OPTICAL FIBER COMMUNICATIONS

Principles and Practice

John M. Senior

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Preface

The concept of guided lightwave communication along optical fibers has stimulated a major new technology which has come to maturity over the last fifteen years. During this period tremendous advances have been achieved with optical fibers and components as well as with the associated optoelectronics. As a result this new technology has now reached the threshold of large scale commercial exploitation. Installation of optical fiber communication systems is progressing within both national telecommunication networks and more localized data communication and telemetry environments. Furthermore, optical fiber communication has become synonymous with the current worldwide revolution in information technology. The relentless onslaught will undoubtedly continue over the next decade and the further predicted developments will ensure even wider application of optical fiber communication technology in this 'information age'.

The practical realization of wide-scale optical fiber communications requires suitable education and training for engineers and scientists within the technology. In this context the book has been developed from both teaching the subject to final year undergraduates and from a successful series of short courses on optical fiber communications conducted for professional engineers at Manchester Polytechnic. This book has therefore been written as a comprehensive introductory textbook for use by undergraduate and postgraduate engineers and scientists to provide them with a firm grounding in the major aspects of this new technology whilst giving an insight into the possible future developments within the field. The reader should therefore be in a position to appreciate developments as they occur. With these aims in mind the book has been produced in the form of a teaching text enabling the reader to progress onto the growing number of specialist texts concerned with optical fiber waveguides, optoelectronics, integrated optics, etc.

In keeping with the status of an introductory text the fundamentals are included where necessary and there has been no attempt to cover the entire field in full mathematical rigor. However, selected proofs are developed in important areas throughout the text. It is assumed that the reader is conversant with differential and integral calculus and differential equations. In addition, the reader will find it useful to have a grounding in optics as well as a reasonable familiarity with the fundamentals of solid state physics.

Chapter 1 gives a short introduction to optical fiber communications by considering the historical development, the general system and the major advantages provided by this new technology. In Chapter 2 the concept of the optical fiber as a transmission medium is introduced using a simple ray theory approach. This is followed by discussion of electromagnetic wave theory applied to optical fibers prior to consideration of lightwave transmission within the various fiber types. The major transmission characteristics of optical fibers are then discussed in some detail in Chapter 3.

Chapters 4 and 5 deal with the more practical aspects of optical fiber communications and therefore could be omitted from an initial teaching program. In Chapter 4 the manufacture and cabling of the various fiber types are described, together with fiber to fiber connection or jointing. Chapter 5 gives a general treatment of the major measurements which may be undertaken on optical fibers in both the laboratory and the field. This chapter is intended to provide sufficient background for the reader to pursue useful laboratory work with optical fibers.

Chapters 6 and 7 discuss the light sources employed in optical fiber communications. In Chapter 6 the fundamental physical principles of photoemission and laser action are covered prior to consideration of the various types of semiconductor and nonsemiconductor laser currently in use, or under investigation, for optical fiber communications. The other important semiconductor optical source, namely the light emitting diode, is dealt with in Chapter 7.

The next two chapters are devoted to the detection of the optical signal and the amplification of the electrical signal obtained. Chapter 8 discusses the basic principles of optical detection in semiconductors; this is followed by a description of the various types of photodetector currently utilized. The optical fiber receiver is considered in Chapter 9 with particular emphasis on its performance in noise.

Chapter 10 draws together the preceding material in a detailed discussion of optical fiber communication systems, aiming to provide an insight into the design criteria and practices for all the main aspects of both digital and analog fiber systems. A brief account of coherent optical fiber systems is also included to give an appreciation of this area of future development. Finally, Chapter 11 describes the many current and predicted application areas for optical fiber communications by drawing on examples from research and development work which has already been undertaken. This discussion is expanded into consideration of other likely future developments with a brief account of the current technology involved in integrated optics and optoelectronic integration.

Worked examples are interspersed throughout the text to assist the learning process by illustrating the use of equations and by providing realistic values for the various parameters encountered. In addition, problems have been provided at the end of relevant chapters (Chapters 2 to 10 inclusive) to examine the reader's understanding of the text and to assist tutorial work. A Teacher's Manual containing the solutions to these problems may be obtained from the publisher. Extensive end-of-chapter references provide a guide for further reading and indicate a source for those equations which have been quoted without derivation. A complete glossary of symbols, together with a list of common abbreviations employed in the text, is provided. SI units are used throughout the text.

