Optical Fiber Communications

Principles and Practice

John M. Senior

Second Edition

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Preface to the second edition

It was suggested in the preface to the first edition that the relentless onslaught in the development and application of optical fiber communication technology would continue over the next decade. Now the greater part of that period is over, it may be observed that this was clearly an accurate statement as improvements and developments in the technology have occurred with tremendous rapidity in parallel with its increasingly widescale deployment. In particular, developments in relation to single-mode fibers, mid-infrared transmission, optical couplers, fiber lasers, narrow linewidth and frequency tunable lasers, superluminescent diodes, optical amplifiers, integrated optics and optical computation, together with coherent transmission techniques, have caused increases in the sophistication of the component technology whilst the trend towards greater transmission capacity and optical fiber networking (rather than point-to-point communications) has continued unabated. These substantial advances made the writing of a second edition both essential and urgent.

The above factors are particularly important when considering the major worldwide utilization of the first edition within academia and industry. In this context the question could also be asked as to why there has been a gap of seven years between the two editions. Although the continuing popularity of the first edition has provided a strong indication that the material it contains is still very relevant, it is not the answer to the aforementioned question. The answer is simply that at the commencement of the writing of the second edition, it was apparent that a substantial amount of additional material would need to be incorporated both to update the text and to take it into the new areas of technological development which have evolved since the mid-1980s. Hence this second edition constitutes a major revision which has necessitated the inclusion of much important new material whilst retaining the essential elements of the first edition. For example, the book now has three additional chapters as well as many new sections.

In common with the first edition, this edition has been developed from both teaching the subject to final-year undergraduates as well as from the continuation of a series of successful short courses on optical fiber communications conducted for professional engineers at the Manchester Metropolitan University (formerly Manchester Polytechnic). Furthermore it draws upon the diverse research activities of the Research Group which I lead in the area of optical fiber communications and networks. The book remains a comprehensive introductory text for use by both undergraduate and postgraduate engineers and scientists to provide them with a firm grounding in all significant aspects of the technology whilst providing strong insights into the potential future developments together with the growing areas of application.

The reader should therefore be in a position to appreciate such developments as they occur.

The enhanced treatment of the practical areas, together with the incorporation of the relevant standardization issues, will enable the book to continue to find major use as a reference text for practising engineers and scientists. Nevertheless, the book has been produced as a teaching/learning text and to this end it includes over 100 worked examples interspersed throughout in order to assist the learning process by illustrating the use of equations, by providing realistic values for parameters encountered and to aid the reader in aspects of design associated with optical fiber communication systems and networks. A total of 275 problems is also provided at the end of relevant chapters to examine the reader's understanding and to assist tutorial work. In a number of cases they also extend and elucidate the text, and in this context they should be considered as an integral part of the book. A *Solutions Manual* containing solutions to these problems may be obtained from the publisher.

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 rigour. 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 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 light wave transmission within the various fiber types. The major transmission characteristics of optical fibers are then discussed in some detail in Chapter 3. A particular focus in this second edition within both Chapters 2 and 3 concerns the properties and characteristics of single-mode fibers.

Chapters 4 and 5 deal with the more practical aspects of optical fiber communications and therefore could be omitted from an initial teaching program. A number of these areas, however, are of crucial importance and thus should not be lightly overlooked. Chapter 4 deals with the manufacture and cabling of the various fiber types, whilst in Chapter 5 the different techniques to provide optical fiber connection are described. In this latter chapter both fiber to fiber joints (i.e. connectors and splices) are discussed as well as fiber branching devices, or couplers, which provide versatility within the configuration of optical fiber systems and networks.

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 direct detection receiver is then considered in Chapter 9, with particular emphasis on its performance characteristics.

Active optical devices and components are described in Chapter 10, which commences with detailed consideration of the various types of optical amplifier, followed by an account of the technology involved in integrated optics and optoelectronic integration. This is continued by discussion of optical bistability and digital optics which leads into an overview of optical computation.

Chapter 11 draws together the preceding material in a detailed discussion of the major current implementations of optical fiber communication systems (i.e. those using intensity modulation and the direct detection process) in order to give an insight into the design criteria and practices for all the main aspects of both digital and analog fiber systems. Both optical fiber distribution systems and advanced multiplexing strategies, together with the application of optical amplifiers within systems, are discussed to provide an understanding of these fast-growing areas.

It is apparent from the attention that has been devoted to coherent optical fiber communications over recent years that this is a future area of major exploitation of the technology. Hence coherent optical fiber systems are dealt with in some detail in Chapter 12, which covers all major aspects of this developing communications strategy in relation to both single and multicarrier systems.

Chapter 13 gives a general treatment of the major measurements which may be undertaken on optical fibers in both the laboratory and the field. This chapter, which occurred earlier in the book in the first edition, has been repositioned in order to enable the reader to obtain a more complete understanding of optical fiber subsystems and systems prior to consideration of these issues. Furthermore, it has been extended to include the measurements normally required to be taken on single-mode fibers and focused on to the measurement techniques which have been adopted as national and international standards.

Finally, Chapter 14 describes the many current and predicted application areas for optical fiber communications by drawing on practical examples from deployed systems as well as research and development activities. In particular, consideration is given to the possible developments in the telecommunication local access network together with the standardization associated with synchronous optical networks. The discussion is also expanded into the areas of optical fiber sensing together with optical fiber local area networking, both of which demonstrate major potential for the future application of optical fiber communication technology.

The book is referenced throughout to extensive end-of-chapter references which 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 also 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 the many readers of the first edition for their positive and helpful feedback which has assisted me greatly in the formulation of this second edition. I am also grateful to my family and friends who have continued to tolerate my infrequent appearances over the period of writing and revising the book. In particular I would like to dedicate this second edition to my late father, Ken, whose interest and encouragement in this work was never failing and who tragically did not quite see it completed. Finally, very special thanks are due to Judy for her patience and support in doing all the things that I should have done during the time I devoted to writing this edition.

Professor John M. Senior

Glossary of symbols and abbreviations

A	constant, area (cross-section, emission), far field pattern size, mode amplitude, wave amplitude (A_0)
A_{21}	Einstein coefficient of spontaneous emission
A_c	peak amplitude of the subcarrier waveform (analog transmission)
a	fiber core radius, parameter which defines the asymmetry of a planar guide (given by equation (10.21)), baseband message signal ($a(t)$)
$a_b(\lambda)$	effective fiber core radius
a_{eff}	bend attenuation fiber
a_k	integer 1 or 0
$a_m(\lambda)$	relative attenuation between optical powers launched into multimode and single-mode fibers
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_{fib}	fiber bandwidth
B_{FPA}	mode bandwidth (Fabry–Perot amplifier)
B_m	bandwidth of an intensity modulated optical signal $m(t)$, maximum 3 dB bandwidth (photodiode)
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, linewidth broadening factor (injection laser)
C	constant, capacitance, crack depth (fiber), wave coupling coefficient per unit length, coefficient incorporating Einstein coefficients
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_j	junction capacitance (photodiode)
C_L	total optical fiber channel loss in decibels, including the dispersion–equalization penalty (C_{LD})
C_0	wave amplitude
C_T	total capacitance
CT	polarization crosstalk

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, diffusion coefficient, corrugation period, decision threshold in digital optical fiber transmission, fiber dispersion parameters: material (D_M); profile (D_P); total first order (D_T); waveguide (D_W), detectivity (photodiode), specific detectivity (D^*)
D_c	minority carrier diffusion coefficient
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), thickness of recombination region (optical source), pin diameter (mode scrambler)
d_f	far field mode-field diameter (single-mode fiber)
d_n	near field mode-field diameter (single-mode fiber)
d_o	fiber outer (cladding) diameter
E	electric field, energy, Youngs modulus, expected value of a random variable, electron energy
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 ($F(M)$), optical amplifier noise figure
$\mathcal{F}$	Fourier transformation
F_n	noise figure (electronic amplifier)
F_{to}	total noise figure for system of cascaded optical amplifiers
f	frequency
f_D	peak to peak frequency deviation (PFM–IM)
f_d	peak frequency deviation (subcarrier FM and PM)
f_o	Fabry–Perot resonant frequency (optical amplifier), pulse rate (PFM–IM)
G	open loop gain of an optical fiber receiver amplifier, photoconductive gain, cavity gain of a semiconductor laser amplifier
$G_i(r)$	amplitude function in the WKB method
G_o	optical gain (phototransistor)
G_R	Raman gain (fiber amplifier)

G_s	single pass gain of a semiconductor laser amplifier
Gsn	Gaussian (distribution)
g	degeneracy parameter
$\bar{g}$	gain coefficient per unit length (laser cavity)
g_m	transconductance of a field effect transistor, material gain coefficient
g_0	unsaturated material gain coefficient
g_R	power Raman gain coefficient
$\bar{g}_{th}$	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 optical fiber ($h(t)$), mode coupling parameter (PM fiber)
$h_A(t)$	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_S	output current from photodetector resulting from intermediate frequency in coherent receiver
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 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, 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, coupling coefficient for two interacting waveguide modes, constant
k_f	angular frequency deviation (subcarrier FM)
k_p	phase deviation constant (subcarrier PM)
L	length (fiber), distance between mirrors (laser), coupling length (waveguide modes)
L_{ac}	insertion loss of access coupler in distribution system
L_B	beat length in a monomode optical fiber
L_{bc}	coherence length in a monomode optical fiber
L_c	characteristic length (fiber)
L_D	diffusion length of charge carriers (LED)
L_{ex}	star coupler excess loss in distribution system
L_0	constant with dimensions of length
L_t	lateral misalignment loss at an optical fiber joint
L_{tr}	tap ratio loss in distribution system
$\mathscr{L}$	transmission loss factor (transmissivity) of an optical fiber
l	azimuthal mode number, distance, length
l_a	atomic spacing (bond distance)
l_0	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, optical modulation index (subcarrier amplitude modulation)
m_a	modulation index
N	integer, density of atoms in a particular energy level (eg N_1, N_2, N_3), minority carrier concentration in n type semiconductor material, number of input/output ports on a fiber star coupler, number of nodes on distribution system, noise current
NA	numerical aperture of an optical fiber
NEP	noise equivalent power
N_g	group index of an optical waveguide
N_{ge}	effective group index or group index of a single-mode waveguide
N_0	defined by equation (11.80)
N_p	number of photons per bit (coherent transmission)
n	refractive index (eg n_1, n_2, n_3), stress corrosion susceptibility, negative type semiconductor material, electron density
n_e	effective refractive index of a planar waveguide
n_{eff}	effective refractive index of a single-mode fiber
n_0	refractive index of air
n_{sp}	spontaneous emission factor (injection laser)
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 ($P(1/0)$), optical power (P_1, P_2, etc.)
P_a	total power in a baseband message signal $a(t)$
P_B	threshold optical power for Brillouin scattering
P_b	backward travelling signal power (semiconductor laser amplifier), power transmitted through fiber sample
P_c	optical power coupled into a step index fiber, optical power level
P_D	optical power density
P_{dc}	dc 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_{in}	input signal power (semiconductor laser amplifier)
P_{int}	internally generated optical power (optical source)
P_L	optical power of local oscillator signal (coherent system)
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 (prior to degradation) power from an optical source
P_p	optical pump power (fiber amplifier)
P_{po}	peak received optical power

