Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

Submission Title: Millimeter-wave Photonics for High Data Rate Wireless Communication Systems

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Abstract: Millimeter-wave Photonics for High Data Rate Wireless Communication Systems

Purpose:

Millimeter-wave Photonics for High Data Rate Wireless Communication Systems

Presentation to
IEEE 802.15 THz Interest Group

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July 16, 2008

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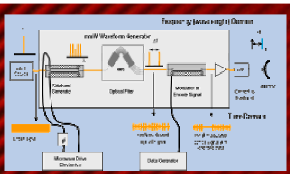
Outline of Summary

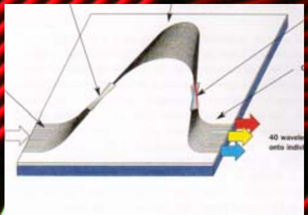
- History of Integrated Optics at Battelle
- Millimeter-wave Photonics
- Understanding the Problem
- Overview of System
- System Performance
- Field Test Results
- Millimeter-wave Photonics Test Bed
- The Battelle Development Team

Three decades of Integrated Photonics



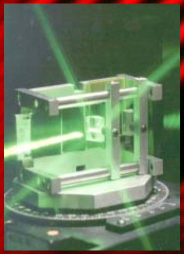
2000

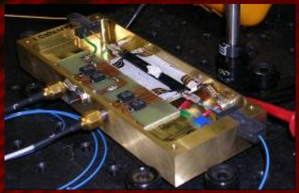
2000 PIRI is sold
2001 Optimer Photonics in Launched
2002 EO-Clad Silica Waveguides
2003 Modulator-Multiplexer
2005 mmw Communications Link
2006 World's Record for Wireless Transport
2007 Toroidal Sensors and Signal Processing

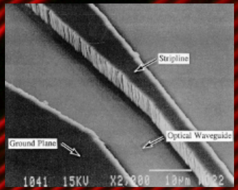


1990

1991 Biorefractometer
1993 Grating Biosensor
1993 EO Spectrum Analyzer
1995 PIRI sells AWG







1980

1982 AO Scanner
1983 EO Digital Correlator
1985 Microwave Sampler
1986 Pipelined Polynomial Processor
1987 PIRI is Launched
1989 94 GHz Optical Modulator

1970

1976 Lithium Niobate Waveguides
1978 NASA Preprocessor in LN

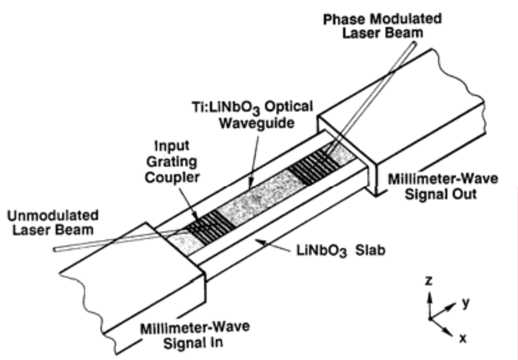
Battelle
The Business of Innovation

Millimeter-wave Photonics

94 GHz Electrooptic Modulator

Ref: Ridgway, et. al. Integrated optical modulator operating at millimeter-wave frequencies, IGWO Conference Paper MEE5-1, 1989.

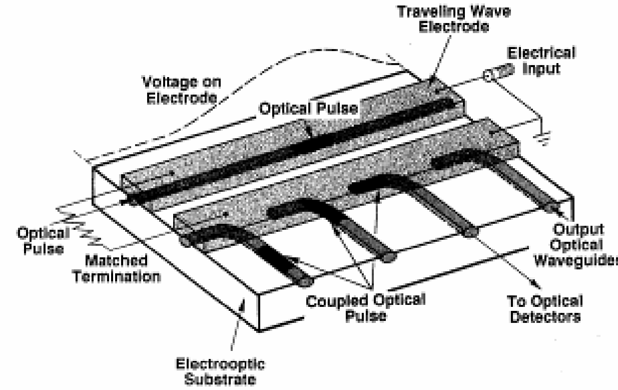
5,015,052 Optical Modulation at Millimeter-Wave Frequencies, Issued May 14, 1991.

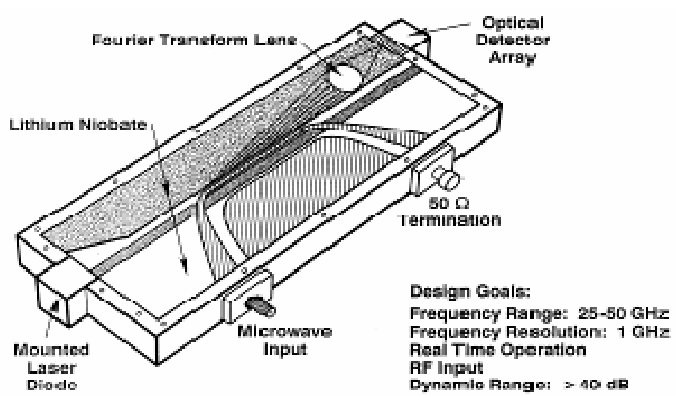


100 G sample/second Sampler for Microwave Signals

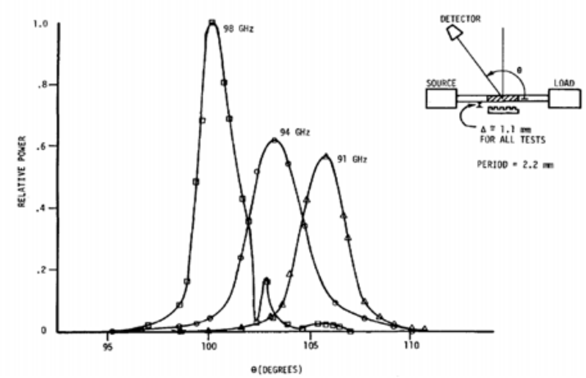
Ref: R. Ridgway, et. al. “Spatial Sampler using Integrated Optic Techniques”, J. Lightwave Tech. VOL.LT-4, No 10 Oct 1986

4,770,483 Electrooptic Sampling Apparatus for Sampling Electrical and Optical Signals, Issued Sept. 13, 1988.





