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Th2E-3

A W-Band SPDT Photoconductive Evanescent-Mode Waveguide Switch

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Outline

- Motivation
  - Millimeter-wave high-speed and high-power waveguide switches
- Objective
  - Proposed structure:
    Photoconductive evanescent-mode (EVA) waveguide SPDT switch at W-band
- Principle of Operation
- Fabrication
- Experimental Results
  - Small-signal S-Parameter measurement
  - Power handling measurement
  - Switching speed measurement
- Conclusion

Motivation

- Spectrum is abundant at millimeter-wave (mmWave) bands for 5G and 6G deployment
  - Greater bandwidth and data transfer rates
- Switches are fundamental components in all telecommunication frontends
- Waveguides can be designed to have low-loss propagation up to THz frequencies
- Advantages of silicon micromachining
  - Ease of integration with planar technologies
  - Micrometer precision
  - Volume manufacturing

Photo Credit: Samsung

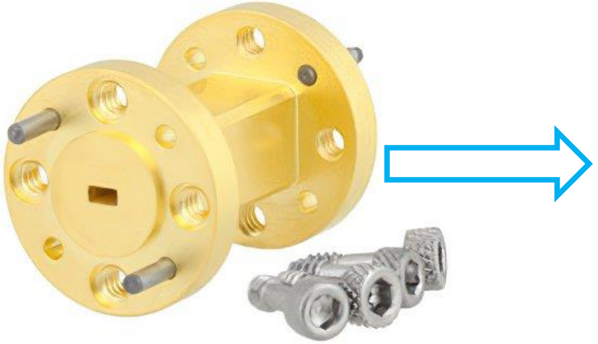
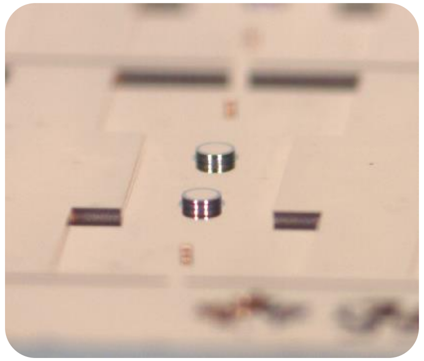


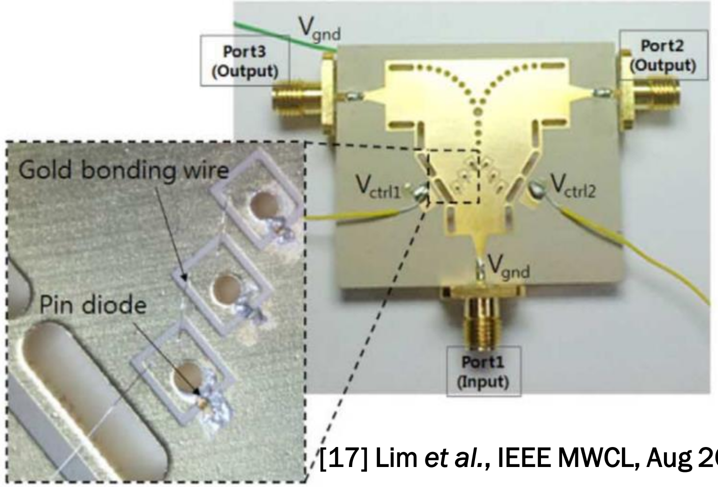
Photo Credit: Pasternack



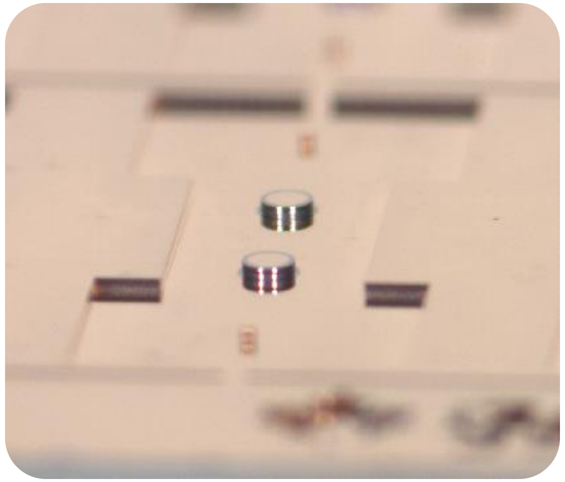
This Work

Motivation

- Technology challenge for waveguide switching at mm-wave frequencies.



