Outline

(1) Technological overview of optical communication infrastructure

(2) Ultrafast and high spectral efficiency optical transmission
   • 1024~2048 QAM transmission
   • Optical Nyquist pulse TDM transmission

(3) Multi-core fibers for SDM transmission
   • Mode-coupling measurements along an MCF using a 7 channel OTDR

(4) Summary
Technological overview of optical fiber transmission

100M Link Capacity / fiber(s) [bps]

1.6G 2.4G


40% increase per year

1 Tbit/s@2009

Increase in Internet Traffic in Japan

2nd Innovation
- Multi-level coherent transmission
- Multi-core fiber
- Multi-mode control

1st Innovation
- EDFA, WDM

Moore’s Law

EDFA 10G

TDM

10Gx80

40G 100G

100T

1E 1P

1T 1G

1G 100M


Internet traffic [Gbit/s]

1st Innovation
- EDFA, WDM

Physical dimensions for modulation and multiplexing

WDM: Wavelength Division Multiplexing
SDM: Space Division Multiplexing

By courtesy of P. Winzer
**First “M”: Multi-level modulation**

**QAM (Quadrature Amplitude Modulation):**
- Two carriers with the same frequency are amplitude-modulated independently.
- The phase of the two carriers is 90 deg. shifted each other.
- $2^N$ QAM processes $N$ bits in a single channel, so it has $N$ times spectral efficiency compared with OOK.

![Constellation map for 16 (=2^4) QAM](image)

**Challenges to 1024 and 2048 QAM**

**SNR requirement for FEC limit (BER = 2x10^-3)**

- **512 QAM:**
  - $E_b/N_0=21$ dB $\rightarrow$ SNR=30.5 dB (1 Symbol =9 bit)

- **1024 QAM:**
  - $E_b/N_0=24$ dB $\rightarrow$ SNR=34 dB (1 Symbol =10 bit)

- **2048 QAM:**
  - $E_b/N_0=27$ dB $\rightarrow$ SNR=37.4 dB (1 Symbol =11 bit)

![Constellation of back-to-back signal](image)
Polarization-multiplexed 3 Gsymbol/s, 1024 QAM (60 Gbit/s) coherent optical transmission system

3 Gsymbol/s 1024 QAM signal
- Nyquist raised cos. filter (roll off = 0.35)
- Pre-equalization with FDE
  (FFT size = 16384, Frequency resolution = 0.73 MHz)

C2H2 Frequency
Stabilized Fiber Laser
- Linewidth: 4 kHz

IQ Mod.
Amplifier

PC: Polarization Controller
OFS: Optical Frequency Shifter
PBC: Polarization Beam Combiner
SSMF: Standard Single-mode Fiber
DBM: Double Balanced Mixer
B-PD: Balanced Photo-Detector


Experimental results for 60 Gbit/s 1024 QAM transmission

BER characteristics

Spectral efficiency (single-channel)

\[
\text{Spectral efficiency} = \frac{60 \text{ Gbit/s}}{4.05 \text{ GHz} \times 1.07} \approx 13.8 \text{ bit/s/Hz}
\]

- Roll-off factor \( \alpha = 0.35 \)
- Signal bandwidth: 3 Gsymbol/s \((1+\alpha) = 4.05 \text{ GHz}\)

After 150 km transmission
Trend in high speed, high capacity coherent transmission

High-speed transmission
OTDM/ETDM

OOK, DPSK, DQPSK
Driving force for high-speed optical networking
100 Gbit/s Ethernet

RZ-OTDM

Optical Nyquist pulse transmission

Spectrally efficient transmission
Multi-level modulation

M-PSK, QAM, OFDM
Driving force for ultra-efficient/large capacity FTTH

OTDM/RZ-QAM

Realization of high-speed, high spectral efficiency transmission

Proposal of optical Nyquist pulse and its TDM

Nyquist filter has a sinc-function-like impulse response with zero crossing at every symbol period ➔ Intersymbol interference (ISI) can be suppressed even in smaller bandwidth
Comparision between Nyquist filtering and optical Nyquist pulses

Baseband data signal (QPSK, QAM, …)

Nyquist filter

Bandwidth limited data signal (not a “pulse”)