50 GHz Real-Time Spectrum Analyzer

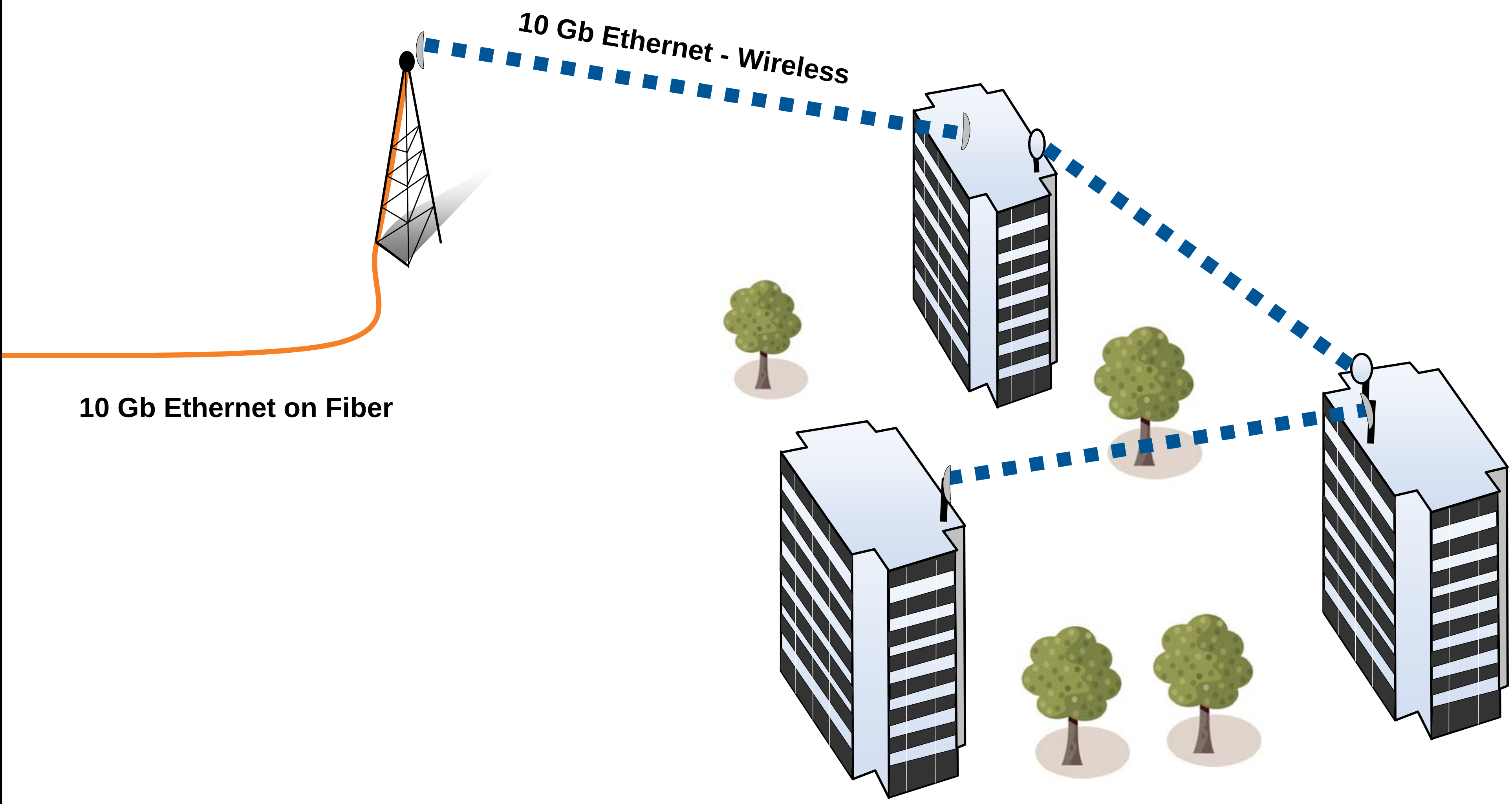


94 GHz Beam Steering Antenna

Ref: M.R. Seiler, R.W. Ridgway “Studies of Millimeter-Wave Diffraction Devices and Materials” Final Report, AFOSR, DTIC AD-A216 504, Dec 28, 1984