P_r	reference optical power level, optical power level
P_R	threshold optical power for Raman scattering
$P_{Ra}(t)$	backscattered optical power (Rayleigh) within a fiber
P_S	optical power of incoming signal (coherent system)
P_s	total power transmitted through a fiber sample
P_{sc}	optical power scattered from a fiber
P_t	optical transmitter power, launch power (P_{tx})
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 (eg R_{in}, R_{out}); facet reflectivity (R_1, R_2)
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 output power to 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_t	total carrier recombination rate (semiconductor optical source)
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_{nr}	nonradiative carrier recombination rate per unit volume
r_p	incident photon rate at an optical detector
r_r	radiative carrier recombination rate per unit volume
r_t	total carrier recombination rate per unit volume
S	fraction of captured optical power, macroscopic stress, dispersion slope (fiber), power spectral density $S(\omega)$
S_f	fracture stress
$S_i(r)$	phase function in the WKB method
$S_m(\psi)$	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_0	scale parameter; zero dispersion slope (fiber)
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 to 90% rise time arising from intramodal dispersion on an optical fiber link
T_D	10 to 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 to 90% rise time arising from intermodal dispersion on an optical fiber link
T_0	threshold temperature (injection laser), nominal pulse period (PFM–IM)
T_R	10 to 90% rise time at the regenerator circuit input (PFM–IM)
T_S	10 to 90% rise time for an optical source
T_{syst}	total 10 to 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, carrier transit time, slow(t_s), fast (t_f)
t_c	time constant
t_d	switch on delay (laser)
t_e	$1/e$ pulse width from the centre
t_r	10 to 90% rise time
U	eigenvalue of the fiber core
V	electrical voltage, normalized frequency for an optical fiber or planar waveguide
V_{bias}	bias voltage for a photodiode
V_c	cutoff value of normalized frequency (fiber)
V_{CC}	collector supply voltage
V_{CE}	collector–emitter voltage (bipolar transistor)
V_{EE}	emitter supply voltage
V_{eff}	effective normalized frequency (fiber)
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_d	drift velocity of carriers (photodiode)
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
w	depletion layer width (photodiode)
X	random variable
x	coordinate, distance, constant, evanescent field penetration depth, slab thickness, grating line spacing
Y	constant, shunt admittance, random variable
y	coordinate, lateral offset at a fiber joint
Z	random variable, constant
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}), linewidth enhancement factor (injection laser), optical link loss
$\bar{\alpha}$	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 kilometre
α_i	internal wavelength loss per unit length (injection laser)
α_j	fiber joint loss in decibels per kilometre
α_m	mirror loss per unit length (injection laser)
α_N	signal attenuation in nepers
α_0	absorption coefficient
α_p	fiber transmission loss at the pump wavelength (fiber amplifier)
α_r	radiation attenuation coefficient
β	wave propagation constant
$\bar{\beta}$	gain factor (injection laser cavity)
β_c	isothermal compressibility
β_0	proportionality constant
β_r	degradation rate
Γ	optical confinement factor (semiconductor laser amplifier)
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
Δf	linewidth of single frequency injection laser
ΔG	peak–trough ratio of the passband ripple (semiconductor laser amplifier)
Δn	index difference between fiber core and cladding ($\Delta n/n_1$ fractional index difference)

δ_E	phase shift associated with transverse electric waves
δf	uncorrelated source frequency widths
δ_H	phase shift associated with transverse magnetic waves
$\delta\lambda$	optical source spectral width (linewidth), mode spacing (laser)
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})
δT_g	polarization mode dispersion in fiber
ε	electric permittivity, of free space (ε_0), relative (ε_r), semiconductor (ε_s), extinction ratio (optical transmitter)
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 injection laser
η_{int}	internal quantum efficiency (LED)
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)
θ_B	Bragg diffraction angle, blaze angle diffraction grating
Λ	acoustic wavelength, period for perturbations in a fiber
Λ_c	cutoff period for perturbations in a fiber
λ	optical wavelength
λ_B	Bragg wavelength (DFB laser)
λ_c	long wavelength cutoff (photodiode), cutoff wavelength for single-mode fiber, effective cutoff wavelength (λ_{ce})
λ_0	wavelength at which first order dispersion is zero
μ	magnetic permeability, relative permeability, (μ_r), permeability of free space (μ_0)
ν	optical source bandwidth in gigahertz
ρ	polarization rotation in a monomode 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 dispersion 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
τ	time period, bit period, signalling interval, 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_{ph}	photon lifetime (semiconductor laser)
τ_r	radiative minority carrier lifetime
τ_{sp}	spontaneous emission lifetime (equivalent to τ_{21})
Φ	linear retardation
ϕ	angle, critical angle (ϕ_c), photon density, phase shift
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), pump frequency (ω_p), Stokes component (ω_s) antistokes component (ω_a), intermediate frequency of coherent heterodyne receiver (ω_{IF}), normalized spot size of the fundamental mode
ω_0	spot size of the fundamental mode
∇	vector operator, Laplacian operator (∇^2)

A–D	analog to digital
ac	alternating current
AFC	automatic frequency control
AGC	automatic gain control
AM	amplitude modulation
APD	avalanche photodiode
AR	antireflection (surface, coating)
ARROW	antiresonant reflecting optical waveguide
ASK	amplitude shift keying
ATM	alternative test method (fiber), asynchronous transfer mode (multiplexing)
BAP	broadband access point
BER	bit error rate
BH	buried heterostructure (injection laser)
BIDS	broadband integrated distributed star (potential local access network)
BOD	bistable optical device
CAM	computer aided manufacture
CATV	common antenna television
CCITT	International Telephone and Telegraph Consultative Committee
CCTV	close circuit television
CDH	constricted double heterojunction (injection laser)

CMI	coded mark inversion
CMOS	complementary metal oxide silicon
CNR	carrier to noise ratio
CO	central office (telephone switching centre)
CPFSK	continuous phase frequency shift keying
CPU	central processing unit
CSMA/CD	carrier sense multiple access with collision detection
CSP	channelled substrate planar (injection laser)
CW	continuous wave or operation
D–A	digital to analog
dB	decibel
D–IM	direct intensity modulation
DC	depressed cladding (fiber design)
dc	direct current
DF	dispersion flattened (single-mode fiber)
DFB	distributed feedback (injection laser)
DH	double heterostructure or heterojunction (injection laser or LED)
DLC	digital loop carrier
DLD	dark line defect (semiconductor optical source)
DPSK	differential phase shift keying
DQDB	distributed queue dual bus (emerging standard for metropolitan area networks)
DS	dispersion shifted (single-mode fiber)
DSB	double sideband (amplitude modulation)
DSD	dark spot defect (semiconductor optical source)
ECL	emitter coupler logic
EH	traditional mode designation
EIA	Electronics Industries Association
ELED	edge-emitter light emitting diode
EMI	electromagnetic interference
EMP	electromagnetic pulse
erf	error function
erfc	complementary error function
ESI	equivalent step index (fiber)
FBT	fused biconical taper (fiber coupler)
FC	fiber connector
FDDI	fiber distributed data interface
FDM	frequency division multiplexing
FET	field effect transistor, junction (JFET)
FM	frequency modulation
FMS	flexible manufacturing systems
FOTP	fiber optic test procedure
FPA	Fabry–Perot amplifier
FSK	frequency shift keying

FWHP	full width half power
FWHM	full width half maximum (equivalent to FWHP)
GRIN	graded index (rod lens)
HB	high birefringence (fiber)
HBT	heterojunction bipolar transmitter
HDB	high density bipolar
HDTV	high definition television
HE	traditional mode designation
HEMT	high electron mobility transistor
He–Ne	helium-neon (laser)
HF	high frequency
HV	high voltage
IF	intermediate frequency
ILD	injection laser diode
IM	intensity modulation, with direct detection (IM/DD)
IO	integrated optics
I/O	input/output
I & Q	inphase and quadrature (coherent receiver),
ISDN	integrated services digital network, broadband (BISDN)
ISI	intersymbol interference
ISO	International Standardization Organization
LAN	local area network
LB	low birefringence (fiber)
LEC	long external cavity (laser)
LED	light emitting diode
LLC	logical link control (LAN)
LOC	large optical cavity (injection laser)
LP	linearly polarized (mode notation)
LPE	liquid phase epitaxy
MAC	medium access control (LAN), isochronous (I-MAC)
MAN	metropolitan area network
MAP	manufacturing automation protocol
MBE	molecular beam epitaxy
MC	matched cladding (fiber design)
MCVD	modified chemical vapour deposition
MESFET	metal Schottky field effect transistor
MFD	mode-field diameter (single-mode fiber)
MFSK	multilevel frequency shift keying
MISFET	metal integrated-semiconductor field effect transistor
MMF	multimode fiber
MOSFET	metal oxide semiconductor field effect transistor
MOVPE	metal oxide vapour-phase epitaxy
MQW	multiquantum-well
MUSE	multiple sub-Nyquist sampling encoding

Nd:YAG	neodymium-doped yttrium-aluminium-garnet (laser)
NRZ	non-return to zero
OC	optical carrier (SONET)
OCWR	optical continuous wave reflectometer
OEIC	optoelectronic integrated circuit
OFDM	optical frequency division multiplexing
OOK	on–off keying (equivalent to binary amplitude shift keying)
ORL	optical return loss
OSI	open systems interconnection
OTDM	optical time division multiplexing
OTDR	optical time domain reflectrometry
OVPO	outside vapour-phase oxidation
PAM	pulse amplitude modulation
PANDA	polarization maintaining and absorption reducing (fiber)
PC	physical contact (fiber connector)
PCM	pulse code modulation
PCS	plastic-clad silica (fiber)
PCVD	plasma-activated chemical vapour deposition
PCW	planar convex waveguide (injection laser)
PD	photodiode, photodetector
PDF	probability density function
PFM	pulse frequency modulation
PHY	physical layer protocol (FDDI)
PIN–FET	*p–i–n* photodiode followed by a field transistor
PLL	phase locked loop
PM	phase modulation, polarization maintaining (fiber)
PMD	physical medium dependent (FDDI)
PMMA	polymethyl methacrylate
PoLSK	polarization shift keying
PON	passive optical network, telephony (TPON), broadband (BPON), asynchronous (APON)
POTDR	polarization optical time domain reflectrometer
PPL	passive photonic loop (optical local access network proposal)
PPM	pulse position modulation
PSK	phase shift keying
PTT	post, telegraph and telecommunications
PWM	pulse width modulation
QAM	quadrature amplitude modulation
RAPD	reach through avalanche photodiode
RIN	relative intensity noise (injection laser)
rms	root mean square
RNF	refracted near field (method for fiber refractive index profile measurement)
RO	relaxation oscillation

RTM	reference test method (fiber)
RZ	return to zero
SAGM	separate absorption, grading and multiplication (avalanche photodiode)
SAM	separate absorption and multiplication (avalanche photodiode)
SAW	surface acoustic wave
SBS	stimulated Brillouin scattering
SC	subscriber connector (fiber)
SCM	subcarrier multiplexing
SDH	synchronous digital hierarchy
SDM	space division multiplexing
SEED	self-electro-optic device, symmetric (S-SEED)
SHF	super high frequency
SIU	subscriber interface unit
SLA	semiconductor laser amplifier
SLD	superluminescent diode
SLED	surface emitter light emitting diode
SMA	subminiature assembly (fiber connector)
SMF	single-mode fiber
SML	separated multiclad layer (injection laser)
SMT	station management (FDDI)
SNR	signal to noise ratio
SONET	synchronous optical network
SOP	state of polarization
SPE	synchronous payload envelope (SONET)
SQW	single quantum-well
SRS	stimulated Raman scattering
ST	straight tip (fiber connector)
STM	synchronous transport module (SDH)
STS	synchronous transport signal (SONET)
TDM	time division multiplexing
TDMA	time division multiple access
TE	transverse electric
TEM	transverse electromagnetic
TJS	transverse junction stripe (injection laser)
TM	transverse magnetic
TTL	transistor–transistor logic
TWA	travelling wave amplifier
UHF	ultra high frequency
VAD	vapour axial deposition
VCO	voltage controlled oscillator
VHF	very high frequency
VPE	vapour-phase epitaxy
VSB	vestigial sideband (modulation)

VT	virtual tributary (SONET)
WDM	wavelength division multiplexing
WKB	Wentzel, Kramers, Brillouin (analysis technique for graded fiber)
WPS	wideband switch point
ZD	zenner diode
ZMD	zero material dispersion (fiber)

To my father, Ken

1

Introduction

Communication may be broadly defined as the transfer of information from one point to another. When the information is to be conveyed over any distance a communication system is usually required. Within a communication system the information transfer is frequently achieved by superimposing or modulating the information on to an electromagnetic wave which acts as a carrier for the information signal. This modulated carrier is then transmitted to the required destination where it is received and the original information signal is obtained by demodulation. Sophisticated techniques have been developed for this process using electromagnetic carrier waves operating at radio frequencies as well as microwave and millimetre wave frequencies. However, 'communication' may also be achieved using an electromagnetic carrier which is selected from the optical range of frequencies.

