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Power Handling of Vanadium Dioxide Metal-Insulator Transition RF Limiters

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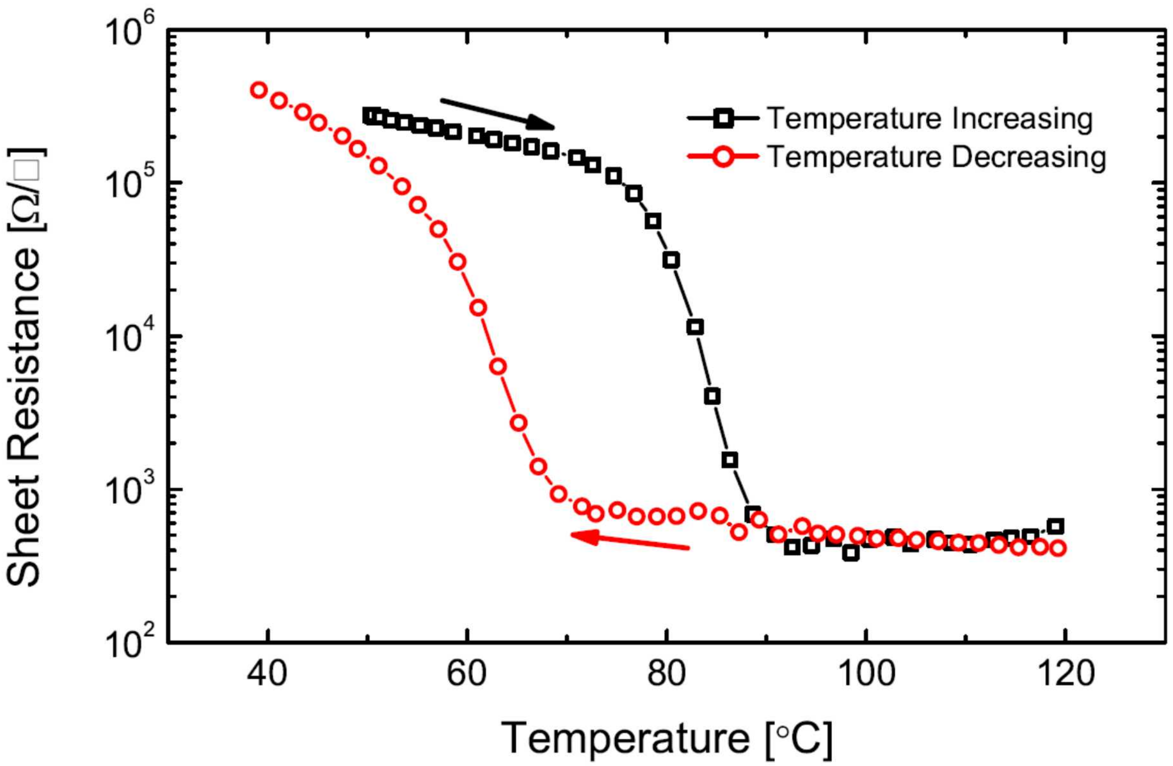
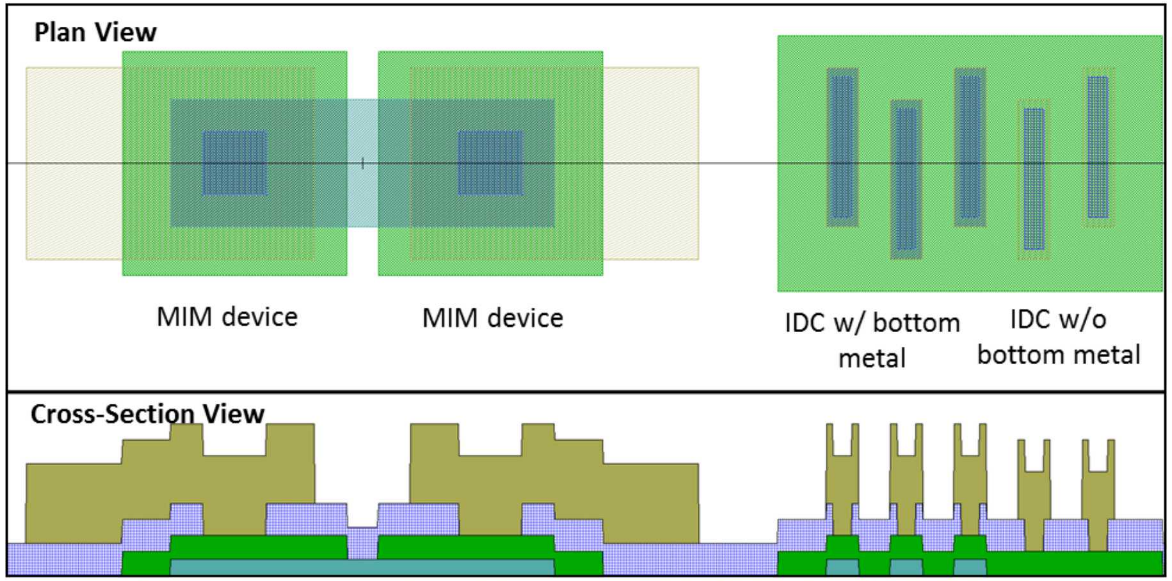
Introduction and Background

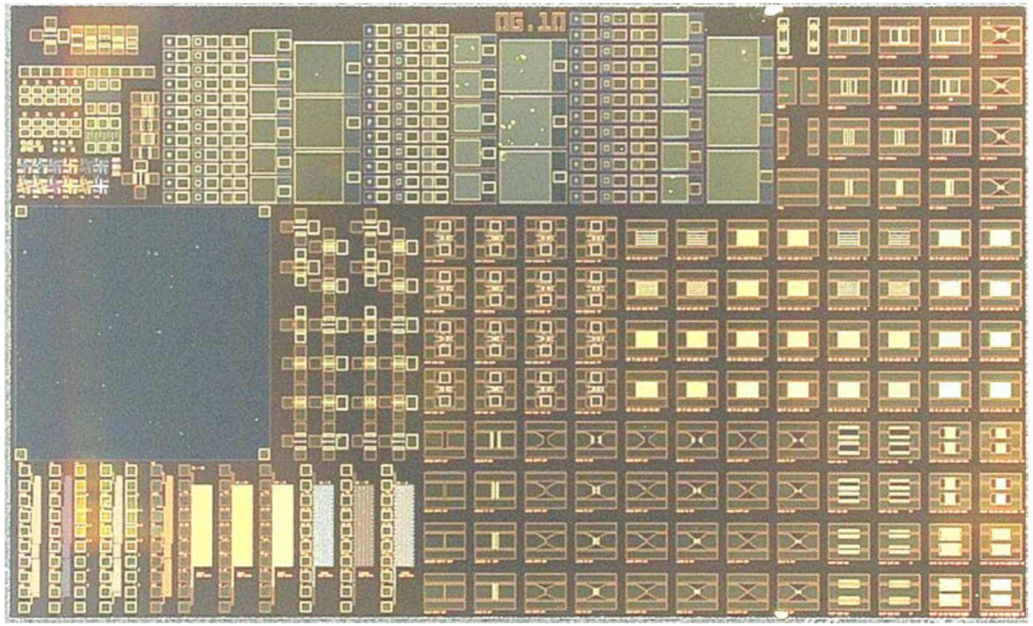
- RF limiters are required to protect sensitive receiver electronics from interferers
  - Co-site and multi-user interference: powerful Tx signals reflected back into Rx chains
  - Prevent damage to receiver components such as LNAs
- Traditional approach: Anti-parallel shunt diodes between trace and ground
  - Advantages: fast, inexpensive, commonly available
  - Disadvantages: capacitance, non-linearity, increasing leakage with power
- Proposed Approach: Metal-Insulator Transition Limiters
  - Device response is determined by R_{on}/R_{off} of temperature dependent film – broadband operation
  - "Slow" thermal response should improve linearity relative to diode limiters
- Previous related work
  - CW and pulsed power response at powers up to 4 Watts (Limoges, France)
  - Numerous two- and four- terminal switch reports with VO_2 films (TSC, U. Dayton, others)
- New contributions of this work
  - Characterization of Planar Metal-Insulator Transition Limiters to Powers > 10 Watts
  - Discussion of Failure Mechanisms