I am very grateful for the many useful comments and suggestions provided by reviewers which have resulted in significant improvements to this text. Thanks must also be given to the authors of numerous papers, articles and books which I have referenced whilst preparing the text, and especially to those authors, publishers and companies who have kindly granted permission for the reproduction of diagrams and photographs. Further, I would like to thank my colleagues in the Dept. of Electrical and Electronic Engineering at Manchester Polytechnic for their many helpful comments on the text; in particular Dr. Norman Burrow, Dr. John Edwards and Stewart Cusworth for the time spent checking the manuscript. I am also grateful to my family and friends for tolerating my infrequent appearances over the period of the writing of this book. Finally, words cannot express my thanks to my wife, Marion, for her patience and encouragement with this project and for her skilful typing of the manuscript.

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Glossary of Symbols and Abbreviations

A	constant, area (cross-section, emission), far field pattern size, mode amplitude, wave amplitude (A_o)
A_{21}	Einstein coefficient of spontaneous emission
A_c	peak amplitude of the subcarrier waveform (analog transmission)
a	fiber core radius, parameter defining the asymmetry of a planar guide (eqn. 11.6), baseband message signal ($a(t)$)
a_k	integer 1 or 0
B	constant, electrical bandwidth (post detection), magnetic flux density, mode amplitude, wave amplitude (B_0)
B_{12}, B_{21}	Einstein coefficients of absorption, stimulated emission
B_F	modal birefringence
B_m	bandwidth of an intensity modulated optical signal $m(t)$
B_{opt}	optical bandwidth
B_r	recombination coefficient for electrons and holes
B_T	bit rate, when the system becomes dispersion limited (B_T (DL))
b	normalized propagation constant for a fiber, ratio of luminance to composite video
C	constant, capacitance, crack depth (fiber), wave coupling coefficient per unit length
C_a	effective input capacitance of an optical fiber receiver amplifier
C_d	optical detector capacitance
C_f	capacitance associated with the feedback resistor of a transimpedance optical fiber receiver amplifier
C_L	total optical fiber channel loss in decibels, including the dispersion–equalization penalty (C_{LD})
C_0	wave amplitude
C_T	total capacitance
c	velocity of light in a vacuum, constant (c_1, c_2)
c_i	tap coefficients for a transversal equalizer
D	amplitude coefficient, electric flux density, distance, corrugation period, decision threshold in digital optical fiber transmission
D_f	frequency deviation ratio (subcarrier FM)
D_L	dispersion–equalization penalty in decibels
D_p	frequency deviation ratio (subcarrier PM)
d	fiber core diameter, distance, width of the absorption region (photodetector), pin diameter (mode scrambler)
d_o	fiber outer (cladding) diameter
E	electric field, energy, Youngs modulus, expected value of a random variable

