IMPROVEMENT OF FIBER OPTIC SYSTEM PERFORMANCE BY SYNCHRONOUS PHASE MODULATION AND FILTERING AT THE TRANSMITTER

By

Virach Wongpaibool

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Ira Jacobs, Chair
J. Kenneth Shaw
Timothy Pratt
Roger H. Stolen
Brian D. Woerner

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Committee Chairman: Dr. Ira Jacobs

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ABSTRACT

In this dissertation the performance of a novel variant of a return-to-zero (RZ) modulation format, based on square-wave phase modulation and filtering of a continuous-wave (CW) signal, is investigated and compared with various modulation formats considered in the literature. We call this modulation format continuous-wave square-wave (CWSW). With CWSW an RZ pulse train is generated by phase modulating the CW signal by a periodic square-wave phase function having an amplitude of $\pi/2$ and frequency of half the bit rate, and then filtering the signal. The filter performs phase-to-amplitude conversion, resulting in an alternate-sign RZ pulse train, which is shown to be resistant to fiber dispersion. The alternate-sign RZ pulse train is then amplitude modulated with the data before the transmission. Alternate signs between adjacent pulses makes this signal format robust to impairments caused by the optical fiber, similar to a conventional alternate-sign RZ signal format. However, the unique property of the CWSW signal format is that individual pulses can induce peak intensity enhancement (PIE), a phenomenon by which the peak of a pulse increases during the initial propagation in the presence of dispersion. The PIE in effect delays the decrease in the pulse peak, which represents the signal level for bit 1. Thus, the eye opening at the receiver is improved. An analytically tractable model is developed to explain the occurrence of the PIE, which cannot be achieved with a conventional pulse shape. The

sources of performance degradations for different modulation formats in single-channel 40 Gb/s systems are also discussed in this dissertation. Various transmission system configurations of practical interest are considered and the performance of CWSW is compared with alternative modulation formats. It is found that the CWSW signal format performs significantly better than the other considered modulation formats in systems not employing dispersion compensation and is comparable to the others in dispersion-managed systems. Furthermore, the transmitter configuration of the CWSW signal format is simpler than the other approaches.

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Chapter 7

Table 7.1 Summary of maximum transmission distance $z_{\max}$ and corresponding optimum system parameters for different fiber configurations investigated in this dissertation…….. 239

List of Acronyms and Symbols

Acronyms

AMI	Alternate Mark Inversion
APM	sinusoidal Alternate Phase Modulation
ASE	Amplified Spontaneous Emission
CPM	Cross Phase Modulation
CRZ	Chirped Return-to-Zero
CS-RZ	Carrier-Suppressed Return-to-Zero
CW	Continuous Wave
CWSW	Continuous-Wave Square-Wave
DC	Direct current
DCF	Dispersion Compensating Fiber
DCS-RZ	Duobinary Carrier-Suppressed Return-to-Zero
DSF	Dispersion-Shifted Fiber
EDFA	Erbium-Doped Fiber Amplifier
EHS-DK	Extra-High-Slope Dispersion Compensating Fiber
EOP	Eye Opening
FFT	Fast Fourier Transform
FWM	Four-Wave Mixing
GVD	Group-Velocity Dispersion
IFWM	Intrachannel Four-Wave Mixing
IM	Intensity Modulation
ISI	Intersymbol Interference
IXPM	Intrachannel Cross Phase Modulation
LEAF	Large Effective Area Fiber
MZ	Mach-Zehnder
NLSE	Nonlinear Schrödinger Equation
No PM	No Phase Modulation

NRZ	Non-Return-to-Zero
NZDF	Non-Zero Dispersion Fiber
NZ-DSF	Non-Zero Dispersion-Shifted Fiber
OTDM	Optical Time Division Multiplexing
PIE	Peak Intensity Enhancement
PMD	Polarization-Mode Dispersion
PSD	Power Spectral Density
RDF	Reverse-Dispersion Fiber
RMS	Root Mean Square
RZ	Return-to-Zero
SaPM	sinusoidal Same Phase Modulation
SBS	Stimulated Brillouin Scattering
SNR	Signal to Noise Ratio
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
SSF	Split-Step Fourier
SSMF	Standard Single-Mode Fiber
SW	Square Wave
SWM	Square-Wave Phase Modulation
TDM	Time Division Multiplexing
TRSF	(Lucent) TrueWave Reduced Slope Fiber
USCA	Unequally Spaced Channel Allocation
VSB-RZ	Vestigial Sideband RZ
WDM	Wavelength Division Multiplexing
XPM	Cross Phase Modulation