Integrated VO_2 Device Technology

- 4-mask flow allowing for top and bottom contact to VO_2 film
- VO_2 film is reactively sputtered and then annealed to achieve proper stoichiometry
- Enables fabrication on a range of substrates

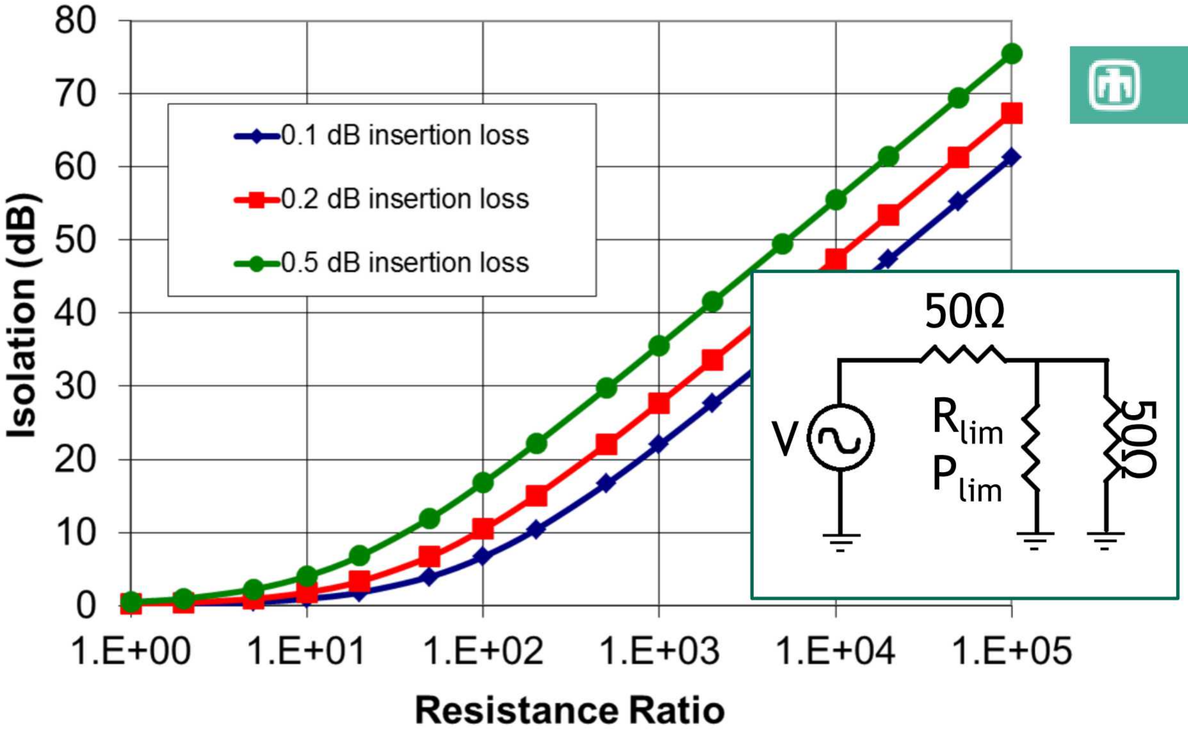




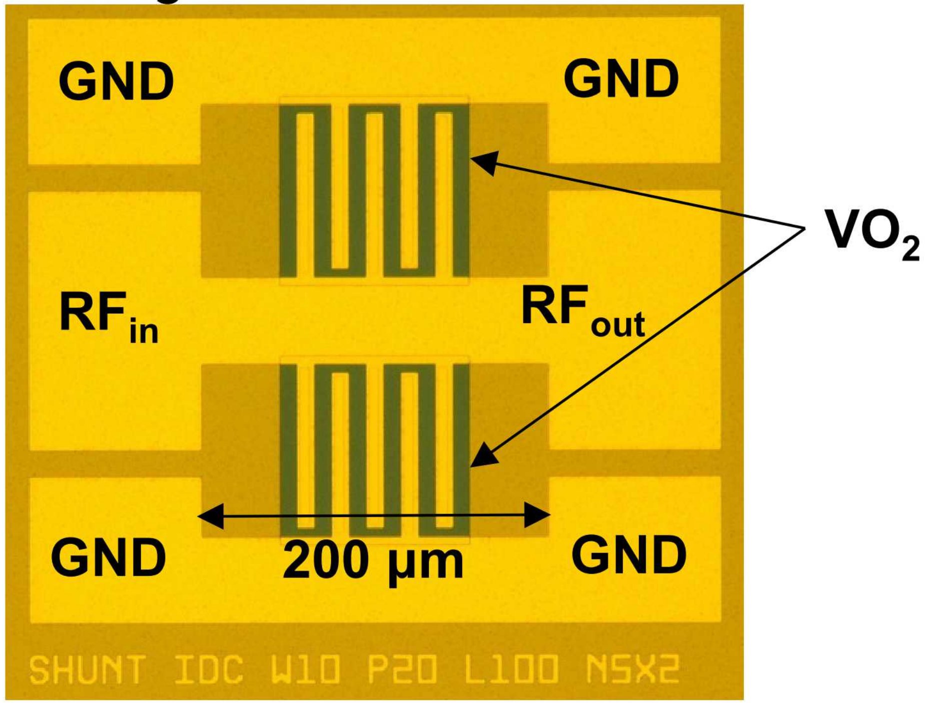


VO_2 Limiter Designs

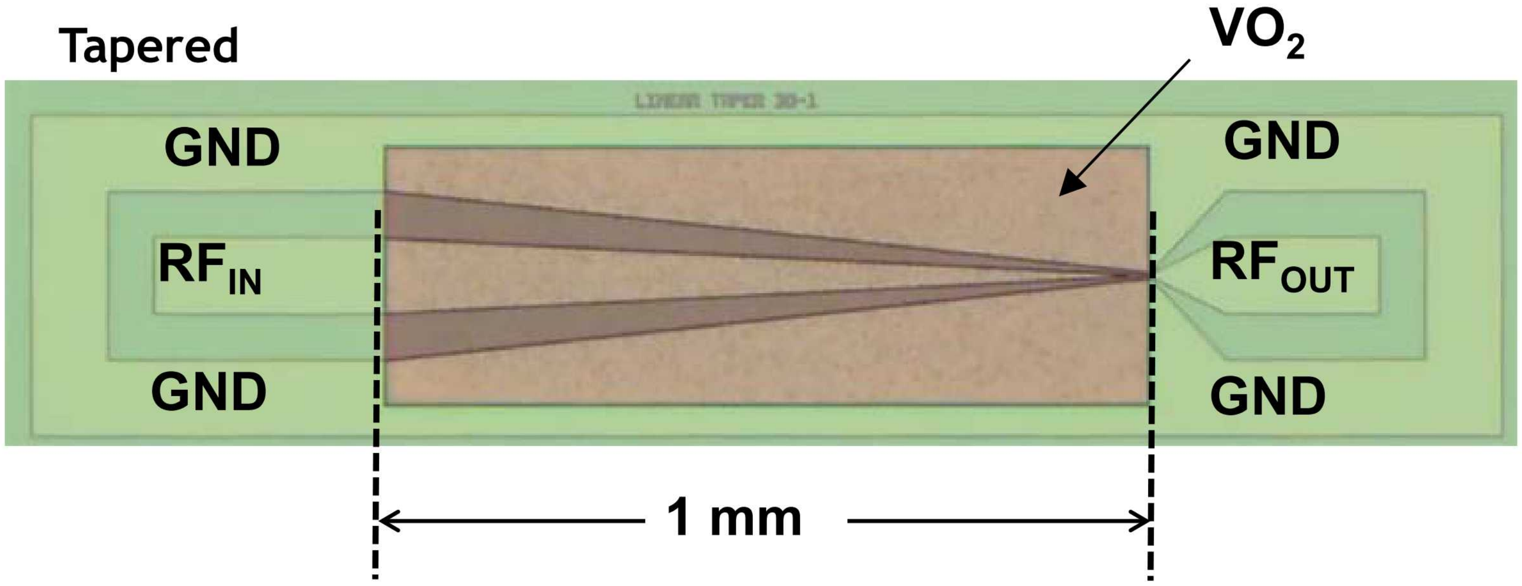
- Thermally tunable shunt resistor between the center conductor and ground
- Thermal tuning is provided by RF dissipation within the resistive film
- Resistance ratio determines insertion loss / isolation
- Current handling determines power limits