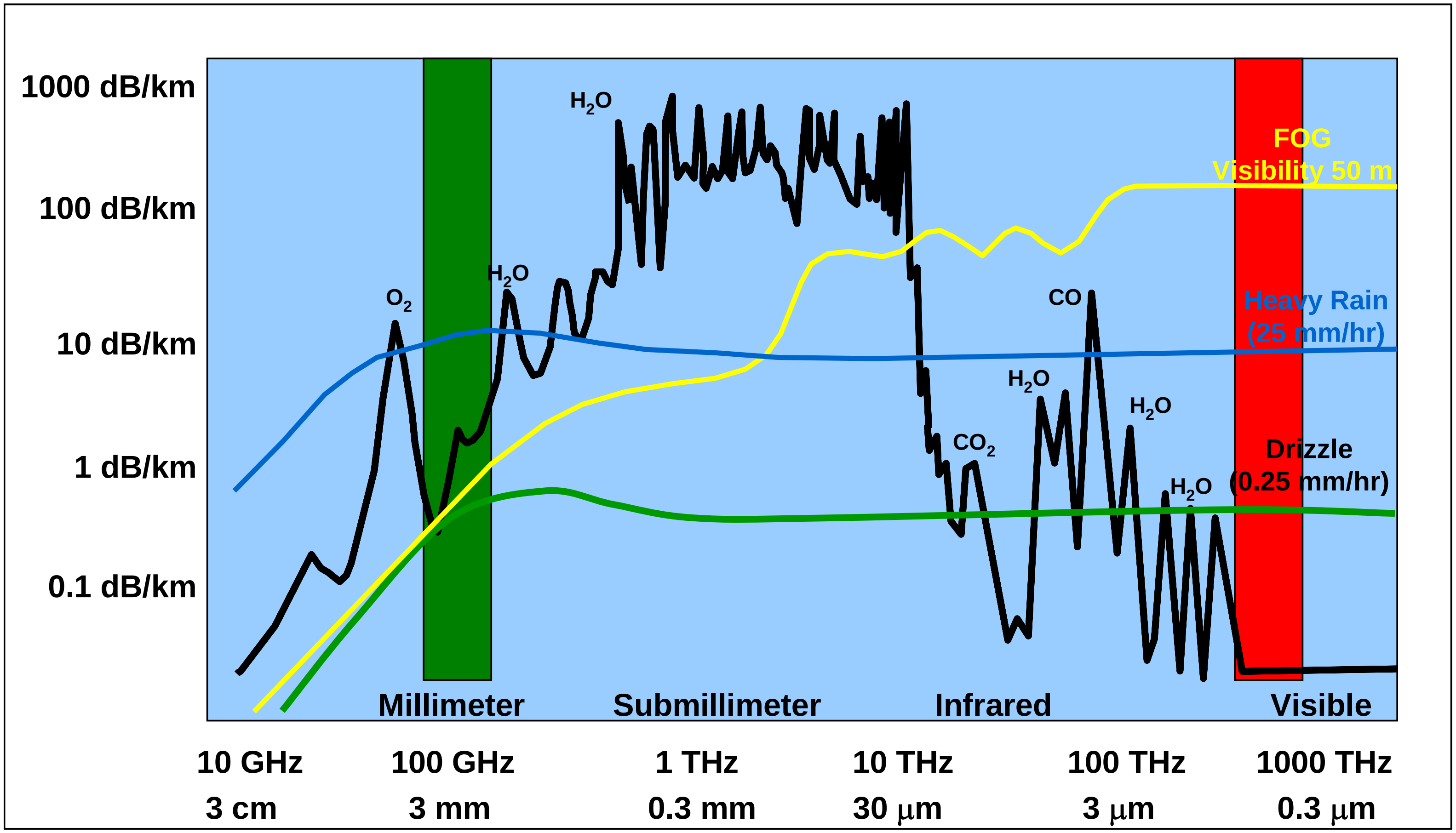
Battelle
The Business of Innovation

Millimeter-wave Communications



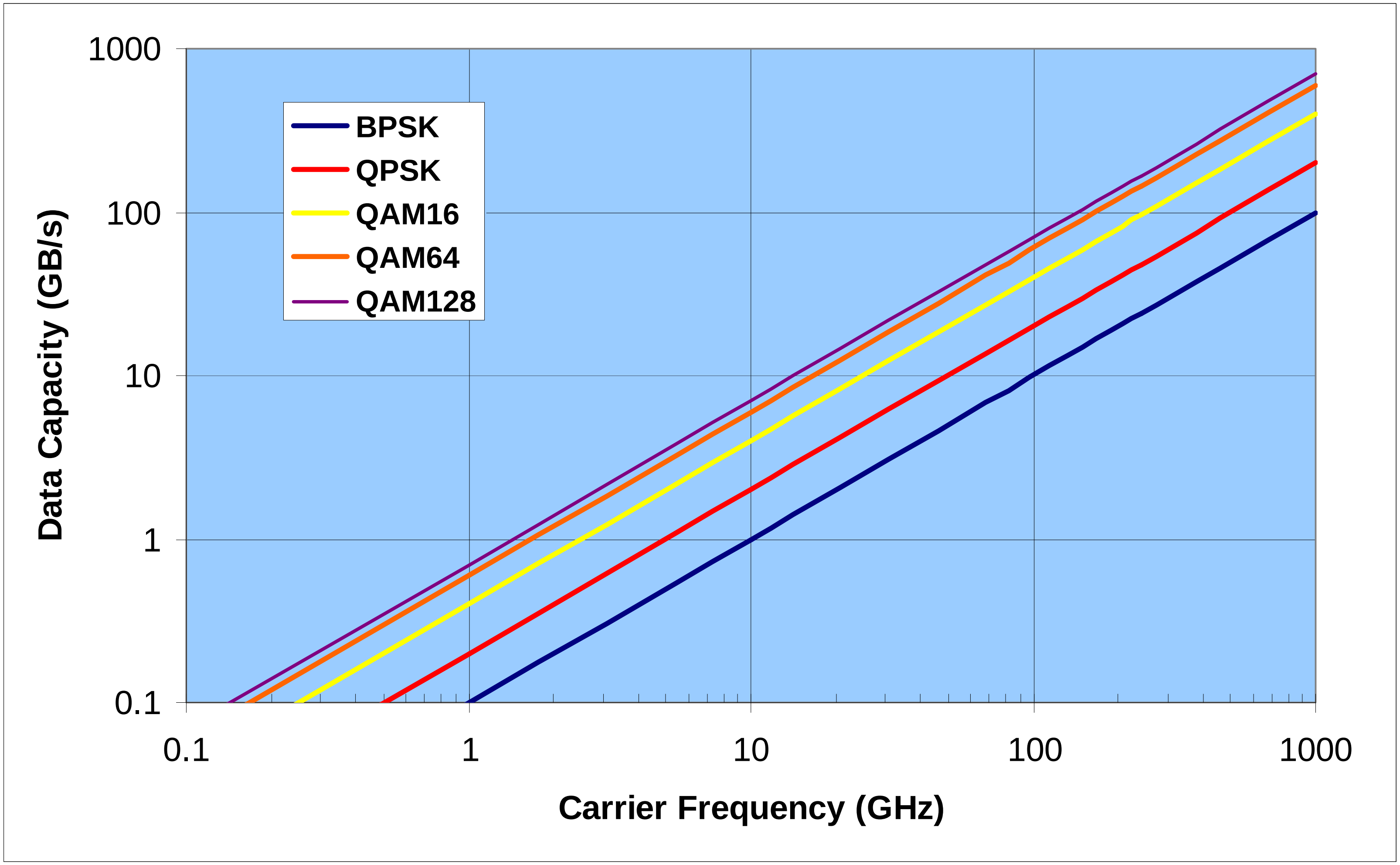
Battelle has developed a method to transmit 10 Gb/s over a wireless link. The application allows the wireless transport of 10 Gb Ethernet at distances to 2-5 km.

Why Millimeter-waves?



Millimeter-wave frequencies offer good transmission through fog, clouds and rain

Why Millimeter-waves?



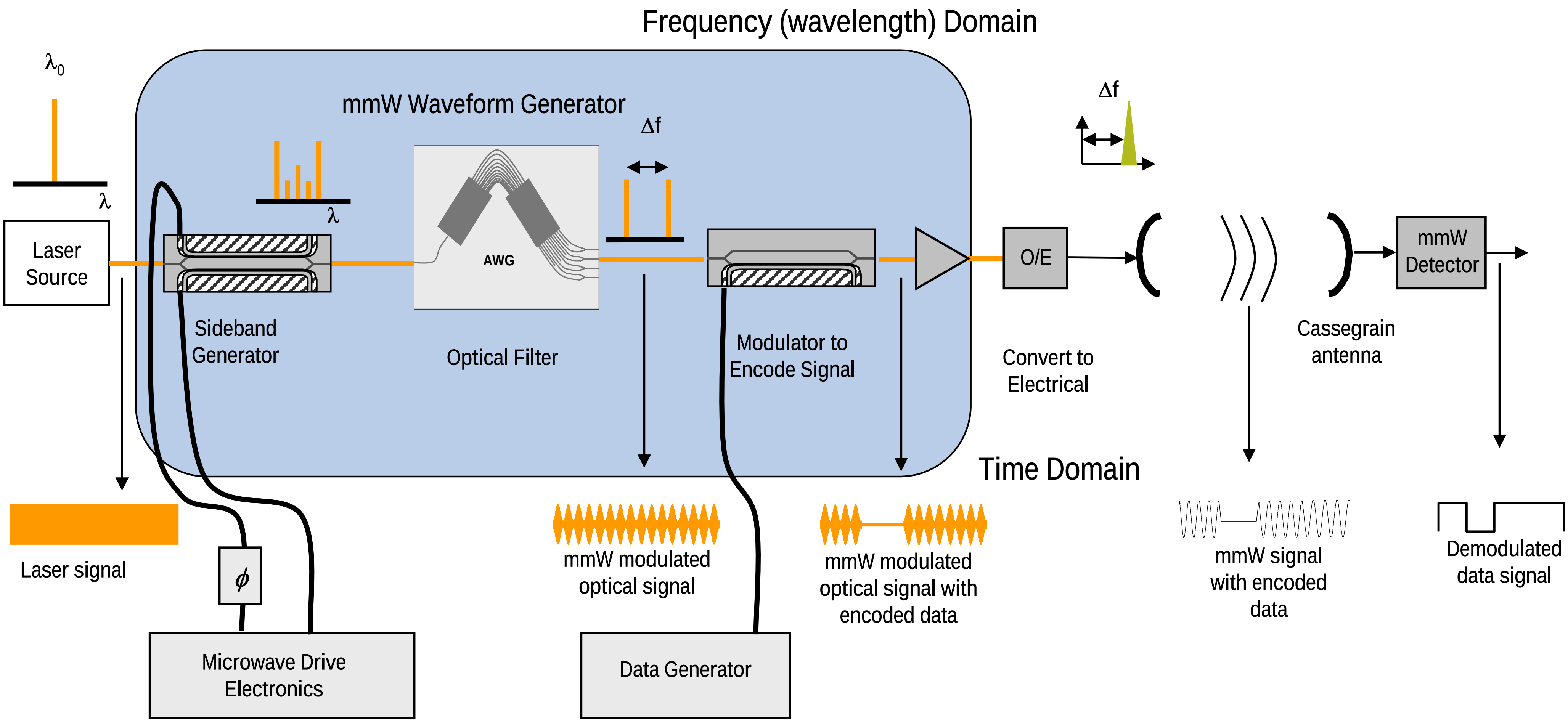
Millimeter-wave frequencies can support large data capacities

Why Work in the Optical Domain?