[17] Lim *et al.*, IEEE MWCL, Aug 2014



Electromechanical Waveguide Switches, Quinstar Technology, www.quinstar.com

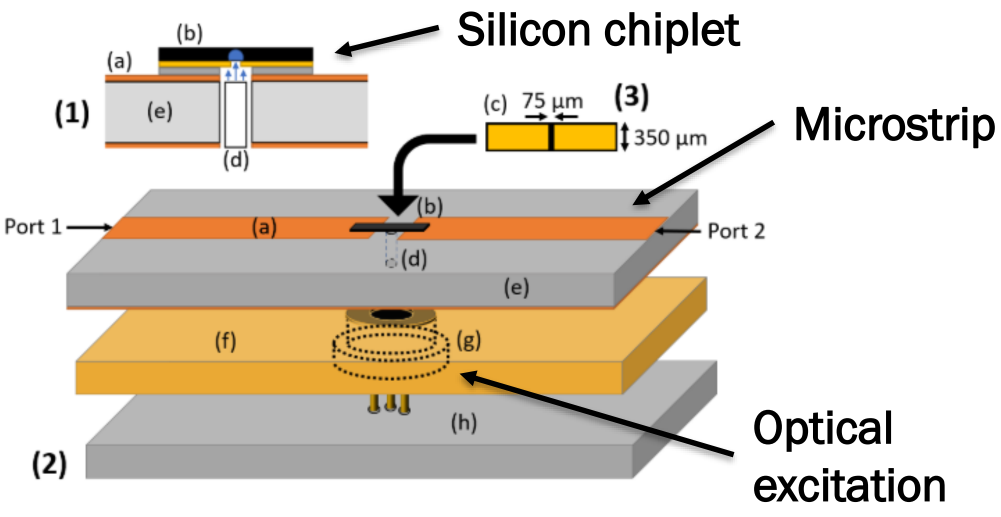
PIN Diode Switching	Photoconductive Switch	Electromechanical Switch
ns Switching Speed	< 5 μs Switching Speed	ms Switching Speed
High Insertion Loss (IL)	Low Insertion Loss	Low Insertion Loss
Low W-Band Power Handling	High W-Band Power Handling	Very High W-Band Power Handling
Integrated Form Factor	Integrated Form Factor	Mechanical Structure
Low Isolation	High Isolation	Very High Isolation

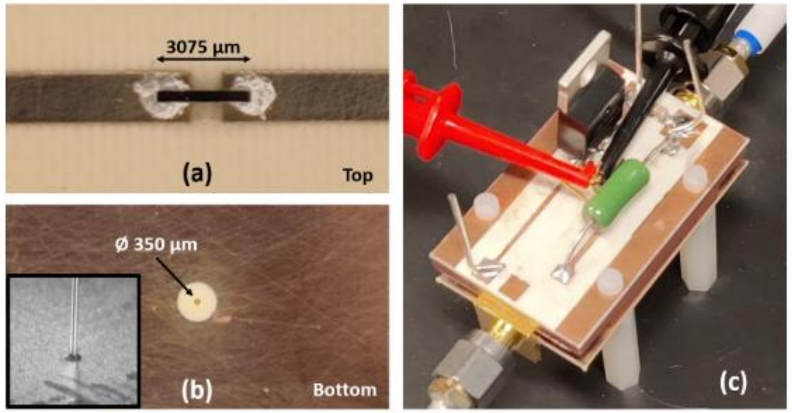
Photoconductive switches are an excellent compromise between switching speed and power handling.