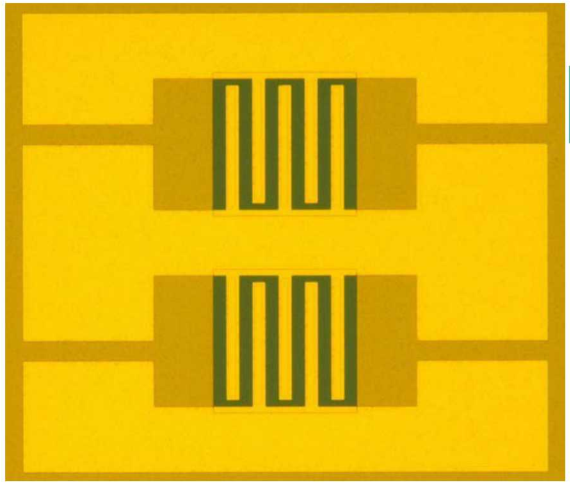
Interdigitated



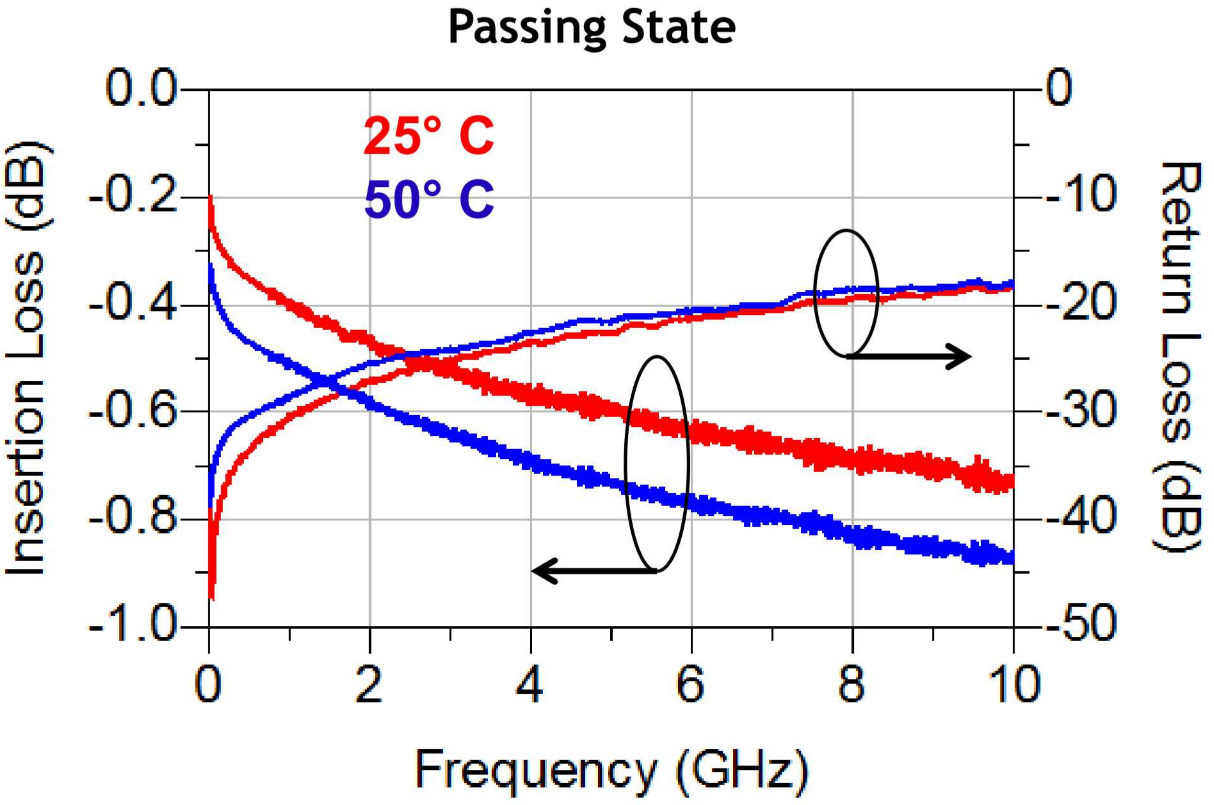
Tapered

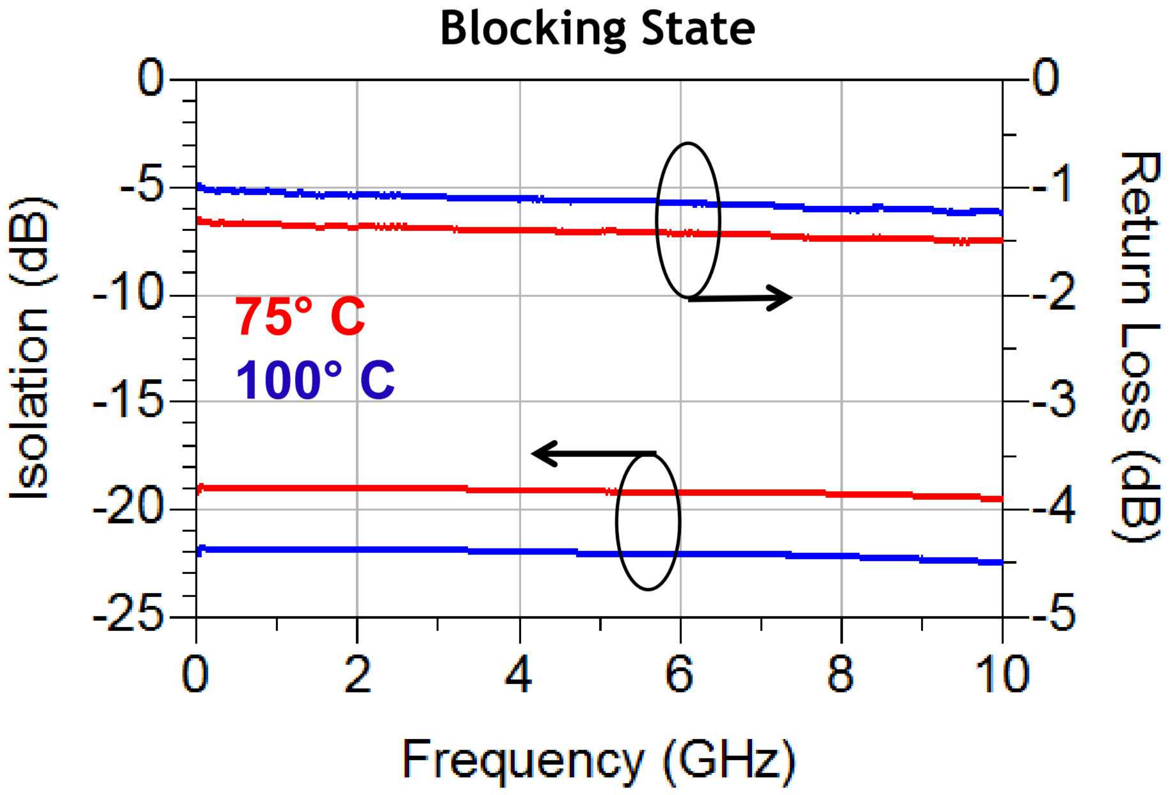


Interdigitated Limiter Response vs. Temperature