Advantages of Optical Approach:

1. **Frequency Agile**
   - mmW carrier can be varied for 35 GHz to 700 GHz from the same optical source. There are no millimeter-wave systems that have this level of frequency agility.
2. **Signal Interconnections**
   - Optical interconnects are used throughout system, reducing loss and improving signal quality. With millimeter-wave systems, all interconnections will be either waveguide or cable. Both have higher loss than the equivalent optical interconnects.
3. **Low Reflections Between Components**
   - Optical interconnections have inherently low back reflections due to the excellent index match between the optical fibers and optical waveguide components.
4. **Antenna Remoting**
   - Is accomplished with optical fibers to the photodiode
5. **Phase Independent Amplification (PIA)**
   - Optical amplifiers have significantly better PIA over millimeter-wave amplifiers
   - This will improve the overall phase noise of the system
6. **Direct Modulation not possible at millimeter-waves**
   - There is no present means of modulating a millimeter-wave carrier directly at 10 Gb/s. Therefore, spectral efficient modulation approaches will be required.
7. **Power Consumption**
   - The electronic components needed to achieve 10 GB/s modulation on a millimeter-wave components will require at least 10x the power needed for achieving the same modulation rate using the optical technique.
8. **System Cost**
   - It is estimated that the component costs for achieving 10 GB/s using millimeter-wave components will be at least 10X higher than for the optical system achieving the same data rates.

mmW Signal Generation

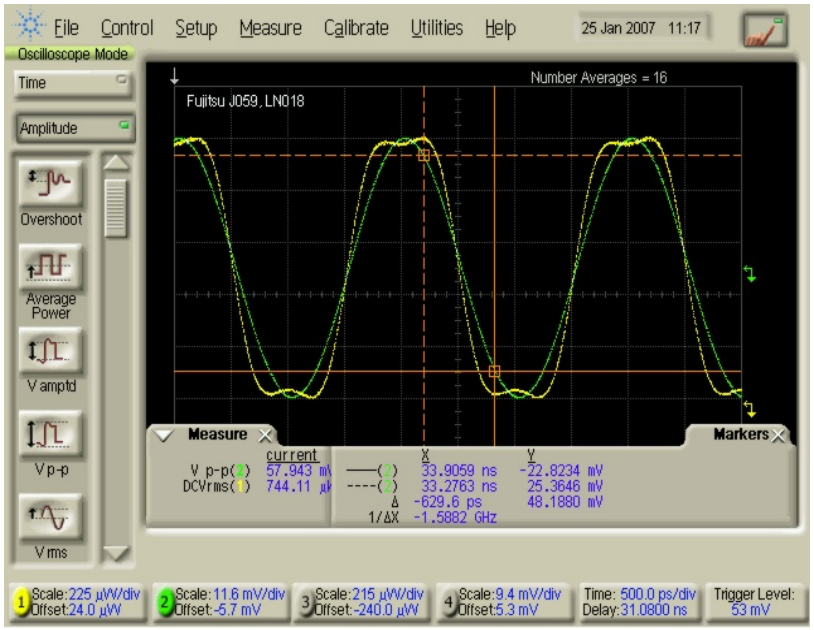


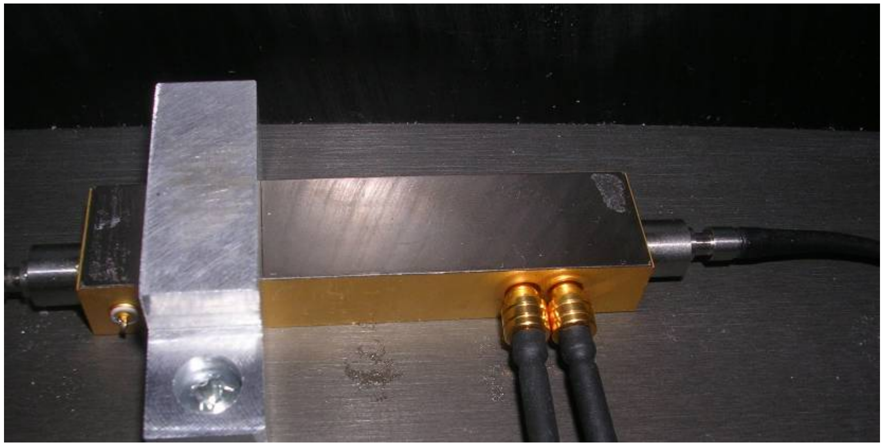
This block diagram outlines a wireless communication system capable of transmitting data in excess of 10 GB/s that uses an over-driven modulator to generate multiple sidebands. Various modulators, including lithium niobate and electrooptic polymer modulators, have been used to generate sidebands and encode data.

Ref: 1) A. Hirata, M. Harada, and T. Nagatsuma, *J. Lightw.Tech.*, Vol. 21, No. 10, Oct. 2003.
2) R. Ridgway and D. Nippa, *Photonics Tech. Let.*, Vol. 20, No. 8, April 15, 2008

Lithium Niobate Modulators

- Fujitsu FT7912ER
  - Dual Drive 10 GB/s Modulator
  - Specifications
    - Vπ (push-pull) = 2.6 volts @10 GHz
    - Optical Loss = 6.0 dB
  - Measured
    - Vπ(push-pull) = 2 volts @DC
    - Vπ(push-pull) = 2.4 volts @500 MHz
    - Optical Loss = 5.25 dB