Motivation

- Significant promise in light-activated photoconductive switches
  - Old technology, new applications
  - High speed and high power applications
  - Most demonstrations in planar microstrip or CPW technology
  - Low insertion losses (0.37 dB)[1]
  - Potential for high power handling (35 W)[1]
  - Fast switching times (17 μs)[2]
  - High linearity (IIP3 >77 dBm)[3]
  - DC bias network isolated from RF signal

Microstrip implementation[1]



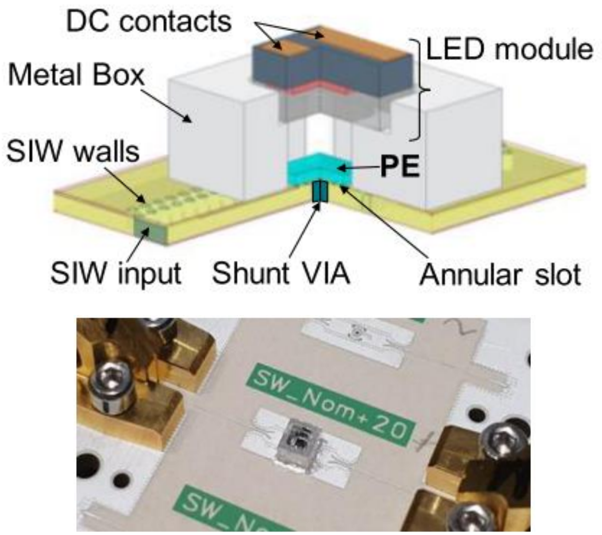


1. Fisher *et al.*, IEEE IMS, Jun 2021
2. Kowalczuk *et al.*, LAPC, Nov 2013
3. Pang *et al.*, IEEE IMS, Jun 2018

Motivation

- mm-wave photoconductive switches implemented in waveguide structures

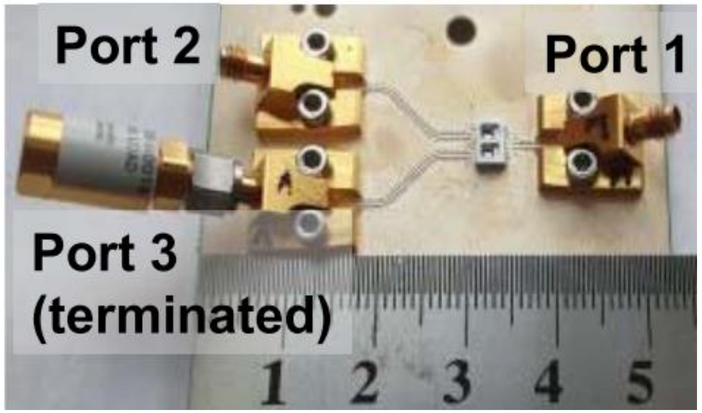
Substrate Integrated Waveguides (SIW) SPST[1]



W-band: 0.9 dB IL & >25 dB Iso.
60 mW Optical Power
Large structure, integration issues

1. Shepeleva *et al.*, *IEEE MWCL*, Jul 2021

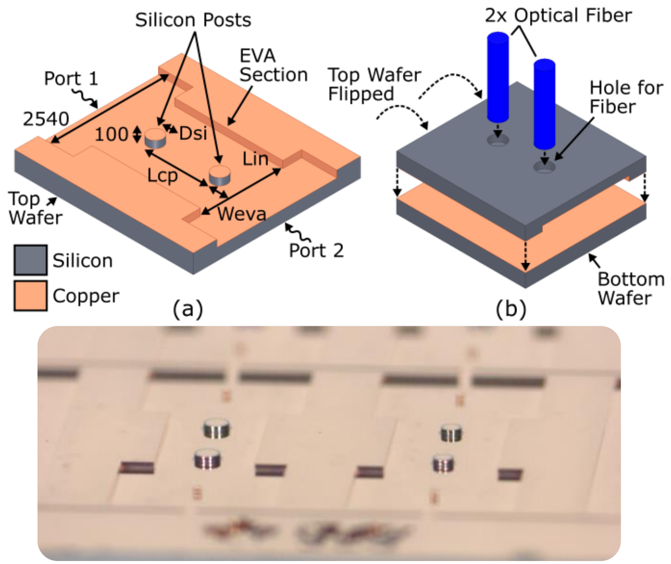
SIW SPDT[1]



W-band: 2.2 dB IL & >30 dB Iso.
60 mW Optical Power
Large structure, lossy.

1. Shepeleva *et al.*, *IEEE MWCL*, Jul 2021

Si Micromachined EVA Waveguides SPST[2]



W-band: 0.52 dB IL & >25 dB Iso.
~25 mW Optical Power
Very low optical power, IL, and form-factor

2. Jones *et al.*, *IEEE IMS 2022*, Jun 2022

Multi-throw switches critical for 5G & 6G frontends have yet to be developed on this highly promising technology.