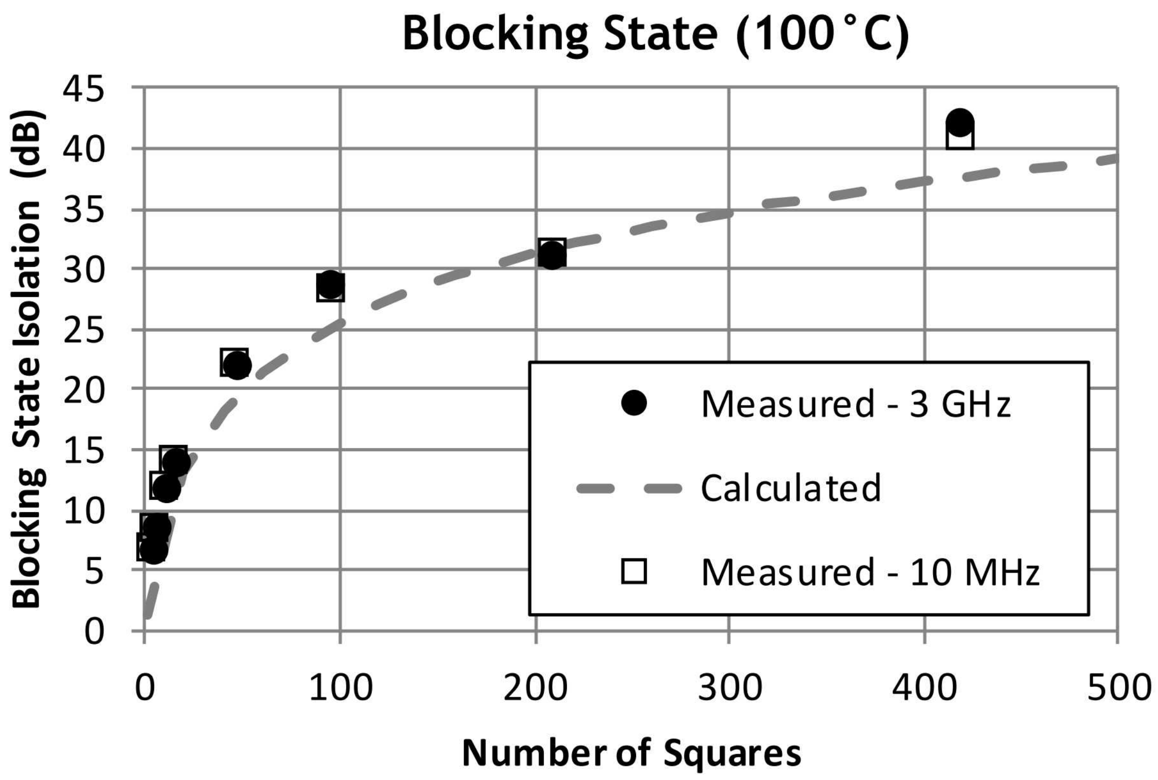
- Representative device with 48 squares of material
- Sheet resistance varies from 140 Ω/□ (100° C) to 140 kΩ/□ (25° C)
- Silicon substrate contributes 0.1-0.2 dB of loss