Roman Symbols

A	Slowly-varying amplitude of pulse envelope
A_{eff}	Effective core area of an optical fiber

a	Pulse width
a_0	Initial pulse width
B	Bit Rate
B	Modulation index of phase modulation
B_e	Electrical equivalent noise bandwidth
B_0	Bandpass noise equivalent bandwidth of ASE noise (3-dB bandpass bandwidth of optical filter at optical amplifier output)
$BW_{3dB,Filter,BB}$	3-dB equivalent baseband bandwidth of bandpass filter
BW_{Tx}	3-dB bandwidth of bandpass filter
BW_{Mux}	3-dB bandwidth of bandpass filter
b	Chirp
C	Normalized chirp, $C = -2a_0^2 b_0$
c	Velocity of light
C_e	Effective noise capacitance
C_{opt}	Optimum normalized chirp
D	Dispersion parameter
D_M	Material dispersion
D_W	Waveguide dispersion
f	Physical frequency
f_n	Normalized frequency, $f_n = f/R_b$
G	Optical amplifier gain
G	Amplitude of Gaussian pulse
g_B	Brillouin gain coefficient
g_R	Raman gain coefficient
h	Planck's constant
i_{q-sp}	Signal-spontaneous photocurrent
i_{sp-sp}	Spontaneous-spontaneous photocurrent

i_{ph}	Photocurrent
k	Boltzmann's constant
L	Transmission distance (Fiber length)
L	Amplifier spacing
L	Lagrangians
L_D	Dispersion length
L_{NL}	Nonlinear length
$\tilde{L}_{NL}$	Effective nonlinear length
M	The number of FWM-generated signals
M	The number of spans
N	The number of channels
N	Nonlinearity parameter, $N^2 = L_D / L_{NL}$
$\tilde{N}$	Effective nonlinearity parameter
n_0	Linear refractive index
n_2	Nonlinear refractive index
n_{sp}	Spontaneous emission factor
P_0	Pulse peak power
P_{ASE}	ASE noise power
P_{avg}	Average transmitted power
P_e	Probability of bit error
P_{th}	Threshold power
Q	Performance measure related to P_e
q_e	Elementary charge constant
$\mathcal{R}$	Responsivity of the photodiode
R_b	Bit rate
R_e	Effective noise resistance
S	Dispersion slope

T	Retarded time, $T = t - z / v_g$
T	Room temperature
T_b	Bit period, $T_b = 1/R_b$
U	Normalized pulse envelope
V_T	Thermal voltage, $V_T = kT/q_e$
v_g	Group velocity
v_p	Signal spectral width
v_B	Brillouin gain bandwidth
t	Physical time
z	Transmission distance (Fiber length)
$z_{\max}$	Maximum transmission distance
z_n	Normalized transmission distance, $z_n = z / L_D$

Greek Symbols

α	Fiber attenuation
β	Propagation (phase) constant
β_2	(Second-order) group-velocity dispersion parameter
β_3	Third-order group-velocity dispersion parameter
$\Delta\omega$	Pulse spectral width
ΔT	Pulse broadened caused by dispersion
η	Quantum efficiency of photo diode
η	Four-wave mixing efficiency
γ	Nonlinear coefficient
λ	Wavelength
λ_0	Operating wavelength
λ_c	Operating wavelength
λ_{ZD}	Zero-material dispersion wavelength

μ_0	Average photocurrent for bit 0
μ_1	Average photocurrent for bit 1
ν	Operating frequency
σ	RMS pulse width
σ_{q-sp}	Standard deviation of signal-spontaneous beat noise
$\sigma_{q-sp,1}$	Standard deviation of signal-spontaneous beat noise for bit 1
$\sigma_{q-sp,0}$	Standard deviation of signal-spontaneous beat noise for bit 0
σ_{sp-sp}	Standard deviation of spontaneous-spontaneous beat noise
σ_{th}	RMS width of thermal noise
σ_0	Standard deviation of photocurrent for bit 0
σ_1	Standard deviation of photocurrent for bit 1
τ	Retarded time,
τ_n	Normalized retarded time, $\tau_n = \tau / T_b$
ω_0	Operating frequency