1.1 Historical development

The use of visible optical carrier waves or light for communication has been common for many years. Simple systems such as signal fires, reflecting mirrors and, more recently, signalling lamps have provided successful, if limited, information transfer. Moreover, as early as 1880 Alexander Graham Bell reported the transmission of speech using a light beam [Ref. 1]. The photophone proposed by Bell just four years after the invention of the telephone modulated sunlight with a diaphragm giving speech transmission over a distance of 200 m. However, although some investigation of optical communication continued in the early part of the twentieth century [Refs. 2 and 3] its use was limited to mobile, low capacity communication links. This was due to both the lack of suitable light sources and the problem that light transmission in the atmosphere is restricted to line of sight and is severely affected by disturbances such as rain, snow, fog, dust and atmospheric turbulence. Nevertheless lower frequency and hence longer wavelength electromagnetic waves* (i.e. radio and microwave) proved suitable carriers for information transfer in the atmosphere, being far less affected by these atmospheric conditions. Depending on their wavelengths these electromagnetic carriers can be transmitted over considerable distances but are limited in the amount of information they can convey by their frequencies (i.e. the information-carrying capacity is directly related to the bandwidth or frequency extent of the modulated carrier, which is generally limited to a fixed fraction of the carrier frequency). In theory, the greater the carrier frequency, the larger the available transmission bandwidth and thus the information-carrying capacity of the communication system. For this reason radio communication was developed to higher frequencies (i.e. VHF and UHF) leading to the introduction of the even higher frequency microwave and, latterly, millimetre wave transmission. The relative frequencies and wavelengths of these types of electromagnetic wave can be observed from the electromagnetic spectrum shown in Figure 1.1. In this context it may also be noted that communication at optical frequencies offers an increase in the potential usable bandwidth by a factor of around 10^4 over high frequency microwave transmission. An additional benefit of the use of high carrier frequencies is the general ability of the communication system to concentrate the available power within the transmitted electromagnetic wave, thus giving an improved system performance [Ref. 4].

A renewed interest in optical communication was stimulated in the early 1960s with the invention of the laser [Ref. 5]. This device provided a powerful coherent light source, together with the possibility of modulation at high frequency. In addition the low beam divergence of the laser made enhanced free space optical transmission a practical possibility. However, the previously mentioned constraints of light transmission in the atmosphere tended to restrict these systems to short distance applications. Nevertheless, despite the problems some modest free space optical communication links have been implemented for applications such as the linking of a television camera to a base vehicle and for data links of a few hundred

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* For the propagation of electromagnetic waves in free space, the wavelength λ equals the velocity of light in a vacuum c times the reciprocal of the frequency f in hertz or $\lambda = c/f$.

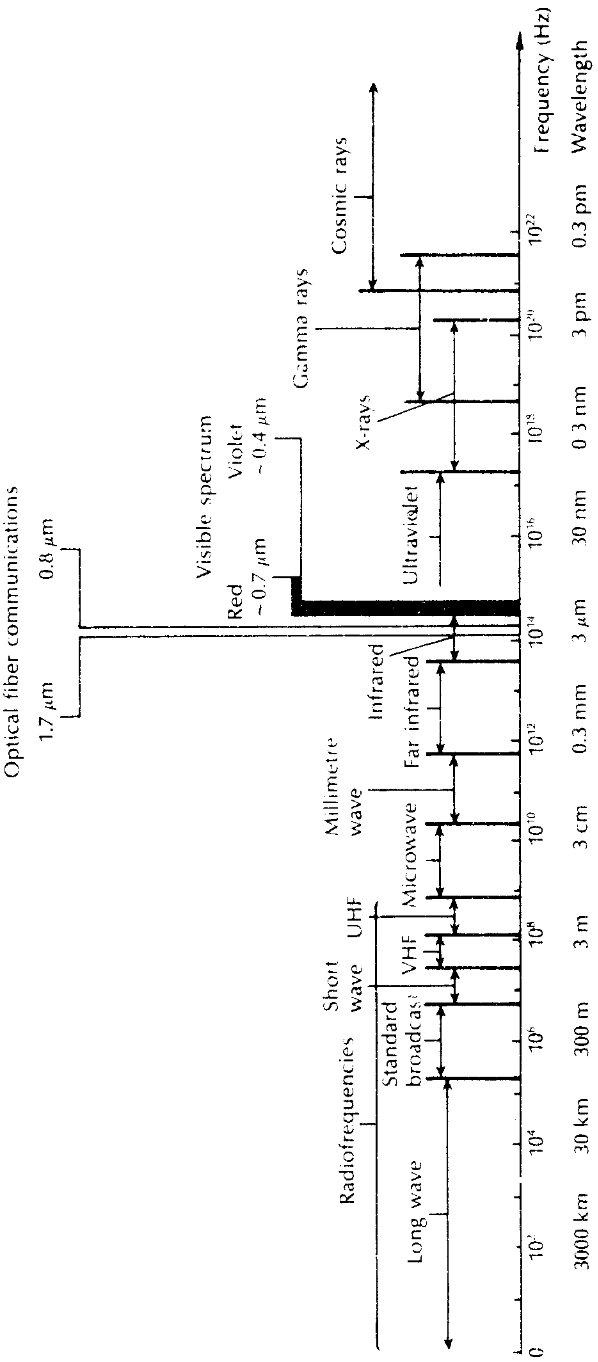

Figure 1.1 The electromagnetic spectrum showing the region used for optical fiber communications.

metres between buildings. There is also some interest in optical communication between satellites in outer space using similar techniques [Ref. 6].

Although the use of the laser for free space optical communication proved somewhat limited, the invention of the laser instigated a tremendous research effort into the study of optical components to achieve reliable information transfer using a lightwave carrier. The proposals for optical communication via dielectric waveguides or optical fibers fabricated from glass to avoid degradation of the optical signal by the atmosphere were made almost simultaneously in 1966 by Kao and Hockham [Ref. 7] and Werts [Ref. 8]. Such systems were viewed as a replacement for coaxial cable or carrier transmission systems. Initially the optical fibers exhibited very high attenuation (i.e. 1000 dB km^{-1}) and were therefore not comparable with the coaxial cables they were to replace (i.e. 5 to 10 dB km^{-1}). There were also serious problems involved in jointing the fiber cables in a satisfactory manner to achieve low loss and to enable the process to be performed relatively easily and repeatedly in the field. Nevertheless, within the space of ten years optical fiber losses were reduced to below 5 dB km^{-1} and suitable low loss jointing techniques were perfected.

In parallel with the development of the fiber waveguide, attention was also focused on the other optical components which would constitute the optical fiber communication system. Since optical frequencies are accompanied by extremely small wavelengths the development of all these optical components essentially required a new technology. Thus semiconductor optical sources (i.e. injection lasers and light emitting diodes) and detectors (i.e. photodiodes and to a certain extent phototransistors) compatible in size with optical fibers were designed and fabricated to enable successful implementation of the optical fiber system. Initially the semiconductor lasers exhibited very short lifetimes of at best a few hours, but significant advances in the device structure enabled lifetimes greater than 1000 hr [Ref. 9] and 7000 hr [Ref. 10] to be obtained by 1973 and 1977 respectively. These devices were originally fabricated from alloys of gallium arsenide (AlGaAs) which emitted in the near infrared between 0.8 and 0.9 μm.

Subsequently the above wavelength range was extended to include the 1.1 to 1.6 μm region by the use of other semiconductor alloys (see Section 6.3.6) to take advantage of the enhanced performance characteristics displayed by optical fibers over this range. In particular for this longer wavelength region, semiconductor lasers and also the simpler structured light emitting diodes based on the quarternary alloy InGaAsP are now available which have projected median lifetimes in excess of 25 years (when operated at 10 °C) for the former and 100 years (when operated at 70 °C) for the latter device type [Ref. 11]. Direct modulation of the commercial devices is also feasible at rates of several giga bit s^{-1} which is especially useful in the first longer wavelength window region around 1.3 μm where fiber intramodal dispersion is minimized and hence the transmission bandwidth is maximized, particularly for single-mode fibers. It is also noteworthy that this fiber type has quickly come to dominate system applications within telecommunications. Moreover, the lowest silica glass fiber losses of about 0.2 dB km^{-1} are obtained in the other longer wavelength window at 1.55 μm, but, unfortunately, intramodal dispersion is greater at this wavelength thus limiting the maximum bandwidth achievable with conventional single-mode fiber.

To obtain both the low loss and low dispersion at the same operating wavelength, new advanced single-mode fiber structures have been realized: namely, dispersion shifted and dispersion flattened fibers. Hence developments in fiber technology have continued rapidly over recent years, encompassing other specialist fiber types such as polarization maintaining fibers, as well as glass materials for even longer wavelength operation in the mid-infrared (2 to 5 μm) and far-infrared (8 to 12 μm) regions. In addition, the implementation of associated fiber components (splices, connectors, couplers, etc.) and active optoelectronic devices (sources, detectors, amplifiers, etc.) has also moved forward with such speed that optical fiber communication technology would seem to have reached a stage of maturity within its developmental path [Ref. 12]. Therefore, high performance, reliable optical fiber communication systems are now widely deployed both within telecommunications networks and many other more localized communication application areas.

1.2 The general system

An optical fiber communication system is similar in basic concept to any type of communication system. A block schematic of a general communication system is shown in Figure 1.2(a), the function of which is to convey the signal from the information source over the transmission medium to the destination. The communication system therefore consists of a transmitter or modulator linked to the information source, the transmission medium, and a receiver or demodulator at the destination point. In electrical communications the information source provides an electrical signal, usually derived from a message signal which is not electrical (e.g. sound), to a transmitter comprising electrical and electronic components which converts the signal into a suitable form for propagation over the transmission medium. This is often achieved by modulating a carrier, which, as mentioned previously, may be an electromagnetic wave. The transmission medium can consist of a pair of wires, a coaxial cable or a radio link through free space down which the signal is transmitted to the receiver, where it is transformed into the original electrical information signal (demodulated) before being passed to the destination. However, it must be noted that in any transmission medium the signal is attenuated, or suffers loss, and is subject to degradations due to contamination by random signals and noise, as well as possible distortions imposed by mechanisms within the medium itself. Therefore, in any communication system there is a maximum permitted distance between the transmitter and the receiver beyond which the system effectively ceases to give intelligible communication. For long-haul applications these factors necessitate the installation of repeaters or line amplifiers (see Section 11.4) at intervals, both to remove signal distortion and to increase signal level before transmission is continued down the link.