Waveform:

\[ r(t) = \frac{\sin(\pi t / T) \cos(\alpha \pi t / T)}{\pi t / T} \frac{1}{1 - (2\alpha t / T)^2} \]

Spectrum:

\[ R(f) = \begin{cases} 
1, & 0 \leq |f| \leq \frac{1 - \alpha}{2T} \\
\frac{1}{2} \left(1 - \sin \left(\frac{\pi}{2\alpha} (2T|f|-1)\right)\right), & \frac{1 - \alpha}{2T} \leq |f| \leq \frac{1 + \alpha}{2T} \\
0, & |f| \geq \frac{1 + \alpha}{2T} 
\end{cases} \]

Transfer function:

\[ H(f) = \begin{cases} 
1, & 0 \leq |f| \leq \frac{1 - \alpha}{2T} \\
\frac{1}{2} \left(1 - \sin \left(\frac{\pi}{2\alpha} (2T|f|-1)\right)\right), & \frac{1 - \alpha}{2T} \leq |f| \leq \frac{1 + \alpha}{2T} \\
0, & |f| \geq \frac{1 + \alpha}{2T} 
\end{cases} \]

Optical Nyquist “pulse”


Transfer function:

\[ H(f) = \begin{cases} 
1, & 0 \leq |f| \leq \frac{1 - \alpha}{2T} \\
\frac{1}{2} \left(1 - \sin \left(\frac{\pi}{2\alpha} (2T|f|-1)\right)\right), & \frac{1 - \alpha}{2T} \leq |f| \leq \frac{1 + \alpha}{2T} \\
0, & |f| \geq \frac{1 + \alpha}{2T} 
\end{cases} \]

Pulse shaper

Optical Nyquist “pulse”


Ultrahigh-speed OTDM transmission using optical Nyquist pulses[1]

Optical Nyquist pulse train

40G 25 ps
40G 25 ps
40G 25 ps
40G 25 ps

Multiplexer

160G 6.25 ps

Optical Fiber

Demultiplexer

40G 40G 40G

Ultrafast optical sampling

Demultiplexed signal

40 GHz optical Nyquist pulse \((\alpha = 0.5)\)

160 Gbaud OTDM waveform

Demultiplexed signal

1.28 Tbit/s/ch - 525 km polarization-multiplexed DPSK transmission with 640 Gbaud optical Nyquist pulse

Optical Nyquist pulse for 640 Gbaud transmission

- Due to narrower spectral width of the Nyquist pulse, the growth rate of the depolarization-induced crosstalk is much lower than a Gaussian pulse.
- Crosstalk was 4 dB lower than that of a Gaussian pulse after 525 km propagation.

Growth of depolarization-induced crosstalk
1.28 Tbit/s/ch-525 km polarization-multiplexed transmission experiments

Spectral efficiency: \( \frac{1.28 \text{ Tbit/s}}{960 \text{ GHz} \times 1.07} = 1.25 \text{ bit/s/Hz for DPSK} \) (Typical SE is 0.5 bit/s/Hz for DPSK)

Multi-core fibers for SDM transmission

<table>
<thead>
<tr>
<th># of cores</th>
<th>19</th>
<th>7</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core pitch</td>
<td>35 ( \mu \text{m} )</td>
<td>45 ( \mu \text{m} )</td>
<td>37 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Cladding diameter</td>
<td>200 ( \mu \text{m} )</td>
<td>150 ( \mu \text{m} )</td>
<td>225 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Loss</td>
<td>0.23 dB/km</td>
<td>0.18 dB/km</td>
<td>0.199 dB/km</td>
</tr>
<tr>
<td>Aeff</td>
<td>72 ( \mu \text{m}^2 )</td>
<td>80 ( \mu \text{m}^2 )</td>
<td>88 ( \mu \text{m}^2 )</td>
</tr>
<tr>
<td>Crosstalk</td>
<td>-42 dB/km</td>
<td>-92 dB/km</td>
<td>-55~49 dB/km</td>
</tr>
</tbody>
</table>
**Space-division multiplexed transmission using MCF**

