Waveguide-based Spatial Combiners

Beyond the 100 Watt X-band System

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Program Goal

Broadband High-Power Sources

• Spatial Power Combining
  - integration of a large number of amplifiers

• Broadband Characteristics
  - passive structure design
  - active circuit design

• Appropriate Thermal Management
  - test fixture design
Power-Added Efficiency of Combiner Systems

Single Amplifier Cell

\[ \eta = \frac{P_{oa} - P_{ia}}{P_{dca}} = \frac{(G - 1)P_{ia}}{P_{dca}} \]

N-way Combiner System

\[ \eta_{sys} = \frac{P_o - P_i}{P_{dc}} = \frac{(L_i G L_o - 1)P_i}{N P_{dca}} = \frac{(L_i G L_o - 1)}{L_i (G - 1)} \eta_a \]

\[ \eta_{sys} \rightarrow \eta_a L_o \text{ for high gain} \]
N-way Combiner System with Pre-Amp

\[ \eta_{\text{sys}} = \frac{P_o - P_{ip}}{P_{dc}} = \left( \frac{NP_{dca}}{NP_{dca} + P_{dcp}} \right) \left( \frac{G_p L_i G L_o - 1}{G_p L_i (G - 1)} \right) \eta_a \]

Conclusions:
→ Output losses alone determine ultimate performance of a combiner
→ Input losses can be overcome by pre-amplification
When does it make sense to use a spatial combiner?

Combining efficiency:
- **Binary Wilkinson tree**, $\eta = L^k$, where $L =$ loss per stage, $k =$ number of stages
- **Spatial combiner**: $\eta = L_0$ (independent of number of amplifiers)

Typical numbers at X-band:
- **Corporate**: 0.15 dB loss/stage
- **Spatial**: 0.5 dB output loss
- Transition point: $N \approx 16$

Using general expression for system PAE shown earlier:
Assumes: $G = 10$, $\eta_a = 50\%$
Guided-Wave Spatial Combiner

- Broadband antenna arrays
- Waveguide environment
- Slotline-to-microstrip transition
- Off-the-shelf MMIC amplifiers
- Hybrid circuit configuration
- Ceramic substrate with good thermal conductivity

*US Patent: 5,736,908 Awarded April 7, 1998 (University of California)*
MMIC-based approach
Spec Ref: www.ti.com/mgp

- 6.5 to 11.5-GHz Frequency Range
- 5-Watt Output Power at 7V, 6-Watt at 8V, 8-Watt at 9V Bias
- 19-dB Typical Small Signal Gain
- 40% Power Added Efficiency at 7V, 35% PAE at 9 Volt Bias
- 12-dB Typical Input Return Loss, 9-dB Typical Output Return Loss
- On-chip Active Bias Circuit Option Simplifies Biasing

We wish to acknowledge the generous support of TriQuint/TI in providing a large quantity of these excellent devices at a substantial discount to the University and MAFET project
8-MMIC (4 tray) Combiner


- **CW Operation (2x4 Array)**
- **Pout, max = 42.9W**
- **Combining Efficiency ≈ 70%**
- **Gain = 15.1 ± 1.2dB @ 2dB Gain Compression**

Primary Sponsorship through DARPA MAFET
**Preliminary Results using 8 MMIC (4-tray) Array Configuration**

- **Return Loss < -10dB**
- **Psat = 43.1W at 8.7GHz**
- **Linear Gain = 18.2dB**
- **Graceful Degradation**

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**Return Loss Measurement**

- **Gain, linear = 18.2dB**
- **Psat = 43.1W**

**Pout vs. Pin Measurement**

- **Graceful Degradation**
• **MMIC amplifier mounted on metal carrier**
• **Elevated temperature degrades power performance**
• **About 8% reduction in output power when temperature rose from 43° to 70°C**
Analytical Approach

*EM Modelling codes are important for design verification, but are not well suited to design*

UCSB/HRL Approach for design optimization:

- Apply/extend analytical “Theory of small reflections” and Klopfenstein taper to *non-TEM* finline structures
- Analyze and establish relationships between propagation constants and geometric parameters of finline array using Itoh’s Spectral Domain Method
- Combine the above to determine the physical layout of the taper and associated transitions
Design of Finline Arrays

- Target slotline gaps are specified at both ends
- Operating band is specified
- Taper length and shape optimized to minimize return loss over the band