E_a	activation energy of homogeneous degradation for an LED
E_F	Fermi level (energy), quasi-Fermi level located in the conduction band (E_{Fc}), valence band (E_{Fv}) of a semiconductor
E_g	separation energy between the valence and conduction bands in a semiconductor (bandgap energy)
$E_m(t)$	subcarrier electric field (analog transmission)
E_o	optical energy
E_q	separation energy of the quasi-Fermi levels
e	electronic charge, base for natural logarithms
F	probability of failure, transmission factor of a semiconductor–external interface, excess avalanche noise factor ($F(M)$)
$\mathcal{F}$	Fourier transformation
F_n	noise figure (amplifier)
f	frequency
f_D	peak to peak frequency deviation (PFM–IM)
f_d	peak frequency deviation (subcarrier FM and PM)
f_o	pulse rate (PFM–IM)
G	open loop gain of an optical fiber receiver amplifier
$G_i(r)$	amplitude function in the WKB method
G_o	optical gain (phototransistor)
Gsn	Gaussian (distribution)
g	degeneracy parameter
g	gain coefficient per unit length (laser cavity)
g_m	transconductance of a field effect transistor
g_{th}	threshold gain per unit length (laser cavity)
H	magnetic field
$H_{(\omega)}$	optical power transfer function (fiber), circuit transfer function
$H_A(\omega)$	optical fiber receiver amplifier frequency response (including any equalization)
$H_{CL}(\omega)$	closed loop current to voltage transfer function (receiver amplifier)
$H_{eq}(\omega)$	equalizer transfer function (frequency response)
$H_{OL}(\omega)$	open loop current to voltage transfer function (receiver amplifier)
$H_{out}(\omega)$	output pulse spectrum from an optical fiber receiver
h	Planck's constant, thickness of a planar waveguide, power impulse response for an optical fiber ($h(t)$)
$h_A(t)$	optical fiber receiver amplifier impulse response (including any equalization)
h_{eff}	effective thickness of a planar waveguide
h_{FE}	common emitter current gain for a bipolar transistor
$h_f(t)$	optical fiber impulse response
$h_{out}(t)$	output pulse shape from an optical fiber receiver
$h_p(t)$	input pulse shape to an optical fiber receiver
$h_t(t)$	transmitted pulse shape on an optical fiber link
I	electrical current, optical intensity
I_b	background radiation induced photocurrent (optical receiver)
I_{bias}	bias current for an optical detector
I_c	collector current (phototransistor)
I_d	dark current (optical detector)
I_o	maximum optical intensity
I_p	photocurrent generated in an optical detector
I_{th}	threshold current (injection laser)
i	electrical current

i_a	optical receiver preamplifier shunt noise current
i_{amp}	optical receiver preamplifier total noise current
i_D	decision threshold current (digital transmission)
i_d	photodiode dark noise current
i_{det}	output current from an optical detector
i_f	noise current generated in the feedback resistor of an optical fiber receiver transimpedance preamplifier
i_N	total noise current at a digital optical fiber receiver
i_n	multiplied shot noise current at the output of an APD excluding dark noise current
i_s	shot noise current on the photocurrent for a photodiode
i_{SA}	multiplied shot noise current at the output of an APD including the dark noise current
i_{sig}	signal current obtained in an optical fiber receiver
i_t	thermal noise current generated in a resistor
i_{TS}	total shot noise current for a photodiode without internal gain
J	Bessel function, current density
J_{th}	threshold current density (injection laser)
j	$\sqrt{-1}$
K	Boltzmann's constant, constant dependent on the optical fiber properties, modified Bessel function
K_I	stress intensity factor, for an elliptical crack (K_{IC})
k	wave propagation constant in a vacuum (free space wave number), wave vector for an electron in a crystal, ratio of ionization rates for holes and electrons, integer
k_f	angular frequency deviation (subcarrier FM)
k_p	phase deviation constant (subcarrier PM)
L	length (fiber), distance between mirrors (laser)
L_B	beat length in a single mode optical fiber
L_{bc}	coherence length in a single mode optical fiber
L_c	characteristic length (fiber)
L_o	constant with dimensions of length
L_t	lateral misalignment loss at an optical fiber joint
$\mathcal{L}$	transmission loss factor (transmissivity) of an optical fiber
l	azimuthal mode number, distance, length
l_a	atomic spacing (bond distance)
l_o	wave coupling length
M	avalanche multiplication factor, material dispersion parameter, total number of guided modes or mode volume; for a multimode step index fiber (M_s); for multimode graded index fiber (M_g), mean value (M_1) and mean square value (M_2) of a random variable
M_a	safety margin in an optical power budget
M_{op}	optimum avalanche multiplication factor
M^x	excess avalanche noise factor, (also denoted as $F(M)$)
m	radial mode number, Weibull distribution parameter, intensity modulated optical signal ($m(t)$), mean value of a random variable, integer
m_a	modulation index
N	integer, density of atoms in a particular energy level (e.g. N_1, N_2, N_3), minority carrier concentration in n type semiconductor material, group index of an optical waveguide (N_1)
NA	numerical aperture of an optical fiber
NEP	noise equivalent power

