High Power Millimeter Wave Grid Array Sources*

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A novel, broadband quasi-optical frequency multiplier system has been designed, simulated and fabricated for high efficiency, high power millimeter wave applications. Initial proof-of-principle doubler and tripler systems are being tested using a conventional 10 W Ka-band TWT as the driver. Preliminary results have achieved > 6.7% and > 3.4% efficiency, respectively, and generated > 410 mW output power at V-band and > 148 mW output power at W-band with tunable bandwidths of 6.6 GHz and 0.5 GHz, respectively. Larger arrays have been designed, fabricated and are presently under test. These arrays will be driven by an 80 W Ka-band TWT and are expected to achieve 20% efficiency and 16 W output power at V-band and 10% efficiency and 8 W output power at W-band. The long-term goal of this research is a high power source using a Millimeter Wave Power Module (MMPM) driver (100 W output power). This is predicted to produce > 20 W cw output power at V-band or > 10 W cw output power at W-band, and to offer dramatic savings in size, weight and cost as compared to conventional coupled-cavity TWT sources.

* This work has been supported by the US AFOSR under MURI '95 (Contract No. F49620-95-1-0253) and MURI '99 (Contract No. F49620-99-1-0297) and by the US DOE (Contract No. DE-FG03-95ER54295).


Introduction and Motivation

- Low cost, high power, compact millimeter-wave sources are needed.
  - Solid-State: Low cost and compact, but low power or low frequency.
  - Electron Beam Devices: High power and high frequency, but become expensive and bulky at high frequencies.
  - Both technologies can provide inexpensive and moderately compact high power sources at low frequencies.

- High power microwave sources are available.
  - Frequency Multipliers efficiently convert microwaves into millimeter-waves.
  - Quasi-Optical Grid Arrays use quasi-optical power combining to achieve high power handling (>100 W) with inexpensive solid-state devices in extremely compact (< 5 in³) and extremely lightweight (< 2 lb.) systems.
  - Overmoded waveguide mounting structures permit larger, more efficient and higher power quasi-optical grid arrays.

- Frequency Multiplier Grid Arrays create inexpensive, compact, high power systems by converting high power low frequency sources into high power high frequency sources.
  - Simulations predict a Frequency Multiplier Grid Array based source capable of generating > 16 W at V-band and > 8 W at W-band (when driven by a 80 W source).
Project Overview

- The prototype systems currently being fabricated and tested are designed to explore the basic physics of frequency multiplier grid arrays in overmoded waveguides.
  - Initial proof-of-principle prototype systems driven by a pulsed 10 W TWT have achieved excellent preliminary results.
  - New wafer designs currently being fabricated explore physics of grid array unit cell dimensions and varactor device layout.
  - New fixture designs reduce losses inherent in current biasing techniques (doublers).
  - New filter/matching techniques and designs are being fabricated and tested.
- The next stage in development explores the challenges of increased drive power.
  - Larger arrays will be fabricated to handle higher input powers.
  - Heat generation by the array will be measured and heat dissipation systems designed and evaluated.
  - EM simulations and experiments will be performed to evaluate the effects and optimize the performance of significantly overmoded waveguides.
  - New fixtures will be fabricated to incorporate the results of these experiments and new designs.
- The long-term goal of this project are high power cw sources.
  - High output powers: > 20 W at V-band and > 10 W at W-band.
  - High multiplication efficiencies: > 20% for doublers and > 10% for triplers.
  - Broadband: Tunable bandwidths of 60 - 70 GHz and 90 - 110 GHz.
# State-of-the-Art in Moderate/High Power Frequency Multipliers