Complication:
wave impedances and propagation constants are all functions of frequency. Standard taper theory is based on TEM guides.
For a gradual impedance taper of length $L$ on a non-TEM structure, the input reflection coefficient is given by,

$$
\Gamma_{in}(f) = \frac{1}{2} \int_{0}^{\theta} e^{-j\theta} \frac{d}{d\theta} \ln \frac{Z(\theta)}{Z_0} d\theta
$$

with

$$
\theta(f, z) = \int_{0}^{z} 2\beta(f, z') dz'
$$

$\theta(f, z)$ is the round-trip phase delay to a point $z$ along the taper

and $\theta_t = \theta(f, L)$

To maintain an input reflection coefficient to be less than $G_m$ in the passband, the wave impedance $Z(\varphi)$ must take the form,

$$
\ln \frac{Z(\varphi)}{Z_0} = \frac{1}{2} \ln \frac{Z_L}{Z_0} + \Gamma_m A^2 F(2\theta/\theta_t, -1, A) \quad \text{with} \quad F(x, A) = \int_0^x \frac{I_1(A\sqrt{1-y^2})}{A\sqrt{1-y^2}} dy
$$

$G_m$ is the maximum allowable reflection coefficient over the passband and 

$$
A = \text{Cosh}^{-1} \left( \frac{\Gamma_0}{\Gamma_m} \right) \quad \text{defines the passband, where } bL > A
$$

Design Procedure

- Propagation constant is determined, as a function of the position along the taper, through an iterative process
- Wave impedances are used in place of characteristic impedance
- TE mode is assumed for wave propagating on finline structure

\[
\beta(f_0, z) = \sqrt{\beta_L \beta_0} \exp[-\Gamma_m A^2 F(2\theta(f_0, z) / \theta_t - 1, A)]
\]

\[
\theta(z_i) \approx \sum_{k=0}^{i-1} 2\beta(z_k) \Delta z = \theta(z_{i-1}) + 2\beta(z_{i-1}) \Delta z
\]

\[
\theta_t = \int_0^L 2\beta(f, z')dz'
\]

where \( \beta_L \) and \( \beta_0 \) correspond to \( Z_L \) and \( Z_0 \), and \( \beta = \frac{\omega \mu}{Z_{TE}} \)
Spectral Domain Method

- Used to establish the relationship between propagation constant and geometrical parameters of finline structure
- Integral equations set up for calculating propagation constant and solved by moment method

Electric field profile

Two Card System
Computational Results

- 2x2 finline array in standard WR-90 waveguide
- Propagation constant (effective permittivity) calculated for expected slot widths and frequencies using SDM
- Optimized taper designed for $S_{11} < -20$dB from 8-12 GHz

Theory assumes taper is matched
Need to know target slot-line characteristic impedance
• 2x2 finline array in WR-90 waveguide
• Propagation constant (effective permittivity) calculated for expected slot widths and frequencies using SDM or FD
• Optimized taper designed for $S_{11} < -20$ dB from 8-12 GHz
Return Loss Measurements

- Taper designed for 2-card system
- Characteristic impedance of final slot is evidently \(~100\Omega\).
- Return loss <-19dB for X-band for 2-card system, < -16dB for 4-card array.
Simulation vs. Measurement

- Theoretical and measured results agree quite well
- Suggests additional impedance transformation needed for 50Ω MMIC amplifiers

Slotline Antenna with Microstrip Taper

- Microstrip transformer terminated with 50Ω chip resistor
- Return loss <-15dB for X-band for 2-card system
Circuit Topology

- Modular Tray Architecture
- Excellent Thermal Property
- High Power Performance
- Broadband Characteristics

- Ease of Operation & Maintenance
- MMICs Directly Attached to Test Fixture
- Capability for Large Scale Integration
- Adapt to Different Device Technology
Copper carrier, 24 elements (120 W)
Four (4) 5-Watt MMICs per tray

Results from *Tanner* Thermal Simulator

- More cards in standard aperture → *thinner cards*
- Copper fixture doubles thermal capacity
- Air-cooled heatsink system will be employed
New Antenna Card Design

MMICs & Bypass Capacitors

Antenna

Broadband Impedance Transformers
Passive Measurement (6x4 Array)