N_o	defined by equation 10.80
n	refractive index (e.g. n_1, n_2, n_3), stress corrosion susceptibility, negative type semiconductor material
n_e	effective refractive index of a planar waveguide
n_o	refractive index of air
P	electrical power, minority carrier concentration in p type semiconductor material, probability, of error ($P(e)$), of detecting a zero level ($P(0)$), of detecting a one level ($P(1)$), of detecting z photons in a particular time period ($P(z)$), conditional probability, of detecting a zero when a one is transmitted ($P(0/1)$), of detecting a one when a zero is transmitted ($P(1/0)$)
P_a	total power in a baseband message signal $a(t)$
P_B	threshold optical power for Brillouin scattering
P_c	optical power coupled into a step index fiber
P_D	optical power density
P_{dc}	d.c. optical output power
P_e	optical power emitted from an optical source
P_G	optical power in a guided mode
P_i	mean input (transmitted) optical power launched into a fiber
P_{int}	internally generated optical power (optical source)
P_m	total power in an intensity modulated optical signal $m(t)$
P_o	mean output (received) optical power from a fiber
P_{opt}	mean optical power travelling in a fiber
P_{out}	initial output optical power (prior to degradation) from an optical source
P_{po}	peak received optical power
P_r	reference optical power level
P_R	threshold optical power for Raman scattering
$P_{Ra}(t)$	backscattered optical power (Rayleigh) within a fiber
P_{sc}	optical power scattered from a fiber
$P_i(\omega)$	frequency spectrum of the mean input optical power launched into a fiber
$P_o(\omega)$	frequency spectrum of the mean output optical power received from a fiber
p	crystal momentum, average photoelastic coefficient, positive type semiconductor material, probability density function ($p(x)$)
q	integer, fringe shift
R	photodiode responsivity, radius of curvature of a fiber bend, electrical resistance (e.g. R_{in}, R_{out})
R_{12}	upward transition rate for electrons from energy level 1 to level 2
R_{21}	downward transition rate for electrons from energy level 2 to level 1
R_a	effective input resistance of an optical fiber receiver preamplifier
R_b	bias resistance, for optical fiber receiver preamplifier (R_{ba})
R_c	critical radius of an optical fiber
R_D	radiance of an optical source
RE_{dB}	ratio of electrical input power in decibels for an optical fiber system
R_f	feedback resistance in an optical fiber receiver transimpedance preamplifier
R_L	load resistance associated with an optical fiber detector
RO_{dB}	ratio of optical output power to optical input power in decibels for an optical fiber system
R_{TL}	total load resistance within an optical fiber receiver
r	radial distance from the fiber axis, Fresnel reflection coefficient, mirror reflectivity, electro-optic coefficient

r_e	generated electron rate in an optical detector
r_{ER}, r_{ET}	reflection and transmission coefficients respectively for the electric field at a planar, guide-cladding interface
r_{HR}, r_{HT}	reflection and transmission coefficients respectively for the magnetic field at a planar guide-cladding interface
r_p	incident photon rate at an optical detector
S	fraction of captured optical power, macroscopic stress
S_f	fracture stress
$S_i(r)$	phase function in the WKB method
$S_m(\omega)$	spectral density of the intensity modulated optical signal $m(t)$
S/N	peak signal power to rms noise power ratio, with peak to peak signal power $[(S/N)_{p-p}]$, with rms signal power $[(S/N)$ rms$]$
S_t	theoretical cohesive strength
s	pin spacing (mode scrambler)
T	temperature, time
T_a	insertion loss resulting from an angular offset between jointed optical fibers
T_c	10–90% rise time arising from intramodal dispersion on an optical fiber link
T_D	10–90% rise time for an optical detector
T_F	fictive temperature
T_l	insertion loss resulting from a lateral offset between jointed optical fibers
T_n	10–90% rise time arising from intermodal dispersion on an optical fiber link
T_o	threshold temperature (injection laser), nominal pulse period (PFM–IM)
T_R	10–90% rise time at the regenerator circuit input (PFM–IM)
T_S	10–90% rise time for an optical source
T_{syst}	total 10–90% rise time for an optical fiber system
T_T	total insertion loss at an optical fiber joint
T_t	temperature rise at time t
T_∞	maximum temperature rise
t	time
t_c	time constant
t_d	switch on delay (laser)
t_e	1/e pulse width from the center
t_r	10–90% rise time
U	eigenvalue of the fiber core
V	electrical voltage, nomalized frequency for an optical fiber or planar waveguide
V_{bias}	bias voltage for a photodiode
V_c	cutoff value of normalized frequency
V_{CC}	collector supply voltage
V_{CE}	collector–emitter voltage (bipolar transistor)
V_{EE}	emitter supply voltage
V_{opt}	voltage reading corresponding to the total optical power in a fiber
V_{sc}	voltage reading corresponding to the scattered optical power in a fiber
v	electrical voltage
v_a	amplifier series noise voltage
$v_A(t)$	receiver amplifier output voltage
v_c	crack velocity
v_g	group velocity
$v_{out}(t)$	output voltage from an RC filter circuit