Combining the Filtered Signals

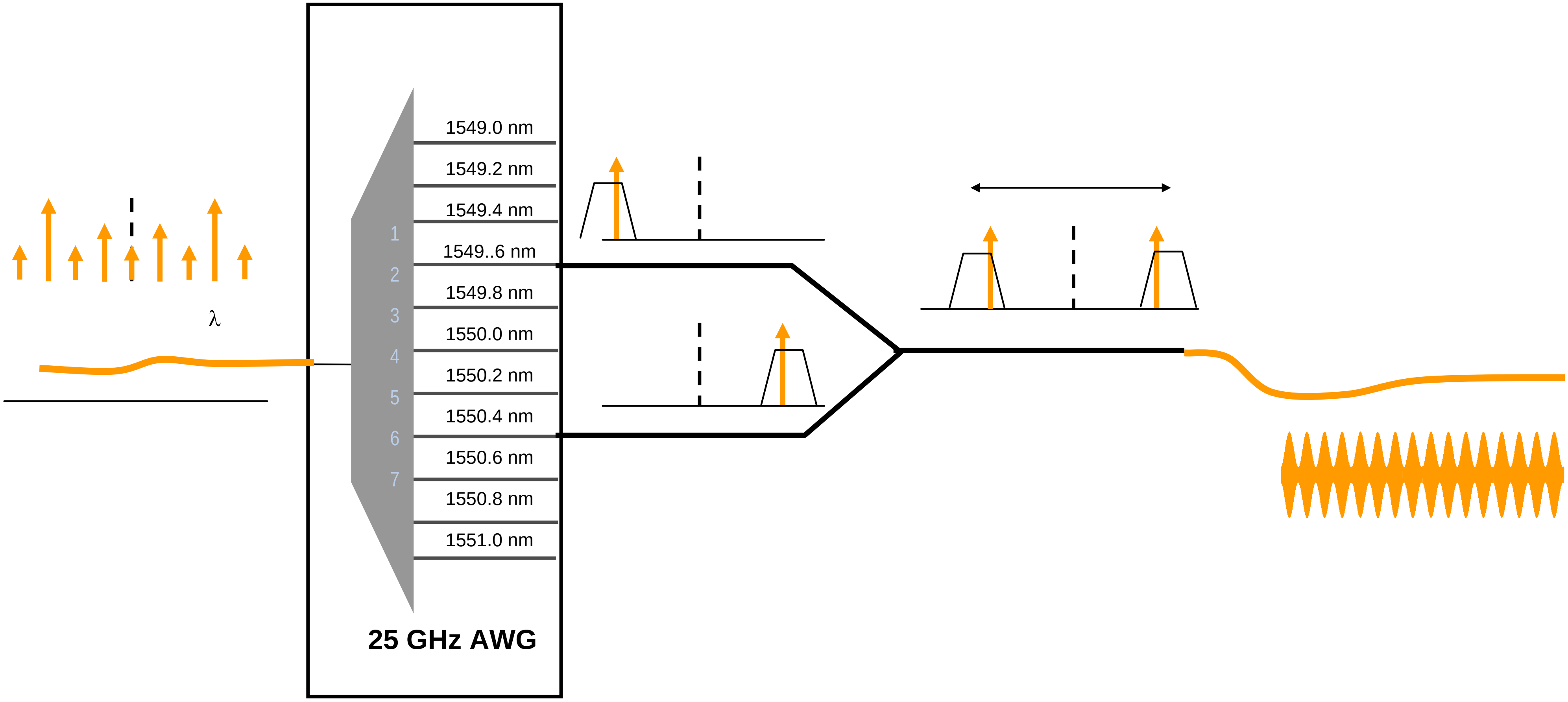
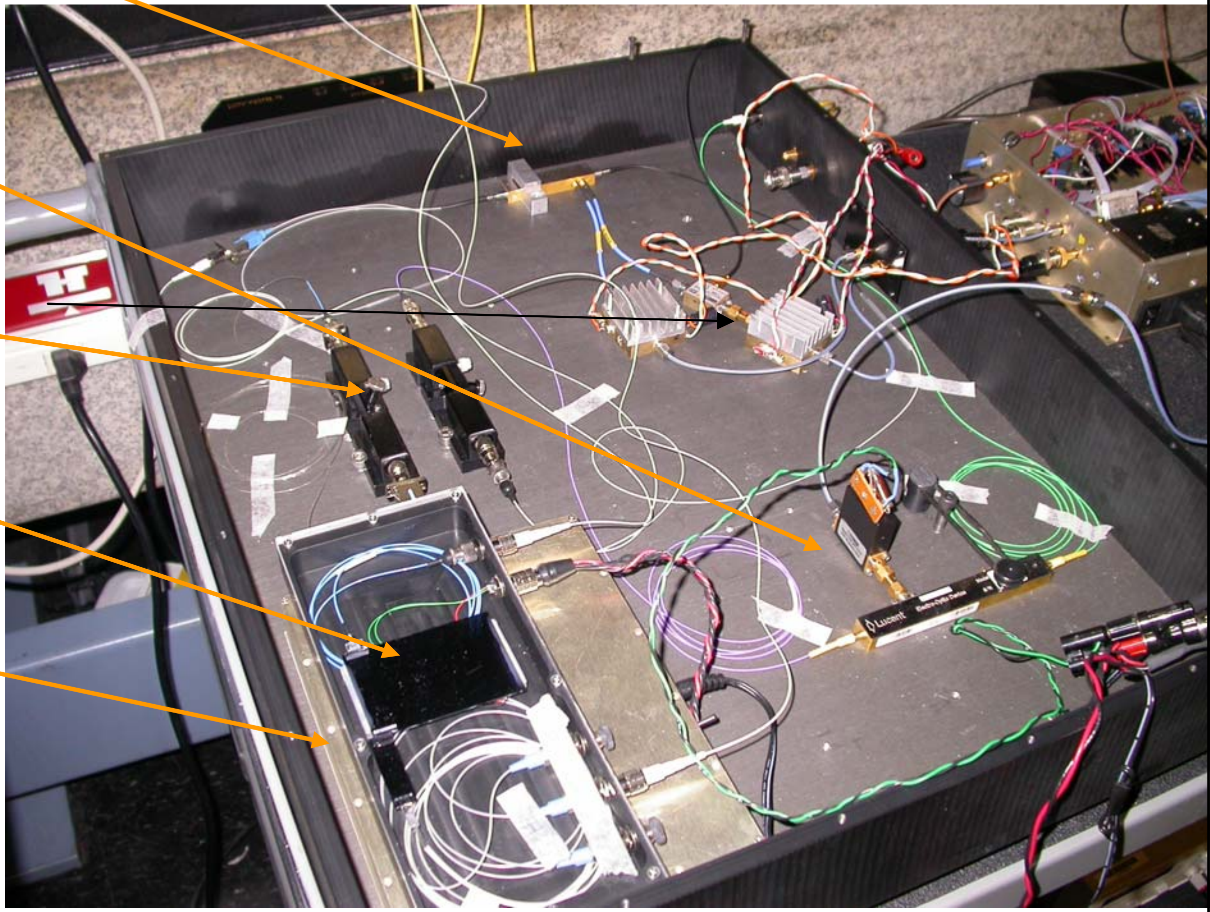


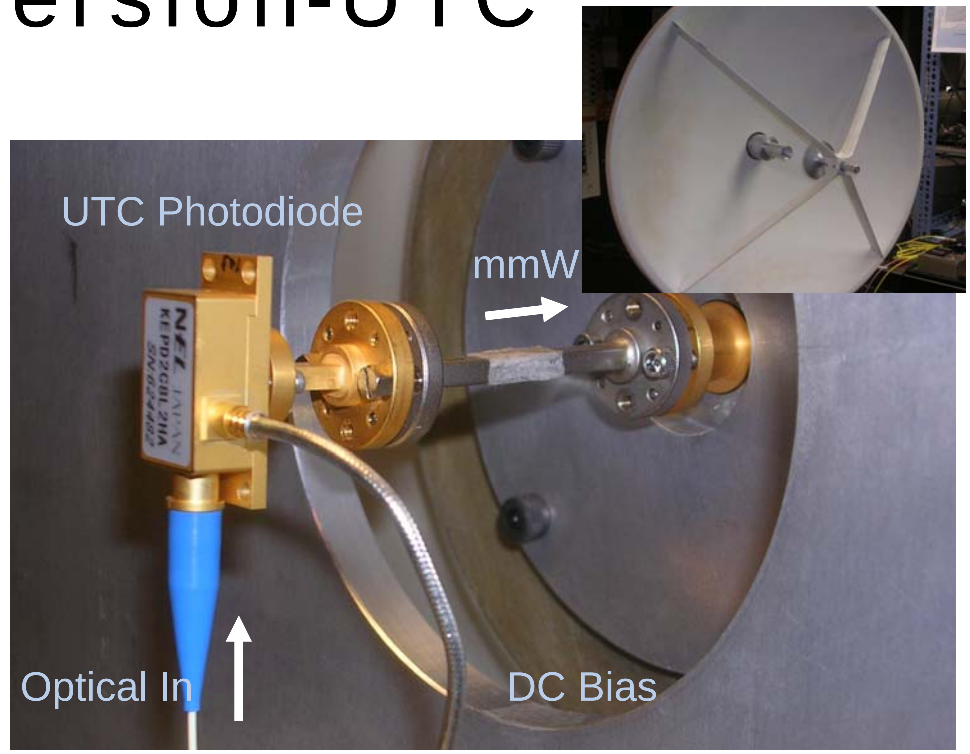
Photo of Waveform Generator

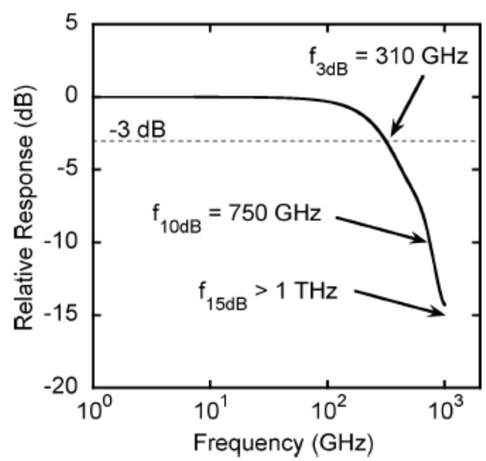
- Modulator as Sideband Generator
- Modulator as Data Encoder
- Polarization Controllers
- Arrayed Waveguide Grating
- Diode Laser Source