<table>
<thead>
<tr>
<th>Author</th>
<th>Devices</th>
<th>Harmonic</th>
<th>Output Frequency</th>
<th>Output Power</th>
<th>Efficiency</th>
<th>Array Size (devices)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jou</td>
<td>Schottky varactors</td>
<td>2x</td>
<td>66 GHz</td>
<td>500 mW</td>
<td>9.5 %</td>
<td>760</td>
</tr>
<tr>
<td>Qin</td>
<td>BNN</td>
<td>2x</td>
<td>66 GHz</td>
<td>2.1 W</td>
<td>7.5 %</td>
<td>1760</td>
</tr>
<tr>
<td>Liu</td>
<td>SQBV</td>
<td>3x</td>
<td>99 GHz</td>
<td>5 W</td>
<td>2 %</td>
<td>3100</td>
</tr>
<tr>
<td>Rahal <em>et al.</em></td>
<td>MSQBV</td>
<td>3x</td>
<td>93 GHz</td>
<td>91 mW</td>
<td>10 %</td>
<td>1 (waveguide)</td>
</tr>
<tr>
<td>Staecker, <em>et al.</em></td>
<td>ISIS</td>
<td>2x</td>
<td>88 GHz</td>
<td>280 mW</td>
<td>14 %</td>
<td>1 (whisker contacted)</td>
</tr>
<tr>
<td>Crowe <em>et al.</em></td>
<td>Schottky varactors</td>
<td>2x</td>
<td>262 GHz</td>
<td>10 mW</td>
<td>24 %</td>
<td>1 (whisker contacted)</td>
</tr>
<tr>
<td>Rosenau</td>
<td>Schottky varactors</td>
<td>2x</td>
<td>66 GHz</td>
<td>410 mW</td>
<td>6.7 %</td>
<td>56</td>
</tr>
<tr>
<td>Rosenau</td>
<td>SQBV</td>
<td>3x</td>
<td>96 GHz</td>
<td>77 mW</td>
<td>2.4 %</td>
<td>250</td>
</tr>
<tr>
<td>Rosenau</td>
<td>MQBV</td>
<td>3x</td>
<td>90 GHz</td>
<td>148 mW</td>
<td>3.4 %</td>
<td>270</td>
</tr>
</tbody>
</table>

**Goals:**
- 20 W, 20 %, 2100 dev.
- 10 W, 10 %, 6150 dev.
Varactor Grid Arrays

- Frequency multiplier grid arrays are composed of arrays of varactor devices.
- Frequency doublers use biased single sided devices: Schottky, BNN, RTD or other varactor devices.
- Frequency tripler grid arrays use un-biased devices with symmetric dc characteristics: back-to-back arrays of MQBV, SQBV, SSQBV or other QBV devices.
Quasi-Optical Frequency Multiplier Grid Arrays

- Overmoded waveguide is employed to reduce diffraction losses, contain input and output signals and provide a mounting structure for quasi-optical grid array elements.
- Quasi-Optical Grid Array elements include:
  - Varactor Grid Array, to provide frequency multiplication
  - Filters, to isolate input and output signals
  - Matching Networks, to impedance match waveguide to GaAs based array
  - Heat Spreader, to remove heat to waveguide walls for dissipation outside the system
Overmoded waveguide is employed to reduce diffraction losses, contain input and output signals and provide a mounting structure for quasi-optical grid array components.

Broadband quasi-optical filters have been developed and are in use. New filter design techniques are currently being investigated.

High power, cw operation planned using advanced cooling systems like the CVD diamond heat spreader shown above.
Incident power in a metal waveguide follows a $\sin^2$ distribution across the long dimension.

Varactor device performance varies with incident power, resulting in reduced efficiency.

Alternative waveguides offer potential solutions:

- photonic band gap (PBG) materials
- dielectric-loaded waveguide
- metal disk-loaded waveguide

Dielectric-loaded waveguide with fundamental mode ($\text{LSE}_{10}$) electric field profile.
Schottky Varactor Devices

- Frequency doubler grid arrays using Schottky varactors fabricated by Martin-Marietta have been tested.
- $C_{\text{min}} = 15 \text{ fF}$, $C_{\text{max}} = 60 \text{ fF}$ resulting in $C_{\text{max}}/C_{\text{min}} = 4$
- $R_s = R_{\text{diode}} + R_{\text{strip}} = 6 \Omega$
Preliminary Frequency Doubler Results

Schottky diodes, fabricated by Martin-Marietta (Baltimore), were used in an overmoded waveguide frequency doubler grid array.