- Antenna structure scaled from previous design
- Characteristic impedance at slotline: $70\Omega$
- Return loss < -10dB for X-band for 6-tray system

![Graphs of Return Loss vs. Frequency]

- Antenna Only
- 70\Omega Termination

- Antenna w/ transformer
- 50\Omega Termination

![Graphs of Return Loss vs. Frequency]
Preliminary Results using 24 MMIC (6-tray) Array Configuration

- CW Operation (6x4 Array)
- 4 MMICs on each tray
- $P_{out, \text{max}} = 126\,\text{W at 8.1GHz}$
- $Gain = 11.2 \pm 1.9\,\text{dB (8-11GHz)}$
- $V_d = 8.0\,\text{V, } P_{in} = 38\,\text{dBm}$
Recent Results

Preliminary Results using 24 MMIC (6-tray) Array Configuration

- 4x6 Array (CW Operation)
- Average $P_{dc} \approx 250$ W
- Average $I_d \approx 45$ A
- PAE $\approx 13 - 34\%$
- Graceful Degradation (8.1 GHz)
HRL pHEMT Based Combiner

- pHEMT MIC power amplifiers
- 1x4 Array (CW Operation)
- Return loss for passive structure better than -15 dB
- $P_{out,max} \cong 3.2$ W at 9.75 GHz
Waveguide Combiners

- Broadband antenna arrays
- Waveguide environment
- Slotline-to-CPW line transition
- Off-the-shelf MMIC amplifiers
- Hybrid circuit configuration
The oversized waveguide opening has the dimension of 2cm x 0.7cm, which allows TE_{10}, TE_{20}, and TE_{30} modes to propagate.
Passive Card Design and Verification

- Taper length and shape optimized for 40% bandwidth and low loss.
- The Slotline was terminated to a 50Ω CPW line using slot-to-cpw transition.

![Diagram with components labeled: Air bridge, Add ground plane, Terminating resistor.](image)

![Graph showing return loss in dB against frequency in GHz.](image)
Path to Broadband Power

• High efficiency favors small-area devices
  *Heat removal (see empirical chart)*

• Broad bandwidth favors small-area devices
  *Small Cgs and high output impedance*

• Lower phase noise favors large number of devices
  *Excess phase noise goes as 1/N*

**Conclusion:**

*Use a large number of small devices for broadband power*

*Efficient broadband combining of many devices favors spatial combining*
**K-band SSPA Benchmark Data**

Source: Mike Delaney, Hughes Space & Communications, El Segundo, CA

### 18 GHz Power Devices: Industry Comparison

![Graph showing industry comparison of 18 GHz power devices. The graph plots power added efficiency (%) against output power (Watts). The data points represent different manufacturers and technologies, such as HRL K4 (Amplifier), HRL K4 (Load Pull), HRL K3, TRW, Martin Marietta, Avantek, and MIT. A trend line indicates the 1996 industry trend.](image-url)

- **HRL K4 (Amplifier)**
- **HRL K4 (Load Pull)**
- **HRL K3**
- **TRW**
- **TI**
- **Martin marietta**
- **Avantek**
- **MIT**
Phase Noise in Combiners

- Broadband Splitter/Combiner

\[ s_{ij} = \frac{1}{\sqrt{N}} \quad \text{for} \quad i \neq j \]

- Consider only near-carrier phase noise

\[ A_{in} = A \cos(\omega t + \delta \theta_{in}) \]

\[ a_{in,i} = \frac{A}{\sqrt{N}} \cos(\omega t + \delta \theta_{in}) \]

\[ b_{out,i} = \frac{AG}{\sqrt{N}} \cos(\omega t + \delta \theta_{in} + \delta \phi_{i}) \]

\[ \delta \theta_{in}(t) \equiv \text{input noise fluctuation} \]

\[ \delta \phi_{i}(t) \equiv \text{amplifier noise contribution} \]

\[ \delta \theta_{out}(t) \equiv \text{total output noise fluctuation} \]
A closer look at output noise:

\[ B_{out} = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} b_{out,i} \]

Sum all amplifier outputs through combiner

\[ = \frac{AG}{N} \sum_{i=1}^{N} \cos(\omega t + \delta\theta_{in} + \delta\phi_i) \]

Assume small fluctuations

\[ = \frac{AG}{N} \left\{ N \cos(\omega t) - \sum_{i=1}^{N} (\delta\theta_{in} + \delta\phi_i) \sin(\omega t) \right\} \]