<table>
<thead>
<tr>
<th><strong>Total Bit rate</strong></th>
<th>1.01 Pbit/s (456 Gbit/s PDM-32QAM x 222 WDM x 12 core)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance</strong></td>
<td>52 km</td>
</tr>
<tr>
<td><strong>MCF coupling</strong></td>
<td>Fan in/fan out device</td>
</tr>
</tbody>
</table>

**Mode coupling measurement along MCF using multi-channel OTDR**

1. **Optical pulse**
   - Pulse width: $\Delta \tau$
   - Input power: $P_0$

2. **MCF**
   - MCF fiber length
   - Optical pulse input
   - Backscattered power

3. **Mode coupling between core 1 and core m:**
   \[
   \begin{align*}
   \frac{dP_1}{dz} &= -\alpha_1 P_1 + h_{1,m} (P_m - P_1) \\
   \frac{dP_m}{dz} &= -\alpha_m P_m + h_{1,m} (P_1 - P_m)
   \end{align*}
   \]

   From $P_{bsm} / P_{bs1}$, mode coupling coefficient $h_{1,m}$ and its longitudinal variation can be measured.

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Mode coupling measurement results

- **Core pitch**: 46 μm
- **Cladding diameter**: 217 μm
- **Length**: 2.9 km

**MCF under test**

**Original backscattered signals**

- **Mode coupling ratio from center to outer cores**: 0.20 dB/km
- **Mode coupling coefficient**: 2.9 km
- **Length**: 217 μm
- **Cladding diameter**: 46 μm
- **Core pitch**: 183 μm

**M. Nakazawa et al., OFC2012, OTh3I.3**

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**Mode-division-multiplexed transmission using MIMO**

(1) **SISO (Single Input Single Output) (One Tx, One Rx)**

Received signal: \( y(t) = \sum_{k=1}^{Q} h_k x(t) + n(t) \)

Distortion in mode \( k \): \( h_k = a_k \kappa_k e^{j\omega_k \tau_k} \)

- \( a_k \): Loss of mode \( k \)
- \( \kappa_k \): Group delay of mode \( k \)
- \( \tau_k \): Coupling ratio to mode \( k \)

(2) **MIMO (Multiple Input Multiple Output) (M Tx, N Rx)**

Received signal at Rx \( i \):

\[
 y_i(t) = \sum_{j=1}^{M} \sum_{k=1}^{Q} h_{jk} x_j(t) + n_i(t) = \sum_{j=1}^{M} H_{ij} x_j(t) + n_i(t), \quad i = 1 \cdots N
\]

- \( h_{jk} \): Distortion when transmitted from Tx \( j \) to Rx \( i \) via mode \( k \)

\( \rightarrow \) Matrix representation: \( y(t) = Hx(t) + n(t) \)

Estimate \( H \) from \( x(t) \) and \( y(t) \)
Mode multiplexer / demultiplexer

Free space optics with phase plates \(^1\)

LCOS (Liquid Crystal on Silicon) \(^3\)

Mode-division-multiplexed transmission experiments

5 modes x 100 Gbit/s - 40 km PDM-QPSK transmission using LP\(_{01}\) + LP\(_{11a}\) + LP\(_{11b}\) + LP\(_{21a}\) + LP\(_{21b}\) (2x2 MIMO + 4x4 MIMO + 4x4 MIMO) \(^1\)

6 modes x 40 Gbit/s - 130 km PDM-QPSK transmission using LP\(_{01}\)+LP\(_{11a}\)+LP\(_{11b}\)+LP\(_{21a}\)+LP\(_{21b}\)+LP\(_{02}\) (12x12 MIMO) \(^2\)

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\(^2\) N. Hanzawa et al., OFC2011, OWA4.
\(^3\) C. Koebele et al., Opt. Exp. 19, 16593 (2011).
Recent advances toward the realization of an ultrahigh SE and ultrahigh-capacity SDM transmission are presented with a special focus on the following novel technologies:

1. Ultramulti-level coherent transmission up to 1024 levels
2. Ultrafast coherent pulse transmission with OTDM RZ/QAM
3. Nyquist pulse transmission
4. MCF characterization with longitudinal mode-coupling measurement

Fiber capacity at a Pbit/s level is expected to be achieved with SDM by taking full advantage of the high spectral efficiency and high spatial density in MCF.