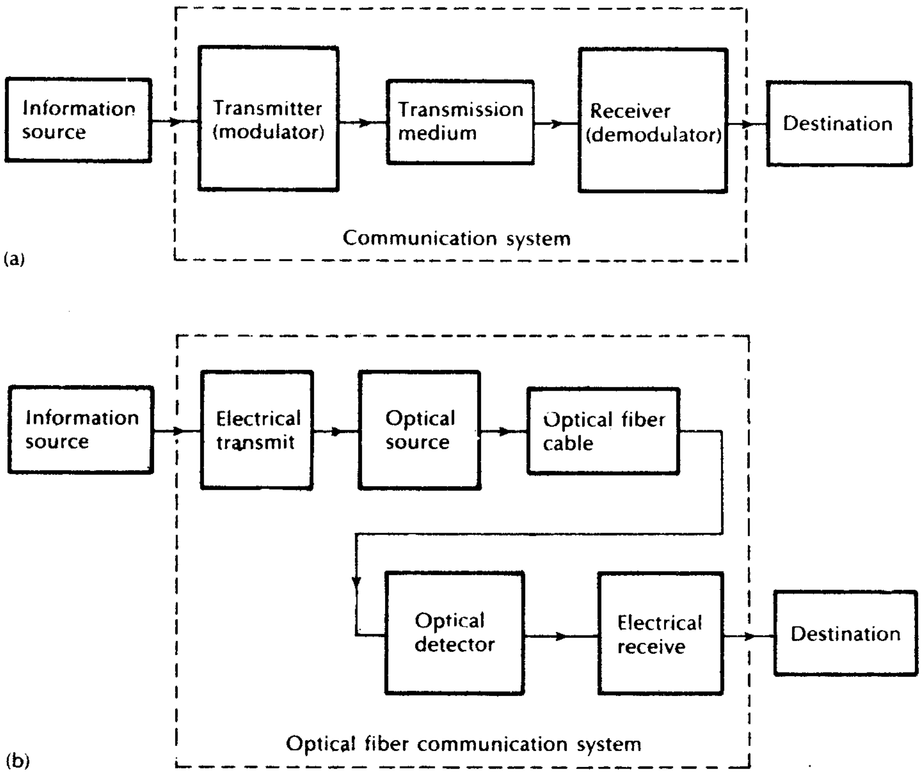

Figure 1.2 (a) The general communication system. (b) The optical fiber communication system.

For optical fiber communications the system shown in Figure 1.2(a) may be considered in slightly greater detail, as given in Figure 1.2(b). In this case the information source provides an electrical signal to a transmitter comprising an electrical stage which drives an optical source to give modulation of the lightwave carrier. The optical source which provides the electrical–optical conversion may be either a semiconductor laser or light emitting diode (LED). The transmission medium consists of an optical fiber cable and the receiver consists of an optical detector which drives a further electrical stage and hence provides demodulation of the optical carrier. Photodiodes (*p–n*, *p–i–n* or avalanche) and, in some instances, phototransistors and photoconductors are utilized for the detection of the optical signal and the optical–electrical conversion. Thus there is a requirement for electrical interfacing at either end of the optical link and at present the signal processing is usually performed electrically.*

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* Significant developments have already taken place in devices for optical signal processing which may alter this situation in the future (see Chapter 10).

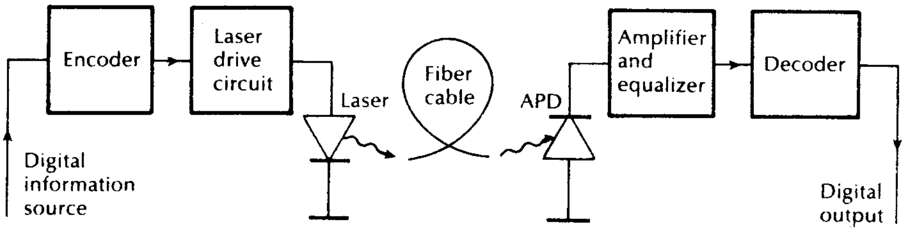

Figure 1.3 A digital optical fiber link using a semiconductor laser source and an avalanche photodiode (APD) detector.

The optical carrier may be modulated using either an analog or digital information signal. In the system shown in Figure 1.2(b) analog modulation involves the variation of the light emitted from the optical source in a continuous manner. With digital modulation, however, discrete changes in the light intensity are obtained (i.e. on–off pulses). Although often simpler to implement, analog modulation with an optical fiber communication system is less efficient, requiring a far higher signal to noise ratio at the receiver than digital modulation. Also, the linearity needed for analog modulation is not always provided by semiconductor optical sources, especially at high modulation frequencies. For these reasons, analog optical fiber communication links are generally limited to shorter distances and lower bandwidths than digital links.

Figure 1.3 shows a block schematic of a typical digital optical fiber link. Initially, the input digital signal from the information source is suitably encoded for optical transmission. The laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal. Hence a digital optical signal is launched into the optical fiber cable. The avalanche photodiode (APD) detector is followed by a front-end amplifier and equalizer or filter to provide gain as well as linear signal processing and noise bandwidth reduction. Finally, the signal obtained is decoded to give the original digital information. The various elements of this and alternative optical fiber system configurations are discussed in detail in the following chapters. However, at this stage it is instructive to consider the advantages provided by lightwave communication via optical fibers in comparison with other forms of line and radio communication which have brought about the introduction of such systems in many areas throughout the world.

1.3 Advantages of optical fiber communication

Communication using an optical carrier wave guided along a glass fiber has a number of extremely attractive features, several of which were apparent when the technique was originally conceived. Furthermore, the advances in the technology to date have surpassed even the most optimistic predictions, creating additional advantages. Hence it is useful to consider the merits and special features offered by optical fiber communications over more conventional electrical communications. In this context we commence with the originally foreseen advantages and then consider additional features which have become apparent as the technology has been developed.

(a) Enormous potential bandwidth. The optical carrier frequency in the range 10^{13} to 10^{16} Hz (generally in the near infrared around 10^{14} Hz or 10^{5} GHz) yields a far greater potential transmission bandwidth than metallic cable systems (i.e. coaxial cable bandwidth up to around 500 MHz) or even millimetre wave radio systems (i.e. systems currently operating with modulation bandwidths of 700 MHz). At present, the bandwidth available to fiber systems is not fully utilized but modulation at several gigahertz over a hundred kilometres and hundreds of megahertz over three hundred kilometres without intervening electronics (repeaters) is possible. Therefore, the information-carrying capacity of optical fiber systems has proved far superior to the best copper cable systems. By comparison the losses in wideband coaxial cable systems restrict the transmission distance to only a few kilometres at bandwidths over one hundred megahertz.

Although the usable fiber bandwidth will be extended further towards the optical carrier frequency, it is clear that this parameter is limited by the use of a single optical carrier signal. Hence a much enhanced bandwidth utilization for an optical fiber can be achieved by transmitting several optical signals, each at different centre wavelengths, in parallel on the same fiber. This wavelength division multiplexed operation [Ref. 13], particularly with dense packing of the optical wavelengths (or, essentially, fine frequency spacing), offers the potential for a fiber information-carrying capacity which is many orders of magnitude in excess of that obtained using copper cables or a wideband radio system.

(b) Small size and weight. Optical fibers have very small diameters which are often no greater than the diameter of a human hair. Hence, even when such fibers are covered with protective coatings they are far smaller and much lighter than corresponding copper cables. This is a tremendous boon towards the alleviation of duct congestion in cities, as well as allowing for an expansion of signal transmission within mobiles such as aircraft, satellites and even ships.

(c) Electrical isolation. Optical fibers which are fabricated from glass, or sometimes a plastic polymer, are electrical insulators and therefore, unlike their metallic counterparts, they do not exhibit earth loop and interface problems. Furthermore, this property makes optical fiber transmission ideally suited for communication in electrically hazardous environments as the fibers create no arcing or spark hazard at abrasions or short circuits.

(d) Immunity to interference and crosstalk. Optical fibers form a dielectric waveguide and are therefore free from electromagnetic interference (EMI), radiofrequency interference (RFI), or switching transients giving electromagnetic

pulses (EMP). Hence the operation of an optical fiber communication system is unaffected by transmission through an electrically noisy environment and the fiber cable requires no shielding from EMI. The fiber cable is also not susceptible to lightning strikes if used overhead rather than underground. Moreover, it is fairlv easy to ensure that there is no optical interference between fibers and hence, unlike communication using electrical conductors, crosstalk is negligible, even when many fibers are cabled together.

(e) Signal security. The light from optical fibers does not radiate significantly and therefore they provide a high degree of signal security. Unlike the situation with copper cables, a transmitted optical signal cannot be obtained from a fiber in a noninvasive manner (i.e. without drawing optical power from the fiber). Therefore, in theory, any attempt to acquire a message signal transmitted optically may be detected. This feature is obviously attractive for military, banking and general data transmission (i.e. computer network) applications.

(f) Low transmission loss. The development of optical fibers over the last twenty years has resulted in the production of optical fiber cables which exhibit very low attenuation or transmission loss in comparison with the best copper conductors. Fibers have been fabricated with losses as low as $0.2\,\mathrm{dB\,km^{-1}}$ (see Section 3.3.2) and this feature has become a major advantage of optical fiber communications. It facilitates the implementation of communication links with extremely wide repeater spacing (long transmission distances without intermediate electronics), thus reducing both system cost and complexity. Together with the already proven modulation bandwidth capability of fiber cable this property provides a totally compelling case for the adoption of optical fiber communication in the majority of long-haul telecommunication applications.

(g) Ruggedness and flexibility. Although protective coatings are essential, optical fibers may be manufactured with very high tensile strengths (see Section 4.7). Perhaps surprisingly for a glassy substance, the fibers may also be bent to quite small radii or twisted without damage. Furthermore, cable structures have been developed (see Section 4.9.4) which have proved flexible, compact and extremely rugged. Taking the size and weight advantage into account, these optical fiber cables are generally superior in terms of storage, transportation, handling and installation to corresponding copper cables, whilst exhibiting at least comparable strength and durability

(h) System reliability and ease of maintenance. These features primarily stem from the low loss property of optical fiber cables which reduces the requirement for intermediate repeaters or line amplifiers to boost the transmitted signal strength. Hence with fewer repeaters, system reliability is generally enhanced in comparison with conventional electrical conductor systems. Furthermore, the reliability of the optical components is no longer a problem with predicted lifetimes of 20 to 30 years

now quite common. Both these factors also tend to reduce maintenance time and costs.

(i) Potential low cost. The glass which generally provides the optical fiber transmission medium is made from sand – not a scarce resource. So, in comparison with copper conductors, optical fibers offer the potential for low cost line communication. Although over recent years this potential has largely been realized in the costs of the optical fiber transmission medium which for bulk purchases is now becoming competitive with copper wires (i.e. twisted pairs), it has not yet been achieved in all the other component areas associated with optical fiber communications. For example, the costs of high performance semiconductor lasers and detector photodiodes are still relatively high, as well as some of those concerned with the connection technology (demountable connectors, couplers, etc.).

Overall system costs when utilizing optical fiber communication on long-haul links, however, are substantially less than those for equivalent electrical line systems because of the low loss and wideband properties of the optical transmission medium. As indicated in (f), the requirement for intermediate repeaters and the associated electronics is reduced, giving a substantial cost advantage. Although this cost benefit gives a net gain for long-haul links it is not always the case in short-haul applications where the additional cost incurred, due to the electrical–optical conversion (and vice versa), may be a deciding factor. Nevertheless, there are other possible cost advantages in relation to shipping, handling, installation and maintenance, as well as the features indicated in (c) and (d) which may prove significant in the system choice.