- 410 mW output power at 66 GHz
- 6.7 % efficiency at 63 GHz (reduced efficiency caused by fixturing)
- 56 devices
- 7.3 mW per device

- 6.6 GHz (10%) tuned output bandwidth
- 3.6 GHz (6%) instantaneous output bandwidth
Frequency Doubler Grid Array Designs in Fabrication

<table>
<thead>
<tr>
<th>Bias Method</th>
<th>Number of Devices</th>
<th>a/b Ratio</th>
<th>Max. Operating Frequency (GHz)</th>
<th>Fixture Waveguide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Bias Line</td>
<td>168</td>
<td>1</td>
<td>82</td>
<td>K-band</td>
</tr>
<tr>
<td>Resistor Network on Chip</td>
<td>168</td>
<td>1</td>
<td>82</td>
<td>K-band</td>
</tr>
<tr>
<td>Standard Off-Chip</td>
<td>168</td>
<td>0.5</td>
<td>82</td>
<td>Ka-band</td>
</tr>
<tr>
<td>Standard Off-Chip</td>
<td>84</td>
<td>1</td>
<td>82</td>
<td>Ka-band</td>
</tr>
<tr>
<td>Standard Off-Chip</td>
<td>140</td>
<td>1.5</td>
<td>82</td>
<td>Ka-band</td>
</tr>
<tr>
<td>Standard Off-Chip</td>
<td>136</td>
<td>1</td>
<td>103</td>
<td>Ka-band</td>
</tr>
<tr>
<td>Standard Off-Chip</td>
<td>560</td>
<td>1</td>
<td>207</td>
<td>Ka-band</td>
</tr>
</tbody>
</table>

- Two designs investigate a new method of providing bias to the array (see following viewgraph). These designs will be housed in a new, larger fixture currently being fabricated.
- Three designs vary the shape of the unit cell. This will allow experimental investigation into the physics of this aspect of grid array technology. The values a and b are the width and height, respectively, of the unit cell. Values of a/b less than one result in tall, thin unit cells, values greater than one result in short, fat unit cells.
- Two designs are have smaller dimensions. This allows higher frequency operation. In order to avoid potential grating modes caused by the diode grid, the largest grid dimension must be less than an effective half wavelength of the highest frequency signal.
New Frequency Doubler Diode Bias Techniques

- Previous arrays required $n + 1$ bias lines for an $n \times m$ array.
- Two new bias techniques both result in only two bias connections.
- Fixture provides one connection resulting in only one bias line penetrating the waveguide wall.
- Double bias line design uses two closely spaced bias lines.
- Resistor network on chip design places the resistive voltage divider on the grid array substrate.

Millimeter Wave Technology Research Group, UC Davis
The combination of novel layered semi-conductor device structures and photonic crystals, together with the newly developed microwave/millimeter wave power module (MPM / MMPM) promises revolutionary, compact high power sources in the 30-300 GHz region for next generation DoD systems.
Preliminary Frequency Tripler Results

Multiple Quantum Barrier Varactor (MQBV) devices, fabricated at Rockwell Science Center, were used in an overmoded waveguide frequency tripler grid array.

- 148 mW output power at 90 GHz
- 3.4 % efficiency (reduced efficiency due to low yield)
- 270 devices
- 0.55 mW per device

- 0.5 GHz (0.6%) tuned output bandwidth
Proof-of-principle frequency tripler grid arrays have been tested.

- A 270 device MQBV grid array fabricated by Rockwell Science Center achieved 148 mW output power and 3.4% efficiency.
- A 250 device SQBV grid array fabricated by UCD achieved 77 mW output power and 2.4% efficiency.

New designs are in fabrication with 10% predicted conversion efficiencies.

An improved varactor layout has been developed utilizing advanced fabrication techniques.

- Planarized technique improves metal layer design.
- Mesa etch improves isolation and device performance.
A new technique has been implemented which incorporates a heat spreader, output filter and output matching network in a single device. This results in reduced complexity and lower insertion loss resulting in greater efficiency of the frequency multiplier system. This structure has been implemented using an AlN heat spreader to achieve a cw frequency tripler grid array system.
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