v_p	phase velocity
W	eigenvalue of the fiber cladding, random variable
W_e	electric pulse width
W_o	optical pulse width
X	random variable
x	coordinate, distance, constant, evanescent field penetration depth, slab thickness
Y	constant, shunt admittance, random variable
y	coordinate, lateral offset at a fiber joint
Z	random variable
Z_0	electrical impedance
z	coordinate, number of photons
z_m	average or mean number of photons arriving at a detector in a time period τ
z_{md}	average number of photons detected in a time period τ
α	characteristic refractive index profile for fiber (profile parameter), optimum profile parameter (α_{op})
$\bar{\alpha}$	loss coefficient per unit length (laser cavity)
α_{cr}	connector loss at transmitter and receiver in decibels
α_{dB}	signal attenuation in decibels per unit length
α_{fc}	fiber cable loss in decibels per kilometer
α_j	fiber joint loss in decibels per kilometer
α_N	signal attenuation in nepers
α_o	absorption coefficient
α_r	radiation attenuation coefficient
β	wave propagation constant
β	gain factor (injection laser cavity)
β_c	isothermal compressibility
β_o	proportionality constant
β_r	degradation rate
γ	angle, attenuation coefficient per unit length for a fiber
γ_p	surface energy of a material
γ_R	Rayleigh scattering coefficient for a fiber
Δ	relative refractive index difference between the fiber core and cladding
δ_E	phase shift associated with transverse electric waves
δ_f	uncorrected source frequency width
δ_H	phase shift associated with transverse magnetic waves
$\delta\lambda$	optical source spectral width (linewidth)
δT	intermodal dispersion time in an optical fiber
δT_g	delay difference between an extreme meridional ray and an axial ray for a graded index fiber
δT_s	delay difference between an extreme meridional ray and an axial ray for a step index fiber, with mode coupling (δT_{sc})
ε	electrical permittivity, of free space (ε_o), relative (ε_r)
ζ	solid acceptance angle
η	quantum efficiency (optical detector)
η_{ang}	angular coupling efficiency (fiber joint)
η_c	coupling efficiency (optical source to fiber)
η_D	differential external quantum efficiency (optical source)
η_{ep}	external power efficiency (optical source)
η_i	internal quantum efficiency (optical source)
η_{lat}	lateral coupling efficiency (fiber joint)
η_{pc}	overall power conversion efficiency (optical source)
η_T	total external quantum efficiency (optical source)

θ	angle, fiber acceptance angle (θ_a), Bragg diffraction angle (θ_B)
Λ	acoustic wavelength, period for perturbations in a fiber
Λ_c	cutoff period for perturbations in a fiber
λ	optical wavelength
λ_c	long wavelength cutoff (photodiode)
λ_o	wavelength at which first order dispersion is zero
μ	magnetic permeability, relative permeability (μ_r), permeability of free space (μ_o)
ν	optical source bandwidth in gigahertz
ρ	polarization rotation in a single mode optical fiber
ρ_f	spectral density of the radiation energy at a transition frequency f
σ	standard deviation, (rms pulse width), variance (σ^2)
σ_c	rms pulse broadening resulting from intramodal dispersion in a fiber
σ_m	rms pulse broadening resulting from material dispersion in a fiber
σ_n	rms pulse broadening resulting from intermodal disperion, in a graded index fiber (σ_g), in a step index fiber (σ_s)
σ_T	total rms pulse broadening in a fiber or fiber link
σ_λ	rms spectral width of emission from optical source
τ	time period, bit period, pulse duration 3 dB pulse width (τ(3 dB))
τ_{21}	spontaneous transition lifetime between energy levels 2 and 1
τ_E	time delay in a transversal equalizer
τ_e	$1/e$ full width pulse broadening due to dispersion on an optical fiber link
τ_g	group delay
τ_i	injected (minority) carrier lifetime
τ_r	radiative minority carrier lifetime
Φ	linear retardation
ϕ	angle, critical angle (ϕ_c)
ψ	scalar quantity representing E or H field
ω	angular frequency, of the subcarrier waveform in analog transmission (ω_c), of the modulating signal in analog transmission (ω_m)
ω_o	spot size of the fundamental mode
∇	vector operator, Laplacian operator (∇^2)