Optical-to-mmW Conversion-UTC

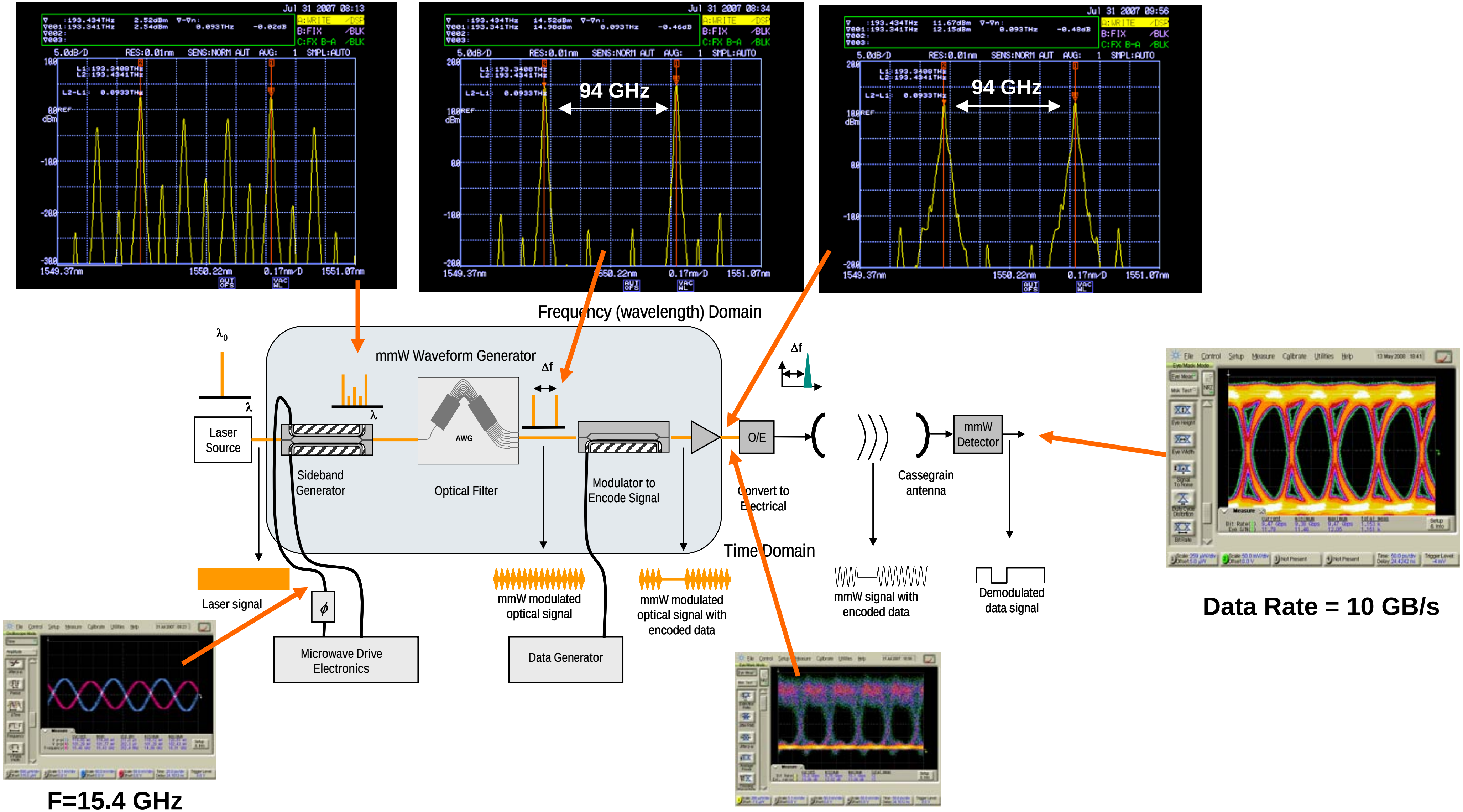
- Uni-Traveling-Carrier Photodiode
  - Developed by NTT
  - Technology: InP/InGaAs
  - 3 dB Bandwidth = 310 GHz
  - mmW Power Out at 100 GHz:
    - 20 mW (pulsed)
    - 6 mW (continuous)
  - Efficiency
    - Input Optical = 20 mW
    - Output mmW = 3 mW (at 94 GHz)