Noisy output signal

where:

\[ \delta\theta_{out} = \delta\theta_{in} + \frac{1}{N} \sum_{i=1}^{N} \delta\phi_i \]

Total output noise fluctuation in terms of input noise and individual amplifier contributions
“Output Noise” is noise power spectral density defined as:

\[ \langle |\delta \tilde{\theta}|^2 \rangle = \langle \delta \tilde{\theta}^* \delta \tilde{\theta} \rangle \]

Ensemble average

\[ \delta \tilde{\theta} \]

Fourier transform

Assume input noise and amplifier noise contributions are uncorrelated:

\[ \langle \delta \tilde{\theta}_{in}^* \delta \tilde{\phi}_i \rangle = 0 \quad \text{for all } i, \quad \langle \delta \tilde{\phi}_i^* \delta \tilde{\phi}_j \rangle = 0 \quad \text{for } i \neq j \]

Excess noise from each amplifier is:

\[ \langle |\delta \tilde{\phi}|^2 \rangle \]

Output noise is then:

\[ \langle |\delta \tilde{\theta}_{out}|^2 \rangle = \langle |\delta \tilde{\theta}_{in}|^2 \rangle + \frac{1}{N} \langle |\delta \tilde{\phi}|^2 \rangle \]

Noise contributed by the ensemble is reduced by 1/N compared with a single amplifier.
Coaxial Combiner System

- Antennas uniformly loading an oversized coaxial (TEM) waveguide
- Array is uniformly illuminated
- No low-frequency cutoff: bandwidth limited by finline transitions
- Accommodates large numbers of amplifiers
- Electrically and thermally symmetrical
5-15 GHz Coaxial Array

- 32 Card System, 2 transitions per card (**64-way splitter/combiner**)
- Broadband coaxial tapers cover 2-20GHz
- AlN-based slot tapers cover 5-18GHz range

Front view of loaded section  Exploded perspective
32 Card (64-Way) Response

- 64-way splitter/combiner system
- 1-2 dB insertion loss over 5-20GHz range
- some suppression of high-order modes
- Need to improve impedance match
- cards introduce <1dB loss
## Performance Predictions

**Combiner Module**

- 6-card (24 MMICs)
- 70% C.E.

**Note:** CW Power

### Combiner Module Dimensions

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<tr>
<th><strong>Combiner Module</strong></th>
<th><strong>GaAs</strong></th>
<th><strong>GaN</strong></th>
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<tbody>
<tr>
<td>6-card (24 MMICs)</td>
<td>5 Watt MMIC, 20% PAE</td>
<td>20 Watt cell, 40% PAE</td>
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<tr>
<td></td>
<td>25°C base temp</td>
<td>25°C base temp</td>
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<tr>
<td></td>
<td><strong>100 Watts</strong></td>
<td><strong>400 Watts</strong></td>
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<td></td>
<td>(38 W/cm², 4 W/cm³)</td>
<td>(150 W/cm², 16 W/cm³)</td>
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<tr>
<td><strong>Ku-band</strong></td>
<td>1.5 Watt MMIC, 20% PAE</td>
<td>6 Watt MMIC, 40% PAE</td>
</tr>
<tr>
<td></td>
<td>25°C base temp</td>
<td>25°C base temp</td>
</tr>
<tr>
<td></td>
<td><strong>25 Watts</strong></td>
<td><strong>100 Watts</strong></td>
</tr>
<tr>
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<td>(50 W/cm², 12 W/cm³)</td>
<td>(200 W/cm², 52 W/cm³)</td>
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- Area $\propto \lambda^2 / 8$
- Volume $\propto \lambda^3 / 4$
UCSB MURI Effort

Enclosure
- thermal management
- modeing

Antennas
- Impedance matching
- Field distribution

20 GHz in

Tripler Array
- bandwidth
- efficiency

60 GHz out

Amplifier array
- power
- bandwidth
- efficiency
- stability
Summary

- High power, broadband spatial combiners demonstrated at X-band
- Optimization procedure and numerical code for finline arrays has been developed
- K-band system in development using oversized waveguide
- Passive system with 5-18GHz bandwidth demonstrated in oversized coax with 64 channels
- Noise, Combining efficiency, PAE, bandwidth, graceful degradation issues have been explored