Objectives

1. Develop a high-speed mm-wave SPDT switch with the potential to handle high RF power while reducing optical power requirements compared to state-of-the-art

2. Maintain low insertion losses and high isolation comparable to electromechanical waveguide switches with higher switching speeds.

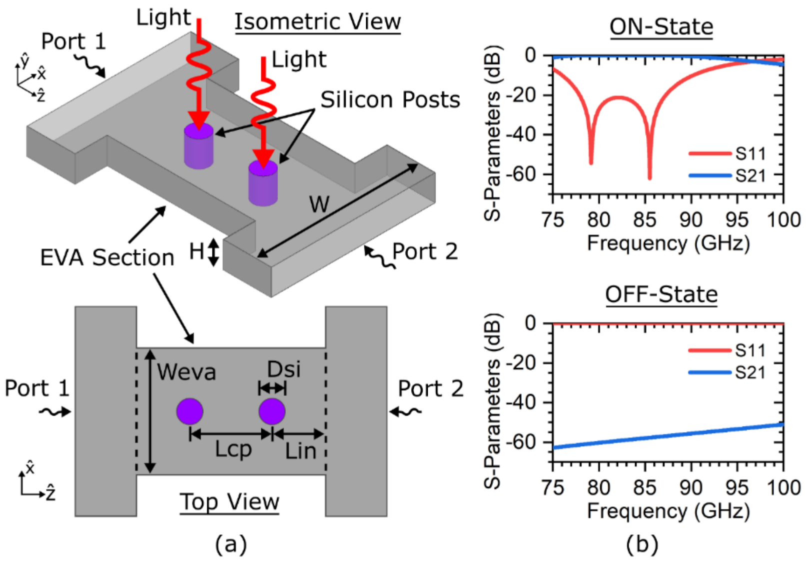
3. Allow for future integration with mainstream semiconductor platforms

Proposed structure:

Photoconductive EVA-mode waveguide SPDT switch at W-band manufactured using bulk silicon micromachining technology

Principle of Operation

- The conductivity depend on the **dimensions** and **carrier lifetime** of the silicon posts and **power density** of optical excitation.
  - Higher channels require higher optical power to achieve a given OFF-state conductivity



[1]Jones et al, IMS 2022

Photoconductivity Model

$$n = \frac{P_0/h\nu}{\alpha H^2}\tau(n)(1-R)(1-e^{-\alpha H}) \qquad \sigma_{DC} = q(\mu_n + \mu_p)n$$

- n – free carrier concentration
- P_0 – optical power density
- $h\nu$ – photon energy (> 1.12 eV for Si)
- τ – free carrier lifetime
- R – optical reflection coefficient
- α – optical absorption coefficient
- H – post height

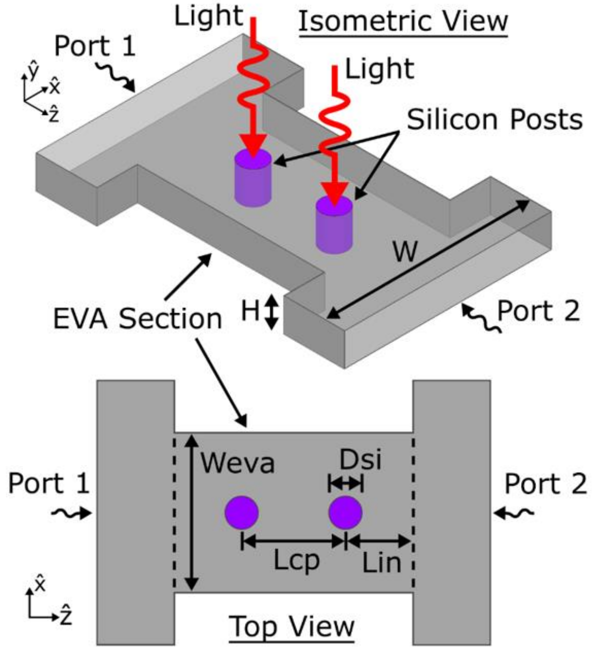
1. Jones *et al.*, *IEEE T-MTT*, Dec 2021

- σ_{DC} – DC photoconductivity
- $\mu_{n,p}$ – mobility
- q – electron unit charge