The reducing costs of optical fiber communications has not only provided strong competition with electrical line transmission systems, but also for microwave and millimetre wave radio transmission systems. Although these systems are reasonably wideband the relatively short span 'line of sight' transmission necessitates expensive aerial towers at intervals no greater than a few tens of kilometres. Hence optical fiber is fast becoming the dominant transmission medium within the major industrialized societies.

Many advantages are therefore provided by the use of a lightwave carrier within a transmission medium consisting of an optical fiber. The fundamental principles giving rise to these enhanced performance characteristics, together with their practical realization, are described in the following chapters. However, a general understanding of the basic nature and properties of light is assumed. If this is lacking, the reader is directed to the many excellent texts encompassing the topic, a few of which are indicated in Refs. 18 to 25.

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2

Optical fiber waveguides

2.1 Introduction

The transmission of light via a dielectric waveguide structure was first proposed and investigated at the beginning of the twentieth century. In 1910 Hondros and Debye [Ref. 1] conducted a theoretical study, and experimental work was reported by Schriever in 1920 [Ref. 2]. However, a transparent dielectric rod, typically of silica glass with a refractive index of around 1.5, surrounded by air, proved to be an impractical waveguide due to its unsupported structure (especially when very thin waveguides were considered in order to limit the number of optical modes propagated) and the excessive losses at any discontinuities of the glass–air interface. Nevertheless, interest in the application of dielectric optical waveguides in such areas as optical imaging and medical diagnosis (e.g. endoscopes) led to proposals [Refs. 3 and 4] for a clad dielectric rod in the mid-1950s in order to overcome these problems. This structure is illustrated in Figure 2.1, which shows a

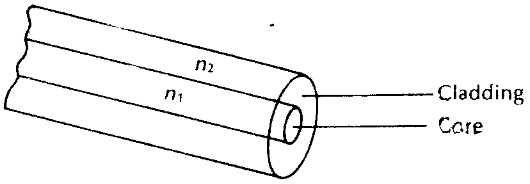

Figure 2.1 Optical fiber waveguide showing the core of refractive index n_1, surrounded by the cladding of slightly lower refractive index n_2.

transparent core with a refractive index n_1 surrounded by a transparent cladding of slightly lower refractive index n_2. The cladding supports the waveguide structure whilst also, when sufficiently thick, substantially reducing the radiation loss into the surrounding air. In essence, the light energy travels in both the core and the cladding allowing the associated fields to decay to a negligible value at the cladding–air interface.

The invention of the clad waveguide structure led to the first serious proposals by Kao and Hockham [Ref. 5] and Werts [Ref. 6], in 1966, to utilize optical fibers as a communications medium, even though they had losses in excess of 1000 dB km^{-1}. These proposals stimulated tremendous efforts to reduce the attenuation by purification of the materials. This has resulted in improved conventional glass refining techniques giving fibers with losses of around 4.2 dB km^{-1} [Ref. 7]. Also, progress in glass refining processes such as depositing vapour-phase reagents to form silica [Ref. 8] has allowed fibers with losses below 1 dB km^{-1} to be fabricated.

Most of this work was focused on the 0.8 to 0.9 μm wavelength band because the first generation optical sources fabricated from gallium aluminum arsenide alloys operated in this region. However, as silica fibers were studied in further detail it became apparent that transmission at longer wavelengths (1.1 to 1.6 μm) would result in lower losses and reduced signal dispersion. This produced a shift in optical fiber source and detector technology in order to provide operation at these longer wavelengths. Hence at longer wavelengths, especially around 1.55 μm, fibers with losses as low as 0.2 dB km^{-1} have been reported [Ref. 9].

Such losses, however, are very close to the theoretical lower limit for silicate glass fiber and, more recently, interest has grown in glass forming systems which can provide low loss transmission in the mid-infrared (2 to 5 μm) and also the far-infrared (8 to 12 μm) optical wavelength regions. At present the best developed of these systems which offers the potential for ultra-low-loss transmission of around 0.01 dB km^{-1} at a wavelength of 2.55 μm is based on fluoride glass [Ref. 10].

In order to appreciate the transmission mechanism of optical fibers with dimensions approximating to those of a human hair, it is necessary to consider the optical waveguiding of a cylindrical glass fiber. Such a fiber acts as an open optical waveguide, which may be analysed utilizing simple ray theory. However, the concepts of geometric optics are not sufficient when considering all types of optical fiber, and electromagnetic mode theory must be used to give a complete picture. The following sections will therefore outline the transmission of light in optical fibers prior to a more detailed discussion of the various types of fiber.

In Section 2.2 we continue the discussion of light propagation in optical fibers using the ray theory approach in order to develop some of the fundamental parameters associated with optical fiber transmission (acceptance angle, numerical aperture, etc.). Furthermore, this provides a basis for the discussion of electromagnetic wave propagation presented in Section 2.3, where the electromagnetic mode theory is developed for the planar (rectangular) waveguide. Following, in Section 2.4, we discuss the waveguiding mechanism within cylindrical fibers prior to consideration of both step and graded index fibers. Finally, in Section 2.5 the theoretical concepts and important parameters (cutoff wavelength, spot size, propagation constant, etc.) associated with optical propagation in single-mode fibers are introduced and approximate techniques to obtain values for these parameters are described.

2.2 Ray theory transmission

2.2.1 Total internal reflection

To consider the propagation of light within an optical fiber utilizing the ray theory model it is necessary to take account of the refractive index of the dielectric medium. The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum to the velocity of light in the medium. A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect. When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs, as illustrated in Figure 2.2(a). It may be observed that the ray approaching the interface is propagating in a dielectric of refractive index n_1 and is at an angle ϕ_1 to the normal at the surface of the interface. If the dielectric on the other side of the interface has a refractive index n_2 which is less than n_1, then the refraction is such that the ray path in this lower index medium is at an angle ϕ_2 to the normal, where ϕ_2 is greater than ϕ_1. The angles of incidence ϕ_1 and refraction ϕ_2 are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction [Ref. 11], which states that:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

or

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1} \tag{2.1}$$

It may also be observed in Figure 2.2(a) that a small amount of light is reflected back into the originating dielectric medium (partial internal reflection). As n_1 is

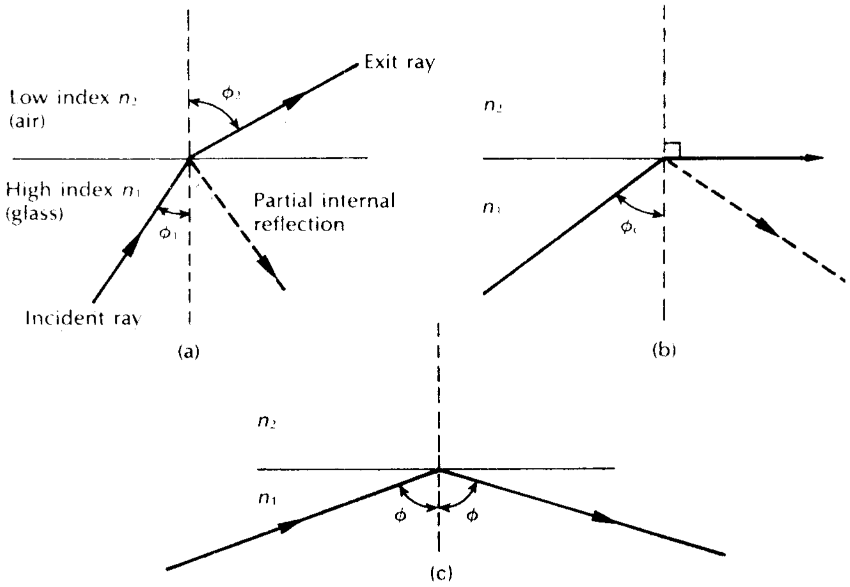

Figure 2.2 Light rays incident on high to low refractive index interface (e.g glass–air): (a) refraction; (b) the limiting case of refraction showing the critical ray at an angle ϕ_c; (c) total internal reflection where $\phi > \phi_c$.

greater than n_2, the angle of refraction is always greater than the angle of incidence. Thus when the angle of refraction is 90° and the refracted ray emerges parallel to the interface between the dielectrics the angle of incidence must be less than 90° This is the limiting case of refraction and the angle of incidence is now know as the critical angle ϕ_c, as shown in Figure 2.2(b). From Eq. (2.1) the value of the critical angle is given by:

$$\sin \phi_c = \frac{n_2}{n_1} \tag{2.2}$$

At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium (total internal reflection) with high efficiency (around 99.9%). Hence, it may be observed in Figure 2.2(c) that total internal reflection occurs at the interface between two dielectrics of differing refractive indices when light is incident on the dielectric of lower index from the dielectric of higher index, and the angle of incidence of the ray exceeds the critical value. This is the mechanism by which light at a sufficiently shallow angle (less than $90° - \phi_c$) may be considered to propagate down an optical fiber with low loss. Figure 2.3 illustrates the transmission of a light ray in an optical fiber via a series of total internal reflections at the interface of the silica core and the slightly lower refractive index silica cladding. The ray has an angle of incidence ϕ at the interface which is greater than the critical angle and is reflected at the same angle to the normal.

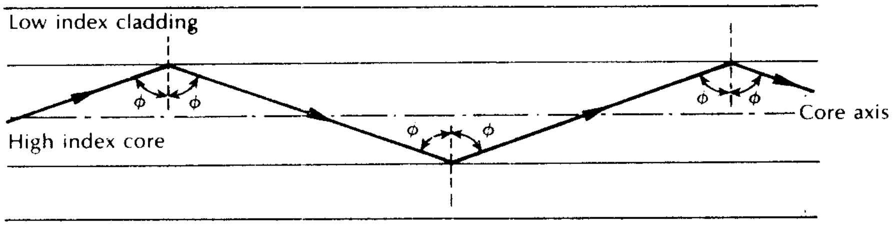

Figure 2.3 The transmission of a light ray in a perfect optical fiber.

The light ray shown in Figure 2.3 is known as a meridional ray as it passes through the axis of the fiber core. This type of ray is the simplest to describe and is generally used when illustrating the fundamental transmission properties of optical fibers. It must also be noted that the light transmission illustrated in Figure 2.3 assumes a perfect fiber, and that any discontinuities or imperfections at the core–cladding interface would probably result in refraction rather than total internal reflection, with the subsequent loss of the light ray into the cladding.

2.2.2 Acceptance angle

Having considered the propagation of light in an optical fiber through total internal reflection at the core–cladding interface, it is useful to enlarge upon the geometric optics approach with reference to light rays entering the fiber. Since only rays with a sufficiently shallow grazing angle (i.e. with an angle to the normal greater than ϕ_c) at the core–cladding interface are transmitted by total internal reflection, it is clear that not all rays entering the fiber core will continue to be propagated down its length.

The geometry concerned with launching a light ray into an optical fiber is shown in Figure 2.4, which illustrates a meridional ray A at the critical angle ϕ_c within the fiber at the core–cladding interface. It may be observed that this ray enters the fiber core at an angle θ_a to the fiber axis and is refracted at the air–core interface before transmission to the core–cladding interface at the critical angle. Hence, any rays which are incident into the fiber core at an angle greater than θ_a will be transmitted to the core–cladding interface at an angle less than ϕ_c, and will not be totally internally reflected. This situation is also illustrated in Figure 2.4, where the incident ray B at an angle greater than θ_a is refracted into the cladding and eventually lost by radiation. Thus for rays to be transmitted by total internal reflection within the fiber core they must be incident on the fiber core within an acceptance cone defined by the conical half angle θ_a. Hence θ_a is the maximum angle to the axis at which light may enter the fiber in order to be propagated, and is often referred to as the acceptance angle[*] for the fiber.

