimize and reconfigure itself.

Such fine-scale integration will lead to:

Analog-to-digital converters than dynamically calibrate themselves and thereby digitize information with many bits higher precision, for greater bandwidth and linearity;

Programmable analog signal processors that process information just as your ear does,
in the analog domain, using far lower powers than today's digital approaches;

Reconfigurable communications and sensor systems capable of changing their frequency of operation, or perhaps their bandwidth, to counter threats and to better exploit the RF spectrum.

Someday, we will *all* have that MTO Phone.

John Zolper wanted to hand them out as giveaways at MTO's DARPATech booth.

Unfortunately,
it's a bit premature:

the technical challenges remain tremendous.

Just to pick one example: *waste heat*.

Those GaN transistors I told you about, efficient though they might be, get *very* hot.

And now we want to put them close to,
very close to, digital silicon transistors that don't like to get so warm.

We will therefore need aggressive means of conducting and removing heat on distance scales all the way down to the scale of the transistors.

The problem we face is how to build the thermal management of electronics *right into* our dense heterogeneous structures.

With your help, though, we *will* solve this and the many other technical problems that lie ahead.

We *will* realize the
MTO Phone.

And in doing so,
we *will* achieve the RF convergence revolution: *3D integration on extremely small distance scales of the best materials and analog and digital device technologies to achieve radical gains in function and performance.*

And now, I'd like to introduce another true revolutionary –
a guy who has *already* placed *his* advance order for an MTO Phone –
the Deputy Director of MTO, Dr. Dean Collins…