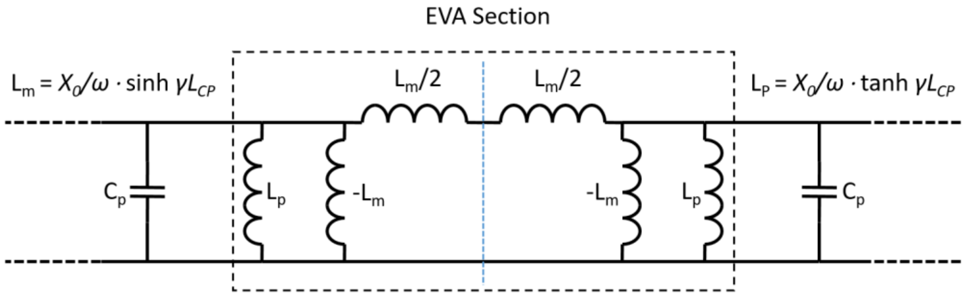
- First order approximation: uniform carrier concentration
- DC photoconductivity a function of P_0 and τ

Principle of Operation

- EVA-mode waveguides have the advantage of very high isolations in the OFF state
  - Combining mismatches from both a waveguide in cutoff and conductive shunt posts
- In the ON state, the switching element behaves as a 2-pole bandpass filter

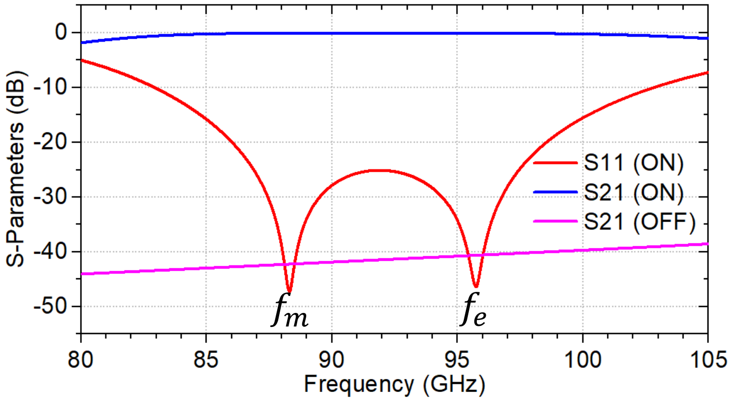


Jones et al, IMS 2022



[12] Craven *and* Mok, *IEEE T-MTT*, Mar 1971

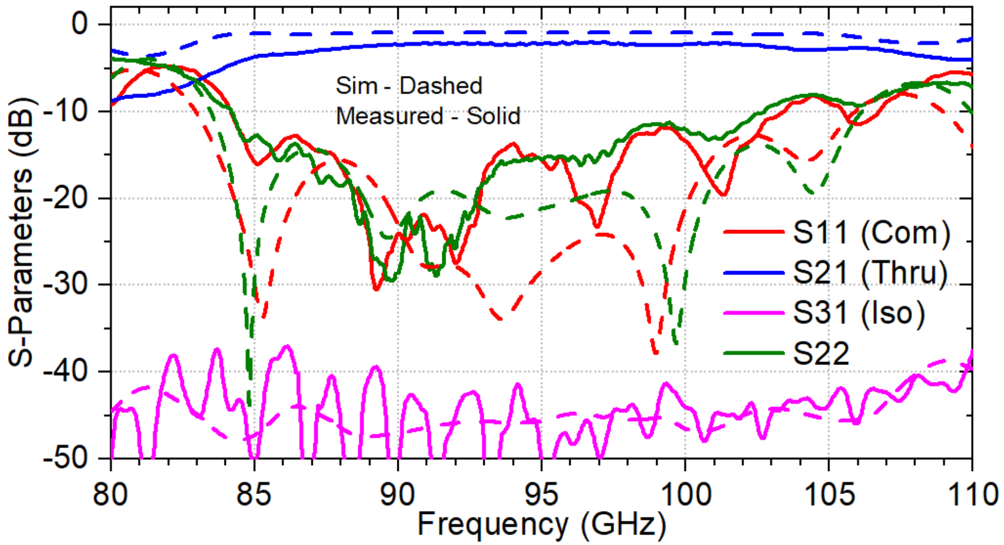
$$f_m = \frac{1}{2\pi\sqrt{\frac{L_m L_p}{L_m - L_p} C_p}} \qquad f_e = \frac{1}{2\pi\sqrt{\frac{L_m L_p}{L_m + L_p} C_p}}$$



