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

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

Date Submitted: July 2008

Source: Richard W. Ridgway, Battelle

Address
Voice: FAX: E-Mail: ridgway@battelle.org

Re:

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

Purpose:

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Millimeter-wave Photonics for High Data Rate Wireless Communication Systems

Presentation to
IEEE 802.15 THz Interest Group

Richard W. Ridgway, Ph.D.
Senior Research Leader
Electronics and Avionics Systems
July 16, 2008

ridgway@battelle.org
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

1970
1976 Lithium Niobate Waveguides
1978 NASA Preprocessor in LN

1980
1982 AO Scanner
1983 EO Digital Correlator
1985 Microwave Sampler
1986 Pipelined Polynomial Processor
1987 PIRI is Launched
1989 94 GHz Optical Modulator

1990
1991 Biorefractometer
1993 Grating Biosensor
1993 EO Spectrum Analyzer
1995 PIRI sells AWG

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

1976 Lithium Niobate Waveguides
1978 NASA Preprocessor in LN
**Millimeter-wave Photonics**

**94 GHz Electrooptic Modulator**


**50 GHz Real-Time Spectrum Analyzer**

**100 G sample/second Sampler for Microwave Signals**


**94 GHz Beam Steering Antenna**
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.
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.

Lithium Niobate Modulators

- **Fujitsu FT7912ER**
  - Dual Drive 10 GB/s Modulator
  - Specifications
    - $V_\pi$ (push-pull) = 2.6 volts @10 GHz
    - Optical Loss = 6.0 dB
  - Measured
    - $V_\pi$(push-pull) = 2 volts @DC
    - $V_\pi$(push-pull) = 2.4 volts @500 MHz
    - Optical Loss = 5.25 dB
Combining the Filtered Signals

25 GHz AWG

1549.0 nm
1549.2 nm
1549.4 nm
1549.6 nm
1549.8 nm
1550.0 nm
1550.2 nm
1550.4 nm
1550.6 nm
1550.8 nm
1551.0 nm

λ
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.

Data Rate = 10 GB/s
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

\[ P_{\text{receiver}} = P_{\text{transmitter}} + G_t + G_r - 20 \log \left( \frac{R}{\lambda_{\text{mmw}}} \right) \]

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

![Wireless Data Rates Graph](attachment:image.png)

- **Cell Phone 3G**
- **WiMAX (802.16)**
- **DARPA Orcle**
- **DARPA ORCA**
- **Commercial mmW links**
- **Photicorn-mmW Demonstration**
- **Bluetooth**
- **WiFi (802.11b)**
- **UWB (802.11n)**

**Distance**
- 1 m
- 10 m
- 100 m
- 1 km
- 10 km
- 100 km

**Data Rate**
- 0.1 MB/s
- 1 MB/s
- 10 MB/s
- 100 MB/s
- 1 GB/s
- 10 GB/s
- 100 GB/s
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

![Diagram](attachment://diagram.png)

- Dielectric waveguides confine the mm-Wave signals in two dimensions
- Antenna module (2" x 2") is completely passive (No Heat!!!)
- mm-Wave Bragg Diffraction for >35 dB passive gain
- UTC Photodiodes to convert from optical domain to mm-Wave domain
- Schottky-diode detection of mm-Wave signals
- Photonic Approach for mm-Wave Generation and modulation (5 GB/s data signal applied while in the optical domain)
- Angle scanning through Bragg diffraction ($\theta = +/- 20^\circ$)
- 10 mW of modulated mm-Wave signal at a carrier of 200 GHz is generated w/o mm-Wave amplifiers

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