High-speed mm-wave signal transmission over dielectric waveguides: applications, challenges, and opportunities

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Outline

• Motivation and applications
• Background and characteristics of Dielectric Waveguide (DWG) systems
• Example applications in high-speed link systems
• A fully-integrated 130 GHz link using DWG medium
• An alternative approach to DWG systems: a 60 GHz NRD waveguide system
• Conclusions
Advanced mm-Wave Array Radar & Imaging

Large-aperture distributed mm-wave systems achieve unprecedented resolution

Automotive Applications

F-35 APG-81 Radar

Courtesy of Northrop Grumman
F-35 Aircraft

>6,000 elements
>5kW power

Rohde and Schwarz

Dr. Sherif Ahmed
R&S
Signal Distribution in Large Aperture Array

- Signal distribution is a key enabler in mm-wave phased-array and MIMO systems to support large aperture arrays.
- This requires low loss, compact, and wideband signal distribution methods at mm-wave frequencies.

[1] TI 77-GHz radar system, ISSCC’21
4 chips cascaded (12Tx/16Rx)

[2] Ruhr-University Bochum 120-GHz radar system, TMTT’20
12 chips cascaded (24Tx/24Rx)
Signal Distribution for mm-Wave Wireless Comm. (Wireless Fiber Systems)

Example: point-to-point LoS communication systems with Rayleigh spacing

Large-aperture mm-wave arrays: Distribution networks to feed the extended aperture across 100 wavelengths or more.

Applications of high-speed point to point links
Project Terragraph (Facebook), backhaul and 5G networks, and data center data/control planes
Mm-Wave Fiber System

- Chip-to-chip interconnect
- Point-to-point communication


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• 10-Gbps Equalizer for mm-Wave DWG Communication: early concepts and results
• Conclusions
DWG Applications

Chip-to-chip interconnect, MIT, TMTT, 2017 [8]

Opportunity in cars to reduce weight and increase automotive Ethernet data rates, NXP, ISSCC, 2016 [9]


Galvanic isolation barrier, KU Leuven, RFIC, 2018 [7]
Mm-Wave Dielectric Waveguides

- **Objective:**
  - Low cost, scalable, and energy efficient Interconnects
  - *Data Flux Density* >100Gbps per mm footprint
  - Achieve lengths/array size that exceeds 100-1000 λ’s

- **Approach:** Non-TEM modes; Dielectric waveguides at mm-waves
  - Compatibility with CMOS →
    low cost and low power consumption
  - Large BW/pitch
    - High data rate with simple modulation schemes
    - Reduced equalization → lower power consumption
  - Reusing degenerate fundamental mode to double capacity

[N. Dolatsha, ICUWB 2013]
DWG Design Considerations

- Single-mode bandwidth:
  \[ BW = \frac{Kc}{2\pi a \sqrt{\varepsilon_{r-1}}} \propto \frac{1}{a} \]
  \[ a = \frac{4.5c}{2\pi f_0 \sqrt{\varepsilon_{r-1}}} \propto \frac{1}{f_0} \]  \[ BW \propto f_0 \]

- Attenuation characteristics:
  \[ \sim e^{-\alpha_d l}, \ l \text{ is length} \]
  \[ \alpha_d = \frac{2\pi}{\lambda} \sinh \left\{ 0.5 \sinh^{-1} \left[ \left( \frac{\lambda}{\lambda_0} \right)^2 \varepsilon_r \tan \delta \right] \right\} \sim \frac{1}{\lambda} \propto f \]

[K. Bierwirth, 1986]

B-V diagram of waveguide modes

B: normalized wave number
V: normalized frequency
High-Level Design Considerations

- General trend for
  - BW/pitch: increasing with $f^2$ (assumption pitch = 2a)
  - Attenuation: increasing with $f$ & increasing with loss tangent
  - Maximum acceptable length (e.g., for 50 dB transmission loss): decreasing with $1/f$

\[ \alpha \propto \varepsilon_r R \tan \delta / \lambda_0 \]

[N. Dolatsha, ICUWB 2013]
Multi-Mode Excitation of Single Lines

Doubling the available bandwidth by launching two polarization-orthogonal fundamental modes
Multi-Mode Excitation of Single Lines

Planar excitation structures

- $E_x^{11}$ mode (electric dipole on top)
- $E_y^{11}$ mode (slot dipole on the bottom)

Coupling loss: 2.5-3 dB

[N. Dolatsha, ICUWB 2013]
HDPE Dielectric Waveguide Measurements

HDPE (low-cost plastic) properties

Open cavity resonator setup

Damaskos inc., model 900T

$\varepsilon_r$: 2.25  
Loss tangent: 0.0005
HDPE Dielectric Waveguide Measurements