Ref: H. Ito, et. al. , IEEE, J. Sel Topics Quantum Elec., Vol 10, No. 4, 2004

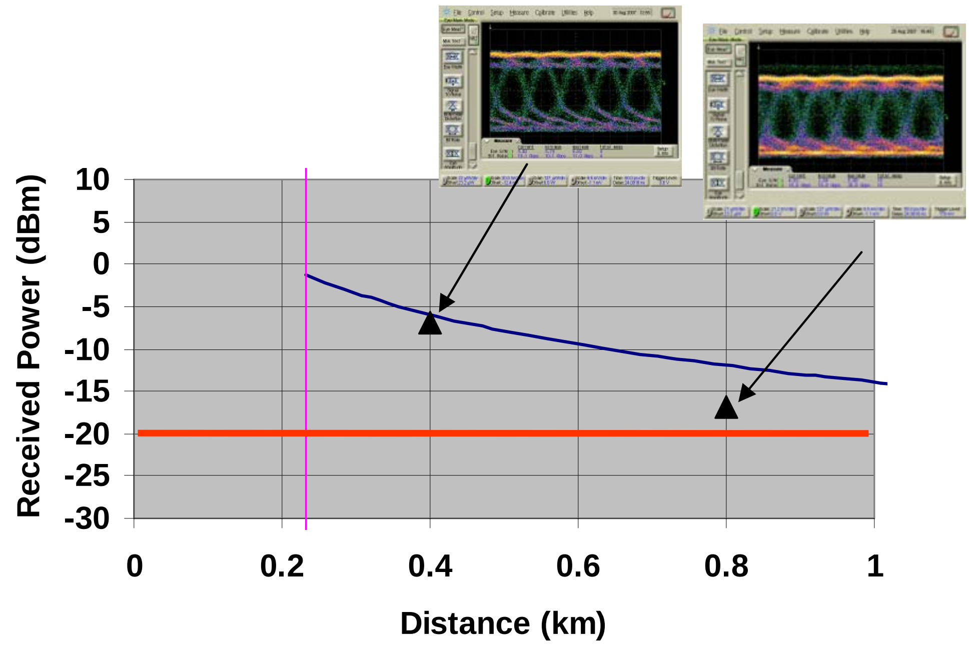
Photonic Generation of Millimeter-waves

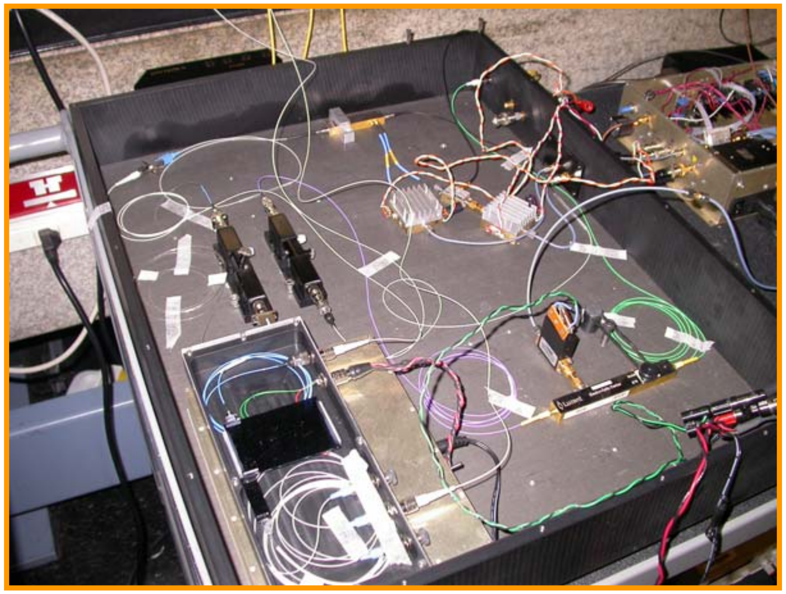


Battelle's IR&D Program is focused on the use of photonic components for the analog and digital modulation of millimeter-waves.

Millimeter-wave Photonics

- **Applications:**
  - Wireless Data Transmission
    - Data Rates to 12.5 GB/s
    - Analog signals to 10 GHz
  - 10 GB Wireless Ethernet
- **Status**
  - mmW Carriers: 30 GHz - 350 GHz
  - mmW Power: +3 dBm w/o amplification
  - Data Rates: 5 GB/s – 12.5 GB/s

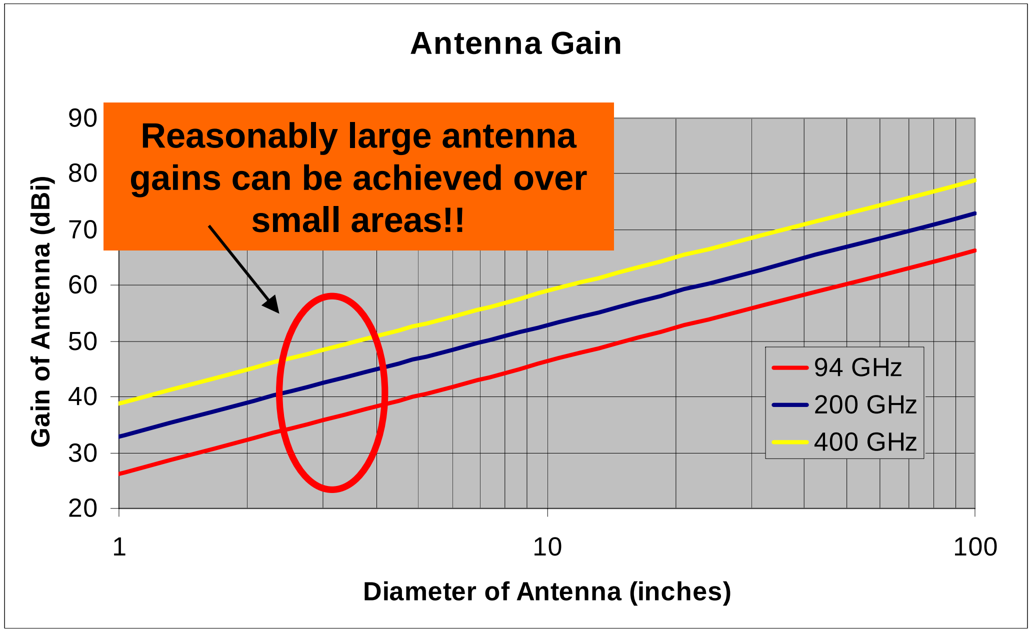


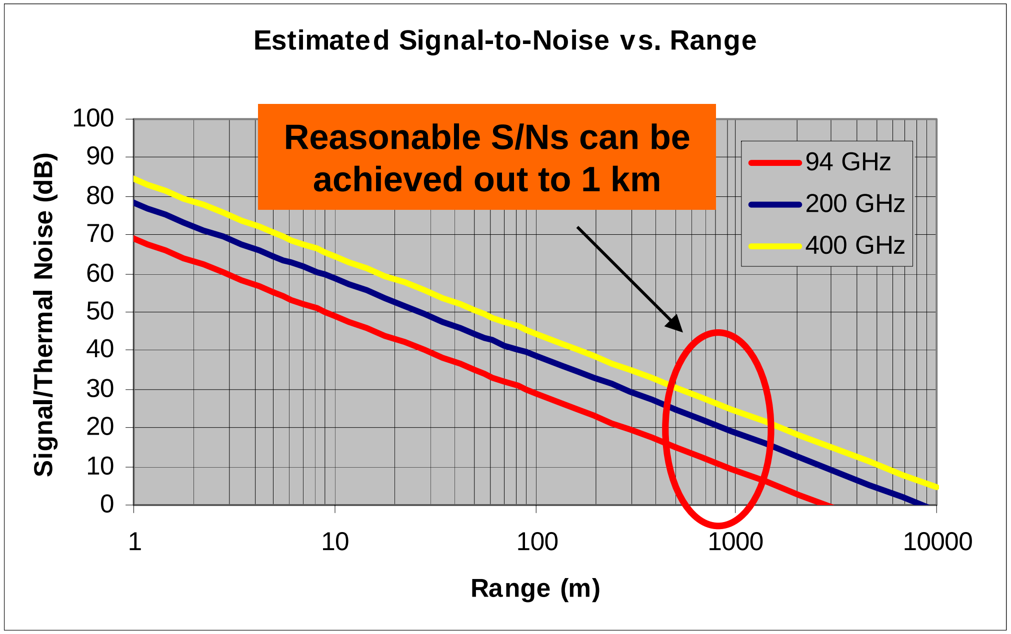


In August 2007, Battelle completed a field test to demonstrate 10 GB/s data transmission at 94 GHz.