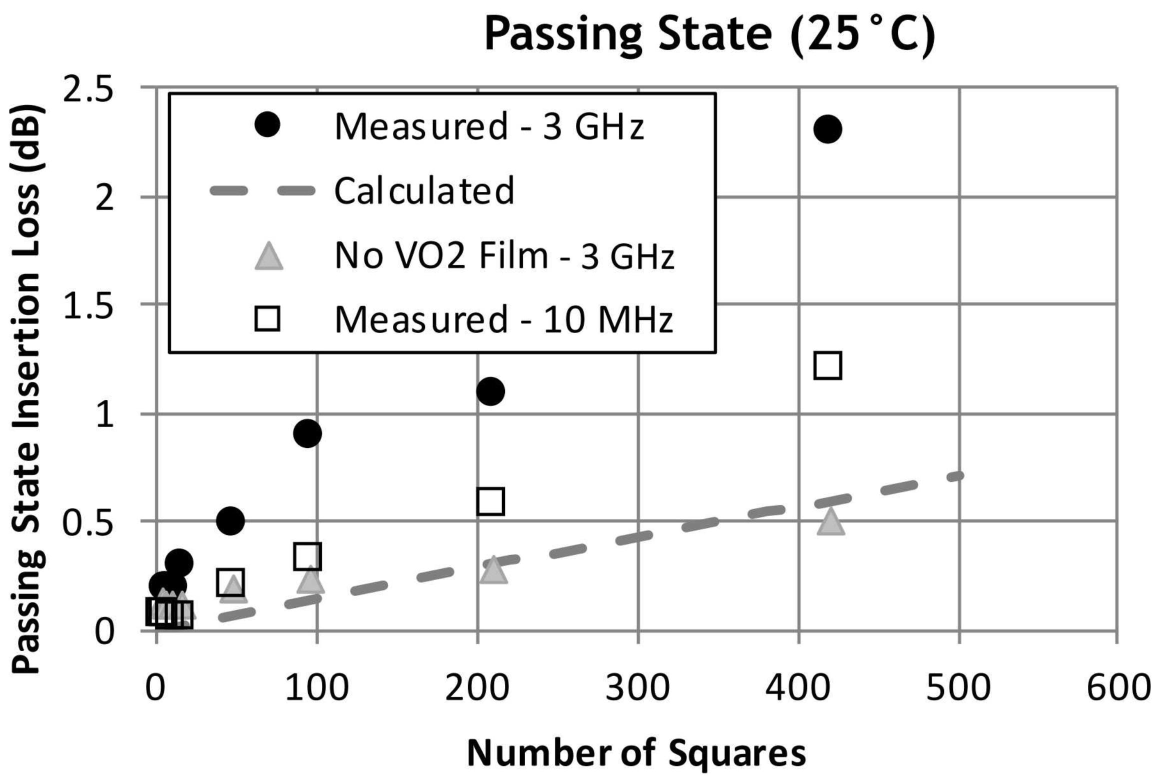




Response as a Function of Device Size vs. Temperature

- Devices range in size from ~5 squares of material to ~420 squares of material
  - Shunt resistance ranges: On-state: ~94 kΩ to ~1 kΩ, Off-state: ~94 Ω to ~1 Ω
- Isolation in blocking state matches simple prediction well and is independent of frequency
- Insertion loss in passing state higher than simple calculation and increases with frequency





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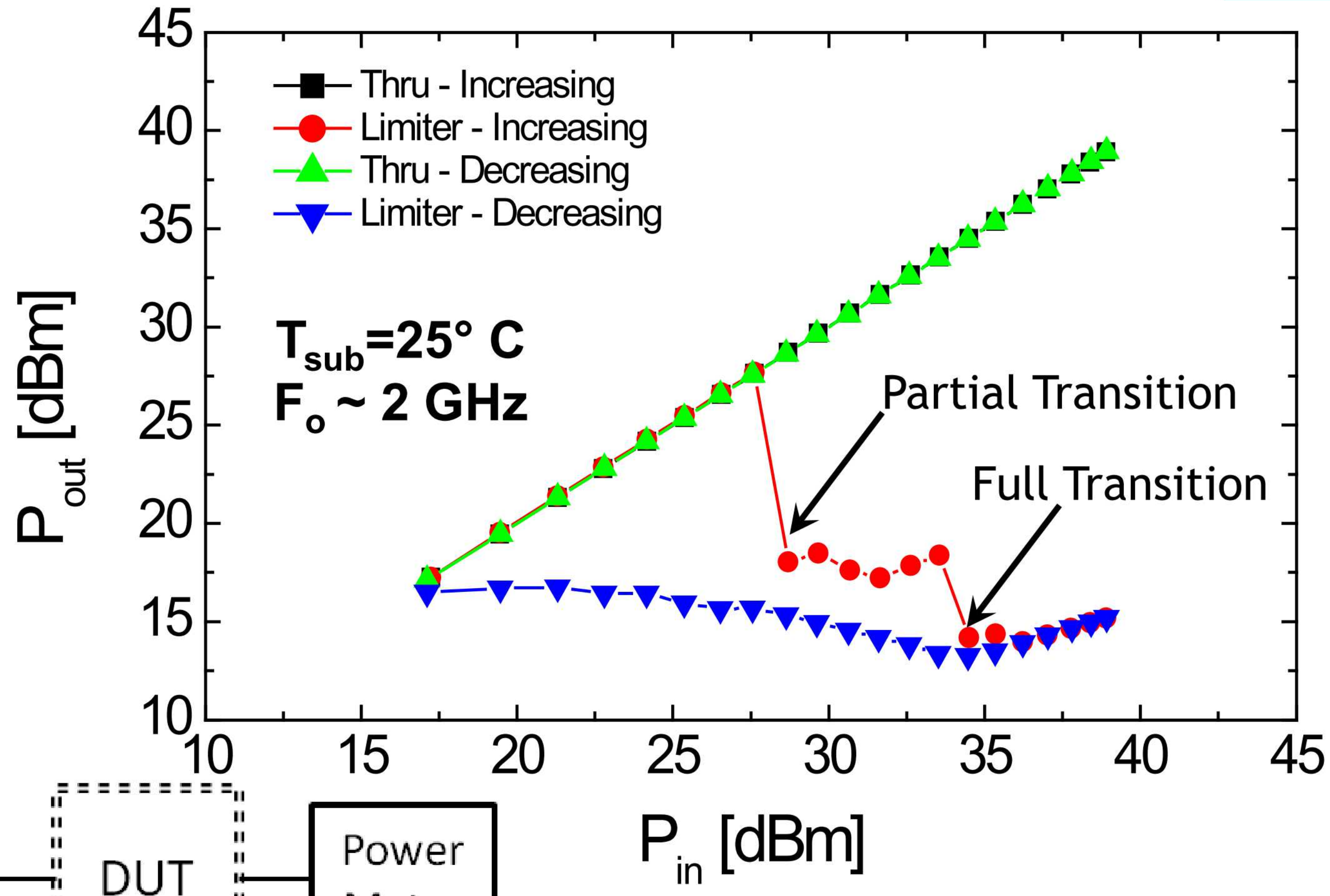
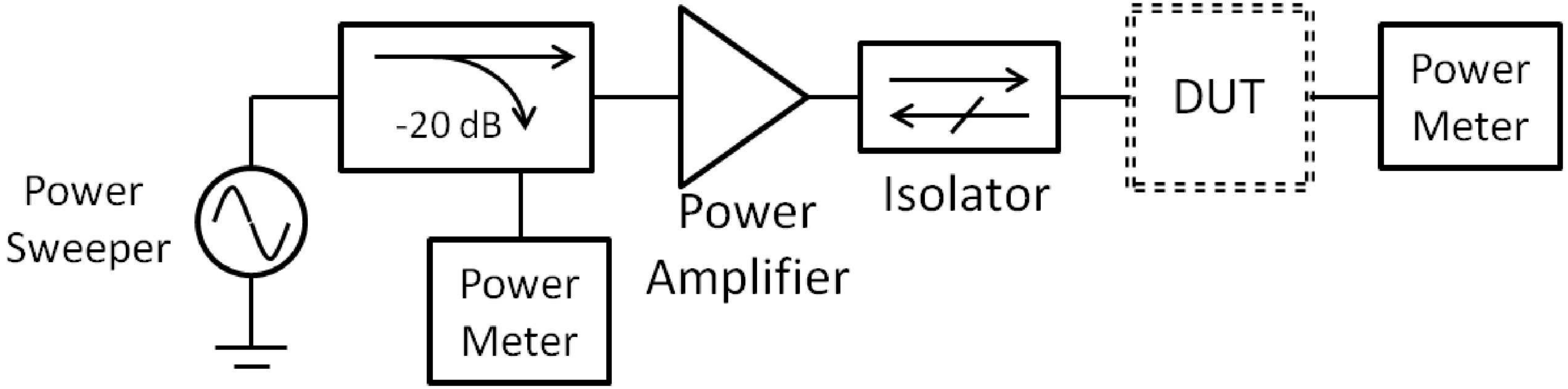
CW Power Sweep: Interdigitated Limiter