Dielectric waveguide measurements

Measurements @ 60 GHz
- Attenuation < 2.5 dB/m
- Mode polarization cross coupling < -30dB (for a 2m DWG)
Proof of Concept Measurements of Multi-Mode Excitation at 60GHz

Back-to-back measurements

[N. Dolatsha, IET EL 2015]
Multi-Mode Excitation: Version 2

**Single side** planar excitation:
- $E_{x}^{11}$ mode: **Vivaldi antenna**
- $E_{y}^{11}$ mode: **Substrate integrated waveguide (SIW)** horn

**Coupling efficiency**: -2.5 dB  
**Coupling isolation**: > 35 dB
DWG Implementations (Solid vs. Hollow)
Tradeoffs between loss and GD variations

DWGs with different cross sections

\[ a_0 \quad a_1 \quad 2r_0 \quad 2r_1 \]

Loss and group delay of DWGs operating at 130GHz (DWGs made of Teflon)

[N. Dolatsha, TTHZ 2016]
Max Capacity and Energy Efficiency

Max capacity is primarily limited by dispersion

\[
\tau_{g,\text{link}} = \left| \frac{\Delta \tau_{g,u}}{\text{BW}_{\text{single-mode}}} \right| \Delta f \leq T_b = \frac{1}{\Delta f}
\]

\[
\text{BW}_{\text{disp}} = \Delta f \leq \frac{\sqrt{\text{BW}_{\text{single-mode}}}}{\Delta \tau_{g,u} \cdot l} \propto \sqrt{f/l}
\]

Rods offer larger capacity

Rods are still energy efficient for short ranges

[N. Dolatsha, TTHZ 2016]
Improvements on DWG (Group Delay)

Loss/GD variation tradeoff space: Lowering the group delay variations of the hollow circular WG at the expense of a tolerable increase in loss.

(DWGs made of HDPE)

Offset added to normalize the group delays at 140 GHz.
Effect of Bending the Waveguide

Even with using degenerate modes for capacity

- Both modes have low loss due to bending
- Mode cross-coupling better than -40 dB
Similar work (4-m long foam-cladded DWG)

KU Leuven, PMF link with a 4-m foam-cladded fiber lying on top of the table. A maximum data rate of 7 Gb/s is achieved across that length [M. D. Wit, JSSC’19]
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Datacenter Bottlenecks for Cloud Computing: 
Bringing the optics closer to the processor for interconnect scale-out

• I/O bandwidth scaling faster than I/O pins per package.
• Optics coming closer to the “box”
• Capacity of electrical lines is limited:

\[ B = B_0 \frac{A}{L^2} \]

A is the cross-sectional area of the wires, L is the length of the wires, and \( B_0 \) is a constant.
• Bandwidth density mismatch between the optical system and the electrical.

Optical/Copper Distribution using Mid-Board Optical Transceivers/Modules

- MBO: Transitioning between the optical domain (Fiber) to the electrical domain (Copper).
- Fan-out system that matches the signal bandwidth density of optics to the electronics.
Mid-Board Dielectric Waveguide (MBDWG)

Pushing for ultra-high data flux (1-5 m distances)

- Each MBDWG supports several transceivers for multiple DWG
- Each QPSK TRX achieves 56 Gbps, reusing DWG degenerate modes w/ 2mm pitch
- Data flux density: $\frac{56 \text{ Gb/s} \times 2}{2 \text{ mm}} = 56 \text{ Gb/s/mm} \ @ \ 140\text{GHz for 1m}$
Mid-Board Dielectric Waveguide (MBDWG)

Scalable solution for 1-10 Tb/s packet switch in data center
- Flexible choice for number of transceivers per MBDWG and number of MBDWG per package
- For example, DWG array supporting ~ 5 Tb/s needs 48 channel and takes around 2.5 cm X 2.5 cm area (12 DWG per side: ~ 2.5 cm)

2mm for 140 GHz
Link Design w/QPSK Modulation

- At 1m: 28Gbps per I/Q (left) → 56Gbps per carrier → **112Gbps** per DWG
- Data rate without equalization vs. length (right)
  - Roll-off with $\sqrt{l}$, where $l$ is the waveguide length

QPSK per I/Q or OOK @1m

Data rate vs. distance
Adjacent Waveguide Interference

For interference level of -20dB

- Simulation results
- Without interference, horizontal opening: 0.79 UI

Degradation with -20 dB coupling: negligible
- Horizontal opening diff: 0.07 UI
- Vertical opening: -1 dB
16-QAM Approach

- Baud rate is reduced by half, to 14GBaud/s, for the same data rate as QPSK (56Gbps/TRX)
  - For 5m square rod waveguide, without equalization, the eye opening is well behaved
  - Horizontal opening: 27 ps, or 0.37 UI
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Compact Chip-to-DWG Interfaces/ Packaging

• To utilize the processing capabilities of CMOS ICs to the maximum, compact and efficient mm-wave couplers need to be designed to allow for reliable and efficient signal coupling from the IC to the DWG interface.