Range Equations

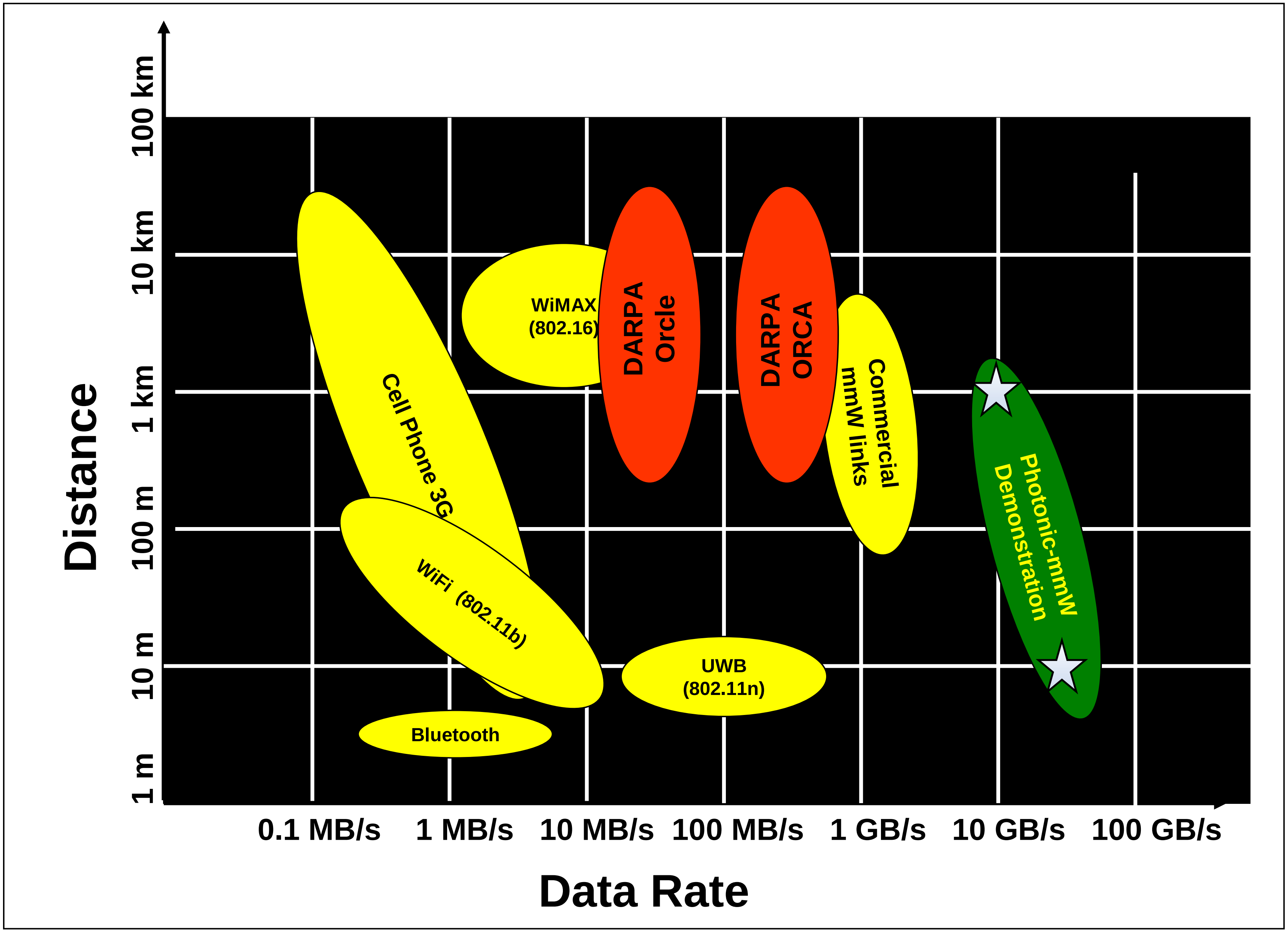
$$P_{receiver} = P_{transmitter} + G_t + G_r - 20\log\left[4\pi \frac{R}{\lambda_{mmw}}\right]$$





It is estimated that the Cell-Phone sized transceiver can have a range of in excess of 1 km with a data rate of 5 GB/s.

Wireless Data Rates

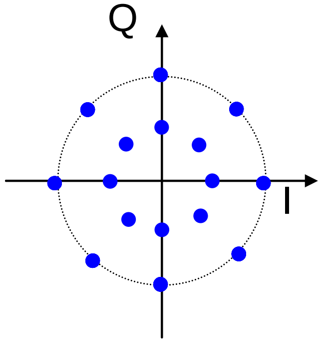


Millimeter-wave Photonics Test Bed

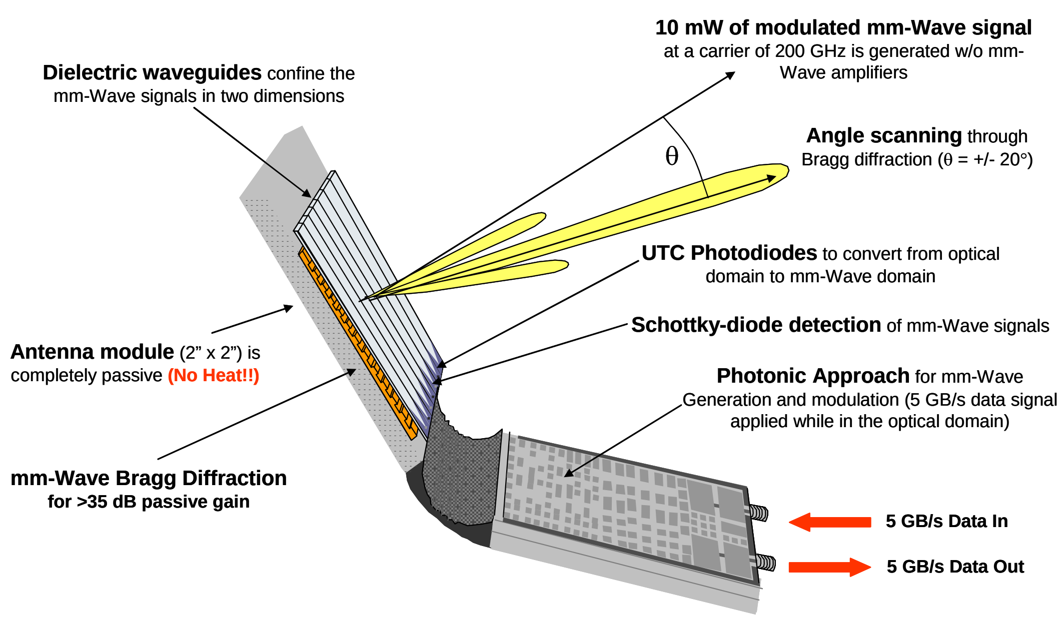
- Photonic Components
  - Fixed and Tunable 1550 nm lasers
  - Arrayed Waveguide Gratings
  - Electrooptic Modulators
  - Optical Amplifiers
  - Polarization Controllers
- Microwave Components
  - Frequency Sources
  - Amplifiers
- Millimeter-wave Components
  - Waveguides, Couplers, Splitters
  - Schottky Diode Detectors
  - Low Noise Amplifiers
  - Cassegrain and Horn Antennas
- Test Equipment
  - Agilent E8363B mmW Network Analyzer
  - 12.5 Gb/s BERT

Accomplishments and Path Forward

- **Battelle has developed a mmW communications link**
- **Field Tests have confirmed operation out to 1 km**
- **A Tri-Band System, operating at 35 GHz, 94 GHz and 140 GHz, has been built and demonstrated in the lab.**
- **Duplex Operation has been verified to 10 Gb/s**
- **Plans for Further Development**
  - Consider Spectral Efficient Coding
    - QAM at millimeter-wave Frequencies



Star 16 QAM



The Battelle Development Team

- Principal Investigator:
  - Dr. Richard W. Ridgway
    - Senior Research Leader at Battelle
    - 25 years of integrated optics and microwave experience with lithium niobate, silica waveguides, and EO polymers.
    - Architect of Battelle's mm-Wave Photonics test bed.
    - Ph.D. in Electrical Engineering (focus: communication theory)
    - 21 U.S. Patents in integrated optical components for microwave and millimeter-wave applications
- Electronics and Avionics Systems
  - 220 engineers and support staff
  - State-of-the-art clean room facility
  - Fully equipped integrated optics test facility
  - Microwave/mm-Wave laboratories and test equipment