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[*] θ_a is sometimes referred to as the maximum or total acceptance angle.

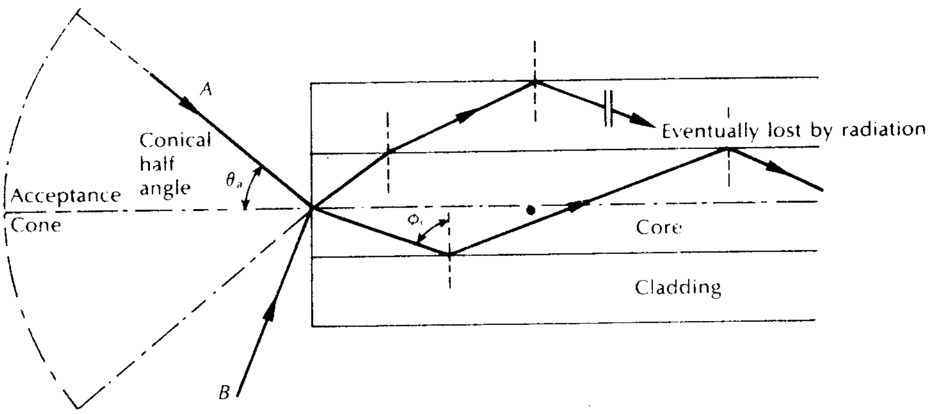

Figure 2.4 The acceptance angle θ_a when launching light into an optical fiber.

If the fiber has a regular cross section (i.e. the core–cladding interfaces are parallel and there are no discontinuities) an incident meridional ray at greater than the critical angle will continue to be reflected and will be transmitted through the fiber. From symmetry considerations it may be noted that the output angle to the axis will be equal to the input angle for the ray, assuming the ray emerges into a medium of the same refractive index from which it was input.

2.2.3 Numerical aperture

The acceptance angle for an optical fiber was defined in the preceding section. However, it is possible to continue the ray theory analysis to obtain a relationship between the acceptance angle and the refractive indices of the three media involved, namely the core, cladding and air. This leads to the definition of a more generally used term, the numerical aperture (NA) of the fiber. It must be noted that within this analysis, as with the preceding discussion of acceptance angle, we are concerned with meridional rays within the fiber.

Figure 2.5 shows a light ray incident on the fiber core at an angle θ_1 to the fiber axis which is less than the acceptance angle for the fiber θ_a. The ray enters the fiber from a medium (air) of refractive index n_0, and the fiber core has a refractive index n_1, which is slightly greater than the cladding refractive index n_2. Assuming the entrance face at the fiber core to be normal to the axis, then considering the refraction at the air–core interface and using Snell's law given by Eq. (2.1)

$$n_0 \sin \theta_1 = n_1 \sin \theta_2 \tag{2.3}$$

Considering the right-angled triangle *ABC* indicated in Figure 2.5, then:

$$\phi = \frac{\pi}{2} - \theta_2 \tag{2.4}$$

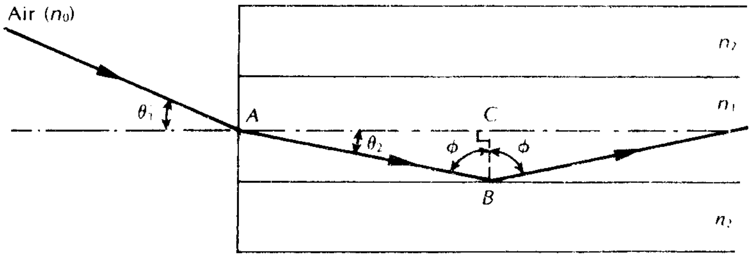

Figure 2.5 The ray path for a meridional ray launched into an optical fiber in air at an input angle less than the acceptance angle for the fiber.

where ϕ is greater than the critical angle at the core–cladding interface. Hence Eq. (2.3) becomes

$$n_0 \sin \theta_1 = n_1 \cos \phi \tag{2.5}$$

Using the trigonometrical relationship $\sin^2\phi + \cos^2\phi = 1$, Eq. (2.5) may be written in the form

$$n_0 \sin \theta_1 = n_1(1 - \sin^2 \phi)^{\frac{1}{2}} \tag{2.6}$$

When the limiting case for total internal reflection is considered, ϕ becomes equal to the critical angle for the core–cladding interface and is given by Eq. (2.2). Also in this limiting case θ_1 becomes the acceptance angle for the fiber θ_a. Combining these limiting cases into Eq. (2.6) gives:

$$n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \tag{2.7}$$

Equation (2.7), apart from relating the acceptance angle to the refractive indices, serves as the basis for the definition of the important optical fiber parameter, the numerical aperture (*NA*). Hence the *NA* is defined as:

$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \tag{2.8}$$

Since the *NA* is often used with the fiber in air where n_0 is unity, it is simply equal to $\sin \theta_a$. It may also be noted that incident meridional rays over the range $0 \leqslant \theta_1 \leqslant \theta_a$ will be propagated within the fiber.

The numerical aperture may also be given in terms of the relative refractive index difference Δ between the core and the cladding which is defined as:*

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

$$\simeq \frac{n_1 - n_2}{n_1} \quad \text{for } \Delta \ll 1 \tag{2.9}$$

---

* Sometimes another parameter $\Delta n = n_1 - n_2$ is referred to as the index difference and $\Delta n/n_1$ as the fractional index difference. Hence Δ also approximates to the fractional index difference.

Hence combining Eq. (2.8) with Eq. (2.9) we can write:

$$NA = n_1(2\Delta)^{\frac{1}{2}} \tag{2.10}$$

The relationships given in Eqs. (2.8) and (2.10) for the numerical aperture are a very useful measure of the light-collecting ability of a fiber. They are independent of the fiber core diameter and will hold for diameters as small as 8 μm. However, for smaller diameters they break down as the geometric optics approach is invalid. This is because the ray theory model is only a partial description of the character of light. It describes the direction a plane wave component takes in the fiber but does not take into account interference between such components. When interference phenomena are considered it is found that only rays with certain discrete characteristics propagate in the fiber core. Thus the fiber will only support a discrete number of guided modes. This becomes critical in small core diameter fibers which only support one or a few modes. Hence electromagnetic mode theory must be applied in these cases [Ref. 12].

Example 2.1

A silica optical fiber with a core diameter large enough to be considered by ray theory analysis has a core refractive index of 1.50 and a cladding refractive index of 1.47.

Determine: (a) the critical angle at the core–cladding interface; (b) the NA for the fiber; (c) the acceptance angle in air for the fiber.

Solution: (a) The critical angle ϕ_c at the core–cladding interface is given by Eq. (2.2) where:

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.47}{1.50}$$
$$= 78.5^\circ$$

(b) From Eq. (2.8) the numerical aperture is:

$$NA = (n_1^2 - n_2^2)^{\frac{1}{2}} = (1.50^2 - 1.47^2)^{\frac{1}{2}}$$
$$= (2.25 - 2.16)^{\frac{1}{2}}$$
$$= 0.30$$

(c) Considering Eq. (2.8) the acceptance angle in air θ_a is given by:

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.30$$
$$= 17.4^\circ$$

Example 2.2

A typical relative refractive index difference for an optical fiber designed for long distance transmission is 1%. Estimate the NA and the solid acceptance angle in air for the fiber when the core index is 1.46. Further, calculate the critical angle at the core–cladding interface within the fiber. It may be assumed that the concepts of geometric optics hold for the fiber.

Solution: Using Eq. (2.10) with $\Delta = 0.01$ gives the numerical aperture as:

$$NA = n_1(2\Delta)^{\frac{1}{2}} = 1.46(0.02)^{\frac{1}{2}}$$
$$= 0.21$$

For small angles the solid acceptance angle in air ζ is given by:

$$\zeta \simeq \pi\theta_a^2 = \pi \sin^2 \theta_a$$

Hence from Eq. (2.8):

$$\zeta \simeq \pi(NA)^2 = \pi\ 0.04$$
$$= 0.13 \text{ rad}$$

Using Eq. (2.9) for the relative refractive index difference Δ gives:

$$\Delta \simeq \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1}$$

Hence

$$\frac{n_2}{n_1} = 1 - \Delta = 1 - 0.01$$
$$= 0.99$$

From Eq. (2.2) the critical angle at the core–cladding interface is:

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1} 0.99$$
$$= 81.9°$$

2.2.4 Skew rays

In the preceding sections we have considered the propagation of meridional rays in the optical waveguide. However, another category of ray exists which is transmitted without passing through the fiber axis. These rays, which greatly outnumber the meridional rays, follow a helical path through the fiber, as illustrated in Figure 2.6, and are called skew rays. It is not easy to visualize the skew ray paths in two dimensions but it may be observed from Figure 2.6(b) that the helical path traced through the fiber gives a change in direction of 2γ at each reflection where γ is the angle between the projection of the ray in two dimensions and the radius of the fiber core at the point of reflection. Hence, unlike meridional rays, the point of emergence of skew rays from the fiber in air will depend upon the number of reflections they undergo rather than the input conditions to the fiber. When the light input to the fiber is nonuniform, skew rays will therefore tend to have a smoothing

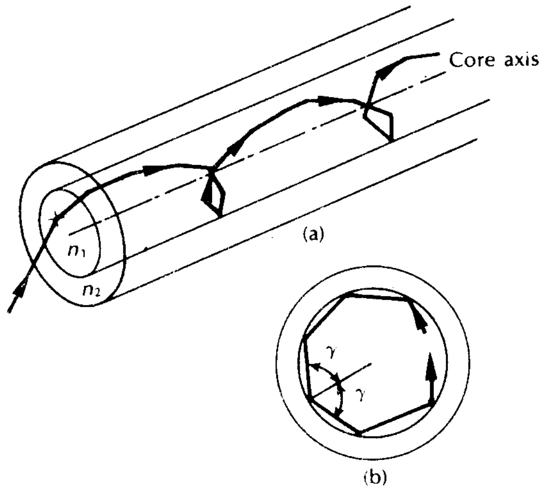

Figure 2.6 The helical path taken by a skew ray in an optical fiber: (a) skew ray path down the fiber; (b) cross-sectional view of the fiber.

effect on the distribution of the light as it is transmitted, giving a more uniform output. The amount of smoothing is dependent on the number of reflections encountered by the skew rays.

A further possible advantage of the transmission of skew rays becomes apparent when their acceptance conditions are considered. In order to calculate the acceptance angle for a skew ray it is necessary to define the direction of the ray in two perpendicular planes. The geometry of the situation is illustrated in Figure 2.7

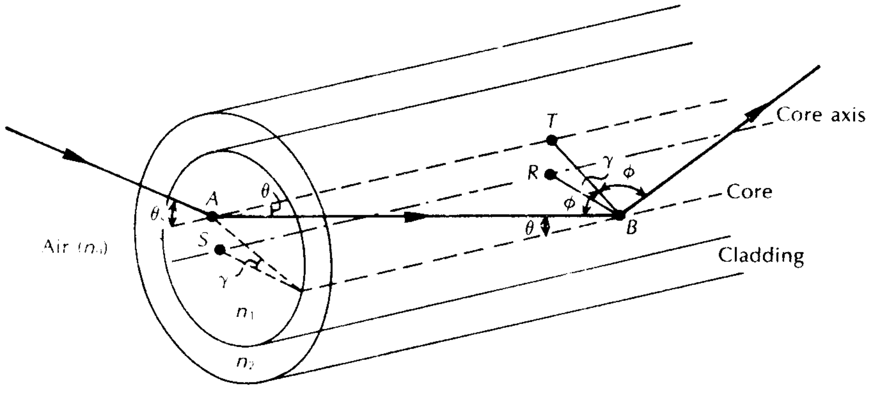

Figure 2.7 The ray path within the fiber core for a skew ray incident at an angle θ_s to the normal at the air–core interface.

where a skew ray is shown incident on the fiber core at the point A, at an angle θ_s to the normal at the fiber end face. The ray is refracted at the air–core interface before travelling to the point B in the same plane. The angles of incidence and reflection at the point B are ϕ, which is greater than the critical angle for the core–cladding interface.