• With advanced in current organic substrates and packaging, custom packages is designed to build low loss DWG couplers.
Proof of Concept: Fully Packaged mm-Wave DWG Link

- Proof of concept demonstration with fully-packaged 130-GHz chip and waveguide interface
- Demonstrate feasibility of DWG above 100 GHz and achieving speeds ~40 Gbps
- Link reliability, phase stability, loss and dispersion characteristics

[M. Sawaby, SSCL, 2018.]
130 GHz Tx Chip for the DWG Link

- 130 GHz QPSK TX chip on 55 nm SiGe BiCMOS Process (ST B55)
- $P_{\text{out}} = 2.5$ dBm, $P_{\text{DC}} = 216$ mW
- 40 GHz BW in CW
- Highly efficient integrated built-in PRBS generators
- Power limited by the LO drive from the built-in frequency multiplier

[M. Sawaby, SSCL, 2018.]
The Prototype Tx System (130 GHz)

Grounded DWG with E-Field Conceptualization

Organic mm-Wave Substrate + Chip

Mother Board

RO4350 (250 μm)
LCP 3850HT (25 μm)
Pre-preg (25 μm)
LCP 3850HT (100 μm)

[M. Sawaby, SSCL, 2018.]
Proof-of-Concept: 36 Gbps DWG 1-meter Link @130 GHz
Proof-of-Concept: 36 Gbps DWG 1-meter Link

(a) Measured eye diagram and (b) bathtub curve at 25 Gb/s, as well as at (c) 30 Gb/s and (d) 36 Gb/s (only in-phase component of data is shown).

[M. Sawaby, SSCL, 2018.]
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DWG Interface

- Antenna-based chip / PCB to DWG mode transition are usually complex, high loss (~5 dB), and could be narrower bandwidth
- Larger antenna size for better signal transition
- Sensitive to metal surrounding

Prior 130-GHz DWG interface [SSCL’18]

KU Leuven 120-GHz DWG interface [SSCL’20]
NRD Waveguide

- Non-radiative dielectric waveguide
- Invented by Tsukasa Yoneyama and Shigeo Nishida in 1981
- Dielectric strips that are sandwiched between two parallel metal plates separated by a distance smaller than half a wavelength.
- Allow bends and junctions to be incorporated into the circuits with very little radiation and interference.

[T. Yoneyama, TMTT’1981]
Proposed NRD Waveguide

- Rogers RT5880 substrate
- Thickness: 0.508 mm, width: 0.4 mm
- Operating mode: longitudinal section electric (LSE) mode
- Support single-mode operation below 120 GHz
- Confine the EM-field well in a 5-mm radius bend

[J. Zhang, IMS’21]
PCB-to-NRD Coupler

- A symmetric stripline transmission line where only the lower side of the stripline is excited.
- EM signal is gradually coupled from the lower to the upper side.

[J. Zhang, IMS’21]
Measurement

- Dielectric constant ($\varepsilon_r$): 2.2
- Dissipation factor ($\tan\delta$): $9 \times 10^{-4}$
- 35-µm copper cladding
- 10-cm and 20-cm length

Setup

- Measured by Vector Network Analyzer (VNA) with 1.85-mm coaxial connectors
- Short-open-load-through (SOLT) calibration
Measurement Results

- Insertion loss for 10-cm and 20-cm links is $5.0 \pm 0.6$ dB and $8.1 \pm 0.7$ dB
- Coupling loss is $1.0 \pm 0.4$ dB
- Propagation loss is on average 10-dB lower than the microstrip line
Effect of Bending the Waveguide

- Measured $S_{21}$ of 10-cm NRD waveguide with bend

[J. Zhang, IMS’21]
Channel-to-Channel Isolation

- Measured channel-to-channel isolation spaced by 5 mm

![Image of channel-to-channel isolation](image)

![Graph showing channel-to-channel isolation](graph)

[S Parameter (dB)](graph) vs. [Frequency (GHz)](graph)

- $S_{21}$ (10 cm)
- $S_{31}$ (10 cm)

[J. Zhang, IMS’21]
Conclusions

• Millimeter-wave dielectric waveguide systems are a powerful alternative to optical fiber for short distance links
• Cost-effective, low loss, and high bandwidth density solutions could be achieved at mm-wave frequencies ranging from 60 GHz - 300 GHz
• Reviewed challenges and opportunities in scaling up the use of mm-wave DWGs: losses, dispersion, capacity, and sensitivity factors
• Applications of these systems range from large aperture mm-wave communication or imaging systems, to design of efficient and high-speed links for datacenters.
Reference


Reference