A–D	analog to digital
a.c.	alternating current
AGC	automatic gain control
AM	amplitude modulation
APD	avalanche photodiode
ASK	amplitude shift keying
BER	bit error rate
BH	buried heterostructure (injection laser)
BOD	bistable optical device
CAM	computer aided manufacture
CATV	common antenna television
CCTV	close circuit television
CDH	constricted double heterojunction (injection laser)
CMI	coded mark inversion
CMOS	complementary metal oxide silicon
CNR	carrier to noise ratio
CPU	central processing unit
CSP	channelled substrate planar (injection laser)
CW	continuous wave or operation
D–A	digital to analog
dB	decibel
D–IM	direct intensity modulation
DBF	distributed feedback (injection laser)
DBR	distributed Bragg reflector (injection laser)
d.c.	direct current
DH	double heterostructure or heterojunction (injection laser or LED)

DSB	double sideband (amplitude modulation)
EH	traditional mode designation
EMI	electromagnetic interference
EMP	electromagnetic pulse
erf	error function
erfc	complementary error function
FDM	frequency division multiplexing
FET	field effect transistor
FM	frequency modulation
FSK	frequency shift keying
FWHP	full width half power
HDB	high density bipolar
HE	traditional mode designation
He–Ne	helium–neon (laser)
HF	high frequency
HV	high voltage
IF	intermediate frequency
ILD	injection laser diode
IM	intensity modulation
IO	integrated optics
I/O	input/output
ISI	intersymbol interference
LAN	local area network
LED	light emitting diode
LOC	large optical cavity (injection laser)
LP	linearly polarized (mode notation)
LPE	liquid phase epitaxy
MCVD	modified chemical vapor deposition
MESFET	metal Schottky field effect transistor
MISFET	metal integrated-semiconductor field effect transistor
Nd:YAG	neodymium-doped yttrium–aluminum–garnet (laser)
NRZ	nonreturn to zero
OTDR	optical time domain reflectometry
OVPO	outside vapor phase oxidation
PAM	pulse amplitude modulation
PCM	pulse code modulation
PCS	plastic-clad silica (fiber)
PCVD	plasma-activated chemical vapor deposition
PCW	plano-convex waveguide (injection laser)
PDF	probability density function
PFM	pulse frequency modulation
PIN–FET	*p–i–n* photodiode followed by a field effect transistor
PM	phase modulation
PPM	pulse position modulation
PSK	phase shift keying
PTT	Post, Telegraph and Telecommunications
PWM	pulse width modulation
RAPD	reach-through avalanche photodiode
RFI	radio frequency interference
rms	root mean square
RO	relaxation oscillation
RZ	return to zero
SAW	surface acoustic wave
SDM	space division multiplexing
SHF	super high frequency
SML	separated multiclad layer (injection laser)
SNR	signal to noise ratio
TDM	time division multiplexing
TE	transverse electric
TEM	transverse electromagnetic
TJS	transverse junction stripe (injection laser)
TM	transverse magnetic
TTL	transistor–transistor logic
UHF	ultra high frequency
VAD	vapor axial deposition
VCO	voltage controlled oscillator
VHF	very high frequency
VPE	vapor phase epitaxy
WDM	wavelength division multiplexing
WKB	Wentzel, Kramers, Brillouin (analysis technique) for graded fiber
WPS	wideband switch point
ZD	zenner diode

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