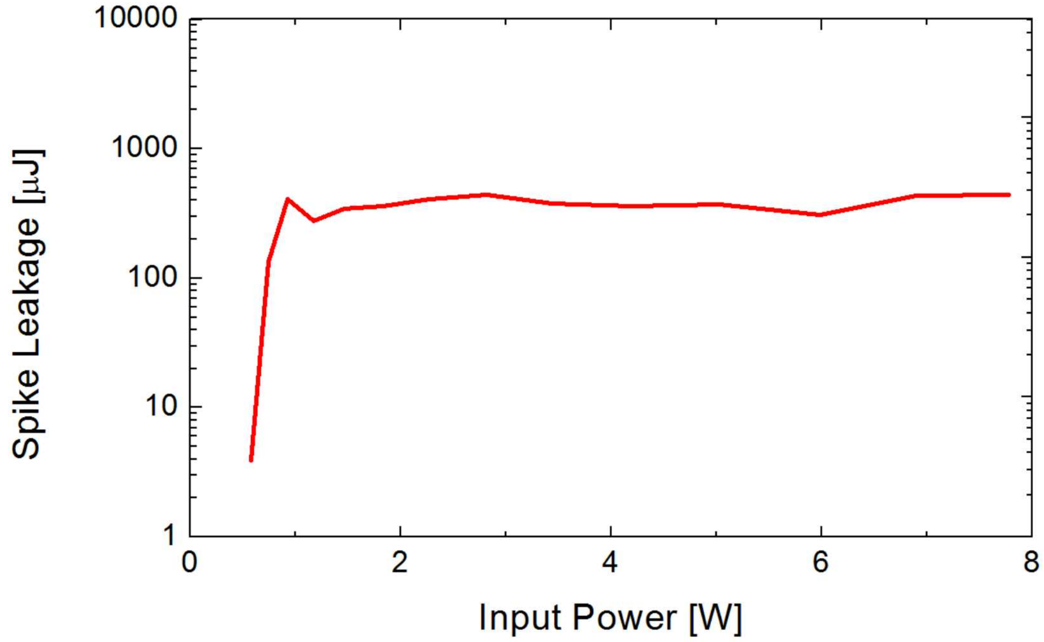
- Device Triggers in "Stages"
  - Transition at One Point Lowers Voltage Across All VO_2 Material
  - The amount of remaining material that transition depends on the VO_2 resistance and lateral vs. vertical thermal conductivity of the device
- Maximum Isolation >20 dB
  - Isolation increases with higher power
  - Flat leakage