When considering the ray between A and B it is necessary to resolve the direction of the ray path AB to the core radius at the point B. As the incident and reflected rays at the point B are in the same plane, this is simply $\cos \phi$. However, if the two perpendicular planes through which the ray path AB traverses are considered, then γ is the angle between the core radius and the projection of the ray on to a plane BRS normal to the core axis, and θ is the angle between the ray and a line AT drawn parallel to the core axis. Thus to resolve the ray path AB relative to the radius BR in these two perpendicular planes requires multiplication by $\cos \gamma$ and $\sin \theta$.

Hence, the reflection at point B at an angle ϕ may be given by:

$$\cos \gamma \sin \theta = \cos \phi \tag{2.11}$$

Using the trigonometrical relationship $\sin^2 \phi + \cos^2 \phi = 1$, Eq. (2.11) becomes

$$\cos \gamma \sin \theta = \cos \phi = (1 - \sin^2 \phi)^{\frac{1}{2}} \tag{2.12}$$

If the limiting case for total internal reflection is now considered, then ϕ becomes equal to the critical angle ϕ_c for the core–cladding interface and, following Eq. (2.2), is given by $\sin \phi_c = n_2/n_1$. Hence, Eq. (2.12) may be written as:

$$\cos \gamma \sin \theta \leqslant \cos \phi_c = \left(1 - \frac{n_2^2}{n_1^2}\right)^{\frac{1}{2}} \tag{2.13}$$

Furthermore, using Snell's law at the point A, following Eq. (2.1) we can write:

$$n_0 \sin \theta_a = n_1 \sin \theta \tag{2.14}$$

where θ_a represents the maximum input axial angle for meridional rays, as expressed in Section 2.2.2, and θ is the internal axial angle. Hence substituting for $\sin \theta$ from Eq. (2.13) into Eq. (2.14) gives:

$$\sin \theta_{as} = \frac{n_1}{n_0} \frac{\cos \phi_c}{\cos \gamma} = \frac{n_1}{n_0 \cos \gamma} \left(1 - \frac{n_2^2}{n_1^2}\right)^{\frac{1}{2}} \tag{2.15}$$

where θ_{as} now represents the maximum input angle or acceptance angle for skew rays. It may be noted that the inequality shown in Eq. (2.13) is no longer necessary as all the terms in Eq. (2.15) are specified for the limiting case. Thus the acceptance conditions for skew rays are:

$$n_0 \sin \theta_{as} \cos \gamma = (n_1^2 - n_2^2)^{\frac{1}{2}} = NA \tag{2.16}$$

and in the case of the fiber in air ($n_0 = 1$):

$$\sin \theta_{as} \cos \gamma = NA \tag{2.17}$$

Therefore by comparison with Eq. (2.8) derived for meridional rays, it may be noted that skew rays are accepted at larger axial angles in a given fiber than meridional rays; depending upon the value of $\cos\gamma$. In fact, for meridional rays $\cos\gamma$ is equal to unity and θ_{as} becomes equal to θ_a. Thus although θ_a is the maximum conical half angle for the acceptance of meridional rays, it defines the minimum input angle for skew rays. Hence, as may be observed from Figure 2.6, skew rays tend to propagate only in the annular region near the outer surface of the core, and do not fully utilize the core as a transmission medium. However, they are complementary to meridional rays and increase the light-gathering capacity of the fiber. This increased light-gathering ability may be significant for large NA fibers, but for most communication design purposes the expressions given in Eqs. (2.8) and (2.10) for meridional rays are considered adequate.

Example 2.3

An optical fiber in air has an *NA* of 0.4. Compare the acceptance angle for meridional rays with that for skew rays which change direction by 100° at each reflection.

Solution: The acceptance-angle for meridional rays is given by Eq. (2.8) with $n_0 = 1$ as

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.4$$
$$= 23.6^\circ$$

The skew rays change direction by 100° at each reflection, therefore $\gamma = 50^\circ$. Hence using Eq. (2.17) the acceptance angle for skew rays is:

$$\theta_{as} = \sin^{-1}\left(\frac{NA}{\cos\gamma}\right) = \sin^{-1}\left(\frac{0.4}{\cos 50^\circ}\right)$$
$$= 38.5^\circ$$

In this example, the acceptance angle for the skew rays is about 15° greater than the corresponding angle for meridional rays. However, it must be noted that we have only compared the acceptance angle of one particular skew ray path. When the light input to the fiber is at an angle to the fiber axis, it is possible that γ will vary from zero for meridional rays to 90° for rays which enter the fiber at the core–cladding interface giving acceptance of skew rays over a conical half angle of $\pi/2$ radians.

2.3 Electromagnetic mode theory for optical propagation

2.3.1 Electromagnetic waves

In order to obtain an improved model for the propagation of light in an optical fiber, electromagnetic wave theory must be considered. The basis for the study of electromagnetic wave propagation is provided by Maxwell's equations [Ref. 13]. For a medium with zero conductivity these vector relationships may be written in terms of the electric field **E**, magnetic field **H**, electric flux density **D** and magnetic flux density **B** as the curl equations:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{2.18}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \tag{2.19}$$

and the divergence conditions:

$$\nabla \cdot \mathbf{D} = 0 \quad \text{(no free charges)} \tag{2.20}$$

$$\nabla \cdot \mathbf{B} = 0 \quad \text{(no free poles)} \tag{2.21}$$

where ∇ is a vector operator.

The four field vectors are related by the relations:

$$\begin{aligned} \mathbf{D} &= \varepsilon \mathbf{E} \\ \mathbf{B} &= \mu \mathbf{H} \end{aligned} \tag{2.22}$$

where ε is the dielectric permittivity and μ is the magnetic permeability of the medium.

Substituting for **D** and **B** and taking the curl of Eqs. (2.18) and (2.19) gives

$$\nabla \times (\nabla \times \mathbf{E}) = -\mu\varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} \tag{2.23}$$

$$\nabla \times (\nabla \times \mathbf{H}) = -\mu\varepsilon \frac{\partial^2 \mathbf{H}}{\partial t^2} \tag{2.24}$$

Then using the divergence conditions of Eqs. (2.20) and (2.21) with the vector identity

$$\nabla \times (\nabla \times \mathbf{Y}) = \nabla(\nabla \cdot \mathbf{Y}) - \nabla^2(\mathbf{Y})$$

we obtain the nondispersive wave equations:

$$\nabla^2 \mathbf{E} = \mu\varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} \tag{2.25}$$

and

$$\nabla^2 \mathbf{H} = \mu\varepsilon \frac{\partial^2 \mathbf{H}}{\partial t^2} \tag{2.26}$$

where ∇^2 is the Laplacian operator. For rectangular Cartesian and cylindrical polar coordinates the above wave equations hold for each component of the field vector, every component satisfying the scalar wave equation:

$$\nabla^2\psi = \frac{1}{v_p^2}\frac{\partial^2\psi}{\partial t^2} \tag{2.27}$$

where ψ may represent a component of the **E** or **H** field and v_p is the phase velocity (velocity of propagation of a point of constant phase in the wave) in the dielectric medium. It follows that

$$v_p = \frac{1}{(\mu\varepsilon)^{\frac{1}{2}}} = \frac{1}{(\mu_r\mu_0\varepsilon_r\varepsilon_0)^{\frac{1}{2}}} \tag{2.28}$$

where μ_r and ε_r are the relative permeability and permittivity for the dielectric medium and μ_0 and ε_0 are the permeability and permittivity of free space. The velocity of light in free space c is therefore

$$c = \frac{1}{(\mu_0\varepsilon_0)^{\frac{1}{2}}} \tag{2.29}$$

If planar waveguides, described by rectangular Cartesian coordinates (x, y, z), or circular fibers, described by cylindrical polar coordinates (r, ϕ, z), are considered, then the Laplacian operator takes the form:

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} + \frac{\partial^2\psi}{\partial z^2} \tag{2.30}$$

or

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial r^2} + \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\psi}{\partial\phi^2} + \frac{\partial^2\psi}{\partial z^2} \tag{2.31}$$

respectively. It is necessary to consider both these forms for a complete treatment of optical propagation in the fiber, although many of the properties of interest may be dealt with using Cartesian coordinates.

The basic solution of the wave equation is a sinusoidal wave, the most important form of which is a uniform plane wave given by:

$$\psi = \psi_0 \exp \mathrm{j}(\omega t - \mathbf{k}\cdot\mathbf{r}) \tag{2.32}$$

where ω is the angular frequency of the field, t is the time, $\mathbf{k}$ is the propagation vector which gives the direction of propagation and the rate of change of phase with distance, whilst the components of $\mathbf{r}$ specify the coordinate point at which the field is observed. When λ is the optical wavelength in a vacuum, the magnitude of the propagation vector or the vacuum phase propagation constant k (where $k = |\mathbf{k}|$) is given by:

$$k = \frac{2\pi}{\lambda} \tag{2.33}$$

It should be noted that in this case k is also referred to as the free space wave number.

2.3.2 Modes in a planar guide

The planar guide is the simplest form of optical waveguide. We may assume it consists of a slab of dielectric with refractive index n_1 sandwiched between two regions of lower refractive index n_2. In order to obtain an improved model for optical propagation it is useful to consider the interference of plane wave components within this dielectric waveguide.

The conceptual transition from ray to wave theory may be aided by consideration of a plane monochromatic wave propagating in the direction of the ray path within the guide (see Figure 2.8(a)). As the refractive index within the guide is n_1, the optical wavelength in this region is reduced to λ/n_1, whilst the vacuum propagation constant is increased to n_1k. When θ is the angle between the wave propagation vector or the equivalent ray and the guide axis, the plane wave can be resolved into two component plane waves propagating in the z and x directions, as shown in Figure 2.8(a). The component of the phase propagation constant in the z direction β_z is given by:

$$\beta_z = n_1k \cos\theta \tag{2.34}$$

The component of the phase propagation constant in the x direction β_x is:

$$\beta_x = n_1k \sin\theta \tag{2.35}$$

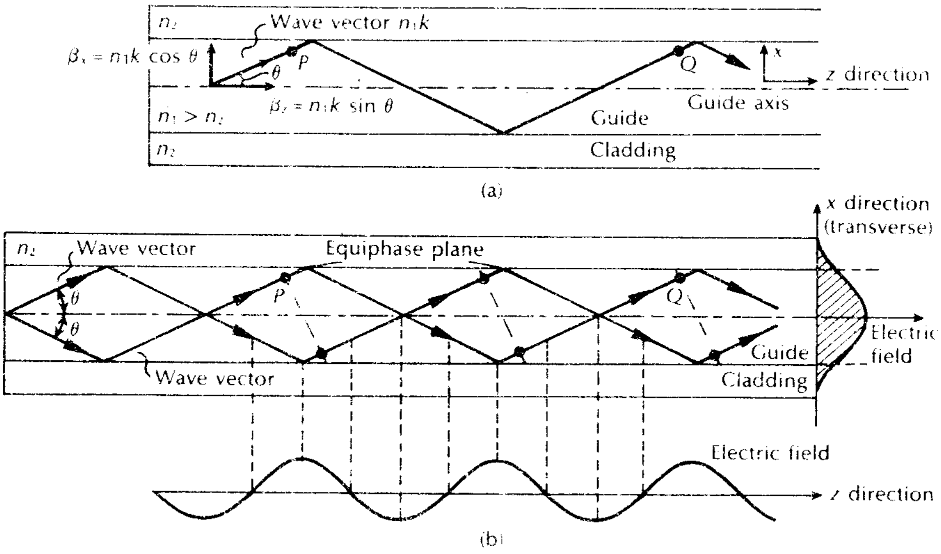

Figure 2.8 The formation of a mode in a planar dielectric guide: (a) a plane wave propagating in the guide shown by its wave vector or equivalent ray – the wave vector is resolved into components in the z and x directions; (b) the interference of plane waves in the guide forming the lowest order mode ($m = 0$).