Trade-offs:
Decreasing L_{CP} → increases S_{11} FBW
Decreasing W_{EVA} → decreases S_{11} FBW

Experimental Results

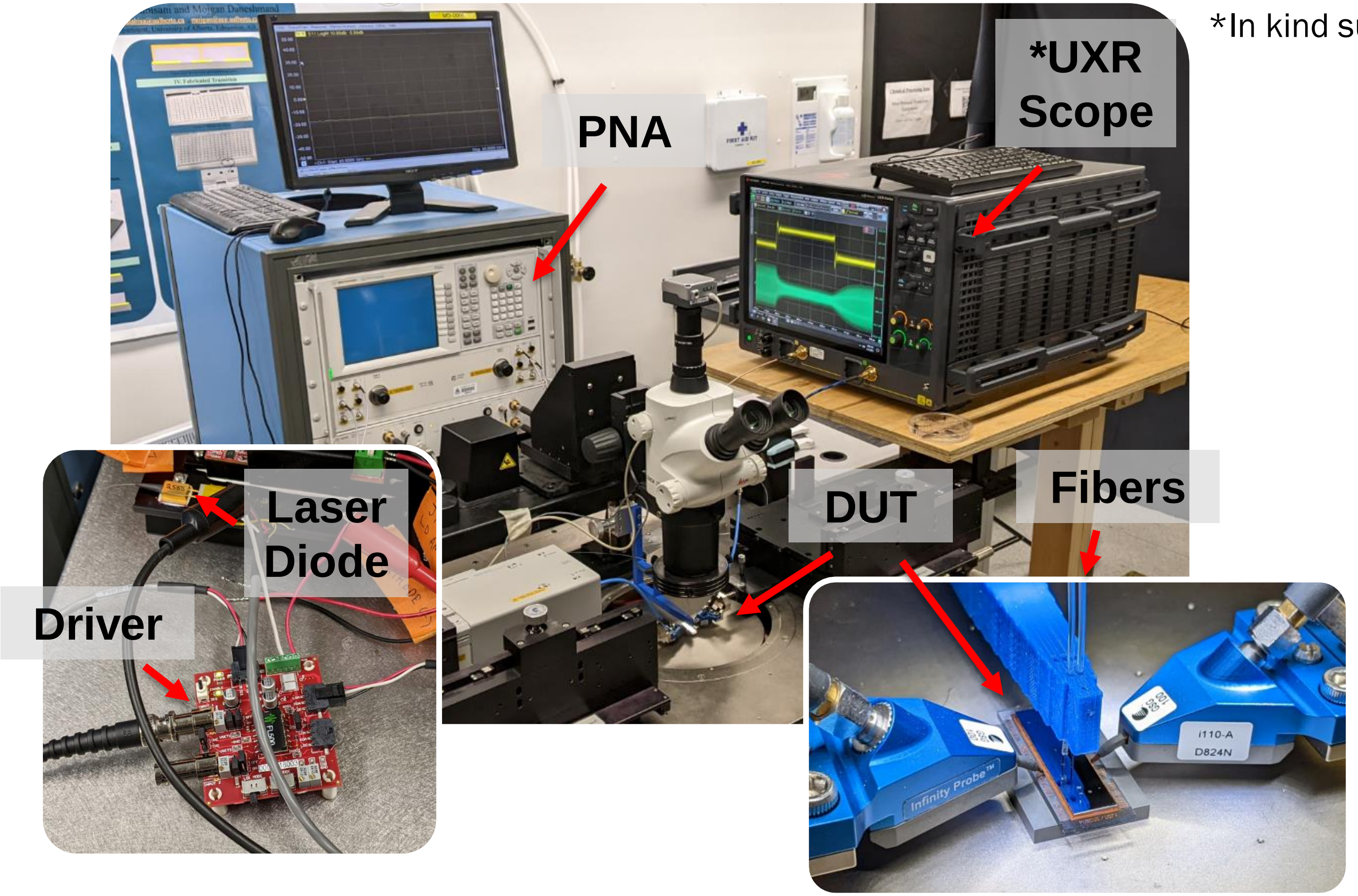
Measured Results



- 0.4 dB extracted switch insertion loss at 95 GHz
- **>35 dB** isolation up to 100 GHz with just **187 mW** total optical power
- 10-dB return loss BW from 84 GHz to 102 GHz