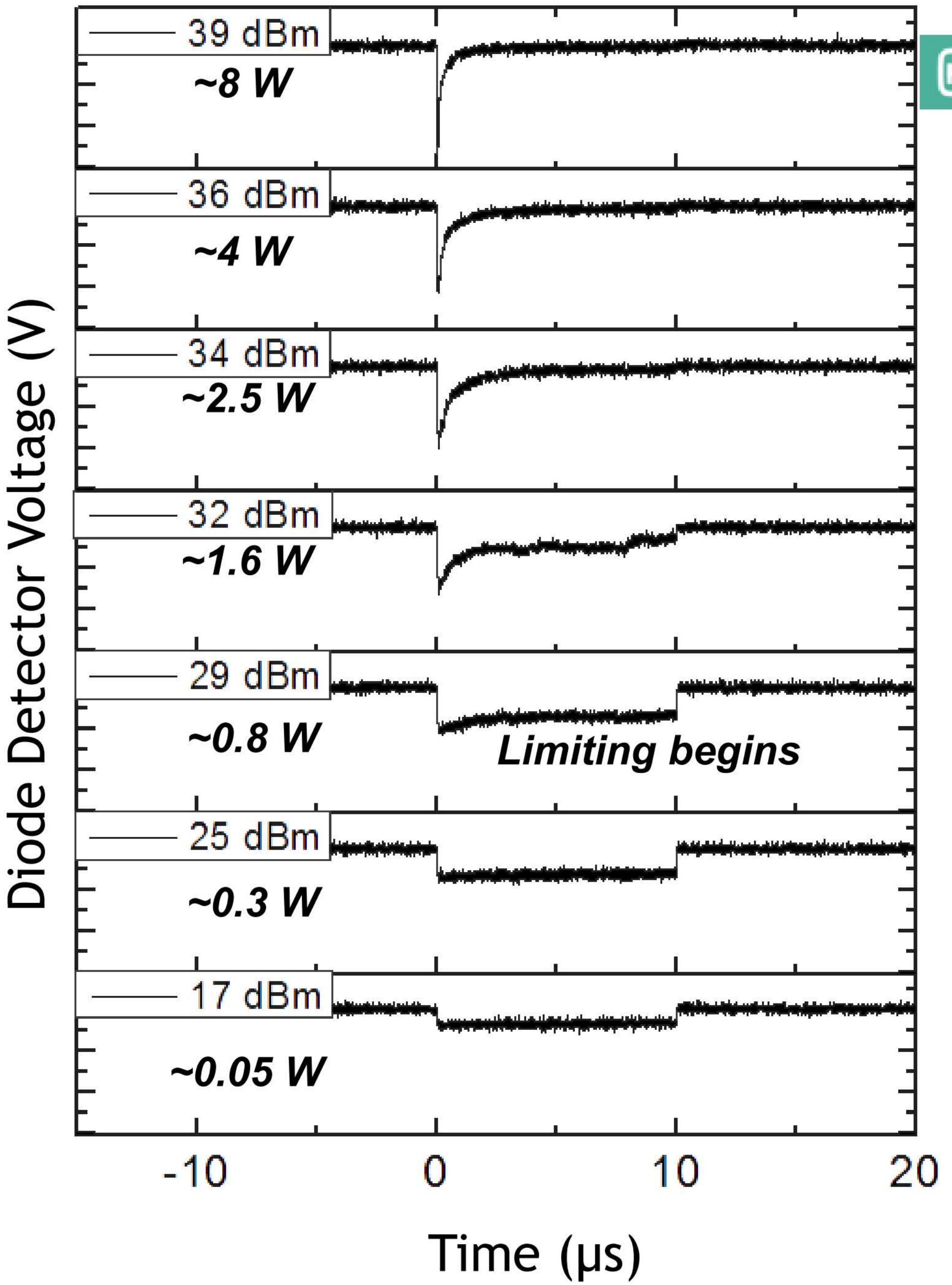




Interdigitated Limiter: Pulsed

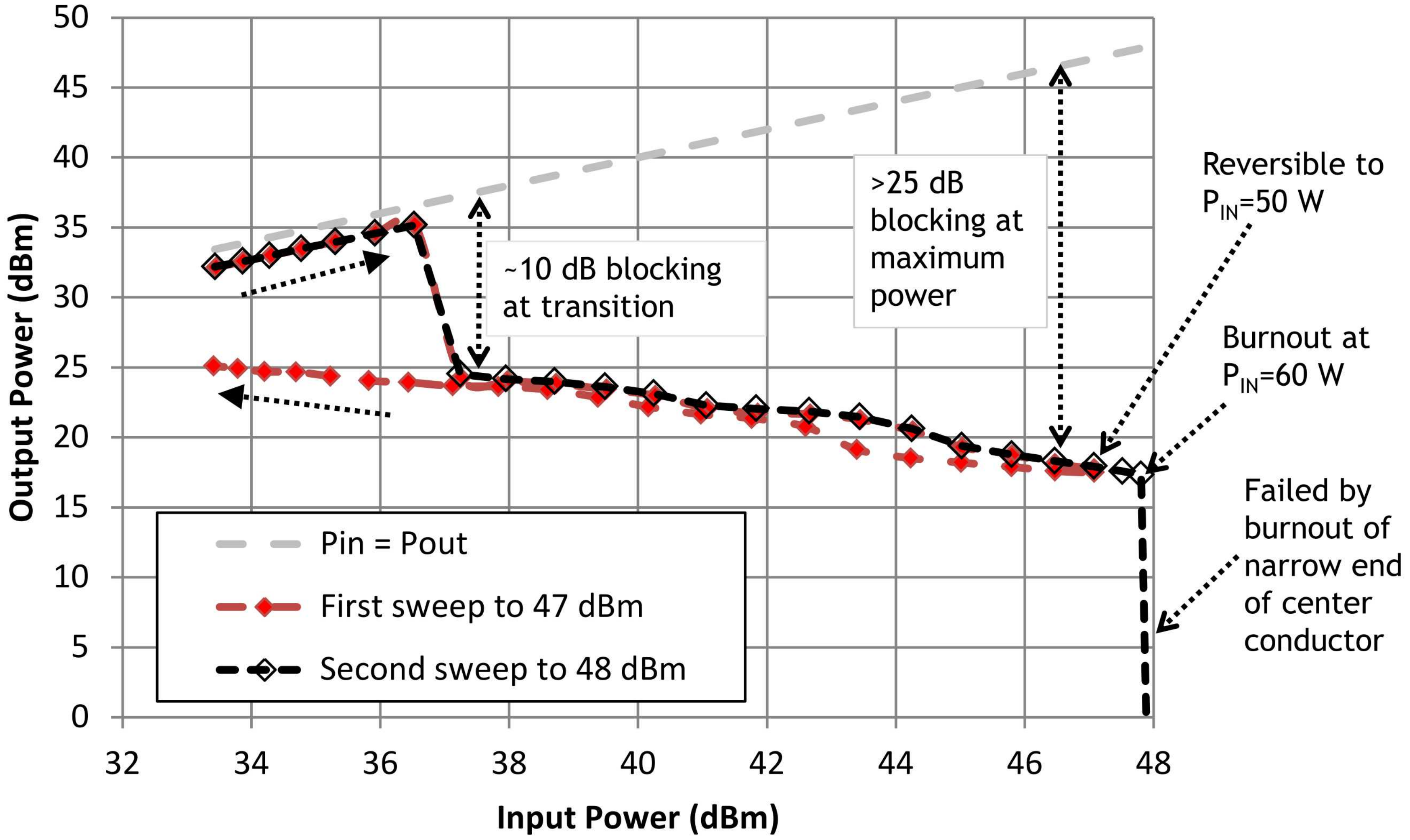
- Limiting begins at 0.8 Watts of input power
- As power increases, triggering time decreases
- Amount of energy required to transition limiter is approximately constant
- Reducing spike leakage requires reducing transition time
- Also observed history-dependent triggering (not shown)