The component of the plane wave in the x direction is reflected at the interface between the higher and lower refractive index media. When the total phase change[*] after two successive reflections at the upper and lower interfaces (between the points P and Q) is equal to $2m\pi$ radians, where m is an integer, then constructive interference occurs and a standing wave is obtained in the x direction. This situation is illustrated in Figure 2.8(b), where the interference of two plane waves is shown. In this illustration it is assumed that the interference forms the lowest order (where $m = 0$) standing wave, where the electric field is a maximum at the centre of the guide decaying towards zero at the boundary between the guide and cladding. However, it may be observed from Figure 2.8(b) that the electric field penetrates some distance into the cladding, a phenomenon which is discussed in Section 2.3.4.

Nevertheless, the optical wave is effectively confined within the guide and the electric field distribution in the x direction does not change as the wave propagates in the z direction. The sinusoidally varying electric field in the z direction is also shown in Figure 2.8(b). The stable field distribution in the x direction with only a periodic z dependence is known as a mode. A specific mode is obtained only when the angle between the propagation vectors or the rays and the interface have a particular value, as indicated in Figure 2.8(b). In effect, Eqs. (2.34) and (2.35) define a group or congruence of rays which in the case described represents the lowest order mode. Hence the light propagating within the guide is formed into discrete modes, each typified by a distinct value of θ. These modes have a periodic z dependence of the form $\exp(-j\beta_z z)$ where β_z becomes the propagation constant for the mode as the modal field pattern is invariant except for a periodic z dependence. Hence, for notational simplicity, and in common with accepted practice, we denote the mode propagation constant by β, where $\beta = \beta_z$. If we now assume a time dependence for the monochromatic electromagnetic light field with angular frequency ω of $\exp(j\omega t)$, then the combined factor $\exp j(\omega t - \beta z)$ describes a mode propagating in the z direction.

To visualize the dominant modes propagating in the z direction we may consider plane waves corresponding to rays at different specific angles in the planar guide. These plane waves give constructive interference to form standing wave patterns across the guide following a sine or cosine formula. Figure 2.9 shows examples of such rays for $m = 1, 2, 3$, together with the electric field distributions in the x direction. It may be observed that m denotes the number of zeros in this transverse field pattern. In this way m signifies the order of the mode and is known as the mode number.

When light is described as an electromagnetic wave it consists of a periodically varying electric field **E** and magnetic field **H** which are orientated at right angles to each other. The transverse modes shown in Figure 2.9 illustrate the case when the

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[*] It should be noted that there is a phase shift on reflection of the plane wave at the interface as well as a phase change with distance travelled. The phase shift on reflection at a dielectric interface is dealt with in Section 2.3.4.

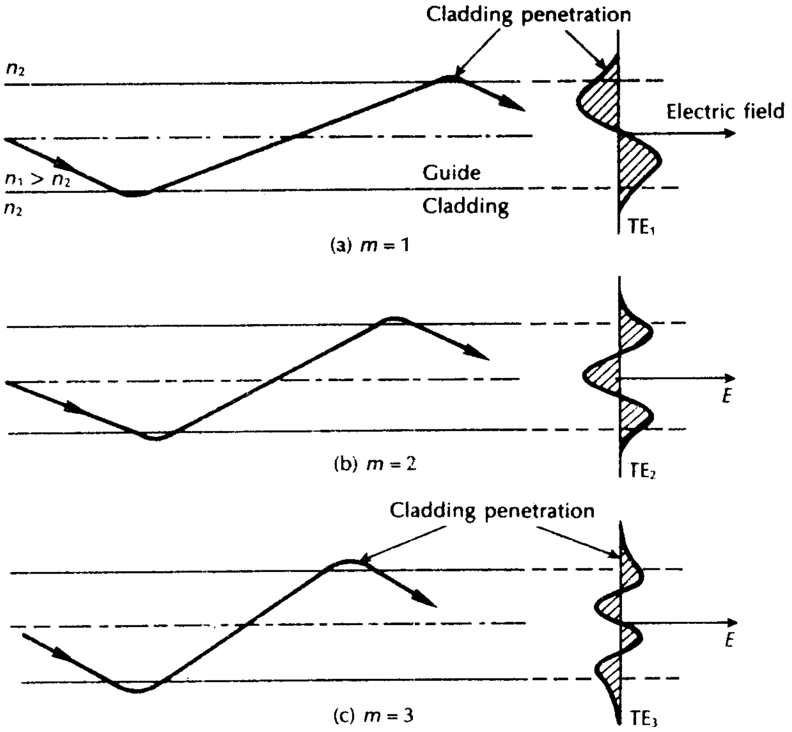

Figure 2.9 Physical model showing the ray propagation and the corresponding transverse electric (TE) field patterns of three lower order models ($m = 1, 2, 3$) in the planar dielectric guide.

electric field is perpendicular to the direction of propagation and hence $E_z = 0$, but a corresponding component of the magnetic field $\mathbf{H}$ is in the direction of propagation. In this instance the modes are said to be transverse electric (TE). Alternatively, when a component of the $\mathbf{E}$ field is in the direction of propagation, but $H_z = 0$, the modes formed are called transverse magnetic (TM). The mode numbers are incorporated into this nomenclature by referring to the TE_m and TM_m modes, as illustrated for the transverse electric modes shown in Figure 2.9. When the total field lies in the transverse plane, transverse electromagnetic (TEM) waves exist where both E_z and H_z are zero. However, although TEM waves occur in metallic conductors (e.g. coaxial cables) they are seldom found in optical waveguides.

2.3.3 Phase and group velocity

Within all electromagnetic waves, whether plane or otherwise, there are points of constant phase. For plane waves these constant phase points form a surface which is referred to as a wavefront. As a monochromatic light wave propagates along a waveguide in the z direction these points of constant phase travel at a phase velocity v_p given by:

$$v_p = \frac{\omega}{\beta} \tag{2.36}$$

where ω is the angular frequency of the wave. However, it is impossible in practice to produce perfectly monochromatic light waves, and light energy is generally composed of a sum of plane wave components of different frequencies. Often the situation exists where a group of waves with closely similar frequencies propagate so that their resultant forms a packet of waves. The formation of such a wave packet resulting from the combination of two waves of slightly different frequency propagating together is illustrated in Figure 2.10. This wave packet does not travel at the phase velocity of the individual waves but is observed to move at a group velocity v_g given by

$$v_g = \frac{\delta\omega}{\delta\beta} \tag{2.37}$$

The group velocity is of greatest importance in the study of the transmission characteristics of optical fibers as it relates to the propagation characteristics of observable wave groups or packets of light.

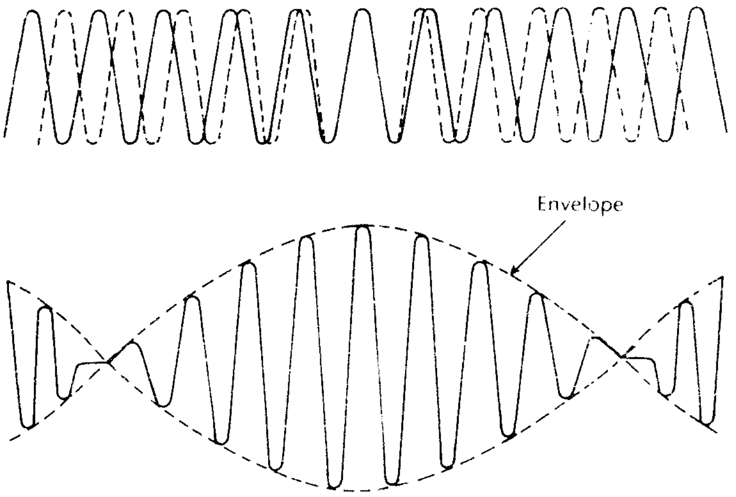

Figure 2.10 The formation of a wave packet from the combination of two waves with nearly equal frequencies. The envelope of the wave package or group of waves travels at a group velocity v_g.

If propagation in an infinite medium of refractive index n_1 is considered, then the propagation constant may be written as:

$$\beta = n_1 \frac{2\pi}{\lambda} = \frac{n_1 \omega}{c} \tag{2.38}$$

where c is the velocity of light in free space. Equation (2.38) follows from Eqs. (2.33) and (2.34) where we assume propagation in the z direction only and hence $\cos\theta$ is equal to unity. Using Eq. (2.36) we obtain the following relationship for the phase velocity

$$v_p = \frac{c}{n_1} \tag{2.39}$$

Similarly, employing Eq. (2.37), where in the limit $\delta\omega/\delta\beta$ becomes $d\omega/d\beta$, the group velocity:

$$\begin{aligned} v_g &= \frac{d\lambda}{d\beta} \cdot \frac{d\omega}{d\lambda} = \frac{d}{d\lambda}\left(n_1 \frac{2\pi}{\lambda}\right)^{-1}\left(\frac{-\omega}{\lambda}\right) \\ &= \frac{-\omega}{2\pi\lambda}\left(\frac{1}{\lambda}\frac{dn_1}{d\lambda} - \frac{n_1}{\lambda^2}\right)^{-1} \\ &= \frac{c}{\left(n_1 - \lambda \dfrac{dn_1}{d\lambda}\right)} = \frac{c}{N_g} \end{aligned} \tag{2.40}$$

The parameter N_g is known as the group index of the guide.

2.3.4 Phase shift with total internal reflection and the evanescent field

The discussion of electromagnetic wave propagation in the planar waveguide given in Section 2.3.2 drew attention to certain phenomena that occur at the guide–cladding interface which are not apparent from ray theory considerations of optical propagation. In order to appreciate these phenomena it is necessary to use the wave theory model for total internal reflection at a planar interface. This is illustrated in Figure 2.11, where the arrowed lines represent wave propagation vectors and a component of the wave energy is shown to be transmitted through the interface into the cladding. The wave equation in Cartesian coordinates for the electric field in a lossless medium is:

$$\nabla^2 \mathbf{E} = \mu\varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} = \frac{\partial^2 \mathbf{E}}{\partial x^2} + \frac{\partial^2 \mathbf{E}}{\partial y^2} + \frac{\partial^2 \mathbf{E}}{\partial z^2} \tag{2.41}$$

As the guide–cladding interface lies in the y–z plane and the wave is incident in the x–z plane on to the interface, then $\partial/\partial y$ may be assumed to be zero. Since the phase fronts must match all points along the interface in the z direction, the three waves shown in Figure 2.11 will have the same propagation constant β in this