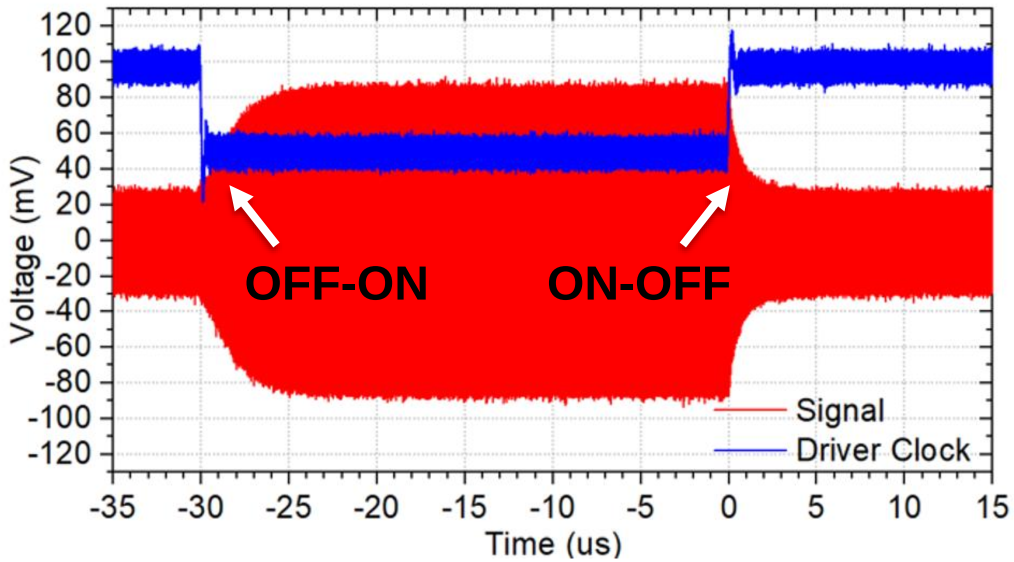
Measured extracted **0.4 dB insertion loss** and **>35 dB isolation** up to 100 GHz

Switching Speed Measurement



*In kind support from Keysight Technologies

Measurement Results @ 90 GHz



- Characterized the mm-wave switching speed of a probe-fed SPST waveguide switch at 90 GHz
- 10-90% rise and 90-10% fall times of **3.8 μs** and **1.4 μs,** respectively

Measured **switching speeds < 4 μs**, where typical electromechanical speeds in the ms!

Performance Comparison Table

State-of-the-art photoconductive mm-wave waveguide switches

Ref.	Technology	Frequency Range (GHz)	10-dB RL FBW (%)	Peak IL (dB)	Isol. (dB)
This Work	Photoconductive Si (Waveguide)	84.3–102.4[a]	19.4[a]	2.0[a]	36.5[a]
[16]	Photoconductive Si (SIW)	74 – 85.8	15	2.2	30
[17]	PIN Diode (SIW)	7.0 – 10.2	37	2.1	10

[a] Results reported include transition losses.

The proposed switch achieves both **low insertion loss** and **high isolation** in a small **integrated form factor** at W-band compared to the state-of-the-art.

[16] Shepeleva *et al.*, IEEE MWCL, Jul 2021
[17] Lim *et al.*, IEEE MWCL, Aug 2014

Conclusion

- First successful demonstration of a photoconductive EVA-mode waveguide SPDT switch at W-band
- ON-state insertion loss of 0.5 dB at 95 GHz
- OFF-state isolation above 36 dB up to 100 GHz
- Power handling of +32 dBm CW at 85 GHz
- Measured switching speeds less than 4 µs
- Low optical power versus OFF-state isolation and smaller footprint compared to state-of-the-art mm-wave photoconductive switches
- Integrated form factor for future implementation in well-established semiconductor platforms for wide technology adaptation

Acknowledgments

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  - Purdue University
  - University of Alberta
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Thank you!