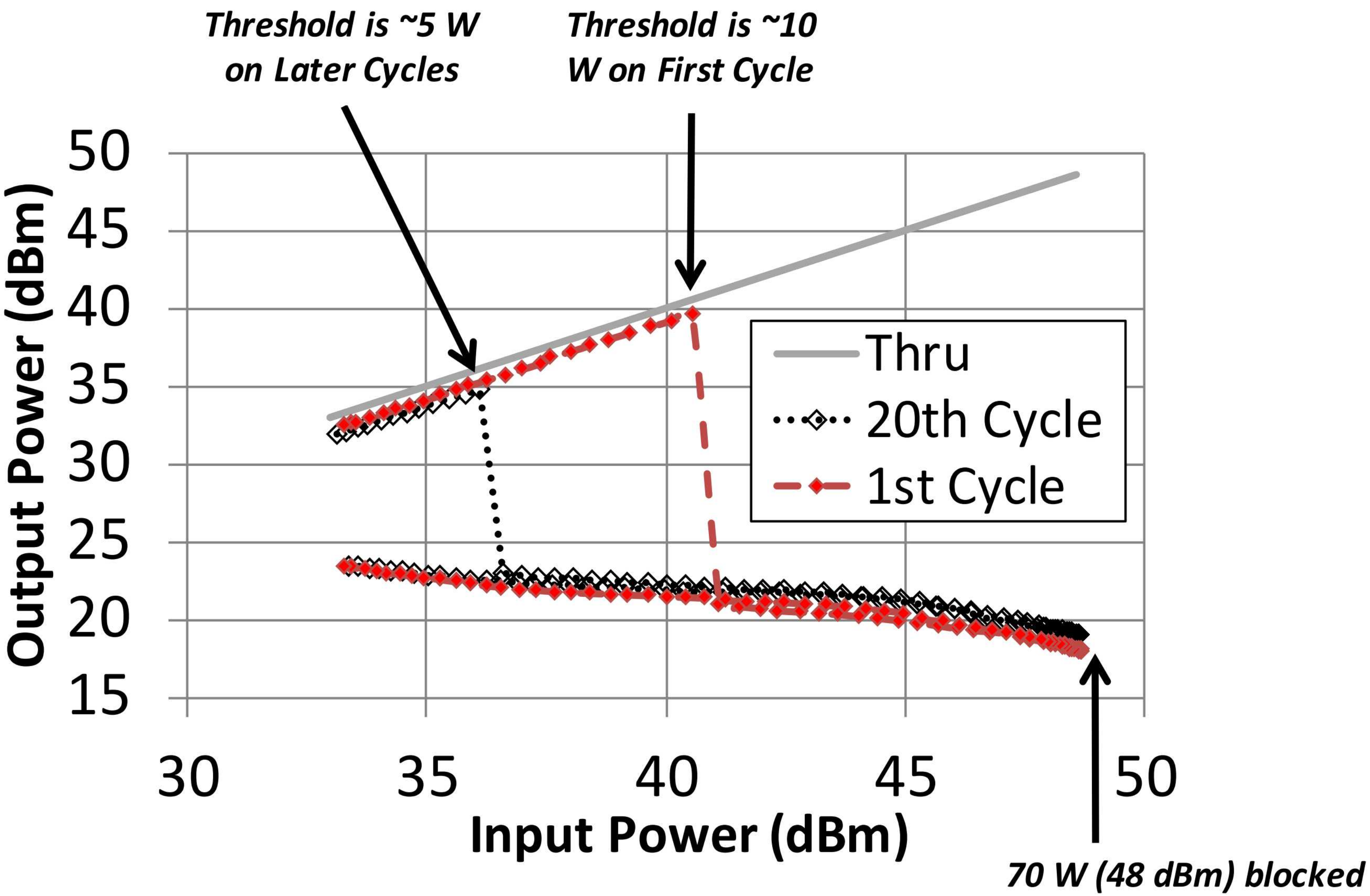
Tapered Limiter: CW Response

- Repeated measurements with increasing power until device failure is observed
- >50 Watt (47 dBm) Power Blocking Reversibly Demonstrated
- Two failure modes:
  - Center Conductor: fails in blocking state due to open circuit in center conductor
  - VO_2 Film: fails in passing state due to destruction of the shunt resistive element



Tapered Limiter: Threshold Shift After Repeated Cycles

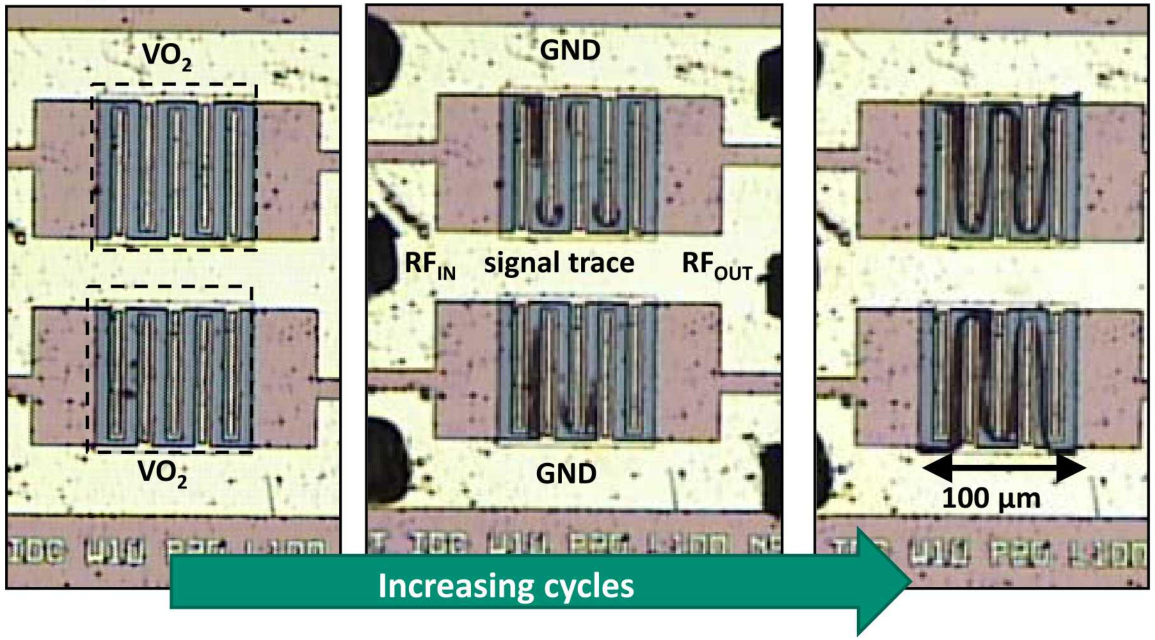
- Observed reduction in limiting threshold after repeated cycles
- Appears to be dependent on time and cycle history
- Suggests changes or damage to VO_2 film during cycling

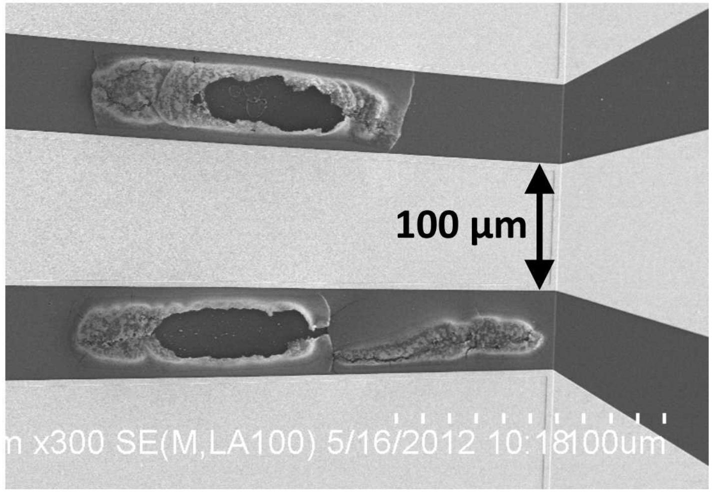


Failure Mechanisms

- Primary failure mechanism is localized burnout of VO_2 film due to current crowding in the conductive layer
- Increasing areas of damage observed with multiple cycles or increasing power
- Mitigation Approaches:
  - Increase film resistivity ratio
  - Thermal engineering to encourage lateral, rather than vertical, heat conduction
  - Design device to ensure power dissipation is lower in high-temperature blocking state than power dissipation in low-temperature passing state

VO_2 Destruction Due to Current Crowding





Conclusions

- VO_2-based Metal-Insulator Transition Limiters Offer Excellent RF Performance
  - Low insertion loss in passing state
  - High isolation in blocking state
  - Flat leakage with increasing power
- However, the Nature of the Transition Presents Several Challenges
  - High spike leakage due to slow thermally-triggered response
  - Threshold shifts with temperature (and possibly history)
  - Device failures due to current crowding
- Intentional Material and Device Engineering may Address these Challenges
  - Active temperature stabilization may be required to address threshold variations
  - Better material properties will improve on/off ratio and burnout thresholds
  - Device thermal optimization may mitigate failures due to current crowding and VO_2 burnout